Automatic Ship Detection in Satellite Images

Project Summary Report 2017

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Australia is required to secure a vast area of ocean to ensure that ocean trade, vital to the economy is able to occur. The task of patrolling these oceans could be made far easier through the use of LEO (Low Earth Orbit) satellite images which are able to cover large areas in a very short amount of time. The spectral and spatial resolution of satellite remote sensing units has increased to the point where maritime targets are now clearly visible. The aim of this project is to develop an automatic target detection algorithm to locate ships in satellite images. This is achieved by analysing a number of techniques to exploit the spectral and spatial properties of maritime targets. A number of these techniques are then fused to form a single algorithm. This target detection method is highly effective when applied to Multispectral satellite images and can detect up to 98% of maritime targets 10 pixels or more in length.

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Nomenclature

LEO = Low Earth Orbit
OLI = Operational Land Imager
MSI = MultiSpectral Instrument
SWIR = Short Wavelength Infrared
MWIR = Mid Wavelength Infrared
NDWI = Normalised Differential Water Index
NDVI = Normalised Differential Vegetation Index
AWEI = Advanced Water Extraction Index
SAR = Synthetic Aperture Radar
ROC = Receiver Operating Characteristic
RGB = Red Green Blue
MGRS = Military Grid Reference System
NIR = Near Infrared

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I. Introduction

A. Motivation

Australia is an isolated island continent and as a direct consequence of this geographical position, is required to monitor and protect a vast area of ocean. A large proportion of Australian trade arrives by sea and additionally, Australia is responsible for one of the largest maritime search and rescue areas in the world. [1] The Australian naval approaches are currently monitored by aircraft and patrol vessels from the ADF and other government search and rescue authorities. Although patrol vessels are able to physically intercept and interact with ships that they find, they can take several days in transit before arriving at a point of interest and only search a small area. Patrol aircraft, can also interact to some extent with naval vessels although they are limited to some extent by their range and search area.

The emergence of remote sensing satellite technology has provided an opportunity to survey large areas very quickly. Although satellites are unable to physically interact with potential targets, the images which they provide may be able to provide a great deal of information about these targets which can be used to direct other resources as required. As sensor technology improves and is put into space, it is possible to detect, classify and track ships and other watercraft in an area of interest very quickly.

Low earth orbit (LEO) satellites have been collecting remote sensing data since the early 1970s when the Landsat program was launched by NASA. [2] Remote sensing satellites are typically placed into a sun synchronous, near polar orbit to capture consistent images of the entire surface of the earth on a regular basis. Commercial remote sensing satellites are now able to provide images with spatial resolution of 0.5m across various spectral bands. [3] Based on this we can assume that a mission launched by the government would be able to achieve similar or better performance. Ship detection is then possible. However, it relies on the development of advanced image processing and machine learning techniques.

This project focuses on developing an automatic detection algorithm for detecting maritime targets in LEO satellite images to meet the Australia’s needs for maritime monitoring and management.

B. Aim

The aim of this project was to develop an automatic maritime target detection method through the fusion of several detection techniques exploiting the spatial and spectral properties of ships and boats.

MATLAB code used for maritime target detection in multispectral, satellite images are included as an output of the project. The performance of the developed algorithm is evaluated and the limitations and capabilities of the technique are discussed.

C. Scope

This project is primarily concerned with the application of and analysis of target detection algorithms to detect clearly visible ships in multispectral satellite images.

The target detection algorithm developed is capable of working effectively in locations containing objects with similar properties to a ship and avoid detection of these false targets. For this reason, many of the satellite images used for testing will be close to shore where objects such as rocks and buildings are present.

The algorithm is designed to work with multispectral images with bands primarily in the visible and NIR spectrum, as they are low cost in collection and processing. Although there are other sensors potentially capable of detecting ships such as synthetic aperture radar (SAR), these were not considered as part of this project.

Optical images of the Earth inevitably contain clouds which may partially or completely obstruct a sensors view of a target. Although the developed detection algorithm should where possible identify partially obscured targets, the removal of weather effects in order to improve the view of a target was beyond the scope of this project.

As mentioned previously, current LEO satellites have shown spatial resolution as low as 0.5m it is safe to assume that if a maritime detection satellite were put into orbit all targets would be large enough to occupy several pixels. [3]
II. Methodology

This project has primarily used data from the OLI (Operational Land Imager) instrument mounted on the Landsat 8 satellite and the MSI (MultiSpectral Instrument) mounted on the Sentinel-2 satellites. These two sensors provide data for a number of different bands in the visible to SWIR spectrum with different spectral and spatial resolutions, this is important so that analysis can be made of different detection techniques in different image specifications. These two sources have been chosen due to their suitable data and the ease of which the data and information about the data is available. The spatial resolution of these two sensors is far worse than would be expected from a modern military or commercial imager and because of this small boats and ships did not appear in the images used. As larger ships are still be visible, this was not an issue as larger vessels still appeared as detectable targets and the algorithms ability to detect these only improves with increased spatial resolution.

A. Land Masking

Many areas likely to be selected for the application of a ship detection contain islands or landmasses. Masking the land area of an image is important as it is certain that no maritime targets will be found in this area. The land area of an image is also likely to contain a high density of potential false targets. This is because there are a vastly greater range of different objects on the land, many of which will have similar properties to a ship. This means that a land masking technique, to detect and remove large land areas from an image, should be implemented prior to applying a target detection algorithm. In order to mask the land in an image, the implemented algorithm detects the area of that image which is covered by water and then removes all of the remaining objects which are unlikely to be maritime targets based upon their spatial properties.

The identification of water in a multispectral image is possible through the use of an equation which utilises several spectral bands to highlight areas of an image covered in water. These equations are formulated based on the known spectral signature of water which is quite distinct from other objects. An example of one of these equations is the normalised difference water index (NDWI). The NDWI uses the green and near-infrared spectrum bands as shown by the formula below, this index returns a grayscale image where water is represented by areas of high intensity. [7]

\[
NDWI = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}
\]  

NDWI is simple to implement however in areas where shadowing is prevalent or in images with poor spectral resolution the results are not always accurate. There are several more powerful water extraction tools available and these may be required due to get a high quality land mask. The implemented land masking algorithm utilises another equation known as the advanced water extraction index (AWEI), the equation is shown below. AWEI has been developed more recently, this technique is more complicated and relies on a larger amount of spectral information however it is able to produce much more reliable results. The output of the AWEI is also a grayscale image with areas of high intensity representing water. [7, 8]

\[
AWEI = 4 \times (\text{Green} - \text{MWIR}) - (0.25 \times \text{NIR} + 2.75 \times \text{SWIR})
\]
A comparison between the NDWI and AWEI water index is shown in figure 1 above. Both indexes accurately highlight the water within the image quite well in this example, a clear outline of the land is visible. It is noteworthy that the NDWI image displays a lot of extra variation in the land area, this can cause areas to be falsely identified as water.

A threshold is applied to the indexed image in order to define which areas of the image are water and which are not in absolute terms. The value at which the threshold is taken requires tuning initially however as the water is highlighted quite distinctly in the image, it is quite easy to separate the water from everything else. The figure below shows an image after the threshold has been applied when compared to the original image. It can be seen in figure 2b that all areas of the image other than the water are highlighted including both the land and potential targets.

The land masking algorithm is then required to identify which of the highlighted areas of an image are land and which are not. This task is performed through the use of structuring elements. A structuring element is a shape or structure of pixels that can be used in binary image processing to determine if that structure fits into any area of the image. The land masking algorithm makes use of a disk and many line structuring elements. If any group of black pixels is able to either fit a disk of 10 pixel radius or a single line of 45 pixels in length, that cluster of pixels is determined to be too big to be a ship and is then considered to be land. The result of the structuring element filtering process is shown below in figure 3b.
After potential targets have been filtered out of an image using structuring elements, the final output of the land masking stage is a binary image where land areas are black. This mask is then applied to an image before any ship detection methods are applied, this ensures that no false targets are detected in the land area.

B. Application of Target Detection Techniques

Target detection is the identification of a particular object or class of objects within an image. In order to develop an automatic target detection algorithm, the spatial and spectral properties of the desired target must be examined to determine how the targets differ from other objects likely to be present in an image. Beyond detection, it is possible to use specific details about a target’s spatial or spectral properties or those of the terrain around it to provide further information about the target. In order to do create a target detection algorithm, the spectral and spatial properties which separate ships from their surroundings will be identified and a number of methods able to exploit these properties will be implemented and analysed. [10]

Spectral Properties

Different materials have different reflectance values for light of different wavelengths. Using spectral information for target detection involves analysing the reflectance values of each pixel at different wavelengths and classifying that pixel into a class based on the known reflectance properties of objects of interest.

Detection of ships in an image with no land or other objects is relatively easy. Calm water has a very low reflectance in all of the spectral bands we are utilising and as a result will have a very low brightness relative to ships. Due to the low reflectance of water, any features on or above the surface with a much higher reflectance, such as ships, will stand out quite distinctly.

![RGB Image](image1.png)  
![Final Land Mask](image2.png)

Figure 4 - Relative reflectance for different object classes

Figure 5 – Distribution of pixel intensity, Water vs Ship (NIR)
The chart above (figure 4) shows the relative reflectance of some different types of objects found in one particular image. The chart demonstrates that ships and other objects are quite distinct from water across the entire spectrum that is being considered. Separating ships from other objects based on their spectral signature becomes more difficult where target objects have a wide within class variation. Within class variation is due to the different kinds of objects that make up a class. The ship class for example may contain a variety of different ships, some will be wooden and some will be metal, these will have drastically different reflectance properties however these must both be identified within an image as a ship. [10]

The histogram above (figure 5) shows the intensity of a number of pixels manually selected as either ship or water pixels in the NIR band. As expected, the intensity of the water pixels is quite low making them quite easy to separate from a large majority of the ship pixels by using a threshold. In this particular example, although there is some cross over, water pixels are seen to be quite distinct from the ships in an image. It is evident however that there is a large amount of within class variation present in the ship class, as mentioned previously this may represent ships of different colour or material. This large within class variation creates a problem for target detection as there is a very wide variety of different reflectance values that may represent a true target. By accommodating for such a wide variety of true targets, a detection algorithm may also be prone to finding a large amount of false positive targets.

The OLI and MSI multispectral images that are being utilised for this project contain several spectral bands in the visible to SWIR region which can each be individually exploited in order to best allow the detection of ships. As was identified by figure 4, each band will require a unique threshold value to separate the ships from the remainder of the objects within an image. The value at which these threshold values should be set is not immediately obvious. As is seen in figure 5, there is some overlap between the intensity values of the water and ship pixels. The consequence of this overlap is that a single threshold value will never be able to perfectly separate the ships from the water or other objects in an image using a single data band in isolation. The threshold value for each band needs to be tuned in order to maximise the detection rate of the overall system whilst minimising false target detections.

This tuning process can be performed through the use of ROC curves. An ROC curve is developed by varying the intensity at which a threshold occurs and then manually identifying the probability of a ship being detected within an image and the probability of false targets being detected. Each threshold value will form a point on a curve characterising the performance of the detection method. An example of an ROC curve that was used to tune the spectral detection method for the NIR band is included in figure 6.

![ROC Curve - MSI NIR Band](Figure 6 – ROC Curve – MSI NIR Band)

Once this curve has been produced, the priorities of the desired method will need to be used to select an appropriate threshold value. In this particular case, a range of data bands will be combined together in order to form the completed spectral target detection. Due to the combination of data, it is determined that the priority of these thresholds should be to remove a large portion of the false targets. This priority has been determined as many of
the true targets that may be missed by one band are likely to be captured by other data bands, if any false targets are introduced they will negatively affect the final result. Based on this priority, the threshold used for each band is set to ensure that the probability of a false target detection is below 10% in each band.

Once the appropriate threshold has been determined for each data band, the pixels which have been identified as targets can be combined together to form one complete binary image. By adding the data directly together it can be assured that even if a ship only has a high reflectance on one area of the spectrum it will still be detected as a target. The downside of this approach is that many objects in the water that aren’t ships will be detected as targets, this is not really a problem as more methods will be used later in the application to further discriminate between ships and falsely detected targets.

An example of the output of the spectral target detection method is shown in the image above. The output of targets detected with the NIR band alone are shown in white and the targets that were detected using a combination of all of the provided MSI data bands is shown in pink. It is clearly evident that the use of one band alone is not sufficient to detect all of the possible targets and that by utilising several data bands a much more accurate result is able to be achieved.

Spatial Properties

The within class spectral variation of different ships makes the separation of ships and other objects within the ocean impossible with spectral information alone. Having separated the targets likely to be ships from those which are not ships using spectral information alone, the spatial properties of the desired targets can be utilised to further remove a large amount of false targets from an image.

Although there a wide variety of ship and boat sizes it is possible to quite easily place an upper limit on what would be considered to be a reasonable size of a ship. This target detection method uses the surface area of detected targets and their length to filter out false targets.

By using the MATLAB region properties function on the binary output of the targets detected using spectral properties, it is possible to see each detected object as a separate entity and view some properties about that object including the total area in pixels. By inputting the spatial resolution of the image being used, the surface area of the target can easily be determined as each pixel will represent a known area. For the case of a sentinel image each pixel has a spatial resolution of 10m and thus represents an area of 100m². The largest ships in existence have a deck area of just over 31000m². In order to account for situations where multiple ships are sitting against each other however, a circumstance which has been observed in multiple images, the upper limit for detected target deck area is set at 55000m². All objects detected with an area greater than 55000m² are ruled out as possible targets.[15]

The second test of target spatial properties is the use of structuring elements to eliminate all targets with a length which is longer than 450m, the reverse of what was done in the land masking section of the code. The length of 450m is set based on the length of the longest ship known to have existed.
A user of this target detection method will be able to further tune the spatial filters in order to detect targets more applicable to their situation. An example of this may include placing upper and lower limits on the detected surface area of detected targets to roughly match that of a particular type of ship which they are looking for.

**Edge Detection**

The reflectance of a ship is almost always vastly higher than that of the water which surrounds it in all of the data bands in the visible to SWIR region. This large difference in reflectance causes a large discontinuity in pixel intensity to appear around the edge of a ship in an image. An example of such a discontinuity in an image is shown below in figure 8.

![Figure 8 – An example of a discontinuity in an image](image)

A number of mathematical methods have been developed to find discontinuities in an image, this process is known as edge detection. Due to the homogenous nature of the ocean environment and the sharp discontinuities likely to exist between a ship and its surroundings it was determined that edge detection is an effective method of detecting ships in an image. A variety of edge detection algorithms exist and for the most part these pass a kernel over an image looking for certain conditions in a small group of pixels which it defines as an edge. By trialling a number of different edge detection methods with the target detection algorithm, it was observed that Sobel edge detection was able to produce superior performance to that of the other methods available.

After sharpening each of the given data bands and then applying Sobel edge detection to them, the discontinuities present around the border of a ship appear in the output as a high intensity pixels. By thresholding this output, the detected targets will be highlighted. An example of the output for this stage is shown below in figure 9b.
Data Fusion

The methods of target detection that have been implemented above have their own significant flaws, however once these methods are combined a far more accurate detection result can be obtained.

In the application of the techniques so far, the methods have been tuned using ROC curves so as to ensure that a very large proportion of true targets are highlighted and this consequently results in a large amount of false target detections.

For detections through the spectral properties, as the reflectance value thresholds were set quite low, shallow areas of water often show as a false target. On the other hand, for the edge detection method, many small reefs and rocks around the edge of land are picked up as false targets.

To combine these methods I have determined that the best technique is to filter out targets by requiring that they are detected by the spectral detection method, the edge detection method and also fall within the spatial filter. The performance of this method will be further analysed below however it is immediately evident that this fusion of the above techniques has produced much greater performance than could be achieved with any of them individually.

C. Data Output

In order for the ship detection method to be of maximum use to a potential user, some information about the detected targets that may allow for further classification is also returned by the code. In particular, the target detection method returns the geographical location of a target and its detected surface area.

The geographical coordinates of a target can be returned based on the metadata that is provided with the image being used. The method I have used is based on the MGRS location which is provided with MSI images. Although this information may not be available to the user with a different image, the method can be adjusted to utilise the information that they are provided with. MSI images each occupy one square of the MGRS, each tile in the MGRS is 100km x 100km square on the Earth’s surface. This MGRS tile covers a small enough area that by using the coordinate points which mark each corner of the tile occupied by the image, a simple linear approximation can be made based upon where in the image a target pixel is located. This approximation is shown to output correct geographical coordinates within 10m of the actual target on the Earth’s surface. This method could be improved by accounting for the curvature of the Earth’s surface if required.

The surface area of the detected target is returned based on the spatial resolution of the image and the number of pixels that a target is detected to occupy.
III. Performance Analysis

In order to test the target detection method, a selection of different scenes from five locations around the world were run through the method. The testing images that were chosen represent a wide variety of the possible scenarios that a ship detection algorithm could face. The images included many different types of land mass from small rocks to large islands, a number of different water depths from ranging from deep ocean to shallow ports and a very wide variety of different ships. The data which was used to analyse the performance of this method over the test images included covered over 150 potential true targets. A selection of some of the testing images used is included below, the targets which have been detected by the method are highlighted in a yellow ring.

![Figure 13 – Target Detection method applied in various test locations. (a) Darwin Harbour (b) Singapore Site 1 (c) Singapore Site 2 (d) Istanbul (e) Singapore Site 1 (f) Singapore Site 2](image)

The performance of the method with regards to the detection of true targets was seen to be quite high. Over the 150 possible true ship targets that were visible to a human operator in the testing images, the method recorded a 90% detection probability for a ship longer than 6 pixels in length and a 98% detection probability for ships over 10 pixels in length. The MSI images used have a spatial resolution of 10m per pixel and thus this method can be used within these images to reliably detect targets greater than 60m in length, the effect of the resolution of the image on the detection performance will be analysed in a later section of this report.

The targets considered to be true targets in this analysis are only ships and boats in the open water. Ships that are moored to land are often surrounded by similar looking objects and a land mass, this means that the detection of these ships is very difficult and my method was only able to detect these ships on a rare occasion.

Although the method was quite good at detecting ships there were some possible true targets missed by the method. The ships that were most commonly missed by the target detection method were generally either stationary or slow moving in nature and almost always appeared dark in colour and blended in to the water around the ship. A moving ship creates a wake of turbulent water around itself, this water has a higher reflectance than stationary water and appears to make a ship look much larger than it actually is making it easier for the spectral method to detect. Slow moving or stationary targets do not have this wake and are thus more commonly missed by the spectral detection method. An example of some small, stationary targets that are missed is shown in figure 13a. Ships that appear dark in colour often appear to blend into the water around them. By blending into the water, the edges of the ship are often less defined and more difficult to pick up through edge detection.
The most common error noted in the output of the ship detection method was a high prevalence of falsely detected targets. This ship detection method has been tuned through the use of ROC curves so as to ensure that true targets are almost always detected however this has had the trade-off effect of increasing the probability of false targets appearing. False targets were not reliably detected in every test image but rather they were only found in very specific circumstances that may or may not appear in a given image, the most commonly occurring of these were small islands and clouds. The small islands that were detected were always small in nature, usually the size of a large container ship. These islands feature much higher reflectance than the ocean around them and this causes them to be picked up by the spectral detection method as possible ships. An example of islands being detected as a ship is present in figure 13b. As a future development, it may be possible make use of a vegetation index to remove some of these falsely detected islands. The removal of clouds in an image is was beyond the scope of this particular project however implementing a cloud masking or removal process would allow for vastly superior performance in images containing clouds. An example of clouds registering as a false target is provided in figure 13f.

Spatial Resolution Significance

An important metric for considering the performance of this target detection algorithm is to compare the likelihood of a target being detected with the size of the target relative to the pixels in the image. As the resolution of an image is decreased, potential targets will be represented by a smaller number of pixels. As the pixels of the target become larger, they blend with the surrounding objects and it becomes vastly more difficult to detect them. To graph this behaviour I chose a large area of a high resolution sentinel image and gradually reduced the resolution and graphed the probability of target detection. It can be seen quite evidently in figure 14 that where a pixel makes up less than 15% of the length of a ship, the probability of target detection is fairly constant and is above 95%. Where a single makes up more than 20% of the length of a ship, the performance of this method is seen to drop off dramatically.

Spectral Information Significance

By reducing the number of input data bands it was possible to observe the overall importance of each band on the overall performance of the system. It was observed that by far the most significant band to the detection performance was the NIR and SWIR bands. The least important bands that were analysed were blue and red, this is because ships are less separable from other objects in these bands.

The target detection method is capable of operating with less bands of reflectance data however the Green, NIR, SWIR and MWIR are all vital in order to be able to conduct land masking on the images. It was noted that as the number of data bands provided was reduced, the number of false targets detected was greatly increased and the probability of detecting a true target was modestly decreased. The removal of data bands was seen to be less significant to the detection performance than the reduction of spatial resolution as tested in the above section.
IV. Future work

There are several areas of this target detection code which could be further developed in order to either improve the performance of the target detection or to specialise in working for different kind of images or applications.

The primary areas to continue the development of this detection method to improve performance would be through further removal of false targets within the image. As was mentioned in the performance analysis section, the major shortcoming with the target detection method is the high probability of false target detection when operating in areas where small islands, rocks or clouds are present.

In order to remove false targets that are present in these results work should be dedicated to the improvement of the land masking technique and the development of a cloud masking or cloud removal method. The detection of smaller islands could be attempted through the use of a vegetation index such as NDVI which would be able to identify all of the islands containing vegetation. An alternative to this could involve further analysis of the spatial features of detected targets, ships have a distinct straight rectangular shape with either a point or curve at one end. A detailed structural element may be able to identify objects with this ship like shape to remove other false targets.

With the current development of the RAAF satellite program, there may be an opportunity to utilise aspects of this project to aide in the development of their maritime target detection capability. The sensor on the RAAF satellite to be used for ship detection is panchromatic rather than multispectral which this target detection method has been designed to work with. Although the use of a panchromatic sensor inevitably means that some parts of this project are not relevant, there are certainly significant aspects that will be able to be applied.

The biggest problem which the lack of spectral information would present to the application of this method in a panchromatic image is with regards to land masking. The Land masking technique used in this report relies on four bands of spectral information to mask the land in an image. An alternative method to mask land in a panchromatic image may be to use a geographical mask based on an accurate map of all islands in the area required. This technique may actually improve upon the technique used in this project as it has the opportunity to remove the biggest source of false targets if implemented correctly.

The application of a single band threshold, spatial techniques and edge detection could all be implemented in panchromatic images to provide the RAAF satellite with target detection capability. Although the threshold method would be unable to produce the highly accurate results seen in multispectral images, it is likely that with an improvement in spatial resolution, the capabilities of edge detection and spatial identification would further improve and possibly offset the drop in performance.

V. Conclusion

Through application and fusion of several target detection techniques exploiting the spectral and spatial properties of a ship, a highly effective automatic target detection algorithm has been developed for use in high resolution, multispectral satellite images.

The target detection method developed has proven to be very reliable with regards to the detection of true targets, where the detection method is applied to targets greater than 10 pixels in length there is a 98% detection probability.

The major shortfall of the developed method is the presence of a large number of false targets in certain areas where objects that are similar to a ship are present. The primary area for future development on this target detection method should aim to address this shortfall through the methods discussed.
References


