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Interference Analysis for Synthetic Aperture Radar Calibration Sites with Triangular Trihedral Corner Reflectors

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Abstract

The typical method for performing an absolute radiometric calibration of a Synthetic Aperture Radar (SAR) System is to analyze its response, without interference, to a target with a known Radar Cross Section (RCS). To minimize interference, an error-free calibration site for a Corner Reflector (CR) is required on a wide and flat plain or on an area without disturbance sources (such as ground objects). However, in reality, due to expense and lack of availability for long periods, it is difficult to identify such a site. An alternative solution is the use of a Triangular Trihedral Corner Reflector (TTCR) site, with a surrounding protection wall consisting of berms and a hollow. It is possible in this scenario, to create the minimum criteria for an effectively error-free site involving a conventional object-tip reflection applied to all beams. Sidelobe interference by the berm is considered to be the major disturbance factor. Total interference, including an object-tip reflection and a sidelobe interference, is analyzed experimentally with SAR images. The results provide a new guideline for the minimum criteria of TTCR site design that require, at least, the removal of all ground objects within the fifth sidelobe.

Key words: Synthetic Aperture Radar(SAR), Calibration Site, Interference, Corner Reflector, Radar Cross Section

1. Introduction

Synthetic Aperture Radar (SAR) imaging uses radar scattering, which comprises numerous sets of Radar Cross Sections (RCS), and reveals various characteristics of objects. Therefore, radar scattering is typically used for the RCS of a test object [1, 2].

A fundamental test for radar is to gauge its response to a target with a known RCS. For a test case using simple targets, the RCS can be calculated analytically with a high degree of accuracy and precision [3]. The RCS of an object plays an important role in its detection by radar [2]. A thorough understanding of the electromagnetic scattering characteristics of an object is necessary for successful implementation and control of its RCS [2].

Disturbances caused by the environment are classified as 'reflection' and 'interference'. Previous studies [3-6], primarily consider the effect of reflections, and/or the characteristics of target limitations in disturbance analysis. Previous studies [3-6] do not consider the whole effect of interference because the tests were conducted in the controlled conditions at good test facilities, such as the 'St. Kilda ground reflection range', or at other sites, such as 'an area in the north Canberra in the Australian Capital Territory' [4].

In reality, it is difficult to control and maintain good site conditions for a long period, due to lengthy occupation, and

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invasion by animals of the sites with point targets. During a calibration activity, ground configuration and objects in the external site environment are carefully considered when improving RCS accuracy. In this study, using an example of a Corner Reflector (CR) site with a surrounding protection wall, minimum site criteria to ensure an error-free test site are suggested.

2. Corner Reflector Protection Scheme

2.1 Triangular Trihedral Corner Reflector (TTCR)

In general, calibration activity uses point targets as CRs, and a transponder to identify radiometric errors. During calibration, a simple CR is useful as a passive target, due to its stable response if the environment and physical conditions remain unchanged.

A typical trihedral CR is comprised of three orthogonal planar plates intersecting at a corner point, or apex. Fig. 1 shows three common plate shapes: right-angled triangles, squares, and quarter-discs [3].

In general, the most effective plate shape may be the Triangular Trihedral CR (TTCR). The equation to calculate a TTCR RCS–σ is published in many studies [2-5, 7, 8]. The 'tip' region of no reflection in the TTCR is especially important for interference analysis (Fig. 2).

2.2 Corner Reflector Protection

The most appropriate location for CR deployment is a remote area without man-made structures [8]. Fig. 3 depicts a wide and flat plain in Mongolia. However, this area is a challenge as a calibration site, due to poor accessibility for the deployment and maintenance of the CRs.

During a long mission lifetime, CRs need to be installed on the ground for accessibility. In addition, for their maintenance and to enable long periods of SAR calibration, the CRs need to be protected from damage by animals.

An installation experiment for TTCRs has been undertaken on a very wide, flat plain in Mongolia. To prevent access by animals, protective walls were built around the TTCR (Fig. 4), which as ground objects, are an error source for measurement of the target RCS. Therefore, it is necessary to analyze the protection wall in order to identify the minimum criteria for an effectively error-free site.

The protection wall in the installation experiment was constructed of two berms and one hollow (Fig. 5a, b). Fig. 5c indicates that this was a successful protection against farm animals.

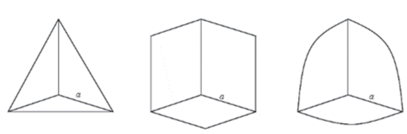

Fig. 1. Common trihedral corner reflector shapes [3]

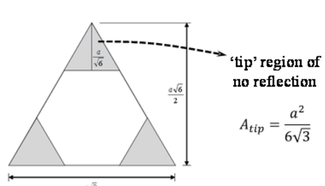

Fig. 2. The region of no reflection in a Triangular Trihedral Corner Reflector [3]

Fig. 3. Calibration site in Mongolia

3. Interference Analysis

3.1 Interference

The test scenario impacts directly on RCS accuracy, due to the protection acting as an error source and causing a multipath reflection unrelated to TTCR shape. During the experiment, certain problems were analyzed to maintain absolute radiometric accuracy.

In general, when measurement accuracy of the RCS of TTCRs is considered for absolute radiometric calibration, two categories are recognized:

- Self-Reflection (S_3)
- Interference (C_I)

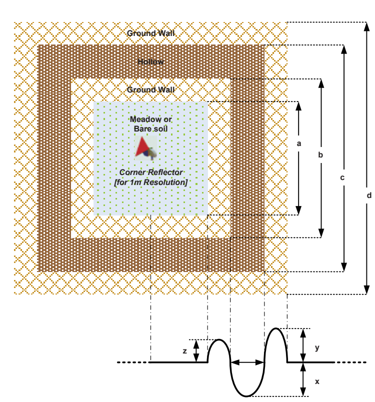

Fig. 4. TTCR protection wall

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Self-reflection is related directly to the shape of the TTCR with a triple-bounce mechanism.

Interference refers to the amount of errors caused by all mechanisms, except triple-bounce. One error is caused by the relative position of the TTCR and surrounding berms, as they are additional surfaces in proximity to the reflector (termed "Ground Plane Interference" [3]). Ground plane interference could be classified as both "Perfect Reflection", and "Imperfect Reflection" [3]. However, in this experiment, only "Perfect Reflection" is considered due to its complexity, and "Ground Object Interference" is also considered as the main category of "Ground Interference", instead "Ground Plane Interference". This is due to the berms being considered as ground obstacles, which is a different type of interference (a point-like target) causing a new error source.

Figure 6 shows the geometric configuration of the protection wall, including the berms and hollow. The dimensions of the wall were calculated to allow simple site construction, and to avoid any effect on sidelobe levels (over the fifth sidelobe), based on one meter per pixel. The first-bounced radar beam travels toward the tips at the edge of the TTCR, due to this configuration. The reflection on the tip area by the double-bounced beam causes an error in the TTCR RCS estimation. The error is dependent on the distance between the TTCR and the inner berm, and the height of the berms. The dependency effect among range resolutions and incidence angles is shown in Fig. 7. This represents responses within different ranges, with the range differential calculated as follows [3]:

$$\Delta r = |2 \cdot r_1 - (r_2 + r_3)| > 3 \cdot \rho_{ra} \quad (1)$$

Where, in Fig.8, heights (h1~h6) equal h_{pole} (0.55m)-h_{berm} (0.5~0.05m).

If the range differential Δr is less than the three range resolution unit, the response (r_2~r_3 path) as interference is added in-phase constructively on the response (r_1 path) of "Self-Reflection" [3]. The interference of the berm impacts the main response, as Δr<3·ρ_{ra} [3]. Therefore, "Ground Interference" can be defined as "Object-Tip Reflection" ($C_{ObjectTip}$) and is caused by the berms (Fig. 6). However, determining the exact size of the berm's geometric configuration is not possible for all applications for various beams (or all incidence angles), or for systems with different SAR parameters. The site configuration, which is fixed for a protection functionality, or appears as a natural ground object, can be used for all beams with different SAR parameters. Therefore, for all beams (or incidence angles), the berm reflection condition is considered the worst case, which ensures that all reflections aim for the tip area only.

"Sidelobe Interference" ($C_{Sidelobe}$), which is caused by the focusing of the berms, also requires investigation as a new interference factor. This effect is not related to a physical interaction between the TTCR and the site environment, but to the point-like target characteristic of berms.

An additional error is caused by a support mechanism for the TTCR, termed the "Mounting Structure Reflection (MSR)" [3]. However the MSR is not relevant to this experiment, and its contribution is ignored. The pole does not reflect the SAR signal as it is mounted backward on the TTCR [3]. Finally,


(a) Overview of protection wall


(b) Inner/outer berms and hollow


(c) Protection from animal invasion

Fig. 5. Constructed protection wall

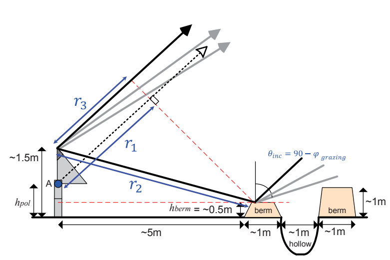

Fig. 6. Object-tip reflection

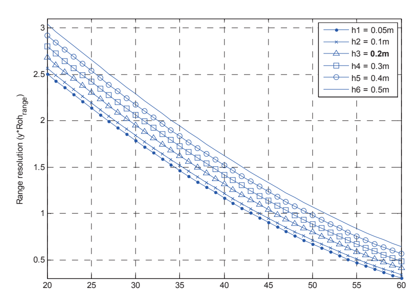

Fig. 7. Relation of range resolutions and incidence angles

except for two cases discussed in an earlier study [3], in the category of "Ground Interference", the modified types of interference (C_I) relevant to the current experiment are:

- Object-Tip Reflection ($C_{ObjectTip}$)
- Sidelobe Interference ($C_{Sidelobe}$)

3.2 Experimental Conditions

It is not always appropriate to use a very wide and flat plain without man-made structures for a CR deployment site. However, the current experiment was designed to consider types of interference specifically caused by ground objects near a TTCR. In this case, to avoid such interference, an open area of plain in Mongolia was chosen as a test site.

To investigate $C_{ObjectTip}$, berms were constructed within the one meter width of a resolution cell. To minimize $C_{ObjectTip}$ by the outer berm, the height of the outer berm is designed lower than one of the mounting structure. Practically, this also provides effective protection from animal invasion.

To easily discern the responses of berms using SAR, an image has been acquired for a case with a not-pointed-CR as a TTCR (where the CR does not face the satellite). Fig. 8 shows the Single Look Slant Range Complex (SSC) product image for a not-pointed-CR case. The weak response of a not-pointed-CR on the left image in Fig. 8 is because it was not pointed appropriately.

The aim of this study is to ascertain guidelines for eliminating interference sources in real situations, especially for sites that are not wide, flat, open plains.

3.3 Object-Tip Reflection

The berms are an error source due to their bright response (Fig. 6). The worst reflection occurs when all reflections from the berms travel toward the 'tip' region of the TTCR (Fig. 6).

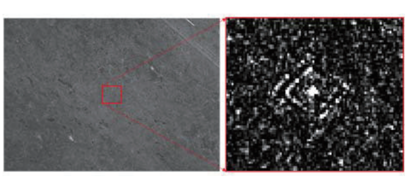

Fig. 8. TerraSAR CR site image with a not-pointed-CR (2009.07)

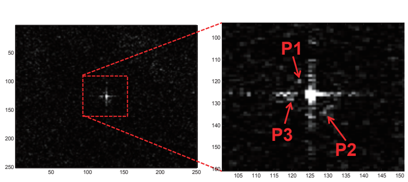

Fig. 9. TerraSAR CR site image with a pointed-CR (2009.09)

In contrast, the hollow is not an error source, as it does not cause a reflection [3] (Fig. 8).

To analyze the response of the berms and the TTCR, the image as a SSC product in Fig. 9 has been acquired for a case with a pointed-CR (where the CR faces the SAR satellite, TerraSAR). The response of a pointed-CR in the left image in Fig. 9 is strong in comparison with Fig. 8, due to its exact pointing. The berms are not clearly seen, due to the image intensity being normalized by the strong response of the TTCR.

Using the formula in Fig. 2, the amplitude of the undesired signal can be evaluated as the product of the RCS value of the 'tip' region in the worst case scenario, and the RCS value of the inner berm:

$$A_{Tip} = a^2/6\sqrt{3}\Big|_{a=1m} = 0.10m^2 \tag{2}$$

$$\sigma^0_{Berm} = {10^{-0.57}}/{(0.86 \times 1.30)} \approx 0.24 \tag{3}$$

$$\sigma^0_{Berm} \cdot A_{Tip} = 0.024 \rightarrow -16.20dBsm \tag{4}$$

To calculate the RCS, the mean value of the berm (Table 2) is scaled by its unit area (Table 1).

Berm $C_{ObjectTip}$ is calculated using the following formula:

$$C_{ObjectTip} = 36.32\big|^{TTCR}_{level} - 16.20\big|^{Berm}_{level} = 20.12dB \tag{5}$$

3.4 Sidelobe Interference

The sidelobe responses of the berms cause additional interference as they are regarded as another point target, if the sidelobe is strong enough to change the estimated RCS value of a pointed-CR.

The width of the berm is less than one meter, which is similar to the size of a resolution cell. However, the berm is not a point target, due to its shape. Therefore, it is modeled, using a summation of the sinc functions for a point target response. The summation of two sinc functions can be

Table 1. SSC product parameters with the pointed-CR

Parameter	Value
Bandwidth	150 MHz
Range Sampling Freq.	164.83 MHz
PRF	8,200 Hz
Zero Doppler Velocity	7,046 m/s
Azimuth Spacing	0.859 m/pixel
Range Spacing	1.292 m/pixel

Table 2. TTCR & berm measurements

Point	CR [dBsm]	P1 [dB]	P2 [dB]	P3 [dB]	P–Mean [dB]
Value	**36.32**	-6.031	-5.796	-5.140	**-5.656**

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used, due to its continuous construction within a one meter resolution cell.

Figure 10 presents two ways for acquiring a TTCR site, taking into account the flying direction of the satellite. In order to reduce complexity of the analysis, both cases have four points at the range and azimuth direction, which are perpendicular to the TTCR. These are the worst interference sources, due to the SAR focusing technique, which is performed step-by-step through range and azimuth pulse compressions. The results in the sidelobes of berm responses affecting the response of the TTCR only in the range and azimuth directions. The total contribution of sidelobe interferences is as follows:

$$C_{total}^{side} = C_{RL}^{side} + C_{RR}^{side} + C_{AT}^{side} + C_{AB}^{side} \quad (6)$$

The inner berm is a dominant factor, due to its proximity to the TTCR. The pixel positions of the sidelobe interferences (Table 1) are as follows:

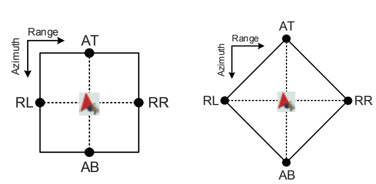
- Sidelobe interference positions from the berm's mainlobe:
  - RL : 7 m / 1.292 m/pixel = 5.42 pixels
    = 4.93 pixels (@1.1 times sampling)
  - AT : 7 m / 0.859 m/pixel = 8.15 pixels
    = 6.79 pixels (@1.2 times sampling)

Peak levels of sidelobes from the RL, RR, AT, and AB mainlobe are referred to the relative sidelobe values of the summation of the sinc functions. (Fig. 10)

- Relative peak levels at sidelobe positions
  - RL : -19.91 dB (@4.93 pixels)
  - AT : -22.88 dB (@6.79 pixels)

The range interference, which is caused by RL and RR sidelobes, is -16.91 dB. The azimuth interference, which is caused by AT and AB sidelobes, is -19.88 dB. The total contribution of sidelobe interferences in both directions is -16.91 dB, which is the dominant value of the summation of interferences.

The mean peak value of the berms is -5.66 dB, derived from the reference used to normalize the image (Table 2).



(a) case (b) case

Fig. 10. Berm image acquisitions

Therefore, considering that the image is normalized with respect to the peak value of the TTCR, the level of interference using this same reference is -22.57 dB. The contribution of "Sidelobe Interference" by the berm is:

$$C_{Sidelobe} = 36.32 - 22.57 = 13.75dB \quad (7)$$

3.5 Guidelines for a TTCR Site

To check the effect of total "Interference (C_I)", with respect to the "Self-Reflection (S_3)", the ratio between the values of S_3 and C_I is defined as follows:

$$Variation = \left|\frac{S_3}{S_3 + C_I}\right| \quad (at\ linear\ scale) \quad (8)$$

Total variation, which is produced by object-tip reflection and sidelobe interference, is as follows, with respect to the RCS:

$$\left|\frac{1}{1+\frac{C_{ObjectTip}+C_{Sidelobe}}{S_3}}\right| \rightarrow \pm 0.13dB \quad (9)$$

Where, S_3 is the estimated RCS value of the TTCR in the SAR image.

With an absolute radiometric accuracy of 1.0 dB, a ±0.13 dB variation is not a significant error. However, if a higher accuracy of 0.5 dB is required for a new SAR satellite system, this level of variation can create a critical error.

Total variation is primarily dependent on a pixel distance of approximately five pixels, which represents the peak of the fifth sidelobe. Therefore, pixel distance is the dominant factor in a significant error, despite the width of the berm being within one meter, similar to the resolution of a cell. To minimize interference with respect to pixel distance, the physical location of the berms and the relationship of their characteristics should be considered (Table 1).

A range of variations caused by sidelobe interferences are analyzed in this study. Assuming that a ground object is located within the third (-15.27 dB) or seventh sidelobe (-22.88 dB) of a mainlobe, the effects of its interference are

Table 3. Interference analysis in the case without berms

Item	TerraSAR-X		KOMPSAT-5	
	Case–01	Case–02	Case–01	Case–02
RCS [dBsm]	36.04		35.95	
Background [dB]	-16.23		-12.29	
Inner berm [dB]	Back–ground	-7.69	Back–ground	-8.72
$C_{ObjectTip}$ [dB]	9.05	17.80	17.97	21.54
$C_{sidelobe}$ [dB]	0	11.44	0	4.23
C_{Total} [dB]	**±0.01**	**±0.08**	**±0.07**	**±0.16**

as follows:

$$\left|\frac{1}{1+\frac{C_{ObjectTip}+C_{Sidelobe}}{S}}\right| \rightarrow \pm 0.17\ or \pm 0.11dB \qquad (10)$$

Ground objects at the site of the third sidelobe are not sufficient to achieve 0.5 dB absolute radiometric accuracy. Therefore, ground objects around the TTCR are removed at least from the fifth sidelobe position to ensure a high level accuracy. In addition, the effect on interference of removing two berms has been analyzed. An extra hollow was constructed to improve protection. Fig. 11 and 12 depict a TTCR site in Mongolia and its SAR image after removing two of the berms.

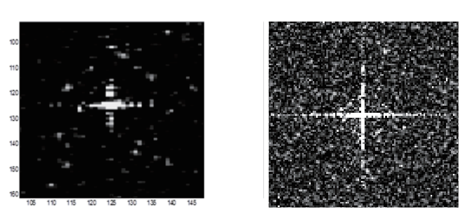
Partial responses, which are caused by the traces of berms, can be detected, but are difficult to eliminate (Fig. 12). Two cases of interference contributions for TerraSAR-X and KOMPSAT-5 images have been analyzed. 'Case-01' assumes that all berms are clearly eliminated, and 'Case-02' assumes that all berms are not clearly eliminated in reality (Table 3).

In both 'Case-01' scenarios, inner berms are considered background, due to perfect elimination. $C_{ObjectTip}$ is calculated using the background measurement value, and $C_{Sidelobe}$ is excluded. The total contribution of interferences in both 'Case-01' tests can be ignored by estimating absolute radiometric accuracy.

Due to imperfect elimination, $C_{ObjectTip}$ and $C_{Sidelobe}$ are calculated using the measurement values of the inner berm for both 'Case-02' scenario.

For TerraSAR-X, the estimated value of the TTCR RCS without berms is 36.04 dBsm, which is less than the RCS with berms (36.32 dBsm). It is reasonable that the sum of the experimental result (±0.13 dB), and the 'Case-02' result (±0.08 dB), is similar to the difference of 0.28 dBsm. This suggests that interferences are minimized by the elimination of berms. The designed TTCR RCS value of 35.76 dBsm, suggests that accuracy (0.28 dBsm) has been improved. Therefore, all berms at CR sites have to be eliminated before the launch of KOMSPAT-5, to prepare for the on-orbit calibration. This suggests that when considering calibration, absolute radiometric accuracy can be improved by careful design of the location of ground objects.

Fig. 11. TTCR site without berms (2010.05)



(a) TerraSAR-X (2010.06) (b) KOMPSAT-5 (2015.10)

Fig. 12. CR site image without berms

For KOMPSAT-5, the estimated value of the TTCR RCS without berms is 35.95 dBsm. There is a difference of 0.19 dBsm between the estimated value and the designed value of 35.76 dBsm. The $C_{ObjectTip}$ of 21.54 dB for KOMPSAT-5 is higher than 17.80 dB for TerraSAR-X, due to beams with different incidence angles and system parameters. Assuming the same pixel spacing as TerraSAR-X, $C_{ObjectTip}$ is 16.61 dB, and $C_{Sidelobe}$ is 8.23 dB, total variation is ±0.06 dB, which is less than ±0.08 dB for TerraSAR-X. Therefore, the two cases for TerraSAR-X and KOMPSAT-5 yield a similar result, whereby interference is minimized by the removal of berms(and/or ground objects around the CR).

These results suggest that in absence of a wide and flat area for the TTCR site, an area that ensures a distance of at least the fifth sidelobe from the mainlobe of the target response, is enough for a RCS measurement.

4. Conclusion

To eliminate interference errors, the condition of the point target site is important for a SAR calibration activity. Performing the calibration activity once at a selected time, should not be a significant concern, as the environment can be organized by operators beforehand to be free of errors. However, managing the site for continuous and routine calibration operations is challenging, as all activities are directly related to calibration performance.

In addition, if long-term maintenance of the point target site for calibration is required, the results of this experiment suggest the removal of all ground objects at least within the fifth sidelobe around the TTCR. Further, it is recommended to keep the size of any object around the TTCR within a resolution cell.

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