Estimates of ocean coherence time by an interferometric SAR

L. SHEMER
Department of Fluid Mechanics, Faculty of Engineering, Tel-Aviv University, Israel

and M. MAROM
Israeli Navy, Mil. P.O. Box 01068, Israel

(Received 3 April 1992; in final form 30 July 1992)

Abstract. The azimuthal resolution of the Synthetic Aperture Radar (SAR) when imaging the permanently moving ocean surface is determined by the coherence time of the imaged scene. The scene coherence time thus constitutes one of the major parameters in SAR imagery of the ocean. The present study shows how the direct estimate of this parameter under the actual experimental conditions can be performed using a two-antenna interferometric SAR. The present results are in agreement with earlier estimates.

1. Introduction

It is well known that linear aperture synthesis process provides a method to obtain high resolution images. The principles of operation of the Synthetic Aperture Radar (SAR) are well understood and were reviewed by Tomiyasu (1978). The application of SAR to the imaging of the permanently moving ocean surface reveals, however, that interpretation of ocean imaging by SAR represents considerable difficulties. The accumulated experience clearly indicates that the azimuthal resolution of the ocean surface images is far below the estimates based on synthetic aperture processing of a stationary, or ‘frozen’, surface. This low pass effect results in azimuth cut-off in SAR spectra of the ocean wave fields, as well as in the shift of the peak location in the spectrum towards lower wave numbers and rotation towards the range direction (Beal et al. 1983, Lyzenga and Shuchman 1983).

Raney (1980) was the first to consider SAR response for a real world situation, where both the imaged scene and the imaging system are only partially coherent. One of the main reasons for the lack of full coherence is continuous temporal and spatial variability of the imaged scene. In order to deal with this variability, a two-scale SAR model was suggested (Valenzuela 1980, Plant and Keller 1983), which is based on the fact that the size of nominal SAR resolution cell is larger by at least order of magnitude than the length of the resonant Bragg wave. Thus, in this model the resolution cell of the SAR image is considered to consist of a large number of the so-called facets. Each facet is of the size of a few resonant Bragg waves. The backscattered signal decorrelation can result both from the finite Bragg wave train length, or due to movement of the facets by ocean waves. It is generally assumed that the facet retains its identity over the SAR integration process, i.e., the life span of Bragg wave trains is sufficiently long (Alpers et al. 1981, Tucker 1985). Under this
assumption the decorrelation time of each facet can be seen as infinite. The random relative movement of facets during the synthetic aperture process results, however, in decorrelation of the backscatter returns from each resolution cell and thus in finite scene coherence time $\tau_s$, which in turn leads to degradation of the azimuth resolution (Lyzenga and Shuchman 1983, Kasilingam and Shemdin 1988).

Knowledge of the scene coherence time is therefore indispensable for estimate of the best attainable azimuth resolution and for determination of the effective SAR integration time. There have been several attempts to estimate $\tau_s$ for various sea states. One of the suggestions (Tucker 1985) is to use the Pierson–Moskowitz (1964) spectrum for a fully arisen sea in order to estimate the mean-square radial surface velocity and thus to calculate the scene coherence time. A similar approach was adopted by Alpers and Brüning (1986) for obtaining estimates of this parameter for Seasat SAR operational conditions. Their estimates appropriate for L-band were of the order of 100 ms, the actual value depending on the assumed wind velocity. It should be stressed here that estimation of the scene coherence time $\tau_s$ by this technique is sensitive to the particular power spectrum of the surface elevation. It is also important to know a priori the effective azimuthal resolution of SAR, which in turn is critically dependent on $\tau_s$. Frustration in attempting to estimate this crucial resolution parameter by independent means has recently led to the suggestion to abandon the two-scale SAR model (West 1991).

Recently, an interferometric SAR (INSAR) has been applied to the imaging of the ocean surface (Goldstein and Zebker 1987, Goldstein et al. 1989). In this modification of conventional SAR technique, complex SAR images are obtained by two separate antennas along the platform flight path. These images are further combined interferometrically resulting in a complex map of the imaged area. The advantages of INSAR over regular SAR in imaging of the ocean are discussed in Marom et al. (1990, 1991).

The purpose of the present study is to show that the INSAR images, constructed from time-shifted images of two individual SARs, allow one to calculate the actual scene coherence time of the imaged surface, and thus to estimate the effective azimuthal resolution of the image. In conventional SAR the image represents the map of the absolute value of the complex reflectivity of the ocean (Hasselmann et al. 1985). For INSAR image analysis we are primarily interested in the phase component of the complex interferogram, which contains direct information about the distribution of radial velocity components over the ocean surface. Interferometric SAR imagery thus represents a remote sensing tool with a well-defined mechanism of ocean imaging, which can quantitatively measure the mean ocean currents and directional wave spectra (Marom et al. 1990, 1991, Shemer et al. 1993). The theoretical foundations of the INSAR imagery of the ocean waves and currents were recently presented by Shemer and Kit (1991). It appears, though, that additional important information can be extracted from the absolute values of the complex INSAR image.

2. Theoretical background

Let us consider first the time independent (frozen) random backscattering surface. It is generally assumed that the backscattered signals from different scattering elements $r_0(x)$ of such a surface are statistically decorrelated, so that

$$\langle r_0(x)r_0^*(x+\xi) \rangle = \sigma_0(x)\delta(\xi),$$

(1)
where $\langle \ldots \rangle$ denotes ensemble averaging, $\sigma_0(\mathbf{x})$ represents the backscatter cross-section and $\delta(\xi)$ is the Dirac $\delta$-function. The backscattering process is thus assumed to be statistically spatially white (cf., Hasselmann et al. 1985). In a real system which images a frozen surface, one has to take into account the time-dependent additive system noise. The resulting time-dependent complex reflectivity coefficient can be presented as

$$r(\mathbf{x}, t) = r_0(\mathbf{x}) + n(\mathbf{x}, t).$$  \hspace{1cm} (2)

Assuming stationary noise, (1) for the noisy system can be rewritten as

$$\langle r(\mathbf{x}, t)r^*(\mathbf{x} + \xi, t) \rangle = [\sigma_0(\mathbf{x}) + |\langle n^2 \rangle|] \delta(\xi),$$  \hspace{1cm} (3)

where $\langle n^2 \rangle$ is the system noise variance. The additive noise for the separate INSAR receiving channels can be assumed to be uncorrelated, so that $\langle n_i(t) \cdot n_j^*(t) \rangle = 0$, where the indices denote the number of antenna. The INSAR output constructed by combining the outputs of the two INSAR antennas is therefore given for the stationary frozen surface by

$$\langle r_1(\mathbf{x}, t)r_2^*(\mathbf{x} + \xi, t) \rangle = \langle r_0(\mathbf{x})r_0^*(\mathbf{x} + \xi) \rangle \delta(\xi) = \sigma_1(\mathbf{x}) \delta(\xi).$$  \hspace{1cm} (4)

The cross-covariance coefficient $K_\nu$ which accounts for the additive system noise can therefore be determined from the absolute values of the INSAR image and the two separate SAR images:

$$K_\nu(\mathbf{x}) = \frac{\langle |r_1(\mathbf{x}, t)||r_2(\mathbf{x}, t)| \rangle}{\langle |r_1^2(\mathbf{x}, t)| \rangle^{1/2} \langle |r_2(\mathbf{x}, t)| \rangle^{1/2}} = \frac{\sigma_1(\mathbf{x})}{\sigma_0(\mathbf{x}) + |\langle n^2 \rangle|^{1/2} \sigma_1(\mathbf{x})}.$$  \hspace{1cm} (5)

Note that the indices assigned to the radar backscatter cross-sections $\sigma$ in (4) and (5) account for possible differences in the characteristics of the two receiving antennas.

The situation is more complicated in the case of the moving reflecting surface. Invoking the two-scale SAR model, one can distinguish between the length scales longer than the spatial resolution of SAR, which must be treated deterministically, and shorter length scales, which can only be taken into account statistically (Tucker 1983). As mentioned above, the limited temporal coherence due to both system noise and the random movement of the ocean surface at subresolution scales determines the actual azimuthal resolution of SAR and thus the domain of the ocean wave lengths which can be treated deterministically. Similar distinction can be made between the corresponding time scales, i.e., the long-time scale corresponding to the times comparable with the periods of deterministically treated waves, and the short-time scale for durations less than the wave period of the shortest resolvable by SAR ocean wave. The complex radar reflectivity of any moving scattering element in the presence of the additive system noise and randomly varying phase can be presented as

$$r(\mathbf{x}, t) = [r_0(\mathbf{x}, t) + n(\mathbf{x}, t)] \phi(t) \exp \left[ -2\pi \int_0^1 U(\mathbf{x}, \eta) d\eta \right].$$  \hspace{1cm} (6)

where the factor $\phi(t)$ represents the complex fade of the scene element at $\mathbf{x}$ and is normalized so that $|\phi| = 1$. This multiplicative noise model for a partially coherent scene was first suggested by Raney (1980). The assumption of the Gaussian shape of the power spectrum of $\phi(t)$ allows one to present the correlation function in the following form:

$$\langle \phi(t)\phi^*(t + \tau) \rangle = \exp(-\tau^2/2\tau^2_r),$$  \hspace{1cm} (7)
where $\tau_s$ is the scene coherence time due to the multiplicative noise, $\tau_s$ approaching infinity for full coherence in the scene.

The exponent in (6) represents the Doppler phase shift due to large-scale movement, $\mathbf{k}$ being the radar wave vector and $U(x, t)$ the total deterministic velocity of the scattering element, which is the vector sum of the phase velocity of the resonant Bragg waves, surface currents which vary on spatial and temporal scales longer than the corresponding SAR resolution cut-offs, and orbital velocities of the gravity waves longer than the size of the resolution cell. The Doppler shifts due to movements of scattering elements at subresolution scale (facets) are accounted for in the complex value of $r_0(x, t)$. The two-scale SAR model for a spatially white Gaussian ocean surface, together with the assumption of statistical independence between scene coherence and radar performance allows to represent the cross-covariance $I(x, t, \tau)$ as

$$I(x, t, \tau) = \left< r_1(x, t) r_2(x + \xi, t + \tau) \right> = \sigma_{12}(x, t) \exp(-\tau^2/2\tau_s^2) \exp[2ik(U(x, t)\tau)].$$

(8)

where the radar backscatter cross-section $\sigma_{12}(x, t)$ varies spatially and temporally at slow scales. Using (5) and (8), the cross-covariance coefficients $K_s$ for the spatially white moving ocean scene with partial coherence at the platform location $x = Vt$ can be now presented as

$$K_s(x, t, \tau) = \left| I(x, t, \tau) / \left[ \left< r_1^2(x, t) \right> \right]^{1/2} \left< (r_2^2(x, t + \tau)) \right> \right|^{1/2} = K_s(x) \exp(-\tau^2/2\tau_s^2).$$

(9)

It is assumed in (9) that the additive system noise represented by the cross-covariance coefficient $K_s$ remains approximately the same over the stationary shore areas and in the ocean. In the present study advantage is taken therefore of the fact that the available images cover both the shore and the ocean. The covariance coefficient $K_s$ is calculated first from (5) by averaging over the 'frozen' shore area. In the INSAR imaging procedure the image of the identical point in space is obtained by the back antenna with the time shift $\Delta t = B/2V$ relative to the front antenna, where $B$ is the antenna separation distance in the flight direction. Note that the factor 2 in the definition of $\Delta t$ arises due to the fact that only the front antenna serves as the transmitter.

Finally, substituting $\tau = B/2V$ into (9) allows to calculate the scene coherence time of the ocean

$$\tau_s = \frac{B/2V}{(\ln K_s/K_n)^{1/2}}.$$  

Expression (10) can serve as a basis for estimating the scene coherence time using INSAR, provided the cross-covariance coefficient $K_s$ which accounts for the system noise is known.

3. Experiment

Our experiment was carried out on 8 September 1989 in Monterey Bay. The experiment consisted of four overflights of a NASA/JPL DC-8 carrying an interferometric SAR. The initial data processing was performed by R. Goldstein at the JPL. The radar overflights were conducted around 1300 Pacific Daylight Time, close to the time of maximum tidal flood current. The flight pattern and the scene locations of radar data acquired are illustrated in figure 1, while the system and radar parameters are summarized in table 1. Additional details about the experiment can be found in Marom et al. (1990, 1991).
Figure 1. Flight pattern and image boundaries.

Table 1. NASA/JPL DC-8 airborne imaging radar parameters employed during Marina experiment, 8 September 1989.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, MHz</td>
<td>1237–1260</td>
</tr>
<tr>
<td>Centre frequency, MHz</td>
<td>1248.75</td>
</tr>
<tr>
<td>Wavelength, cm</td>
<td>24</td>
</tr>
<tr>
<td>Chirp length, µs</td>
<td>11.25</td>
</tr>
<tr>
<td>PRF/V, Hz m⁻¹ s⁻¹</td>
<td>1.32</td>
</tr>
<tr>
<td>Band width, MHz</td>
<td>20</td>
</tr>
<tr>
<td>Peak power, kW</td>
<td>6</td>
</tr>
<tr>
<td>Azimuthal beamwidth, deg</td>
<td>8</td>
</tr>
<tr>
<td>Vertical beamwidth, deg</td>
<td>44</td>
</tr>
<tr>
<td>Antenna beam centre gain, dB</td>
<td>18.3</td>
</tr>
<tr>
<td>Azimuthal pixel spacing, m</td>
<td>3.03 × 4</td>
</tr>
<tr>
<td>Slant range spacing, m</td>
<td>6.6</td>
</tr>
<tr>
<td>Polarization</td>
<td>VV</td>
</tr>
<tr>
<td>Receiver dynamic range (dB)</td>
<td>30–56</td>
</tr>
<tr>
<td>Number of bits per sample</td>
<td>8</td>
</tr>
<tr>
<td>Number of looks</td>
<td>1</td>
</tr>
<tr>
<td>Available number of pixels</td>
<td>750 × 1024</td>
</tr>
</tbody>
</table>

The environmental conditions during the Marina experiment were typical for late summer in Monterey Bay. Light westerly winds (about 2 m s⁻¹), surface air temperature of 14°–16°C and clear skies up to 300 m blocked by a stratus cloud deck, were observed during the experiment period. The mild meteorological conditions during this period resulted in almost no local wave generation of sea. The sea
surface was predominantly bimodal with long crested, narrow-band swell waves propagating shoreward.

The surface wind had mainly an eastward component with a weaker ambiguous northerly component. Thus in flight paths 360° and 180°, the radar was looking upwind and downwind, respectively, while in flight paths 90° and 270° the radar looked at weakly crosswind scenes. During flight paths 90° and 270°, the resonant Bragg waves trains at the ocean surface (responsible for the radar reflectivity) travelled in the opposite directions, towards as well as away from the aircraft, due to wave and wind spreading.

4. Results and discussion

Figure 2 shows an example of the INSAR image of the shore region of Monterey Bay. The image of figure 2 was obtained during the northbound flight leg (360°). Figure 2(a) depicts the map of the absolute value of the cross-covariance of the surface reflectivity as defined by (8) and looks very similar to a conventional SAR image. Figure 2(b) shows the image representing the phases of the cross-covariance defined by (8). While the phase map of figure 2(b) is not directly relevant to the determination of the scene coherence time according to the method developed in §2,

Figure 2. INSAR image obtained in the northbound (360°) flight leg. Image dimensions 12.4 km by 6400 km. (a) Map of the absolute values. (b) Map of the phases.
it allows one to distinguish clearly between the areas in the image with different propagation velocities of the Bragg resonant scatterers. Four definite regions can be identified in figure 2(b) and analysed separately: solid surface in the upper part of the image, Salinas river, surf zone and open seas. Since the phase shift in (8) is proportional to the radial component $U_r$ of the scatterers' velocity $U$, the image of the solid surface at the shore in figure 2(b) has uniform intensity corresponding to $U_r=0$. An interesting feature of the images of figure 2 is the Salinas river, which at that time of the year is a reservoir of standing water blocked from the ocean. The Salinas river is clearly seen in figure 2(b) due to the different from zero velocity of the scatterers. It thus has a uniform but different from the surrounding solid surface pixel intensity. The Bragg resonant waves for the L-band radar move with a phase speed of about 50 cm s$^{-1}$. The image of the Salinas river as it appears in figure 2(b) allows one to determine the well-defined border of the river and to apply this information in order to obtain the estimates of the scene coherence time of the water surface in the absence of contamination by longer gravity waves.

The intrinsic noise level of the system in each one of the four flight legs was determined first by applying (5). The resulting correlation coefficient, averaged over the solid surface regions obtained in all four images (total number of averaged pixels for each image is of the order of $10^5$) is $K_s=0.9725$, the standard deviation being 0.0068.

This value of $K_s$ is now substituted into (9) and (10), and the value of the correlation coefficient of the moving ocean surface $K_s$ is calculated separately for various flight legs and for various incidence angles. At least $10^4$ data points are taken into account for each estimate of $K_s$. The results on the scene coherence time estimated in the open sea regions of the images are summarized in table 2. The total mean value of the scene coherence time is about 128 ms. This value, based on the actual experimental data, is in reasonable agreement with earlier estimates (see, cf., Alpers and Brüning 1986). It should be noted that in any quantitative comparison of the scene coherence times in different studies the exact definition of $\tau_s$ should be taken into account. In some works the coefficients which differ from the presently adopted form of (7) and (10) are used. Also, the mild sea state during the Monterey Bay experiment on 8 September 1989 resulted in conditions which were well suited for SAR imagery, with a relatively long scene coherence time. The present estimate thus is likely closer to the upper limit of the actual scene coherence time in the ocean.

| Incidence angle | Flight leg |
|-----------------|-----------|-----------|-----------|-----------|
|                 | $90^\circ$ | $180^\circ$ | $270^\circ$ | $360^\circ$ |
| $25^\circ$      | 141       | —         | 122       | —         |
| $31^\circ$      | 148       | —         | 130       | —         |
| $36^\circ$      | 130       | 125       | 117       | —         |
| $42^\circ$      | 117       | 147       | 110       | 132       |
| $46^\circ$      | 109       | —         | 96        | 142       |
| $50^\circ$      | 113       | —         | 95        | 143       |
| Mean value      | 126       | 136       | 110       | 139       |
The situation is, however, quite different if \( \tau_s \) is calculated for the Salinas river region (figure 2(b)). It appears that the value of the cross-correlation coefficient \( K \), over this region is nearly identical to the value of \( K_s \) obtained over the solid surface. The conclusion can thus be made that the finite duration of the resonant Bragg wave trains hardly affects the actual value of the scene coherence time and is thus of only minor importance. This conclusion again is in agreement with the generally adopted assumption (Tucker 1985).

Much smaller values of \( \tau_s \) are obtained for the surf zone of the image presented in figure 2. This zone is about 10 pixels wide along the shoreline. The estimate for this zone is \( \tau_s \approx 80 \) ms, notably below the estimates for the open sea areas. This can be attributed to a different scattering mechanism in the surf zone, where the resonant Bragg waves propagate with much higher velocities typical for the phase velocities of the long breaking waves. These different propagation velocities of the scattering elements in the surf zone are clearly visible in the phase image of figure 2(b). The scatter in the propagation velocities manifests itself in the surf zone of figure 2(b) in the wide range of the pixel intensities.

5. Conclusions

The present study shows that since the image of the identical area is obtained by the two-antenna interferometric SAR with a known time delay, direct estimates of the ocean scene coherence time under actual experimental conditions can be obtained. The possibility of a direct measurement of this parameter, which is extremely important in the INSAR and SAR imagery of the ocean surface, can thus be seen as a valuable by-product of INSAR.

In the present study, advantage was taken of the fact that the available images obtained by INSAR included, in addition to the sea regions, also the stationary 'frozen' surface on the shore. This made possible an estimation of the contribution of intrinsic noise of the system and the possibility of separating this noise from the decorrelation due to the ocean surface movements at subresolution scales.

By using the phase portion of the complex INSAR imagery it became possible to determine clearly the borders between the stationary 'frozen' surface, still water areas and the surf zone. The INSAR phase images were therefore employed in order to define these qualitatively different regions, namely the open sea, the surf zone and the still water area of the Salinas river.

The scene coherence time of the ocean obtained in the present study is in general agreement with the earlier estimates which were based on certain additional assumptions. The coherence time in the surf zone is considerably shorter than that in the open ocean due to a different scattering mechanism.

The study of the scene coherence time in the still water region shows that this parameter is close to the estimates obtained over the stationary solid surface. The conclusion can thus be made that the finite length of the resonant Bragg wave trains does not contribute significantly to the finite coherence of the water surface. While this was generally adopted in various models regarding the estimates of the scene coherence time, the present study provides direct experimental confirmation of this fact.

References


