

# CASCADE – AN ADVANCED COMPUTATIONAL TOOL FOR WAVEGUIDE COMPONENTS AND WINDOW DESIGN

L. Ives, J. Neilson, W. Vogler, Calabazas Creek Research, Inc., Saratoga, USA

## Abstract

CASCADE is an advanced design program for 2-port waveguide components, RF windows, and waveguide systems. It provides rapid and user-friendly analysis of waveguide components such as filters, nonlinear tapers, mode converters, microwave cavities, and RF windows. It calculates scattering parameters (transmission/reflection coefficients) for general waveguide structures composed of cylindrical, rectangular, or coaxial waveguides. Transitions between waveguide types are also allowed. The program includes dielectric properties of ceramic and finite conductivity of metal surfaces. A built-in optimizer dramatically reduces design time, and the program can import scattering matrices from other program, such as HFSS or measured data, for total system scattering matrix analysis. Statistical tolerance analysis provides information for reducing manufacturing costs by identifying the impact of dimensional tolerances on performance. The basic theory is described, and a number of examples are presented.

## INTRODUCTION

In order to transfer RF power from sources, such as klystrons or magnetrons, the power must pass through a series of components. Typically, the power passes through the vacuum window at the source and enters a waveguide. Between the source and the final destination, it may pass through transitions, bends, filters, mode converters or other structures required by the installation or the final load. These components must be designed such that the power is transmitted or converted efficiently without reflecting significant power back toward the source or converting it to parasitic modes or unusable RF or thermal power. CASCADE is an advanced program for designing such components or systems.

A key parameter in the design of any waveguide system is cost. First, the engineering time to design waveguide systems depends on the performance requirements and the device specifications, such as power level, bandwidth, loss/efficiency, reliability, and duty. Once the performance requirements are achieved, the engineer must consider production cost to manufacture and assemble the system. In many cases, hundreds of components must be built for large installations. The unit cost is an important consideration for the total system cost. CASCADE is a highly efficient and accurate tool for designing individual components or large systems consisting of a series of components. The program is very user-friendly and executes very rapidly on standard personal computers. Because of its rapid execution, it becomes possible to

implement automated optimization routines that can iterate geometrical parameters to achieve performance goals specified by the user. Thus, the computer can design the component or system with little interaction by the user, once the optimization process is initiated. This results in a dramatic reduction in engineering time with achievement of performance goals not practical with manual execution.

The statistical tolerancing feature in CASCADE allows the engineer to determine the impact of dimensional tolerances on device performance. Tolerances can then be relaxed as much as possible while still achieving performance goals, significantly reducing machining costs, particularly for large quantity systems.

CASCADE is designed to model 2-port devices consisting of combinations of rectangular, cylindrical, or coaxial structures. The program can model dielectric materials and include the effects of finite conductivity. It can include the impact of 3D structures by importing calculated or measured scattering parameters. This allows performance optimization of complex waveguide systems.

## THEORY OF OPERATION

Calculation of the scattering matrices in CASCADE is implemented by the mode-matching technique. Details of the derivation can be found in numerous papers[1-3], so only a brief outline of the development is presented here. The field in each waveguide section is represented by the expansion of the electric and magnetic eigenmodes  $\vec{e}_i$  and  $\vec{h}_i$  respectively:

$$\vec{E} = \sum_i (f_i + b_i) \vec{e}_i, \quad \vec{H} = \sum_i \left( \frac{f_i - b_i}{Z_i} \right) \vec{h}_i$$

where  $f$  is the modal amplitude of the forward wave,  $b$  is the amplitude of the backward wave and  $Z$  is the characteristic impedance. Applying continuity of tangential E and H across the common aperture area of the waveguides and enforcing zero tangential electric field on the wall of the larger guide yields the scattering matrices:

$$S_{11} = [I + Z_1 P^T Y_2 P]^{-1} [I - Z_1 P^T Y_2 P]$$

$$S_{12} = 2[I + Z_1 P^T Y_2 P]^{-1} Z_1 P^T Y_2$$

$$S_{21} = 2[I + P Z_1 P^T Y_2]^{-1} P$$

$$S_{22} = -[I + P Z_1 P^T Y_2]^{-1} [I - Z_1 P^T Y_2 P]$$

The coupling matrix P is defined as

$$P_{ji} = \int_{CA} \vec{e}_{j2} \cdot \vec{e}_{j1}^* dA$$

where the integration is performed over the common aperture area between the guides. The complete system scattering matrix is obtained by cascading[3] the scattering matrices of each section.

### PROGRAM OPERATION

CASCADE includes a user-friendly, intuitive interface for geometrical input and specification of execution parameters. Each geometrical section is described by completing a GUI screen determined by the type of section. Figure 1 shows the input screen for a rectangular waveguide section.

The GUI allows input of the relevant geometry, the internal medium (vacuum, ceramic, etc.) and the wall conductivity. The waveguide system geometry is sequentially generated using a series of input screens for various waveguide types.

Several types of analysis are supported. These include:

- scattering matrix – used for determining transmission or reflection characteristics,
- resonant frequency calculation – determines frequency and Q of non-reentrant cavities,
- determinant sweep – searches structure for potential trapped of parasitic modes.

GUI screens are provided for determining the type of analysis, accuracy of the calculation, and frequency range of interest. Execution of a single simulation typically takes only a few seconds.

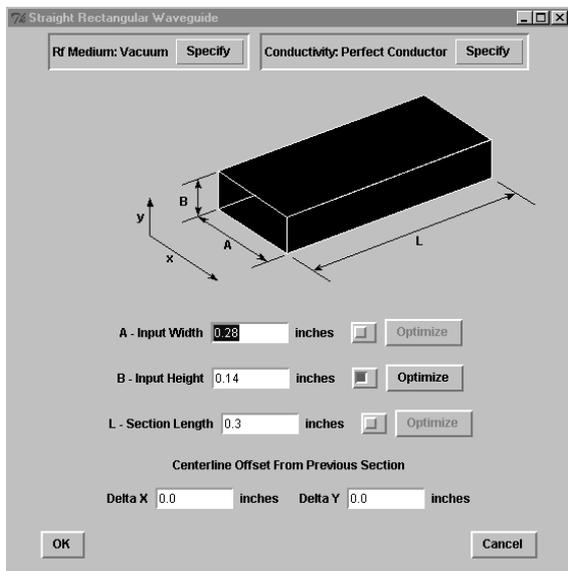


Figure 1. Input screen for rectangular waveguide section

To facilitate rapid component and system design, CASCADE includes three optimization algorithms. These are:

- Quasi-Newton
- Non-Smooth
- Least Squares

To perform an optimization analysis, the user specifies which geometrical parameters can be varied and the allowable variation. The user selects the optimization algorithm and the performance criteria. Once optimization is initiated, the program searches the available parameter space for the optimum solution until it is found or the maximum number of iterations is achieved. In this way, significantly more parameter space can be investigated much faster than practical with manual operation.

Once an acceptable performance is achieved, the user can determine the impact of dimensional tolerances on the performance. The user adds tolerance values to critical dimensions and specifies the number of cases to be investigated, typically 500-1000. The program then sequentially executes analysis of the geometry while varying the critical dimensions within the tolerance ranges specified. When, concluded, the program displays a histogram showing the number of cases falling within various performance ranges (Fig. 2).

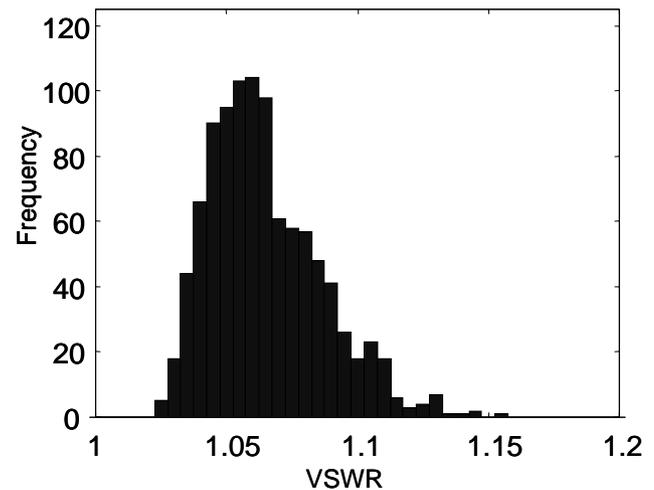


Figure 2. Histogramic display of tolerance analysis results

There are many systems, however, where complex 3D waveguide components exist for which analysis by CASCADE is not applicable. In these cases, the complex 3D component can be modeled using other computer programs, such as MAFIA or HFSS. The scattering matrix for these components can be used as input to CASCADE to design the total system.

An example is the input cavity for a gyrokystron and consists of a rectangular waveguide wrapped around a cylindrical cavity. Power is coupled in using rectangular slots cut between the waveguide and the inner cylindrical cavity. The geometry is shown in Figure 3. Two scattering

matrix files are required from HFSS. One is generated with multiple frequency points across the band of operation. This will allow plotting of S11 across the frequency range of interest. Since coupling to the cavity is optimized at the center frequency of the cavity (45.7 GHz), another scattering matrix file is required from HFSS that includes only the scattering parameters at the center frequency.

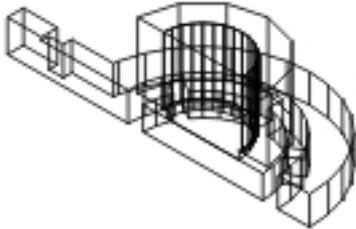


Figure 3. Gyrokystron input coupler

The matching section consists of three rectangular waveguide sections serving as input to the external scattering matrix file. The first section represents a standard rectangular waveguide. The second section represents an iris to provide the matching element. The width of this section and third section are set to match the width dimension of the input cavity. The height of the iris and the distance from the input cavity were initially obtained from rough, analytical calculations. The resulting performance is shown in Figure 4. Note that the match is higher than the operating frequency of the cavity.

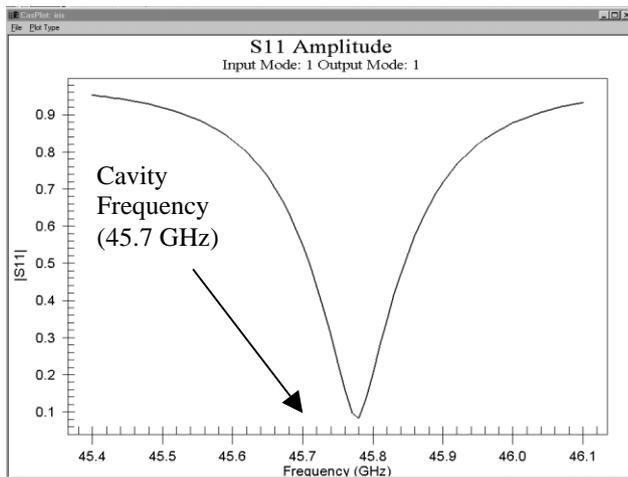


Figure 4. Initial performance of gyrokystron input coupler

The optimizer was then used to modify the geometry to shift the match to the center frequency of the circuit. The

result, shown in Figure 5, required several minutes of computer time to obtain.

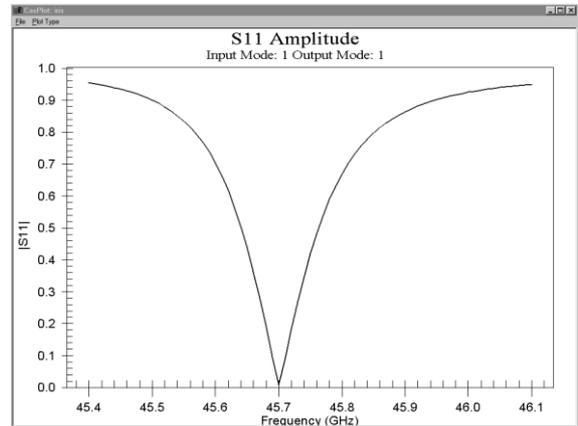


Figure 5. Final performance of gyrokystron coupler

CASCADE provides a variety of output plots, including scattering parameters, VSWR, mode sweeps, and Smith Charts. In addition, a number of tabular outputs are available. Custom plots and data can be displayed by post processing the output binary data file.

## ACKNOWLEDGEMENTS

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