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Original Article

Assimilation of satellite observations in support of hydrocarbon drift forecasting in the Cuban EEZ

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Asimilación de observaciones satelitales en apoyo al pronóstico de deriva de hidrocarburos en la ZEE de Cuba

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ABSTRACT: The initialization of the runs of the numerical model of lagrangian approach PETROMAR-3D, from SAR images, is shown. With this new feature, the model is prepared to give operational response to an oil pollution event in the seas around Cuba. The oil slick polygon outputs of the SEonSE Engine and SNAP-ESA satellite information processing tools were used, developing new functions and Python libraries in the PETROMAR-3D software. With this result, a semi-automatic oil slick surveillance and monitoring service was developed in the seas around Cuba, with the computer tools of satellite data processing and the PETROMAR-3D Lagrangian oil spill model. With this service, users receive the information through a first email from the moment the slick is detected, and then receive another one with the oil drift modeling map for 72 hours. For this purpose, a script was developed that runs automatically through a scheduled task in the operating system, and handles all the software applications of the system designed with new Python functions and libraries.

Key words: PETROMAR, SAR imagery, SEonSE, marine pollution.

RESUMEN: Se muestra la inicialización de las corridas del modelo numérico de enfoque lagrangiano PETROMAR-3D, a partir de imágenes SAR. Con esta nueva característica, el modelo está preparado para dar respuesta operativa ante un evento de contaminación por petróleo en los mares alrededor de Cuba. Fueron empleadas las salidas de polígonos de manchas de hidrocarburos de las herramientas informáticas de procesamiento de información satelital SEonSE Engine y SNAP-ESA, desarrollando nuevas funciones y bibliotecas de Python en el software PETROMAR-3D. Con este resultado, se desarrolló un servicio semi-automático de vigilancia y monitoreo de manchas de petróleo en los mares alrededor de Cuba, con las herramientas informáticas del procesamiento de datos satelitales y el modelo lagrangiano de derrames de petróleo PETROMAR-3D. Con este servicio, los usuarios reciben la información mediante un primer email desde el momento en que se detecta la mancha, y luego recibe otro con el mapa de la modelación de la deriva de petróleo para las 72 horas. Para tal propósito, fue desarrollado un script que corre automáticamente mediante tarea programada en el sistema operativo, y maneja todas las aplicaciones informáticas del sistema diseñado con nuevas funciones y bibliotecas de Python.

Palabras clave: PETROMAR, imágenes SAR, SEonSE, contaminación marina.

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INTRODUCTION

It is estimated that 53% of the oil that reaches the marine environment is produced by man as the maritime transport industry is one of the main contributors to marine pollution. Spills from supertanker accidents represent only 8% of the total oil found in the oceans; However, both large spills (Perdomo et al., 2021; Pupo et al., 2021), and small spills are the focus of attention (Polinov et al., 2021).

The transportation of hydrocarbons, via tankers, is a complex task that has given rise to oil spills as a result of collisions, groundings, fires and other accident events ranging from minor incidents to catastrophic spills. (Kark et al., 2015; Perdomo et al., 2021). Despite this, large oil spills have decreased considerably over recent decades (ITOPF, 2023). This has been achieved through the combined efforts of the oil-shipping industry and governments, as well as the actions of the International Maritime Organization (IMO) (Polinov et al., 2021).

However, another important source of oil pollution from ships is the deliberate discharge of hydrocarbon waste and ballast into the sea. These indisciplines constitute a constant threat to seabirds, benthic organisms and human health; and can cause a considerable number of victims over time, cited by (Polinov et al., 2021). These bad practices can be eliminated by strict implementation of existing regulations, control, monitoring and surveillance of maritime traffic.

PETROMAR-3D model (Calzada et al., 2021) has been developed at the Center for Marine Meteorology (CMM) of the Institute of Meteorology of Cuba (INSMET). This model is the result of the study of the characteristics of numerous oil spill models that operate in different regions of the world, being a technical solution according to the organizational conditions and resources available in the country. (Pupo et al., 2021). In addition to covering the simulations in the seas adjacent to Cuba, a work domain has recently been designed to run the model in the northeast of Brazil (Varona et al., 2024).

With PETROMAR-3D version 2.1 (Calzada et al., 2021), an oil slick fate forecasting service via email was developed operationally. Users had to send an email with a text file containing the model input file; but, if this file was not sent, the application had a default configuration.

Despite the improvement in operational performance in PETROMAR-3D version 2.1, the oil drift and weathering forecast lacked efficiency because it needed information on initial conditions only from the configuration file; and it did not assimilate a polygon with the morphology of the oil slick, but instead calculated the spread of the slick by applying the Fay equation (Fay, 1971) assuming a circle. Consequently, these specialized services to the entities in charge of maritime safety and the mitigation of pollution at sea did not constitute an efficient tool contributing to the Cuban Marine Pollution Early Warning System.

Starting in 2022, with the international collaboration project e-GEOS-INSMET: “Strengthening the Cuban marine system”, with alias “Marine Surveillance”; The acquisition of SAR images was achieved continuously and with full coverage of the territorial seas of the Cuban archipelago every 48 hours for 9 months. This process, completely unprecedented in Cuba, made it possible to download and digitally process SAR images from the COSMO-SkyMED satellite constellation using the SAR digital image processing computer tool SEonSE Engine (Oddone et al., 2021), provided by company e-GEOS SpA, in accordance with the project contract.

In this way, the conditions were created to develop the initialization of the PETROMAR - 3D lagrangian model from satellite information and introduce surveillance, monitoring and forecasting services for drift and weathering of oil slicks with the incorporated technology. So this article aims to show the development of an improved version of the PETROMAR-3D model, which is based on the information resulting from satellite image processing.

After the Introduction, section 2 describes the computer tools used for the digital processing of satellite images, the PETROMAR-3D model and the data used in the operational work of oil slick monitoring, and some considerations that were taken into account to carry out the modeling. Section 3 describes the results of the PETROMAR-3D assimilation of information from SAR image processing and, subsequently, the development of a semi-automatic surveillance and monitoring system for oil slicks at sea. Finally, conclusions and recommendations are presented in Section 4.

2. METHODS AND MATERIALS

Oil is depicted on SAR images by long stripes on the sea surface. The low water dissolution capacity of oil results in high shortwave damping and expansion in surface tension, decreasing wind erosion, appearing in SAR images as a dark region (Gee et al., 2016) that is detected in wind speed ranges between 3 and 12 m/s (Ramsey III et al., 2013).

A hydrocarbon spill into the sea depends on components such as its volume, its physical properties, and meteo-ocean conditions. The different physical-chemical-oceanographic processes in oil affect the sensitivity of SAR images over time (Chaturvedi et al., 2020). The compilations of repeated SAR images, in the same event, are very useful for monitoring the evolution of an oil spill (Liu et al., 2013).

2.1 SAR image processing tools for detection of oil slicks in the sea

With the e-GEOS-INSMET collaboration, two very important tools for SAR image processing were installed at the CMM: SEonSE and SNAP-ESA. SAR images of the COSMO-SkyMed constellation of the ScanSAR Huge type were acquired by Matera Remote Sensing Centre of e-GEOS in Italy and then downloaded by INSMET, comprising an area per image of 200 x 200 km with 100 m spatial resolution, covering 350,000.00 km2 of the Cuban archipelago in 48 hours, reaching 80% coverage.

SEonSE Engine

This is a client-server architecture application, implemented as a QGIS plugin, to detect and characterize ships and oil spills from SAR images acquired by satellite, helping the user to perform the processing. This software can work with COSMO-SkyMed, SAR RADARSAT2, and Sentinel-1 images without requiring pre-processing because the products are read in native format.

Being an application that focuses on maritime surveillance, it automatically loads data from AIS (Automatic Identification System) satellite tracking systems with the tracks and details of the ships present in the analysis area, in addition to wind measurements and waves. Possible polluters of the detected oil spills can then be derived with SAR image processing, among the closest vessels (Oddone et al., 2021).

SNAP-ESA

SNAP (Sentinel Application Platform) responds to a free program offered by the European Space Agency to process and analyze satellite images from the Sentinel fleet of satellites. The application is developed jointly by Brockmann Consult GmbH and has specific tools to work with the images based on the satellite model (Sentinel Booxes); be multiband images (Sentinel 2, Sentinel 3), multispectral images (Envisat, Landsat, MODIS), and SAR images.

The strength of the tool is the strategic combination of bands that allows working on various aspects of territorial issues. To do this, RGB combinations can be made with the satellite bands that are being used to compose images, both in real color and false color, for the treatment of territorial aspects based on agriculture, land use, urban planning, bodies of water, forest management among others.

As part of the SNAP tools are intended for the management of standardized Sentinel products through the folder and metadata structure of the Copernicus platform, the work band structure available for treatment and management can be used in a single step. of Sentinel satellite images, uploading an XML file for bulk incorporation of all image data in a single step (Foumelis et al., 2018).

2.2 The PETROMAR-3D oil spill model

The PETROMAR - 3D model (Calzada et al., 2021) is the modeling tool used in this work. It is a Lagrangian scheme to calculate oil spill trajectories, created at the Center for Marine Meteorology of the Institute of Meteorology. This model incorporates numerical forecast results from various atmospheric, hydrodynamic and wave models, as well as other input data for drift and weathering calculations. The data used in the modeling came from forecast outputs of atmospheric and oceanographic models detailed below:

- **GFS** (Global Forecast System), a global model for numerical weather prediction owned by the National Oceanic and Atmospheric Administration (NOAA). The time domain of the model is presented in two parts: the first has a higher resolution and extends up to 180 hours (7 days), while the second part runs from 180 to 384 hours (16 days) at a lower resolution. . It is used as the spatial domain of the model in a horizontal direction that divides the surface of the earth into cells of 0.5 ° x 0.5 °, although there are outputs of lower resolution (1.0 ° x 1.0 ° and 2.5 ° x 2.5 °). Wind direction and speed variables are used (Ncdc, 2018) with spatial and temporal resolution of 28 km and 3 hours respectively.
- **NAM-CARIBE** (North American Mesoscale-Caribbean Forecast System). The domain considers the entire Greater Caribbean and presents a spatial resolution of 12 km and a time of 3 hours (Nam, 2017). The download site is: http://nomads.ncep.noaa.gov/pub/data.
- **cmems_mod_glo_phy_anfc_0.083deg_PT1H-m**, belonging to the Copernicus product GLOBAL_ANALYSISFORECAST_PHY_001_024. The Operational Mercator global ocean analysis and forecast system at 1/12 degree is providing 10 days of 3D global ocean forecasts updated daily. This product includes hourly mean surface fields for sea level height, temperature and currents. The global ocean output files are displayed with a 1/12 degree horizontal resolution with regular longitude/latitude equirectangular projection. 50 vertical levels are ranging from 0 to 5500 meters (Lellouche et al., 2023). The download is available at: https://data.marine.copernicus.eu/product/GLOBAL_ANALYSISFORECAST_PHY_001_024/description
- **NCOM** (*Navy Coastal Ocean Model*) US Navy operational global ocean model (Martin et al., 2009; Ncom, 2017), which includes several domains including the Gulf of Mexico and the Caribbean Sea. The download website is: http://nomads.ncep.noaa.gov/pub/data

2.3 Considerations in modeling with PETROMAR-3D from SAR images

Operational monitoring and forecasting of oil slicks at sea is very complex. In most cases, when a marine oil spill event occurs, the properties of the hydrocarbons are unknown. The volume dumped, its density, the date and time of occurrence are examples of these properties; which are necessary for numerical modeling and forecasting of the fate and modification of the properties of the slick over time.

Also, it may be the case (and it happens most of the time) that the acquisition of the satellite image in the area of the oil spill occurs several hours after the event began, which makes the task even more complex for modelers. Taking into account these factors, some considerations have been taken into account to make the operational forecast of destination and changes in properties of the oil slicks detected through satellite images:

1. Do not include the spreading calculation in the modeling in operational mode.

The PETROMAR-3D model performs the spreading calculation using the Fay equations (Fay, 1971). This physical process occurs in the first hours of the spill, and its duration depends on the volume spilled (Perdomo et al., 2021). These data are unknown if the modeling is initialized from the processing of a satellite image.

2. Carry out numerical modeling with an average density of the spilled oil.

Table 1 shows the classification of hydrocarbons according to density (Mohammadi et al., 2020).

To carry out the numerical modeling, since the initial value of the density of the spilled oil is unknown, a density value has been considered according to the case. For light oil (in API degrees): 33, 25 for medium and 20 for heavy.

3. Estimate the volume of the slick.

The coordinates of the oil slick polygon can be provided to the PETROMAR-3D model in two ways:

a) With the SNAP-ESA polygon creation tool. The polygons are created manually from both SAR and optical images.

In this case, a division of the polygon into pixels is assumed (square particles of 0.001 degrees, equivalent to 12 m^2), and the area of the slick is calculated by the sum of the total area of the calculated pixels.

b) With the generation of a Shapefile file from SEonSE Engine. The polygons are created from the spill report in shape format and the data on the spill area is included in this file.

Once the area is obtained by any of the methods, the estimated volume of the slick is calculated by multiplying the area by the thickness (assuming that the thickness of the slick is homogeneous). In the same way as the density, 3 average values of slick thickness were established according to the magnitude of the spill. In this way, for hydrocarbon spills: heavy 10^{-2} m, medium 10^{-3} m and light 10^{-4} m (Perdomo et al., 2021).

These considerations do not constitute a factor that undermines the modeling precision because the forecast is updated with the acquisition of a subsequent satellite image; and furthermore, in the hours following the start of the event, data on the properties of the hydrocarbons can be obtained.

3. RESULTS

3.1 Assimilation of satellite information

With the SNAP-ESA and SEonSE Engine software, a polygon output is generated using a file with the coordinate values of the oil slick. This file is assimilated by the PETROMAR-3D model through a Python script that is responsible for locating the polygon in the model's working domain.

The functions developed in the new PETROMAR-3D script are executed with pre-established parameters such as the date, the API degree value and the polygon area. These new features are very advantageous for the operational work of the model because previously the software config file was configured manually.

There has already been the case in which several oil slicks appear in the same SAR image. With the new features of PETROMAR-3D, several slicks can be modeled in the same scenario, each of which are introduced from their respective files (figure 1).

The coordinates of the polygon enter as parameters into the model, which creates the Lagrangian particles that must be processed in the calculations of the functions responsible for modeling.

Table 1. Classification of hydrocarbons according to density

Hydrocarbon classification	API Degree	Density [g/cm^3]
Ligth	> 31.1	<0.87
Medium	22.3-31.1	0.92-0.87
Heavy	10-22.3	1.0-0.92

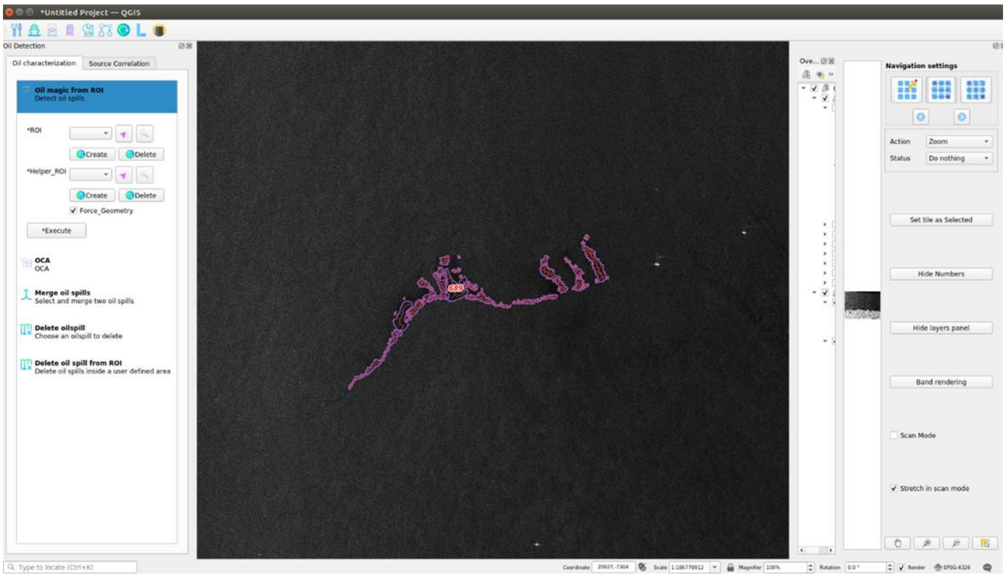

Figure 1. SAR image from October 5, 2022, detected with the SEonSE Engine app.

This is achieved by choosing the smallest rectangular domain from the maximum and minimum longitudes and latitudes that include the spot; and a square grid with a given dxdy is constructed by applying the polygon mask to discriminate the interior nodes. In each interior node an element is planted and its drift is modeled (figure 2).

3.2 Development of a monitoring system for oil slicks in the sea

Based on the outputs of the SEonSE Engine, SNAP-ESA applications, and the initialization of PETROMAR-3D with the generated polygons, a Surveillance and Monitoring System for oil slicks around Cuba was developed. This task was carried out by means of a new Python script running automatically on a server.

This script uses Python libraries for email messaging such as: poplib, smtplib, email.mime.multipart, email.mime.text, email.mime.base, email.mime.image. It has a defined function that is responsible for sending notifications to users in case of oil slick detections through emails. It was scheduled as an automatic task to be executed every 1 hour, although it depends on the pre-processing of the SAR images by the SEonSE Engine operator on duty. This feature makes the oil slick surveillance and monitoring system semi-automatic.

Figure 3 shows a diagram of the semi-automatic surveillance process of the developed system. In it you can see the hardware and software tools that make it up.

The system is made up of a server, with the PETROMAR-3D model installed and the Python script developed in this research (**run_petromar.py**); and 2 NAS servers (network-connected data devices) storing the data from the outputs of the numerical models downloaded from the different regional and global metocean centers, such as: data on ocean currents, wind and waves; and the processed SAR images, polygons of the oil slicks and corresponding **png** images, the PETROMAR-3D scenario and trajectory outputs, and the "**run_petromar.py**" configuration files respectively.

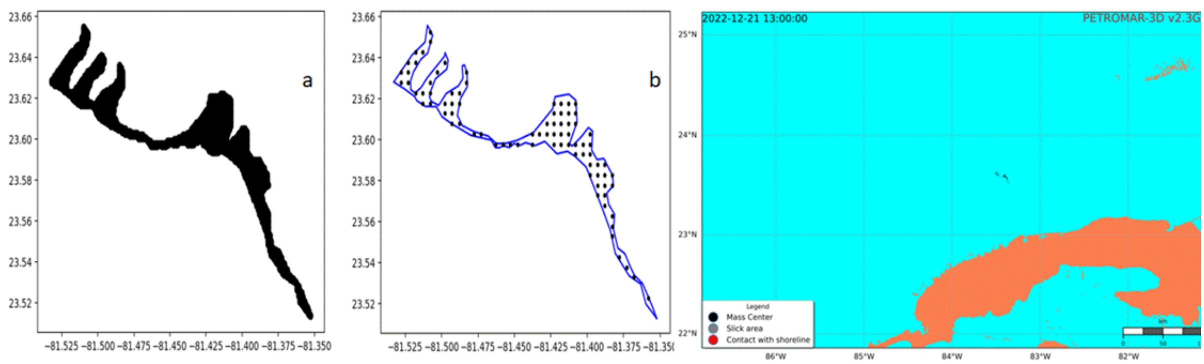

Figure 2. The image shows the process from which the polygon of the slick is assimilated, the grid points that are inside the slick are obtained, and the output of the plotting with PETROMAR-3D.

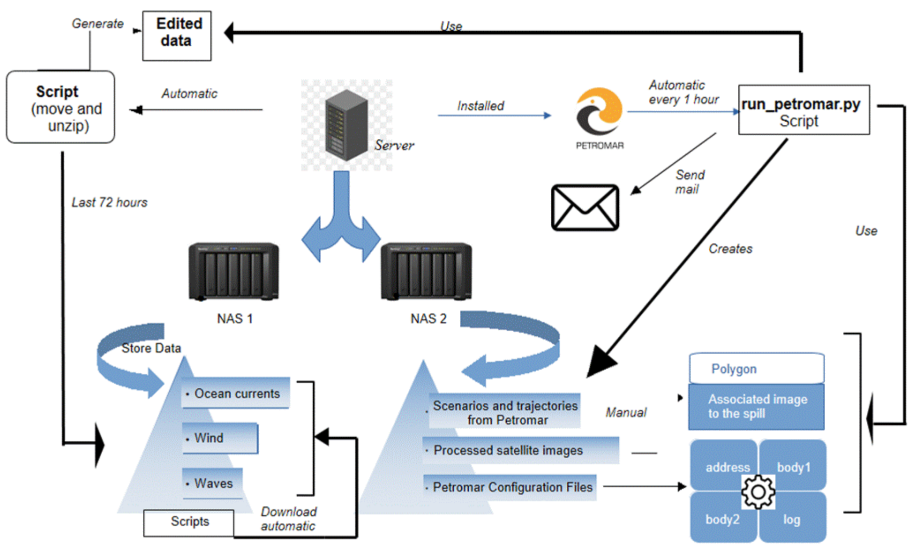

Figure 3. Diagram showing the design of the semi-automatic oil spill surveillance and monitoring system.

In a folder created for the configuration files of "run_petromar.py", there are files that contain the mailing list of the system users, the texts of the notification messages and the oil slick fate forecast for the next 72 hours, and a **log** file that saves the information of each service provided to clients.

So by running the script automatically every 1 hour, it creates a list with the date and time of the last 24 hours, checking the processed images folder to see if they contain any polygon files within the time interval of the previously created list. . The configuration log file that stores the information on the spills that have been simulated is reviewed, and the data is filtered by selecting the new spills detected to execute the modeling.

For each case of interest, the script sends a notification email to the previously configured addresses, attaching the **png** image associated with the spill; and then models the behavior of the oil slick for the next 72 hours by starting the PETROMAR-3D model run. At the end of the run, a second email is sent to the clients with the graphic outputs. The process ends with writing the run data to the log file.

This new service constitutes a new approach in marine surveillance in Cuba. With the previous approach, the user had to provide information on the occurrence of the spill, sent the data on the initial conditions and did not know, in most cases, the cause of the damage. From now on, the monitoring system is the one that discovers the oil slicks, and sends the notification and forecasts to the end users. This constitutes a new paradigm in marine surveillance in our geographical area.

The challenge that this research team faces from now on is the sustainability of this service; given that there is the possibility of obtaining SAR Sentinel 1 images of the Copernicus site daily for free, but with spatial coverage limitations. This challenge can be solved by incorporating into the developed semi-automatic system the oil slick detection methodologies used in satellites with optical sensors. With this technology, free images are also available and several criteria are applied to detect oil slicks in the sea. Only in this case, there will be no automatic information regarding the vessels sailing through the scene of the incident.

CONCLUSION

At the end of this investigation, the following results were achieved:

1. New functions were programmed into the PETROMAR-3D model, creating the capabilities for the initialization of the runs from the SAR images processed with the SNAP-ESA and SEonSE Engine tools.
2. A semi-automatic system for surveillance and monitoring of hydrocarbon slicks in the seas of the EEZ of Cuba was developed.

RECOMMENDATIONS

The authors of this research recommend continuing to delve deeper into:

1. The analysis of the spread of the oil spill from obtaining the polygon from the satellite image.
2. Estimation of the thickness of oil slicks drifting on the marine surface, using SAR technology.
3. Work on the sustainability of this service by incorporating optical satellites and their respective digital oil slick processing techniques.
4. Continue working on the promotion of this service, as well as environmental education to preserve our marine environment.

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