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A Simple Offset "Calibration" Method for the Accurate Geographic Registration of Ship-Borne X-Band Radar Intensity Imagery

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ABSTRACT X-band radar remote sensing of the ocean surface using ground-based installations and radar intensity imagery is a mature technology for the determination of ocean wave properties. In order to transition the analytical methods to data collected from a moving vessel the accurate geo-registration of radar images must be performed. However, finite offsets in azimuth, range and time are generated by the physical installation of equipment aboard a vessel that may not be measurable. This paper details a simple, yet robust method to "calibrate" data recorded by an arbitrary equipment installation to allow accurate geo-registration of the radar imagery. Time-integrated radar images are generated using a set of time-stamped radar intensity images and high-frequency, high-accuracy vessel heading and position information (from global satellite navigation systems and inertial navigation systems). The time-integrated image sharpness is found to be maximal for correctly determined angular, range, and time offsets. The requirements to form an operational system from the proposed method are also discussed.

INDEX TERMS Radar remote sensing, radar imaging, calibration, sea surface.

I. INTRODUCTION

Ground-based X-band radar using intensity imagery is an established tool for the remote sensing of the sea surface through primary determination of ocean wave spectra [1]–[3] and utilizing this spectral information to determine bathymetry through wave-inversion techniques [4]–[7] and near-surface currents through the Doppler shift of directional wave spectra [6]–[8]. Wave-inversion has been demonstrated to work with radar data recorded from a moving vessel for the determination of bathymetry [9], [10] and surface currents [10] as well as estimates of surface elevation [11], sea state [12], directional wave spectra [13] and wind fields [14]. The capabilities of shore based radars for depth and current mapping are well documented, but these systems are inherently limited to line of sight and limited range, usually of the order of 4km. If the same methods can be applied to data from moving vessels, there is potential for a single system to cover a vastly greater area and avoid the blind spots inherent in static systems. For example, if a pilot vessel, tug or port survey vessel were to be equipped with such a system, it could be returning almost continuous updates from entire port operation areas – perhaps monitoring the evolution of sandbanks adjacent to navigation channels. Such systems could also be used for rapid assessment of hurricane or typhoon damage in order to guide more detailed high resolution surveys conducted using the limited resources of conventional survey vessels.

The primary problem associated with transitioning ground-based radar techniques to ship-borne use is the accurate frame-by-frame geographic registration of the digitised radar images. To achieve this, accurate (and frequent) position and heading data for the vessel must be obtained. It is common practice to use multi-antenna Global Navigation Satellite Systems (GNSS) and Inertial Navigation Systems (INS) to record accurate positional and heading data at high temporal resolution. However, the physical installation and mounting of such systems can introduce an unknown (*i.e.*, not routinely or simply measured) angular offset between the GNSS/INS unit, radar transceiver and the vessel's true 'bow up' heading.

As the vessel is in motion any recorded sea echoes must originate from consistent points in geographic space; *i.e.*, the movement of the vessel (horizontal motion or changes in heading) must not affect the recorded geographic position of a sea echo between successive frames. This is a similar problem as is faced in Synthetic Aperture Radar (SAR) or Synthetic Aperture Sonar (SAS) signal processing. In order to generate a clear, high-contrast SAR or SAS image every recorded signal must be accurately and consistently geo-registered.

Three principal, systematic offsets are here identified that need to be known in order to accurately geo-register marine radar data using an accurate GNS/INS system for positional and navigation data.

- The azimuthal alignment error α (unit degrees): The angular offset between the radar transceiver 'North marker' (often generated by a reed switch in the transceiver housing), heading of the GNSS navigation unit and the true 'bow-up' heading. This is generated by the physical mounting of the radar transceiver and GNSS unit in relation to the vessel's bow.
- The start range error β (unit m): The error in the distance from the antenna of the first range bin in the digitised data. This is generated by finite electrical transmission delays along the radar cable between the up-mast transceiver and the down-mast processing unit.
- The system time error γ (unit s): The total time delay generated by the communication of data between processing units, the analogue to digital converter (ADC) and any miscellaneous, computing-induced time delays between the true recording time and the image timestamp. If using a personal computer (PC) to record and log the radar images and the PC is not connected to a system time correction server (*e.g.,* via internet) then the most important component of the time error may be an incorrect PC system time.

Correcting for these principal offsets creates geo-registered radar imagery that is clear and stable enough to perform wave inversion techniques. However there are a number of physical effects that can generate additional offsets that are neglected in this paper. These include:

- The horizontal offset between the mounting of the radar transceiver and the GNSS navigation antenna. This could be of the order of tens of metres on a large vessel and would introduce an offset between the radar image centre and the vessel's true position as well as a variable error in the true echo position due to the lever arm moment caused by the transceiver offset.
- The pitch, roll and heave of a vessel will affect the true point of intersection between the radar beam and the ocean surface compared to the assumed 'flat' condition. This will result in an error in the geographic coordinates of each pixel and will be variable depending on pitch and roll angles, pixel azimuth and the position of the radar transceiver relative to the vessel's centre of mass/rotation. The error is expected to be small (especially for large vessels with reduced pitch and roll movements) but could become important for small craft and high sea states. However this method is designed to 'calibrate' a vessel's radar system when in range of coastal structures such as a port (discussed later) so high sea states are considered less important for consideration.

Reference [10] calculated the alignment error α by adopting the calibration methods of [15] developed for ship-borne Acoustic Doppler Current Profiler (ADCP) measurements. The method requires the determination of radar-derived near-surface current components (via wave inversion techniques) during a period of vessel maneuvering. The method has been shown to be highly effective, however individual estimates of α are dependent on accurate determination of near surface current vectors and therefore tend to be noisy [10], requiring averaging across a number of estimates. The requirement for the use of sea clutter wave inversion techniques also requires the presence of adequate sea clutter (and therefore wave height and wind speed). There are no published methods for determining the start range and system time errors β and γ, leaving trial-and-error as the present solution for the determination of these parameters. For ground-based radar installations this trial-and-error approach may be satisfactory as it technically needs only to be performed once per installation. However for unknown vessel equipment installations and the potential for frequent equipment changes this approach will be prohibitively time consuming. Additionally, the accuracy of trial-and-error offset determination is dependent on the time applied to the problem. An automated, accurate method is therefore required.

As wave inversion using ground-based marine radar intensity imagery is a mature technology there remain significant opportunities expanding the approach to vessel-borne data. However a simple and robust approach is needed to derive these offsets that are critical for accurate image geo-registration. The method presented in this work for the determination of α, β and γ avoids the need for physical parameters (such as wave spectra or surface current components) to be derived from radar intensity imagery, instead relying on accurate position and heading information (from GNSS/INS) and a simple, yet robust, image processing technique. The robustness of the method lies in the SAR-type images that are generated as a result: clear, sharp, time-integrated images can only be generated if the geographic coordinates of each pixel in each recorded frame are accurate and stable as the vessel moves.

II. METHOD

The new automated calibration algorithm is based on the concept that echoes from static targets (*e.g.,* radar marker buoys, sea walls, land clutter from buildings, saltmarshes, *etc.*) must remain in the same position on a geo-referenced radar image even after an arbitrarily large number of sequential scans while the scanning origin (the radar) is both in motion and its reference azimuth (the heading of the vessel) is changing. As the vessel manoeuvres the position of an echo becomes steadily less correct as the errors in geo-referencing are cumulative with the reference point in motion. This apparent motion of static targets can be minimised with prior knowledge of their origin. However it is also possible to quantify their 'static-ness' using simple image processing techniques.

Firstly, each digitised polar-coordinate (azimuth-range) image S_p is converted into a geo-referenced Cartesian coordinate (*e.g.,* OS Grid or UTM) image S_c using high-resolution position and heading information, e.g., from a multi-antenna GNSS/INS system. In this case the Cartesian conversion is performed using a simple but robust bilinear interpolation. Next, a 'synthetic aperture' image I is constructed from an arbitrarily large number n of sequential Cartesian image scans S_c so that

$$I = \left[\sum_{S=1}^{S=n} p\left(S_c\right)\right]\frac{1}{n} \tag{1}$$

where p is the intensity of each pixel in scan S_c and has Cartesian coordinates x, y. Note that each pixel $p\left(S_c\right)$ is averaged independently of others. I is therefore a time-integrated image of a set of n scans in geographic coordinates. The visual sharpness F of image I will be determined by the stability of static targets over the number of scans and can be defined as the variance of the two-dimensional image gradient so that

$$F = Var\left(\frac{dp\left(I\right)}{dx} + \frac{dp\left(I\right)}{dy}\right) \tag{2}$$

The sharpness F is therefore maximised when the variance of gradients across static targets is maximised. This occurs in a visually sharp image as transient targets (*e.g.,* sea clutter) will average out over n scans to give a low pixel intensity whereas static targets will produce a high pixel intensity that in a sharp image has well defined edges. Therefore in a sharp time-integrated image the number of well-defined edges is low compared to the number of poorly defined edges (from sea clutter), producing a high F value.

The new calibration algorithm acts to maximise F by applying calibration offsets and generating image I through an efficient search path. The approach assumes that the three calibration offsets are not covariant and have an order of relative importance to image stability: Angle α, range β and time γ. There may be a degree of co-dependency between the angular and range offsets and their effect on F, although the effect is minimal and is discussed later. The method works using the form of image artifacts caused by incorrectly assumed offsets – i.e. we assume that a perfectly calibrated system will display no artifacts. Azimuthal errors cause smudging and blurring of image I, range errors cause individual pixels to appear to move in two ellipses as the vessel moves past (forming an 'x' in the SAR image) while time errors cause rotational and linear blurring (if the error is large and dependent on the vessel motion). The method works if the artifacts can make an appreciable effect on F_{max} to be picked up as a peak and as azimuthal errors are found to produce the greatest errors in pixel location (and therefore image 'smudging') they need to be solved first in order to find the effects of more subtle artifacts caused by range and time errors.

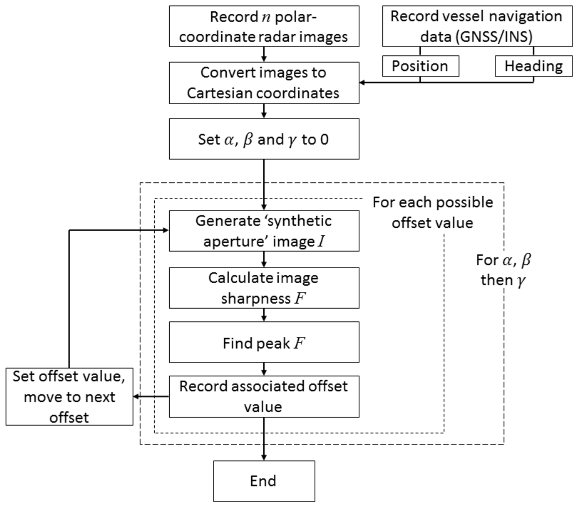

FIGURE 1. Flowchart of the algorithmic process of offset calibration.

Fig. 1 shows a flowchart of the algorithmic application of the proposed method. The program begins with all offsets initially set to equal zero, searches for an optimum value of α and then uses this offset value (with the other two initially set to zero) when gridding images S_c for the second pass to search for the optimum value of β. This process is repeated for the final pass to find γ, with the previously found values for the other two offsets and γ initially set to zero. In this way, the maximum image sharpness F_{max} should increase over each of the three passes in the program, with the maximum possible value of F_{max} found when all three offsets have been optimally determined.

In principal the calibration method requires an arbitrary number of intensity images containing static targets to function correctly. However the accuracy of the process to search for F_{max} is weakly dependent on the number of images provided to the algorithm as well as the relative proportion of static targets to sea in the total gridded area. The implications of the quantity and quality of input data on offset determination are discussed in a later section.

To test the new calibration algorithm a sample radar intensity image dataset was selected, recorded by the Natural Environment Research Council (NERC) research vessel RSS Discovery upon leaving port in Southampton U.K. and travelling South-East through the Solent at a speed of 10 knots. The sea state at the time was very low (WMOg sea state 1–2). The RSS Discovery is equipped with an non-gcoherent 10kW Furuno X-band radar operating on short pulse (50ns) for scientific purposes (separate from the navigational radar), with the transceiver and 1.8m horizontally-polarised ('HH') antenna (providing a 3dB beam-width of 1° in the horizontal and approx. 20° in the vertical) installed approximately 30m above the waterline on the ship's instrumentation tower. The raw radar intensity data were captured and digitised at 30MHz and 12bits by a WaMoS II (OceanWaveS GmbH) radar computer and compressed to polar coordinate images with a pixel resolution of 0.3° in azimuth and 5m in range.

The digitizer was set to record images out to 2km range with an antenna rotation rate of 2.4s (25 rpm) in records 64 images in length. 14 image records were selected providing a total of 896 images in the sample set. The bilinear, nearest-neighbour Cartesian image interpolation was performed to a 20m pixel size to perform the calibration routines and a 5m pixel size for imagery to visually inspect the results.

A second dataset of 512 images recorded as the Discovery sailed through the Sound of Mull, Scotland, was also obtained to demonstrate the image stabilisation effect possible with correctly determined offset variables. In this data set the Discovery was sailing at approximately 12 knots and the sea state was low to moderate (WMO sea state 3).

III. RESULTS

Fig. 2 shows the output of the new calibration program from the test image dataset of the Solent and the port of Southampton with the order of the calculated offsets proceeding from top to bottom. In each subfigure the maximum sharpness F_{max} is presented and is seen to increase between each calculated offset to a maximum value of $F_{max} = 1139$ when all three offsets have been determined. It can be noted that the increase in F_{max} due to a correct value of γ is less pronounced than for either of the other offsets. This is primarily due to the motion of the vessel at the time the data was recorded; as the Discovery was performing little manoeuvring while sailing through the Solent (holding a steady course) the difference in heading a few seconds either side of the true time is small. The primary manifestation of an incorrect value of γ (and therefore an inaccurate time recorded in the radar file) is an error in position and heading, dependent on both the speed of the vessel and its rate of turn.

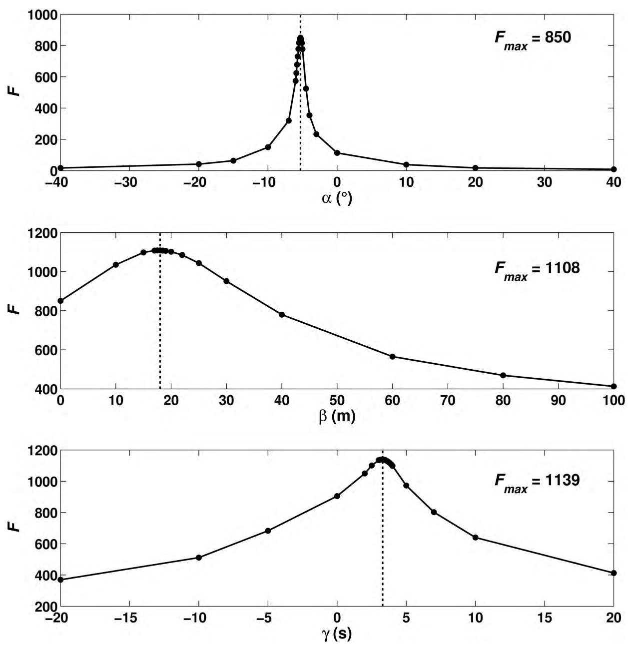

FIGURE 2. Variation in the total image sharpness F for the angular α (top), range β (middle) and time γ (bottom) offsets. The maximum F value is denoted by the dotted black line and its value is shown.

A major component of γ may be an incorrect system time if using a PC to record and log the radar imagery. From the authors' experience this time error can be of the order of minutes; generating a significant error between the recorded time of image capture and the navigational data. The problem that leads to such large time delays is that being on a vessel the data-logging / processing computer may not have direct access to network time servers to keep the PC clock up-to-date (PC clocks gradually drift over time). Therefore the high frequency GNSS position fixes, if accessed from a separate file, may correspond to a radically different time to the time-stamp logged on the radar imagery. This is less of an issue if the GNSS positions, times, *etc*., are logged on the radar files themselves, but does not preclude delays in the ship's data network delivering the information to the PC. If the PC is linked to a time standard there are still likely to be differences of the order of up to a few seconds between the time that position fixes are logged and when the vessel was actually at the logged position; especially if the vessel is moving at speed. It is highly recommended that steps are taken to remove this particular time offset separately as large values for γ will manifest as severe errors in vessel heading.

Fig. 3 shows a visual representation of the offset calibration process with four subsets of time-integrated image I (centred on Fawley oil refinery) in Cartesian UK Ordinance Survey (OS) coordinates at 5m pixel resolution. Each of the subset images shows the effect of correctly determining each offset on the quality of the stabilised imagery generated from the moving vessel, both visually and with the F value of each image. Subset A shows the effect of all offsets set to zero, B a correct value for α only, C a correct value of α and β and D correct values for all three offsets. Clearly visible in the stabilised imagery are the structures associated with the refinery (including the circular gas tanks), vessels docked at their berths and channels within the saltmarshes. An image such as this would not be possible from a static radar as only one aspect of the targets would be illuminated; as the Discovery sailed down the Solent the radar was able to illuminate different aspects of each target, rendering their shape clearly (*e.g.,* the circular reflection patterns of the gas tanks at 104.9km N, 445.5km E). Fig. 4 shows the same image subsets as Fig. 3, centred on the Hythe marina at 5m pixel resolution. Here the effect of each successively optimised offset can be clearly seen in the targets associated with leisure vessels moored in the marina (107.5km N, 443.5km E). The combination of a fine pixel resolution and the stability afforded by the calibration method allows the identification of not only individual boats moored in the marina but also which berths are occupied (brighter, high-magnitude echoes) and which are unoccupied but marked with a buoy (low-magnitude targets).

Fig. 5 shows a 'synthetic aperture' time-integrated image at 5m pixel resolution created by the described calibration method, generated using data recorded by the RSS Discovery as it sailed out of Southampton down the Solent. The offsets used to create this image were determined using the data used in Fig. 2. This image serves as an example of the detail

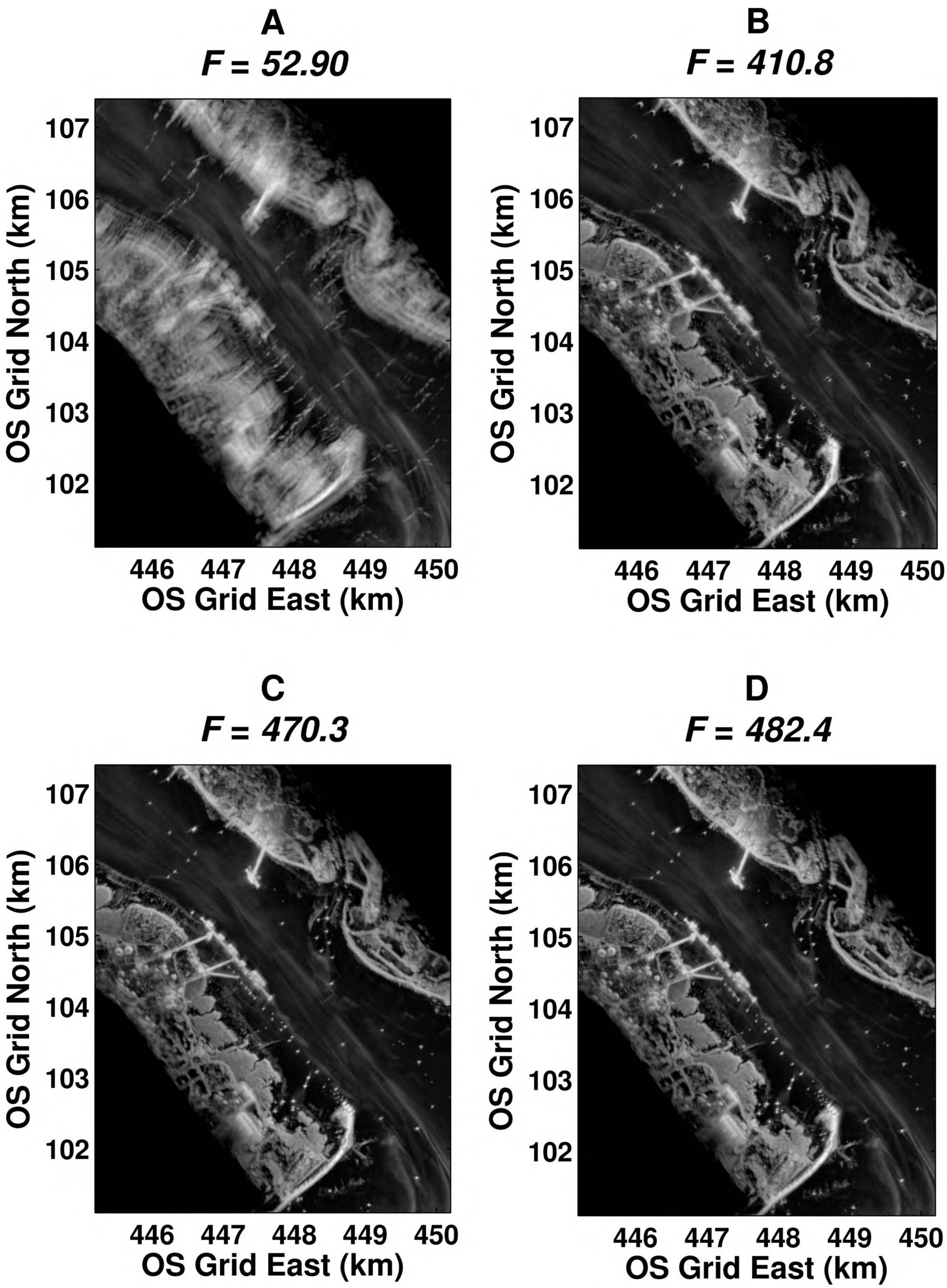

FIGURE 3. Time-integrated images and their associated *F* values generated during the calibration process using data recorded as the Discovery sailed through the Solent, centred on an area around Fawley oil refinery. Image A shows the effect of all offsets set to zero, B a correct value for α only, C a correct value of α and β and D correct values for all three offsets.

inherent in marine radar imagery; much of which is routinely discarded by plan position indicator (PPI) devices.

Fig. 6 shows a 'synthetic aperture' time-integrated image generated from data recorded by the RSS Discovery in the Sound of Mull, Scotland using the same offsets as used for Fig. 5. Due to the wide vertical 3dB beam-width of the antenna (approx. 20°) much of the vertical relief of the cliffs on either side of the Sound are illuminated, producing

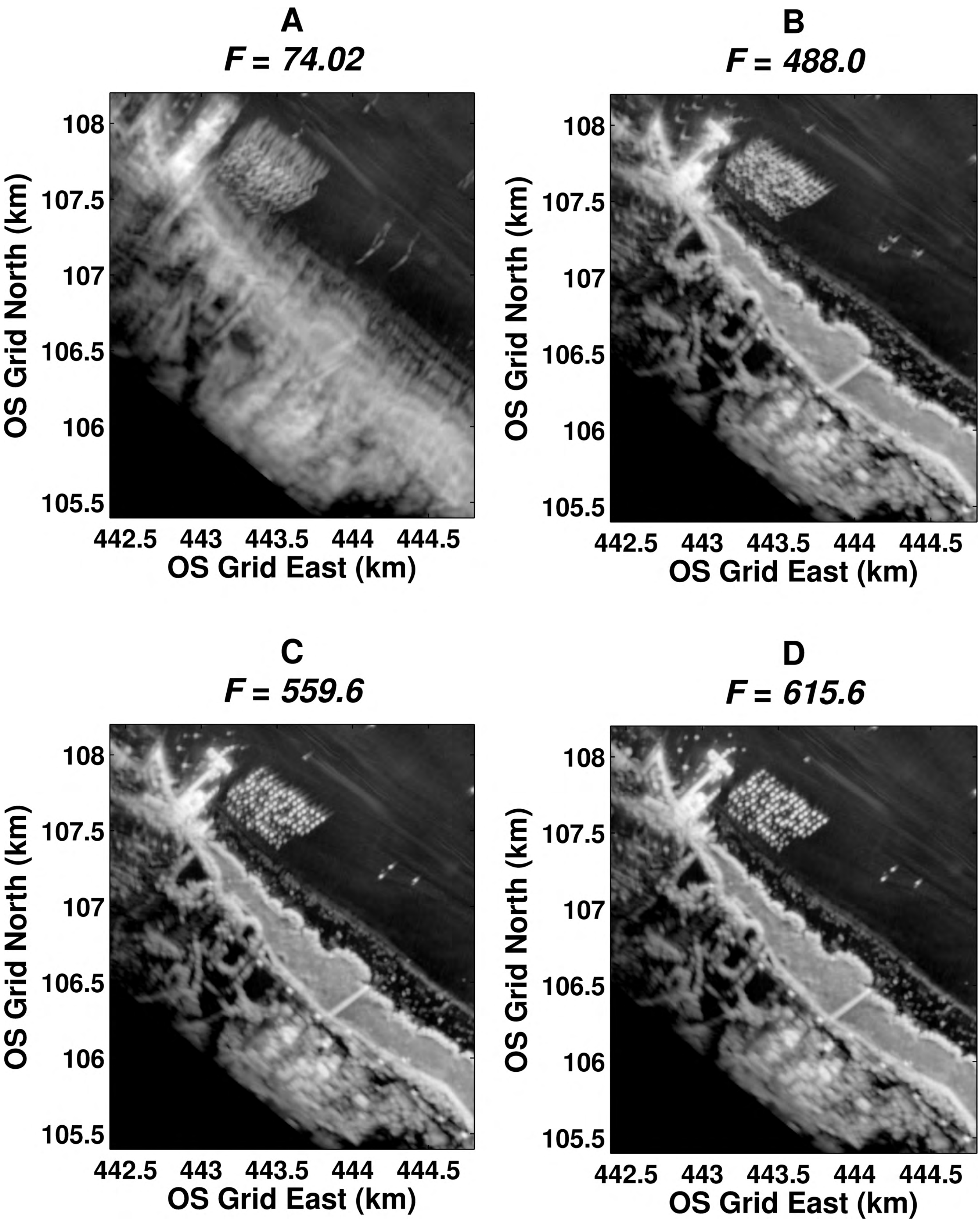

FIGURE 4. Time-integrated images and their associated F values generated during the calibration process using data recorded as the Discovery sailed through the Solent, centred on an area around Hythe marina. Image A shows the effect of all offsets set to zero, B a correct value for α only, C a correct value of α and β and D correct values for all three offsets.

imagery similar to SAR or SAS imagery of mountainous terrain or bathymetry. Visible are a number of fisheries in the sound (*e.g.,* 742.5N, 164E and 743N, 165.2E) including marker buoys and pontoon pilings as well as boundary walls around properties on the Northern shore (746.5N, 162E). The sharpness of the image at 5m pixel resolution would only be possible with accurately determined offsets.

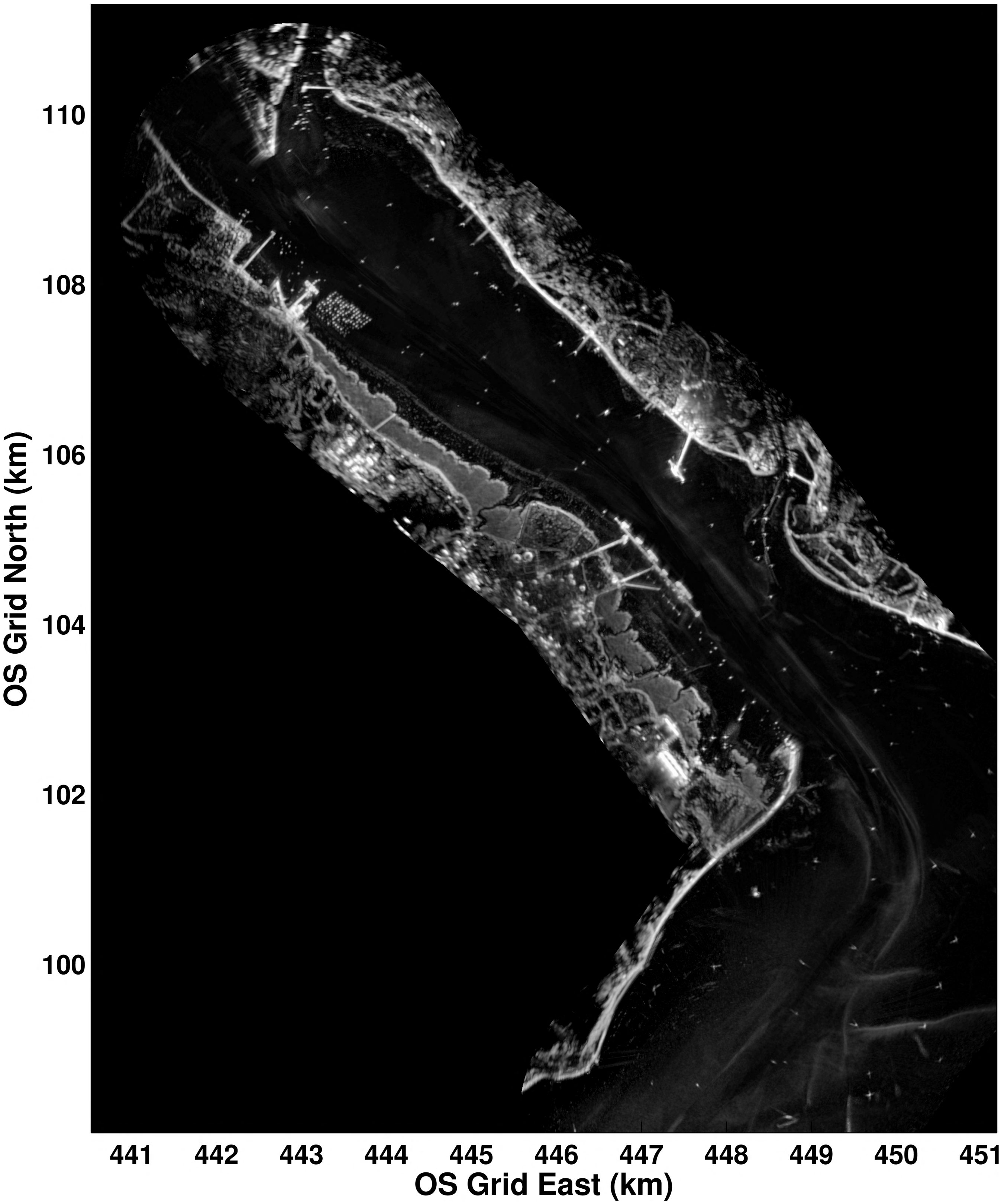

FIGURE 5. 'Synthetic aperture' X-band radar image of the Solent and the entrance to Southampton, generated using data recorded by the RSS Discovery.

IV. DISCUSSION

Regardless of the choice of post-processing of vessel-borne marine radar imagery, the quality of any derived data products will be proportional to the accuracy of geo-registration. Registration offsets caused by the mounting positions of radar and navigational equipment, total radar cable length

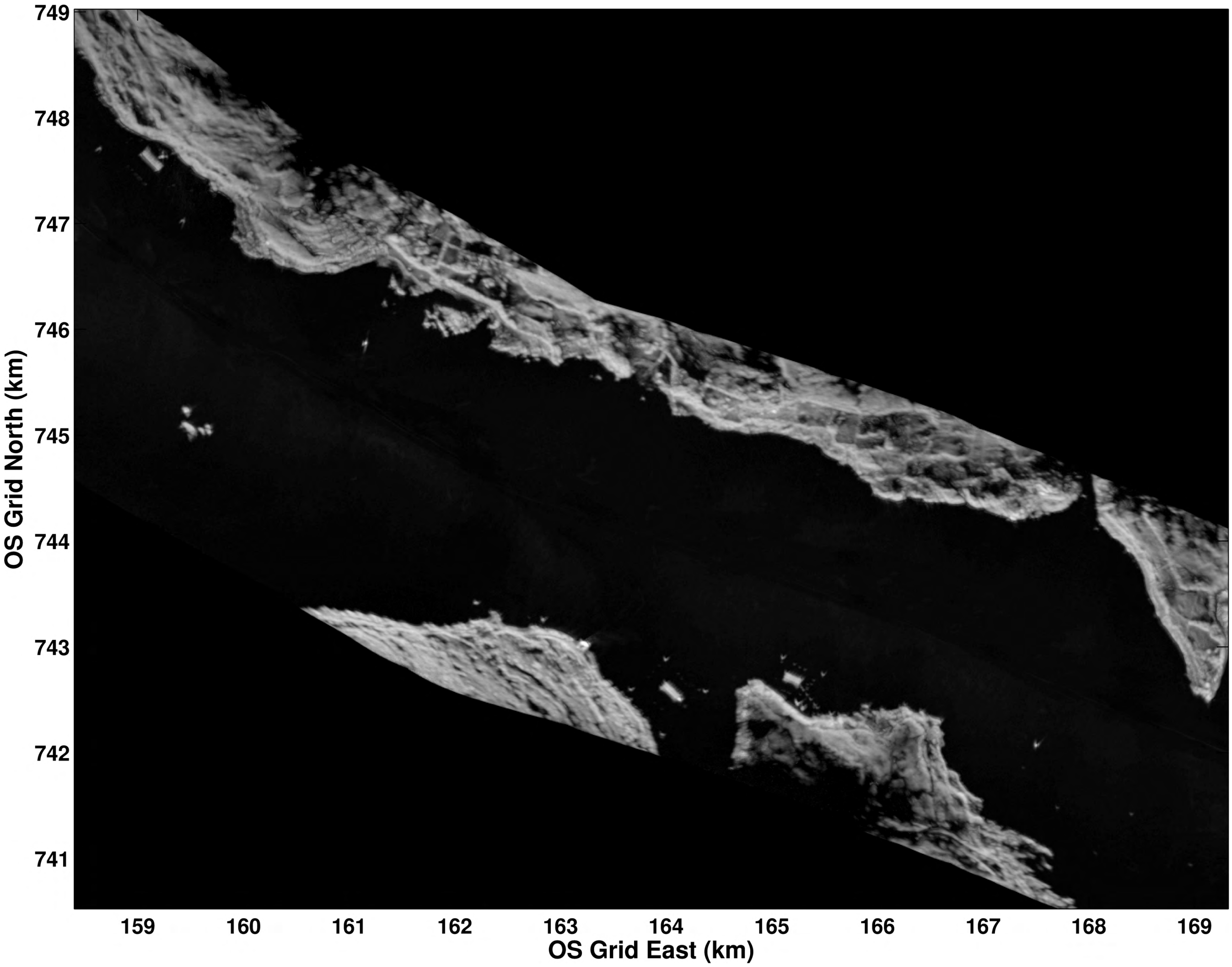

FIGURE 6. **'Synthetic aperture' X-band radar image of the Sound of Mull, Scotland, generated using data recorded by the RSS Discovery.**

and measurement delays caused by all associated recording equipment may not easily or readily measurable. Additionally these offsets will change between vessels or as equipment is replaced. The method proposed in this study requires only a sequence of suitable radar images and the associated vessel heading and position data for the time of recording. This work has described an accurate and robust method for determining the offset parameters required to correctly geo-register vessel-based marine radar imagery. However in order to create an operational system a number of issues must be addressed.

The robustness of the method outlined in this paper derives from the fact that (assuming the GNSS/INS navigation data is accurate) clear, sharp time-integrated imagery is impossible without accurate systematic offsets. If the offsets are inaccurate (especially the azimuthal offset α) image I would be blurred and the geographic registration of each image pixel would be wrong. Clear time-integrated imagery is not possible unless each component image scan is correctly geo-registered. Although this method can effectively and accurately stabilise vessel-borne radar imagery using a simple algorithm it does rely on accurate navigation data. However the proliferation of low-cost GNSS and INS systems in recent years means that accurate navigation data is not difficult to attain.

It is apparent that there is a mild co-dependency of α and β on the calculation of F_{max}. This dependency may be due to the form of input imagery to the algorithm combined with the programmatic method of determination of F (*I.e.,* with β *and* γ set to zero when initially searching for α). The co-dependency manifests an image I with a calculated highest F value but which remains slightly blurred; especially around small, static targets. A simple solution for this could be to use a first guess for β and γ based on prior knowledge of the system under calibration which will lead to a more accurate determination of α.

The number and content of radar intensity images required for the algorithm to perform accurately is dependent on vessel motion and manoeuvres during image acquisition. The most useful images are those that contain between 20% and 50%

land (preferably with a sharply defined land/sea boundary such as coastal defences or harbour walls) and are recorded when the vessel is in motion and turning. In this 'best-case' scenario an image set of between 512 and 1024 scans (20–40 minutes) is recommended to adequately perform the described method.

It must be noted that the proposed method can only work if persistent, static radar targets (sea walls, coastlines, *etc*.) are present in the imagery. The method will not work in open sea as echoes from the sea surface (sea clutter) are either stochastic or periodic in time and therefore average-out when generating a time-integrated image I. The image sharpness F can only be generated by static targets next to water; *i.e.,* high intensity pixels from persistent echoes next to low intensity pixels from sea clutter.

The offsets determined for a given vessel/equipment combination should remain valid for any dataset recorded by that system until the equipment is changed. This paper outlines a simple method to determine geo-registration offsets, however in order to progress this method to operational use there needs to be a full assessment made into how these offsets may change over time. An assessment of the effects of different vessel and equipment combinations is also beyond the scope of this paper but will need to be considered before the method is progressed to operational use.

Accurately geo-registered radar intensity images recorded by ship-borne radars have a number of uses aside from wave inversion of sea clutter. The SAR-type, time-integrated images that are created by the presented method utilize radar data that is not routinely recorded by vessel operators. Traditionally the image information transmitted to a ship's plan position indicator (PPI) is not recorded and is routinely discarded after each scan. Assuming the operator has access to GNSS/INS position and heading data the only additional requirement to transform the PPI to high resolution (~5m) maps of the coast and other static targets is a data recorder, the provision of accurate angular, spatial and time offsets and a small amount of image processing. These high-resolution, geo-registered images could be utilized for coastal surveying, for example using the waterline method [16] for intertidal areas or wave inversion for wet areas in the presence of waves. Survey mapping is also a possibility: especially salt-marsh monitoring (*e.g.,* Fig. 2), with images potentially available from any vessel with suitable radar, data recording and navigational systems. The timing of such imagery would not be constrained by satellite flight paths or the frequency of repeat passes, only the presence of a suitably equipped vessel.

V. CONCLUSION

This paper outlines a simple method to determine the systematic offsets necessary to accurately geo-register radar imagery recorded from a moving vessel. The algorithm is shown to work well enough to produce clear, sharp 'SAR-like' time-integrated radar imagery but there are a number of issues that need to be assessed before the method is progressed to operational use. Firstly the effect of pitch, roll and heave on the true geographic origin of each radar echo should be investigated. Preliminary work showed this to be unimportant for a vessel as large as the RSS Discovery but this will become increasingly important for small vessels in rougher seas. The effect is likely to be an angular offset that varies with azimuth and the pitch and roll angles. Secondly the effect of different geographic coordinate systems and vessel-equipment combinations should be explored. The accuracy of the derived offsets will be determined by the requirements placed on the geo-registered radar data; for wave inversion purposes it may be the case that the accuracy provided by this method is better than required. However if the imagery is to be used for other purposes the accuracy of the derived offsets may need to be improved.

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