A Standard Index of Spatial Resolution for Distributed Targets in Synthetic Aperture Radar Imagery

I. H. WOODHOUSE*, A. MARINO, I. CAMERON

School of Geosciences, The University of Edinburgh, Drummond St Edinburgh, United Kingdom, EH8 9XP

In this paper we outline the need for a consistent method of quoting SAR resolution given the influence of speckle upon SAR images. Standard measures of resolution depend upon the separability of point targets, however this is not a useful analogy in the context of SAR. We contend that quoting resolution for a 3-4 looks product may be unrealistic given the influence of speckle. Our approach considers the separability of targets that differ in intensity by a known contrast ratio, with a ratio of 2, i.e. 3 dB difference, used as threshold value. It is demonstrated that 12 looks represents a more realistic estimate of the capabilities of the system and should be used to quote an equivalent spatial resolution (ESR) when describing potential instrument performance.

1. Introduction

The increasing availability over the last decade of both space-borne and airborne high resolution radar systems has given the user community an ever wider selection of observational tools. However, this abundance of choice has a new problem – users must be able to easily assess the data quality and compare performance across sensors in a straightforward and transparent manner. In this paper we address one aspect of this problem, particularly within the field of land surface applications of radar imagery, by tackling the issue of spatial resolution. It is the experience of the authors that spatial resolution of radar imagery is neither presented consistently across data providers, nor is it widely understood by users of the data. Inconsistency and confusion often leads to inappropriate application and eventual disappointment on behalf of many users.

Spatial resolution is a key performance indicator of remotely sensed imagery and is defined as the separability of two idealised point targets. The point target is characterized by a Dirac delta function and so does not indicate visibility, which is a property of the contrast of any individual target with its background. The limiting factor of any imaging system is therefore the width of the end-to-end point spread function (PSF), or more exactly the ability to separate two overlapping PSFs. Separability usually refers to the distance between the maximum and the first minimum in the point spread function, although there are other arbitrary criteria that can be used to decide at what point they are separable. The problem in radar imagery is that speckle, the noise-like modulation of the signal due to wave interference, does not effect point targets. The strict definition of spatial resolution does not allow direct comparison between differently processed SAR data, nor between

*Corresponding author. Email: i.h.woodhouse@ed.ac.uk
SAR data and comparable optical data.

In this communication we provide a summary of how speckle influences visibility (for the benefit of non-expert users), and from this, propose a new heuristic measure of spatial resolution that is more appropriate for radar images of distributed targets.

2. Background and context

Instruments utilizing optical principles to collect or focus radiation using reflectors or lenses, often have spatial resolutions that are near-diffraction limited. The proportional dimensions of the optical elements to the wavelength govern the angular resolution and from that the spatial resolution is determined for a given flying height. In practice, a digital system may not reach their diffraction limit but are constrained by the digital measurement device, such as a CCD, or the scan rate. In these systems the pixel size (or more usually, the grid spacing) on the surface is often given as synonymous with the spatial resolution, so that it is now common (although often misleading) for the two terms to be used interchangeably. Informally, most people conceive of spatial resolution as equating to a measure of “the smallest object that can be reliably measured”, even though this is a rather lose interpretation of the term.

Comparing spatial resolutions between optical systems is straightforward as they have equivalent meaning and issues relating to noise are usually not limiting factors for these types of devices. However, the spatial resolution of any coherent imaging system, and in particular, synthetic aperture radar, does not equate directly to this common perception. The reason is twofold. First, SAR resolutions in azimuth (along-track) and range (cross-track) are governed by aspects of the system other than the diffraction limit of the antenna. In range, it is the effective length of the radar pulse that governs range resolution, and ground spatial resolution is then a function of incidence angle, which varies across an image swath. Since most SAR systems used chirped pulses, the resolution is actually a function of the bandwidth of the frequency sweep, rather than the pulse length, per se. In a similar way to chirped pulses, the azimuth resolution is governed by the Doppler bandwidth across the beamwidth.

The second reason, and the one that this communication focuses on, is the impact of the coherent noise-like phenomenon of speckle. By definition, resolution is based on the separability of idealised bright point targets within a dark background. However, point targets do not exhibit speckle. In practice speckle introduces stochastic fluctuations in intensity that, for a single-look image, leads to an expected error (one standard deviation) of 100% of the underlying signal. SAR spatial resolution is thus interwoven with radiometric resolution, which is the ability of a sensor to separate targets of similar intensity. In SAR, the term “radiometric resolution”, however, only considers calibration issues and thermal noise, and not speckle, which introduces a separate uncertainty on the measurements. Most applications of SAR imagery use either multi-look processing or spatial averaging to reduce speckle, effectively sacrificing spatial resolution to gain a better estimate of the underlying radar cross-section. With multi-looking this progressively reduces by a factor of $\sqrt{L}$, where $L$=number of looks. The separability of distributed (non-point) targets is therefore strongly
related to the equivalent number of looks. For this reason, spatial resolutions for SAR should normally be quoted for a given number of looks, that number usually being specified by the suppliers of the data.

The literature, however, often muddies the waters somewhat, so that 3-look data are often referred to as standard for the likes of ERS and JERS, e.g. Castela et al. (2002) and Yanasse et al. (1997), but with references to “around 4 look” (e.g. Kurvonen & Hallikainen, 1999) in some instances.

In many instances spatial resolutions are quoted, but no information is given on the number of looks (Baker & Luckman, 1999; Kellndorfer et al., 2003; Ranson & Sun, 2000; Rauste, 2005; Saatchi et al., 2007; Santoro et al., 2006). This is often repeated by data providers who rarely make reference to the number of looks for different SAR products, and tend to quote 3-4 looks data as the standard product. Resolutions are typically quoted as 25-30 m for ERS, JERS, Radarsat and Envisat and 10 m for ALOS. However, 3-4 look images still appear to be dominated by noise and are not comparable to an optical image that a user may be expecting given the specified “spatial resolution”.

To tackle the problem of speckle, it is common for users to apply speckle reduction filters, e.g. (Shimabukuro et al., 2007; Shupe & Marsh, 2004; Taft et al., 2004), or to aggregate pixels, e.g. (Kiage et al., 2005; Lang et al., 2008), prior to analysis. Using the latter method 3x3 or 5x5 kernels are often applied, suggesting that usable spatial resolutions for most current land applications are in the region of 50-100m (Picard et al., 2004). Direct comparison with optical systems is therefore very difficult, and even comparison between radar systems or radar modes (such as ScanSAR) is not easy. Many users interpret the given spatial resolution in the same manner they do for optical systems, namely, “the smallest object that can be reliably measured”, but this is not a helpful definition in the context of SAR images, for the reasons outlined above. For users familiar with optical data these problems may be compounded by the fact that quicklook images tend to be generated by aggregating pixels and show little evidence of speckle, thus new users can be surprised by the graininess of a 3-4 look SAR image.

Here, we propose that a single common index of spatial resolution for distributed targets, with clear meaning and widely used, would allow the user community to better assess the performance of different SAR systems and how they compare to their optical counterparts. The criteria can be formulated as a set of heuristic axioms such that we say that we require the index to:

1. Be easily interpreted and determined for a given system.
2. Equate to the dimension of an equivalent square pixel (so that only one value is required).
3. Be comparable with the expectations of the optical remote sensing user community.
4. Be independent of where or when an image is formed, according to the translation axiom (Wang and Li 1999)

### 3. Definition of an index of distributed spatial resolution

The approach considered here is to determine the separability of two distributed targets,
A and B. For simplicity we consider the underlying normalised radar cross section (NRCS or \(\sigma^0\)) of region A to be a factor \(f\) larger than that of region B, so that \(f = \sigma_A^0 / \sigma_B^0\). \(f\) is the contrast ratio of the target scene, which we define to be \(\geq 1\). When \(f=2\), there will be approximately 3dB difference in the measured normalised radar cross section. The pertinent question is then to ask how many looks are required to allow a difference of \(f\) to be measured with a certain degree of confidence?

Rignot and van Zyl (1993) tackle a similar issue, by asking how many looks are required to classify a difference in NRCS of \(f\). They also demonstrate that the ratio is a more appropriate measure of difference than the absolute magnitude. Here we expand their argument to consider the impact on spatial resolution, and ultimately to aim to establish a standardised resolution based on the separability of targets in space (rather than in time).

The intensity distribution of a spatially homogeneous scatterer, is given by:

\[
P(n) = \frac{L^n n^{L-1}}{\Gamma(L)} e^{-Ln},
\]

where \(L\) is the number of independent looks, \(\Gamma(L)=(L-1)!\). The standard deviation of this distribution is found from the square root of the variance, such that:

\[
\text{std} = \frac{\sigma^0}{\sqrt{L}}.
\]

In the case of a single look image \((L=1)\) this represents an inverse exponential distribution, in which case the mean intensity \((\sigma^0)\) is equivalent to the standard deviation. Let us consider the two distributed targets that have mean cross-sections that differ by a factor of \(f\), so that \(f\sigma_A^0 = \sigma_B^0\). The standard deviations of these two targets for a given number of looks are then

\[
\sigma_A = \frac{\sigma_A^0}{\sqrt{L}} \quad \text{and} \quad \sigma_B = \frac{f\sigma_A^0}{\sqrt{L}}.
\]

Here we define a measure of separability such that the two distributed targets are separable when the sum of the two standard deviations are equal to the difference between the two mean intensities \((I(f-1))\). This is an ad hoc heuristic chosen for its simplicity and reference to the Rayleigh criteria of separability based on the full width at half maximum (FWHM), noting that it is a crude approximation to equate two standard deviations to the FWHM, and only strictly applies for large \(L\).

For our separability criteria we therefore have the difference between the mean intensities:

\[
\text{mean intensity difference} = I(f-1) = \sigma_A + \sigma_B
\]
\[ \sigma_b^0 - \sigma_a^0 = \sigma_a^0 (f - 1) \ , \]  

(4)

and the sum of the standard deviations:

\[ \text{std}_a + \text{std}_b = \frac{\sigma_a^0}{\sqrt{L}} + \frac{f \sigma_a^0}{\sqrt{L}}, \]  

(5)

\[ = \frac{\sigma_a^0}{\sqrt{L}} (1 + f). \]  

(6)

Equations (4) and (6) allows us to define:

\[ \sigma_a^0 (f - 1) = \frac{\sigma_a^0}{\sqrt{L}} (1 + f) \]  

(7)

which can be simplified to define our separability criteria as:

\[ \sqrt{L} = \frac{(f + 1)}{(f - 1)} \text{ or } L = \left[ \frac{(f + 1)}{(f - 1)} \right]^2. \]  

(8)

This result can now be used to estimate the number of looks required to separate any two distributed targets with a contrast ratio, \( f \), between the targets. Table 1 and figure 1 both show the required number of looks for a range of contrast values. We have also estimated the resolution required to provide an equivalent number of looks (\( L \)) in each case based upon the resolution of a 3 look ERS or ASAR image mode product. This assumes that the looks are fully independent, otherwise \( L \) is a lower estimate of the number of looks required. While we assume equivalence between range and azimuth resolution here, in practice the azimuth and range compression may not result in equal dimensions. Thus we include an estimated resolution for purely illustrative purposes.

Considering the “standard” case of a 3 look image we see that targets need to differ in intensity by approximately 5.6 dB, i.e. a factor of 3.73, to be reliably separated. This supports the observation that quoting spatial resolution for a 3-look SAR product may lead to unrealistic expectations. Importantly we find that separating targets that differ in intensity by 3 dB (\( f = 2 \)) requires 9 looks and implies a spatial resolution of approximately 52x52 m² based upon an ERS style sensor. While it is not necessarily simple to estimate a square resolution for a 9-look pixel, \( L = 12 \) is a potentially interesting criterion as it is easy to estimate from a “standard” 3-look image using a 2x2 aggregating filter. As \( f = 1.8 \) for \( L = 12 \), this also provides a more robust estimate of target separability which may be advantageous as our analysis does not consider the effects of systematic noise upon radiometric stability.
4. Demonstration based on simulated data

So far we have demonstrated that to achieve our objective of separating distributed targets that differ in intensity by a factor of 2 requires 9 looks. To gain a better idea of the implications of these results for practical application we evaluated the effect of look number upon the visibility of distributed targets of differing relative size and intensity for a set of simulated SAR images.

Initially a base test pattern was defined that uses alternating dark/light vertical bands of differing intensity to explore the relationship between looks and the contrast of adjacent targets. The first band in the pattern contains a constant intensity, henceforth referred to as $B_1$, with an arbitrary value. The intensity of the second band, $B_2$, varies as a multiple of $B_1$ scaled linearly according to Michelson’s visibility criterion. Michelson’s visibility criterion is a conventional metric for determining the apparent contrast of natural images (Bex & Makous, 2002). It defines the ratio between targets of intensity $I_a$ and $I_b$ according to:

$$m = \frac{I_b - I_a}{I_b + I_a}, \quad (9)$$

where $I_b \geq I_a$. When $m = 0$ this indicates no difference in intensity between $I_a$ and $I_b$, increased values of $m$ indicates greater contrast between targets while a value of $m = 1$ specifies infinite contrast. For this study the intensity of $B_2$ was scaled from a minimum of $m = 0$ to $m = 0.9$, which equates to a maximum intensity of $17B_1$. The relationship between $m$ and the contrast ratio, $f$, is defined by $I_b = fI_a$ and is shown in figure 2. Note that for our arbitrary separability criteria of $f = 2$, $m$ is approximately equivalent to 0.35. The visibility of alternating bands is liable to be influenced by both the visibility ratio between bands and the width of the band itself; thus in the final test image bands $B_1$ and $B_2$, each 100 pixels tall, were gradually increased in width from 1 pixel to 28 pixels wide. The test pattern is shown in figure 3a.

This pattern was subsequently used to generate a simulated single look SAR intensity image by introducing multiplicative noise drawn from a randomly generated inverse exponential distribution with mean values equivalent to the intensity of the test pattern. Multilook images were simulated by generating between 3 and 16 independent images and calculating the arithmetic mean of the images for each pixel. While this approximates the statistically independent nature of a multi-look image it does not account for the loss of resolution that true multi-look imaging entails. These images are shown in figure 3c-f.

Finally an equivalent optical image (figure 3b) was simulated by adding Gaussian thermal noise to the test pattern with a signal to noise ratio (SNR) of 30. This is a lower estimate of the SNR of LANDSAT-5 (Helder et al., 2004) and is chosen to represent a commonly used optical sensor with similar spatial resolution to the image mode configurations of spaceborne SAR systems such as ERS-2 and ENVISAT ASAR.

While there is relatively little difference between the thermal case (3b) and test pattern (3a), speckle is a strong feature in all of the simulated SAR images. Of particular interest is the relationship between the width of the distributed target and visibility, with targets on the
right of the test card (14 – 28 pixels wide) separable at considerably lower contrast ratio than targets in the region of 1 – 7 pixels wide. For the single look image we find that speckle is dominant across the card and eliminates the test pattern at visibilities below ~0.4. Notably, speckle is a dominant factor for the 3-looks image. Considering the case of $f = 2$ ($m = -0.35$), only targets of 6-7 pixels wide are clearly separable, further demonstrating the difficulties of applying the standard definition of resolution to a coherent imaging system. Considering the 9 and 12 look cases we find that speckle is greatly reduced as expected. Importantly for $L = 9$ and $L = 12$ we can separate even the smallest targets at $f = 2$ and the images are beginning to look similar to the thermal noise case that users may be expecting.

5. Conclusions and Summary

Radar imagery often fails to live up to the expectation of new users more familiar with optical imagery as speckle can make images appear dominated by noise at the spatial resolutions and number of looks for image mode SAR scenes commonly quoted by image providers. If radar imagery is to find widespread practical use in an effective way, then new users must familiarize themselves with the properties of spatial resolution in radar, but data distributors also have a responsibility to communicate more effectively the image properties, as understood by the user. To this end, we propose here that a standard number of looks is used, not in the data distribution itself, but as an equivalent spatial resolution (ESR) when describing potential instrument performance for observations of distributed targets. For simplicity in using existing data products, we propose here that all instrument resolutions are quoted for a 12 look (square pixel) equivalent image.

This figure was arrived at by estimating the number of looks required to separate two distributed targets that differ in intensity by a factor of 2 (3 dB) using an approximation of the Rayleigh criteria of separability at full width half maximum. While we have demonstrated that 9 looks are sufficient to meet this criteria, a 12 looks standard may be preferable. Examination of simulated SAR images further demonstrates the inadequacy of quoting resolution for a 3-looks image, and the considerably clearer separability of targets afforded by 12-looks.

6. References


Table 1. Number of looks required to separate targets of differing contrast ratio

<table>
<thead>
<tr>
<th>Contrast Ratio ($f$)</th>
<th>Approx. Diff. in dB</th>
<th>No. of Looks ($L$)</th>
<th>Estimated Resolution ($m^2$) (^i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.4</td>
<td>441</td>
<td>363</td>
</tr>
<tr>
<td>1.55</td>
<td>1.7</td>
<td>21</td>
<td>90</td>
</tr>
<tr>
<td>1.8</td>
<td>2.55</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>9</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>4.7</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>3.73</td>
<td>5.6</td>
<td>3</td>
<td>30</td>
</tr>
</tbody>
</table>

\(^i\) Resolution based on the estimated number of looks for an ENVISAT ASAR 3-look PRI scene (ESA, 2007)
Figure 1: Number of looks needed to discriminate between two targets with a fixed contrast ratio. The trend shows that 9 looks are necessary to discriminate between two targets with contrast equal to 2 (i.e. ±3 dB), shown by the dashed line.

Figure 2: Contrast ratio plotted against Michelson’s visibility. The dependence of the visibility on the ratio between two different target intensities is not linear since for visibility equal to 1 the contrast ratio goes to infinity. The dashed line marks $f = 2$ (i.e. 3 dB).
Figure 3: Results of multilook image simulation. (a) Shows the test pattern used for all other images. (b) Simulated optical image with thermal noise applied. (c-f) SAR scenes simulated using 1 to 12 looks. The left hand scale shows Michelson’s visibility criterion, $m$, calculated as the difference between the alternating bands of the test image (a), while the right hand scale shows the equivalent contrast ratio, $f$. Note that for images (c-f) as the number of looks increases the narrow alternating bands can be visually distinguished at lower visibility levels.