Chapter 7
Slot Antennas

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7.0 Introduction

Slot antennas are popular omnidirectional microwave antennas. These antennas feature omnidirectional gain around the azimuth with horizontal polarization. Waveguide slot antennas, usually with an array of slots for higher gain like Figure 7-1, are used at frequencies from 2 to 24 GHz, while simple slotted-cylinder antennas like Figure 7-2 are more common at the UHF and lower microwave frequencies where the size of a waveguide becomes unwieldy. The Alford slot is an enhanced form of the slotted-cylinder antenna with somewhat higher gain.

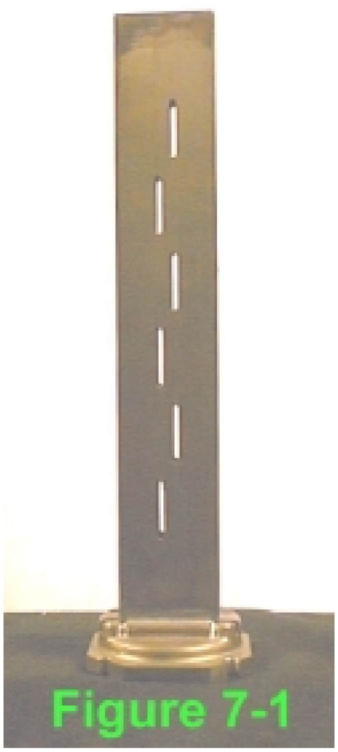


Figure 7-1

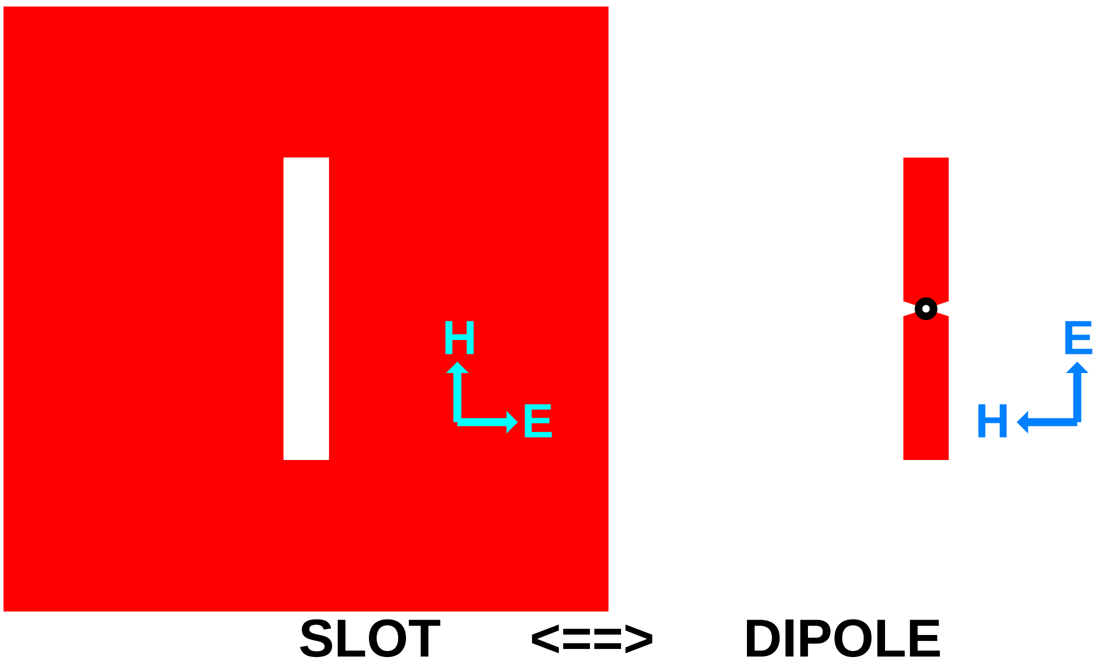
Figure 7-2

7.1 Slots and Dipoles

A thin slot in an infinite ground plane is the complement to a dipole in free space. This was described by H.G. Booker[1], who extended Babinet's Principle[2,3] from optics to show that the slot will have the same radiation pattern as a dipole with the same dimensions as the slot, except that the **E-** and **H-**fields are swapped, as illustrated in Figure 7-3 — the slot is a magnetic dipole rather than an electric dipole. As a result, the polarization is rotated 90°, so that radiation from a vertical slot is polarized horizontally. For instance, a vertical slot has the same pattern as a horizontal dipole of the same dimensions — and we are able to calculate the radiation pattern of a dipole. Thus, a longitudinal slot in the broad wall of a waveguide radiates just like a dipole perpendicular to the slot.

Watson[4] describes a proof of Babinet's Principle, attributed to Sommerfeld, working in a Riemann space. This mind-expanding concept is by no means necessary for understanding slot antennas, but I've never seen Riemann geometry actually used.

Figure 7-3. Babinet's Principle



7.2 Waveguide Slot Antennas

Waveguide slot antennas are often used as omnidirectional microwave antennas. According to Watson[4], the slot array was invented in 1943 at McGill University in Montreal. Unique features of these antennas are horizontal polarization and omnidirectional gain around the azimuth. They are also simple, rugged, and fairly easy to build. While they have been described in several articles in the ham literature, all the articles seem to have the same dimensions, suggesting a common genesis.

The most available reference for waveguide slot antennas is Jasik's[5] *Antenna Engineering Handbook*; the dimensions there look remarkably similar to the ham articles. The third edition[6], by R. C. Johnson, has some additional information. We will try to explain how a waveguide slot antenna works, how to design one, to give some hints for successful fabrication, and to make some suggestions for further experimentation.

The waveguide slot antennas we will be discussing have longitudinal slots in the broad face of standard rectangular waveguide, parallel to the length of the guide. Figure 7-1 is a photograph of a typical waveguide slot antenna, with a total of 12 slots, six on each side, in WR-90 X-band waveguide for 10 GHz operation. There are several other forms of waveguide slot antennas with slots in various locations and in other waveguide shapes; I refer you to Jasik[5] or Johnson[6] for details.

7.2.1 Arrays of slots in waveguide

We are able to calculate the radiation pattern for an array of dipoles as well as a single dipole. The usual technique is to multiply the dipole pattern by the pattern of an array of ideal radiators. An array of slots may be configured to shape the radiation pattern as desired. Two-dimensional arrays of slots may be used to form a beam antenna, but there are easier ways to fabricate a beam antenna, so we will first concentrate on omnidirectional antennas, with a linear array of slots.

The vertical collinear array, consisting of several vertical dipoles connected end-to-end, is a popular VHF omnidirectional antenna with vertical polarization. A vertical dipole has an omnidirectional pattern in the horizontal plane, or azimuth, and adding additional dipoles concentrates the beam into a flatter vertical beam to provide gain. Try to visualize the pattern of a single dipole as a donut or bagel with the vertical dipole passing through the hole; adding more collinear dipoles squishes the donut flat, like a pancake with a hole.

A waveguide slot antenna has a vertical row of slots along the length of a vertical waveguide, with the array of slots increasing the gain by flattening the vertical beam. Since the slots are oriented vertically along the guide, the polarization is horizontal — a comparable dipole antenna would be a stack of horizontal dipoles. Increasing the number of slots provides more gain but flattens the beam (donut) into a narrower elevation angle (pancake). Since a slot in one side of the physical waveguide does not radiate uniformly on both sides like a theoretical slot in infinite plane, an identical row of slots is added on the far side of the waveguide to make the radiation pattern more uniform.

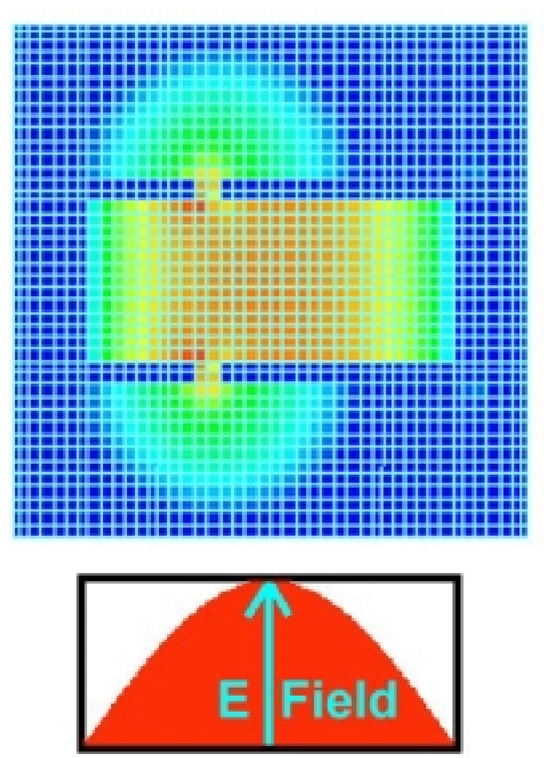
Design of an antenna array involves a number of details: cutting the elements to resonance, spacing the elements properly, splitting the power to distribute to the elements, feeding the elements in phase through a harness of transmission lines, and providing a mounting structure for each element. For traditional arrays, each of these items may be attacked separately, but the waveguide slot antenna combines them all into a single piece of waveguide — we must find a set of dimensions that satisfies all the requirements simultaneously.

7.2.2 Slot impedance in waveguide

A longitudinal slot cut into the wall of a waveguide interrupts the transverse current flowing in the wall, forcing the current to travel around the slot, which induces an electric field in the slot. The position of the slot in the waveguide determines the current flow. Thus, the position determines the impedance presented to the transmission line and the amount of energy coupled to the slot and radiated from the slot. Figure 7-4 shows a cross-sectional view of a slot in a rectangular waveguide, showing the electric fields calculated using Zeland Fidelity[7] software. The fields are depicted as a color map using red for maximum intensity and traversing the rainbow to blue for minimum field intensity. Below the cross-sectional plot is a graph illustrating how the electric field intensity varies sinusoidally across the waveguide cross-section. The current in the walls of the guide must be proportional to the difference in electric field between any two points. Therefore, a slot in the exact center of the broad wall of the waveguide will not radiate at all, since the electric field is symmetrical around the center of the guide and thus is identical at both edges of the slot. As the slot is positioned away from the centerline, the difference in field intensity between the edges of the slot is larger, so that more current is interrupted and more energy is coupled to the slot, increasing radiated power.

As we approach the sides of the waveguide, the field is very small, since the sidewalls are short circuits for the electric field. The induced current must also be small; longitudinal slots far from the center or in the sidewall will not radiate significantly. However, angled slots in the sidewalls can be effective radiators; see Jasik[5] or Johnson[6] for details.

From the point of view of the waveguide, the slot is a shunt impedance across the transmission line, or an equivalent admittance loading the transmission line (admittance is the reciprocal of impedance). Slots further from the centerline of the guide present a larger admittance (lower impedance) to the transmission line. When the admittance of the slot (or combined admittance of all the slots) equals the admittance of the guide, then we have a matched transmission line, or low VSWR.



Waveguide Slot Fields
Figure 7-4

If we wished to make a slot antenna in a circular waveguide, we would need to locate the point of maximum electric field. In a rectangular waveguide, the maximum electric field is conveniently located at the centerline of the broad wall, while in circular guide the maximum electric field is on a line through the center but may be oriented in any direction. So we would require a mechanism to fix the alignment of the electric field in the circular waveguide, and to keep it from rotating when encountering a discontinuity such as a slot. This difficulty makes rectangular waveguide much more attractive for slot antennas.

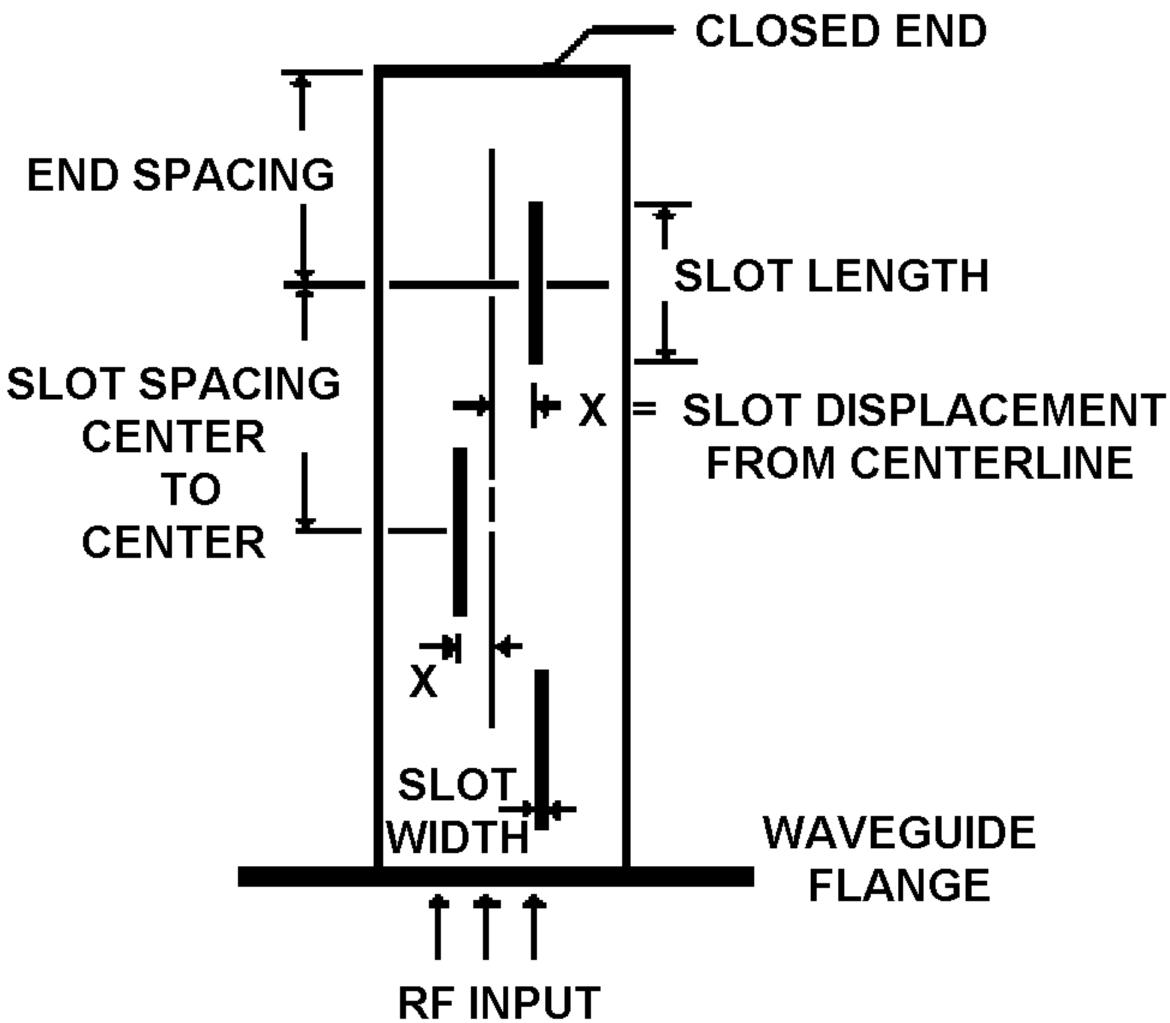


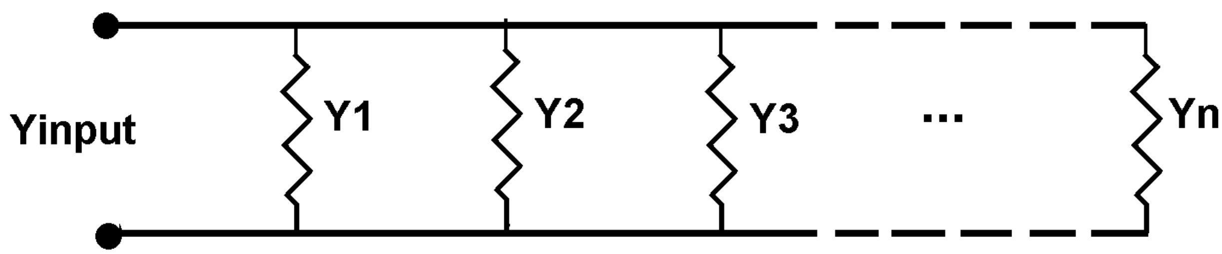
Figure 7-5. Waveguide Slot Antenna

7.2.3 Waveguide slot array design

A sketch of a waveguide slot antenna with the pertinent dimensions is shown in Figure 7-5. The first design consideration is that the slots be resonant so that they provide a resistive load to the (waveguide) transmission line.

Normally, it is desirable for an omnidirectional antenna to radiate in a horizontal (azimuth) plane. This is achieved by feeding all the slots in phase. The radiation pattern may be tilted upward or downward (visualize a shallow cone) by changing the phasing of the slots, if desired. I'm told that vertical collinear arrays for ground-based aviation antennas are sometimes designed with a pattern tilted upward.

Figure 7-6. Schematic of Waveguide Slot Antenna



$$Yinput = Y1 + Y2 + Y3 + ... + Yn$$

The slots are fed in phase by spacing their centers at electrical half-wavelength intervals along the waveguide. The electrical wavelength in waveguide is longer than in free space, so we must calculate the guide wavelength:

$$\lambda_g = 1 \Big/ \sqrt{\left(\frac{1}{\lambda_0}\right)^2 - \left(\frac{1}{\lambda_C}\right)^2}$$

where $\boldsymbol{\lambda_C}$, the cutoff wavelength, equals 2 times the wide dimension of the waveguide.

If the spacing is wrong, or if the frequency is changed significantly so the spacing is no longer $\boldsymbol{\lambda_g/2}$, then the slots will not be fed in phase and the beam will be tilted — we can make a beacon for aliens, or for earthworms.

A half-wavelength of transmission line has the useful property of repeating impedance: the input and output impedance are the same. As a result, the impedances, or admittances, of all the slots appear in parallel. Figure 7-6 shows this schematically. Each parallel resistor represents one slot, so there must be **N** resistances in parallel.

The center of the last slot is a guide quarter-wavelength from the closed end of the waveguide. We know that a short-circuited quarter-wavelength stub of transmission line appears as an open-circuit, so that the closed end does not affect the impedance. Sometimes the closed end is spaced ¾ $\boldsymbol{\lambda_g}$ for mechanical reasons; the additional half-wavelength is transparent.

Assuming that we are successful in making the slots resonant and spacing them exactly $\boldsymbol{\lambda_g/2}$, then the admittance **Y** is purely resistive and the calculation is extremely simple: adding **N** identical admittances together, where N is the number of slots. The books show the admittance normalized to the impedance of the waveguide, so that the slot admittances should add up to 1.0; thus, each slot should have an admittance of 1/**N**.

Spacing the slots at **½**$\boldsymbol{\lambda_g}$ intervals in the waveguide is an electrical spacing of 180° — each slot is exactly out of phase with its neighbors, so their radiation will cancel each other. However, slots on opposite sides of the centerline of the guide will be out of phase (180°), so we can alternate the slot displacement around the centerline and have a total phase difference of 360° between slots, putting them back in phase.

A photograph of a complete waveguide slot antenna is shown in Figure 7-1. This example has 6 slots on each side for at total of 12 slots. The slots have identical length and spacing along the waveguide. Note how the slot position alternates about the centerline of the guide. The far wall of the waveguide has an identical slot pattern, so that you can see through the slots. If the pattern on the far wall were reversed, the two sides would have opposite phasing and the resultant radiation pattern would have a null on each side.

A simple way to estimate the gain of a slot antenna is to remember that it is an array of dipoles. Each time we double the number of dipoles, we double the gain, or add 3 dB. Thus, a 16 slot array would have a gain of about 12 dBd. The approximate gain formula is thus Gain = 10*log*(**N**) dB, for **N** total slots.

Since it is really the vertical aperture of the slots rather than just the number of slots that determine the for gain and vertical beamwidth, DK3BA and DG8SG[8] give better formulas:

$$\text{Gain} = 10\log\left(\frac{\text{N}\cdot \textit{slotspacing}}{\lambda_0}\right)\ \text{dB}$$

and

$$\text{Beamwidth} = 50.7\cdot\frac{\lambda_0}{\text{N}/2\cdot \textit{slotspacing}}\ \text{degrees}$$

where N is the total number of slots and *slotspacing* is normally half the guide wavelength. The beamwidth formula is the same as a uniformly illuminated aperture the length of the slot array, and is the narrowest possible beamwidth for the aperture dimension. Later, we shall see that a tapered aperture illumination can increase beamwidth and reduce sidelobe levels without significantly reducing gain.

Measured gain will rarely be the same as calculated gain, since actual gain usually exhibits some variation around the azimuth; the calculated value is probably close to the gain averaged around the azimuth.

Since the waveguide slot antenna is a resonant antenna, requiring resonant slots and half-wavelength spacing, it is not particularly broadband. Good performance might be expected over a bandwidth of less than 10% for a small number of slots, and even smaller bandwidth for a larger array. Thus, it is important to get the dimensions right for the operating frequency.

7.2.4 Slot dimensions

Several amateur slot antenna designs have been published: a 12-slot version for 10 GHz by WB6IGP[9], a 12-slot antenna with "wings" for 10 GHz by K5SKX and WA5VJB[10], as well as a Mathcad routine for slot design by KB7TRZ[11] which was converted to a BASIC program by W6OYJ[12]. The KB7TRZ routine uses dimensions based on the work of A. F. Stevenson[13] from 1948. The following formula for normalized slot conductance, used to calculate the slot displacement, is from **Stevenson**:

$$\frac{G_{slot}}{G_{waveguide}} = \left[2.09 \frac{\lambda_g}{\lambda_0} \cdot \frac{a}{b} \cdot \cos^2 \frac{\pi \lambda_0}{2 \lambda_g} \right] \sin^2 \frac{\pi x}{a}$$

where **a** and **b** are the large and small dimensions of the waveguide, respectively, and **x** is the slot displacement from centerline.

Conductance **G** is the real (resistive) part of admittance **Y**; if the slot is resonant, then the admittance is has no reactive component and only the conductance is left. The formula assumes a resonant slot in an infinitely thin wall of perfectly conducting material. The resonant slot length is assumed to be a half-wavelength in free space. If we use the normallized conductance, $G_{slot} / G_{waveguide}$, then we don't have to clutter the calculations with the waveguide conductance.

Antennas made using dimensions from this formula work well, but usually require some adjustment to achieve low VSWR. WA1VVH reports successful adjustment by inserting shorting plugs to vary the length of the closed end.

Practical dimensions were measured in WR-90 waveguide by R. J. Stegen[14] at 9.375 GHz. The curves from this paper are reproduced in the *Antenna Engineering Handbook*[6,7]. Most recent work seems to be aimed at reconciling computer calculations with the actual data; much of the work is by R. S. Elliott. His book[15], *Antenna Theory and Design*, has a good treatment of waveguide slot antenna design, and he has also contributed the chapter on waveguide slot antennas in the *Antenna Handbook* by Lee and Lo[16].

The first conclusion from Stegen's measured data is that the slot length is not exactly a half-wavelength. This is hardly surprising — we have all made wire dipoles that are shorter than ½ wavelength using the formula in the *Radio Amateurs Handbook*[17] — so why would we expect an equivalent slot to be exactly a half-wavelength long? Elliott and Kurtz[18] estimate that a square-ended slot in an infinitely thin wall would have a resonant length of $0.464\lambda_0$. In WR-90 waveguide with real wall thickness and rounded ends, the resonant length increases to $0.483\lambda_0$. This length must then be corrected as the slot is moved off-center in the waveguide, using Stegen's measured data.

Elliott and Kurtz[18] then adjusted Stevenson's formula for slot displacement to account for the actual resonant length of the dipole. The equation for slot conductance used to calculate the slot displacement, accounting for the actual length of a resonant slot, is adapted from **Elliott**:

$$\frac{G_{slot}}{G_{waveguide}} = \left[2.09 \frac{\lambda_g}{\lambda_0} \cdot \frac{a}{b} \cdot \left(\cos\left(\frac{0.464\pi\lambda_0}{\lambda_g} \right) - \cos(0.464\pi) \right)^2 \right] \sin^2 \frac{\pi x}{a}$$

The slot length is calculated for each slot displacement using polynomials curve-fitted to Stegen's measured data.

These improved calculations for slot displacement and length, as well as the original Stevenson calculations from the Mathcad routine by KB7TRZ[11], are included in the spreadsheet **slotantenna.xls**, to be described later as part of the design procedure.

The only amateur article[8], by DK3BA and DG8SG, that corrects the length of the slots for slot displacement included data for only the 23 cm band, using a structural aluminum extrusion for the waveguide. The guide dimensions were 172 mm x 42 mm with 4 mm wall thickness. Drawing on some commercial antenna development, they calculate the slot displacement by replacing the constant **2.09** in the Stevenson formula with a new constant of **3.5**, *which is only accurate for these exact dimensions*. When they scaled the dimensions to make a slot antenna for the 13 cm band, no suitable extrusion was available so they were forced to weld aluminum plate into a guide. Slot displacement calculations for these guide dimensions using the formula from Elliott in the spreadsheet match almost exactly the published dimensions. The published slot lengths are 1% or so longer than my calculated lengths.

Another factor affecting slot dimensions is mutual coupling between slots in the array. Mutual coupling is large for parallel slots, which might be found in a two-dimensional array, but small for the end-to-end coupling in linear arrays. Elliott's analysis found that the change in dimensions is perhaps 1%. For a single antenna, this difference is too small to justify the complicated calculations required, so we shall choose to neglect mutual coupling.

For slot antennas in WR-90 waveguide at 10.368 GHz, there is only a small change in the slot displacement dimension. At other frequencies closer to the waveguide cutoff, the differences are larger. The resonant length of the slot at 10.368 GHz is shorter by as much as 3%. This is the critical dimension: a curve from Stegen is included in the *Antenna Engineering Handbook*[6,7] showing the effect of slot length on admittance: a 2.5% error in length would result in a VSWR >2.

The resonant length calculation is for slots with round ends, as might be made by a drill or milling cutter. Slots with square ends should be about 2% shorter.

The final dimension is the slot width. While the KB7TRZ calculations specified one-twentieth of a wavelength, Stegen's measurements were based on a slot width of 0.062 inch (1/16 inch, or 1.5875 mm) in WR-90 waveguide — a convenient size. For other waveguide sizes, the slot width should probably be scaled accordingly, but small variations to fit available tooling should not be critical.

For each microwave band, several of the standard waveguide sizes are usable. At 10 GHz, for instance, WR-75 and WR-112 are usable as well as the ubiquitous WR-90. When we enter the inner dimensions of each size into the spreadsheet, we find that, compared to WR-90, the WR-75 slot dimensions have a smaller displacement from the centerline and a larger slot spacing, since λ_g is larger in the smaller waveguide. Increasing spacing in an antenna array tends to produce larger sidelobes; in this case, the sidelobes are in the elevation pattern. The change in slot dimensions for WR-112 is just the opposite: a larger displacement and a smaller slot spacing. The larger displacement makes the tolerance less critical. Since both effects, sidelobe levels and dimensional tolerance, tend to favor the larger waveguide, it would seem preferable to choose the largest available waveguide that is usable at a given frequency. Later, we will see that the largest size might not be the best choice, but the small size will always require tighter construction tolerances.

7.2.5 Waveguide slot antenna design procedure

We can summarize the design procedure for a waveguide slot antenna:

1. Choose the number of slots required for the desired omnidirectional gain and vertical beamwidth.
2. Choose a waveguide size appropriate for the operating frequency. Smaller sizes require more critical construction tolerances.
3. Calculate the wavelength in the waveguide at the operating frequency.
4. Determine the slot position from centerline for a normalized admittance of 1/**N**, where **N** is the number of slots in both walls of the waveguide.
5. Determine the slot length for resonance at the operating frequency.
6. The slot width should be roughly one-twentieth of a wavelength, or proportional to 0.062 inches in WR-90 waveguide. Since cutting tools only come in certain sizes, choose the closest smaller size for the slot width.

A convenient way to make the design calculations is to use the Microsoft Excel spreadsheet **slotantenna.xls** available at http://www.w1ghz.cx/slotantenna.xls. A typical calculation using the spreadsheet is shown in Figure 7-7.

Waveguide Slot Antenna Calculator

W1GHZ 2000

Parameter	Metric	Inches	Metric	Inches
ENTER INPUT PARAMETERS HERE:				
Frequency	10.368 GHz	**10.368** GHz		
Waveguide large dim	22.86 mm	**0.9** inch		
Waveguide small dim	10.16 mm	**0.4** inch		
Number of slots	16	**16 total on two sides**		
Estimated Performance	**Gain =**	**10.1** dB	**Beamwidth=**	**9.8** deg
READ FINAL SLOT DIMENSIONS HERE:				
	old from KB7TRZ		*improved from Elliott*	
Offset from centerline	2.13 mm	0.084 inch	**2.35 mm**	**0.092 inch**
Length	14.47 mm	0.570 inch	**14.04 mm**	**0.553 inch**
Width	1.87 mm	0.074 inch	**1.59 mm**	**0.063 inch**
Spacing between slots	18.69 mm	0.736 inch	**18.69 mm**	**0.736 inch**
End space = 1/4 wave	9.34 mm	0.368 inch	**9.34 mm**	**0.368 inch**
End space = 3/4 wave	28.03 mm	1.103 inch	**28.03 mm**	**1.103 inch**

End space is from shorted end to center of last slot

Wavelength - free space	28.94 mm	1.139 inch		
Wavelength - cutoff	45.72 mm	1.800 inch		
Guide wavelength	37.37 mm	1.471 inch		

INTERMEDIATE TERMS -- DON"T MESS WITH THESE!

Gslot	0.0625		0.0625	enter taper admittance here
G1	0.7322		0.6028	
Y	0.0854		0.1037	
Offset calculation: Mathcad from KB7TRZ:			**New offset calc from Elliott:**	
OFFSET	2.13 mm	0.084 inches	2.35 mm	0.092 inch
Offset calculation: BASIC from W6OYJ:				
AG	0.09 mm			
Offset	2.13 mm	0.084 inches		
Slot Length Calculation from Stegen curves:				
Slot in wavelengths			0.4851	
Slot Length			14.04 mm	0.553 inch

Figure 7-7

7.2.6 Waveguide slot antenna performance

I began with the two 10 GHz slot antennas: the twelve-slot version shown in Figure 7-1 and a larger one with 24 slots total. Bob Barrett, WA1ZJG, machined these from the original Stevenson dimensions. Then Dave McGee, W2KV, measured the radiation patterns shown in Figure 7-8 on a commercial antenna range. Obviously, I didn't do much of the heavy lifting!

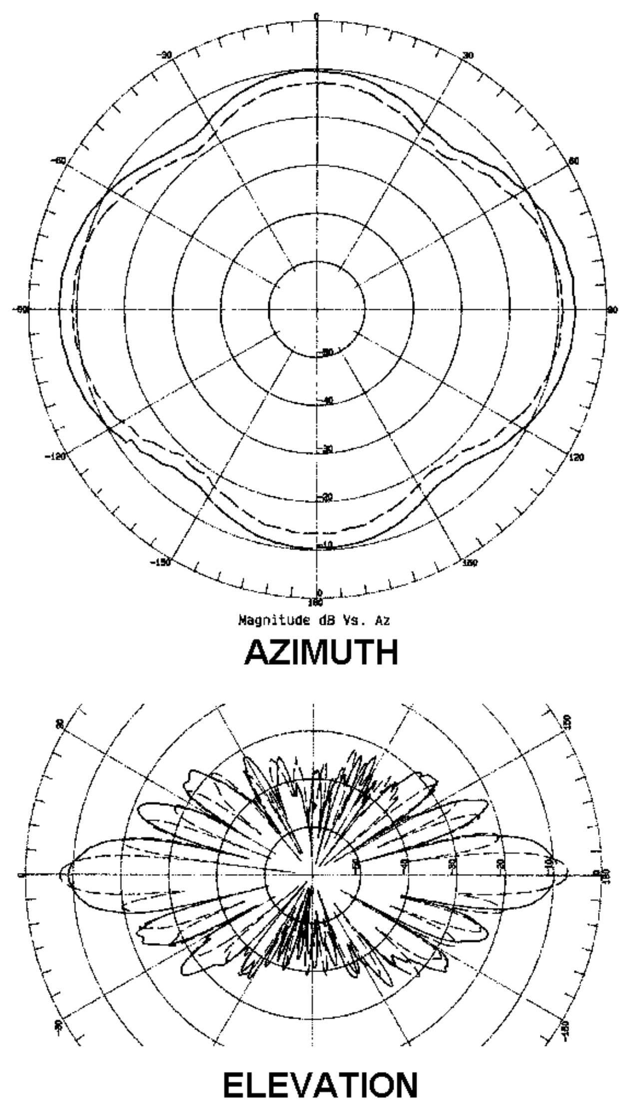
The measured radiation patterns in Figure 7-8 show the expected difference between the two versions: the larger antenna with twice as many slots has about 3 dB more gain, with a narrower beam in the elevation pattern. Both elevation patterns have large sidelobe levels; the 24-slot version has roughly twice as many sidelobes as the 12-slot version. Neither azimuth pattern is truly omnidirectional — the gain varies as much as 10 dB over the full 360° azimuth.

The larger slot antenna, with 24 slots, has a gain as high as 16 dB in some directions. While this is very good gain for an omnidirectional antenna, it is a much lower gain antenna than a small dish or even a reasonably large horn. Using a slot antenna for microwave communications may lead to frustration — believe me, I've tried and not been heard.

More recently, I used the Zeland Fidelity[7] software to calculate the radiation patterns for a computer model of a 12 slot antenna, with the Stevenson dimensions. These patterns, shown in Figure 7-9, are very similar to the measured patterns shown in Figure 7-8. Both measured and calculated patterns show large variations in gain around the azimuth, as well as significant sidelobes at high elevation angles, wasting energy into space.

Since all the antennas so far, both measured and calculated, used the original Stevenson dimensions, we may conclude that these dimensions will yield a working omnidirectional antenna but not a really good one.

Figure 7-8. Measured Radiation Pattern at 10.368 GHz for waveguide slot antenna with 12 and 24 slots



Radiation patterns of 12-slot WR-90 antenna at 10.368 GHz with uniform amplitude distribution

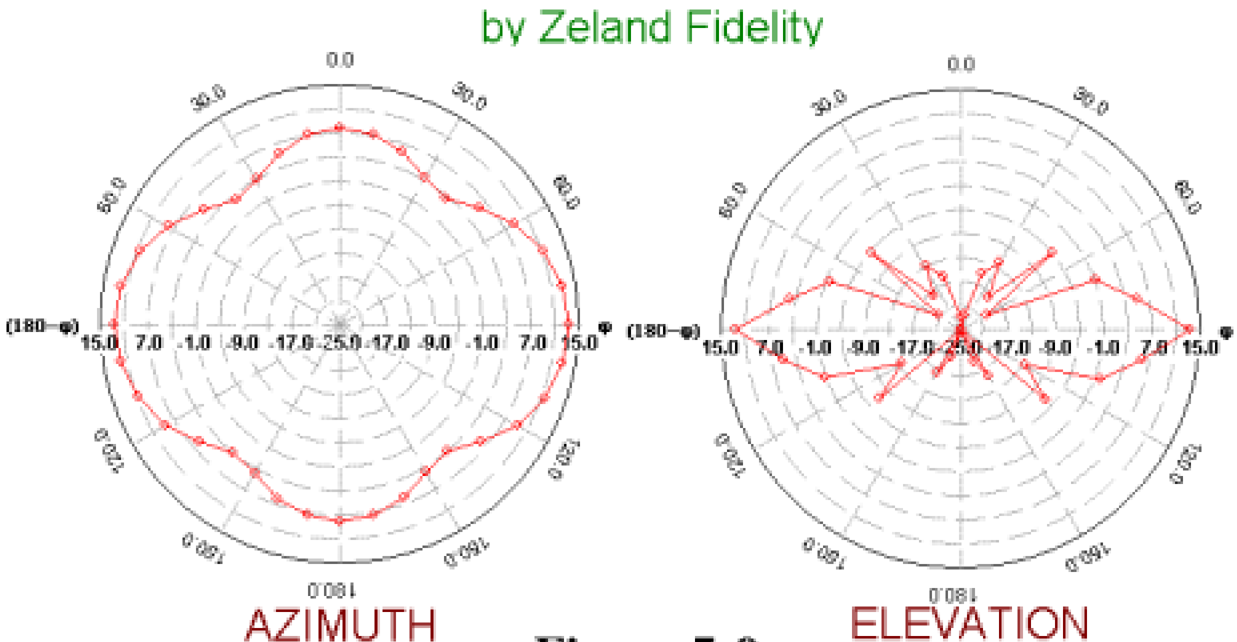


Figure 7-9