2015

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Bolton, S. (2015) 'Use of space and airborne imagery to monitor and detect oil spills', The Plymouth Student Scientist, 8(1), p. 158-166.
http://hdl.handle.net/10026.1/14089

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2015, **8**, (1), 158-166*

Use of space and airborne imagery to monitor and detect oil spills

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Abstract

Satellite and airborne remote sensing are the two main methods for mapping and identifying oil spills. It is important to accurately map oil spills so that a response effort is most effective. Although it is relatively easy to identify oil spills from remotely sensed imagery, it is more difficult to estimate oil thickness and type. However, it has been noted that due to an increasing issue of potential oil spills, technology is being developed to resolve some of these issues. Other ways that science is aiding in the identification of the specific oil characteristics is through developing models and algorithms by means of laboratory experimentation to update algorithms for oil dispersion rate etc.

1. Introduction

Remote sensing is a technique used to identify an object using electromagnetic energy without physical engagement; it can be achieved using a number of methods and platforms, such as satellites and aircraft (Campbell and Waynne, 2011). The techniques used vary to meet the requirements such as limitations i.e. cost, availability and atmospheric absorption (Carolis, *et al.,* 2013; Klemas, 2010; Goodman, 1994). This often requires a combination of sensor measurements, for example many satellite observations require ground truthing due to the broad swathe, high natural variability in the geophysical parameters of interest and also often poor spatial resolution (Sydnes and Sydnes, 2013; Carolis, *et al.,* 2013; Lillesand, *et al.,* 2008; Goodman, 1994). This requirement for better spatial resolution is discussed here by means of a comparison between the use of satellite imagery and airborne imagery of oil spill detection. The importance of good spatial resolution and the implications of insufficient spatial resolution are also discussed throughout this review. Finally, the importance of precise identification of oil spills e.g. the type and thickness of oil is discussed as this is essential when responding to oil spills and oil spill tracking (Carolis, *et al.,* 2013; Svejkovsky, *et al.,* 2012; Klemas, 2010).

1.1 Oil spills

There are a number of causes that release oil into the water column, such as shipping accidents, illegal dumping, ocean drilling, ship wrecks and also some natural seeps that release oil into the water column (Lillesand, *et al.,* 2008; Brekke and Solberg, 2005). It is important to respond to oil spills promptly and efficiently to minimise the environmental damage and this is enforced by law and legislations in many countries (Sydnes and Sydnes, 2013; Lindsey and Long, 2012; Law, *et al.,* 2011; The Merchant Shipping Regulations, 1998). An efficient response is especially important in the polar regions due to their delicate/vulnerable ecosystems and adverse weather; which causes dispersion of the oil on time-scales of hours to days, with oil possibly becoming en-captured in ice, making clean-up efforts increasingly difficult (Al-Majed, *et al.,* 2012; Sydnes and Sydnes, 2013).

Regular ocean imagery is required to have an archive of data prior to a spill and data from during and after a spill to aid in future spill management and assess the potential damage caused (Sydnes and Sydnes, 2013; Lindsey and Long, 2012; Law, *et al.,* 2011; The Merchant Shipping Regulations, 1998). Models can be produced to predict the effects of advection and spreading which is important in areas of fast ocean currents, such as the Gulf Stream which can cause great dispersion of the spill (Klemas, 2010). Oil spill detection and monitoring requires a short (1-2 days) revisit time so that mapping of the oil spill can occur, allowing relevant predictions i.e. size of spill, can be applied (Carolis, *et al.,* 2013; Leifer, *et al.,* 2012).

1.2 Oil processes at the surface

Oil spills cause extensive damage to marine animals and costal ecosystems i.e. beach and shoreline (Al-Majed, *et al.,* 2012). The extent of damage is related to how quickly the clean-up can be mobilised and the environmental kinetics i.e. sea state and meteorological influences as well as the quantity of spilled oil (Al-Majed, *et al.,* 2012; Brekke and Solberg, 2005). Processes which influence sea surface oil occur almost immediately after oil reaches the surface (Al-Majed et al., 2012). Al-Majed *et al*. (2012), also gives a time frame for some of these processes. In environments with a strong wind influence it greatly increases the spreading rate compared to the spread caused by current and tides; the spread can cause a greater zone of environmental damage, which is the reason for having an oil management system in place to accurately map and monitor so that clean-up is efficient (Carolis, *et al.,* 2013; Sydnes and Sydnes, 2013; Al-Majed, *et al.,* 2012; Law, *et al.,* 2011; Klemas, 2010).

2. Satellite remote sensing

Several wavebands within the electromagnetic (EM) spectrum are used for remote sensing of oil spills (Klemas, 2010). Each method of obtaining data has its own unique advantages and disadvantages when applied to oil spill detection (Klemas, 2010). Most of the advantages and disadvantages relate to the EM frequency and type of sensor used (Svejkovsky, *et al.,* 2012; Klemas, 2010; Brekke and Solberg, 2005). However, a general issue that affects all types of electromagnetic radiation is the attenuation and re-emission of energy caused by various particles, such as water and dust at varying levels of the atmosphere (Lillesand, *et al.,* 2008; Goodman, 1994).

2.1 Passive remote sensing

Passive measurements of oil spill are achieved by measuring temperature or measuring the reflectivity changes across the ocean surface (Leifer, *et al.,* 2012). Various types of passive remote sensors are used to detect oil, such as the use of infra-red, visible and ultraviolet (UV) wavebands. The choice of wavelength relates to how strongly attenuated by clouds and fog the wavelength is which thus inhibits the use of the sensor (Campbell and Wynne, 2011; Goodman, 1994). Other possible issues with visually identifying spills can be caused by a low sun zenith, which results in increased surface glint causing possible masking of oil spills (Carolis, *et al.,* 2013; Goodman, 1994).

2.1.2 *Ultraviolet*

UV sensors can be used to measure surface reflection and hence to determine the difference between oil and water due to oil having a greater reflectivity (oil- 1.02 and water- 0.722) (Klemas, 2010; Goodman, 1994). It is capable of detecting very thin oil spills but unable to determine oil spill thickness or type and “biogenic slicks, sun glint, wind slick” are often misinterpreted as oil spills in UV data (Leifer, *et al.,* 2012; Klemas, 2010). This type of remote sensing requires clear skies and only functions during “daylight hours and is unable to work during the night” possibly indicating that it is unsuitable in highly dispersive conditions, which make it difficult to precisely map and monitor oil (Carolis, *et al.,* 2013; Goodman, 1994). The ability to record a time series of an oil spill is of great advantage as it allows tracking of movement and provides evidence for successful clean-up, which is important when the oil spill is located close to a delicate ecosystem (Carolis, *et al.,* 2013; Sydnes and Sydnes, 2013; Lindsey and Long, 2012; Law, *et al.,* 2011).

2.1.3 *Visible*

Despite being restricted to daylight hours, visible remote sensing is the most common form of remote sensing used to detect oil spills (Klemas, 2010). This is due to the systems being inexpensive and having a reliable transmission window in which they function (Klemas, 2010). An advantage with using visual multispectral imagery is that a polarizing filter can be applied, which greatly increases the ability to detect oil, due to the flattening of the capillary waves forming a flat surface which reflects more efficiently and the reflected light is strongly polarised compared to polarisation of water reflections (Svejkovsky, *et al.,* 2012; Campbell and Wynne, 2011; Brekke and Solberg, 2005). It is also possible to begin to estimate oil thickness from the appearance on the image when calibrated using physical interaction i.e. “in situ measurements” or using laboratory observed ratios for specific wavelengths which are reflected by exact oil thicknesses (Leifer, *et al.,* 2012; Svejkovsky, *et al.,* 2012). The use of highly skilled observers, who combine algorithms with observed characteristics or the spectral signature from the data to estimate the thickness of oil deductively, is recommended when interpreting visible data (Sverjkovsky, *et al.,* 2012; Campbell and Wynne, 2011). When observing, thin oil spills appear metallic and are capable of reflecting most visible wavelengths (Klemas, 2010). Whereas, thicker spills appear brown since they reflect in the 600-700nm region and absorb at the other visible wavelengths (Klemas, 2010). Limitations of visible remote sensing and any predictive algorithm is that it’s only a estimate so contains a high risk associated possibly causing greater environmental damage, as thicker spills could be over looked and time wasted due to misinterpretation of natural slicks (Svejkovsky, *et al.,* 2012; Klemas, 2010).

2.1.4 *Infrared*

The infrared wave band (0.7nm-1mm) is utilized by satellite remote sensing and during oil spill detection; satellites are capable of measuring in the 1-3nm (near infrared), 3-5nm (mid band) and 8-14nm (thermal infrared) (Campbell and Wynne, 2011; Goodman, 1994). The advantages and disadvantages for the types of infrared vary for each operating system as each uses part of the spectrum i.e. sub-divided into specific wavelengths and each wavelength has different interaction characteristics (Goodman, 1994). Infrared systems are suitable for detecting oil due to the ability to derive an emissivity difference between oil and water or a temperature variation across a surface; emissivity is only identifiable after derivation in the thermal infrared band (Goodman, 1994).

2.1.4.1 <u>Thermal infrared</u>

Thermal infrared sensors are one of the few remote sensing systems capable of detecting oil thickness due to temperature difference between thinner and thicker spills; thicker spills are isolated from the surrounding water so appear cooler as oil reradiates heat more efficiently than water (Leifer, *et al.,* 2012; Goodman, 1994). As stated in Leifer, *et al.* (2012), it is important for a prompt revisit time over the oil spill, in the case of the Deep Water Horizon (DWH) spill, the Aqua and Terra satellites had a high revisit time (1-2 days) (Leifer, *et al.,* 2012). However, these satellites tend to have a wide swathe which is suboptimal due to large pixel size, which may be greater than the extent of oil or make it difficult to resolve the edge of the spill (Leifer, *et al.,* 2012; Klemas, 2010). In contrast, a satellite with a high spatial resolution and small pixel size, such as Landsat has a 16 day revisit time making it also unsuitable for mapping oil spills (Leifer, *et al.,* 2012).

2.2 Active satellite sensors

Active satellite sensor measurements involve emitting a signal and monitoring the return strength; an example of an active satellite sensor is the ASCAT (advanced scatterometer) sensor aboard the MetOp-A satellite, which was used to monitor the DWH spill (Lindsey and Long, 2012). This type of scatterometer is capable of measuring 'Bragg waves' or 'Capillary waves', which are useful indicators of oil spills due to Bragg wave dampening caused by a density difference (Lindsey and Long, 2012; Goodman,1994). Bragg waves or capillary waves are low amplitude waves caused by wind roughening the sea surface; when an oil spill is present the surface tension is decreased, prohibiting formation of Bragg waves and therefore areas of oil appear dark as no backscatter is received (Svejkovsky, *et al.,* 2012; Brekke and Solberg, 2005).

Satellite Synthetic aperture radar (SAR), also utilises the microwave frequency to detect capillary wave dampening (Klemas, 2005; Brekke and Solberg, 2005). SAR systems are capable of 24 hour observation and "all-weather" working conditions as only heavy rain interferes with the signal (Klemas, 2005; Brekke and Solberg, 2005). However, SAR is only suitable to detect new spills rather than to monitor spill development, because of limitations in swath size resulting in poor spatial resolution and discrimination abilities (Leifer, *et al.,* 2012: Svejkovsky*, et al.,* 2012).

3. Airborne remote sensing

Most if not all the sensor types described above can be mounted on an aircraft and used in a similar manner as from a satellite, although some sensors, such as the TIR sensors, if aircraft mounted, require lens cooling (Klemas, 2010; Goodman, 1994). It has also been shown that those sensors that are generally associated with aircraft remote sensing can be mounted on satellites i.e. SAR (Svejkovsky, *et al.,* 2012; Brekke and Solberg, 2005). Airborne remote sensing is primarily used to "validate satellite observed" oil spills and due to the higher resolution and detail obtainable to observe coastal and ecosystem impacts (Leifer, *et al.,* 2012). There is a requirement for multiple closely spaced survey lines so as to get complete coverage of the area of interest; however, there are issues with obtaining complete coverage such as cost and repeatability of survey required for mapping of oil (Leifer, *et al.,* 2012).

3.1 Synthetic aperture radar (SAR)

SAR mounted on an aircraft gives the advantage of smaller swath and better monitoring capabilities i.e. good temporal resolution, also SAR is useful to "identify the polluter by mapping the extent and type of spill" (Brekke and Solberg, 2005). Small swath SAR systems have advantages and disadvantages, such as being unable to "discriminate between oil and biogenic slicks" and that SAR imagery is very suitable for "Temporal differentiation" (Svejkovsky, *et al*., 2012). SAR is an important method for mapping and monitoring the extent of oil spills and was used to map the DWH spill despite lacking the ability to discriminate between oil and organic slicks (Leifer, *et al.,* 2012; Svejkovsky*, et al.,* 2012). However, a recognised advantage is the all-weather capability and when aircraft mounted SAR can obtain a high detail (spatial resolution on the order of centimetres) of imagery when compared to satellite SAR systems such as EnviroSat and ERS-SAR (spatial resolution on the order of metres to tens of metres) (Leifer, *et al.,* 2012).

3.2 Side looking airborne radar (SLAR)

SLAR is less modern than SAR and is also less expensive but uses similar principles to SAR; when observing the returned microwave signal or backscatter, areas where a weaker signal is returned appear dark which indicates a possible oil slick (Campbell and Wynne, 2011; Brekke and Solberg, 2005; Goodman, 1994). Aircraft mounted SLAR systems, can operate at a high altitude which gives a large swath, indicating that a large area can be covered in good detail, but due to wind causing mixing and the areas of capillary wave dampening are 'roughened' thus the contrast between oil and water surfaces is reduced, so therefore SLAR is wind speed dependent (Al-Majed, *et al.,* 2012; Campbell and Wynne, 2011; Goodman, 1994). SLAR, is often paired with a "microwave radiometer and laser-fluro-sensor" to form a multi-functional system which is used to map thickness and identify oil type which is important for response efforts (Brekke and Solberg, 2005). Goodman (1994), comments that SLAR is incapable of mapping thickness or type of oil but as explained by Brekke and Solberg (2005), by coupling the SLAR with other sensors it becomes a key component when managing oil spills (Goodman,1994).

4. Algorithms

When managing an oil spill it is important to understand, predict movement of and model the oil spill, so that clean up time is minimised therefore reducing the environmental impact (Carolis, *et al.,* 2013; Sydnes and Sydnes, 2013; Al-Majed, *et al.,* 2012; Leifer, *et al.,* 2012; Svejkovsky, *et al.,* 2012; Klemas, 2010). Algorithms are developed through scientific experimentation and problems include how to control natural variables, such as wind speed and low angle sun zenith (Carolis, *et al.,* 2013; Svejkovsky, *et al.,* 2012; Goodman, 1994). These algorithms are applied to models and also aid when interpreting sensor imagery as to identify oil by its "spectral" characteristics but any algorithm prediction requires some form of ground truthing to test accuracy and often it is difficult to obtain "simultaneous measurements" (Leifer, *et al*., 2012). A real world example of applying algorithms is the DWH spill in which algorithms were used to help characterise oil type by varying reflectance properties of differing oil types and thicknesses (Leifer, *et al.,* 2012). The DWH spill is a relevant example of specific models used such as the "GNOME trajectory model" and the "dispersion and circulation" models, which give timings of ocean current interaction such as the Gulf Stream and provides estimates for rate of dispersion (Klemas, 2010).

4.1 Legislation

With regards to oil spills management, there are a number of laws that must be adhered to that relate to agreements between countries (Sydnes and Sydnes, 2013; Law, *et al.,* 2011). It is important to develop action plans especially for areas of vulnerable ecosystems such as the Barents Sea and the polar regions which are becoming sites for offshore development and have an increased oil risk through increased shipping and offshore infrastructure (Sydnes and Sydnes, 2013; Al-Majed, *et al.,* 2012). Such plans should include how to image and detect an oil spill i.e. which sensor system and should take into consideration the limitations of those sensors e.g. atmospheric windows and attenuation (Campbell and Wynne, 2011). It should also specify who is responsible and who should govern e.g. "Barents euro-arctic region collaboration" (Sydnes and Sydnes, 2013; Law, *et al.,* 2011).

Accurate evaluation of oil spill management requires prior oil spill data so that any impact on the environment/ecosystem caused by the spill can be detected (Law, *et al.,* 2011). Primary data which should be collected prior to an accident would include fish stocks and the "general state of the ecosystem" (Law, *et al.,* 2011). Due to a constant update of data being required, this is one of the main reasons satellite remote sensing is as applicable, as satellites can offer good regular (2-3 days) coverage of an area and can measure multiple variables at any one time - important when mapping/monitoring atmospheric conditions and oil spill extent (Al-Majed, *et al.,* 2012; Leifer, *et al.,* 2012; Lindsey and Long, 2012).

5. Sensors

Many satellites have many multiple sensor capabilities, for example NASA's Terra and Aqua satellites are capable of measuring in the Visible, Mid-IR and TIR (Leifer, *et al.,* 2012). The issues that face oil spill detection relate to the spatial resolution, as a spatial resolution of 1 km will be unable to accurately detect the location of spills that have a smaller extent i.e. < 1 km (Leifer, *et al.,* 2012; Lindsey and Long, 2012; Brekke and Solberg, 2005). The spatial resolution is determined by the area of the Earth's surface corresponding to one pixel at the detector (Campbell and Wynne, 2011; Lillesand, *et al.,* 2008). Often, sensors with narrower swaths are designed to have finer spatial resolution (Lillesand, *et al.,* 2008; Brekke and Solberg, 2005). However, smaller swath systems have a longer revisit time (10 day+), so they may be unsuitable for mapping as constant/frequent monitoring is needed in a highly dispersive system (Carolis, *et al.,* 2013; Leifer, *et al.,* 2012; Klemas, 2010). An example of a long revisit time with small swath is the Landsat satellite which has a repeat rate of 16 days thus making it impractical for oil monitoring (Carolis, *et al.,* 2013; Leifer, *et al.,* 2012; Klemas, 2010).

Satellite remote sensing is useful for an accurate estimation of spill size and for data when modelling the spill as other observations such as from meteorological systems can be applied; for example weather fronts i.e. hurricanes can intensify the dispersion process (Al-Majed, *et al.,* 2012; Leifer, *et al.,* 2012; Lindsey and Long, 2012; Klemas, 2005). For higher quality mapping of the exact extent of spill, airborne systems such as SEBASS and other SAR and SLAR systems are used due to the high spatial resolution used to accurately define the slick boundaries (Svejkovsky, *et al.,* 2012; Brekke and Solberg, 2005). Aircraft is an ideal platform as planes can be launched and map exact areas of interest quickly and efficiently, but they are not as economically viable as satellite systems (Svejkovsky, *et al.,* 2012; Leifer, *et al.,* 2012; Goodman, 1994).

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