MOVING TARGET INDICATION IN MODERATE RESOLUTION, PASSIVE MISR SATELLITE IMAGERY

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ABSTRACT

Moving target indication – locating and estimating the velocity of moving objects – is of vital importance for both reconnaissance and surveillance. Here we describe novel data analysis methods to interpret such target detections using passive, multi-angle imagery from the Multi-angle Imaging SpectroRadiometer (MISR) instrument on NASA's Terra Earth Observing System satellite. MISR observes a 380-km swath in visible and near-infrared spectral bands with nine pushbroom cameras over a seven minute period with a single-pixel resolution of 275 m or 1,100 m depending on the band and camera. We demonstrate that sub-pixel targets such as ships can be be unambiguously identified and tracked in ocean images with a minimum detectable speed of 0.68 ms^{-1} (1.3 knots), which is more than four times smaller than similar synthetic aperture radar-based systems. MISR's multiple views further enable the estimation of target trajectory. Finally, data mining methods can be employed to produce meaningful summaries of target frequency, behavior, and changes over time.

***Index Terms*—** moving target indication, MISR, satellite imaging, data mining

1. INTRODUCTION

Target detection and moving target indication (MTI) – the task of locating and estimating the velocity of moving objects – are of vital important for both reconnaissance and surveillance. Synthetic aperture radar (SAR) systems, with their high spatial resolution, all weather, and day/night capability, have demonstrated success for target identification and ground MTI (GMTI), particularly over the ocean (e.g., [1], [2], [3]). However, spaceborne SAR systems have limitations due to their significant power requirements, relatively large antenna size, and narrow swaths (∼100 km). In addition, slowly moving targets are challenging for a single radar system, which may only be able to detect targets moving faster than about 4 ms^{-1} (7.8 knots) in the most optimal conditions [4].

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Ship detection in SAR imagery, in particular, has received a great deal of attention. A common approach is to construct a land mask, identify bright points, then search around these initial targets for wakes to improve discriminability [1]. The target detection step often employs an adaptive threshold constant false alarm rate (CFAR) approach [4]. Challenges include compensating for SAR speckle; image blurring from lack of scene coherence, which can be especially important for ocean surfaces; and azimuth image shift [5].

Here we describe a novel approach to synthesize and interpret information about moving targets over the ocean using passive, moderate resolution, multi-angle imagery from the Multi-angle Imaging SpectroRadiometer (MISR) instrument that has been operational on NASA's Terra satellite since early 2000. We provide both a theoretical analysis and an empirical demonstration that targets such as ships, despite being much smaller than the 275-m MISR red band pixel size, can be unambiguously detected in the data. This demonstration is performed via careful manual extraction, reserving the development and validation of an automated detection system for future work. In support of the practicality of the approach, we provide examples of the detectibility of such targets via image histogram analysis. Assuming some source of detected targets, whether manual or automatic, we further describe methods to aggregate and analyze this information to extract meaningful spatial and temporal summaries of target occurrence and behavior.

2. SHIP DETECTION WITHIN MODERATE RESOLUTION IMAGERY FROM MISR

Although not designed for these tasks, the capabilities of the MISR instrument make it uniquely suited for target detection and MTI over the ocean. MISR is a pushbroom imaging system that acquires visible and near-infrated imagery across an approximately 380-km-wide common swath at resolutions of 275 m or 1,100 m depending on the spectral band and camera with a georegistration better than ∼0.2 pixels (55 m) [6]. The MISR swath is relatively wide in comparison to typical SAR-based systems, providing the potential for more extensive detection and tracking. Unlike the single snapshot provided by a SAR image, every location with the common swath is imaged from nine different angles over a span of approximately seven minutes, yielding multiple estimates of target location and resultant motion that can be combined to produce more robust results. Current operational processing of the MISR data provides stereo-photogrammetric cloud-top height and motion retrievals [7][8][9].

The presence of ships within 275-m spatial resolution MISR imagery has been noted anecdotally numerous times and an example has even been published in the online MISR image gallery (https://misr.jpl.nasa.gov/images/PIA03422-AaBaCaDa_O4344_NCcoast.gif). Although ships are much smaller than a single pixel, they are bright enough relative to the ocean background to be clearly visible in MISR imagery. This is the same principle by which stars are visible to the naked eye in the night sky, even though they do not subtend any appreciable angular diameter. Detection in the MISR data is enhanced by the 14-bit image depth and the high signal-to-noise (SNR) of the instrument. Figure 1 shows four examples of ships observed in different viewing conditions from MISR. The 14-bit digital numbers (DNs), ranging from 0 to 16,383, have been manually stretched to fit into the 8-bit image range extending from 0 to 255 independently for each case. Note that the features in Fig. 1 span multiple pixels, increasing the confidence of a given detection.

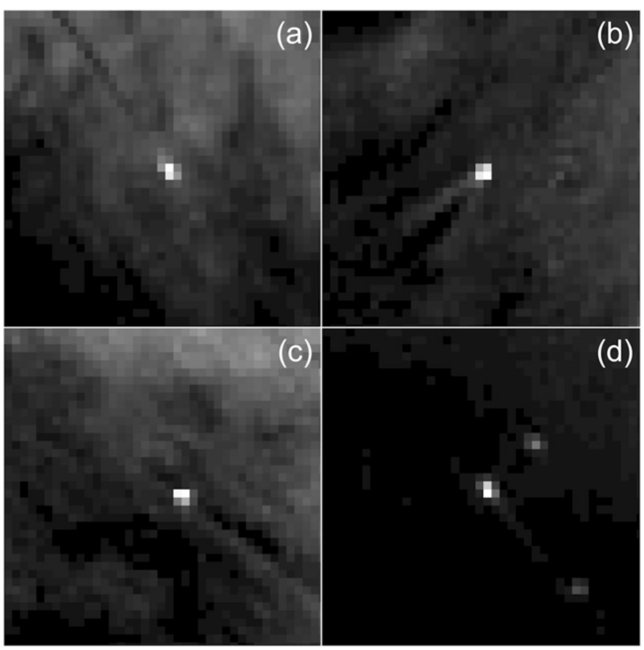

Fig. 1. Four examples of ships in dynamically stretched MISR data showing the multi-pixel features they generate: (a) Red Sea, 2 April 2003; (b) Atlantic coast off Long Island, NY, 1 April 2008; (c) Strait of Malacca, 18 August 2009; (d) three ships, Gulf of Oman, 24 February 2010.

To quantitatively assess the ability to discriminate ships from the background in these images, Fig. 2 shows pixel histograms for each of the scenes in Fig. 1. These histograms demonstrate that the pixels belonging to ships are well separated from the distribution corresponding to the ocean background. Signal-to-noise (SNR) values were determined by first fitting a Gaussian distribution to the clear ocean DN values. Based on this, the target SNR is:

$$SNR = \frac{t}{\sigma}, \tag{1}$$

where t is the DN value of the target minus the mean DN for the background and σ is the standard deviation of the Gaussian fit. In all cases, the SNR meets or exceeds the “Rose criterion” of five, which indicates that the signal is readily detectable against the background [10]. If the background is well approximated by a Gaussian distribution, the Rose criterion is equivalent to the target differing from the mean background by five or more standard deviations, which has the probability of occurring by chance of less than 0.00006% [11]. Theoretically, a specularly reflecting target as small as 1.6 m^2 is detectable in MISR imagery under ideal viewing conditions.

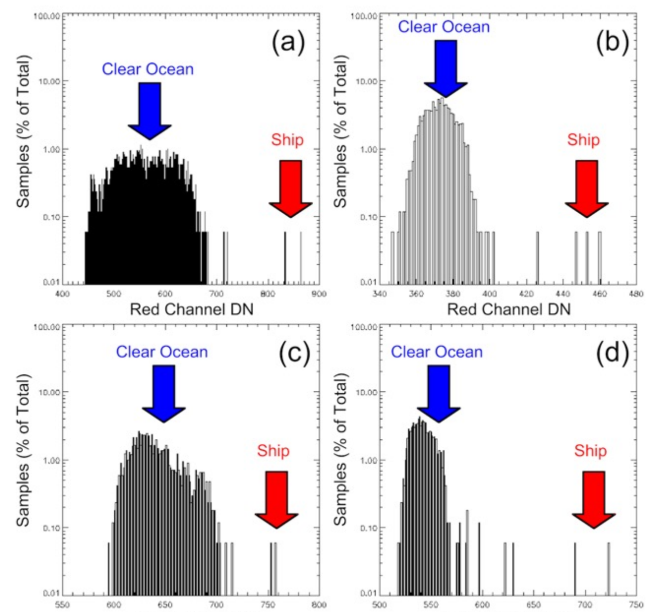

Fig. 2. Histograms of MISR red band digital numbers (DNs) for scenes displayed in Fig. 1. The SNR in decibels (SNR_{dB})is calculated by multiplying the log base 10 of the SNR by 20. Most values belong to clear ocean (low DN), with high values corresponding to ships. (a) SNR=5, SNR_{dB}=13.9; (b) SNR=10, SNR_{dB}=20.4; (c) SNR=7, SNR_{dB}=16.5; (d) SNR=18, SNR_{dB}=24.9.

3. MANUAL TARGET EXTRACTION

Subtracting the mean background values from dark ocean scenes, which can be accomplished through the application of an edge-preserving bilateral filter (e.g., [12]) and retaining the residuals, reveals rich detail contained in the MISR 14-bit data. Processing images from all nine MISR cameras in this way allows targets to be tracked manually through the image sequence, as demonstrated in Fig. 3 for imagery acquired near Cape Cod on 17 April 2008. In addition to manual target identification, quantitative information on target speed and direction can be extracted by measuring the pixel offset and taking into account the time difference between consecutive views of the scene. Since the MISR data are projected to the Earth ellipsoid, features on the ocean surface do not have any parallax, so any observed pixel shift is due to true motion [6]. The high speed and pixel "smearing" of the bottommost target in Fig. 3 indicates that it is most likely an airplane in flight.

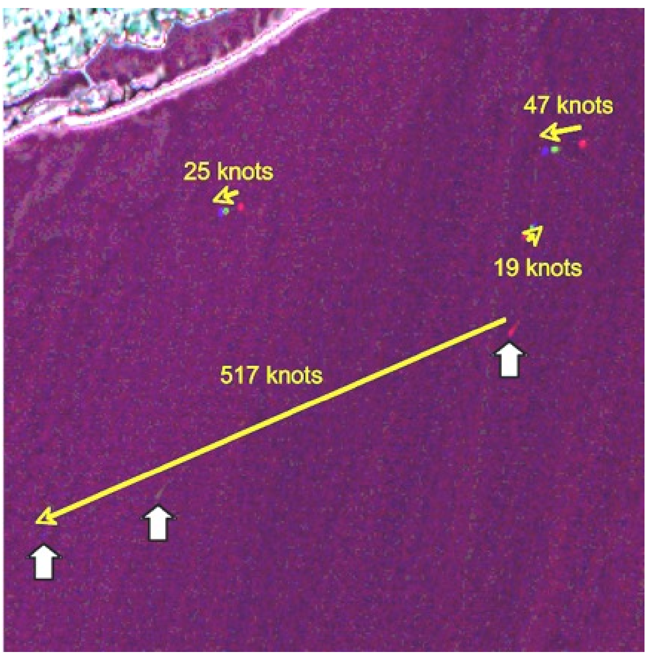

Fig. 3. Multiangle color composite [+70° (red), -46° (green), -70° (blue] from MISR images (17 April 2008) enhanced by the application of a bilateral filter. Long Island, NY, is at the upper edge of the image. Moving targets appear as sequences of red, green, and blue points. Yellow arrows (short = ship, long = airplane) indicate manually derived trajectories (speed and direction).

The uncertainty in target locations is a combination of the mean (random) error within a 275 m $\times$ 275 m region, which is 105 m, and the mean geolocation error in MISR data of 0.2 pixels or 55 m. Adding these in quadrature yields a mean location error of about 120 m. Trajectories for each target can be expressed as a heading (relative to north) and a speed in ms^{-1} or knots. The minimum detectable speed (a single pixel shift over the total observing time of 6.8 minutes) is 0.68 ms^{-1} (1.3 knots), far lower than the typical figure given for SAR-based systems of 4 ms^{-1} [4]. The uncertainty in this speed is $\pm$0.3 ms^{-1} ($\pm$0.6 knots). The typical minimum speed for an ocean-going ship is about 3 knots, which is well within the detection limit when using MISR data.

4. DATA MINING AND VISUALIZATION TO EXTRACT HIGH LEVEL KNOWLEDGE

MTI analysis of MISR imagery would ultimately yield a global catalog of targets that can be updated with every new orbit acquisition. The target catalog generated would represent a compressed view of ship activity that would consume far less space than the raw imagery while focusing attention on the observed moving target. This represents the first step in converting raw observations into useful information. However, the expected size of this catalog would still be so large that it would present a significant obstacle to human comprehension as to what such a data collection *means* in both space and time.

The next step in progressing from data to information to knowledge is to synthesize the target catalog into a map of target activity. Such an "activity map" serves two purposes: 1) it provides a high-level visualization of activity for any location and time period of interest, and 2) it enables automatic identification of high activity (spatially anomalous) regions. As a demonstration, we being with an MTI catalog, in which each target is described by its location, approximate size, speed, and direction of motion. First, using the location information alone we generate a smoothed estimate of the spatially distributed activity by applying a Gaussian filter to the gridded target frequency data. The two-dimensional Gaussian filter is given by:

$$g(x,y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right), \tag{2}$$

where x and y are the coordinates of a given location and σ is the standard deviation of the two-dimension Gaussian filter; larger values of σ generate more smoothing. To obtain the Gaussian model, we use two-dimensional kernel density estimation with a Gaussian kernel, which allows us to automatically determine the optimal value of σ for a given target catalog [13].

An example obtained with this procedure is shown in Fig. 4, which covers the Cape Cod area for a single day on 1 September 2009. Locations such as Boston Harbor, Providence Bay, and ship traffic to and from Block and Nantucket Islands are easily detectable as anomalously high activity relative to their surroundings. Incorporating additional target features from the catalog permits each location on the activity map to be annotated with the average surface target trajectory, for example.

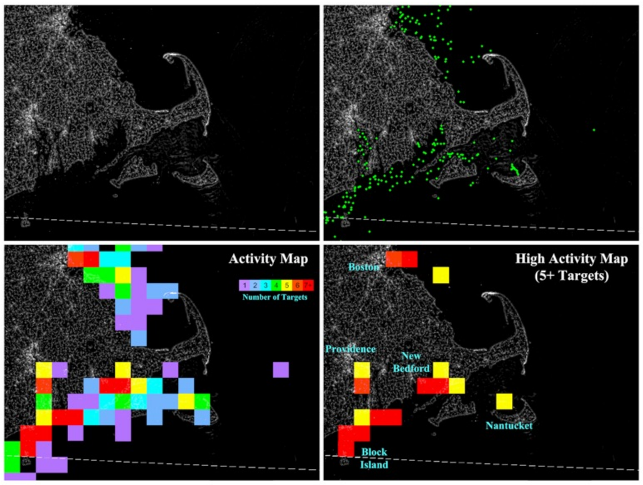

Fig. 4. (*Top Left*) MISR nadir view of Cape Cod, 1 September 2009. (*Top Right*) Moving ships identified through manual inspection of MISR imagery. (*Bottom Left*) Corresponding activity map summarizing vehicle activity. (*Bottom Right*) Summary map of highest vehicle activity (defined as more than 5 targets per region.

Having provided a synthesis of the spatial information in the catalog, the final step is to integrate the temporal aspects of the data. After generating the activity map for a given MISR orbit, the activity observed in a particular region can be compared to a model based on archived observations of the same location to identify temporal anomalies. These indicate a change in activity level (unusually high or unusually low) that point to an event of possible interest. Such anomalies can be immediately flagged for further investigation by another asset that possesses higher spatial resolution, but requires precise targeting, for example.

MISR's multi-year image data archive provides the necessary temporal information for time series analysis and the identification of long-term patterns. We do not yet have empirical results from this stage of analysis as it requires the generation of activity maps from a series of MISR observations – a product requiring the creation of an automatic MTI system, as it would be infeasible to construct so many maps manually.

5. CONCLUSIONS

We have demonstrated that sub-pixel ships can be detected in MISR passive, moderate resolution satellite observations. Data mining converts observations to intelligence/knowledge and can help inform follow-up imaging by more capable assets. There is also great potential for the expansion of this technology to accommodate other sensor types and reconnaissance goals.

6. REFERENCES

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