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Imaging Ships From Satellites

BY PAUL A. MALLAS AND HANS C. GRABER

ABSTRACT. The ocean has provided an important means of commerce and transport for centuries and does so to this day. With the ocean covering roughly 70% of Earth's surface, much maritime activity occurs well out of sight of land. In addition to legitimate ocean activities, there may also be undesirable ones, such as dumping of pollutants, illegal fishing, drug and human trafficking, pirating, and perhaps even terrorism-related activities. Satellites provide a robust platform for observing shipping activities beyond shore-based sensors. Today's commercially available satellite imagery offers a variety of data types and imaging opportunities. Electro-optical systems can provide quality imagery but are useless at night or when clouds are present. Synthetic aperture radar systems offer all-weather and day/night collection opportunities, and their importance has grown in recent years. These systems are promising tools for aiding those responsible for monitoring the environment, managing ecosystems, and enforcing the law.

INTRODUCTION

Ship detection has long been of interest, initially with the goal of collision avoidance. The crow's nest was developed to address this problem, first making an appearance in the early nineteenth century (Wikipedia). In 1904, the German engineer Christian Hülsmeyer demonstrated a basic radar system for detecting ships up to 3,000 m away (Hollmann, 2007). Taylor and Young of the US Naval Aircraft Radio Laboratory (now called the Naval Research Lab) demonstrated ship detection with radar on the Potomac in 1922 (IEEE Global History Network).

More recently, low Earth orbiting (LEO), near-polar satellites, traveling at speeds of about 7.5 km s^{-1}, orbit Earth approximately 15 times daily (depending on the specific orbital parameters). Such a satellite equipped with an imaging system can provide access to global imagery with repeating coverage every few days to several weeks. Constellations of LEO satellites—groups of satellites flown in a coordinated fashion—provide global coverage with increased revisit frequency. With all of the commercial imaging systems present today, we now have numerous constellations with which to make observations of the ocean surface. It's like accessing a virtual surveillance system—the user has global reach with short revisit times. Under these conditions, the use of commercial satellites to monitor maritime activity becomes feasible.

The two primary satellite-imaging modalities are electro-optical (EO) sensors and synthetic aperture radar (SAR) sensors. EO sensors, which operate in the visible or near-visible portion of the electromagnetic spectrum (EM), have long been used on satellites to provide images such as those used by Google Earth. SAR sensors have more recently been placed on satellites and operate in the microwave portion of the EM, well outside the human visual response range. SAR images require some training to interpret. Both EO and SAR sensors have their strengths and weaknesses, as discussed below.

SHIP OBSERVABLES AND ENVIRONMENTAL CONDITIONS

The hull and superstructures of large ships provide targets for satellites. They have lines and patterns that indicate man-made objects, and they contrast with the ocean's generally random and cluttered background (Pichel et al., 2004). The structures' corners and edges strongly reflect a SAR's microwaves. Paint schemes can also affect the target's observability (but generally do not affect SAR sensor observation). Most often, the ship itself can be directly observed on an image. In some cases, wakes are easier to observe because of the satellites' overhead perspective. Given favorable environmental conditions, wakes can persist for hours and thus can be many kilometers long (Vesecky et al., 1982). On occasion, especially with a small, fast-moving vessel, a wake is clearly present in the image although no vessel is observed.

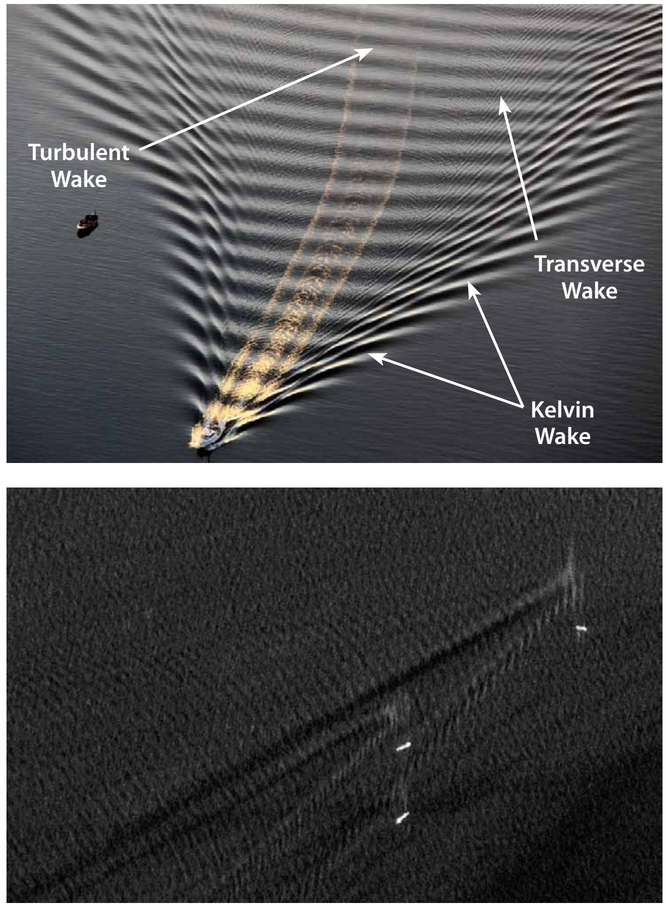


Figure 1. (top) Optical image of a ship wake showing the different wave patterns produced by a ship. The bow wave is oriented at the Mach angle of 19°28' and the transverse wake is composed of circular waves emanating from the ship's stern. *© 2009 Chris Goldberg used by permission* (bottom) TerraSAR-X image of several ships showing the same kind of wave patterns as in those in the optical image. *Note*: The inside of the left arm of the Kelvin wake is dark, indicating a smoother water surface. The most pronounced artifact is the Doppler shift of the vessel from its wake. *© 2007 Astrium Services / Infoterra GmbH*

If a vessel is underway, it is assumed that a wake will be present at some level. The amplitude of the wake is dependent on a variety of variables, for example, vessel speed, vessel size, and hull structure. Also, while the term "wake" implies a single entity, wakes are actually interactions of several different phenomena and can be quite complex in structure. Generally, a wake can consist of a Kelvin wake, a turbulent wake, and a transverse wake (Figure 1, top). The Kelvin wake may be generated by either the bow or stern of the vessel, or both. Depending on the size of vessel, the two wakes may be distinctly visible or merge into one V-shaped Kelvin wake pattern. The turbulent wake is created by the ship's propellers and creates a strip of still water directly astern of the vessel (Peltzer et al., 1987). Lastly, the transverse wake appears as waves between the Kelvin wake arms that travel in the direction of the vessel. Not all of these wake features may be observable. Also, some wake structures are symmetrical (e.g., the Kelvin wake), and it may be possible that only one arm of the wake is observable, say, the starboard arm for a given image, while the opposite side is not. The SAR image in Figure 1 (bottom) shows the same wake patterns as the optical image and emphasizes the associated roughness of the wake more strongly. Darker pixels indicate smoother water. Furthermore, the SAR image clearly illustrates the Doppler shift effect, which displaces the vessel from its wake. Complexity of the wake features can provide an interpretation challenge to the human observer, not to mention difficulty in developing computer-aided automated detection algorithms.

Environmental conditions can play a large role in the ability to observe a vessel. Winds and waves can take a normally serene background and create strong returns in both EO and SAR sensors. This situation can create "false-alarms" in the observation of

Paul A. Mallas *(pmallas@rsmas.miami.edu) is Senior Systems Engineer and* **Hans C. Graber** *is Executive Director at the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS), Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA.*

ships, making the actual ship difficult to distinguish from the background. Environmental conditions can disperse wake features. Waves can cause a vessel to pitch, creating smeared lines in SAR images.

ELECTRO-OPTICAL SENSORS AND SHIP OBSERVATION

Images from EO sensors are by far the most ubiquitous type of satellite imagery available. These sensors use approximately the same portion of the EM as the human eye so that most observers feel comfortable with the images they produce. However, these sensors have the same shortcomings as the human eye: clouds can obscure the field of view, and sunlight is required to make observations. Despite these issues, EO images have better potential for identifying ships or features on ships, they are more easily interpreted by humans, and vessels made from low radar-scattering materials such as wood or fiberglass can be detected in them. Although little research has been conducted on the use of EO sensors for ship detection (Proia and Page, 2010), it has become a topic of recent interest.

EO sensors typically come in two types: panchromatic and spectral. Panchromatic (often just shortened to "pan") sensors collect radiation over a wide band of the EM spectrum (generally from blue to near-infrared on the optical spectrum) and create a single black and white image. Spectral sensors operate over the same region of the EM spectrum as the pan sensor, but divide the EM spectrum into a number of smaller bandwidths or channels. Depending on the number of channels (or bands) used, the term "spectral" may be preceded by "multi-" (for tens of channels) or "hyper-" (for hundreds of channels). The trade-off between the number of channels in panchromatic, multispectral, and hyperspectral sensors is resolution: more bands means lower resolution. Most sensors that are practical for ship observation tend to have higher resolution and fewer bands. The remainder of this paper will focus on panchromatic and multispectral sensors.

Because panchromatic images are single-band black and white, they depend solely on structural features to discriminate the ship from the ocean background. In most cases, the ocean background is dark and the ship is brighter due to greater optical reflectivity. However, ships can be dark colored, causing the ship, or portions of it, to blend into the dark ocean background. Textures and statistics of objects in the scene thus play an important role in ship detection in panchromatic imagery. The ocean background can be modeled mathematically in the spatial realm (Jubelin et al., 2012), and this can lead to automated EO ship detection. Panchromatic imagery has the highest EO resolution and probably offers the best chance of identifying or classifying ships by type (Figure 2).

Multispectral images can introduce color to the observer and increase the contrast between the ship and the ocean background. Paint schemes may play a role in identifying or discriminating ships. Also, there are quite mature spectral analysis techniques that can be used. Spectral analysis uses all the available band data together, not as an image but as a set of spectral features. For example, say a multispectral image has four bands (blue, green, red, and near-infrared).

Figure 2. (top) EROS-B panchromatic image (~ 70 cm resolution) of a large ship and support vessels. Note the clouds in upper right corner and the cloud shadow (dark) in the lower right corner. (bottom) An EROS-B panchromatic image (~ 70 cm resolution) shows small vessels underway, jet skis in the upper half, and two small airplanes pulling banners. *©2013 ImageSat International N.V., Licensed by ImageSat International N.V.*

Multispectral analysis examines the image as a set of spectral vectors (in this case, four elements in the vector). These vectors can be used to classify and discriminate features based on spectral signatures alone (Figure 3).

A common technique for enhancing the visual interpretability of EO data is called pan-sharpening. It involves fusion of a panchromatic image with a spectral image covering the same area of interest (Carper et al., 1990). The end product contains high-spatial-resolution detail from the panchromatic data and color information from the spectral image. Care must be taken to ensure the two scenes have similar collection parameters and are registered (i.e., aligned) with high precision in order to produce high-quality output. Newer EO systems collect both panchromatic and multispectral images simultaneously, enabling high-quality registration between the two images. While processing artifacts may occur, pan-sharpened image products can provide information to identify or classify a ship beyond the possibility of each of the input images alone.

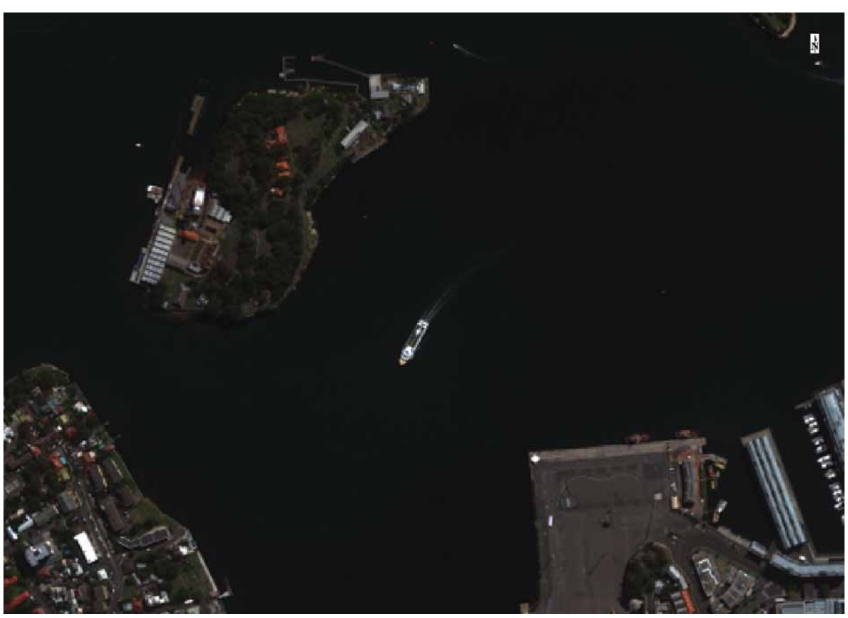
SYNTHETIC APERTURE RADAR SENSORS AND SHIP OBSERVATION

While SAR sensors are newer to the field of Earth observation than EO sensors, they have dominated the world of ship detection for more than a decade. SAR sensors are active, meaning the sensor supplies its own illumination of the target. In contrast, EO sensors are passive and require external illumination (i.e., sunlight and/or skylight). This means that SAR sensors can operate day and night. Also, because SAR sensors operate in the microwave region of the EM spectrum, they can penetrate clouds. These two strengths alone create advantages over the traditional EO sensor.

There are, of course, some drawbacks. As the "synthetic" portion of the name implies, SAR produces images that are not created through a natural process. Rather, they are created through signal processing of coherent radar pulses (see Ager, 2013, this issue for more details). The result is that the images tend to be less pleasing to the eye than a typical cloud-free EO image, and they can be a little more difficult to interpret. Some of these interpretation problems can be overcome by training and familiarity with the imagery gained over time. Also, ship detection algorithms can be used to detect and report ship locations free of human biases. This, in fact, is the current favored paradigm for detecting ships using satellite imagery.

Due to historical reasons, specific portions (bands) of the microwave spectrum are referred to by a letter designation. The most used SAR bands are L-band, C-band, and X-band. The differences between these bands are the wavelengths of EM energy employed: 15–30 cm for L-Band, 3.75–7.5 cm for C-Band, and 2.4–3.75 cm for X-Band. The practical result of these differences is how the microwave energy interacts with the illuminated area: shorter wavelengths interact with smaller objects. While this can be important for the returns from the ship target, there are greater consequences from the ocean background.

Waves are the primary scattering mechanism on the ocean surface, and they come in a wide range of sizes, from capillary waves on the order of centimeters to gravity waves on the order of



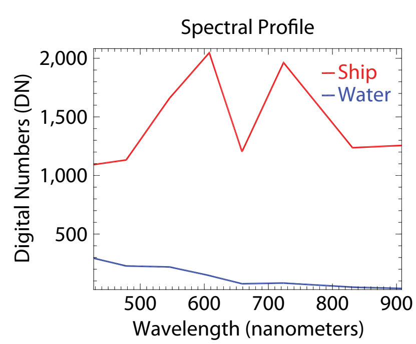


Figure 3. (left) DigitalGlobe Worldview2 multispectral image (resolution ~ 2 m). (right) Spectral response of ship target and water background. © *DigitalGlobe Inc. all rights reserved*

hundreds of meters. The background clutter in the image is the size of the waves in the scene interacting with microwave energy (Holt, 2004). Also, due to the fact that SAR is always side looking, the incidence angle used can greatly affect the background clutter present in an image. Incidence angle is a very important parameter to consider when tasking a SAR sensor, especially in the maritime environment.

Creating a SAR image requires applying signal-processing techniques to radar signals. This process assumes that the SAR sensor is moving and all objects on the ground are stationary, meaning that all of the Doppler effect observed by the sensor is due to the relative motion of the satellite with respect to Earth's surface. This is not always true, especially with regard to moving objects such as ships. The effect is that signal processing applied during image formation will shift the object from its actual position (see Figure 1, bottom). While, at first glance, this artifact is undesirable, it provides a way to estimate the ship's velocity (Zilman et al., 2004): the further the ship is from the actual position (which can be established by the wake position), the faster the ship is traveling.

One distinct advantage of SAR over EO systems is the variability of SAR collection modes. The sensor can collect in a variety of modes of different resolutions, sort of acting as a telephoto lens. ScanSAR modes have the widest collection areas and lowest resolution. The images can be hundreds of kilometers wide with a resolution on the order of 50 to 100 m. This mode is often used to detect ships due the very large area it covers, but because the ships tend to be small blobs in the image, not much structure can be observed. Stripmap mode offers higher resolution (generally 3–20 m) with swaths up to 150 km wide. Large ships can show some structure in these images, and this mode is also used for ship detection. Lastly, there is spotlight mode, which has the highest resolution (usually around 1 m) and a swath width of about 10 km. This is rarely used for ship detection, but can offer fine detail of ships. It can be used in areas such as ports or choke points, where it is very likely an observer's ship of interest is located (Figure 4).

Another factor in SAR ship detection is polarization. Polarization refers to the direction of electric field oscillation, which is perpendicular to the direction that the wave travels. The coordinate system used for these directions is horizontally (H) and vertically (V) referenced with respect to the satellite antennas. EM energy is transmitted in either H or V, and the sensor then detects returns in either the H or V direction. This leads to four permutations for transmit/receive: HH, VV, HV, and VH. HH and VV are often called "co-polarizations" because both transmit and receive directions are aligned, and HV and VH are called "cross-polarizations" due to their perpendicular transmit/receive directions.

Co-polarization modes have the strongest returns because most natural scattering mechanisms return the same polarization. The ocean tends to have stronger returns from vertically polarized incident energy, so VV generally shows the strongest ocean signal. In order to provide higher contrast with ships, HH is often chosen for ship observations. Of the cross-polarizations, HV and VH are generally equivalent due to reciprocity (i.e., they have the same information content). Cross-polarization returns result from reflections of tilted dihedral or corner-like structures. Ship structures offer a variety of dihedral features, and cross-polarizations present the strongest returns from man-made structures. Cross-polarized images show the highest contrast with respect to ocean background; however, overall image quality tends to suffer in cross-polarization images.

SAR imaging systems do not necessarily operate only in single polarization mode; multiple modes can be imaged simultaneously if supported by the sensor. Much like multispectral EO systems, multiple polarization imagery

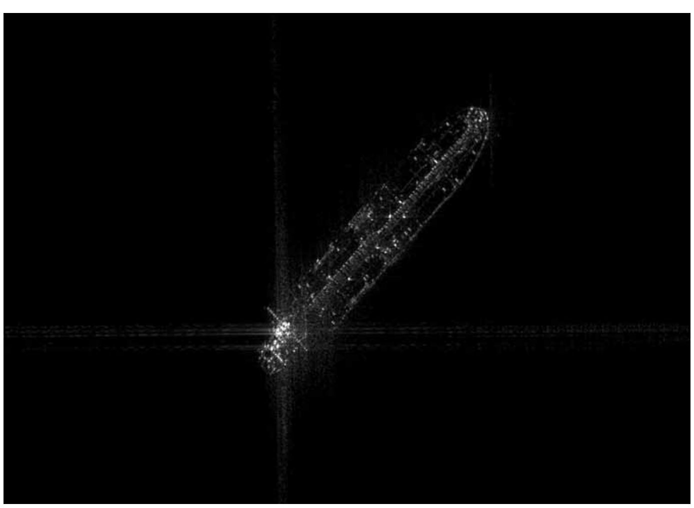


Figure 4. A COSMO-SkyMed spotlight mode image of a tanker showing the central pipeline structure, the pilot house (very bright reflector), and pump locations. *© COSMO-SkyMed™ Product -ASI 2010 processed under license from ASI (Agenzia Spaziale Italiana), all rights reserved distributed by e-GEOS*

comes at a cost of either reduced resolution or reduced areal coverage, but it offers increased richness of information. Dual polarization modes are sets of two polarizations (HH/VV, HH/VH, HH/HV, VV/VH, or VV/HV), and quad-polarization modes (Figure 5) collect all four combinations (HH/VV/VH/HV). Spaceborne polarimetric SAR sensors are a relatively new development so research into the exploitation of this type of data is also relatively new.

CONCLUSION

Ship observation from satellites is becoming an increasingly important tool in maritime surveillance. Activities such as illegal fishing or dumping at sea negatively impact the ocean and damage commerce of neighboring nations. With the current constellation of commercial imaging satellites, considerable resources are available to image and detect ships at sea. While EO sensors can provide high-resolution images that include structural and color details of a vessel, clouds and nighttime hamper this technology. SAR technology has the advantage of penetrating clouds and not requiring sunlight, but difficulties arise in visual interpretation due to the nature of the SAR imaging process. However, use of SAR data in concert with advanced detection algorithms is the primary method for detecting ships.

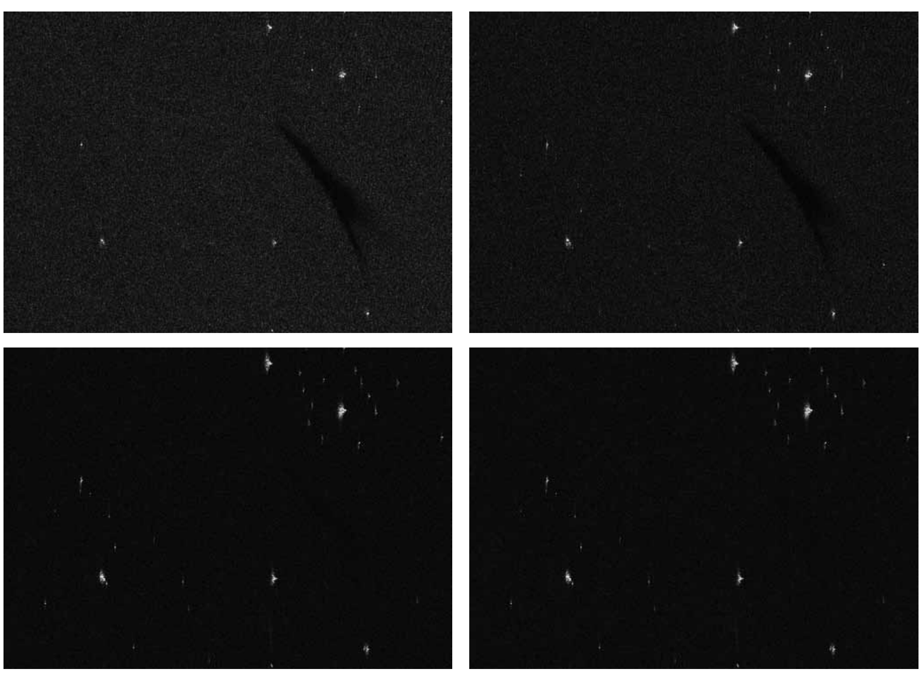


Figure 5. A RADARSAT-2 fine quad-polarization image of vessels in the open ocean. Note the dark oil slick area on the right sides of images. (upper left) VV polarization. (upper right) HH polarization. (lower left) VH polarization. (lower right) HV Polarization. *RADARSAT-2 Data and Products © 2008 MacDonald, Dettwiler and Associates Ltd., all rights reserved*

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