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MEASUREMENT PERFORMANCE OF BASIC COMPACT RANGE CONCEPTS

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ABSTRACT

Compact range test facilities represent a high standard for fast real-time and precision measurements. Nowadays, test applications are varying from single antennas to full payload antenna platforms, full-scale RCS and imaging objects to be tested within a frequency range starting from some 100 MHz up to 1000 GHz and beyond.

Different facility types were developed during the last 30 years and for the different applications a variety of facility optimizations were performed. Up to now, mainly three different types of compact test ranges are used and installed worldwide.

This paper gives an overview of the facility types i.e. Single Reflector, Dual Cylindrical Reflector and Compensated Compact Ranges with its advantages for specific applications and also pros and cons when compared to each other. The facilities were analyzed with a proven software tool so that performance data for the plane wave quality, the measurement accuracy and system characteristic data including impact on radiation pattern related to different sizes of test antennas could be extracted for comparative analyses.

Keywords: Compact Range, Compact Antenna Test Range

1. Introduction

The compact antenna test range was invented and firstly manufactured by Richard Johnson from Georgia Tech with a lot of initial work done by Doren Hess from MI Technologies, the formerly Scientific Atlanta, in 1969 [1], [2]. This facility type was a single reflector compact range mainly used for RCS measurements. Next improvements for this type of range were mainly done in the institute of Walter Burnside from Ohio State University with different analyses and experiments on reflector edge treatment [3]. In a next step, the first dual reflector systems with two cylindrical parabolic reflectors were firstly presented by Vaclav Vokurka from Technical University of Eindhoven, later March Microwave [4]. For space applications and the required high cross-polarization purity, the first Compensated Compact Ranges (CCR) with cross-polarization levels lower than - 40 dB in the full quiet zone were developed by Dietmar Fasold and his team at MBB, which is now EADS Astrium GmbH, Ottobrunn [5]. A similar range was manufactured and installed at ESA/ESTEC at the beginning of the nineties [6]. An alternative Dual Shaped Reflector Compact Range design with a smaller shaped subreflector – analog to an offset Cassegrain system – was published by Burnside in 1987 [7] and realized at the Wright Laboratory in Dayton, Ohio. In a last step, during the late 1990s, the serrated edges were numerically analyzed and finally improved at the Munich University of Applied Sciences [8]. The design of the serrations was in the meantime applied at several compensated compact ranges e.g. [9].

To summarize, three different types of compact ranges are nowadays primarily in use:

- **S**ingle (Reflector) **C**ompact **R**anges (SCR)
  - with short focal length (**SCR-S**)
  - with long focal length (**SCR-L**)
- **D**ual **C**ylindrical **P**arabolic (Compact) **R**anges (**DCPR**) consisting out of two single curved cylinder parabolic reflectors
- **C**ompensated (Double Reflector) **C**ompact **R**anges (**CCR**) consisting out of two double curved and compensated reflectors

The three compact range types exhibit advantages for different test applications but have very seriously to be analyzed and considered w.r.t. its quiet zone performance and characteristic data. All analyzed range types are equipped with identical serrated edge rim structures of constant length.

In the following, the performed facility analyses, facility geometries and at last the results for plane wave field performance and measurement accuracy will be shown in detail for each facility type.

2. Compact Range Analysis

For comparison of the different facility types the electromagnetic field in the quiet zone has to be calculated, firstly. With these data, in a second step, different analyses can be performed in order to extract accuracy and characteristic facility data.

For calculation of the quiet zone field, the well known and verified software tool GRASP (Version 9.2.01) is applied. The scattering effects of the compact range reflectors are calculated by using physical optics (PO) and the serrated edges are modeled as shown in Figure 1 with a GRASP internal model, based on a cosine tapered rim structure. Within this model, the reflector is defined with a so-called inner reflector rim and the serrated edge area with an outer rim. A verification of this model is given in the reference manual of the GRASP software [10].

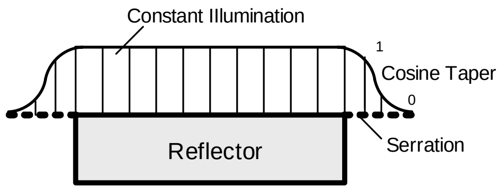
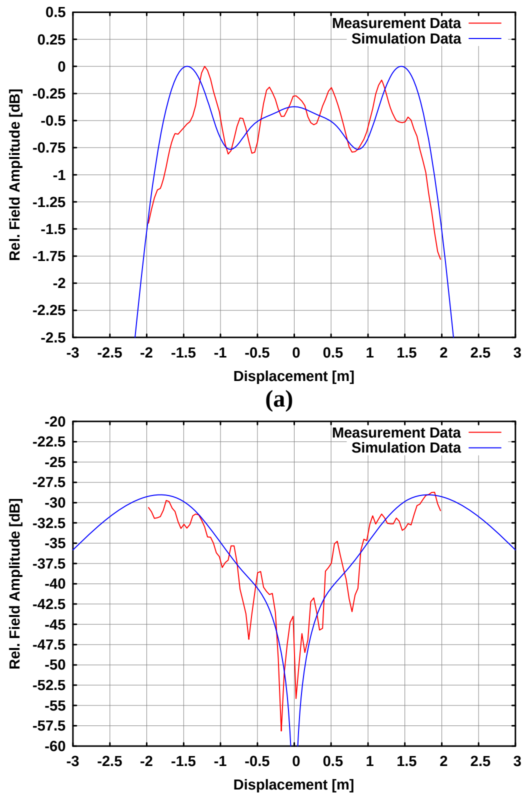


Figure 1 GRASP Modeling of Serrated Edge Area

Some verification results between simulation and measurement for a compact range operated at lower frequency are given in Figure 2.



(b)

Figure 2 Verification of Simulated and Measured Data in QZ, SCR with 3 x 3 m^2 Reflector, 2.5 GHz, 90° Cut, (a) CP-, (b) XP-Field

The results exhibit a sufficient good agreement for using the serration simulation model of GRASP also for relatively small reflectors and serration lengths compared to the wavelength. For frequencies below 3 GHz the serration length has to be slightly reduced to match simulated with measured results.

2.1 Facility Geometries

All four considered types of compact-ranges have to provide an identically sized quiet zone of 5 m in diameter lateral to plane wave field incidence. Related to this requirement, the reflector dimensions are determined and a serration rim structure with a length of 1.5 m is selected for all reflectors. In Table 1 the main relevant geometry data of the analyzed facility types are given.

Subject	Focal Length (Equiv. FL)	Dimensions Main Reflector
SCR-S Reflector	11 m (n.a.)	7.0 m x 6.7 m
SCR-L Reflector	14 m (n.a.)	6.9 m x 6.7 m
DCPR Main Reflector	16 m (16 m)	7.5 m x 6.0 m
CCR Main Reflector	40 m (130 m)	7.5 m x 6.0 m
Serration Length	1.5 m	
Quiet Zone Size	∅ 5 m	

Table 1 Geometry Data of Considered Facility Types

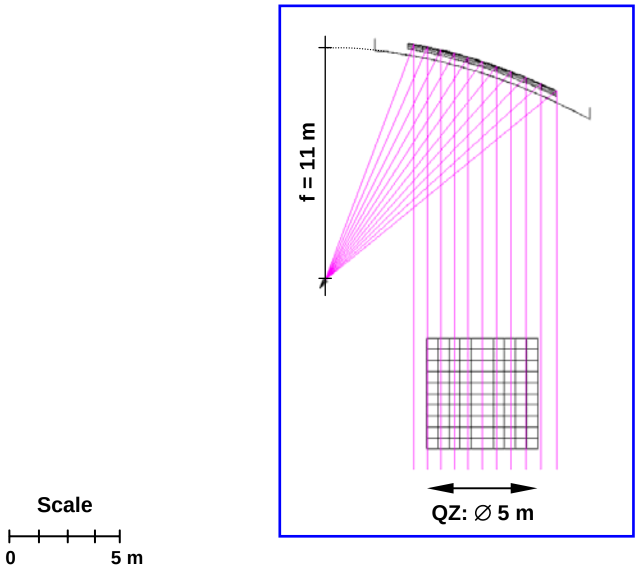
In Figure 3, the outlines of the four facilities with reflectors, feeds, quiet zones, QZ and required chamber sizes as well as simple ray tracing lines are shown. All ranges are drawn to equal scale.

For the two double reflector systems an additional equivalent focal length can be calculated and is given in Table 1. This value of double reflector compact ranges represents the focal length which can be compared to the focal length of a (single range) reflector so that both facilities exhibit identical behavior. For double reflector ranges with double curved reflectors, two different equivalent focal lengths can be calculated according to (1) for the large and (2) for the small value [11]. The value given in Table 1 shows the large equivalent focal length.

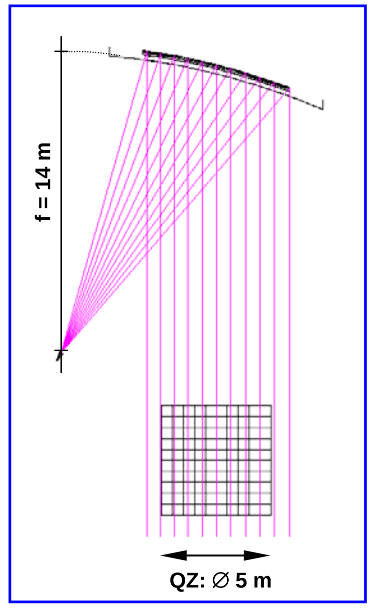
$$fL_{\text{Equiv., large}} = M \cdot fL_{\text{Main Reflector}} \tag{1}$$

$$fL_{\text{Equiv., small}} = \frac{1}{M} \cdot fL_{\text{MainReflector}} \tag{2}$$

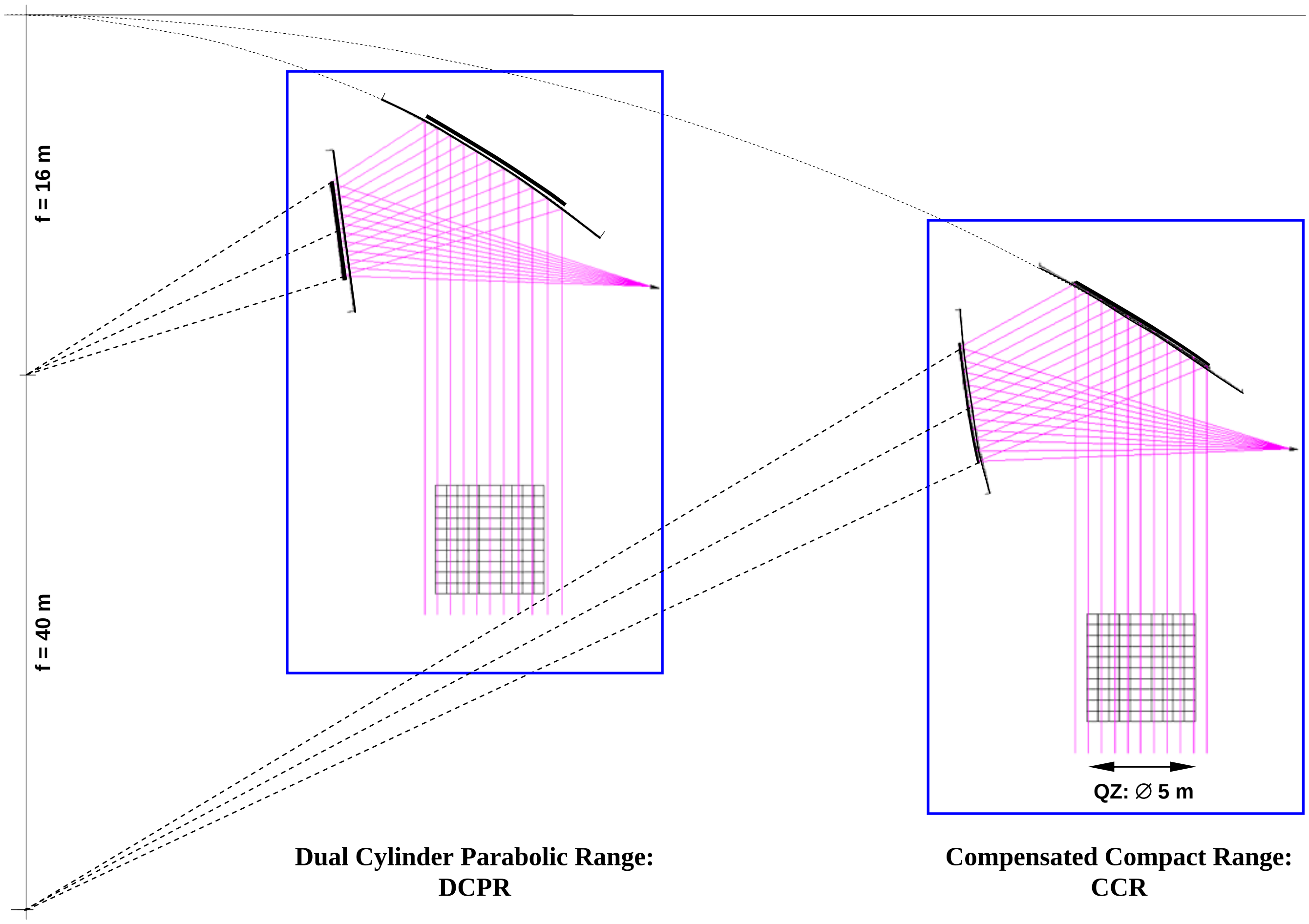
with M : Magnification Factor



Single Reflector Compact Range,
Short Focal Length: SCR-S



Single Reflector Compact Range,
Long Focal Length: SCR-L



Dual Cylinder Parabolic Range:
DCPR

Compensated Compact Range:
CCR

Figure 3 Outlines and Ray-Tracing of Analyzed Types of Compact Ranges, Drawn to Scale

For double reflector ranges with single curved reflectors, the magnification factor M is given in (3). For double reflector ranges with double curved reflectors and e.g. hyperbolic subreflector the magnification factor M can be calculated with given eccentricity e of the subreflector according to (4).

$$M_{DCPR} = 1 \tag{3}$$

$$M_{CCR} = \frac{e+1}{e-1} \tag{4}$$

Considering the RF-performance in view of differential path loss between ray paths emanating from the feed via the reflectors into the quiet zone, the maximum path loss of a double reflector system is determined by the large equivalent focal length $fL_{\text{Eqiv.,large}}$ of the reflector system. If considering the scanning capability or scanning performance, i.e. boresight tilting w.r.t. lateral feed shifting, the small equivalent focal length $fL_{\text{Eqiv., small}}$ has to be applied.

2.2 Analysis Parameter

For the comparative analyses of the four analyzed facility types the following test parameters as listed in Table 2 have been defined.

Parameter	Setting
Facility Geometries	see Table 1
Feed	- Edge Taper 0.5 dB at Reflector Edge - Linear Polarization - No Cross-Polarization
Frequencies	- 1.5 GHz - 12 GHz
Device Under Test, DUT for Pattern Accuracy Analyses (Co-, Cross-Polar)	- Low Gain Antenna: Linear Dimension: 0.05 m (0.4 m for 1.5 GHz) Constant Aperture Illum. - Medium Gain Antenna: Linear Dimension: 1.5 m Constant Aperture Illum. - High Gain Antenna: Linear Dimension: 3.0 m Constant Aperture Illum.
DUT Positions for Pattern Accuracy Analyses	- Center of Quiet Zone - 1 m Offset of Center - Cuts at 0°, 45°, 90°, 135°

Table 2 Parameter for QZ and Pattern Analyses (Co- and Cross-Polar)

The pattern accuracy analyses are based on a MATLAB tool which predicts the impact of the non-ideal plane wave field in the QZ on the co- and cross-polar radiation pattern of the DUT. This is performed by the convolution of the QZ field with the pattern of the DUT. A one-dimensional convolution is carried out for discrete cuts in the 0°, 45°, 90°, 135° planes. This means that a line feed antenna with different lengths of 5 cm up to 3 m is considered as test antenna in the quiet zone.

3. Analysis Results

The analysis results comprise the following evaluations:

- Plane Wave Field Performance Data
- Measurement Accuracy Values Derived from Convolution Analyses of One-dimensional Test Antennas with Different Lengths
- Characteristic Facility Data

3.1 Plane Wave Field Performance

As a result of calculations with the GRASP program, the Figures 4 – 7 show the contour plots of the quiet zone fields with the marked 5 m quiet zone for the SCR-S, SCR-L, DCPR and CCR. The plots show the co- and cross-polar fields at a low frequency of 1.5 GHz and a medium frequency of 12 GHz, each. In the cross-polar plots of Figure 7 (b, d) no contour lines are shown as the cross-polar levels for this type of facility are lower than –58 dB at 1.5 GHz and –60 dB for all frequencies above 2GHz.

Some general conclusions can be drawn from the predicted plane wave fields in the QZ:

- At very low frequencies (1.5 GHz) a rather similar co-polar performance of the considered facilities is observed. If only single reflector compact ranges are compared to each other the SCR-S is superior to the SCR-L.
- At higher frequencies the most symmetric and plane field characteristics of the co-polar QZ fields are nearly identical for all range types. The flatness of the QZ field is directly related to the value of the equivalent focal length. But due to the fact that an edge taper of 0.5 dB is imposed at the reflector edge all error figures are rather equal for all ranges.
- Concerning the cross-polarization the CCR is the only one that exhibits no system inherent cross-polarization in the QZ. For the other ranges the SCR-S shows the worst cross-polarization in the QZ, as it exhibits the largest offset angle.

  The DCPR shows similar high cross-polarization figures as the SCR-L.

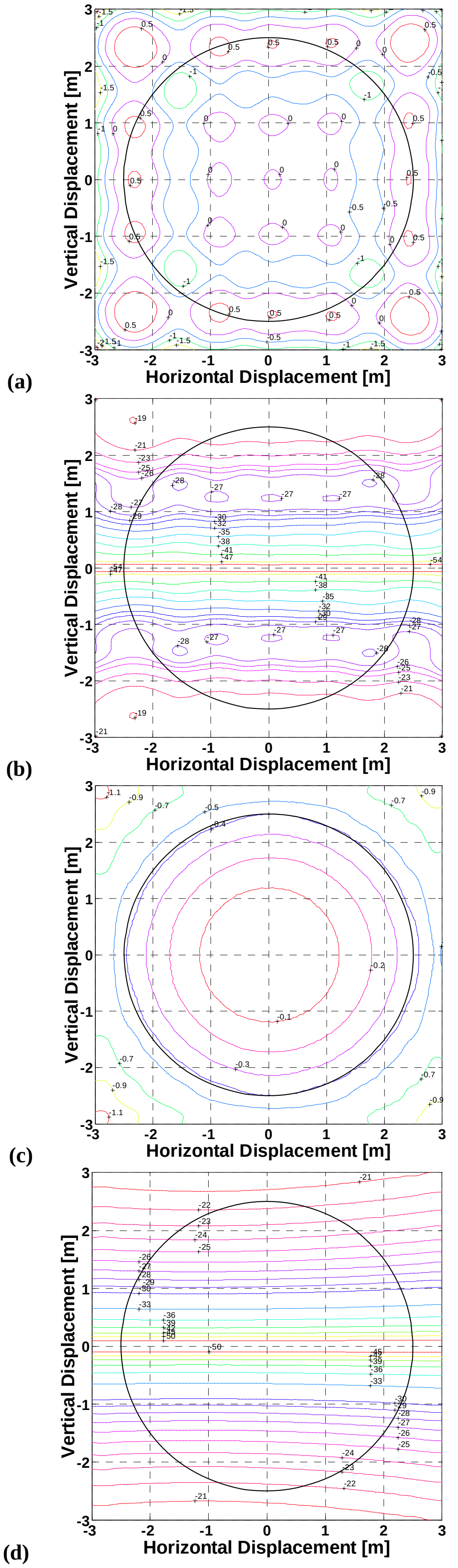


Figure 4 Simulated Plane Wave Field of SCR-S:
(a, b) Co-, Cross-Polar Field, 1.5 GHz
(c, d) Co-, Cross-Polar Field, 12 GHz

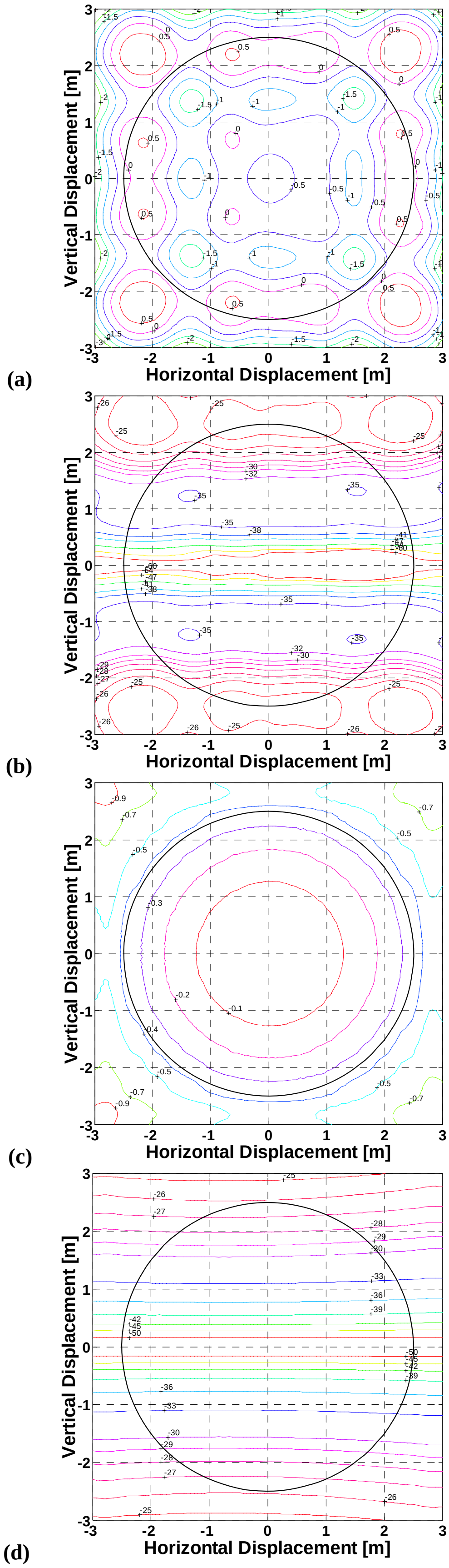


Figure 5 Simulated Plane Wave Field of SCR-L:
(a, b) Co-, Cross-Polar Field, 1.5 GHz
(c, d) Co-, Cross-Polar Field, 12 GHz

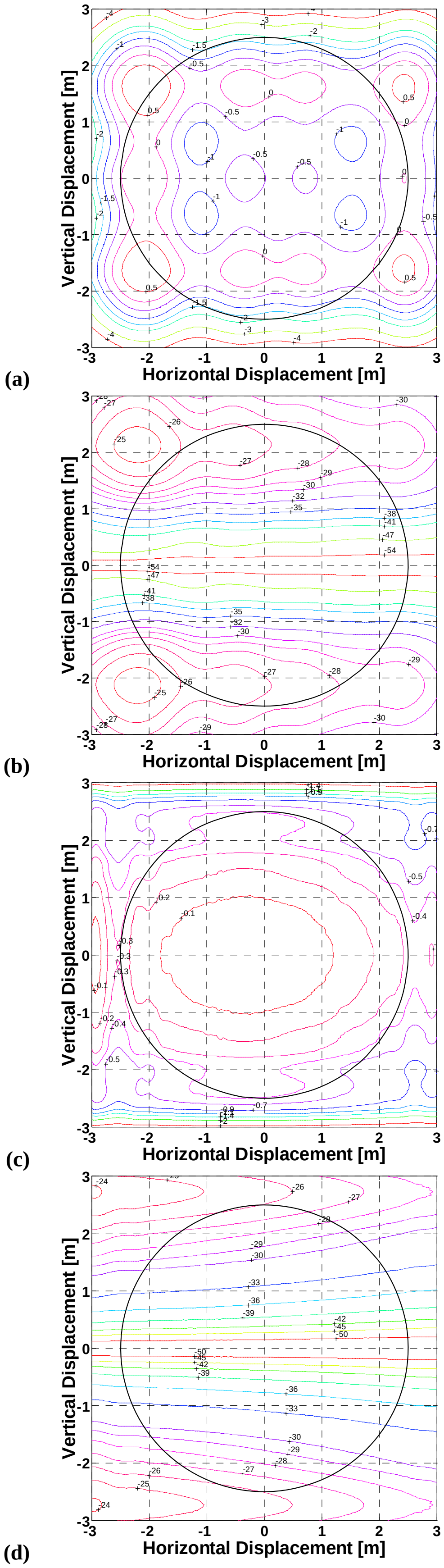


Figure 6 Simulated Plane Wave Field of DCPR:
(a, b) Co-, Cross-Polar Field, 1.5 GHz
(c, d) Co-, Cross-Polar Field, 12 GHz

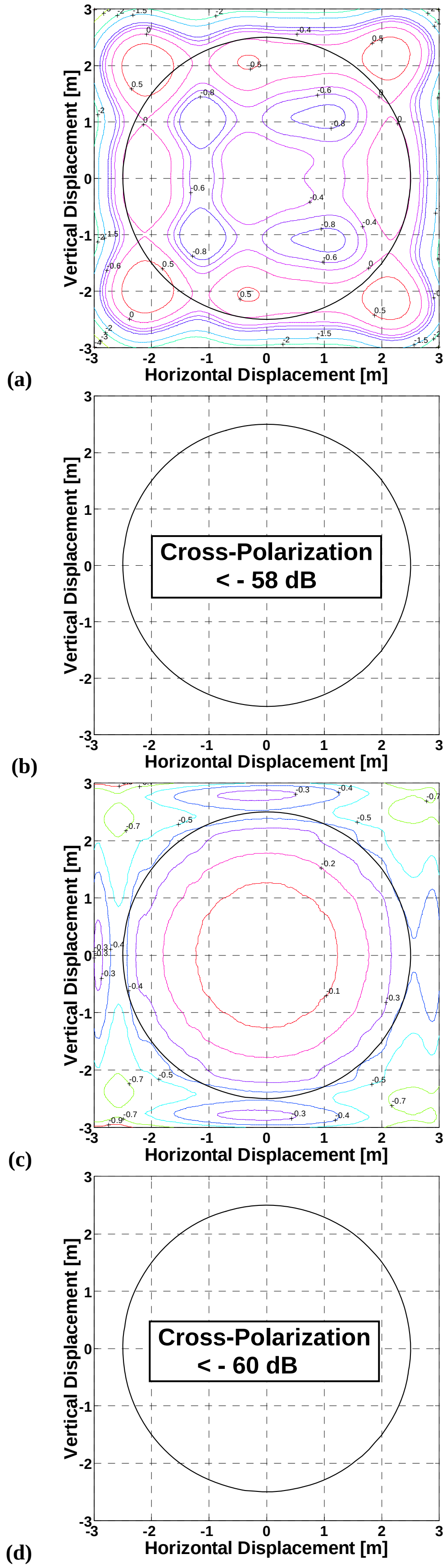


Figure 7 Simulated Plane Wave Field of CCR:
(a, b) Co-, Cross-Polar Field, 1.5 GHz
(c, d) Co-, Cross-Polar Field, 12 GHz

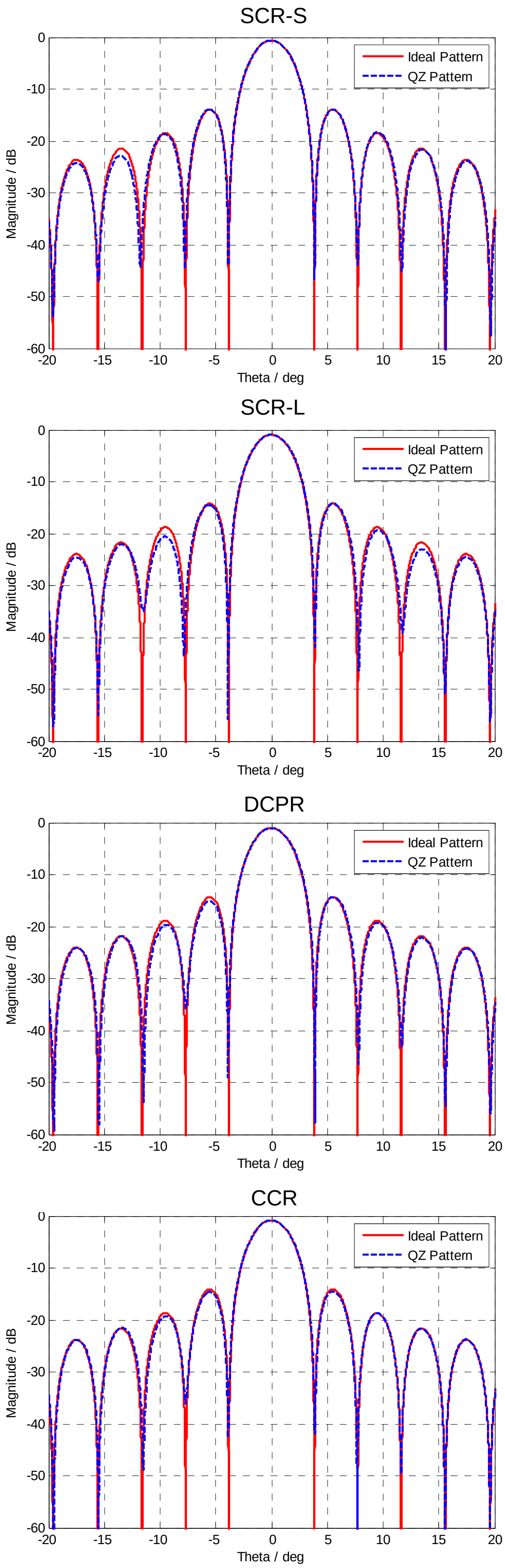


Figure 8 **Co-Polar Far-Field Pattern of QZ @ 1.5 GHz, 3 m Antenna Aperture in Center of QZ, $\phi = 0°/180°$ Cut**

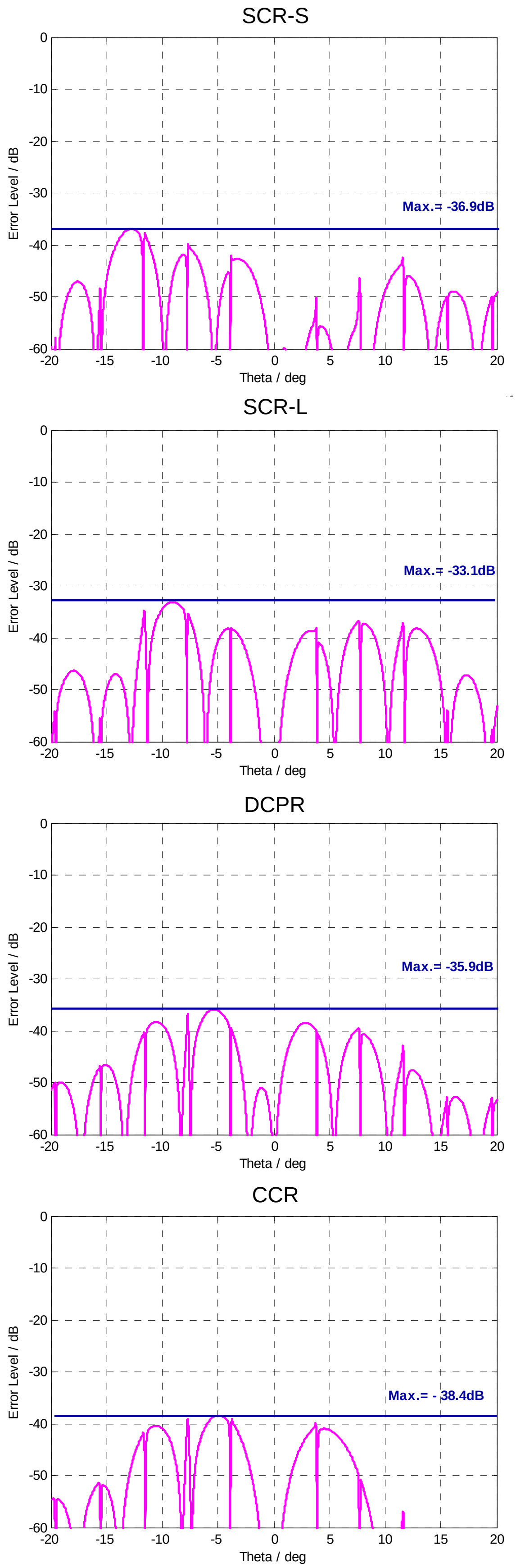


Figure 9 **Far-Field Pattern Error of QZ Pattern of Fig. 8 w.r.t. Ideal Pattern**

3.2 Analysis of Measurement Accuracy

The measurement accuracy of different sizes of test antennas are calculated for the four considered compact ranges by convolving the one-dimensional radiation pattern of the test antennas with the QZ fields. This is performed as summarized in Table 2 for 2 positions in the QZ-center and 1 m offset and for two frequencies 1.5 GHz and 12 GHz.

The analysis results obtained with a dedicated MATLAB tool are shown in the Figures 8-13. As an example Figure 8 shows the co-polar far-field patterns at 1.5 GHz of a 3m antenna positioned in the center of the QZ exhibiting an ideal plane wave field or the real plane wave fields as predicted for the four different types of compact ranges (Figures 4 to 7). Figure 9 shows the associated error plots. The error plots for the co-polar and cross-polar far-field pattern are referenced to an ideal, constant illuminated test antenna with zero cross-polarization. For the co-polar pattern the presented value is an average of the maximum figures of four cuts at ϕ = 0°, 45°, 90°, 135°. For the cross-polar pattern the worst case cut at ϕ = 90° is selected.

The following general statements can be derived from these predictions:

- The co-polar performance decreases for all ranges if the test antenna is moved from the center of the QZ to outer positions. A partly similar effect is achieved if the size of the test antenna is increased.
- The co-polar error figures predicted for high frequencies above 3 GHz are in the same order of magnitude for all considered ranges (variation less +/- 1.5 dB). For the lowest frequency at 1.5 GHz the double reflector compact ranges are slightly superior to the SCR-L. This degradation is mainly related to the too large distance of the QZ of the SCR-L to the main reflector.
- For the cross-polar far-field pattern the CCR is superior to all other ranges, as in this range type no system inherent cross-polarization occurs. The pattern errors of the other ranges are significantly higher but all in a rather equal range with a variation of less than +/- 2.5 dB. Especially the SCR-L and DCPR show to a large extent same results. As an example the Figures 10 and 11 visualize for the SCR-S and DCPR the impact of the cross-polarization in the QZ on the measured cross-polar far-field pattern of the test antenna. Here the 1.5 m test antenna is one meter positioned outside the center of the QZ.

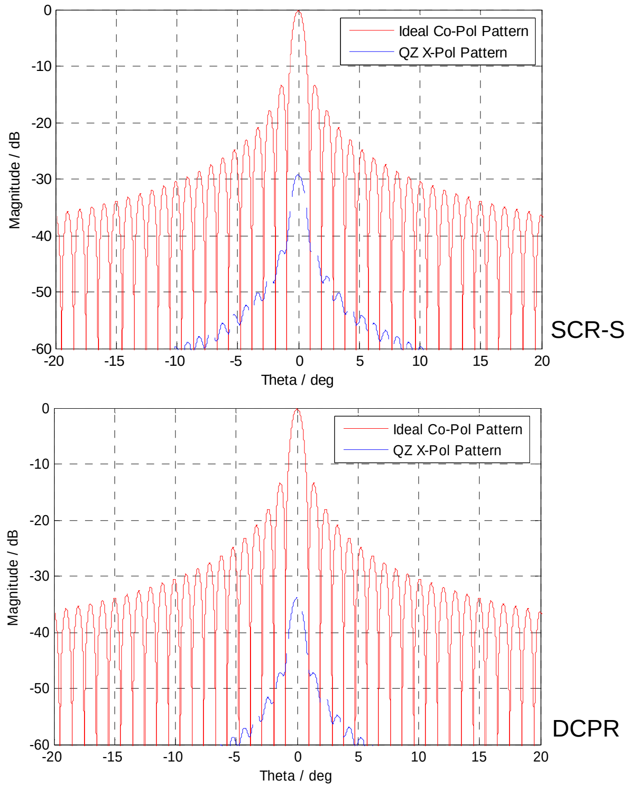


Figure 10 Real Cross-Polar Far-Field Pattern Plot w.r.t. Ideal Co-Polar Pattern @ 12 GHz, 1.5 m Antenna Aperture Measured 1 m Outside of Center QZ

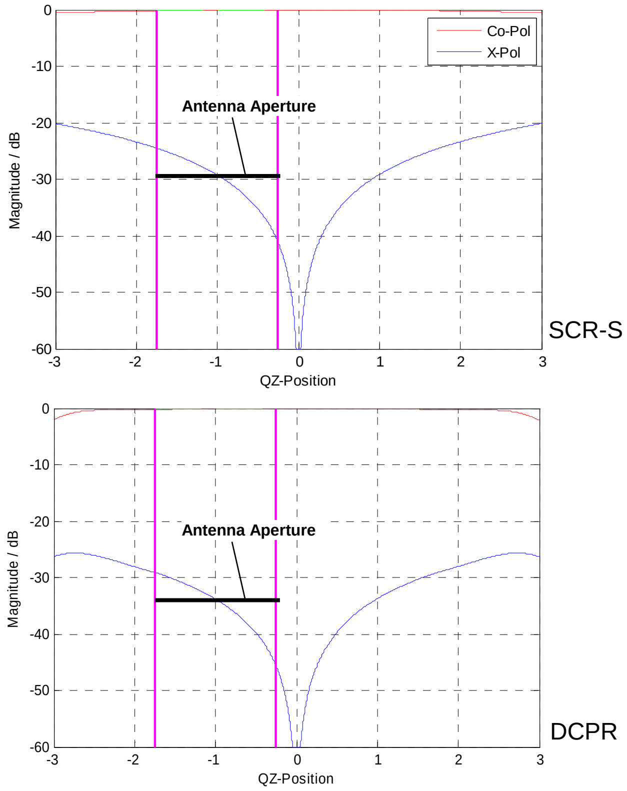


Figure 11 Co- and Cross-Polar Cut in Quiet Zone, ϕ = 90 degree @ 12 GHz

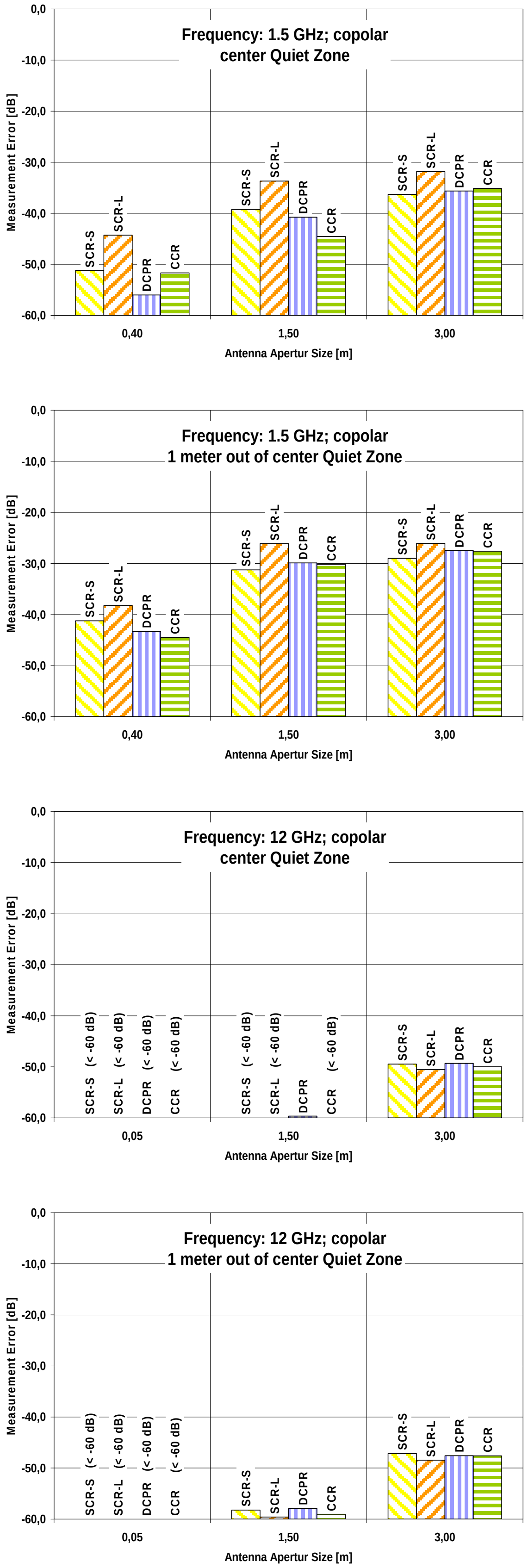


Figure 12 Summary of Co-Polar Far-Field Pattern Error, Average of 4 Cuts at $\phi = 0°, 45°, 90°, 135°$

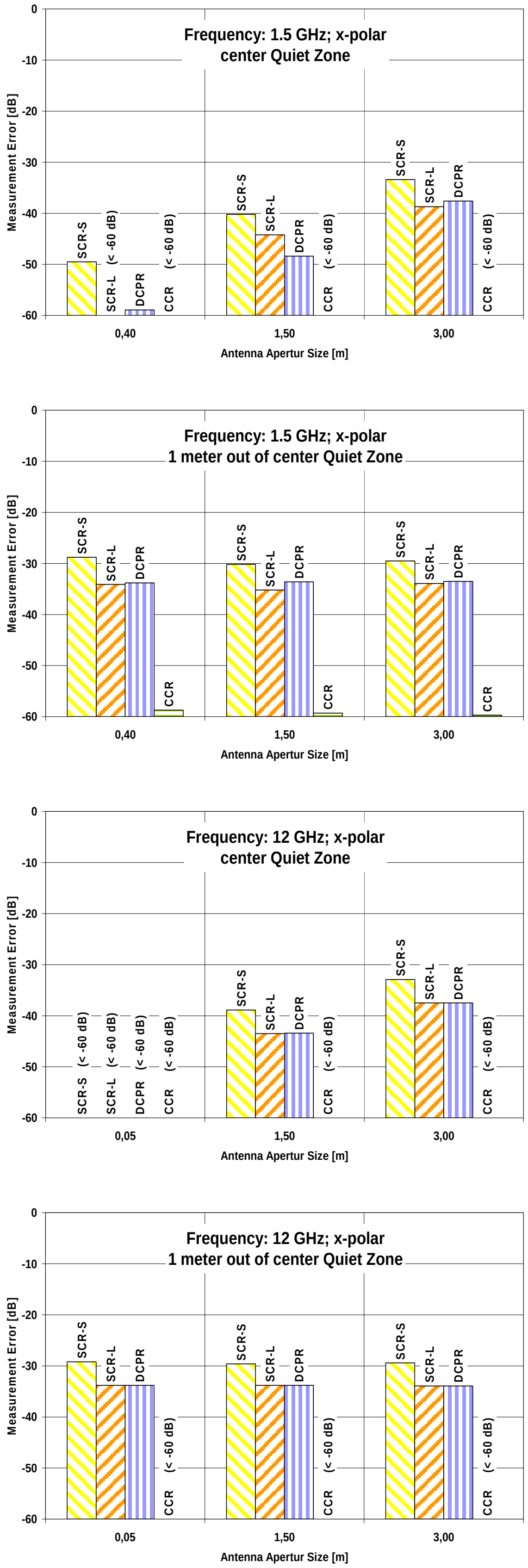


Figure 13 Summary of Cross-Polar Far-Field Pattern Error, Worst Case Cut at $\phi = 90$ degree

3.3 Characteristic Facility Data

In general the compact antenna test ranges have system inherent advantages for antenna and RCS testing compared to standard far-field and near-field ranges. These are:

- Real far-field environment in the quiet zone
- Low and constant free space loss:
  The free space loss of a compact antenna test range can accurately be calculated from the reflector geometry, as mentioned before. The free space loss is calculated as follows:

  $$L_{FreeSpace} = 20 \cdot \log\left(\frac{4 \cdot \pi \cdot D_{eff}}{\lambda}\right)$$

  with D_{eff} : Effective Free Space Distance, dependent on individual facility

  λ : Free Space Wavelength

  This makes gain measurements very easy and independent from axial movement of the DUT (provided that standing waves in the QZ are avoided).
- Real-time measurement capability

Besides quiet zone performance accuracy values, the analyzed compact range test facility can also be categorized w.r.t. different test applications. For that aim state-of-the-art measurement applications are selected which are discussed below:

- Communication Antenna Testing:
  Antennas for communication satellites are predominantly complex antennas which are designed to fulfill high performance requirements. Most of them have contoured and shaped beams, operated over a broad frequency range and apply frequency re-use (Polarization Diversity) i.e. transmission of two channels at one frequency by applying orthogonal polarizations. All these antenna characteristics have to be measured with highest accuracy. For that a low tapered co-polar and very low level cross-polar field below -40 dB is required in the QZ. In [12] the CCR was already identified as the most adequate facility type to fulfill such outstanding requirements. The analysis results shown in Figs. 12, 13 confirm this statement.
- RCS Testing:
  In order to achieve maximum dynamic range for extremely low test signals test facilities are preferred for RCS measurements which produce minimum diffraction contributions in the QZ. This can be best achieved when using single reflector compact ranges. On the other hand, for full polarimetric measurements and mainly signature testing and analyses, very low cross-polarization contributions of the facilities itself are required. This in turn can be best achieved when using the CCR.
- Payload Testing:
  The testing of payload parameters comprises measurements in a compact test range facility and calculation of parameters like EIRP, IPFD, G/T, PIM, auto-compatibility and group delay. The measurement accuracy for these tests is mainly correlated to the gain measurement accuracy in a test facility.
- Low Frequency Antenna Testing:
  The lowest operation frequency of a compact antenna test range is mainly determined by the size of the reflectors and reflector edge zones i.e. length of serrations. In this context the simulations at 1.5 GHz have shown widely similar values for the co-polar performance of all considered test facilities. For the cross-polar performance the CCR is again superior to all other ranges.

The room efficiency can be defined as a further parameter for comparison of the different facility types. This parameter can easily be calculated by the relation of quiet zone volume w.r.t. room volume. For the four analyzed facilities mentioned within this paper the values are given in Table 3. For the calculations, the **Quiet Zone Volume** of all analyzed facilities was assumed with **100 m³**.

Facility	Room Volume	Room Efficiency
SCR-S	2940 m³	3.4 %
SCR-L	3360 m³	3.0 %
DCPR	4000 m³	2.5 %
CCR	4000 m³	2.5 %

Table 3 Required Room Volumes and Room Efficiency of Analyzed Ranges

4. Summary

Today mainly three different types of compact ranges are used and installed worldwide. With this paper an attempt is undertaken to systematically analyze and identify the specific performance characteristics of these compact antenna test range types: Single Reflector (SCR) with short and long focal length, Dual Cylindrical Reflector (DCPR) and Compensated Compact Range (CCR). After definition of the geometries of these four ranges, which are designed for a quiet zone of 5 m diameter, the plane wave fields in the quiet zone are calculated with GRASP, a well proven software tool applying PO.

Additionally the impact of the predicted, non ideal quiet zone field on the co- and cross-polar radiation pattern of a test antenna is systematically analyzed. Different sizes and positions of the test antenna are considered. The advantages and disadvantages of the four facility types are extracted from these results and discussed with regard to different test applications.

The results can be roughly summarized in a short form, that

- for co-polar measurements at low frequencies (1…2 GHz) all four facilities show similar results,
- for all measurements requiring high polarization purity the CCR is superior to all of the considered facilities and
- for other standard measurements all four facility types can be applied with only minor performance differences.

As modeling of the reflector serrations with a taper function is the most critical and error prone contribution to the overall simulation results it is recommended for future calculations to apply dedicated numerical field simulation and analysis programs (full wave analysis) to improve the prediction accuracy in this field.

5. References

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