Design Techniques for Beam Waveguide Systems

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ABSTRACT

Various design techniques used for beam waveguide (BWG) feed systems are characterized. These include the use of gaussian beam, Geometrical Optics and physical optics systems. Also introduced is a new technique based upon a conjugate phase matching focal plane technique. Advantages, disadvantages and range of applicability of each technique is give.n. In addition, comparisons of computed and measured results from each type of design are presented.

Keywords: Beam waveguide antennas, Physical Optics, Geometrical Optics, Gaussian beam, high -power, focal plane matching.

1. INTRODUCTION

A BWG feed system is composed of one or more feed horns with a series of flat arid curved mirrors arranged so that power can be propagated from the horn through the mirrors with minimum losses. Horns and equipment can then be located in a large stable enclosure at an accessible location.

Feeding a large iow-noise, ground antenna via a beam waveguide (BWG) system has several advantages over placing the feed directly at the focal point of a dual reflector antenna. For example, significant simplifications arc possible in the design of high-power, wale.r cooled transmitters and low-noise cryogenic amplifiers, since, these systems do not have to rotate. as in a normally feel dual reflector. Also, since a BWG system can transmit power over considerable distances at very low losses, they are useful in the design of very high-frequency feed systems.

Many existing beamwaveguide systems use a quasi-optical design, based on Guassian wave print.iplc.s, which optimizes performance over an intended o~r-sting frequency range. These designs can be made to work well with relatively small reflectors (a very few tens of wavelengths) and may be viewed as "bandpass," since performance suffers as the wavelength becomes very short as WCH as very long. The long wavelength end is naturally limited by the approaching small D/λ of the individual beam reflectors used; lhc shor t wavelength end dots not produce the proper focusing needed to image the feed at t he dual-reflector focus. In contrast, a purely geometrical optics (GO) design has no upper frequency limit, but performance suffers at long wavelengths. These designs may be viewed as "highpass." Both "highpass" and "bandpass" de-sign techniques are illustrated by example.

If there is a need to add additional frequencies to an existing BWG design outside of the original design criteria, it is sometimes difficult to generate a new solution by a straightforward design by analysis because of the large number of scattering surfaces required for computation. A unique application of the conjugate phase matching technique which simplifies the design process is described: An example of incorporating a low frequency S-band system in the "highpass" BWG system is included.

Most BWG systems refocus the energy at some point along the path, but this may not be desired in a high-power applications. A design technique using physical optics is described that dots not degrade either the peak or average power handling capability beyond the limitations imposed by either the feed or the dual reflector configurat ion. An example of a "high-power" design is described.

2. HIGH-PASS DESIGN TECHNIQUES

The design for a highpass BWG system is based upon a GO criteria introduced by Mizusawa and Kitsuregawa [1,2] which guarantees a perfect image from a reflector pair. Mizusawa's criteria can be briefly stated as follows. For a circularly symmetric input beam, the conditions on a conic reflector pair necessary to produce an identical output beam are:

1) the four loci (Iwo of which may be coincident) associated with the two curved reflectors must be arranged on a straight line; and

?) the eccentricity of' the second reflector must be equal to the eccentricity or the reciprocal of the eccentricity of the first reflector.

Figures l(a) i(c) show some of the orientations of the curved reflector pair that satisfy Mizusawa's criteria.

This technique was used in the design of NASA's first Deep Space Network (DSN) BWG Antenna named DSS-13. A profile of the design is shown in Figure ?. The design of the center fed BWG consists of a beam magnifier ellipse in a pedestal room located below ground level that transforms a 22-dB gain feedhorn into a high gain 29-dB pattern for input to a Mizusawa four-mirror (two hat and two paraboloid-case lb) BWG system. The system was initially designed for operation at 8.45 GHz (X-band) and 32 GHz (Ka-band) and has less than 0.2 dB loss (determined by comparing the gain of a 29-dB gain horn feeding the dual-shaped reflector system with that obtained using the BWG system) [3,4].

Since the upper BWG has a 2.44 meter (8-feet) diameter projected aperture the mirrors are 70 wavelengths at X-band rind 260 wavelengths at Ka-band, certainly large enough for using the GO design criteria.

Even though the design was based upon GO all performance analysis was done. using Physical Optics computer programs.

The DSS- 1.4 34-m diameter BWG antenna was constructed in Goldstone, California by 1990 and an extensive measurement program conducted [5]. The predicted gains at)(-band were 68.54 dBi for f1 (the focus of the dual reflector system) and 68.29 dBi for f3 (the focal point of the BWG feed system). The measured efficiency and gain at 8.45 GHz was reported to be 0.754 and 68.34 dBi for f1 and 0.7?4 and 68.17 dBi for f3 [6]. Since the antenna had a significant main reflector surface distortion as a function of elevation angles, the Ka-band predictions arc applicable only for a main reflector adjustment or rigging angle near 45-cic& elevation. The predicted f1 total efficiency and overall gain are 0.527 anti 78.36 dBi, respectively. The corresponding measured efficiency and gain are 0.523 and 78.33 dBi [6]. At f3, the predicted total ante.nna efficiency and overall gain at 32 GHz are, respectively, ().452 anti 77.70 dBi, as compared to the measured efficiency and gain values of 0.449 and 77.66 dBi [8]. In general, the agreement between predicted and measured Ka-band efficiencies and gains are very good.

3. FOCAL PLANE MATCHING hilt'I'1101)

As stated above, the DSS-13 BWG system was initially designed (Phase 1) for operation at 8.45 GHz (X-band) and 32 GHz (Ka-band) and utilized a GO design technique. In Phase 2, 2.3 GHz (S-band) was to be added. At S-band the mirror diameter is oniy 18.7 wave.lengtlis, clearly outside the original GO design criteria,

If a standard 22-dB S-band horn is placed at the input focus of the ellipse, the BWG loss is greater than i .S dB, 111 imarily due to the fact that, for low frequencies, the diffraction phase centers are far from the GO mirror focus, resulting in a substantial spillover and defocusing 10ss. This defocusing is c.specially a problem for the magnifier ellipse, where the S-band phase center at the output of the ellipse is 3 meters from the. GO focus.

A potential solution is to redesign the horn to provide an optimum solution for S-band. The question is how to determine tile appropriate gain and locat ion for this feed.

A straightforward design by analysis would prove cumbersome because of the large number of scattering surfaces required for the computation. Rather, a unique application was made of the conjugate phase-matching techniques to obtain the desired solution [7]. A plane wave was used to illuminate the main reflector and the fields from the currents induced On the subreflector propagated through the BWG to a plane centered on the input focal point. By taking the complex-conjugate of the currents induced on the plane and applying the radiation integral, the far-field pattern was obtained for a theoretical horn that maximizes the antenna gain.

There is no a priori guarantee that the pattern produced by this method would be easily realized. However, the pattern is nearly circularly symmetric and the theoretical horn was able to be matched fairly Well by a circular corrugated horn.

To synthesize a horn quickly and inexpensively, the theoretical horn was matched as well as possible by an appropriately sized circular corrugated horn. Figure 3 shows the nc:it-field E-plane patterns of the theoretical horn and a 19-dBi circular corrugated horn. The agreement in amplitude and phase is quilt good out to theta = '2 1", the angle subtended by the beam magnifier ellipse.

The corrugated horn performance was only 0.2 dB lower than the optimum theoretical horn abut 1.4 dB above the standard 22-dB horn. A system employing the corrugated horn was built and tested and installed in the 34m BWG antenna as part of a simultaneous S/X-trend receiving system.

Table I lists the Physical Optics analysis results of the antenna at S-band. In this table, the spillover of the antenna mirrors, the antenna efficiency, and system noise temperature are listed for the 19-dBi corrugated horn and the theoretical horn pattern predicted by the Focal-Plane Method. Also, for comparison purposes, the calculated performance of a 22-dBi corrugated horn is presented from [8].

The S-trend feed is part of a simultaneous S/X-band receive system implemented on the new BWG antenna. The general configuration of the feed system, the detail design, and measured feed system performance are described in [9].

The 34-m BWG antenna predicted S-band efficiency from "1'able I was 68% and the measured efficiency was 67.5%, demonstrating the successful design and implementation. For comparison, the predicted X-band efficiency (at the rigging angle of 45") as "/2.'/% and the measured efficiency, including the dichroic plate, was 70.1%.

4. GAUSSIAN BEAM

While GO is useful for designing high-frequency or electrically large mirrors >50 wavelengths in diameter with 20 dB edge tape.r), some BWG may be operated at low frequencies where the mirrors may be as small as 20 wavelengths in diameter. Due to diffraction effects, the characteristics of a field propagated between small BWG mirrors (<30 wavelengths in diameter) will be substantially different from the GO solution. For these cases, the Gaussian beam technique has been utilized,

The Gaussian beam mode is an approximate solution of a wave equation describing a beam of radiation that is unguided but effectively confined near an optical axis. The zero-order mode is normally used in the design. A major advantage of the Gaussian technique is the simplicity of the Gaussian formula, which is easy to implement and has negligible computation.

Because of the negligible computation time, a Gaussian solution can be incorporated with an optimization routine to provide a convenient method to seal-ul] the design parameters for a specified frequency range, mirror sizes and locations and horn parameters.

(i. Goubau gave the first mathematical expression of Gaussian modes derived from the solution of Maxwell's equations described by a continuous spectrum of cylindrical waves [10]. '1'. S. Chu developed the Fresnel zone imaging principle of the Gaussian beam to design a pseudo-frequency-independent BWG feed [11]. S. Betsudan; "1'. Katagi , anti S. Urasaki used a similar imaging technique to design large groun(l-based BWG antennas [1?]. N.J. McEwan and P.F. Goldsmith developed a simple design procedure based on the Gaussian beam theory for illumination of reflector antennas where the. reflector is electrically small or in the near-field of a feed [13].

Although Gaussian beam analysis is fast and simple, it is less accurate. than the. Physical Optics (I'()) solution for smaller mirrors. However, by designing with Gaussian beam analysis, checking and adjusting using 1'0 analysis, an accurate and efficient tool can be fashioned. Veruttipong [14] ctc.vc.lope.d such a tool for designing a second 34-meter BWG antenna for the Deep Space Network, The goal was to provide, good performance over the range of ?-32 GHz.

The design is similar to the HS-13 antenna (see Figure 1) in that it uses 3 curved mirrors (oat in the basement room and two rotating in azimuth) and a 34-meter dual shaped reflector antenna (Figure 4). Multiple frequency operation is provided by the use of' dichroic mirrors. The dc.sire is to have the radius of curvature and 18 dB beam diameter of the gaussian beam at the subreflector be the same at all frequencies. The size and locations of the mirrors are relatively fixed because of the basic structure geometry, so the pertinent variables arc the horn diameters, horn positions and mirror curvatures. Approximating the mirrors by a thin lens formula (Figure 5) and utilizing Gaussian mode analysis to iterate the various design parameters a design is achieved which meets the initial design constraint of' identical patterns at the subreflector. The 34 meter BWG antenna was built and measured at S- and X-band [15]. The peak measured efficiency was '/I. 1 % at X-trend and '/I .5% at S-band.

s. HIGH-POWER DESIGN

Observe that the GO designed BWG system images (refocuses) the feedhorn al a location near the main reflector (position f I in Figure ?).

The refocussing of the feed system energy near the main reflector has two distinct disadvantages. For oat., the peak field point is generally at or in front of the feed itself so this peak power point is imaged in front of the main reflector. If the peak field point can be contained within the BWG system there is the possibility to f-ill the BWG tube with a gas to enhance the peak power handling capability of the system. Also when the energy is reflected from a surface such as a BWG mirror, there is a 6-dB enhancement of the power mar the reflector since the incident and reflector field add coherently near the reflection point.

It is thus important to have the energy near the mirrors al least 6 dB below the peak point in order to prevent the mirrors from degrading the power handling capability of the system. This is difficult to do if the energy is refocussed in the BWG system. For these reasons, an unconventional design has been chosen for the beamwaveguide optics. Figure 6 strews the geometry of optics for the proposed antenna. [16]

For this design, only one curved mirror a paraboloid is used along with three flat mirrors The radiation from the feedhorn is allowed to spread to the paraboloid, where it is focused to a point at infinity. That is, after reflection a collimated beam exists which is directed to the subreflector by the three flat reflectors. The energy is thus spread over the entire ?.74 meter (9-foot) diameter of the BWG tube. The beam reflected by the paraboloid does not begin to spread significantly due to diffraction until it exists through the main reflector. Additional spreading occurs in the region between the main reflector and the. subreflector. Since a collimated beam exists beyond the first mirror, this antenna is closely related to a scar-fic.]d Cassegrain design, if the feed system is defined to include both the feedhorn and a parabolic mirror. The main and subreflector arc then determined through a standard symmetric uniform aperture synthesis program using the Physical Optics determined input pattern radiated from the feed and four mirrors.

Figure 7 shows the predicted fa-field patterns of the ovc.rail antenna. The calculated axis gain (at the center frequency of 7.2 GHz) is 67.67 dB. This number is base.d upon a purely theoretical calculation, and the following effects arc neglected: polarizer and duplexing grid effects on the. feedhorn radiation pattern, shroud effects, rms surface accuracy of all mirrors, subreflector, and main reflector, quadripod blockage, and feedhorn 10ss. The specification for surface accuracy is 0.008 in. rms for the subreflector and beamwaveguide mirrors, and ().()35 in. rms for the main reflector at the rigging angle. If we define antenna efficiency as the actual gain for the antenna as designed divided by the maximum theoretical gain for a 34-meter diameter circular aperture al 7.'2 GHz, we may estimate the following efficiency for the present design. The calculated gain quote.rl above represents an RF efficiency of 91%. The efficiency due. to main reflector surface accuracy is calculated to be 93. I %, and quadripod blockage gives an efficiency of 89.2%, for an overall efficiency of 75.6%. The other factors described above will reduce this value by several more percent to correlate with the measured efficiency of around 70[',.

6. CONCLUSIONS

Four different design techniques have been described. Each of these techniques was utilized in a JPL built and measured 34-meter BWG antenna. All met the required performance objectives. The choice of which design technique to use depends upon the system requirements. As demonstrated by design and measurements, the use of the GO technique in conjunction with the focal plane matching technique produced an antenna with virtually the same characteristics as the Gaussian mode technique.

8. ACKNOWLEDGMENTS

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7. REFERENCES

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Table]. S-band Physical Optics Calculations

	22-dBi Corrugated Horn [7]	19-dBi Corrugated Horn	Theoretical Horn
Spillovei (%)			
M6		0.41	
MS	?.05	2.46	().?4
M4	1.57	0.70	1.19
M3	5.91	0.73	0.86
M?	5.55	0.96	1.29
Ml	1.36	0.26	0.40
Sub		1.14	1.94
Main		0.94	3.61
Efficiency			
Total Efficiency	0.48415	0.6827	().695()2
Total Efficiency (dB)	55.10?	56.594	56.07?

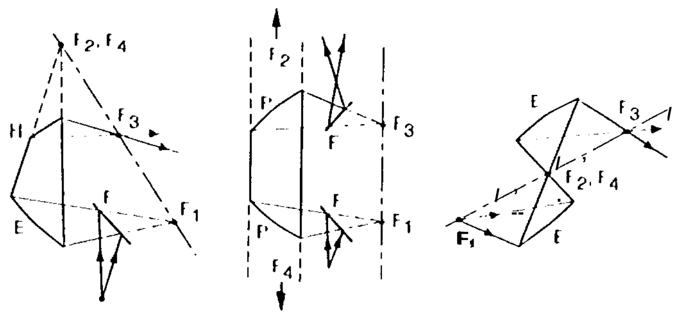

Figure 1. Examples of Two-curved Reflector Beamwaveguide Configurations;
E = ellipsoid, H = hyperboloid, P = paraboloid, F = flat plate

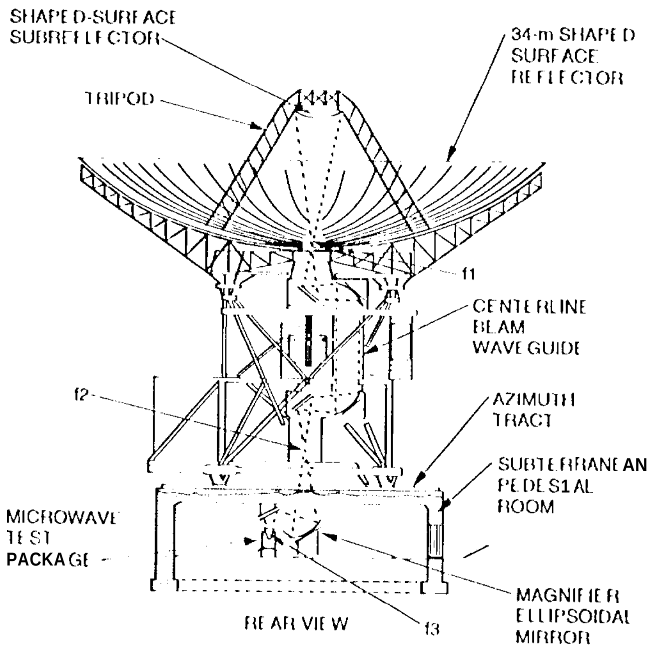

Figure 2. First NASA Beam-waveguide Antenna

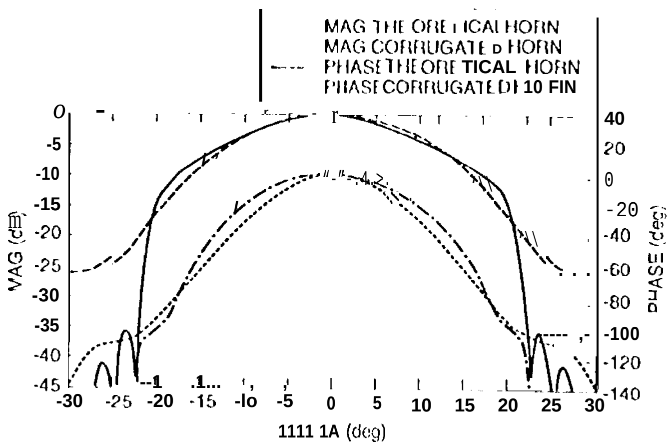

Figure 3. E-plane Near-field Patterns (input to the ellipse)

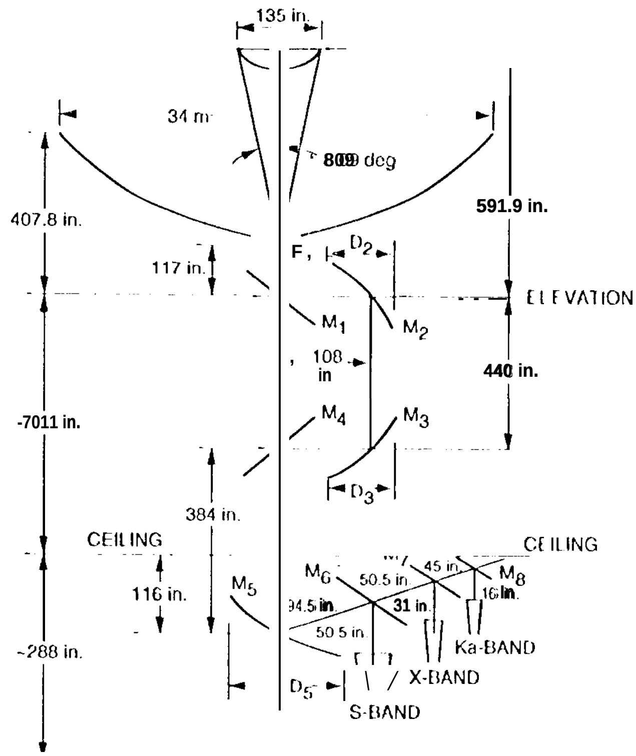

Figure 4. Detailed Dimensions of the Beam Waveguide Configuration for 1) SS-24

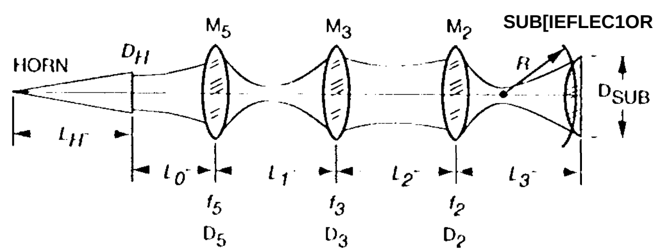

Figure 5. Beam Waveguide Design Parameters.

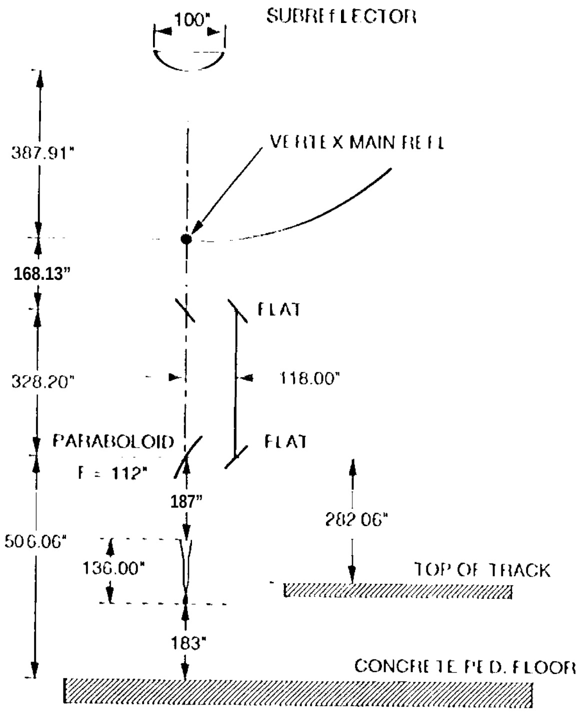

Figure 6. Geometry of Optics for the "High-power" Antenna

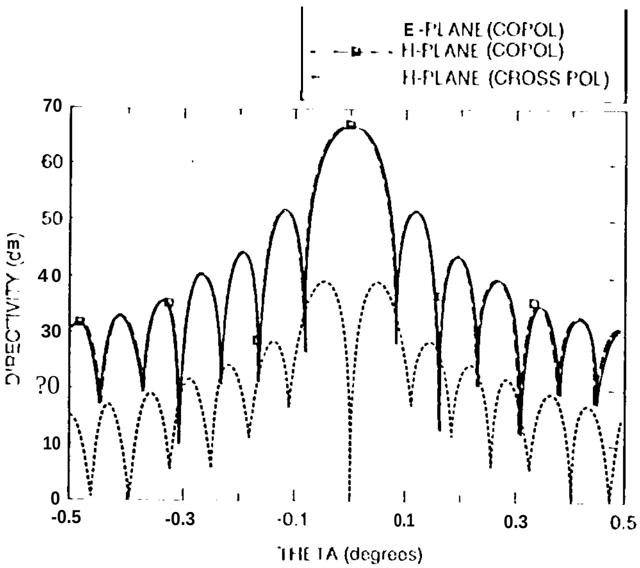

Figure 7. Far-field Patterns of the High power 34-meter Antenna at 7.2 GHz