The Estimation of Ship Velocity From SAR Imagery

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***Abstract*-The estimation of ship heading and speed from a high resolution Synthetic Aperture Radar (SAR) image of a ship and its wake is important for monitoring and tracking ships from satellites. Though the ship can often be imaged clearly, its orientation may be difficult to estimate from its image because of the effects of ship motion. The wake can provide direct information about the ship heading; the cross-range separation between the location of the ship in the image and the wake provides an estimate of the speed. The performance of algorithms on ship and wake extractions from Radarsat and other satellite imagery is discussed.**

1. Introduction

There is a military requirement to extract the ship velocity vector from a SAR image such as that produced by Radarsat. The estimation of velocity assists the tracking of vessels, which is an important component of ocean surveillance. The ship heading and its speed can be estimated from the structure of wake arms in an image. The displacement of the ship from the wake in the cross-range direction provides an estimate of the ship speed. In some circumstances, however, the ship speed can be estimated from the opening angle of the wake or from the wavelength of the transverse waves in the Kelvin wake. An automatic processor is desirable to extract this information and, when necessary, to fuse it intelligently. The objective of the current work is to study the process of ship velocity determination, mainly using the first of these techniques, and to estimate its performance. A software tool, written in Microsoft's Visual C++, has been coded to achieve this goal and has been exercised on a library of about 250 radar wake extractions from Radarsat, ERS, and Seasat images.

The displacement of a ship from its wake in a Synthetic Aperture Radar (SAR) image and its relation to the ship velocity is well known [1,2]. Nevertheless, its application to velocity extraction must overcome some hurdles. The first of these is that not all ship images are accompanied by a wake in a radar image. The appearance of a wake depends on many factors including the ship type, size, and speed. The radar characteristics including frequency and polarization are important as are the directions of the wind and the ship track relative to the radar. One of the principal parameters, however, is the sea state. Any hydrodynamic perturbation associated with a wake must compete against the ambient sea in the radar imaging process. Surface perturbations include changes in sea height, slope, and velocity components. Velocity components are related to the orbital motion of surface gravity or internal waves [3], to wind drift layers [4], and to turbulent flows.

The occurrence of a wake in a radar image is not fully understood. Nevertheless, in sea states four or less, large ships with a length of several hundred meters and traveling at speeds over 7 m/s seem to consistently produce at least a significant turbulent wake. In contrast, ships of length less than 100 m, traveling at speeds of less than 3 m/s, only produce wakes sporadically; their occurrence is often associated with sea states less than three and the presence of internal layers.

Wakes usually appear in a SAR image as near-linear features that may be brighter or darker than the ocean background. Radar images also tend to exhibit naturally occurring linear features. For a surface ship, these can usually be eliminated by only accepting lines that pass close to it.

The detection of linear wake features can be implemented using the Radon transform [5]; this transforms straight lines in an image to points in the Radon domain, but a two-dimensional high pass filter should precede the Radon transform to remove variations of low spatial frequency. Though a variety of linear wake structures is often detected, the automatic determination of the ship heading is not trivial. This is because some hydrodynamic wake arms may not be visible in the radar image.

The most common type of wake in a SAR image is the turbulent wake. Since the opening angle of this wake is small, it can yield an accurate estimate of the ship heading. It is usually dark, but may be flanked by one or two bright lines. Therefore it is best identified by the dark line, while if they exist, the bright lines can be used to obtain a better heading estimate.

Another type of wake that is commonly observed is the steady internal wave wake. An internal wave wake can only exist if there are internal layers present on which the waves can propagate. The wake image may comprise a full set of wake arms associated with the crest structure of divergent waves or it may consist of two bright arms or even one bright arm and one dark arm. The appearance of this type of wake depends on the orientation of the wake relative to the radar as well as the wind direction.

The Kelvin wake is observed occasionally and, for the radars on Radarsat, ERS or Seasat, is usually associated with ships traveling at speeds above about 10 m/s. This is because, at low speeds, the maximum wavelength in the Kelvin wake is typically of the order of or less than the pixel size. The resulting aliasing along with inevitable velocity bunching effects tend to wash out the Kelvin wake in the image.

Sometimes several types of wake are present simultaneously. It is worth noting that additional wake types are produced when the pattern of water flowing around the ship hull is not stationary in the frame of reference of the ship. For example, an unsteady wake can be produced when a ship encounters a periodic swell. The opening angle of the wake depends on the speed of the ship and the encounter frequency [6,7]. There are some examples of these wakes in the library of wake extractions.

To extract an accurate heading estimate, it is necessary to remove extraneous linear features, to separate the various types of wakes, and then to classify them. Following this, wake information can be fused. For example, if the turbulent wake can be identified, it may define the center of an internal wave wake from which the angle of the internal wave wake can be estimated even if there is only one arm in the image.

2. Suppression of Natural Features

Natural internal waves produce peaks in the Radon domain and these are likely to be misinterpreted by an automatic wake arm detector. To avoid this, the detection algorithm can utilize the position of the ship and restrict detection to only those lines that pass close to the ship image. The distance between a wake arm and the ship image is affected mainly by the velocity component of the ship along the line of sight to the radar. A source of error in the displacement between the wake line and the ship is the curvature of wake lines, but most wake crests exhibit small curvature. Ship maneuvers can also cause errors due to curvature.

The cross-range displacement, Δ, of the ship image due to its Doppler shift is given by

$$\Delta = Rv/V \, , \tag{1}$$

where R is the range of the radar, V is the platform velocity and v is the target line of sight velocity. For example, using values of R=1000 km, V=7.5 km/s, and v=10 m/s, we find Δ=1.3 km. For example, with a grazing angle of about 45 degrees, this displacement should be appropriate to ships with speeds of about 15 m/s (30 knots); all wake lines should lie within about 1.3 km of the ship for most practical ship speeds.

All the lines that pass through a single point, such as the center of a ship image, map into a sinusoidal curve in the Radon domain. The radial distance of the ship from the origin in the spatial image domain provides the amplitude of the curve while its phase is related to the angle that the line makes with some fixed axis. If we wish to consider all lines within a certain distance of the ship location, they will map into the area between two sinusoidal curves on either side of that corresponding to the center of the ship.

Sometimes there are two or more ships sailing close together and it is desirable to separate their wakes. This is usually possible when the acceptance regions that surround each ship in the spatial domain are disjoint.

3. Wake Arm Extraction

Prior to the Radon transform the image is high-pass filtered. The cut-off frequency varies according to the radar image properties and is chosen adaptively. The adaptation is currently based on the mean and variance of the pixel intensity.

The Radon transform can only determine the ship heading within a range of 180 degrees. The ambiguity can be resolved by performing the transform separately over four small adjacent tiles placed so that the ship image lies centrally within the group and is in one corner of each tile. The tile containing the most wake arms is identified. This removes the ambiguity and allows another tile to be placed over the wake and a further transform to be performed. The new tile is larger and it covers a large portion of the wake. Thus the transform tends to provide a large processing gain, and the signal to noise ratio in the Radon domain is enhanced. Because the ship is typically near one edge of the tile, however, there may be false detections due to the low statistical stability of short Radon lines. Therefore short lines are suppressed.

In practice the area of the image that is transformed is predetermined, but this can be adjusted manually to match the size of the tile to the actual wake length when the wake arms are unexpectedly long or short.

False detections can be further reduced by considering the points at which wake lines intersect. To be an acceptable wake line, at least one intersection should occur within a fixed distance from the ship.

The detection process starts with a low threshold in the Radon domain and, if many line detections are made, the threshold is raised and the detection repeated, until there are less than six bright and six dark lines.

4. Wake Classification and Heading

The most common wakes are the turbulent wake and the internal wave wake, though there are often other lines probably associated with unsteady effects. If a turbulent wake is present, it is likely to provide an accurate estimate of ship heading and avoids problems associated with missing arms. A turbulent wake can be identified in the Radon domain as a cluster of contiguous dark pixels with no bright pixels within their immediate vicinity.

If a turbulent wake is found, it determines the ship heading. Otherwise the angles between lines at the outermost edge of the wake are bisected to give the heading.

5. Ship Velocity

To estimate the ship velocity, the center of the ship in the radar image must be identified. At present, this is implemented manually by clicking in a zoom box. The number of pixels separating this point from the heading vector in the cross-range direction is established so that, using the pixel spacing, (1) can be employed to estimate the line of sight velocity. The radar grazing-angle is then estimated from the published satellite parameters and the position of the ship in the image. This grazing-angle, together with the heading angle, provides all the information required to determine the ship speed.

When the heading is nearly parallel to the cross-range direction, the speed cannot be determined accurately, but if the heading is greater than about 10 degrees from this direction, observations suggest that there may be errors in speed of between 10 and 20 percent, depending on the geometry.

6. OTHER TECHNIQUES

At least two additional techniques are pertinent. The first of these involves an estimation of the (maximum) internal wave speed. The estimation can be based on models of the ocean that include the depth and strength of internal layers near the surface. In many cases the models are probably sufficiently accurate to provide at least a check on the ship speed derived using another source. The speed estimate is typically obtained from the internal wake opening angle using a formula similar to that for the angle of a Mach cone of a supersonic aircraft.

The second method is based on measurements of the wavelength of transverse waves of a Kelvin wake. Near the ship's track, the crests are perpendicular to it. Because the waves are steady in the frame of reference of the ship, the phase velocity of the transverse waves on the water is equal to the ship velocity, U. This fact can be combined with the dispersion relation for waves on deep water (i.e. $\omega^2=gk$, where ω is the angular velocity of the waves, g is the acceleration due to gravity and k is the angular wavenumber). Thus we have for the phase velocity, c [3]:

$$c = \omega / k = \sqrt{g/k} = U \quad (2)$$

This enables the ship velocity to be expressed in terms of the wavelength, $\lambda=2\pi/k$:

$$U = \sqrt{g\lambda /(2\pi)} \quad (3)$$

There are also unsteady wakes that could be used in principle to estimate ship speed.

7. PERFORMANCE

The performance of the algorithms has been studied using Radarsat images with truth from the Canadian Coast Guard (CCG). Ship and wake imagery from the Gulf of St. Lawrence and the Straits of Juan de Fuca have been extracted and heading and speeds estimated. The headings are almost all consistent with those estimated by an operator: The heading accuracy is either about ±1 degrees, totally incorrect (rarely) or indeterminate.

Table 1 provides data for three ships from the Gulf of St. Lawrence; the service speeds were found in [8], while the actual speeds were derived using data from various CCG reporting points. Table 2 shows the speeds obtained from the offset between the ship image and the wake-heading vector found from the software tool. The ship lengths were also estimated by the tool and are included.

TABLE 1
SHIP PARAMETERS

Name	Type	Length (m)	Service speed (km/hr)	Actual Speed (km/hr)
Canmar Pride	Container Carrier	244	39	41.8±1.5
Hope 1	Bulk Carrier	188	28	20.4±0.7
Turid Knutsen	Chemical Tanker	163	25	18.9±0.7

TABLE 2
IMAGE DERIVED LENGTHS AND SPEEDS

Name	Length (m)	Speed (km/hr)
Canmar Pride	200-260	36.5-41.7
Hope 1	172-240	23.2-27.5
Turid Knutsen	200-260	22.6-28.0

The data in the tables reveal that the ship lengths from the image tend to be overestimated, while the speeds are quite reasonable (noting that the CCG speeds are averaged over several hours). The range of wake-derived speeds is related mainly to the uncertainty in the ship location on the image plane; the quoted ranges correspond to setting the ship location at a variety of points within the ship image.

The accuracy of the velocity seems to be about ±15 percent for most of the images that both exhibit a clear wake and are not closely aligned with the cross-range direction.

Fig. 1 shows the wake of the Canmar Pride; there is a clear Kelvin transverse structure with a wavelength of about 78 m. Equation (3) gives a ship speed of about 11 m/s or 40 km/hr.

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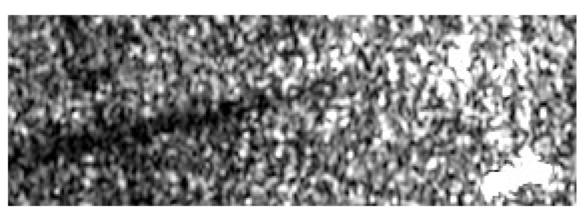

Figure 1. Canmar Pride Image and Wake.