Design of Throat Section of Conical Corrugated Horns

A. D. Olver[1]
Queen Mary College, London, England

A simple graphical method is presented for designing the junction between a conical corrugated horn and a smooth-wall circular waveguide. The method gives both an insight into the field behavior along the horn and an indication of the reflection coefficient at the horn-waveguide junction. It has been applied to the design of the DSN X-S band feedhorn and an improved corrugated throat section.

I. Introduction

Conical corrugated horns are usually connected to a section of smooth-wall circular waveguide as the means of transferring power between the radiating horn and a transmission line. The junction, Fig. 1, must be correctly designed if optimum performance is to be achieved. Any mismatch between the modes in the circular waveguide and the modes in the horn will lead to a nonzero reflection coefficient. In addition, any sharp changes in impedance along the throat section of the horn can give rise to mode conversion to a higher order mode. Once excited, this unwanted mode may radiate and cause increased cross-polar power and/or reduced efficiency. The effects can be more complicated if operation over an appreciable frequency band is desired.

This note sets out a graphical method of designing the throat section that gives an estimate of the reflection loss that can be expected from a conical corrugated horn.

[1]Consultant to JPL Sections 333 and 336. Dr. Olver's complete address is: Department of Electrical Engineering, Queen Mary College, Mile End Road, London E1, England.

II. Simple Model

The standard method of matching into a corrugated horn has been to make the first slot $\lambda/2$ deep at the highest frequency of operation, and then taper over a few slots to $\lambda/4$ depth slots. This procedure is adequate for single-frequency or narrow-band systems, but is too simple for a wideband system, as Fig. 2 indicates. This shows the change in guide wavelength against normalized inner radius (r_1/λ) for a smooth-wall circular waveguide and a corrugated waveguide with slot depth chosen to match at $r_1/\lambda = 0.5$. The horizontal scale should be interpreted as changing frequency, not changing radius. The variation with frequency is different for the two waveguides, so a good match can be achieved at only one frequency. The reflection coefficient at the junction of the two waveguides is given simply by (Ref. 1)

$$\rho = \left| \frac{\lambda_{g2} - \lambda_{g1}}{\lambda_{g2} + \lambda_{g1}} \right|$$

where λ_{g1} and λ_{g2} are the guide wavelengths in the two waveguides. Knowledge of these guide wavelengths will give an immediate estimate of the return loss.

The above discussion referred to the junction between two waveguides whereas in reality we have the junction between one waveguide and a conical horn. However, the horn can be approximated as a series of constant diameter waveguides. The guide wavelength for each corrugated waveguide section can be computed and plotted on a composite graph to give an indication of the way in which the field changes as it propagates along the horn. The guide wavelength will be high at the junction and decrease toward the free-space wavelength at the horn aperture. Sharp changes in guide wavelength along the horn are indicative of a change in impedance that can cause a higher order mode to be excited. Thus not only should the guide wavelength on either side of the smooth-wall-to-corrugated waveguide junction be equal, but the change in guide wavelength with distance along the horn (i.e., $\partial\lambda_g/\partial z$) should be as low as possible.

III. Design Curves

The information needed to design or analyze the throat section of a corrugated horn can be conveniently displayed on a single graph. Curves showing the normalized guide wavelength against normalized slot depth for various normalized inner radii are shown in Fig. 3. These have been computed by solving the HE_{11} mode propagation equation for a corrugated waveguide using a model that includes the effects of space harmonics (Ref. 2). The space harmonic representation enables the exact slot geometry to be studied. In general, this is not strictly necessary for calculation of the propagation coefficient and the simpler surface impedance representation should be adequate (the space harmonic model is needed for the study of attenuation or cross-polar radiation characteristics).

The use of the curves is indicated in Fig. 4. This shows a trajectory for a corrugated horn obtained by plotting the inner radius and slot depth for each corrugation along the horn. The guide wavelength for the smooth-wall waveguide occurs on the slot depth/λ = 0.5 line, point A. The first slot (from the junction) in the corrugated section gives point B. The second slot point C, and so on. When the tapering of the slot depths has stopped and the slot depth is constant, point D is reached and from then on the guide wavelength will decrease along the line E.

A good match at the design frequency would have points A and B coincident and a smooth change along the horn. In the example shown in Fig. 4, there would be a mismatch at the junction giving a return loss of about -34 dB. The mode conversion along the horn depends on whether a higher order mode is propagating at the relevant radius. The most troublesome mode is the HE_{12} mode because this is excited by changes in waveguide cross section. The cut-off line for the HE_{12} mode is shown in Fig. 4, and in this case the uneven curve occurs at a point in the horn where the HE_{12} mode cannot propagate.

The guide wavelength curves can be used to design a throat section. An ideal smooth trajectory would be drawn on Fig. 3 between the chosen smooth-wall waveguide value and the chosen final slot-depth value. Points would then be chosen along the curve at which slots could be placed. Care must be taken to ensure that the inner radius changes smoothly with distance along the horn.

The situation becomes more complicated when a band of frequency operation is desired. Then the trajectories at the upper and lower operating frequencies must be placed on the guide wavelength curves. Some compromise will be needed as a perfect match is possible at only one frequency. It is generally better to choose the design frequency for optimum match to be near the middle of the band, rather than at the upper frequency. This is because the guide wavelength changes more rapidly at low frequencies; see Fig. 2. The fact that this makes the first slot depth greater than half a wavelength at the upper frequency is not desirable, but may be a necessary compromise to obtain the lowest return loss over the complete operating band.

A further complication occurs if a tracking mode is present at the junction. It will then be necessary to repeat the analysis for the tracking mode and try to obtain a design that is a compromise between the matching of the signal mode and matching of the tracking mode.

IV. Application to X-Band Throat Section of DSN X-S-Band Feed Horn

The current design of the throat section has been analyzed using the method described in the previous section. Figure 5 shows the guide wavelength curves at 7.15 GHz, 7.90 GHz, and 8.60 GHz. Clearly the best match occurs at a frequency of about 8.1 GHz with a substantial deterioration at the lower frequencies. This is because the smooth-wall waveguide is operating near to its cut-off frequency where the guide wavelength changes rapidly. The trajectories are smooth and little trouble can be expected from higher order mode excitation.

The values of the reflection coefficient estimated from Fig. 4 are compared with the measured values in Fig. 6. The general agreement is reasonable at the band edge, but not in the middle of the frequency range; the disagreement may be due to the external matching network. However, the relatively simple model gives an indication of the level of performance of a circular waveguide-to-corrugated waveguide junction.

V. Redesign of Throat Section

It is possible to improve the overall impedance match of the throat section by shifting the effective operating band of the first few slots to a higher frequency. This improves the performance because the guide wavelength changes more rapidly at lower frequencies compared to higher frequencies, so the return loss at the lower frequency can be reduced without a corresponding increase at the upper frequency. The criteria is applied that the theoretical return loss at 8.6 GHz should not be greater than -30 dB; this then fixes the inner radius of the first slot. Next a smooth trajectory is drawn on the guide wavelength curves, Fig. 7. The exact location of the slots along the trajectory is obtained by sketching a smooth geometric profile of the inner radius of the corrugations, Fig. 8. Some juggling of the parameters is needed at this stage to maintain a smooth geometric and smooth electromagnetic profile. The profile shown in Fig. 7 does not fit any analytical function, unlike the original design, which is an arc of a circle. The inner radii and slot depths are given in Table 1.

The redesigned profile is chosen to have the same axial length as the original. The length is not actually necessary, as Fig. 7 shows; most of the transformation takes place in the first seven slots. The major difference between the original design and the new design is the inner radius of the first slot. In the original design this is the same as the radius of the smooth-wall waveguide (17.4 mm). Increasing the radius to 17.8 mm gives the improved match at the junction. This feature is often useful in corrugated horn design to give added flexibility. Sometimes a short section of smooth-wall conical guide can be inserted between the smooth-wall circular waveguide and the first slot as a way of introducing a larger initial radius for the corrugated horn.

References

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2. Clarricoats, P. J. B., Olver, A. D., and Chong, S. L., "Attenuation in Corrugated Circular Waveguides. Pt I Theory." *Proc IEE* (London), Vol. 122, 1975, p. 1173.

Table 1. Redesigned Throat Section

Slot no.	Inner radius, mm	Slot depth, mm
1	17.8	18.5
2	18.8	16.9
3	19.8	15.2
4	20.9	14.2
5	22.2	13.3
6	23.5	12.8
7	25.0	12.3
8	26.8	12.1
9	28.7	11.9
10	31.0	11.7
11	33.5	11.6
12	36.3	11.5
13	39.6	11.4

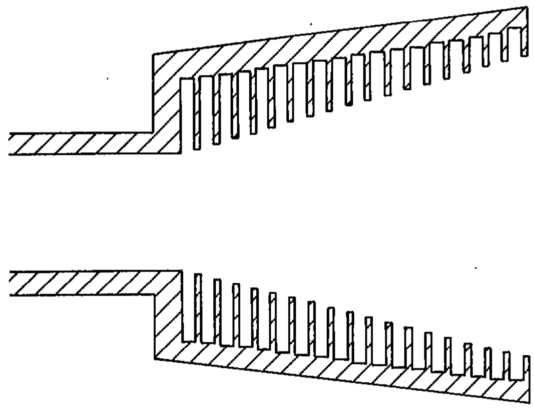

Fig. 1. The junction of corrugated horn

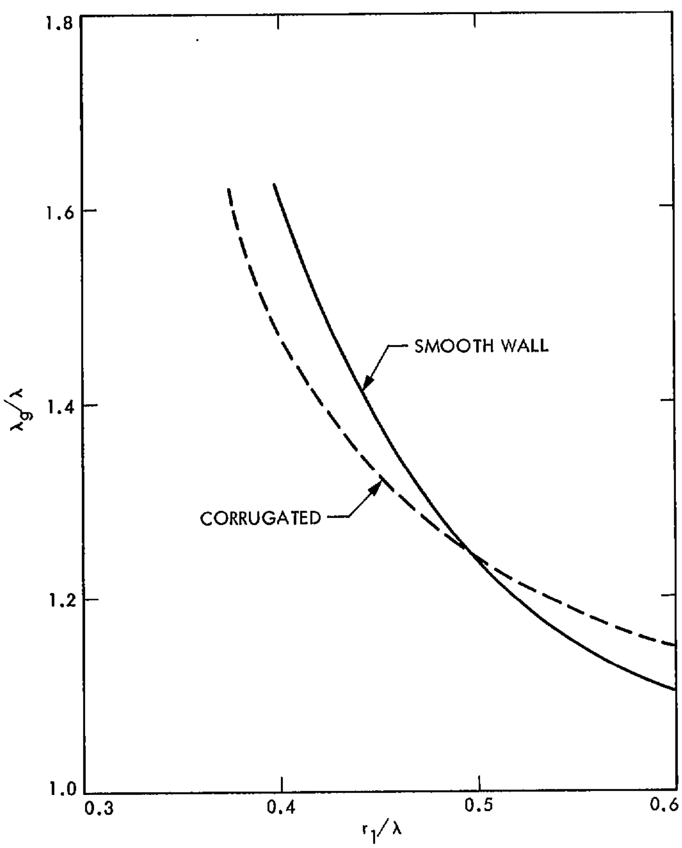

Fig. 2. Normalized guide wavelength of smooth-wall and corrugated waveguides

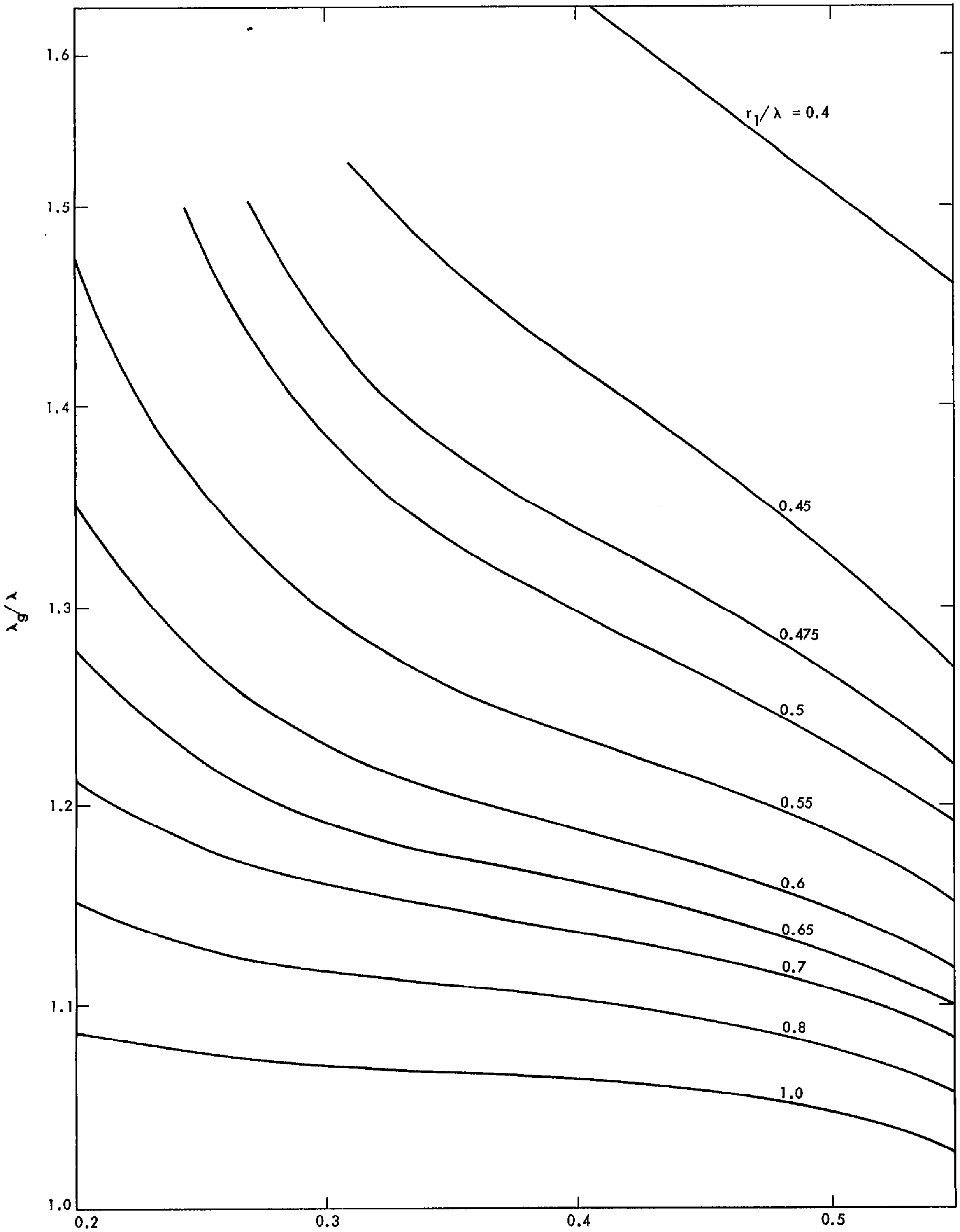

Fig. 3. Design curves for junction of corrugated horns

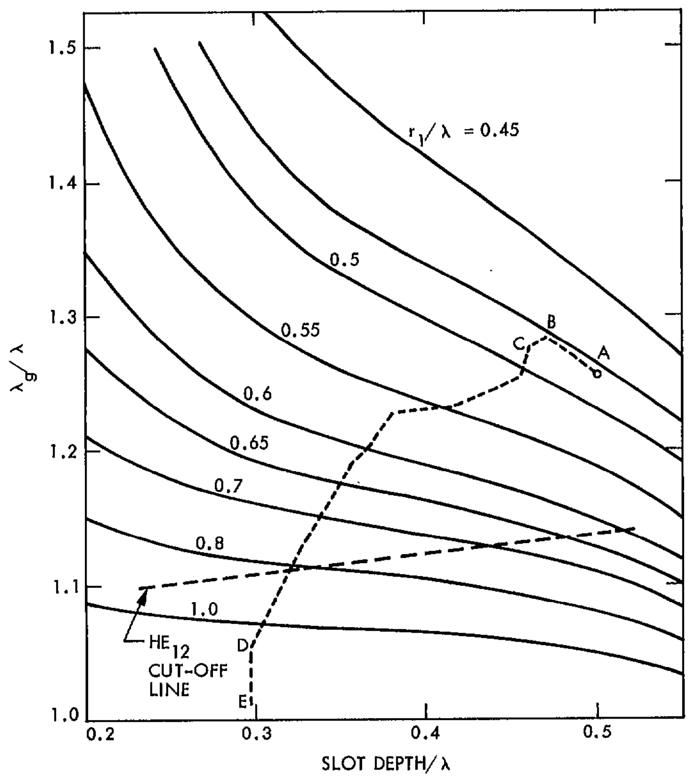

Fig. 4. Trajectory of typical junction

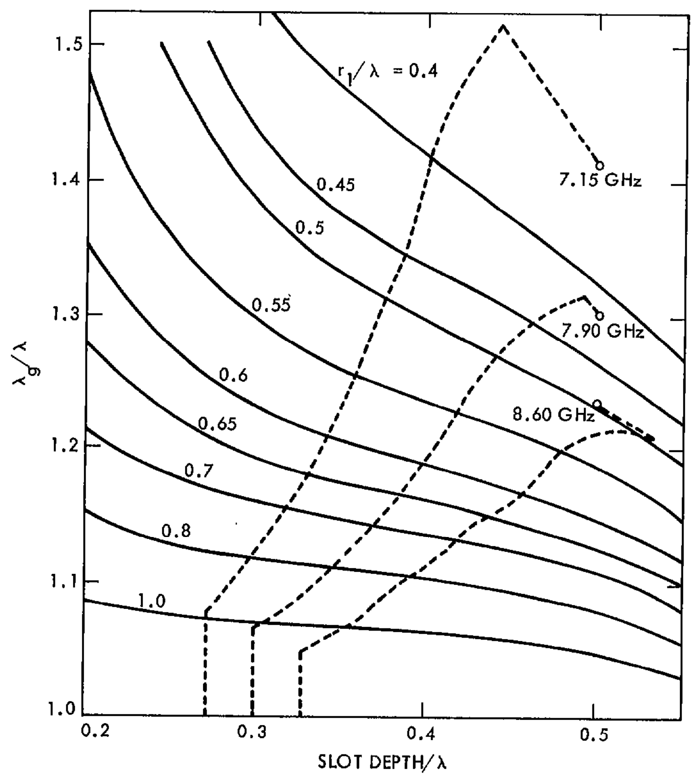

Fig. 5. Guide wavelength curves for DSN X-S-band feedhorn

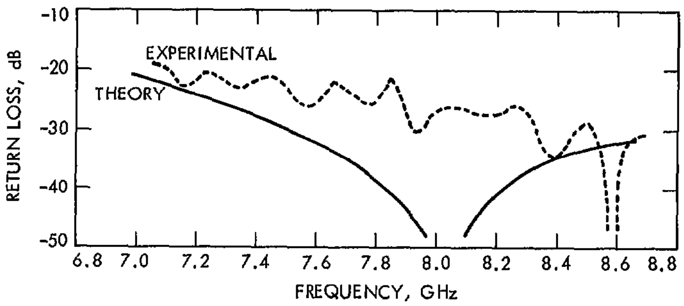

Fig. 6. Predicted and measured return loss of DSN feedhorn

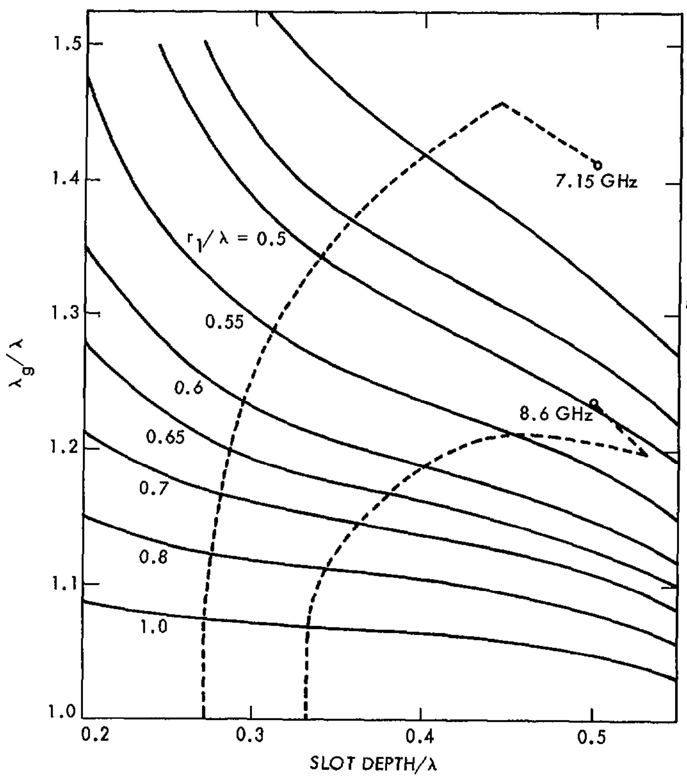

Fig. 7. Redesigned trajectories of DSN X-S-band feedhorn

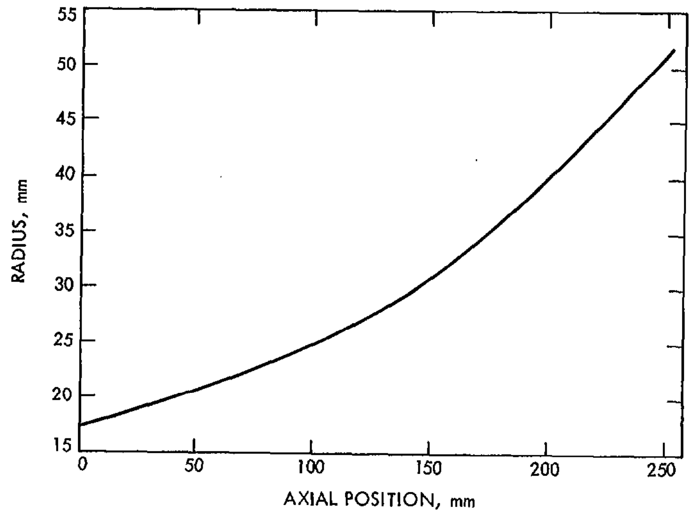

Fig. 8. Geometric profile corresponding to Fig. 7