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Uncertainties in Bistatic RCS Measurements

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Radar Cross Section (RCS) is a far field parameter and limited test range length produces error in its measurements. RCS measured with co-located Tx and Rx antennas is termed as monostatic RCS and with spatially separated Tx and Rx antennas as Bistatic RCS (BRCS). Interest in BRCS measurements has grown due to increase in use of multi-static Radars for detecting low-observable targets. In literature BRCS measurement techniques explored are either horn antenna based far field setups or Compact Antenna Test Range (CATR) based setups. All the techniques have inherent limitations and errors, which need to be assessed as the information generated plays a decisive role in the design of military platforms. In the present paper, the errors in each measurement technique are obtained through extensive numerical computation and measurements on various canonical as well as complex shapes. The results highlight the effect of the phase curvature in either or both, Tx, and Rx paths, affect the measurement accuracies, thereby limiting the target size and highest frequency of operation of present techniques.

Keyword: Antenna, Compact antenna test ranges, Far field, Plane wave, Radar

Introduction

Radar Cross Section (RCS) is a quantitative measure of the detectability of a target by radar, often referred as its Radio Frequency (RF) signature. Generally, in military setups ground radars are deployed at fixed locations to detect the presence of targets in its search volume. RCS measured in such scenario is termed as mono static RCS where the Tx and Rx are co-located. Due to the advancement in RF stealth technology, new aircrafts, Unmanned Arial Vehicles and missiles are being designed to produce a very small radar echo in certain aspects when illuminated by a monostatic Radar. Detecting such low observable targets becomes very difficult using monostatic radar. To overcome this drawback, a network of radars in multi static configuration is employed. RCS measured by a pair of spatially separated Tx and Rx is termed as Bistatic RCS (BRCS). Accurate RCS signature information of a target is essential in estimating its detection range for given radar which is directly linked to its survivability in hostile environment. Several computational techniques like PO (Physical Optics), GO (Geometrical Optics), MoM (Method of Moments), MLFMM (Multi Level Fast Multipole Method) etc. are adopted worldwide to estimate the RCS. However, in a practical scenario these simulated RCS values differ from that of the measurements due to the inherent limitations belonging to the software and hardware. Therefore, accurate and logical measurement techniques that emanate in reliable and repeatable results will contribute for the better understanding of the target's signature. Unlike antenna measurements that are carried out in a defined far field, the minimum range criterion for RCS measurements is not well defined. In general, for the antenna measurements, the far field is specified as $\frac{2D^2}{\lambda}$ where, D is the maximum dimension of the Antenna Under Test (AUT) and λ is the operating wavelength.[1] Many researchers have carried out monostatic and BRCS measurements by placing the Target Under Test (TUT) just beyond the minimum far field antenna distance criteria. Bradley *et al.*[2] while investigating the bistatic calibration targets at 5–15 GHz, have adopted a 10 m range far field set up that allows only a 30 cm sized target at the highest frequency for the above mentioned far field criterion. Similarly, in the same far field range while studying the bistatic characteristics of some complex targets, Eigel *et al.*[3] carried out measurements in the

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7–15 GHz range with the maximum target dimension as 30 cm. He evaluated prediction accuracies of various techniques with the measurement data. In another work, Gurel *et al.*[4] measured BRCS of a 1/10th scaled down model of 45 cm long dimension at 4 GHz in a 5.5 m range which would define RCS values at 400 MHz. The error which could directly be attributed to the size of the target vis-à-vis the adopted range length have not been addressed by authors. The same issue was addressed by Knott *et al.*[5] in a mono static setup, suggesting that the complex targets be placed at least five times beyond the above mentioned far field criterion to account for an error of less than 1 dB thereby leading to the conclusion that wave front planarity and illumination uniformity are key parameters for radar cross measurement range. This can be achieved either by utilizing a very large anechoic chamber or by a Compact Antenna Test Range (CATR) that produces an approximate plane wavefront in the most compact volume. A CATR is an anechoic chamber with a collimating device such as a paraboloid that generates a uniform plane wave across the aperture of an AUT.[6] Single Reflector Compact Range (SRCR) is the simplest and the most common configuration. Multiple reflector configurations have also been developed[7] to enhance the test range performance. CATR by its inherent geometry with a fixed focal point is normally not suitable for BRCS measurements. But Chang *et al.*[8] introduced the CATR based BRCS measurements for the first-time by laterally displacing the transmit and receive feeds as shown in Fig. 1.

It compared the BRCS results of flat plate with PO calculations. Another configuration of bistatic setup which is a hybrid of far field and CATR setups is implemented in CATR by Potgieter *et al.*[9] In this hybrid configuration, the target is illuminated by a plane wave of CATR and the scattered energy is collected by a wideband antenna placed at 7.8 m distance from the target at fixed bistatic angle. The measurements were carried out on 1.8 m target up to 12 GHz, in the receiving mode, the target size chosen is much larger, with no range separation criteria.

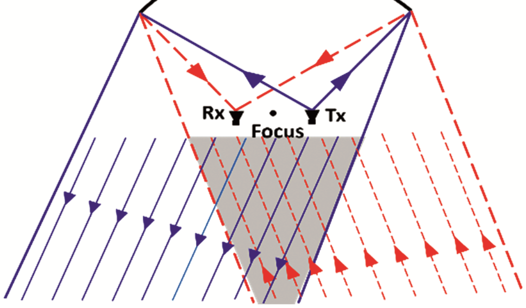

Fig. 1 — BRCS measurement setup with feed offset[8]; Shaded portion is the bistatic measurement sector

Based on the above arguments, we propose to compare the measured results in various measurement setups (Far field, Hybrid and CR offset) as depicted in Fig. 2. These measured results are also compared with the computational outcomes using MLFMM solver. Detailed explanation of the set up geometries is given in the following section. Canonical to complex targets like flat plate, cylindrical rod, ogive and wedge shape have been considered for analysis. The prime aim of this study is to analyse the performance of each of the BRCS measurement technique and to understand the magnitude of errors that can be present in each of them.

Materials and Methods

Experimental Setup

All the proposed BRCS measurements were carried out in the same anechoic chamber in all three setup arrangements at 10 GHz. The minimum angle of 7° is selected for the comparison, so as to avoid the higher errors that could arise in CRFO setup due to large offset separation and minimum limitation of the hybrid setup. The target is placed on a Styrofoam column placed over a positioning system. To maintain a commonality among all the setups the Tx and Rx were angularly separated by 7° in space in all cases. The sizes of the targets are purposefully chosen smaller and larger than the maximum size that could be accommodated as per the antenna far field criterion, so that the errors are predominantly captured and can be explained accordingly.

Far Field (FF) Setup

The far field range setup is shown in Fig. 3 with Tx and Rx antennas spatially separated at an angular

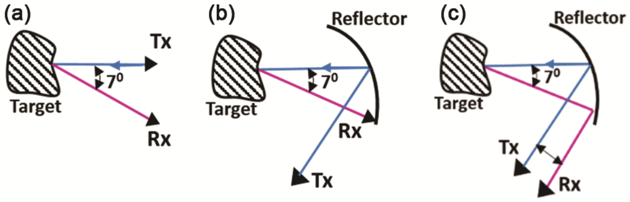

Fig. 2 — The three Setups to study various BRCS range configurations: (a) Far Field (b) Hybrid (c) CR Offset

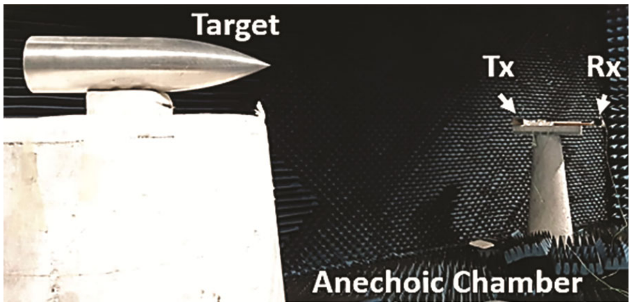

Fig. 3 — Far field set up with two horns at 7° angular separation with respect to the target

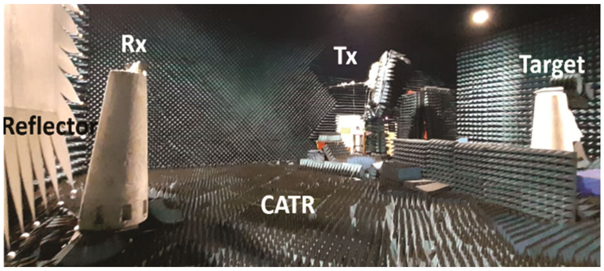

Fig. 4 — Hybrid set up in a CATR with Rx placed near the reflector

distance of 7° with respect to the target and are placed 8.5 m away from the target. The Tx-Rx antennas and the target are placed on Styrofoam structures to avoid reflections from the mounting platforms. The setup as per Fig. 2(a) is implemented as shown in Fig. 3.

Hybrid Setup

In hybrid setup the paraboloid reflector is illuminated by a feed (Tx antenna) placed at its focus and the plane wave is generated. The target is placed in the quiet zone formed in the anechoic chamber. The reflected energy from the target is received by the Rx antenna placed adjacent to the CATR reflector at a bistatic angle of 7° with respect to the axis of the paraboloid. The schematic is shown in Fig. 2(b) and the setup is shown in Fig. 4.

Compact Range Feed Offset (CRFO) Setup

In this setup, the Tx antenna is placed at the focus of the reflector and target is placed in the quiet zone formed in the anechoic chamber. The scattered energy is received by Rx antenna placed in the focal plane of the reflector displaced by a distance such that it receives a wave front tilted by 7° with respect to the transmitting wave front.

The displacement, Δx, is related to this wave front tilt, θ, shown in Fig. 5 as

$$\theta = \frac{1}{F_c}(57.3 - 0.0044\alpha^2)\Delta x \quad \dots (1)$$

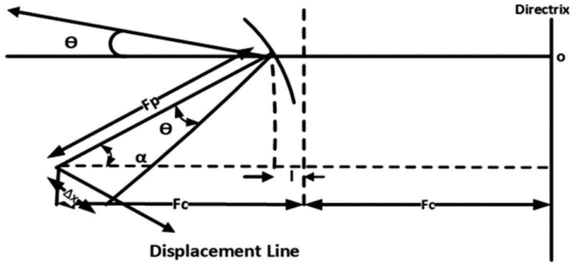

Fig. 5 — Illustration of Wavefront tilt by lateral feed displacement in a CATR.

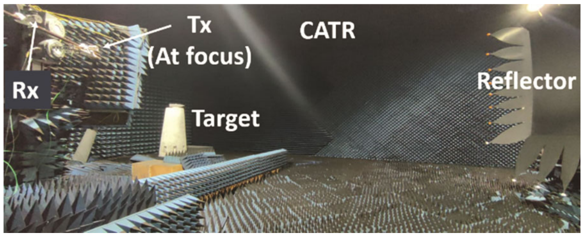

Fig. 6 — CRFO set up in a CATR with Tx-Rx placed in the focal plane of the reflector

where, F_c is focal length of the reflector and α is the offset angle of the CATR which are 6.5 m and 27°, respectively, for the CATR shown in Fig. 6.

Results and Discussion

RCS Measurement Comparison of Setups

Two types of comparative studies are carried out here. The effect of bi-directional range length (far field) on the target and second, the capability of the setup to handle large targets is presented.

Effect of Range Length

To study the effect of target size in BRCS measurements a few canonical models like flat plates and ogives were considered. The study was carried out by considering the sizes of the target to be smaller and larger than the wavelength specified by $\frac{2D^2}{\lambda}$ criterion for the respective range. Two rectangular plates with dimensions shown in Fig. 7 are considered. For a range length of 8.5 m in our experiments, the maximum size allowed by the far field criterion is 350 mm at 10 GHz and for this reason two flat plates, A and B, with dimensions above and below this value are considered.

The theoretical peak RCS value, σ, of a flat plate in the 0° direction is given by[10]

$$\sigma = 4\pi\frac{A^2}{\lambda^2} \quad \dots (2)$$

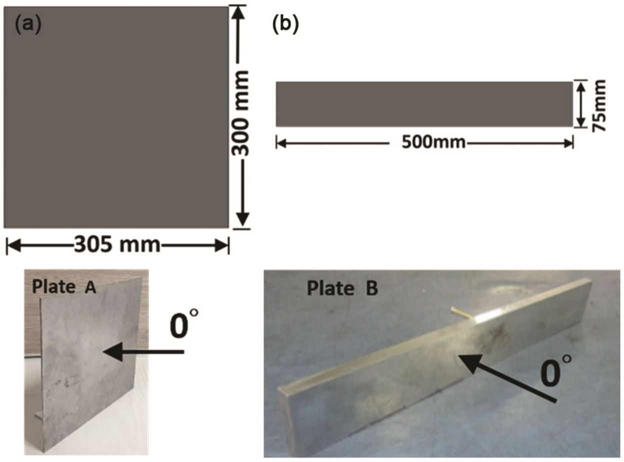

Fig. 7 — Flat plates with their dimensions (a) Plate A (10λ × 10λ) with length smaller than the maximum allowable target size (b) Plate B (16.67λ × 2.5λ) with dimension larger than the maximum allowable target size

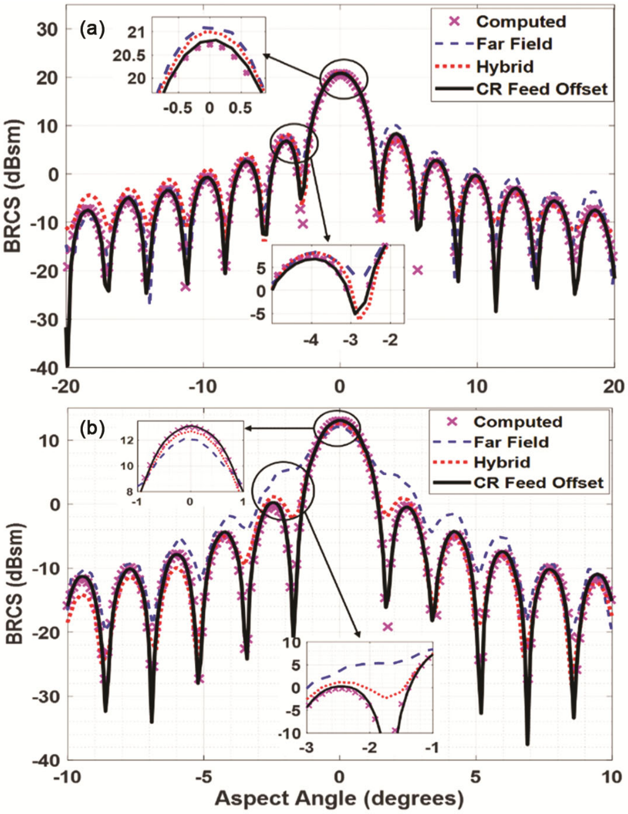

Fig. 8 — BRCS measurements on flat plates (a) Plate A (b) Plate B

where, A is the area of plate and λ is the operating wavelength. The theoretical RCS is thus calculated as 20.7 dBsm for plate A and 13 dBsm for plate B and these values are matching with the computed peak values shown in Figs 8(a) and 8(b), respectively. Since the maximum dimension of plate A is within the limits of far field criterion, it is evident from Fig. 7(a), in all the three set ups the peak values are within 0.5 dB to the computed value. However, the side lobe values are deviating by more than 1dB and first null depth is filled by more than 7 dB for the FF setup, but in the CATR methods (both hybrid and CRFO) the measured values are well matched with the computed values.

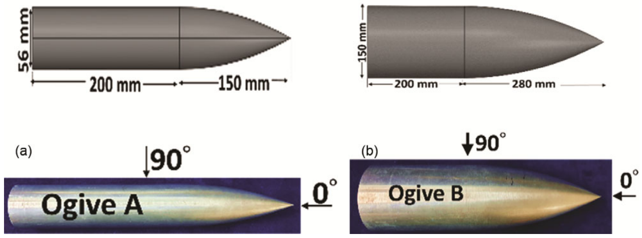

Fig. 9 — Ogive models with their dimensions (a) Ogive A (11.67λ × 1.87λ) (b) Ogive B (16λ × 5λ)

Further in plate B, the deviation in peak values for the FF set up is more than 1 dB and for hybrid it is within 0.5 dB. In FF setup, the side lobe itself could not be formed and in the hybrid setup side lobe is deviated by 1 dB and the null is filled. However, for both the plates, the CRFO setup values are precisely matching with the computed values.

A second set of targets with ogive followed by a cylinder is taken with dimensions as shown in Figs 9(a) and 9(b). Since the smaller dimension target is 350 mm long, the far field range here is considered at 10 m. Ogive A dimensions are within the maximum allowable target size and Ogive B is with dimensions larger than the maximum allowable target size. For both Ogives, the cylindrical portion is of equal length but vary in their diameters. In case of FF the peak BRCS values at 90° aspect angle, are within 1 dB but the peaks are displaced by 1° for both. The nulls are also filled by 4 dB and are displaced in angles (Fig 10). The effect is observed in hybrid set up too, but on a smaller scale. Likewise, the plate that was discussed earlier, even in the case of Ogives also, the CRFO values are closely matching with the computed values. It is clearly seen that even at the far field range, measured characteristics are not free from errors and is not sufficient for accurate BRCS, hence the condition suggested by Knott[5] is relevant. This clearly indicates that the FF range needs to be increased to reduce the phase difference along the spherical wave front that interacts with the target which otherwise increases with the target's size. Since the range length increases proportionally with the square of the target's dimension, CATR is to be

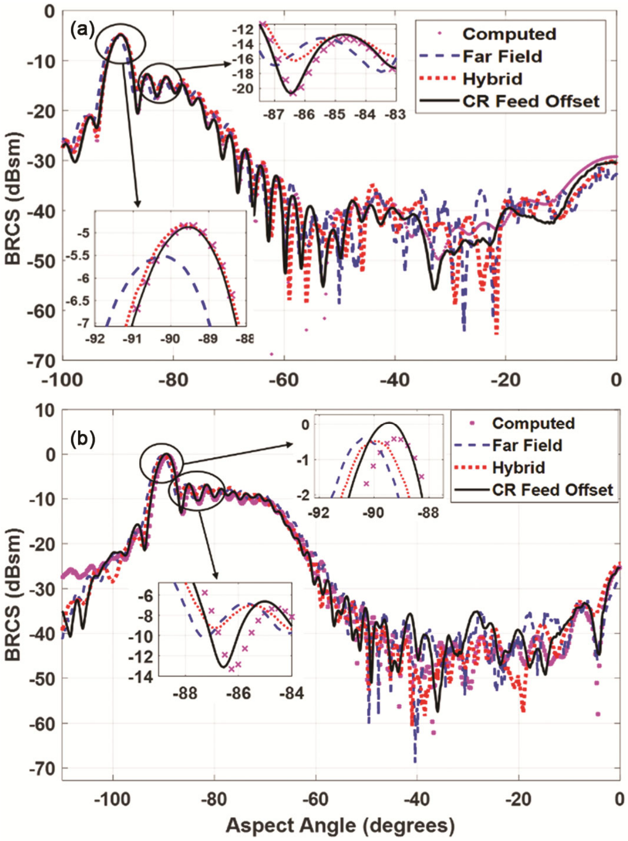

Fig. 10 — BRCS measurements of (a) Ogive A, (b) Ogive B

preferred for larger targets as it produces a plane wave front on the target with smallest phase variation.

Bistatic RCS of Large Objects

It has been verified in the previous results that the phase curvature across the target, directly affects the accuracy of the measurements even when they are close to the allowable maximum size (i.e., slightly smaller and slightly larger than the maximum size). To understand the behavior of very large targets ($\gtrsim 30\lambda$) in these setups, two canonical models like cylindrical metallic bar and wedge-shaped test body are considered. The maximum dimensions of these models are more than 1 m, which thus demands a far field range more than 60 m. But when the measurements are carried out at 10 m distance, the deviations of the measured BRCS values vis-à-vis computational results are alarming. This can be observed from the BRCS measurements of a cylindrical rod whose dimensions are shown in Fig. 11.

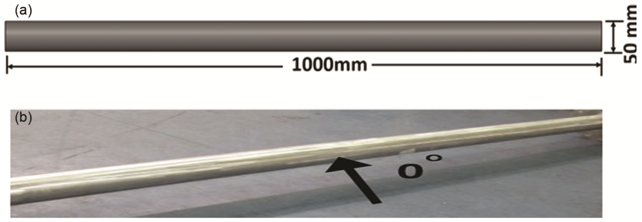

Fig. 11 — 3D model of cylindrical rod with dimensions (33.3λ × 1.66λ) (b) Cylindrical rod used for measurements

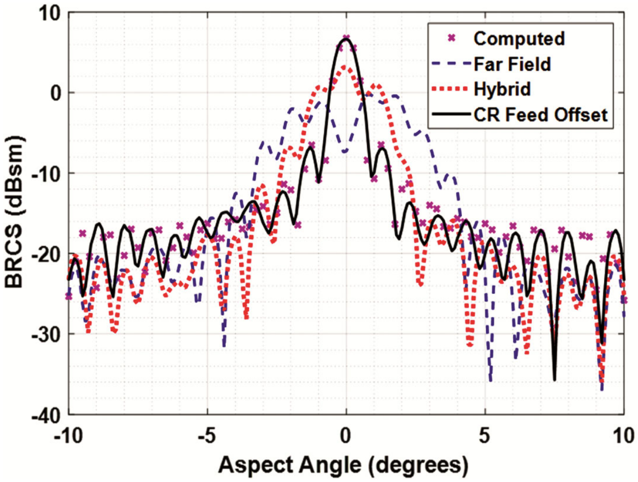

Fig. 12 — BRCS measurements of cylindrical rod

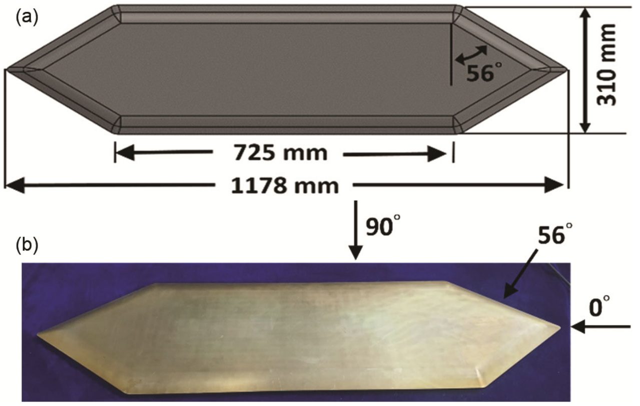

Fig. 13 — Facetedwedge-shaped body (a) 3D model with dimensions (39.27λ × 10.33λ) (b) Actual model

The length of the rod is approximately three times that of the maximum size allowed for a 10 m range at 10 GHz. The effect could clearly be observed in Fig. 12 where the results from FF and hybrid set up measurements are totally away from the computed values. The CRFO set up is in complete agreement with the computational results and depicts the theoretical nature of the RCS of the cylinder.

To further ascertain this behavior, similar measurements are carried out on a more complex faceted wedge-shaped low RCS body as shown in Fig. 13. The structure has three prominent points at which the RCS needs to be analyzed is shown in Fig. 13(b).

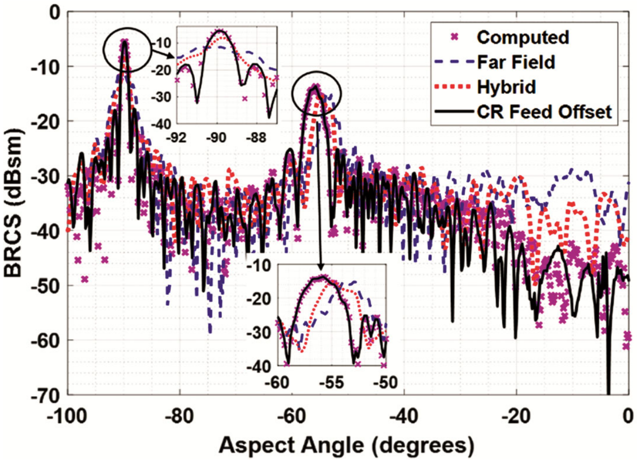

Fig. 14 — BRCS measurements of wedged shaped plate

It is expected to have peak formation at the 56° and 90° due to the straight edge and low RCS at 0°. The same can be seen in Fig. 14, where the computational values and the CRFO setup have yielded a perfect peak matching with each other.

The results of FF setup and hybrid setups have deviated from the expected values in magnitude and angular locations near both the peaks due to the obvious reasons discussed in the previous section. At the sharp edge point where the RCS is very low due to structural characteristics, the measured values in CRFO setup match with the computational results while the data from FF set up and hybrid setups have deviated.

Discussions on Results

FF setup has highest measurement error for all object types and hybrid setup also suffers from errors for large targets. However, error is less compared to FF setup. CRFO setup has highest correlation to the computed data for all varieties of targets. For very large targets, both FF and hybrid setups have totally deviated from expected values. This clearly limits the use of these techniques for large targets as well as high frequency BRCS measurements. The magnitude of errors depends on the shape of the target. Hence for a complex target which will possess a combination of various features the magnitude of error is expected to be different in various sectors. In the setup realization, FF setup has the flexibility of choosing any bistatic angle and hence has the maximum bistatic angular coverage. In hybrid setup bistatic angles are limited to a small sector beyond reflector to the adjacent wall inside a CATR. CRFO setup with lateral feed displacement can generate bistatic angles limited by the lateral relative displacement between the feeds. Here, the bistatic angles are limited to 20–24° degrees depending upon the focal length of the CATR. Based on above experimentations of bistatic measurement correlation of different setups for variety of target types, it can be concluded that waveform planarity is essential for accurate BRCS measurements. The measurement errors are directly related to either one or both the antennas not satisfying the RCS measurement distance criterion. Most importantly, the measurement antenna separation distance of $\frac{2D^2}{\lambda}$ is found inadequate for accurate BRCS measurements.

Conclusions

BRCS measurement techniques have been evaluated for various conditions in the present study. The magnitudes of error and limitations of all the techniques are highlighted. The FF setup is simplest of all the implementations but has the highest measurement error. The feed-target separation distance criterion of antenna measurements is found inadequate for accurate BRCS measurements. The error is also found to depend on the target's physical characteristics. Hybrid setup utilizes plane wave illumination characteristic of the collimator in one path and hence has application in a very limited angular sector. Measurement performance of hybrid set up is marginally better than FF setup, however, it cannot handle large targets. CRFO setup is found to have the highest BRCS measurement accuracy, this implementation also allows for characterization of largest target than other two techniques. CRFO method has limitations in application to larger Bistatic angles. More detailed studies on application of this technique to perform BRCS measurements needs to be carried out. Its application for BRCS measurements at millimetre wave frequencies can also be explored, which otherwise is not possible with other methods. A technique that can extend angular BRCS measurement capability of CRFO for BRCS measurements needs to be explored.

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