The Radiometric Measurement Quantity for SAR Images

Björn J. Döring and Marco Schwerdt

***Abstract*—A Synthetic Aperture Radar (SAR) system measures among other quantities the terrain radar reflectivity. After image calibration, the pixel intensities are commonly expressed in terms of radar cross sections (for point targets) or as backscatter coefficients (for distributed targets), which are directly related. This paper argues that pixel intensities are *not* generally proportional to radar cross section or derived physical quantities. The paper further proposes to replace the inaccurate term *radar cross section* by *equivalent radar cross section* as the radiometric measurement quantity for SAR images. The measurement procedure as such remains unchanged.**

Two problems are seen with using *radar cross section* as the radiometric measurement quantity for point targets. First, the radar cross section is frequency and/or angular dependent for many targets, whereas a SAR system operates not at a single set but through a range of frequencies and aspect angles. This begs the question of which radar cross section within this two-dimensional range should actually be taken as the measurement result. Second, the pixel intensities seen in SAR images are the output of a filtering process, which is affected by the *complex* transfer function of the point target. Radar cross section, on the other hand, does not depend on phase.

The *equivalent radar cross section* expresses the reflectivity in terms of the radar cross section of an equivalent conducting sphere which would result in the same pixel intensity as the one observed if the sphere were to replace the actual target in the scene. This distinction is crucial in defining the measurand for radiometric SAR measurements in principal, and hence it is important for radiometric SAR calibration. It is furthermore of particular practical importance for current and emerging wideband, high-resolution, and high-accuracy SAR systems.

I. INTRODUCTION

Synthetic Aperture Radar (SAR) images play a key role in many remote sensing applications. A SAR instrument, combined with data processing facilities, can be regarded as a measuring device. One of the measurement quantities of the SAR instrument is terrain radar reflectivity. This is then used as input data in numerous inverse problems to derive physical quantities such as soil moisture level, biomass, and salinity. It is therefore crucial to have a clear understanding of the radar observable, namely radar reflectivity.

The quantities directly measurable by a digital SAR system are amplitude and phase, recorded for each image element. After data processing, amplitude and phase remain to be calibrated. At this stage, the pixel magnitudes, and their equivalent pixel intensities, are expressed as uncalibrated digital numbers.

The known systematic radiometric offsets, described by a factor, are used to scale the pixel intensities during calibration, a necessary prerequisite to yield comparable image products [1]. After radiometric calibration, the pixel quantities are commonly expressed in terms of the (specific) backscattering coefficient or similar quantities [1]–[4], which are directly related to the definition of Radar Cross Section (RCS) of point targets. In this paper it is argued that *radar cross section* is not the actual radiometric measurement quantity in SAR images. The underlying reason for this is the neglected spectral and angular-dependent reflectivity of most natural and man-made radar targets. The authors propose to use the terminology *equivalent radar cross section* instead.

Introducing this new terminology does not require a change of the radiometric measurement process as such. For instance, no new correction factors need to be introduced because especially the frequency dependent reflectivity of radar targets is a feature that a SAR system actually desires to, and already does, detect. Multispectral SAR systems, as a point in case, put a focus on taking advantage of the frequency dependent reflectivity. However, the new terminology changes the way in which radiometric SAR products should be annotated and calibrated. The distinction between RCS and *equivalent* RCS has special practical importance for wideband, high-resolution, and radiometrically accurate SAR systems for which the new terminology can resolve an inaccuracy in description.

The proposed changes for radiometric *measurements* as such are necessary but can be perceived as notational only. However, and this is the important innovation from a practical point of view, radiometric calibration with reference point targets needs to be adapted by introducing target-dependent and system-dependent corrections that result from the inherent spectral and angular dependence of reflectivity for every practical reference target.

The discussion in the following sections is concentrated on *point* targets (for which the measurement quantity is the (equivalent) radar cross section), and not on distributed targets (for which the measurement quantity is the (equivalent) backscatter coefficient or related quantities). This is without loss of generality because the determination of the (equivalent) backscatter coefficient for a distributed target depends on prior measurement of a *point* target with known reflectivity during radiometric calibration [1].

This paper initially identifies the problems that are associated with the term RCS as the measurement quantity in Sec. II. The following Sec. III introduces the new terminology to resolve the problems. Finally, Sec. IV and V discuss the implications of the proposed terminology for measurements and calibration, respectively.

The authors are with the Microwaves and Radar Institute of the German Aerospace Center (DLR), Oberpfaffenhofen, Germany.

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II. PROBLEM DESCRIPTION

The fundamental problem of using RCS as the output measurement quantity for describing pixel intensities in SAR images is rooted in the underlying, often only implied, measurement model. In fact, the pixel intensities in SAR images are only accurately representative of the target RCS if the point target transfer function H_t can be modeled as

$$H_t(f, \boldsymbol{\alpha}) = \mathrm{const} \tag{1}$$

within the relevant parameter range, where f is frequency and $\boldsymbol{\alpha} = (\theta, \phi)$ describes the (monostatic) angle under which the target is seen by the radar. Whereas this provides a practical and justified approximation for many natural targets observed by a sufficiently narrow-band SAR system with sufficiently low azimuth resolution, it does not hold for all cases. Principally, natural as well as man-made radar targets have frequency and angular-dependent backscattering characteristics due to their electromagnetic properties, their size, and shape. Therefore, point targets should rather be modeled by

$$H_t(f, \boldsymbol{\alpha}) = A(f, \boldsymbol{\alpha})\, \mathrm{e}^{j\varphi(f,\boldsymbol{\alpha})} \tag{2}$$

where $A(f, \boldsymbol{\alpha})$ and $\varphi(f, \boldsymbol{\alpha})$ are the frequency and angular-dependent gain and phase functions, respectively. The simplified measurement model in Eq. (1) is inherent within the more general definition, Eq. (2).

In the following paragraphs it shall be shown that the received SAR signal reflected by a point target, after pulse compression, is in fact not generally proportional to its radar cross section because the target backscattering depends, in principle, on frequency and angle.

In existing SAR literature, the relationship between the radar system, the point target, and the received signal is typically introduced by considering a monostatic real aperture radar system without a matched filter at the receiver. For these systems, the monostatic radar equation,

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4}\sigma, \tag{3}$$

expresses the received power P_r in terms of the transmitted power P_t, the receive and transmit antenna gain G, the wavelength λ, the radar-target distance R, and the point target radar cross section σ. The radar cross section σ of any target, in this case the wanted measurand, is defined as the scaled ratio of the scattered power (seen at distance R away from the point target) to the incident power. This can be written as

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|\mathbf{E}_s|^2}{|\mathbf{E}_i|^2}, \tag{4}$$

where $\mathbf{E}_s$ and $\mathbf{E}_i$ are the scattered and incident electrical fields [5].

Assuming for the moment no angular dependence of the target reflectivity, Eq. (3) can now be reformulated as

$$P_r(f) = \frac{P_t(f) G^2(f) \lambda(f)^2}{(4\pi)^3 R^4}\sigma(f).$$

All parameters except R depend on frequency f. This points toward the *first* dilemma: A SAR system uses the principle of matched filtering and pulse compression in order to increase the signal-to-noise ratio and range resolution. Therefore, the transmitted SAR signal covers a defined bandwidth; typically a linear frequency modulated pulse is used. If the power scattered back by the point target depends on frequency, then the question arises as to which RCS should actually be annotated in the SAR image. Certainly the RCS at the center frequency is only representative if the target RCS can be approximated to be constant over the relevant bandwidth according to Eq. (1), an assumption which is seldom explicitly stated in the literature. The arithmetic mean of the RCS over the pulse bandwidth also does not lead to the wanted result because receiver hardware and pulse compression introduce a frequency dependence produced by the receiver. In practice, the workaround of annotating a single backscatter coefficient per pixel in SAR products [6], [7] possibly erroneously implies a constant target RCS over the range frequency bandwidth. By doing this a measurement uncertainty is introduced due to the mathematical model of the measurand.

The previous discussion can likewise be extended to the azimuth direction. The azimuth resolution in SAR is achieved by coherent sampling of a point target's complex reflectivity under different aspect angles, and subsequent compression. If the target RCS significantly varies over the processed aspect angle range (as can be the case for dihedrals in urban environments, for instance), then again will the pixel intensity not be proportional to any particular RCS, but it will be proportional to a weighted average of the RCS over the angular range.

The initial dilemma arises for any radar system that does not measure the point target's radar cross section $\sigma(f, \boldsymbol{\alpha})$ at a single frequency or angle. The following problem arises for SAR systems when the transition is made from the raw to the processed data domain, which depends on complex reflectivity, i.e. magnitude *and* phase. The SAR receiver records the target data as complex amplitudes $S(x, y)$; x and y are spatial coordinates. Neglecting noise, the complex SAR image is then formed by

$$V(x, y) = \sqrt{K} S(x, y) * h(x, y), \tag{5}$$

where K is a complex, absolute calibration coefficient (known through calibration), $*$ denotes convolution, and h is the SAR system point-spread function [1]. Conventionally, it is assumed that the raw data resulting from a single point target in the image can be described by

$$S_e(x, y) = \sqrt{\sigma_e}\,\delta(x, y), \tag{6}$$

where σ_e is the point target's radar cross section[1], and $\delta(x, y)$ is the Dirac delta function. This is equivalent to the target description in Eq. (1). The point target's RCS is derived from the square law detected complex image [1]

$$P_e(x, y) = |V(x, y)|^2 = K\sigma_e |\delta(x, y) * h(x, y)|^2 \tag{7}$$

by integration over a sufficiently large region A (allowing the approximation $\iint_A h(x, y)\,\mathrm{d}x\,\mathrm{d}y \approx 1$) [1], [8] so that the

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[1] Later on, σ_e will be called *equivalent* radar cross section. The equivalent radar cross section is identical to the radar cross section σ for targets which can be described by Eq. (1), as is the case in this paragraph.

integrated point target intensity I_e becomes

$$I_e = \iint_A P(x, y)\,\mathrm{d}x\,\mathrm{d}y = K\sigma_e. \tag{8}$$

The integrated pixel intensity is therefore directly proportional to the point target RCS for uniform targets according to Eq. (6). This summarizes the conventional understanding [1]–[4] of how pixel intensities are linked to RCS.

In contrast to the above derivation, a target with arbitrary frequency and angular dependence according to Eq. (2) shall now be considered. Equation (6) becomes

$$S'_e(x, y) = \sqrt{\sigma'_e}h_{tn}(x, y)$$

where h_{tn} is the normalized point target's point-spread function[2] (see Sec. V for details), and σ'_e is a scalar scaling factor describing the magnitude of the reflectivity. Hence, the square law detected image becomes

$$P'_e(x, y) = K\sigma'_e|h_{tn}(x, y) * h(x, y)|^2, \tag{9}$$

and the integrated intensity is

$$\begin{aligned} I'_e &= \iint_A P(x, y)\,\mathrm{d}x\,\mathrm{d}y \\ &= K\sigma'_e \iint_A |h_{tn}(x, y) * h(x, y)|^2\,\mathrm{d}x\,\mathrm{d}y. \end{aligned} \tag{10}$$

The convolution operation effectively performs a weighted average of the point target's point-spread function over frequency and aspect angle. In contrast to Eqs. (7) and (8), the pixel intensities $P'_e(x, y)$ and the integrated pixel intensity I'_e therefore do not only depend on the scaling factor σ'_e anymore, but also on the point target's complex transfer function.

The definition of RCS in Eq. (4) only considers a ratio of powers, i.e., magnitudes; the phase is irrelevant for its definition. The filtering operation in Eq. (10), on the other hand, operates on complex signals, and both the signal magnitude and phase over time influence the filter output. In conclusion, this discrepancy between the definition of RCS (incorporating absolute magnitudes) and filtering (depending on magnitude and phase) is the second reason why target RCS is unsuitable to describe the pixel intensities in SAR images. Two point targets with identical RCS can result in distinct integrated pixel intensities.

In conclusion, the SAR signal of a point target after pulse compression is only proportional to its RCS if its frequency and angle-dependent transfer function can be approximated as constant in amplitude and phase over the relevant frequency and angular range. In the general case, the integrated SAR pixel intensity after processing depends on the transfer function of the point target because the processing is a filtering process over the system bandwidth and aspect angle range.

III. PROPOSED NEW RADIOMETRIC MEASUREMENT QUANTITY TERMINOLOGY

It was argued that, in the general case, the pixel intensities in SAR images are not simply proportional to the target radar cross section σ, neither are derived quantities like the backscattering coefficient σ^0. In other words, the measurement quantity in radiometric SAR measurements is not RCS, and therefore it should not be referred to as RCS.

It is proposed to instead call the measurement quantity for point targets *equivalent radar cross section*. The equivalent radar cross section σ_e shall be equal to the radar cross section of a perfectly conducting sphere which would result in an equivalent pixel intensity if the sphere were to replace the measured target. The definition exploits the frequency and angular independence of the RCS of a sphere with radius a

$$\sigma_{\text{sphere}} = \pi a^2, \tag{11}$$

which is a valid approximation as long as the sphere circumference is much (greater than ten times) larger than the wavelength [5].

Replacing RCS by *equivalent RCS* pays tribute to the two general points of critique. Now,

- the filtering of *complex* signals according to Eq. (5) is correctly distinguished from the definition of RCS, which only takes signal magnitudes into consideration, and
- cases are covered for which the target's RCS dependence on frequency or angle are significant according to Eq. (2).

One could say that the terminology of *equivalent RCS* allows distinction between the target RCS (Eq. (4)) and the target's pixel intensity as seen through the eyes of the SAR processing filter (Eq. (10)). The proposed terminology is applicable to target backscatters with an arbitrary frequency and angular dependence according to Eq. (2), including targets with a flat frequency and angular response. Depending on the target, the measurement uncertainty can appear greatly reduced due to the more accurate measurement model, which especially benefits high bandwidth, high resolution systems requiring a high radiometric accuracy.

The transition from the present to the proposed terminology does not pose difficulties. For instance, the measurement unit for RCS and equivalent RCS is the same: square meter. Also, it is straightforward to transform the backscatter coefficient σ^0 and other derived quantities to equivalent quantities, i. e., to an *equivalent* backscatter coefficient σ^0_e, etc. Furthermore, describing the measurement quantity in terms of an equivalent physical object (a sphere) allows one to form a simple mental model of what this quantity means.

The following two sections address the implications of the proposed terminology for measurements and calibration, respectively.

IV. IMPLICATIONS OF PROPOSED TERMINOLOGY FOR MEASUREMENTS

Embracing rather than neglecting the frequency and angular-dependent radar backscatter is the main mental shift which follows from replacing RCS by *equivalent RCS* as the radiometric measurement quantity. As long as RCS is used as the measurement quantity, a frequency and angular independent backscattering according to Eq. (1) is (often only inherently) assumed. This is common practice in the SAR literature [1]–[4]. The assumption of a frequency and angular independent

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[2] The dependence of the point spread function h_{tn} on spatial coordinates (x, y) can equivalently be expressed as a dependence on azimuth and range time (t_a, t_r), or frequency and angle $(f, \boldsymbol{\alpha})$.

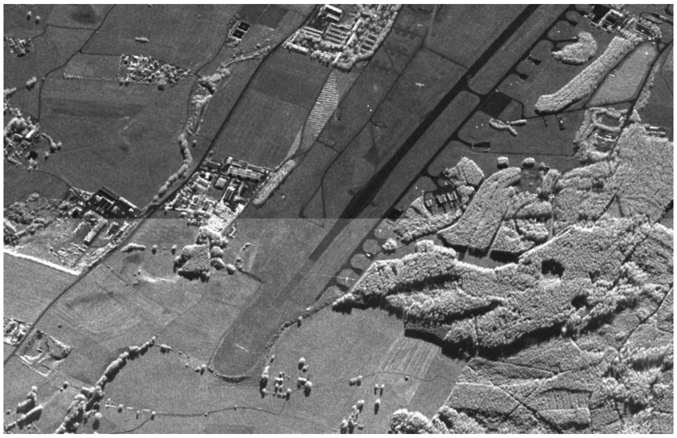

Fig. 1. One scene imaged synchronously by DLR's radiometrically calibrated airborne F-SAR sensor in S-band (upper half) and X-band (lower half), taken in VV polarization on June 8, 2010, at Kaufbeuren, Germany. The desirable difference in backscatter at the two frequency bands is easily discernible. On the other hand, reference point targets with identical equivalent RCS' should appear equally bright in both images.

backscatter introduces a modeling error into the measurement, which in many cases is sufficiently small with respect to the required measurement uncertainty, the utilized range bandwidth and aspect angle range. However, this is not likely to remain the case for upcoming SAR instruments, for which the trend is toward lower radiometric uncertainties combined with higher range bandwidths and longer azimuth integration times for increased resolution. This trend will therefore emphasize this modeling error, which results from the assumption in Eq. (1).

Offered below are two *qualitative* examples for which a frequency dependent radar backscatter not only exists but is actually the focus for the measurement problem at hand. In these and many other cases, the new terminology of *equivalent RCS* allows to be precise when reporting measurement results.

a) Multi-spectral SAR images: The frequency dependence of natural targets like agricultural terrain is most apparent when comparing images taken at different frequency bands but otherwise at equivalent time and perspective. The SIR-C/X-SAR instrument, which was flown during two missions in 1994, was the first space-borne SAR system capable of operating simultaneously at L-, C-, and X-bands [9]. The fractional bandwidth for each channel was still small at below one percent. Several multi-spectral airborne SAR systems exist among which is the F-SAR system from the German Aerospace Center (DLR) [10]. One exemplary scene, which was imaged simultaneously at two different frequency bands, is shown in Fig. 1, where the fractional bandwidths for the S and X-band images is 9% and 8%, respectively. The resulting calibrated images show significant differences in pixel intensities, exemplifying the frequency dependence of the imaged terrain.[3] This is, of course, expected and desired. After all, the added information content is the actual impetus for building multi-spectral SAR systems like SIR-C/X-SAR and F-SAR.

So what would happen if the same scene was imaged by an ultra-wideband SAR system? For instance, a fractional bandwidth of 100% (which is even exceeded by some airborne SAR systems, albeit at the VHF-band [11]) would cover the S- and X-band frequencies in Fig. 1 and all frequencies in between. Hence describing all frequency-dependent terrain radar cross sections within the whole spectrum by a single radar cross section is certainly counter-intuitive and misleading. It would mean that the model uncertainty dominates the radiometric uncertainty budget even if the SAR sensor is well designed and calibrated.

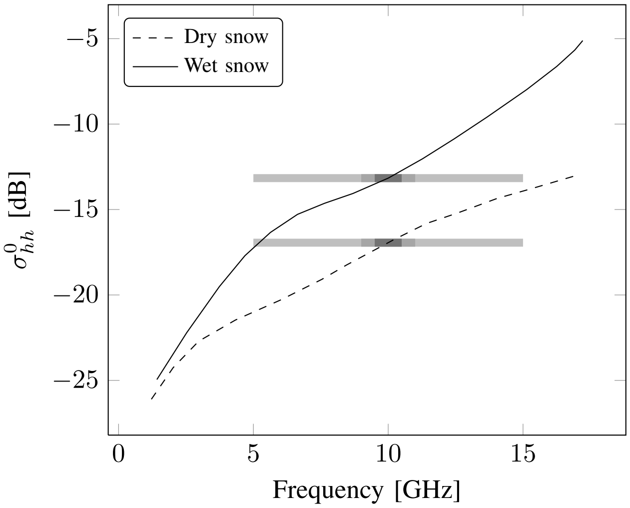

Fig. 2. Frequency dependent backscattering coefficient σ^0 for two exemplary terrain types: dry and wet snow (measured at HH polarization and an incidence angle of 50°, data from [12]). For illustration purposes, fractional bandwidths of (10, 20, 100) % are shown at 10 GHz to emphasize the large frequency dependence within these spectra.

b) RCS over frequency: The frequency dependence of different terrain types was systematically surveyed in [12]. As an example, the frequency dependent backscatter coefficients of dry and wet snow are reproduced in Fig. 2. The backscatter coefficient differs by about 0.4 dB from its value at 10 GHz within a fractional bandwidth of 10% for both terrain types, and the difference expectedly increases significantly for larger bandwidths. If this variation is compared to the radiometric accuracy of current (narrower bandwidth) space-borne SAR instruments, which is typically below 1 dB, it becomes apparent how important the definition of the measurand is. This is especially true in the case of wideband SAR sensors which simply do not see an approximately constant frequency response within their larger range bandwidth. The processed SAR images rather show a weighted RCS average over frequency, a quantity which would be more appropriately termed as *equivalent RCS*.

The next three *quantitative* examples show the difference between RCS and equivalent RCS. The way in which the equivalent RCS was derived through simulation for the respective target transfer functions $H_t(f, \boldsymbol{\alpha})$ and given SAR systems (defined by their point-spread function h) is described in detail in [13], where *equivalent* RCS is called *perceived* RCS. The approach is based on simulating a point target's integrated pixel intensity and relating it to the integrated pixel intensity

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[3] The noise-equivalent σ^0 of both channels is well below the measured intensities as not to significantly contribute to the difference in intensities.

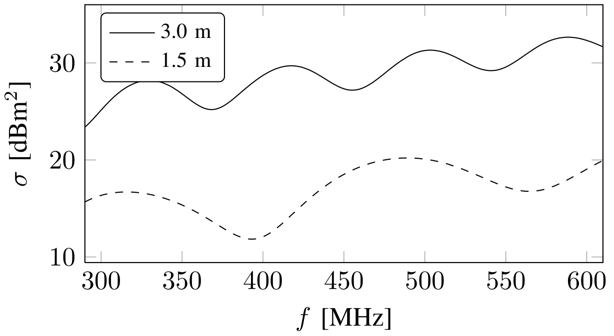

Fig. 3. Peak radar cross section of two small (with respect to the wavelength) trihedral corner reflectors with different inner-leg lengths l, simulated with the method of moments.

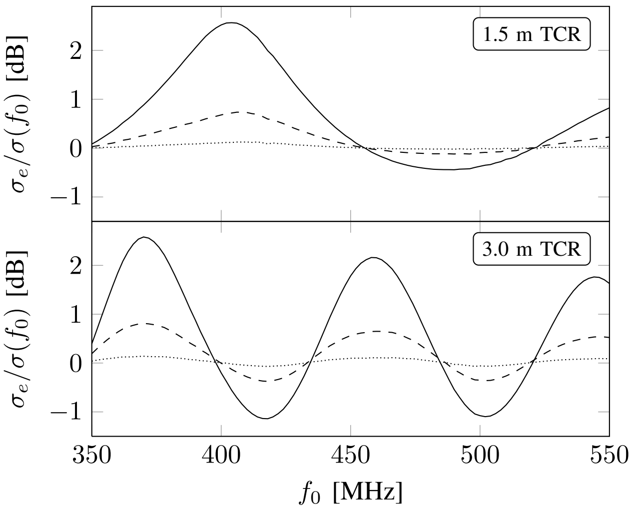

Fig. 4. Difference between equivalent RCS σ_e and RCS $\sigma(f_0)$ at the center frequency f_0 for the two trihedral corner reflectors from Fig. 3 at three bandwidths: 20 MHz (··········), 50 MHz(– – –), and 100 MHz (——).

of an ideal target, such as a perfectly conducting sphere.

c) Corner reflectors at UHF-band: Corner reflectors are often used as reference targets during radiometric calibration. Their backscatter characteristics therefore need to be accurately known. For reflectors which are large with respect to the wavelength, their frequency-dependent peak RCS is approximated as

$$\sigma_{\text{corner}}(f) = \frac{4\pi}{3}\frac{l^4}{\lambda^2}, \tag{12}$$

where l is the inner-leg length of the corner reflector and λ is the wavelength [1]. The RCS at the SAR center frequency lends itself to be the reference RCS.

The simple relationship in Eq. (12) is invalid for reflectors which are small with respect to the wavelength, see Fig. 3. Figure 4 shows the simulated difference between the RCS at the center frequency and the equivalent RCS that would be measured by a F-SAR-like SAR system with varying center frequency and range bandwidth.[4] No phase or angular variation was assumed for this simulation.

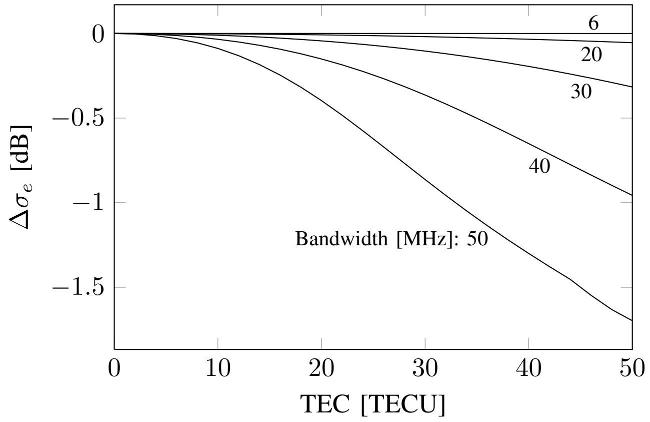

Fig. 5. Effect of phase distortions on the equivalent RCS for a BIOMASS-like system (nominal bandwidth: 6 MHz) at a center frequency of 350 MHz depending on ionospheric activity. The values are normalized to the equivalent RCS at 0 TECU.

The difference between the equivalent RCS and the RCS at the center frequency, a result of the weighted averaging during processing, ranges from fractions of a decibel to several decibels. This demonstrates the importance of discerning RCS from equivalent RCS, especially for targets used during radiometric calibration.

d) Ionosphere and phase response: Typically, the frequency-dependent amplitude response will have a larger effect on the difference between RCS (at the center frequency) and equivalent RCS than the frequency-dependent phase response. This is because the phase response leads to defocussing only, which is typically well compensated by integrating over A in Eq. (10) [8]. Here, a speculative example shall be given which only considers the phase response of a point target and assumes a constant RCS over frequency and angle.

It has been proposed before to use wideband spaceborne L-band SAR systems for mapping of the ionospheric total electron content (TEC) [14]. Such systems exploit the apparent range delay and defocussing of scatterers on ground depending on ionospheric activity. In contrast to previous examples, the measurand is now a point target *including* path effects due to the ionosphere.

Neglecting range delays, the quadratic term (leading to defocussing) after Taylor-series expansion of the two-way phase response can be approximated by [14]

$$\varphi(f) = -\frac{4\pi}{c_0}\frac{40.28}{f_0^3}T(f-f_0)^2,$$

where f_0 is the center frequency, c_0 is the speed of light, and T is the TEC in TECU (which seldom exceeds 100 TECU). From this, a transfer function $H_t(f) = C\,\mathrm{e}^{j\varphi(f)}$ according to Eq. (2) with $A(f,\boldsymbol{\alpha}) = C = \text{const}$ was derived, and the TEC-dependent variation of the equivalent RCS for a BIOMASS-like system simulated, see Fig. 5. Depending on system bandwidth and ionospheric activity, the equivalent RCS deviates by more than 1 dB from the reference. Note that the RCS, which does not depend on phase (see Eq. (4)), stays constant.

This example stresses again that radiometric measurements in SAR do not only depend on the point target's RCS, but also

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[4] Note that the P-band channel of DRL's airborne F-SAR system [10] falls within the plotted range, having a center frequency of 350 MHz and a bandwidth of 100 MHz.

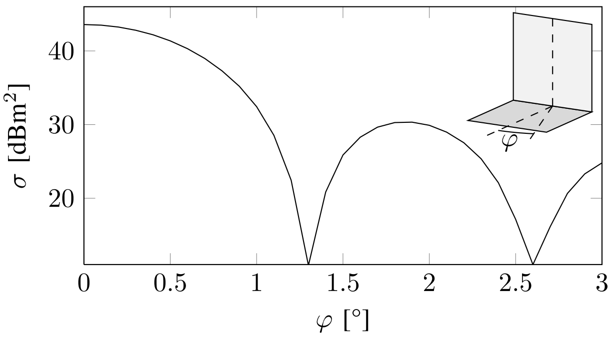

Fig. 6. RCS of a perfectly conducting dihedral corner reflector, where all side lengths are 1 m, at 9.65 GHz. The azimuth cut was simulated with the method of moments at an elevation angle of 45° with respect to the vertical plate.

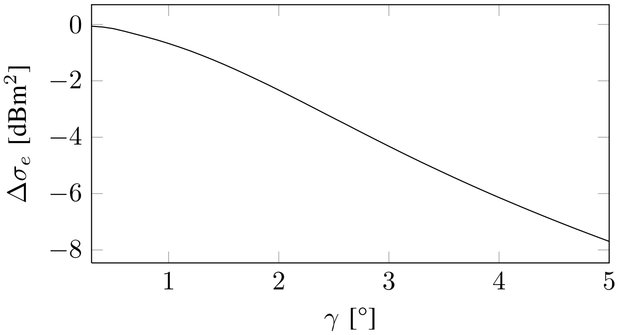

Fig. 7. The normalized equivalent RCS $\Delta\sigma_e$ of the dihedral from Fig. 6 as a function of the target exposure time, converted to the SAR beam steering angle γ, seen by a TerraSAR-X-like system. The values are normalized to the dihedral's peak RCS at $\varphi = 0°$.

on the target's phase response. It is therefore more appropriate to use the measurement quantity *equivalent RCS* than RCS to describe pixel intensities.

e) Dihedral corner reflector and angular-dependent RCS: Besides averaging over frequency f, a SAR system also averages over a range of aspect angles $\boldsymbol{\alpha}$ during azimuth processing. In case of TerraSAR-X, the angular range $\gamma = \phi_+ - \phi_-$ under which a target is seen can be varied from about 0.3° for a nominal StripMap acquisition to 4.4° for a high-resolution, experimental Staring Spotlight acquisition [15].

Within this angular range, the RCS of a point target might vary considerably. Figure 6 shows the RCS over azimuth angle for a 1 m dihedral reflector. Dihedrals with larger dimensions and therefore a higher angular sensitivity are found in urban environments, where many scatterers can be modeled as dihedrals.

Figure 7 shows the large difference between the 1 m dihedral's peak RCS ($\varphi = 0°$) and its equivalent RCS for varying azimuth resolutions and therefore angular ranges. This last example emphasizes once more that pixel intensities should not be described by RCS but by their equivalent RCS.

Concluding the examples, it can be said that many natural and man-made targets exhibit a frequency and sometimes angular-dependent RCS. This realization, coupled with the fact that SAR systems record data over certain and sometimes relatively large range bandwidths, demonstrates that RCS is not well suited as the radiometric measurement quantity. Introducing *equivalent RCS* as the new terminology avoids the ambiguity by distinguishing the body property from the quantity that is seen in a SAR image.

V. IMPLICATIONS OF PROPOSED TERMINOLOGY FOR CALIBRATION

External radiometric calibration is achieved by placing a point target of known backscatter within the imaged scene so that an adequate calibration factor, called K in Eq. (8), can be derived; until now, the reference targets were described by their RCS [1], [2], [16]. With the new understanding that not RCS but equivalent RCS is measured by a SAR instrument, the reference target must now be described by its *equivalent* RCS and not anymore by its RCS. Two strategies are possible:

1) Build reference targets whose amplitude and phase responses are as constant as technically feasible over the relevant range bandwidth (in which case the target RCS at any frequency within the range bandwidth is close to its equivalent RCS). These targets can thus be described by Eq. (1).
2) Compute the equivalent RCS, the radiometric quantity seen in a SAR image, based on the arbitrary but known transfer function of a reference target according to Eq. (2).

In almost all cases, strategy (1) excludes passive point targets for accurate or wideband SAR systems. Specifically, the RCS of commonly used trihedral corner reflectors is frequency dependent, see example (c) in the previous section. Building active targets (transponders) with a constant frequency response over the complete range bandwidth is, while technically possible, still very challenging. For instance, the frequency dependent transmission of antennas, amplifiers, and filters would need to be compensated by the transponder electronics or otherwise a calibration error would result.

Strategy (2) circumvents the mentioned problems for strategy (1), allowing both active and passive reference targets to be used. The following describes how the calibration procedure needs to be adapted in order to take an arbitrary but known reference target transfer function $H_t(f, \boldsymbol{\alpha})$ into account.

Up to now, the calibration coefficient K is simply derived by placing a target of known RCS σ_e (assuming a sphere-like target according to Eq. (1)) within a scene and determining its integrated pixel intensity I_e so that

$$K = \frac{I_e}{\sigma_e} \tag{13}$$

according to Eq. (8). On the other hand, if an arbitrary target according to Eq. (2) is considered, its equivalent RCS σ_e is not immediately known. It can be derived, however, by processing the raw data with a target-dependent correction point-spread function (PSF), explained in the following.

Assumed to be known through laboratory measurements is the target's complex reflectivity over frequency and incidence angle, expressible as the transfer function $H_t(f, \boldsymbol{\alpha})$ or equivalently as the PSF $h_t(x, y)$. The target PSF can be normalized with respect to a known reference RCS σ_r at a single reference frequency f_r (e.g. the center frequency) and a single reference incidence angle (e.g. the angle at closest approach) $\boldsymbol{\alpha}_r$:

$$h_t(x,y) = \sqrt{\sigma_r} h_{tn}(x,y)$$

with the normalized PSF defined in the Fourier domain by

$$H_{tn}(f,\boldsymbol{\alpha}) = \frac{H_t(f,\boldsymbol{\alpha})}{H_t(f_r,\boldsymbol{\alpha}_r)}$$

so that

$$\sqrt{\sigma_r} = H_t(f_r,\boldsymbol{\alpha}_r).$$

A correction filter can now be determined which effectively transforms a point target with an arbitrary transfer function into an equivalent ideal (sphere-like) target with a flat response over frequency and angle:

$$\delta(x,y) = h_{tn}(x,y) * h_{tc}(x,y)$$

with the target correction PSF h_{tc} defined in the Fourier domain by

$$H_{tc}(f,\boldsymbol{\alpha}) = \frac{1}{H_{tn}(f,\boldsymbol{\alpha})}. \tag{14}$$

Now, the recorded complex raw data can be processed with a corrected, target-dependent filter $(h_{tc} * h)$:

$$V_c(x,y) = \sqrt{K\sigma_r}[h_{tn} * (h_{tc} * h)](x,y) \tag{15}$$

In analogy to Eq. (5), an integrated pixel intensity I_c can be derived from V_c. The equivalent RCS σ_e of the reference target is different from the RCS σ_r at the reference operating point. The two are related through

$$\frac{I_e}{I_c} = \frac{\sigma_e}{\sigma_r}. \tag{16}$$

by analogy between Eq. (5) and (15). The ratio I_e/I_c is the point target and SAR mode dependent correction factor described in [13]. Substituting unknown σ_e in Eq. (13) with the expression in Eq. (16), the absolute calibration factor is then given as

$$K = \frac{I_c}{\sigma_r}. \tag{17}$$

In conclusion, radiometric measurements can and have to be tied down to a known *equivalent* RCS by processing the raw data with a filter reversing the frequency and angular-dependent reflectivity, $h_{tc} * h$. By using targets with a known equivalent RCS (instead of a known RCS) for calibration, it is ensured that radiometric differences in measurements are due to the properties of the imaged target and not due to the reference target properties.

VI. CONCLUSION

This paper discussed the problems associated with denoting *radar cross section* as the radiometric measurement quantity for SAR images. The root cause was identified to be the principal frequency and angular dependence of the target's backscatter. It was proposed to replace RCS with *equivalent RCS* as the radiometric measurement quantity in SAR images.

This paper has identified two problems with denoting RCS as the radiometric measurement quantity in SAR images:

- The SAR sensor emits pulses covering a certain bandwidth and angular range. However, only one pixel intensity is annotated in the processed SAR image. The pixel intensity is at best proportional to a weighted average of the target RCS within the frequency and aspect angle range.
- RCS is defined as a power ratio; this entails that all phase information is lost. The processing for SAR images, on the other hand, depends on signal magnitude and phase.

In other words, a SAR system does not measure RCS and therefore another terminology should be used to describe the measurement quantity. This paper proposed that the quantity *equivalent RCS* should be used as a replacement. *Equivalent RCS* was defined to be equal to the radar cross section of a perfectly conducting sphere which would result in an equivalent pixel intensity if the sphere were to replace the measured target.

The implication of the new terminology for measurements was identified to lie in a conscious shift toward recognition of the spectral and angular dependence of target backscatter as a desired feature. It was shown that the difference between RCS and equivalent RCS, prominent especially for wideband and high-resolution SAR systems, can exceed several decibels. On the other hand, in terms of external absolute radiometric calibration, the new terminology asks for a compensation for the frequency and angular dependent backscatter of reference calibration targets by processing raw data with a correction filter during calibration.

By adapting *equivalent RCS* as the measurement quantity, calibrations and measurement results become truly compatible across current and future narrow and especially wideband, high-resolution, and high-accuracy SAR systems.

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Björn J. Döring received the Dipl.-Ing. degree in electrical engineering from the Technical University Berlin, Germany, in 2005. Since 2006, he has been with the Microwaves and Radar Institute at the German Aerospace Center (DLR), Oberpfaffenhofen, Germany. His research concentrates on satellite SAR calibration with a focus on absolute radiometric calibration. His design and characterization of passive and active calibration targets contribute to precisely calibrated SAR systems like TerraSAR-X, TanDEM-X, and GMES Sentinel-1.

Dr.-Ing. Marco Schwerdt received the Dipl.-Ing degree in electrical engineering and the Dr.-Ing. degree, with a thesis on electrooptical E-field sensors, from the Technical University Berlin, Germany. Since 1998, he has been with the Microwave and Radar Institute at the German Aerospace Center (DLR), Oberpfaffenhofen, Germany, where he is working on SAR calibration methods and performance analysis tools. Since 2000, he has been the head of the Radar Calibration Group performing various radar calibration activities for different SAR missions like XSAR/SRTM or the ScanSAR mode of ASAR/Envisat. He was responsible for the successful calibration of the German TerraSAR-X and TanDEM-X satellites, launched in 2007 and 2010 respectively. Furthermore, as part of the Global Monitoring Environment and Security Program (GMES), he is responsible for developing the overall SAR system calibration and validation plan for ESA’s Sentinel-1 mission. Under his leadership, the DLR’s comprehensive radar calibration facilities, including novel tools for product quality control and performance analysis, have been maintained and extended. His major research interest includes the development of innovative and efficient calibration methods.

Dr. Schwerdt received the *Der Deutsche Gründerfonds* award in 1997 for establishing an enterprise of manufacturing electrooptical field sensors under the patronage of the German Federal Minister for Science and Research.