Smooth-Walled Spline-Profile Horn Feed to Enlarge Compact Antenna Test Range Quiet Zone

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***Abstract*—We report the use of an Smooth-Walled Spline-Profile (SWSP) horn shaped beam feed with pattern optimized to achieve maximum compact antenna test range (CATR) quiet zone (QZ) size for a given reflector dimension, thereby minimising the cost of a new systems or increasing the capacity of existing facilities. We illustrate the concept with a sector-shaped, single offset reflector CATR by examining the impact that this has on the amplitude taper and the amplitude and phase peak-to-peak ripple of the QZ. We demonstrate that a Smooth-Walled Spline-Profile horn feeding an un-serrated rim reflector can attain a useable QZ area exceeding 50 percent the size of the 350 wavelengths diameter main reflector. This represents an increase in QZ area of over 60 percent compared to a conventional corrugated horn feed. The Smooth-Walled Spline-Profile horn offers a QZ bandwidth of just 9 percent compared to the 23 percent of the corrugated horn but is considerably cheaper to manufacture.**

***Index Terms*— Compact Antenna Test Range, Quiet-Zone, Smooth-Walled Spline-Profile horn, Reflector Efficiency.**

I. INTRODUCTION

The single-offset compact antenna test range (CATR) is a widely deployed technique for broadband characterization of electrically large antennas at reduced range lengths [1]. The nature of the curvature and position of the offset parabolic reflector as well as the edge geometry ensures that the resulting collimated field is comprised of a pseudo transverse electric and magnetic (TEM) wave. Thus, by projecting an image of the feed at infinity, the CATR synthesizes the type of wave-front that would be incident on the antenna under test (AUT) if it were located very much further away from the feed than is actually the case with the coupling of the plane-wave into the aperture of the AUT creating the classical measured "far-field" radiation pattern. The accuracy of a pattern measured using a CATR is primarily determined by the phase and amplitude quality of the pseudo plane-wave incident on the AUT aperture, with this being restricted by two main factors: amplitude taper (which is imposed by the pattern of the feed), and reflector edge diffraction, which usually manifests as a high spatial frequency ripple in the pseudo plane-wave [2]. It has therefore become customary to specify CATR performance in terms of amplitude taper, and amplitude & phase ripple of this wave over a volume of space, termed the quiet zone (QZ). It is in this volume that the Antenna Under Test (AUT) must remain during its axial rotations that constitute the antenna pattern measurement process. Unfortunately, in most cases it is not directly apparent how a given QZ performance specification will manifest itself on the resulting antenna pattern measurement. However, with the advent of powerful digital computers and highly-accurate electromagnetic (EM) models, it has now become possible to extend the CATR electromagnetic simulation to encompass the complete CATR plus AUT pattern measurement process thereby permitting quantifiable accuracies to be easily determined prior to actual measurement. An extensive study of the accuracy of this approach was reported by the authors in [3, 4]. For the work presented here we choose to use the Current Elements Method to model the CATR feed combination and hence predict the QZ field.

Amplitude and phase ripple of the QZ is still the dominant performance criteria of a given CATR facility with an industry standard of: 1dB amplitude taper, ±0.5dB amplitude ripple and ±5° phase ripple [1]. The amplitude taper is measured as the variation of a 2nd degree polynomial function that is obtained by means of, typically, a least squares best fit through the amplitude data over a cut through the QZ with the value being reported in dB. The amplitude ripple is measured by determining the variation of the amplitude about the 2nd degree polynomial fit with this also being expressed in dB. The phase

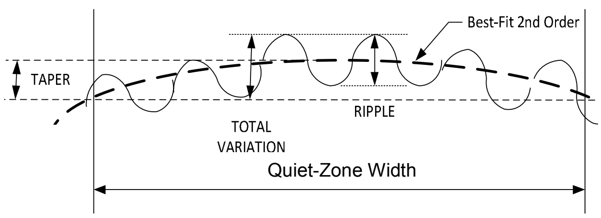

Figure 1: Illustration of CATR amplitude taper and amplitude ripple specifications in the QZ.

ripple is characterized by the deviation from a best-fit straight line over the quiet zone and is expressed in degrees. These linear cuts are typically acquired across horizontal, vertical or inter-cardinal cuts that are transverse to the z-axis of the range and are repeated at various *z* positions down range. The maximum dimensions within a volume of space, typically a circular or elliptical shaped cylinder, throughout which this specification can be achieved, determines the size of the CATR quiet-zone (QZ) [1]. Amplitude taper and amplitude ripple parameters are illustrated in Figure 1 with the phase ripple being analogous to the amplitude ripple shown (without a taper). These field properties are generally characterised as part of the CATR range installation using a procedure based upon a field probe scanner comprising a probe antenna mounted on a linear translation axis [1, 3]. The final facility acceptance is typically predicated upon the vendor being able to successfully demonstrate that these requirements have been met or exceeded.

In a recent paper [5] the authors have detailed the EM simulation of the measurement of a CATR QZ using arbitrary but known near-field probes using both the Plane Wave Spectrum (PWS) and Reaction Integral (RI) based modelling techniques. These models include effects associated with cross polarisation and polarisation purity of the respective scanning field probes and so it is possible to utilise measured *or* simulated patterns for the field probe to predict the "measured" QZ performance.

In [6] the authors presented results of a preliminary design study using an array of waveguide elements as the feed to optimally control the illumination of the CATR reflector. Two techniques were considered, reflector edge serrations and the alternative strategy of tapering the reflected field at the edge of the CATR aperture using a shaped beam such that the edges coincide with "ideally" a pattern null. The aim of the array approach is to maximize uniformity of illumination over some portion of the reflector whilst also providing the field intensity windowing needed to minimize edge diffraction effects thereby enabling greater aperture efficiency to be achieved for a given reflector size [1]. The work in [6] demonstrated a new efficient CATR computational electromagnetic simulation that enables a feed array (including mutual coupling effects) to encompass the design optimization loop.

In this paper we take an alternative approach of using a single CATR feed but one with a shaped radiation pattern more suited to optimising the QZ performance as in the array case above. Here we use the Smooth-Walled Spline-Profile (SWSP) horn [7] to achieve the more optimal pattern and compare results with a conventional corrugated horn feed. To demonstrate the concept we use a sector-shaped single offset reflector CATR having no edge treatment [8]. This 3m 18 panel CATR forms the 8GHz to 60GHz CATR facility at Queen Mary University of London's (QMUL) Antenna Measurement Laboratory.

The offset parabolic reflector has a 5.4m focal length and an overall surface accuracy of approximately 80microns. In our electromagnetic model the surface profile of the CATR is assumed to be formed from a perfect concave paraboloidal surface, and the reflector has no edge treatment, being modelled as a perfect metallic knife-edge. Imperfections can be included within the analysis, however, for the present study these are thought to constitute second order effects and so were omitted. The phase centre of the range's horn feed is placed at the focus of the offset reflector and the feed is tilted to an angle of 38°, with the edges of the reflector being seen at ±14° about this pointing. Here we consider a design of optimal feed horn centred at 35GHz, which represents a CATR reflector size of the 350λ diameter.

II. Smooth-Walled Spline-Profile horn design.

In the SWSP horn design process we first define the profile of the horn as a cubic-spline and then optimize the radiation

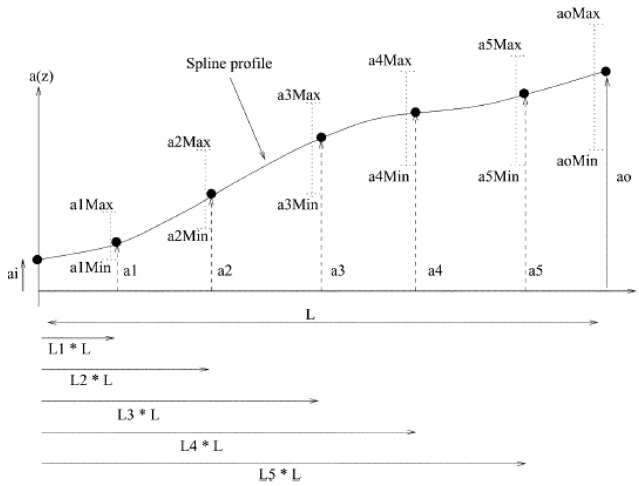

Figure 2. Spline-profile horn geometry.

pattern by shaping the profile, Figure 2. The horn is assumed to be axisymmetric. Only a few points (or nodes) are used along the length of the horn to generate the spline, namely two extreme nodes and five inner nodes. This is done to limit the number of optimization parameters and thereby simplifying the optimization process. Full details of the method can be found in

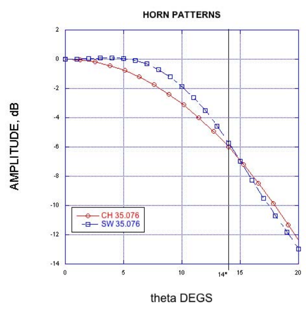

Figure 3. Comparison of SWSP and corrugated horn radiation patterns with -6dB at CATR edge.

[7]. The spline-profile optimization technique was used in [9] to design corrugated and smooth-walled horns for a CATR application. Our experience with this project has enabled us to quickly come up with a suitable horn design for the current application.

As a starting point we chose to design a 35GHz SWSP horn that illuminated the principal plane edges of the CATR reflector (subtended feed angle of ±14°) at a level of -6dB relative to the boresight. With the edges of the reflector being seen at ±14° we choose to design the horn for a flat radiation pattern over ±7° region and then rolling off to -6dB at ±14° reflector edge point. A plot of the radiation pattern of this horn, compared to a corrugated horn with same edge taper is shown in Figure 3. It is clear from this figure that the SWSP horn offers a highly uniform illumination of the CATR reflector over the ±7° region (as was the target pattern) and thus offers much more uniform field over the CATR reflector than a conventional linear taper corrugated horn.

III. CATR QUIET ZONE SIMULATION.

Figure 4 shows the simulated CATR field using the SWSP horn shown in Figure 3 along with the a cut of the offset plane QZ co-polar and cross-polar field in the *y*-plane at x = 4m

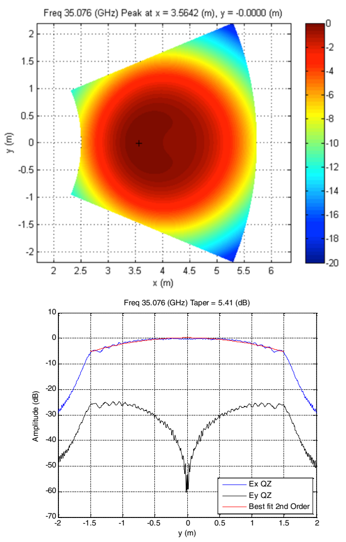

Figure 4. (top) Simulated CATR field using the SWSP horn shown in Figure 3 and (bottom) Co-polar and X-polar QZ field in y-plane at x=4m (Centre of CATR).

(centre of CATR). Figure 5 shows an expanded view the QZ amplitude and phase in the *y*-plane at x = 4m. The simulation results show that the SWSP feed produces an elliptical QZ with dimension of 1.7m in the *x*-plane and 1.6m in the *y*-plane based on the 1dB amplitude taper, ±0.5dB amplitude ripple and ±5° phase ripple criteria described in section 1. The actual values for this case are:

x and y amplitude taper =0.94dB and 0.59dB;
x and y peak-to-peak amplitude ripple = 0.98dB and 1.01dB;
x and y peak-to-peak phase ripple = 4.7° and 5.4°
area of elliptical QZ= 2.1m^2.

We then varied the SWSP horn aperture size to determine what level of CATR edge illumination gave the maximum QZ size. The results of Table 1 show that indeed -6dB edge illumination design offered the best QZ size. We then repeated the process for the corrugated horn, with radiation pattern shown in Figure 3. These results are also shown in Table 1 and

feed	edge taper dB	x plane QZ size m	y plane QZ size m	QZ area (ellipse)	x taper dB	y taper dB
SWSP	4	1.5	1.5	1.8	0.68	0.31
SWSP	6	1.7	1.6	2.1	0.98	0.59
SWSP	9.5	1.5	1.4	1.6	1.06	0.73
SWSP	12	1.3	1.3	1.3	0.85	0.77
Corrugated	4	1.4	1.1	1.2	0.86	0.64
Corrugated	6	1.2	1.1	1.0	1	0.91
Corrugated	9.5	1	0.9	0.7	1.05	0.94
Corrugated	12	0.9	0.8	0.6	1.04	0.85

Table 1. Comparison of QZ size for SWSP and corrugated horn feeds for different CATR reflector edge illuminations, frequency 35GHz.

indicate that the optimal edge illumination is -4dB and that the QZ ellipse dimension for this case is 1.4m in the x-plane and 1.1m in the y-plane (area of 1.2m^2). So at this centre frequency

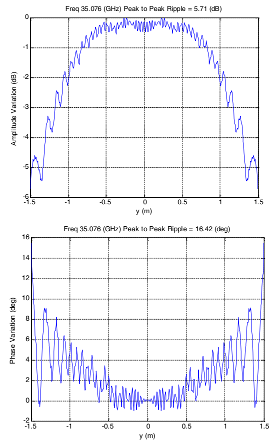

Figure 5. Expanded view the QZ amplitude (top) and phase (bottom) in the y-plane at x=4m.

of 35.08GHz the SWSP horn offers an increase in the area of the QZ of a factor of 1.77 over that of the corrugated horn.

Of course, bandwidth is an important factor for a CATR feed horn and both SWSP and corrugated horns can offer wide bandwidths. However, in this application the SWSP horn has limited bandwidth due to the large amount of modes needed to shape the pattern to have a "flat-top". It is this ability to control the modes to produce a flat-top pattern that subsequently impacts the usable QZ bandwidth. We thus calculated the QZ bandwidth for both the optimal SWSP and corrugated feed horn cases based on the definition of QZ bandwidth as being that where the edge of band has a QZ area of 0.75 that of the peak area. Table 2 shows the results for the SWSP horn indicating a QZ bandwidth of 3.35GHz (9.1%) and Table 3 shows the results for the corrugated horn indicating a bandwidth of 8.43GHz (23.6%). Whilst the corrugated horn offers over twice the bandwidth of the SWSP horn the cost of manufacture of the SWSP is considerably less and it is likely that two SWSP horns would cost the same as one corrugated horn therefore so long as the user is prepared to change horns more frequently the superior QZ area offered by the SWSP horn yields significant performance gains in

freq	edge taper -dB	x plane QZ size m	y plane QZ size m	QZ area (ellipse)	x taper dB	y taper dB
33.25	-6	1.2	1.3	1.2	0.96	0.63
33.86	-6	1.4	1.45	1.6	1.05	0.64
35.08	-6	1.7	1.6	2.1	0.94	0.59
36.75	-6	1.6	1.6	2.0	0.67	0.4
37.05	-6	1.6	1.6	2.0	0.68	0.46
37.21	-6	1.3	1.7	1.7	0.64	0.49
37.36	-6	1.1	1.6	1.4	0.66	0.32
37.51	-6	0.9	1.5	1.1	0.49	0.34

Table 2. SWSP horn QZ bandwidth performance (QZ bandwidth shown shaded)

freq	edge taper -dB	x plane QZ size m	y plane QZ size m	QZ area (ellipse)	x taper dB	y taper dB
28.00	-4	0.5	1.1	0.4	0.21	0.04
30.00	-4	0.9	1.1	0.8	0.31	0.4
31.57	-4	1.4	1	1.1	0.79	0.06
33.86	-4	1.5	1.2	1.4	0.93	0.67
37.05	-4	1.4	1.1	1.2	0.86	0.64
37.21	-4	1.4	1.1	1.2	0.95	0.4
38.58	-4	1.4	1.1	1.2	1.03	0.63
40.00	-4	1.3	1	1.0	0.94	0.62

Table 3. Corrugated horn QZ bandwidth performance (QZ bandwidth shown shaded)

terms of the size of AUT that can be accommodated in a given CATR facility.

IV. Performance of SWSP Horn with a Serrated Edge CATR Reflector.

In the previous section we have demonstrated the value of using the SWSP feed for achieving our target of increasing the QZ of the QMUL sector shaped single offset CATR. However this is an unusual configuration, as it does not follow the industry norm of using reflector edge treatment (such as

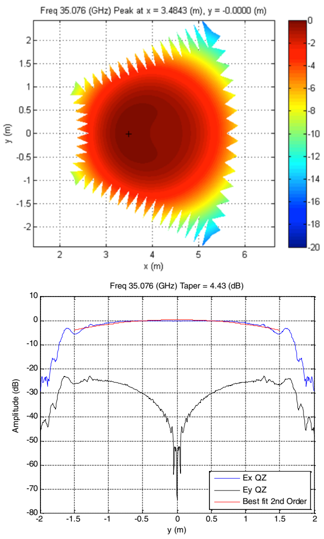

Figure 6. (top) Simulated CATR field using the SWSP horn with -4dB edge illumination (bottom) Co-polar and X-polar QZ field in y-plane at x=4m (Centre of CATR).

serrations or blended rolled edges) to mitigate edge diffraction. A detailed exposition of CATR reflector edge treatment can be found in [1]. In this section we re-evaluate the SWSP feed performance using the same QMUL sector CATR reflector but add serrations to the reflector edges in the simulation. As in the above section we have evaluated the QZ size of the serrated edge CATR using different size SWSP horns to determine the optimal edge illumination. Figure 6 shows the simulated CATR field using the SWSP for an edge illumination of -4dB this yielding the optimal QZ area for this CATR. In this case the SWSP feed produces an elliptical QZ with dimension of 1.9m in the x-plane and 2.0m in the y-plane based on the 1dB amplitude taper, ±0.5dB amplitude ripple and ±5° phase ripple criteria. Table 4 summarises the results for the SWSP feed and the actual values for the -4dB edge illumination case are:

x and y amplitude taper =0.98dB and 0.75dB;
x and y peak-to-peak amplitude ripple = 0.83dB and 1.06dB;
x and y peak-to-peak phase ripple = 3.1° and 5.1°;
area of elliptical QZ= 3.0m^2.

feed	edge taper dB	x plane QZ size m	y plane QZ size m	QZ area (ellipse)	x taper dB	y taper dB
SWSP	4	1.9	2	3.0	0.98	0.75
SWSP	6	1.7	1.7	2.3	0.94	0.95
SWSP	9.5	1.5	1.4	1.6	0.68	0.67
SWSP	12	1.3	1.3	1.3	0.85	0.73
Corrugated	4	1.5	1.5	1.8	1	0.91
Corrugated	6	1.2	1.2	1.1	1.02	0.93
Corrugated	9.5	0.9	0.9	0.6	0.89	0.81
Corrugated	12	0.9	0.9	0.6	1.06	1

Table 4. Comparison of QZ size for SWSP and corrugated horn feeds for different serrated edge CATR reflector edge illuminations.

Compared to the plain edge reflector case we see that as expected the serrations enable a larger QZ area (3.0m^2) to be achieved whilst still attaining the QZ ripple criteria, a significant increase in QZ area compared to 2.1m^2 for the plain edge reflector. As in the previous section we again compare the performance of the SWSP feed with a conventional corrugated horn, and the results are shown in Table 4. In this case the optimal edge illumination remains at -4dB and as expected the corrugated horn also offers increased QZ area (1.8m^2) compared to the non-serrated case (1.2m^2). So at this centre frequency of 35.08GHz the SWSP horn offers an increase in the area of the QZ of a factor of 1.67 over that of the corrugated horn, a very similar improvement found for the non-serrated CATR case.

V. Cross-Polarisation Performance.

One disadvantage of increasing the size of the QZ relative to the CATR reflector size is that the QZ peak cross-polar level increases due to the inherent cross-polarisation of a single offset reflector in the offset plane. In Figure 4 (bottom) we see that the peak-cross polar, that occurs at the edge of the QZ (±0.8m), for the optimal SWSP horn is -25dB down on the peak co-polar level. This corresponds to a feed pattern angle of ±7.4° and the peak cross-polar from the feed alone (which is in the 45° degree plane) is -34.5dB (with zero cross-polar in the principal planes) and so the overall QZ cross-polar level is dominated by the offset reflector geometry. This is confirmed by the result shown in Figure 7 for the optimal corrugated

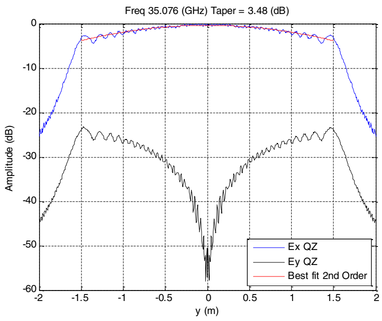

Figure 7. Corrugated horn feed CATR with -4dB edge illumination Co-polar and X-polar QZ field in y-plane at x=4m (Centre of CATR).

horn feed CATR (-4dB edge illumination) which shows the co-polar and cross-polar QZ field in *y*-plane at *x* = 4m (centre of CATR), indicating the same peak-cross polar level of -25dB seen by the SWSP feed. Indeed comparing the patterns of Figure 7 and Figure 4 (bottom) shows the similarity of both QZs. The corrugated horn has inherently lower cross-polarisation than the SWSP horn (by about -20dB) as can be seen by the comparison of the feed radiation patterns for both horns shown in Figure 8. We have thus demonstrated that the inferior cross-polar performance of the SWSP feed does not

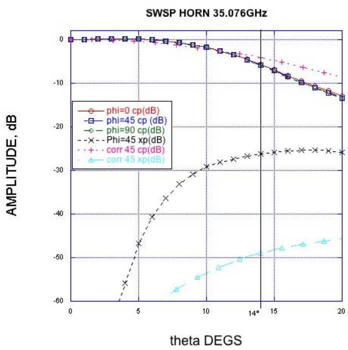

Figure 8. Comparison of the co-polar and cross-polar radiation patterns of the optimal SWSP and corrugated horns used with the plain edge reflector CATR

comprise the CATR QZ performance in the case of single offset reflector CATRs. Figure 8 also demonstrates the high degree of circular symmetry achieved by the SWSP horn design used here.

VI. CONCLUSIONS.

We have demonstrated that a shaped beam feed, as delivered by the Smooth-Walled Spline-Profile horn, can improve the single offset CATR elliptical QZ, with axis dimensions of 1.7m x 1.6m compared to that achieved with a conventional corrugated horn, having axis dimensions of 1.4m x 1.1m. This corresponds to a QZ area of $2.1m^2$ for the SWSP horn compared to $1.2m^2$ for the corrugated horn at the centre of the frequency band. We have shown that this improved QZ performance can be achieved over a bandwidth of 9.1% for the SWSP horn, with an average QZ area of $2.0m^2$, compared to the 23.6% bandwidth for the corrugated horn with an average QZ area of $1.2m^2$. This represents an improvement in QZ area by a factor of 1.6. Whilst the corrugated horn offers over twice the bandwidth of the SWSP horn the cost of manufacture of the SWSP is considerably less and it is likely that two SWSP horns would cost the same as one corrugated horn therefore, so long as the user is prepared to change horns more frequently, the superior QZ area offered by the SWSP horn yields significant performance gains in terms of the size of AUT that can be accommodated in a given CATR facility. The 35GHz SWSP horn described in this paper will be manufactured and experimental measurements of the QZ performance of the QMUL CATR will be reported in the future.

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