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Investigating SAR Algorithm for Spaceborne Interferometric Oil Spill Detection

Abdul Duane Lawal, Gianmarco Radice, Matteo Ceriotti, Abubakar Umar Makarfi

Abstract— **The environmental damages and recovery of terrestrial ecosystems from oil spills can last decades. Oil spills have been responsible for loss of aquamarine lives, organisms, trees, vegetation, birds and wildlife. Although there are several methods through which oil spills can be detected, it can be argued that remote sensing via the use of spaceborne platforms provides enormous benefits. This paper will provide more efficient means and methods that can assist in improving oil spill responses. The objective of this research is to develop a signal processing algorithm that can be used for detecting oil spills using spaceborne SAR interferometry (InSAR) data. To this end, a pendulum formation of multistatic smallSAR carrying platforms in a near equatorial orbit is described. The characteristic parameters such as the effects of incidence angles on radar backscatter, which support the detection of oil spills, will be the main drivers for determining the relative positions of the small satellites in formation. The orbit design and baseline distances between each spaceborne SAR platform will also be discussed. Furthermore, results from previous analysis on coverage assessment and revisit time shall be highlighted. Finally, an evaluation of automatic algorithm techniques for oil spill detection in SAR images will be conducted and results presented. The framework for the automatic algorithm considered consists of three major steps. The segmentation stage, where techniques that suggest the use of thresholding for dark spot segmentation within the captured InSAR image scene is conducted. The feature extraction stage involves the geometry and shape of the segmented region where elongation of the oil slick is considered an important feature and a function of the width and the length of the oil slick. For the classification stage, where the major objective is to distinguish oil spills from look-alikes, a Mahalanobis classifier will be used to estimate the probability of the extracted features being oil spills. The validation process of the algorithm will be conducted by using NASA's UAVSAR data obtained over the Gulf of coast oil spill and RADARSAT-1 data**

Index Terms—**About four key words or phrases in alphabetical order, separated by commas.**

I. INTRODUCTION

Oil spills caused by accidents to seafaring tanker vessels, illegal ship ballast tank discharge or accidents on offshore platform installations are dangerous and hazardous to the marine environment. The global importance of petroleum resources has necessitated the need for its continuous exploration. Furthermore, the development and increase of intercontinental transportation of petroleum products is an important factor for socio-economically growth. However, accidents occur during petroleum exploration and transportation. Additionally, some vessels illegally discharge their ballast tanks within unsanctioned areas. Regardless of the source and cause of petroleum discharge, there is a harmful effect of marine pollution.

The British Petroleum (BP) oil spill of 2010 in the Gulf of Mexico as a result of an explosion which sank the Deepwater Horizon oil rig is regarded as the 'worst US environment disaster'[1]. The accident was responsible for at least 20 million gallons of oil spilled into the Gulf and affecting more than 70 miles of the Louisiana coastline [2 & 3]. In 2011, a cargo ship *MV Rena* ran aground, leading to over 340 tonnes of oil spill into the Astrolabe Reef. It has since been described as New Zealand's worst marine environmental disaster in decades [4].

The BP, *MV Rena* and other oil spill events lead to loss of aquamarine lives, organisms, trees, vegetation, birds, wildlife and destruction to a means of human livelihood. Therefore, the need to monitor and mitigate oil spills becomes imperative. Although there are several methods through which oil spills can be detected, it can be argued that remote sensing via the use of spaceborne platforms provides enormous benefits.

Satellite images of oil spills areas have been processed using various algorithms, to discriminate between look-alikes or oil spills. The use of images from synthetic aperture radar (SAR) satellites operating in monostatic mode for detecting oil spills has been extensively studied [5 - 14].

The brightness of a captured SAR image is a reflection of the properties of the target surface. The backscattering of the sea surface is decreased by oil films. Several mechanisms are responsible for the nature of the radar backscatter, which is strongly dependant on the radar incidence angle. Between incidence angles of 20° and 60° (angles radar backscatter can be described by Braggs scattering theory), short wind-generated short-capillary waves are the main 'sources' of radar backscatter [15]. This, leads to the assumption, that the light winds are responsible for the generated short-capillary waves.

In a typical SAR image, oil spills appear as dark spots as a result of the dampen effects on capillary waves [16 -18]. However, not all dark spots are oil spills. Hence, this underlines the need to process the image for confirmation. Furthermore, in the absence of wind, there are no capillary waves. This causes identical grey scale levels from the lack of contrast between the marine environment and the oil spill [19].

Previous studies show that minimum wind speed is dependent on radar frequency of observation and incidence angle [20].

Abdul Duane Lawal, Researcher, University of Glasgow, Glasgow. Scotland, UK. G12 8QQ.
Gianmarco Radice, Reader, University of Glasgow, Glasgow, Scotland UK. G12 8QQ.
Matteo Ceriotti, Dr, University of Glasgow, Scotland, UK. G12 8QQ
Abubakar Umar Makarfi, Center for Space Transportation and Propulsion, Epe, Lagos, Nigeria.

At wind speeds below 2 m/s, an extremely low backscatter is experienced, and the contrast necessary for detection is absent, implying the oil film becomes undetectable [21]. To effectively detect oil spills using SAR, wind speeds between 3 – 6 m/s is suggested [22]. Thick oil spills can still be detected at wind speeds between 10 – 12 m/s, while at wind speeds above 14 m/s, the oil spill disappears by mixing down the water column [20]. The minimum wind speed that allows for detection of oil spill is between 2 – 3 m/s [20]. Therefore, the wind speed range, between which oil spill can be detected, is 2.5 – 12 m/s.

However, the process of oil spill detection is a combination of: (a) environmental parameters – wind speed, tide and sea state, (b) payload parameter (SAR) – incidence angle, polarization, resolution & frequency, (c) nature and characteristics of oil film – oil type and thickness and (d) extracted image characteristics – contrast, shape and size. Table 1 is a list SAR carrying satellites who's images have been used for investigating oil spills.

Table I. SAR carrying satellites with imagery used for oil detection

Satellite	Status	Band
SEASAT	1978 - 1978	L
ALMAZ	1991- 1992	S
ERS-1	1991-1996	C
ERS-2	1995-2011	C
RADARSAT-1	1995-2013	C
ENVISAT (ASAR)	2002-2012	C
ALOS (PALSAR)	2006-2011	L
RADARSAT-2	2007-Present	C
TerraSAR-X	2007-Present	X
Cosmos Skymed-1/2	2007-Present	X
Tandem-X	2010-Present	X

In addition to low wind speeds leading to dampen capillary waves, various other phenomena like grease ice, downwelling zones, rain cells and shelter from land s can cause dark spots in SAR images.

II. METHODS FOR SPACEBORNE OIL SPILL DETECTION

Generally, oil spill detection is achieved through two main methods: the manual method, where trained operators analyse SAR images for identification of oil spills and the quasi-automatic or automatic methods which utilize some form of mathematical or environmental algorithm to oil detection. The initial step is to locate dark patches within the surrounding area. Upon identification, further investigations are conducted to verify the nature of the dark patch. As expected, the manual approach could be tedious for large number and volume of dark spots within a SAR image. This method is prone to human errors as a result of fatigue. Most quasi-automatic or automatic methods utilise algorithms comprising four steps [10]:

a. Detection and isolation of all dark spots within the SAR image using the thresholding and segmentation processing. Adaptive thresholding is a preferred choice as it is controlled by wind conditions and the specific type of SAR sensor. This allows probable detection of oil spills under low wind conditions.

b. Extraction of statistical parameters of each dark spots. Parameters such as mean backscatter values, geometry, distance to oil rigs and ships are considered.

c. Characterisation of oil spills and look-alikes by testing extracted values against pre-defined values.

d. Classification of detected dark spots as either oil spills or look-alikes. Several studies have adopted various classifiers such as fuzzy logic, neural network, statistical approaches, spatial frequency spectrum, and wind history information.

The figure bellow is a generic process for automatic oil spill detection algorithms.

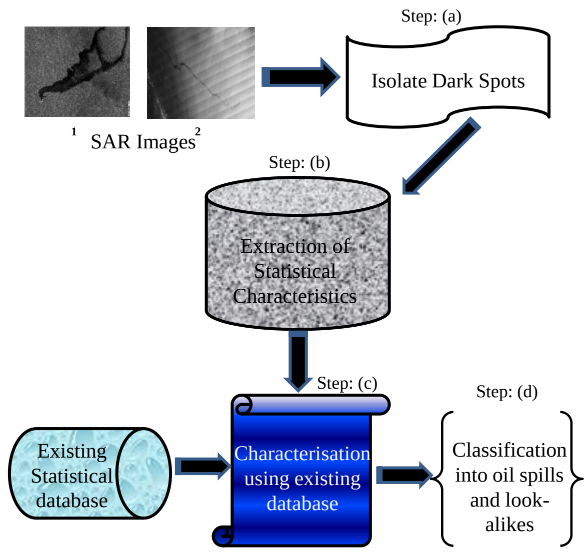

Fig 1: Generic process of oil spill detection algorithms [15]

As previously mentioned, various types of algorithms have been developed for oil spill detection. However, the techniques used may vary within any of the four steps highlighted. Regardless of the techniques adopted, the basic process remains the same. This work proposes a modification to the extraction stage (step (b)) by inputting interferometric SAR data to support a higher degree of certainty when extracting feature statistical parameters. SAR interferometry is a remote sensing technique capable of providing data to understand various natural phenomena on Earth [23]. SAR interferometry is basically the acquisition of two or more complex SAR imagery under identical geometry by the use of the phase differences in the same transmitted signal, received at two or more different locations to compute additional information about the imaged terrain [24]. The acquisition of interferometric data can be achieved in two ways: the bistatic configuration involving two SAR carrying spacecraft and the multistatic configuration which involves more than two SAR carrying platforms.

A bistatic mission provides for additional qualitative and quantitative measurement of surface microwave scattering properties and potentially allows for original scientific activities to be conducted in areas such as [25]:

- Evaluation of the bistatic radar cross-section of natural and man-made targets
- Acquisition of velocity measurements
- Improvement of image classification and pattern recognition procedures
- High resolution measurements of components of sea wave spectra

Bistatic radar operations is carried out with separate transmitter and receiving antenna. Spaceborne bistatic radars can either be implemented using two separate monostatic platforms (active system) or with one monostatic platform and a receiver-only platform (passive system). Generally speaking, not all bistatic missions are interferometric missions owing to the distance between the antennae, defined by the baseline vector from transmitting to receiving antenna. The large baseline of a typical bistatic mission is inherently responsible for the spatial decorrelation when the echoes of a bistatic and monostatic data are compared.

Furthermore, this implies that coherent processing becomes impossible to conduct. It is pertinent to note that the maximum achievable baseline is a function of wavelength when decorrelation avoidance is a primary goal. Studies on bistatic geometry and resolution have been reported [26]; bistatic configurations can be adapted for repeat pass interferometry. Moreover, bistatic missions also provide the possibility of using numerous platforms at varying baseline distances. This configuration is regarded as multistatic.

Multistatic SAR missions are attractive because they offer a plethora of imaging modes for the evaluation of scattering signals from multiple viewing angles in combination [27 & 28]. A multistatic SAR configuration plays an important role in the following application areas:

- Spaceborne tomography
- Width-swath imaging
- Resolution enhancement
- Interference suppression
- Single-pass along-track and across track interferometry
- Ground Target Moving Indication (GTMI)

Most of the listed application areas could be adopted for oil spill detection as beneficial sources of data to assist in more accurate determination/extraction dark oil spots. The use of multistatic configuration for interferometry avoids temporary decorrelation and disturbances when baseline distances are kept within the maximum limits. This also improves performance while enabling fast detection of objects [28]. The same configuration can also be used to detect slow changes when conducting repeat pass interferometry.

This work assumes the interferometric data generated is provided by a passive multistatic configuration of satellites consisting of one monostatic satellite and two receiver satellites. The satellites are configured for monitoring dynamic processes such as ocean and tidal currents. The following data can be acquired as input to the generalised form of oil spill detection algorithm as seen on figure 2:

- Detection of thin oil slick
- Higher resolution image of oil slick showing clearer feature geometry like length and area.
- Detection of weak back scatters
- Detection of potential environmental causes of oil spills such as ships and oil rigs
- Indirect information such as ship's velocity within proximity of oil spill
- Ambiguity suppression
- Detection of scatters' velocities

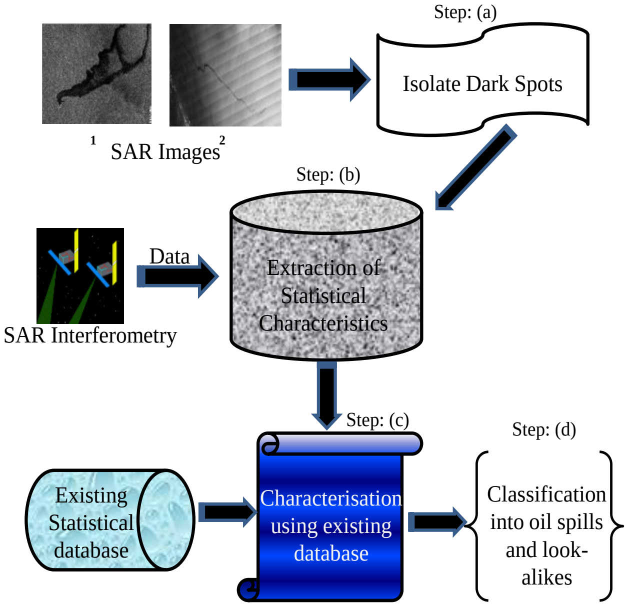

Fig 2: Modified SAR algorithm process to include interferometry data to support dark spot extraction

III. MISSION REQUIREMENTS AND SCENARIO

To investigate the possibilities of generating interferometric SAR data to be used as input to oil spill detection algorithms, a summary of the list of mission requirements are defined:

- Low-cost mission
- High revisit time
- Measurement of ocean dynamics phenomena (current and tides)
- Observe marine and maritime activities within the Equatorial Region (ER) – Atlantic, Pacific and Indian Oceans.

The mission adopts a pendulum configuration as a derived requirement for velocity measurement of ocean and tidal currents and sea-faring vessels. The mission area is defined between ± 10° of the Equator and described as the Equatorial Region (ER). However, the geometry necessary for implementing a single-pass along-track interferometry, exhibits identical configuration to the pendulum configuration. Several other multistatic configurations such as the cartwheel and carpe have been also reported [29 & 30]

IV. ORBIT AND BASLINE DISTANCE

The S-band radar is the primary payload for operation. The selected altitude for nominal operations for the three spacecraft in formation is 700km. Other orbital parameters are listed in Table 2.

Table II Orbital Parameters

Orbit Parameters	Tx/Rx	Rx-1	Rx-2
Altitude (Km)	700	700	700
Revs/day	14.57	14.57	14.57

Inclination (°)	10	10	10
Eccentricity (°)	0	0	0
Period (mins)	98.79	98.79	98.79
RAAN (°)	10	10.0002	10.004
M Anomaly (°)	10	9.99996	9.99992
In. Angle (°)	20 - 50	20- 50	20-50

Each spacecraft shall carry a left-looking SAR transmitter/ receiver (for monostatic) and receiver only (bistatic receiver). The mission is designed to ensure all the spacecraft flying in formation exhibit identical ground track by ensuring the conditions necessary to maintain a constant time separation are satisfied. The baseline separation between successive satellites is design to measure velocities between 0.52m/s and 1.04 m/s. The time separation between each spacecraft is 0.0486s.
Fig3 and
Fig 4 are exaggerated screenshot of the satellite positions.

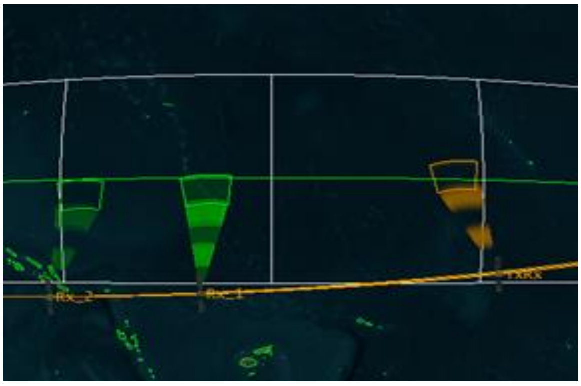

Fig3: Close-up screen shot of satellites in pendulum configuration for interferometry operations

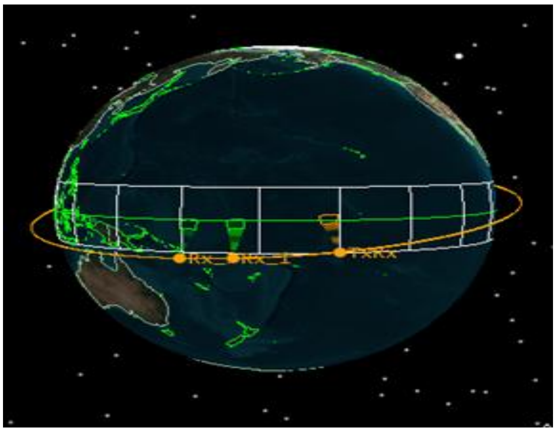

Fig 4: Global view of satellites in pendulum configuration conducting interferometry operation over the Equatorial Region

A detailed analysis of the performance assessment on the velocity measurement and accuracy error budget is been reported [24]. Furthermore, studies on the stability of the relative motion between spacecraft in formation and the control requirements are also documented [31, 32 & 33].

V. COVERAGE AND RE-VISIT

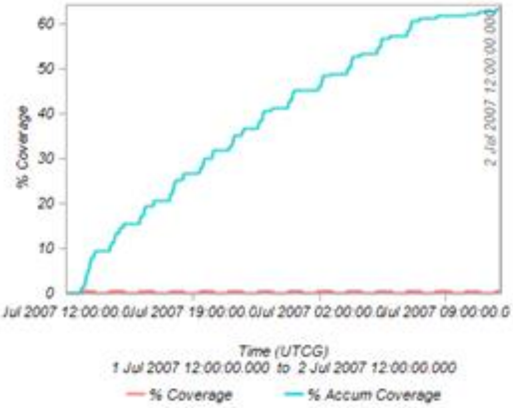

Fig 5: A 24 hour coverage analysis graph

Fig 5 highlights the results of the coverage analysis conducted using all 3 spacecraft in orbit plane A. The monostatic SAR has a swath width of 200 x 150 km, while the receiver-only SAR each has swath widths of 150 x 100 km. The graphs show approximately 70% coverage of the ER is achieved over a 24 hours period. In event that the constellation consists of two orbital planes with equal number of identical spacecraft, it is expected that the coverage will be approximately doubled.

VI. CONCLUSION

Most oil spill detection algorithms generally follow a generic format. The inclusion of SAR interferometric data could potentially improve the level of accuracy, during identification and extraction of oil spills and look-alikes. Implementing a passive multistatic SAR mission is a solution for generating interferometric SAR data.

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Abdul Duane Lawal: Abdul graduated from the University of Surrey, UK where he obtained and MSc in Satellite Engineering. He then proceeded to the Manchester Metropolitan University, UK where he obtained another MSc degree in GIS and Environment. He is currently a final year researcher at the University of Glasgow and a member of the Space Advanced Research Team (Space-ART). His area of research includes space SAR distribution systems for Earth observation. He is also member of AIAA, IET an IEEE.

Gianmarco Radice: Gianmarco graduated with a first class M.Eng degree in Aerospace Engineering from Politecnico di Milano in 1996 and completed his doctoral studies in space systems engineering at the University of Glasgow in 2000. He was then a research assistant on the Phase 2 study of the Improved Mission Autonomy and Robustness (IMAR) funded by the British National Space Centre. In 2003 he was appointed to a permanent lectureship position in the Department of Aerospace Engineering at the University of Glasgow. He was promoted to Senior Lecturer in 2006 and to Reader in 2010. He is currently the Director of Aerospace Programmes, University of Glasgow, Singapore.

Matteo Ceriotti: Dr. Matteo Ceriotti received his M.Sc. summa cum laude from Politecnico di Milano (Italy) in 2006 with a thesis on planning and scheduling for planetary exploration. In 2010, he received his Ph.D. on "Global Optimisation of Multiple Gravity Assist Trajectories" from the Department of Aerospace Engineering of the University of Glasgow (United Kingdom). During 2009-2012, Matteo was a research fellow at the Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, leading the research theme "Orbital Dynamics of Large Gossamer Spacecraft" in the ERC project VISIONSPACE. In 2012, he returned to the University of Glasgow as a lecturer in Space Systems Engineering, within the School of Engineering, division of Systems Power & Energy. He is AIAA member.

Abubakar Makarfi: Dr Makarfi completed a B.Eng. in Electrical and Electronic Engineering at the Nigerian Defence Academy, Kaduna with a First class Hons. degree in 2001. He thereafter received an M.Tech. in Telecommunications & Electronics Engineering at the Obafemi Awolowo University, Ife-Nigeria in 2005 and a PhD in Wireless Communications from the University of Manchester, UK in 2013. His research interests cover several aspects of wireless communication and satellite engineering. He is a member of IEEE, the Nigerian Society of Engineers (NSE) and a corporate member of the Council for the Regulation of Engineering in Nigeria (COREN).