An Assessment of Surface Surveillance Capabilities for Oil Spill Response using Satellite Remote Sensing

Provided for IPIECA and OGP

Abstract. This report provides an assessment of satellite surveillance for oil spill response, carried out for IPIECA and OGP under contract OSR-JIP Polar 001.

10 April 2014

Kim Partington
Polar Imaging Limited

Reference PIL-4000-35-TR-1.2

Polar Imaging

GEOCENTO earth imaging

Issuing Authority			
Name	Kim Partington, Managing Director, Polar Imaging Limited		
Address	"Farthings", Stoke Road, Hurstbourne Tarrant, Andover, Hampshire, United Kingdom SP11 0BA		
Telephone	+44 7796 956594		
Fax	+44 870 705 9990		
Email	Kim.partington@polarimaging.co.uk		
Company registration	5919275	Date of incorporation	30 August 2006
VAT registration	892821689		

Delivery	
Copy No.:	**Delivered to:**
1	Office copy
2	Richard Eyers, Shell
3	Rob Cox, IPIECA

Document Change Record			
Issue	**Revision**	**Date**	**Reason for revision**
1	0	11th January 2013	First issued and delivered version
1	1	3rd March 2014	Revised lead and latency time maps; updated introductory section
1	2	10th April 2014	Added reference to partner IPIECA airborne surveillance report

Frontispiece: Visible satellite image of the Gulf of Mexico from NASA's Terra satellite of the Gulf oil spill on May 17, 2010, from the Moderate Resolution Imaging Spectroradiometer (MODIS) Instrument.

Table of Contents

Acknowledgements

The author acknowledges the important and appreciated support and input from several individuals and organisations, as follows:

- Leadership, management and funding from Oil and Gas Producers Association (OGP) - International Petroleum Industry Environmental Conservation Association (IPIECA) Joint Industry Project, under contract OSR-JIP Polar 001, managed by Rob Cox.
- Technical direction from Richard Eyers (Shell Petroleum Development Company of Nigeria) and members of the work package 2 steering committee, including Roger Abel (Shell Exploration & Production), Louis Demargne (Fugro), Peter Hausknecht (Woodside), Rob O'Brien (BP), Emma Hughes (Oil Spill Response Ltd), Richard Hall (Statoil) and Ola Grabak (European Space Agency).
- Support from GeoCento Limited and Taitus Software Italia S.r.l. in providing and enhancing the multi-mission planning capabilities for the assessment.
- Input from many satellite data vendors, remote sensing value-added organisations, oil spill responders and researchers, many of whom invested significant time in contributing to the workshop and responding to the questionnaire and interviews.

Acronyms

This table does not include the names of satellites or sensors that are made up of acronyms.

Table 1. List and explanation of acronyms.

Acronym	Description	Acronym	Description
AIS	Automatic Identification System	MWIR	Mid-wave Infrared
AoI	Area of Interest	n/a	Not Applicable
API	American Petroleum Institute	NASA	National Aeronautics and Space Administration
ASF	Alaska Satellite Facility	NESZ	Noise equivalent sigma zero (noise floor in relation to radar backscatter)
CEOS	Committee on Earth Observation Satellites	NIR	Near infrared
COP	Common Operating Picture	O&G	Oil and Gas
EM	Electromagnetic	OGP	Oil and Gas Producers Association
ESA	European Space Agency	OPT	Optical
GIS	Geographic Information System	OSR	Oil Spill Response
HH	Horizontal transmit, horizontal receive polarisation	MWIR	Mid-wave Infrared
Hr	Hour	PAN	Panchromatic
IPIECA	The global oil and gas industry association for environmental and social issues	RGB	Red green blue (referring to false colour image)
IR	Infrared	SAR	Synthetic Aperture Radar
JIP	Joint Industry Project	SWIR	Shortwave Infrared
LWIR	Long-wave Infrared	TIR	Thermal infrared
m	Metre	UV	Ultraviolet
MS	Multispectral	VIS	Visible
m/s	Metre per second	VV	Vertical transmit, vertical receive polarisation

Executive Summary

Oil spills have the potential to threaten human health and safety, the integrity of the environment and the viability of local economies, and the oil and gas industry has a responsibility to seek out and deploy all available technologies to both minimise the risk of spills, and to deal effectively with them if and when they occur. In response to this, OGP-IPIECA has funded an Oil Spill Response (OSR) Joint Industry Project (JIP) to optimise the industry's capabilities for oil spill response. This report forms part of work package 2 within this JIP, and focuses on identifying capabilities and gaps associated with surveillance monitoring from satellites. It is complementary to a similar report assessing surveillance capabilities of airborne platforms and sensors for oil spill response [1]. Together, these reports cover remote sensing technologies and platforms for oil spill response, and these are linked to recommendations from the American Petroleum Institute (API) in their assessment of remote sensing for oil spill response [1].

Satellite remote sensing is now an accepted and integral component of effective oil spill response. The capabilities of the technology have developed significantly over the last two decades to the point where the technology is now genuinely meeting useful industry needs in terms of spatial and temporal sampling and timely response. Unlike airborne or in situ platforms, satellites are routinely available being operationally independent of weather, logistics, political or other ground or airspace conditions. They are particularly useful and cost effective for wide area synoptic coverage that can be used to deploy airborne assets both efficiently and, in some cases, safely, and can on occasion contribute to tactical surveillance. Satellite remote sensing has thus developed into an effective and essential contributor to the overall suite of technologies required for effective oil spill response.

In order to make effective use of this technology, key findings are as follows:

- A centralised, operational oil and gas industry facility for coordinating planning of satellite surveillance for OSR should be established,
- It is recommended that a regular satellite remote sensing technology horizon scan be carried out, extending 5 years, to ensure that the industry is aware of upcoming satellite remote sensing technologies and data.
- To exploit data from multiple satellites and sensors, and to support effective multi-sensor integration, technology should be available with which to identify, select and plan suitable data for OSR from among the range of useful satellite missions.
- Local satellite surveillance plans for OSR, incorporated within Field Development and Emergency Response Plans, should be generated. These satellite surveillance plans should be customised for the particular environmental and operational challenges of each local area.
- Once the data requirements have been defined and suitable contractual vehicles put in place to support local satellite surveillance plans, a satellite image acquisition plan should be maintained and refreshed in real time so that, in the event of a spill, the plan can be executed with immediate effect. Such a plan may be maintained and operated from the centralised oil and gas industry satellite surveillance facility.

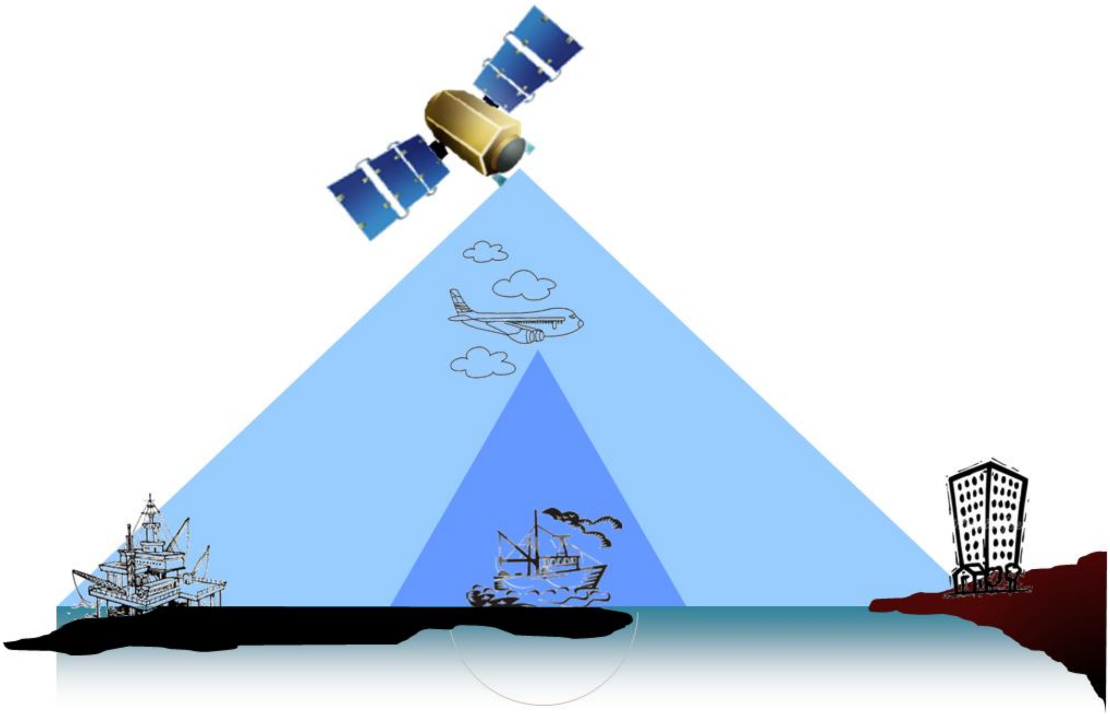
- A programme of baseline satellite monitoring at key industry locations should be carried out, to facilitate early detection of spills and to provide a baseline for any spill event.
- The oil and gas industry should be pro-active in ensuring that research and development is being actively steered towards the goal of effective OSR, through appropriate networks and industry organisations involving the space industry.
- The industry should ensure that criteria are available that define satellite sensor characteristics of value to OSR, and should communicate these to satellite mission planners and designers.
- The industry should encourage the development of promising new instrument and measurement concepts, through collaborative research with academic and other research organisations.
- The industry should be open to innovative satellite platform options for OSR surveillance, potentially involving up-front investment if justified.
- There should be ongoing research focused on SAR, as the primary satellite sensor for synoptic surveillance of oil spills, focusing in particular on L and S band, and on the use of polarimetry.
- In order to better exploit optical data, a programme of research should be focussed on the potential of new sensors including new infrared spectral frequencies, and the application of lab-based spectroscopic techniques to practical OSR application from satellites.
- Satellite data should be routinely included as an element of OSR exercises. Historically, such exercises have tended to focus on ground-based and airborne activities, but satellite technologies should be included.

In summary, satellite remote sensing is a disruptive technology, and the capabilities, number and range of sensors and suppliers is growing significantly. If the findings from this report were to be summarised in terms of one over-arching recommendation, it would be to fully plan satellite surveillance so that nothing has been left to chance prior to an oil spill.

1. Introduction

Oil spills have the potential to threaten human health and safety, the integrity of the environment and the viability of local economies, and the oil and gas industry has a responsibility to seek out and deploy, all available technologies to both minimise the risk of spills, and to deal effectively with them if and when they occur. Satellite remote sensing is one such key technology which has been evolving rapidly in recent years, with many more satellites, a greater variety of sensors, and improving operational capabilities. However, there are two challenges associated with this: the first is to work effectively with suppliers to ensure that such improvements are exploited for OSR and the second is to be aware of the limitations of this technology so that alternative assets can be deployed appropriately. Used judiciously, satellite remote sensing can ensure that costly airborne and ground-based assets can be deployed in an effective and timely manner. This document provides an assessment of the capabilities of the technology for OSR, identifies gaps, and provides findings for enhanced use of the technology by the industry. This work forms part of work-package 2 "Surface Surveillance" of the OGP joint industry project (JIP) 8 "Surface Surveillance and Tracking" for OSR, established to enhance industry practices in connection with oil spills.

Figure 1. Schematic of the role of satellite remote sensing in oil spill response. Satellites can provide an effective synoptic overview of the spill and field of operations and contribute to effective deployment of airborne and other assets.



2. Objectives

The objectives of the surface surveillance work are:

- A review of intrinsic technical capabilities of space-borne sensors, incorporating information from literature, workshop reports and direct from commercial vendors;
- An assessment of current and planned future capabilities of sensors and relevant platforms in terms of actual response to oil spills in different global locations, to include timeliness of response;
- Identification of technology and surveillance gaps;
- Suggestions for follow-on activities, including research, technology development and improved infrastructures, to close gaps.
- Coordination with work from the API and other JIP tasks.

3. Scope

This report focuses on surveillance capabilities of satellite sensors and platforms for oil spill response, considering both intrinsic capabilities and practical, operational capabilities. It is complementary to a similar report assessing surveillance capabilities of airborne sensors for oil spill response [1]. Together, these reports cover remote sensing technologies and platforms for oil spill response. These two reports are also complementary to the API report on Remote Sensing in Support of Oil Spill Response [2]. The API report provides recommendations in terms of how remote sensing is integrated into the overall OSR activity; how to involve remote sensing using a 5 step process in terms of teaming, key individual roles and links to specific applications within OSR, and how to select the most appropriate remote sensing technologies and platforms via an assessment of their strengths and weaknesses. This OGP report does not address issues related to teaming and application to the broader OSR activity; instead, it focuses on some of the practical issues associated with satellite data availability. There is some overlap between the two reports in terms of providing information on intrinsic sensor capabilities, but the results of the two assessments are consistent.

The scope of this report can be described as follows:

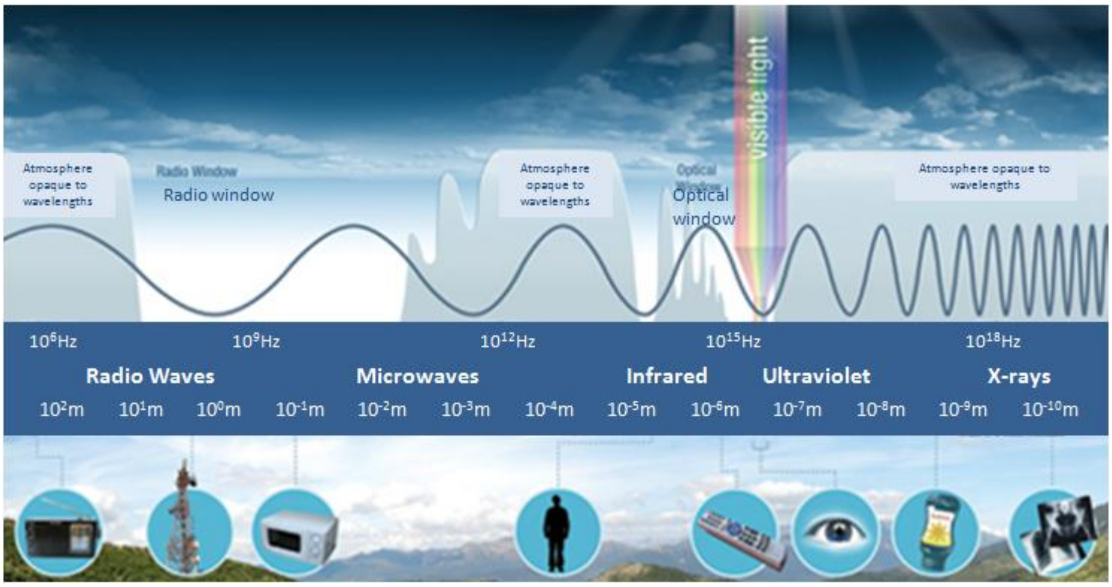
- Surveillance of oil spills from satellite remote sensing only, with an emphasis on commercial suppliers;
- Focus on effective selection of, and access to, remote sensing data rather than on value-added analysis or downstream application of the data. For the latter, OGP/IPIECA JIP 8 WP 5 on GIS/Mapping and Common Operating Picture is relevant [3] as well as the work of the API [2];
- Detection and characterisation of oil spills and not other met-ocean parameters, except for identifying these additional parameters when they are a potential by-product of data acquisition for OSR;
- Surveillance of offshore and coastal domains; land and polar domains are addressed briefly.
- Sampling of the top 25 metres of the ocean surface only (i.e. not covering atmospheric sampling).
- Consideration of technical and operational factors in relation to satellite data, and not commercial factors.

4. Satellite Remote Sensing

Satellites have been providing observations of the Earth since the early weather satellites of the 1960s. There are now a plethora of satellites and sensors available with which to image the surface of the Earth. This creates at once both an opportunity and a challenge for the oil and gas industry, and for planning OSR in particular.

Space-borne remote sensing involves the use of instruments that are measuring properties of the Earth from above the atmosphere, either from a "geostationary" position constantly overhead with respect to a location on the Earth, or in a "polar-orbiting" configuration, in which the satellite is continuously precessing around the Earth and thus building up coverage. The remote sensors on board these platforms cover a wide range of electro-magnetic wavelengths from short optical wavelengths (covering visible and infrared) to long microwave wavelengths. The human eye can detect only the visible portion of this spectrum, which represents a very small component (*Figure 2*). While data collected in the visible part of the spectrum is inherently interpretable to the human eye, other parts of the spectrum offer great advantages, notably in terms of being able to see through clouds (microwave) and being sensitive at various wavelengths to absorption by oil (infrared).

Figure 2. The electromagnetic spectrum, courtesy of NASA [4].



There is an opportunity with remote sensing to use different parts of the electromagnetic spectrum in a complementary fashion, notably to counter sampling limitations and to resolve false target (oil spill) alarms from more restricted sensing. Key spectral bands are identified below for both passive and active sensing.

As well as measuring properties of the Earth at a wide variety of wavelengths, sensors are also designed to be either active (transmitting and receiving radiation) or passive (receiving naturally transmitted radiation). The ability to sample both naturally occurring radiation and specially configured man-made radiation from across the electromagnetic spectrum is a key strength of remote sensing technology (*Figure 3*).

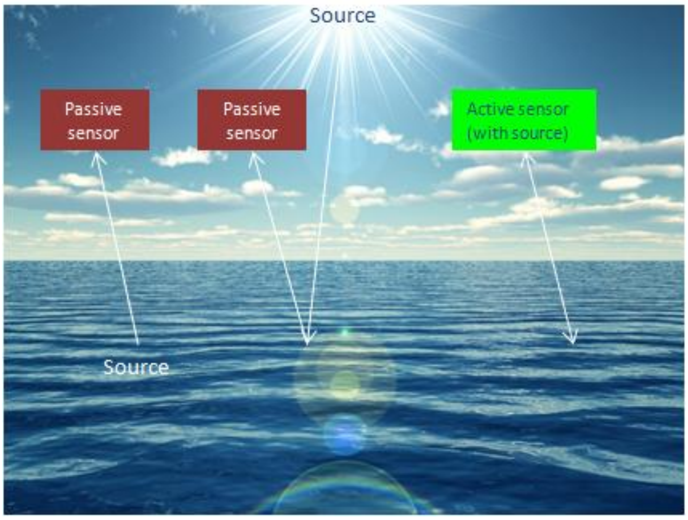


Figure 3. Illustration of passive and active remote sensing.

4.1. Passive Sensing

Passive sensors can collect electromagnetic radiation from across the spectrum, but because they depend on natural processes, there are limitations in terms of diurnal sampling (some need daylight), sensitivity to weather (which can absorb or distort the radiation) and effective spatial resolution (because the radiation cannot be configured to enable high resolution to be achieved through signal processing and other techniques).

Visible (VIS) imaging involves the use of colour in detecting and characterising oil spills and in the case of airborne remote sensing has historically involved trained observers, but now also involves a range of sensors that can support more data intensive and analytical assessment.

Infrared (IR) extends from near IR (NIR) to short wave IR (SWIR). In this part of the spectrum, outside the range of detection of the human eye, there are absorption frequencies associated with oil which can be useful for detection, and potentially other characterisation, including 1.19-1.21, 1.72-1.73, 1.75-1.76, 2.37 and 3.3 µm. The SWIR is able to be used through thin cloud, haze and fog.

The ***thermal infrared*** (TIR) part of the spectrum responds to both the temperature and emissivity of the target. The emissivity is the efficiency with which incoming radiation is emitted by an object, the reference being the idealised case of a black body, in which all incoming radiation is emitted and none absorbed by the surface or object. The thermal properties of a surface can be observed during day or night, which is extremely useful for a time critical application such as OSR. Similar principles apply to the microwave part of the spectrum, but in this case there is less sensitivity to weather conditions.

Passive microwave radiometers (PMR) detect naturally occurring microwave radiation and are also sensitive to the emissivity properties of the surface. The emissivity is the relative ability of a target surface to emit energy by radiation. It is the ratio of energy radiated by the surface to energy radiated by a black body at the same temperature. A black body is an idealized target that absorbs all incident electromagnetic radiation.

4.2. Active Sensing

Active sensors, including radar and laser, are able to observe the Earth during day or night, having their own method of illumination. The energy source is able to be configured to optimise sampling of the surface, focussing the energy to achieve high spatial resolution, for example, or to minimise atmospheric absorption. Because of the complexity of the technology, these sensors come with their own challenges in terms of data processing and interpretation. Coherent imaging sensors, for example, have "speckle" which is a form of radiometric noise that is present when the data are analysed at their full spatial resolution.

Laser is an active optical sensor that receives echoes of transmitted light from regular positions along the surface beneath the satellite orbit. Laser is coherently transmitted optical radiation. The coherence refers to the control over the radiation wavelength and phase. Although laser can be used during day or night, it is impacted by atmospheric attenuation of the signal, for example in conditions of fog or cloud. Laser can be used for measuring distance to the target (via time of flight of the signal) which may be used to estimate surface elevation and is in this configuration is known as "lidar". Over land, lidar may be used to assess vegetation canopy height and over the ocean, may be used to penetrate below the surface, depending on specific wavelength. As in the case of hyperspectral sensors, there are very limited spaceborne sensors currently available, or experience in the use of lidar for OSR, and their spatial sampling is very limited.

Radar also involves the transmission of coherent radiation, but at microwave frequencies, and is sensitive to the roughness and dielectric properties of the surface being imaged, the latter being strongly influenced, for example, by moisture content. Radar can be used to measure distance to the surface, in vertically configured form, or can be used to generate images of the surface. Radars measure radiation at a range of wavelengths which are sensitive to different scales of surface roughness (typically from mm to decimetre scale), and some of the longer wavelengths are able to penetrate vegetation or even dry ground. Although radar sensors are very useful because they can observe the surface during almost all conditions, they are particularly complex to interpret because they are sensitive to very different surface conditions to those of optical sensors and the human eye, and so are far from intuitive to understand.

This variety of fundamental sensor properties comes with a range of surface sampling capabilities and environmental sensitivities, which impact on their appropriateness and roles for OSR. The key categories of satellite remote sensing technologies are illustrated in *Figure 4* and *Table 2* in terms of their sampling and spectral characteristics.

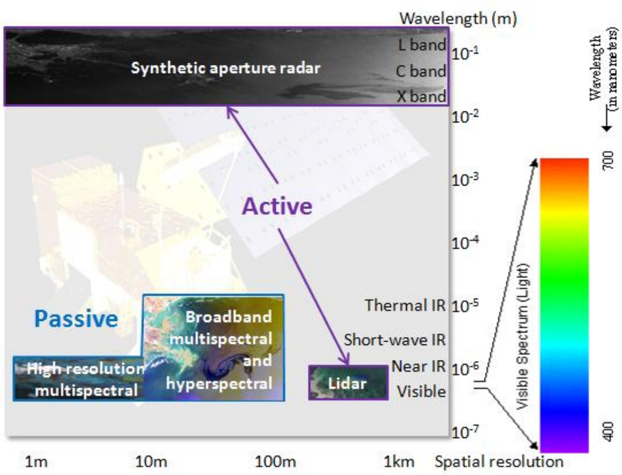


Figure 4. Schematic showing four main categories of satellite remote sensing technologies for OSR.

High resolution multispectral sensors achieve high spatial resolution, but have limited spectral sampling in the VIS and NIR wavebands. As NIR and VIS optical sensors, they are limited by cloud and daylight, and their main value lies in providing detailed spatial information regarding the distribution of the oil spill when conditions allow.

Broadband multispectral and hyperspectral sensors have good spectral sampling in the infrared bands, at and beyond NIR, where there is particular sensitivity to oil on water. Hyperspectral sensors contain many tens of channels of data at different optical wavelengths and with high spectral resolution, while broadband multispectral sensors have fewer channels which are designed to sample particular key wavelengths. While, the spatial resolution of these sensors is relatively coarse, they do provide a wide range of spectral frequencies that can be very useful for detecting and, in some cases, characterising oil. An example is the use of TIR during clear night conditions.

Table 2. Satellite remote sensing categorisation for OSR.

	Microwave	Optical		
	Active	Passive		Active
Sensor category	SAR	High resolution optical	Broadband multispectral and hyperspectral	Lidar
Wavelengths[1]	L to X band	VIS to NIR	VIS to TIR (via NIR, SWIR, MWIR)	VIS to NIR
Number of wavelengths / channels	1 (multiple polarisations often available)	~3 to 8 (not including PAN)	~7 to ~230	~2
Spatial resolution	~1 to ~500m	<1m to ~10m	~10m to ~1km	~300m
Swath width[2]	~5 to 500km	~10 to 90km	~30 to ~60km	~300m
Current sensors	*Table 8*	*Table 10* *Table 11*	*Table 12*	*Table 9*
Future sensors	*Table 13*	*Table 14*	*Table 15*	*Table 16*
False alarms	*Table 7*			

The API have provided an overview of the advantages and disadvantages of many of these remote sensing instruments [2].

[1] Wavelengths are as follows: Microwave (radar): X band ~ 3cm; C band ~5cm; S band ~10cm; L band ~ 20cm. Optical: VIS~0.4-0.74µm; NIR 0.75–1.4 µm; SWIR 1.4-3 µm; MWIR 3–8 µm and TIR 8–15 µm.
[2] Instantaneous coverage perpendicular to the orbit direction.

5. Methodology

5.1. Overview

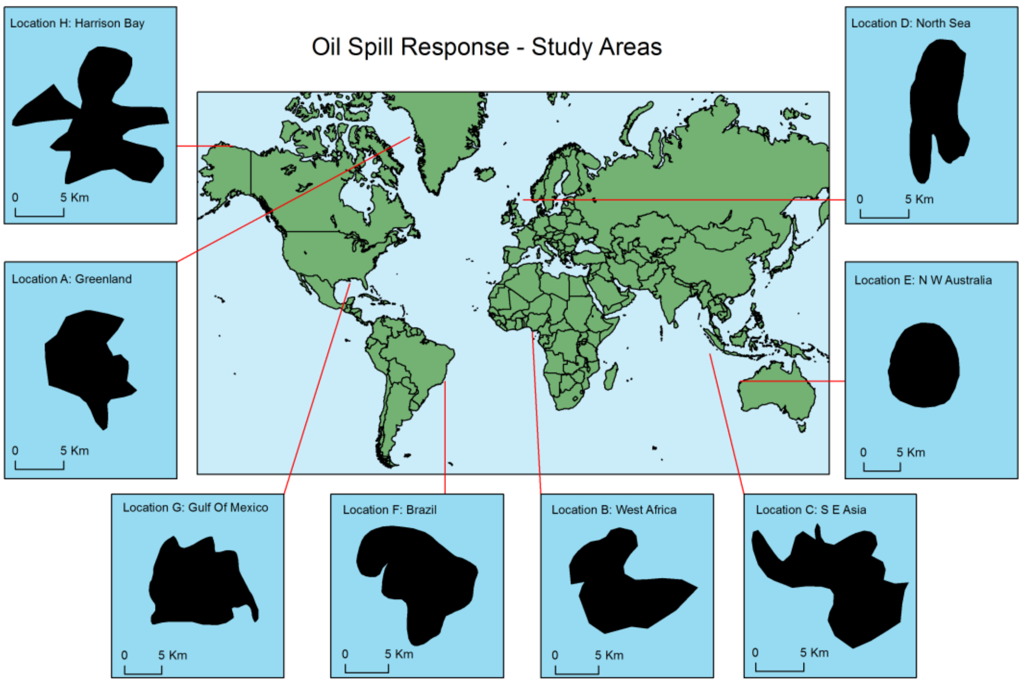
The source material for this assessment of satellite remote sensing capabilities for OSR includes the following:

- Open literature which (a) reviews experiences from oil spills and (b) reviews or assesses specific remote sensing technologies for OSR (e.g. see [5], [6], [7], [8], [9], [10], [11], [12] and [13]).
- A workshop held in Frascati, Italy, 18-19 February 2013, with questionnaires sent prior to the workshop. The workshop was sponsored by IPIECA and hosted by the European Space Agency (ESA), and included both invited presentations, vendor pitches and discussion sessions. The workshop invited the participants to specify requirements for OSR and to identify current capabilities and gaps, leading to a set of findings.
- Post-workshop questionnaires sent to commercial satellite image suppliers. The questionnaire solicited vendor suggestions on which sensors are appropriate for OSR, the capabilities of the sensors in terms of quality of data, sampling and responsiveness, and suggestions in terms of configurations and processing.

5.2. Satellite Surveillance Analysis

An analysis of satellite surveillance capabilities using multi-mission planning software carried out to assess surface surveillance capabilities for eight diverse sample areas (*Figure 5*). These sample areas are entirely theoretical, involve no oil release, and have been selected to cover proximity to oil and gas activity, a range of scenarios from exploration to production and transportation, and wide geographic coverage.

Figure 5. Eight test areas used for assessing OSR capabilities (not linked to actual oil spills).



The analysis involves the use of multi-mission satellite planning software called "Savoir" ([14], *Figure 6*). The scenarios that were implemented are identified in *Table 3*.

Table 3. Satellite surveillance analysis scenarios.

		For each of the eight sample areas:	
		Key suppliers: McDonald Dettwiler and Associates, EADS Astrium, E-GEOS, RapidEye and DigitalGlobe	**All suppliers:**
Image lead time	SAR	<30m spatial resolution 22-45° incidence angle 100% AoI coverage	Not assessed
	High Resolution Optical[3]	<10m spatial resolution 100% AoI coverage Solar zenith angle < 80°	
Image latency	SAR	<30m spatial resolution 22-45° incidence angle 100% AoI coverage	
	High Resolution Optical[3]	<10m spatial resolution 100% AoI coverage Solar zenith angle < 80°	
Image revisit	SAR	<30m spatial resolution 22-45° incidence angle 100% AoI coverage	<30m spatial resolution All incidence angles 100% AoI coverage
	High Resolution Optical	<10m spatial resolution 100% AoI coverage Solar zenith angle < 80°	<10m spatial resolution 100% AoI coverage

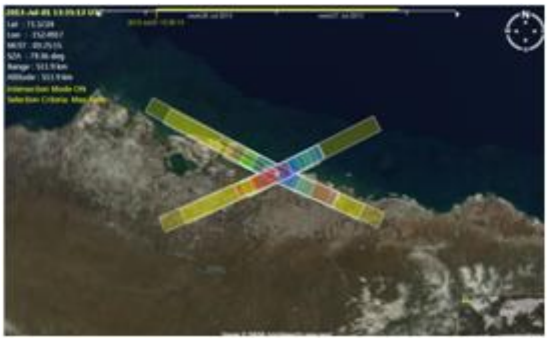
The assessment scenarios were divided into those that focused on moderate to high resolution SAR data, at less than 30m spatial resolution, and high resolution optical imagery, at less than 10m spatial resolution. The former is useful for initial assessment and synoptic monitoring, while the latter is useful for more detailed assessments, when atmospheric and lighting conditions allow. Note that for SAR assessments, the incidence angles are limited to between 22° and 45°, which represents the configuration that is normally adequate for oil spill detection. For the high resolution optical assessments, clear sky conditions are assumed, but acquisitions are discounted is local solar zenith angle is less than 80° (indicating low or no daylight).

Some of the analysis was carried out for so-called "key suppliers". These are suppliers who have the most significant space assets and demonstrated OSR capability, and are listed in *Table 3*. The specific satellites associated with the key suppliers can be identified in *Table 8* and *Table 10*. In the analysis, lead times for data (the time for image order to acquisition) and image latencies (the time from image acquisition to availability) are calculated for so-called "key suppliers", while in analysis of revisit timings for the eight sample areas, calculations are also included for all satellites that meet the sampling constraints, so that it is possible to see the extent to which other suppliers add significantly to revisit times in the different sample areas.

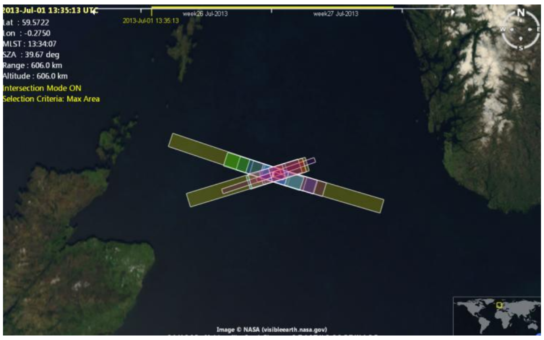
Based on this material, an overall assessment was carried out of satellite surveillance capabilities for OSR, gaps were identified, and findings reported.

3 DigitalGlobe was not included here as a result of a lack of information.

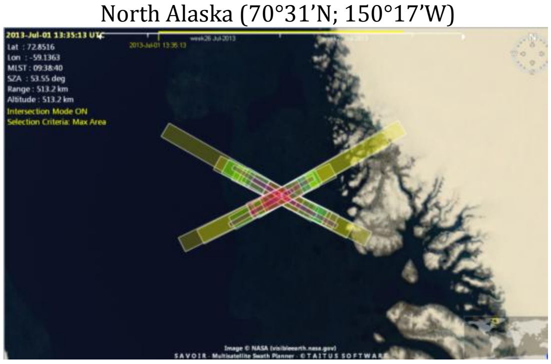
Figure 6. Examples of high resolution optical image coverage of the eight sample areas generated using "Savoir" (different colours relating to different satellites).



North Alaska (70°31'N; 150°17'W)

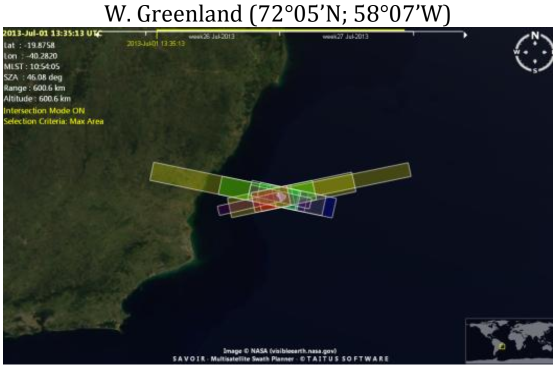


North Sea (58°39'N; 1°08'E)

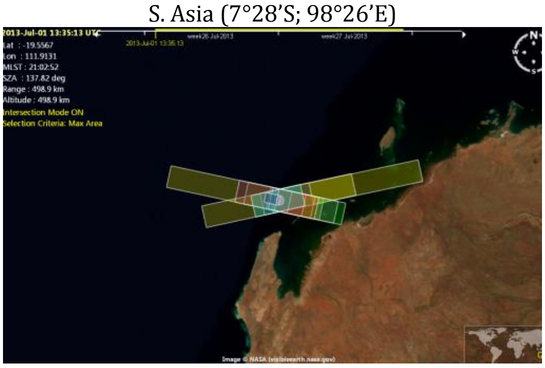


W. Greenland (72°05'N; 58°07'W)

S. Asia (7°28'S; 98°26'E)

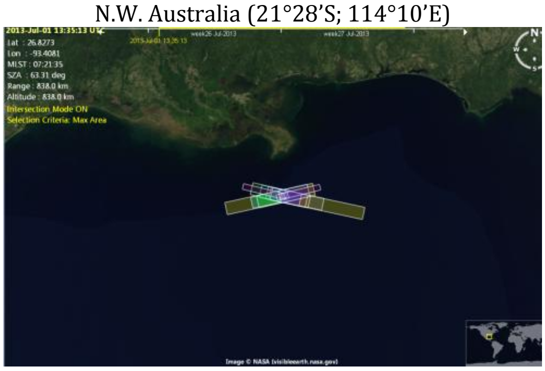


S.E. Brazil (21°11'S; 39°44'W)



N.W. Australia (21°28'S; 114°10'E)

W. Africa (3°55'N; 5°45'E)



Gulf of Mexico (28°10'N; 89°14'W)

6. Oil Spill Response Requirements for Satellite Remote Sensing

The requirements that apply to the use of satellite remote sensing in OSR are summarised in *Table 4*, and derived from the work of the API [1].

Table 4. Satellite Remote Sensing Requirements for OSR, from [1].

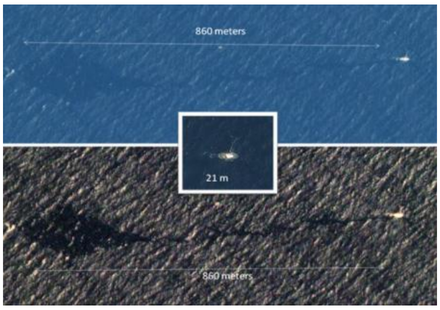
	INITIAL ASSESSMENT	SYNOPTIC MONITORING
Role	• Situational awareness at the source; • Determination of the extent of the release and other characteristics; • Support to selection of appropriate recovery methods.	• Spill extent, location, tracking and condition; • Identification of resources at risk; • Support to modelling / forecasting • Support to tactical operations including: mechanical recovery; application of dispersants; controlled in situ burning; shoreline assessments.
Information lead time	Goal: 3 hours from spill alert, or other emergency request, to data acquisition; Minimum requirement: 24 hours from emergency request to data available.	
Information latency	Goal: available for access (with quality control) <1 hour after acquisition	
Revisit	Minimum requirement: daily (365 days per year)	
Sampling	Goal: 100% of spill with spatial resolution << expected spill dimension.	
Oil parameters	Minimum requirement: oil extent; Goal: concentration, type/condition, thickness distribution, depth distribution.	
Other parameters	Goal: (a) Pre-spill baseline conditions (environment, infrastructure, etc.) for impact assessment, elimination of false alarms, etc. (b) Post-spill near real time conditions: • Nowcast and forecast meteorological, ocean, land and ice environmental parameters as appropriate; • Hazard identification, locations and evolution; • Asset locations, condition and access.	
Other critical requirements associated with satellite or satellite-derived observations	Minimum requirement: compatibility with Common Operating Picture; Goal (if not included in COP): (a) Clear definition of area(s) of updated information and area(s) of no updated information; (b) Clear timing(s) associated with updated information; (c) Text explanations where appropriate, to support interpretations; (d) Available statistics on uncertainty associated with information (location, measurement uncertainty, false alarm rate, detection failure rate, etc.); (e) Information on next update times and areas;	

7. Application of Satellite Remote Sensing to OSR

Satellite remote sensing is now an accepted and integral component of effective oil spill response. The capabilities of the technology have developed significantly over the last two decades to the point where the technology is now genuinely meeting useful industry needs in terms of spatial and temporal sampling and timely response. Unlike airborne or in situ platforms, satellites are routinely available being operationally independent of weather, logistics, political or other ground or airspace conditions. They are particularly useful and cost effective for providing wide area synoptic coverage that can be used to deploy airborne and surface assets both efficiently and, in some cases, safely, and can contribute to tactical surveillance. Satellite remote sensing has thus developed into an effective and essential contributor to the overall suite of technologies required for effective oil spill response. The API provides a detailed overview and set of recommendations regarding how remote sensing should be incorporated into OSR, in terms of teaming, role of personnel, etc [1].

Most experience in the application of satellite surveillance to OSR has been gained in the offshore environment, and this domain represents the main focus of this report. However, satellite surveillance can also be used on land, and over ice-covered seas, which are discussed briefly below. These latter two environments present their own unique challenges for satellite remote sensing.

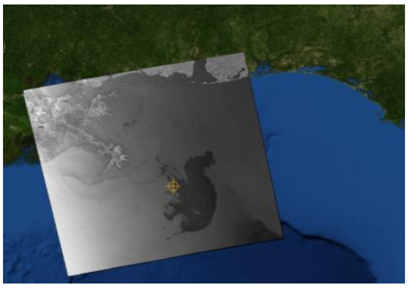
Figure 7. Examples of satellite remote sensing data for OSR.



Sample detection of oil pollution caused by a small vessel using very high resolution optical data from Pléiades. Pléiades Imagery © CNES 2012 – distribution Astrium Services / Spot Image.

HICO hyperspectral image of the mouth of Chesapeake Bay reproduced courtesy of Naval Research Laboratories, Washington DC (north is to the right).

MODIS image of the Gulf of Mexico oil spill, courtesy of NASA. MODIS data is an example of a broadband multispectral sensor, with 36 spectral channels.



RADARSAT-2 SAR (C band microwave) image of the Gulf of Mexico oil spill in 2010, provided courtesy of McDonald Dettwiler and Associates. RADARSAT-2 image ©MDA, 2010. RADARSAT is an official trademark of the Canadian Space Agency.

7.1. Offshore OSR

In the offshore environment, satellites can be used to provide synoptic coverage, and the contrast between oil and water is often great enough, across much of the utilised parts of electromagnetic spectrum, to make this effective. The basic features and principles of satellite remote sensing of oil spills are shown in the *Table 5*.

Table 5. Overview of satellite sensors for offshore OSR.

	Microwave	**Optical**			
	Active (radar)	**Passive**			**Active (lidar)**
Band	SAR	TIR-MWIR	SWIR-NIR	VIS	VIS-NIR
Measurement fundamentals					
Measurement	Radar backscatter	Surface temperature	Natural emitted radiation		Scattered transmitted light
Oil Observations					
Oil detection	Oil spill surface roughness damping from short gravity waves to capillary waves	Temperature of spill relative to surroundings	Absorption from oil at 0.8, 1.2, 1.73 and 2.3μm	Sun glint (non-specific absorption)	Scattering from oil at depth
Oil characterisation (Oil-water ratio, type, thickness and weathering)	Not proven: R&D status	Spill thickness influences temperature differential with sea water	Reflectance and absorption due to compounds in the oil vary with oil thickness and oil-to-water ratio [15]	Colour has some value for thickness and condition	Not proven: R&D status
Ancillary observations	Surface wind vectors, current, ice, hazards, infrastructure	Fire, toxic gas detection, sea surface temperature	Coastal vegetation condition	Infrastructure Coastal vegetation condition (red edge)	Surface wind speed; scattering from aerosols
Applicability of Observations					
Oil type	All				
Oil thickness	All (insensitive to oil thickness)	Minimum detectable ~20 μm; signature transition ~50-150 μm thickness	spills thinner than ~175 μm but not sheens	spills thinner than ~175 μm (VNIR)	Unknown
Oil depth	Surface				Surface to ~few m for turbid coast to ~100m for clear water

However, the technology has limited ability to provide robust quantitative information on oil spill characteristics (other than, perhaps, extent), including oil thickness, type and components, condition (degree of degradation) and concentration. The different types of satellite remote sensors have different uses and constraints for OSR, as follows:

- ***Oil spill detection*** is possible with most remote sensing technologies under the right conditions. SAR is particularly useful, being able to "see" the oil under most environmental conditions and during night and all weather conditions, mainly as a result of the surface roughness contrast between oil and wind-roughened water. VIS and NIR optical sensors can be used under clear skies and sufficient natural lighting to detect spills through the use of sun-glint, but cannot be used under cloudy, foggy or night-time conditions. IR sensors can also detect oil through the use of specific absorption frequencies in the infrared, and thermal contrast with open water during both day and night (again, under cloud-free conditions). Lidar has the potential to detect submerged oil, through the use of green and blue visible wavelengths, which penetrates shallow water.

- ***Oil spill characterisation*** is also possible with satellite remote sensing, although much more challenging. There is the potential for optical sensors to provide some information on the characteristics of the oil spill, by combining information from more than one absorption frequency in the IR band. Different electromagnetic frequencies have varying ratios of absorption in different types and conditions of oil, which can provide exploited to help characterise the oil. In hyperspectral data, the spectral resolution is sufficiently fine that in principle specific compounds can be identified, which can then be identified through fingerprinting, which is the process of matching the spectral signature of a compound, or group of compounds, to a "library" signature.

These observations are potentially extremely useful, but the effective operational use of this information for OSR is in many cases not straightforward because of (a) false alarms; (b) a need for R&D to support exploitation of new satellite remote sensing technologies; (c) sensitivity to atmospheric conditions in the case of optical data and (d) sampling limitations, which are discussed later in the report.

Table 6 provides an overview of remote sensing sensor configurations that are potentially useful, recommended and optimum for OSR.

Table 6. Potentially useful, recommended and optimum satellite sensor configurations for offshore oil spill surveillance.

<table>
<tr><th colspan="2" rowspan="2"></th><th>Microwave</th><th colspan="4">Optical</th></tr>
<tr><th>Active (radar)</th><th colspan="3">Passive</th><th>Active (lidar)</th></tr>
<tr><td colspan="2" rowspan="2">Band</td><td>SAR</td><td>TIR-MWIR</td><td>NIR-SWIR</td><td>VIS</td><td>VIS-NIR</td></tr>
<tr><td>2.5-30cm</td><td>3-14µm</td><td>0.7.4-3µm</td><td>0.4-0.74µm</td><td>~0.47-1.1 µm</td></tr>
<tr><td rowspan="3">Wavelength</td><td>Potentially useful</td><td colspan="4">Any for oil spill detection but not characterisation</td><td>Blue-green (i.e. 0.47-0.53 µm)</td></tr>
<tr><td>Recommended</td><td rowspan="2">C-X band SAR for sensitivity to oil spills</td><td colspan="3">Multispectral including one or more of TIR and oil sensitive red-infrared wavelengths (0.672, 0.8, 1.2, 1,7, 2.3 µm) to enable rejection of spill false alarms (including from SAR)</td><td>Blue-green + NIR (e.g. 1.1 µm)</td></tr>
<tr><td>Optimum</td><td colspan="3">Hyperspectral including all above wavelengths: potential for oil spill characterisation (thickness, etc.)</td><td>>1 blue-green wavelengths + NIR for enhanced vertical sampling</td></tr>
<tr><td rowspan="2">Observation Geometry</td><td>Potentially useful</td><td colspan="2">Solar zenith angle: any
Sensor incidence angle: any</td><td>Solar zenith angle: SWIR (dawn-dusk, < 108°); NIR (daylight, < 80°)
Sensor incidence angle: any</td><td>Solar zenith < 80° (daylight)
Sensor incidence angle: any</td><td>Solar zenith angle: any
Sensor incidence angle: 0°</td></tr>
<tr><td>Recommended & Optimum</td><td>Sensor incidence angle: 22°-45°</td><td></td><td colspan="2">Oil spill detection: sun-glint[4] in oil spill search area AoI;
Oil spill characterisation: no sun-glint in oil spill AoI</td><td>Sensor incidence angle: 0°</td></tr>
<tr><td rowspan="3">Polarisation</td><td>Potentially useful</td><td>HH or VV;</td><td rowspan="3">N/a</td><td rowspan="3">N/a</td><td rowspan="3">N/a</td><td>Cross-polarisation</td></tr>
<tr><td>Recommended</td><td>VV above 40° incidence angle</td><td rowspan="2">Dual polarisation</td></tr>
<tr><td>Optimum</td><td>Dual polarisation</td></tr>
<tr><td rowspan="3">Sampling</td><td>Potentially useful</td><td colspan="5">Spatial resolution < maximum dimension of oil spill
Coverage >0% coverage of the AoI</td></tr>
<tr><td>Recommended</td><td colspan="4" rowspan="2">Spatial resolution <minimum dimension of the oil spill and Coverage: 100% of the AoI (where AoI = search area for detection and AoI = spill coverage for characterisation)</td><td>Vertical resolution < 10m</td></tr>
<tr><td>Optimum</td><td>Vertical resolution <1m</td></tr>
</table>

[4] where sun-glint = {(sun azimuth = sensor azimuth +180) and (sun zenith = sensor zenith) ±X° in both directions where X is related to sea state / wind speed}

7.2. Onshore OSR

The detection of oil onshore, and in rivers and estuaries, is a complex challenge for satellite remote sensing. There are three areas in which remote sensing can help with onshore oil spill response as follows:

- Direct detection of oil spills. Detection of surface oil in the onshore environment has historically relied on airborne sensors. In an emergency, only direct detection methods are appropriate, including such techniques as multi- and hyperspectral imaging and laser fluorescence (and potentially sensors sensitive to low level atmospheric compounds related to oil). Thermal imagery may also be useful for heat detection associated with (for example) pipeline breaches. The primary tool for detecting and mapping surface oil around the world, namely SAR, has not been proven to be effective for oil spill response in these environments because of the number of false positives and the ambiguities associated with interpretation, reflecting the complexity of land cover.
- Indirect detection of oil spills. If a release has been persistent for a period of weeks it may also be detected by indirect methods, for example from stressed vegetation via hyperspectral sensing. These methods are also documented by the API [1]. Remote sensing can also be used to detect potential oil spill threats in the form of third party encroachments (e.g. through the detection of vehicles) and movements of structures such as pipelines that may indicate susceptibility to ruptures and hence spills (through SAR interferometry).
- Up-to-date information on local conditions to support OSR. Effective OSR depends on the ability to access to an area (roads, landing sites, etc), the availability and locations of facilities and buildings, environmental conditions (land cover, the condition vegetation, coastal configuration, etc.) and the presence of any hazards that might interfere with OSR. Remote sensing can provide information on all of these.

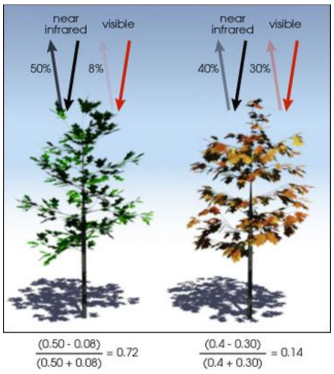



Figure 8. Left: example of oil on land. Right: graphic giving an example of how NDVI is impacted by vegetation degradation (courtesy ESA). *NDVI = (NIR — VIS)/ (NIR + VIS).*

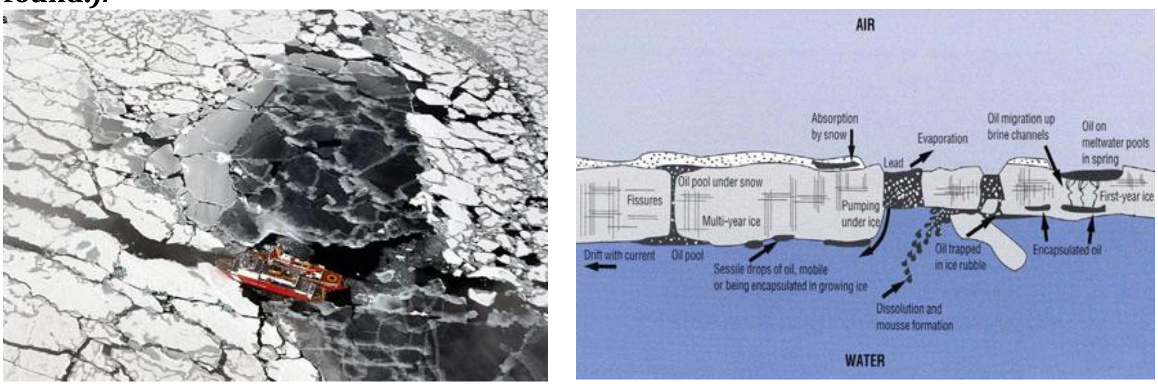
It is recommended that for onshore detections of spills, an archive is maintained of good quality baseline optical imagery in key areas, to support rapid assessment of oil spills and local conditions from new imagery. This imagery would need to be high spatial resolution, ideally with spectral frequencies that are sensitive to the presence of oil, and be supported by the availability of a good quality digital elevation model. Given the scarcity of proven techniques for oil spill detection in onshore areas, it is recommended that research be carried out on defining the best configurations for detecting onshore and coastal oil spills and for defining the extent to which any planned satellite sensors may fulfil this role, taking into account such challenges as atmospheric contamination.

7.3. OSR in ice-covered seas

Arctic OSR is covered in a separate JIP and so will not be covered in detail here ([16]). Satellite remote sensing does have an important role to play in surveillance of oil spills in ice, but there are unique challenges as follows:

- In cases where the oil spill is in ice that has a area concentration in open water of <30%, it is likely that the spill will be detectable, albeit less easily, using similar methods to those described for open water in the previous section, although polar latitudes are very limited in terms of daylight for optical sensing during winter months, and many ice margins suffer from persistent fog.
- When oil is present in ice with a concentration of >30%, the detection of the oil by satellite remote sensing becomes considerably more challenging. Satellite remote sensing tends to sample the surface of sea ice, particularly saline sea ice, and so any oil that is not present on the surface of the sea ice may not be detected by the instrument. Even if the oil is between the ice floes, rather than underneath them, it may be difficult to detect with SAR, because the ice signature may overwhelm and complicate the oil signature, particularly as sea ice takes a wide range of physical forms from very young, thin and smooth nilas ice (<10cm thick) to multi-year ice which can be several metres thick.
- During freeze-up and winter, the ice may move in response to currents and winds, yielding fresh oil the following spring. Because it may be difficult to detect this oil, it may also be difficult to track the oil, although it is possible to track ice in remote sensing imagery, if it is known *a priori* to be contaminated with oil.
- It is possible that certain remote sensing instruments may be able to detect the oil. Lower frequency SAR instruments (e.g. L and P band) are able to penetrate further into ice, although this does depend on salinity and penetration will be highly sensitive to any moisture content, while lidars and other atmospheric sensors may be able to detect volatile compounds in the lower troposphere [10].

Figure 9. Left: example of oil in sea ice (source: USGS/Creative Commons). Right: schematic showing the pathways of oil in sea ice (from* Error! Reference source not found.*).



Although the detection of oil in sea ice is a real challenge for satellite remote sensing, this is compensated to large degree by the critical need for satellite remote sensing to support the effective monitoring of ice hazards for support vessels, and to support activities such as landing on ice, and vessel navigation.

8. Availability of Satellite Remote Sensing for Offshore OSR

While satellite remote sensing has proved useful, and has growing potential for OSR, the practical availability depends on four key factors: the planning process; the turnaround time of the data (how quickly it is available after ordering), the revisit capability (how often data are available over an AoI) and certain environmental factors that impact on the ability to "see" the oil in the data.

8.1. Satellite Data Planning

Most moderate to high resolution satellite data of interest for OSR is not acquired routinely and needs to be tasked. In these cases, it is necessary to submit orders for data from the relevant image suppliers. Whether an order is successful depends on a number of factors as follows:

- Whether the satellite and sensor is physically capable of sampling the area of interest within the time period requested (i.e. as a result of its orbit and sensor configuration). Satellite image planning software can establish this, and suppliers have their own tools to support these assessments, although not always for multiple satellites and sensors.
- Whether environmental conditions are suitable for data acquisition within the requested area and time period requested by the user (e.g. appropriate atmospheric conditions and lighting for optical data). For SAR data, specific images covering a specific area and time can be ordered, but in many cases optical data needs to be ordered using a time window as well as an area of interest, to provide the supplier with a realistic opportunity to obtain imagery that is largely cloud-free.
- Whether the resources of the satellite and sensor are sufficient to support the user request (e.g. in terms of quantity of data collected per orbit). Power consumption associated with the acquisition of high resolution satellite imagery is such that these missions typically come with strict limits on the total amount of image acquisition per orbit.
- Whether there are higher priority acquisitions (and these conflict in some way with the order). For OSR, it is possible to maximise the priority of the data, for a price, although the health of the spacecraft will always take precedence. In some cases, as in the case of Cosmo-Skymed, the mission has been co-financed by one or more organisations which are therefore pre-allocated a proportion of the capacity of the sensor and given priority over other users. In some cases too, particular users have prioritized access to data from particular geographic regions which may conflict with acquisitions requested for OSR from adjacent or overlapping regions.
- Whether the satellite mission supports image ordering from commercial users. In a few cases, the availability capacity of (civilian) satellite sensors for commercial sales is limited or even non-existent for reasons of policy, in many cases reflecting the ownership of the mission.

For OSR planning, it is therefore important to assess the potential for image order rejections and to include consideration of this in any assessment of the value and availability of satellite image data from a particular satellite mission.

8.2. Satellite Data Turnaround

Image turnaround times are defined here as the combination of lead times for ordering data (the time between placing an order and the image being acquired by the satellite sensor) and latency (the time between the image being acquired by the satellite sensor and made available for OSR). The acquisition of satellite data is illustrated in *Figure 10*, as a set of sub-stages in planning and acquiring the data for OSR, to the point where it is available to the user.

Figure 10. Acquisition planning process for satellite data.

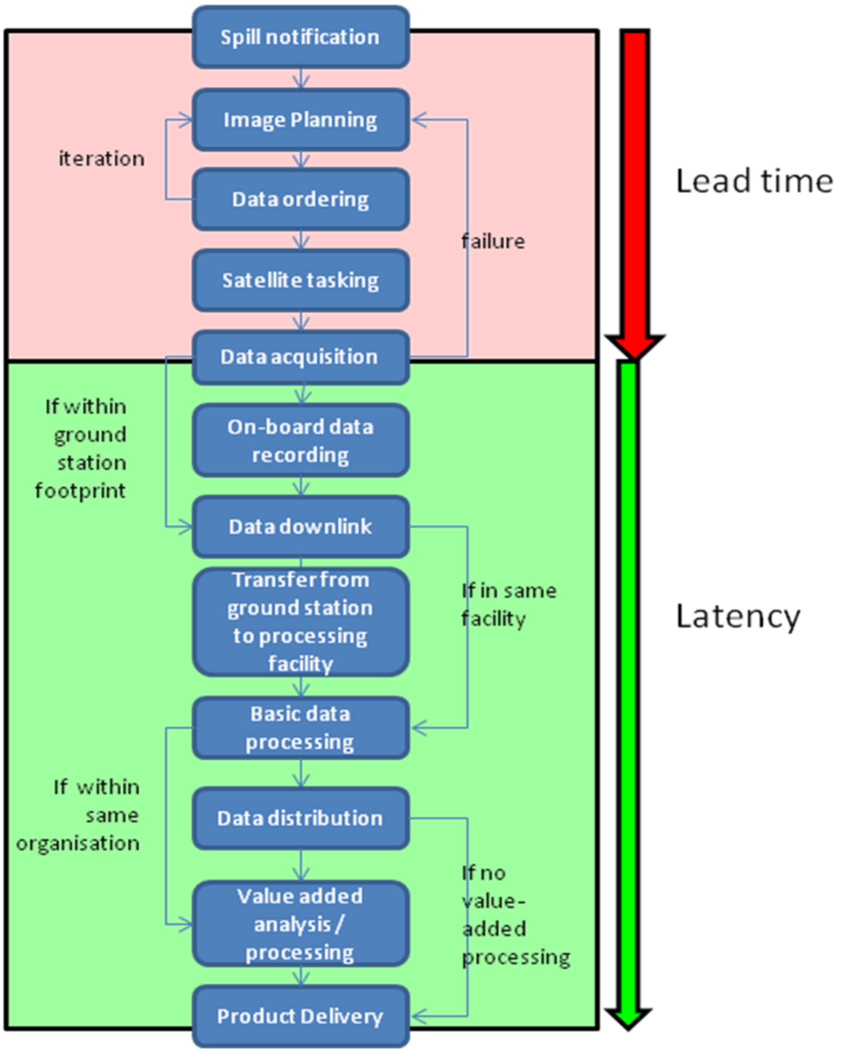


Image planning involves selecting the image data for the area of interest. This can be carried out by the user, a service provider or the image supplier themselves. This may involve iteration between two or more of these organisations, depending on the ability to task an acquisition. Iteration will be required under the following circumstances:

- Higher priority acquisition from another client;
- Satellite unavailability (e.g. for maintenance);
- Restricted area (acquisitions not allowed in a particular area);
- Weather (e.g. cloud cover).

Satellite tasking will then be carried out, at a limited number of times per day. The tasking is associated with a tasking window which is some time in the future, normally some hours later. All together, these processes create a lead time for the acquisition.

Delivery times are also dependent on a number of sub-tasks. Once the acquisition has been taken, the data are then either downloaded directly to a ground station that is immediately in line of communication to the satellite (and which is set up to receive data from the satellite) or, if there is no ground station in line of immediate communication, then the data are recorded on board the satellite until the satellite is in direct line of communication with the ground station. At this point, the data are downlinked to the ground station. Once there, the data may be processed and delivered direct to the end user, but there may also be data transfer to another facility for basic processing (processing into an interpretable, geo-referenced image product) and/or distributed to an additional facility for value-added processing, where compliance to the COP becomes relevant.

There are various limitations related to the ordering of satellite data for OSR.

- Insufficient availability of satellite resources for acquisition. This is not a frequent constraint, but it can become so if the resources of the satellite (e.g. power) are particularly limited.
- Unavailability of the satellite sensor. The satellite may be unavailable due to maintenance. This is mitigated by forward planning by both the supplier and the user, in the context of Field Development Plans and Emergency Response Plans.
- Restricted areas of data acquisition. For some satellites, a user has exclusive access to data from a particular location, for commercial or security reasons. Some sensors are pre-planned and therefore have little scope for new acquisitions outside the pre-plan, although emergency requests may be possible.
- Conflicts from higher priority users. For an oil spill emergency, this is unlikely to be a common occurrence, but it is theoretically possible. Some suppliers can have demand backlogs for data which can add lead time to the initial acquisition. Some suppliers have government customers who can potentially take priority over all commercial acquisitions.

It should be noted that there are many examples in which satellite image turnaround time has been extremely short, for example involving delivery of imagery within 30 minutes of acquisition. However, unless suppliers are willing to guarantee these delivery times, then while these performances can be kept in mind, it remains prudent to plan on the basis of guaranteed delivery times.

8.2.1. SAR Turnaround Time

For SAR data, the critical factor for lead time is the number of times per day that tasking is carried out, and the length of time between the tasking and the start of the sensor acquisition window. At worst, this can be several hours long, resulting in an initial acquisition that is more than a day ahead. The sensor revisit time is less critical to the lead time for the initial acquisition.

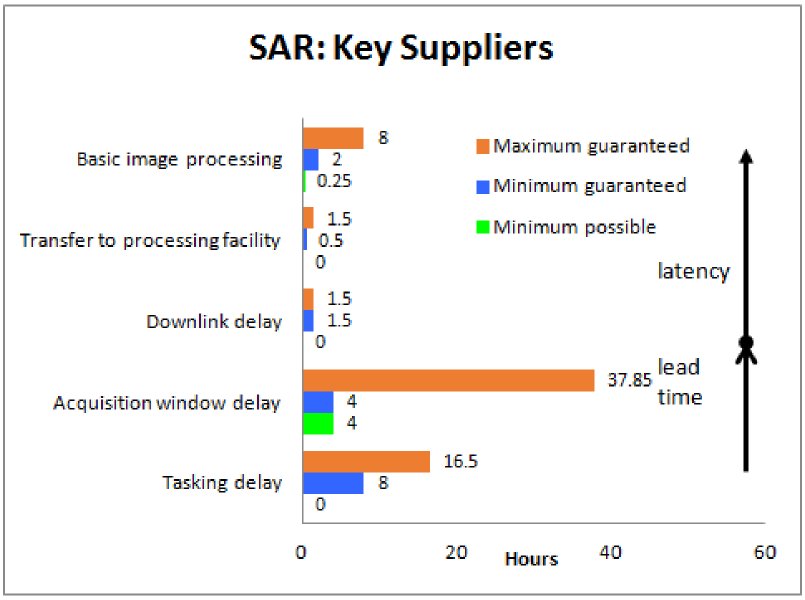
The latency of data is dominated by the distribution of ground stations and the number of ground stations that can be used to download satellite data and then process the data. Some vendors have multiple ground stations distributed globally for download of data, with the result that the maximum latency associated with downloading data to an available ground station is less than an orbit (100 minutes). A single polar ground station such as Svalbard can achieve the same result. Some of the newer satellites, however, have limited ground stations and without a polar ground station, the latency due to on board recording of data and later download can become many hours.

In the following analysis, the sampling is optimised using auto-steering[5] to the locations of interest, thus optimising the coverage and revisit. The imaging modes are selected to be at highest spatial resolution to provide full coverage of the spill, while at the same time the incidence angles are restricted to between 22° and 45° to optimise spill detection capability.

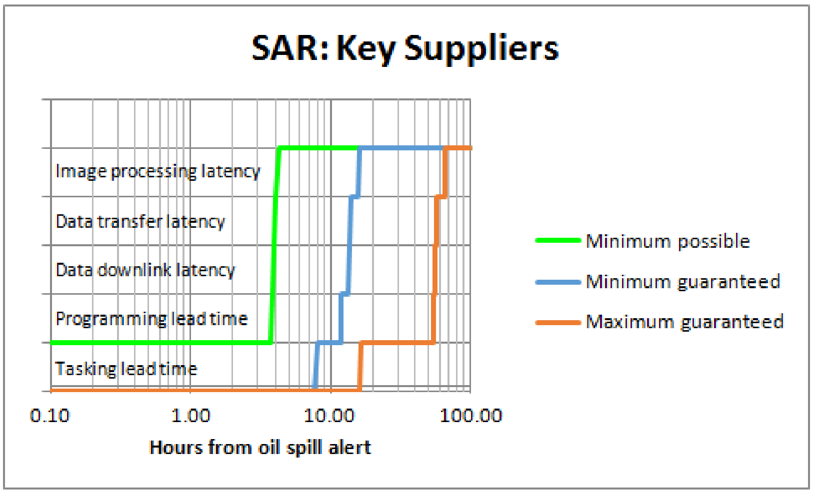
SAR lead times and latencies are shown in *Figure 11*. These show that the key delay in provision of data for OSR lies in the ordering lead time rather than in the latency of the data. At worst, the overall time between the spill alert and data being available can be theoretically ~70 hours, even for the key suppliers, although this would be extremely unlucky. It is more likely that this “turnaround time” would be of the order of 16 hours.

[5] Autosteering is the process of using flexible satellite sensor steering (where available) to optimise sampling of the area of interest.

Figure 11. Lead time and latencies associated with Satellite SAR suppliers MDA, Astrium and E-GEOS (all locations). Maximum (minimum) guaranteed: the largest (smallest) value of guaranteed lead or latency time from any of the suppliers.



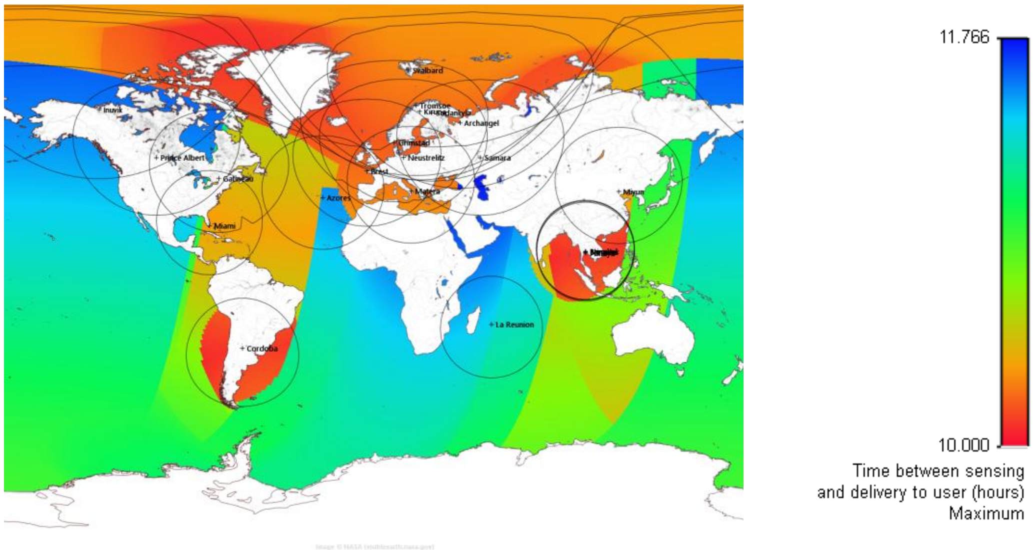
Lead and latency times divided into components of image acquisition and delivery.



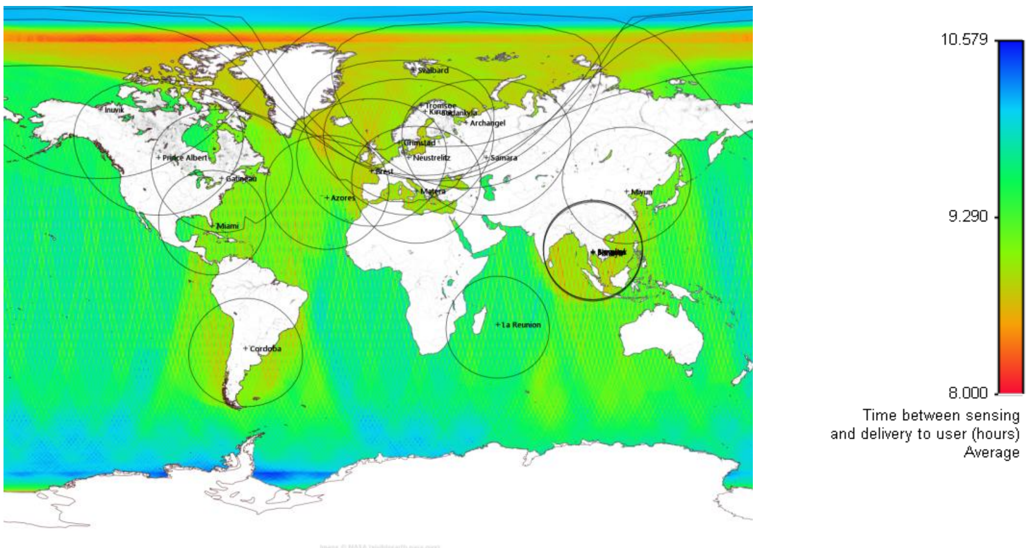
Cumulative lead plus latency time from oil spill alert. The lines indicate the time elapsed from oil spill alert to consecutive stages (rows) in image acquisition and delivery.

This turnaround time is impacted not only by the tasking schedule and positioning in time of the acquisition window associated with each tasking, which are supplier-dependent, but also on the location of the spill in comparison to the nearest along-track downlink ground station and (if different) the data processing facility. The impact of this on turnaround times is shown *Figure 12*. In general, the more northern locations are better served with turnaround times because there is better coverage by downlink ground stations. Equatorial locations are not all covered by ground stations and so need to have data recorded and then downlinked at the next available ground station, leading to a delay that can be as high as 100 minutes (but is generally less for the key suppliers). *Figure 12* also incorporates the impact of published delivery times as well as latencies due to distribution of ground stations.

Figure 12. Global map of SAR data latencies due to downlink and delivery for the key suppliers. Also shown are the ground station reception areas for the key suppliers.



Maximum latency (data downlink plus data delivery) in hours.



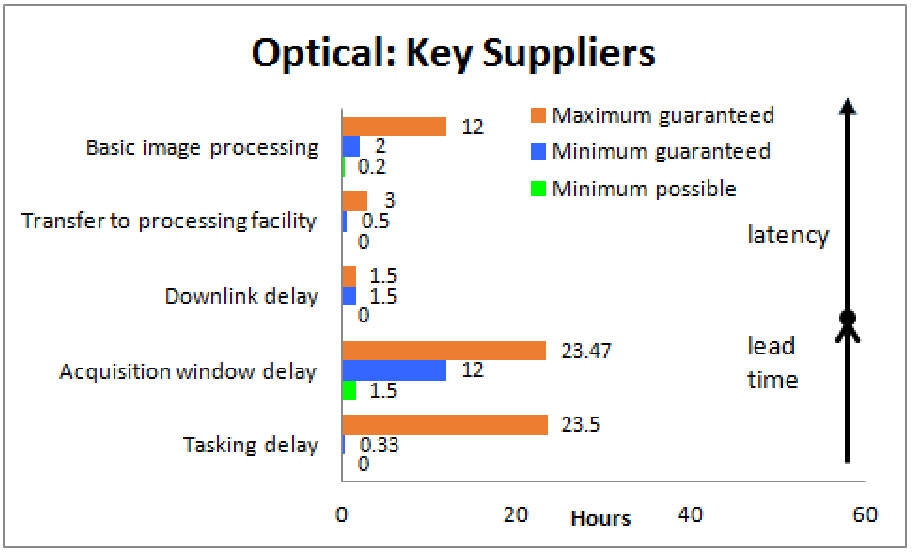
Average latency (data downlink plus data delivery) in hours.

An implication from these statistics is that it is also more challenging to arrange a quick initial survey of the oil spill rather than to carry out synoptic monitoring, because for follow-on monitoring of a spill, the lead time is generally less critical (images can be planned some time in advance). In general, the minimum requirement for daily coverage of a spill from SAR can be met, but the goal of an initial survey 3 hours from the alert is not generally possible.

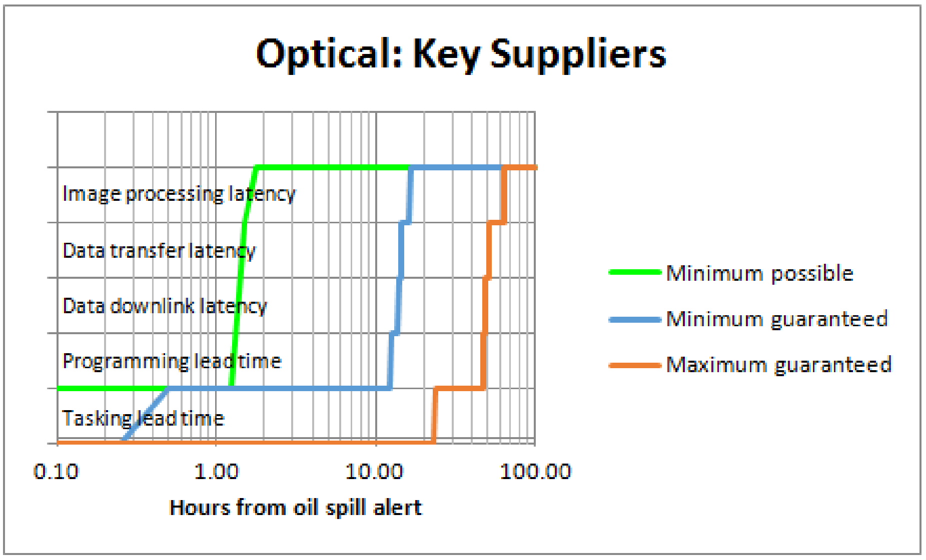
8.2.1. Optical Turnaround Time

Optical data is impacted by daylight and atmospheric conditions. In this analysis, the daylight conditions are taken into account by only accepting data acquisition opportunities that involve a solar zenith angle of less than 80° (this is therefore somewhat conservative). Potential cloud and fog conditions are not taken into account in this analysis, so the relevant cloud statistics need to be taken into account before assessing the results of the turnaround time for optical data.

Figure 13. Lead time and latencies associated with Satellite Optical suppliers DigitalGlobe, Astrium and RapidEye (all locations). Maximum (minimum) guaranteed: the largest (smallest) value of guaranteed lead or latency time from any of the suppliers.



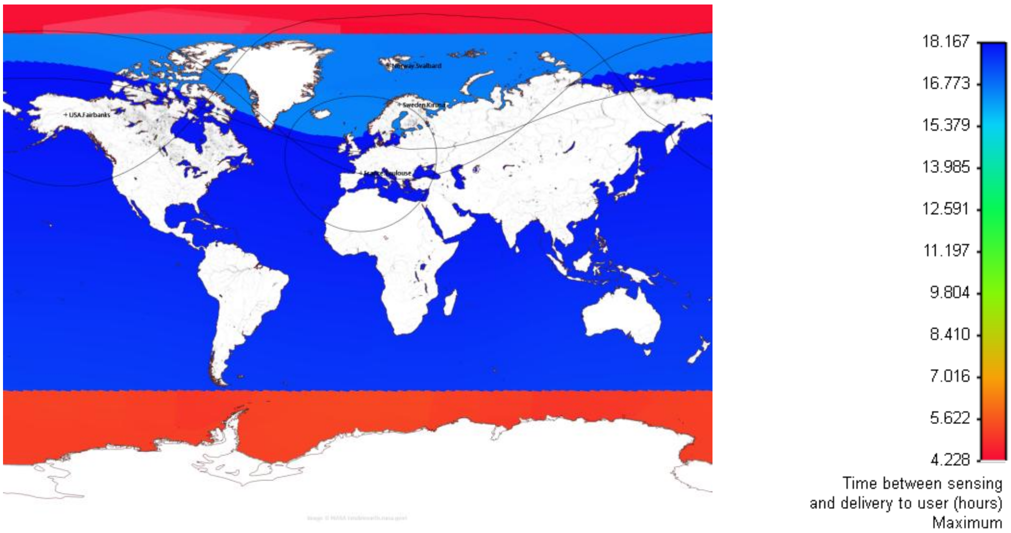
Lead and latency times divided into components of image acquisition and delivery.



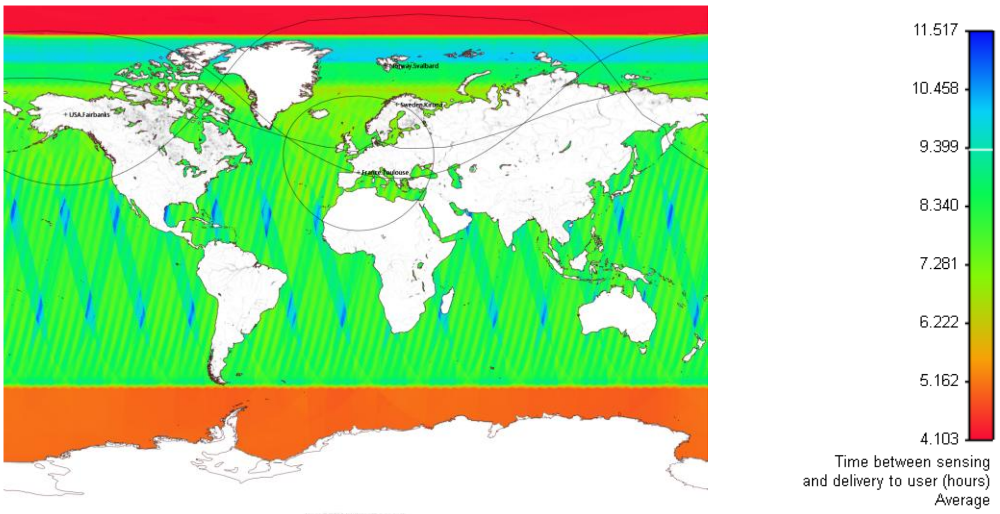
Cumulative lead plus latency time from oil spill alert. The lines indicate the time elapsed from oil spill alert to consecutive stages (rows) in image acquisition and delivery.

With optical data, there is similarity with SAR in terms of the overall turnaround times (maximum and minimum guaranteed and minimum possible), though optical data in general has lower lead time but higher latencies. The impact of cloud needs to be considered here. In general, a potential cloud cover has to be accepted in many areas so that a particular image may have some cloud obscuration of the spill. Thus, there is a risk attached to optical data that is not attached to SAR data. Latencies are shown *Figure 14* for in RapidEye and Astrium (DigitalGlobe has an extensive ground station network for their optical imagery, but this is not included in the figure, because the ground station network cannot be divulged for reasons of security). *Figure 14* also incorporates the impact of published delivery times as well as latencies due to distribution of ground stations.

Figure 14. Global map of optical data latencies due to downlink and delivery for the key suppliers, excepting DigitalGlobe. Also shown are the ground station reception areas for the key suppliers, excepting DigitalGlobe.



Maximum latencies (data downlink plus data delivery) in hours



Average latencies (data downlink plus data delivery) in hours

In general, for the different regions, there is a lead time of many hours to a few days, but this will be worsened for some regions by cloud cover. N.W Australia may have relatively reliable clear sky conditions, and S E Asia during some parts of the year, but most of the other regions will have significant cloud most of the time. Thus, the "average" lead time will in practice be more like a minimum lead time assuming clear sky conditions.

8.3. Satellite Temporal Sampling

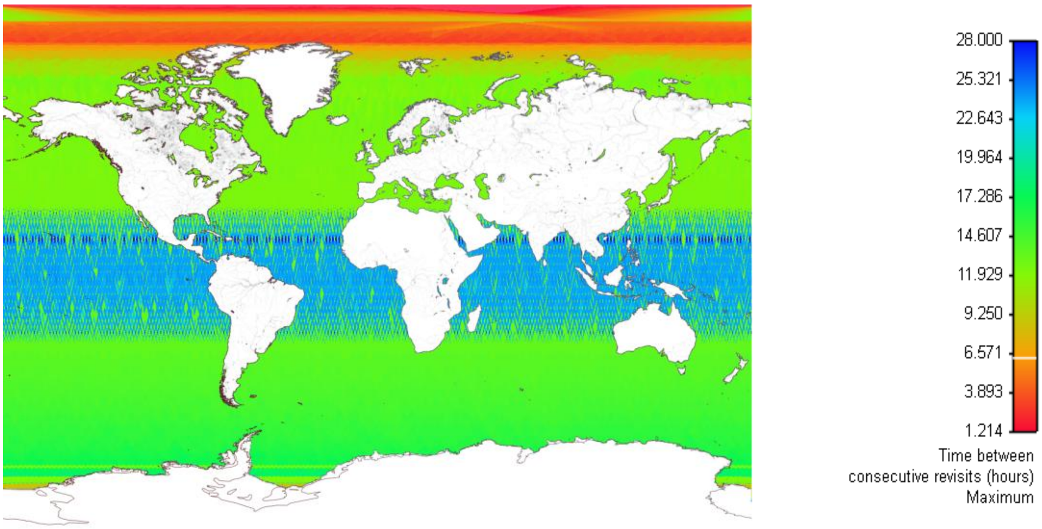
The temporal sampling of satellite sensors over an AoI is not uniform, or even collectively random. Polar orbiting satellites sample the Earth at limited local times during the day. For example, many satellites pass over areas at around 10.30am local time on descending passes. Thus, there is a need to take this into account when planning acquisitions and deployment of other assets. This can work to an advantage in terms of obtaining multiple types of acquisitions around the same time (helping with oil spill false alarm elimination, for example), but it can also result in significant gaps. The number of revisits varies as a function of latitude, with higher latitudes obtaining more potential revisits as a result of the convergence of polar-orbiting satellites.

8.3.1. SAR Revisits

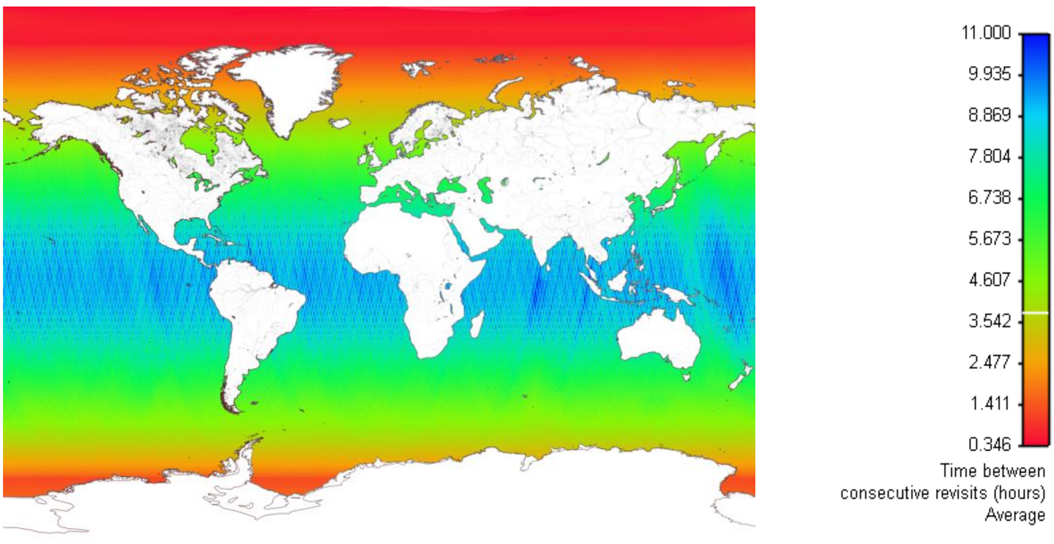
SAR revisits are independent of weather or daylight, and so are relatively predictable. The average and maximum revisit times for the different areas are shown below, for both the key suppliers and for all suppliers. It is clear that there are significant differences from area to area, with the higher latitude locations have the best average and smallest maximum revisit times.

The revisit statistics for current SAR satellites from the key suppliers are shown as a global map in *Figure 15*.

Figure 15. Map of global revisit capabilities from SAR satellites from the key suppliers, without restriction of incidence angle.



Maximum revisit, in hours



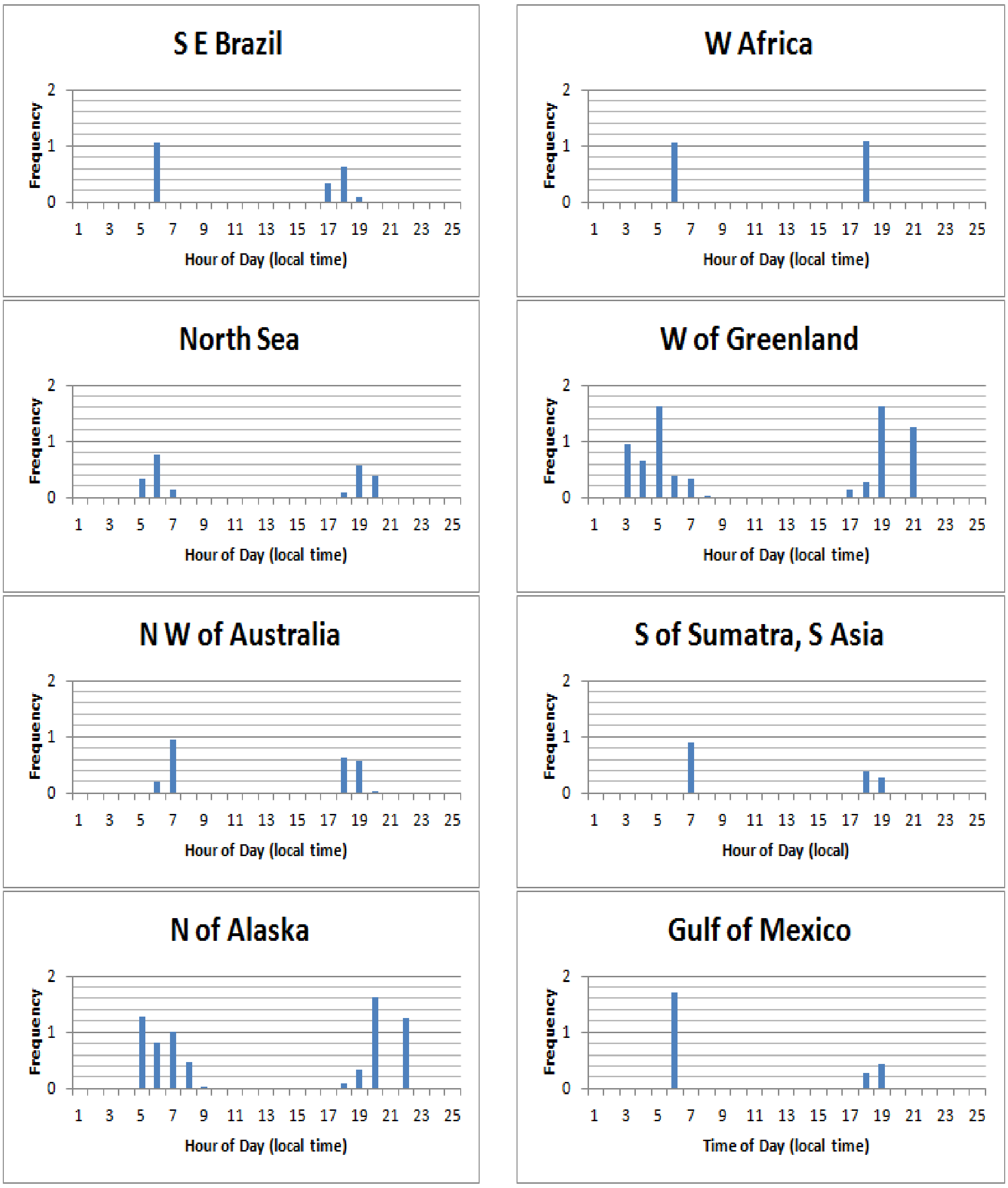
Average revisit, in hours

Revisits can also be shown for the 8 sample areas. In the case of the sample areas, the revisit statistics are shown both for the key suppliers, and all current suppliers of SAR data. Revisits shown in the above figure are not the same as those shown in *Figure 15* because in the case of the latter, the incidence angles are restricted to those that are optimum for oil spill detection.

Figure 16. Revisit times for SAR data for the 8 sample areas for key suppliers with spatial resolution <30m and incidence angles between 22° and 45°, and for all suppliers with similar spatial resolution sensing but with unrestricted incidence angles.

Polar-orbiting satellites sample areas twice a day, once on ascending (north and westward) orbits and once on descending orbits. At low latitudes, the satellites tend to sample around two tightly sampled times in the early morning and in the late afternoon. At higher latitudes, the diurnal sampling becomes more diffuse, although still "bunched" around early morning and late afternoon. The latitude of the AoI therefore has an impact on range of diurnal sampling and this needs to be taken into account in any operational scenario, as it implies that data will become available for analysis (taking into account latency) at particular times of day.

Figure 17. Average numbers of SAR acquisitions per hour of day from Astrium, E-GEOS and MDA. Acquisitions with incidence angle outside the range 22°-45° are rejected.

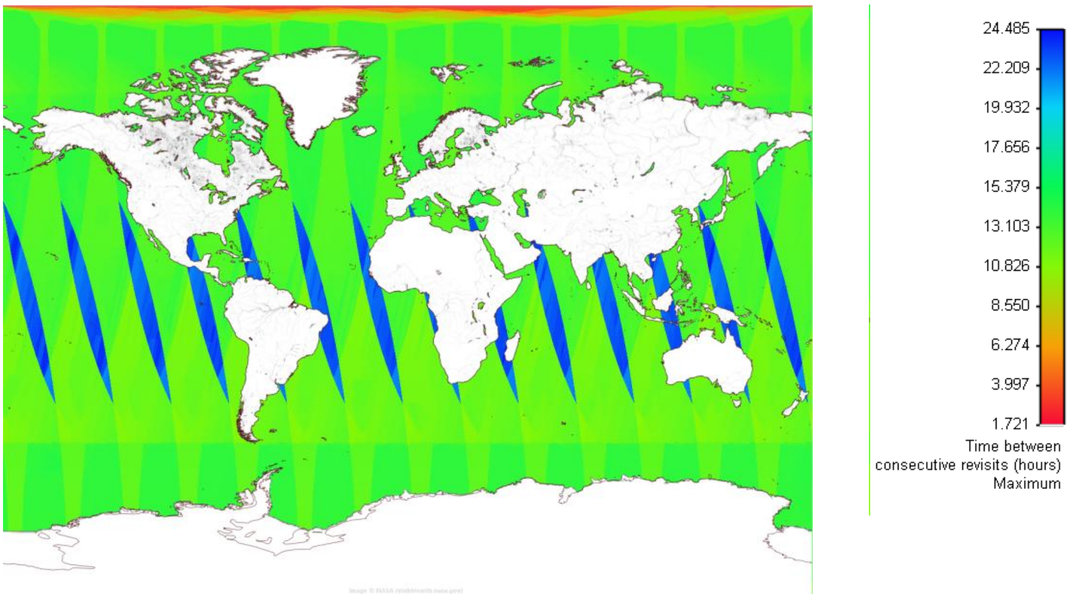


Current missions are likely to exceed their design lifetimes and operate well into the next 5 years, but it is also possible that there will be gaps between one or more of the current missions and their follow-ons (e.g between Radarsat-2 and the Radarsat Constellation mission). It is therefore important to maintain oversight of the status of missions and ensure that back-up options are available should a particular key satellite fail unexpectedly, leading to degraded revisit times.

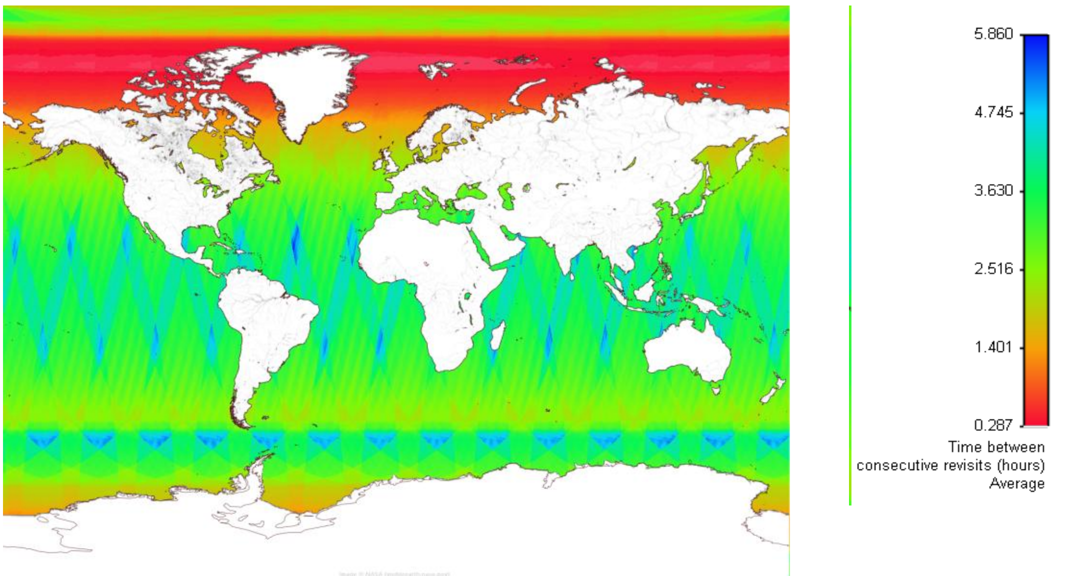
8.3.1. Optical Revisits

For high resolution optical data, with resolution of up to 10m, the revisits are theoretically good. However, as for SAR, the maximum revisit time is many hours and both the average and maximum values are sensitive to latitude. Moreover, with optical data, it is necessary to "add in" the impact of cloud cover and daylight. During December, the revisit times will worsen significantly. Cloud cover will further reduce the effective revisit times, so *Figure 18* is an optimistic view of revisits for optical data.

Figure 18. Map of global revisit capabilities from high resolution optical satellites from the key suppliers.



Maximum revisit, in hours



Average revisit, in hours

Figure 19. Revisit times for optical data for the 8 sample areas for all sensors with spatial resolution <10m, and for similar sensors from just the key suppliers.

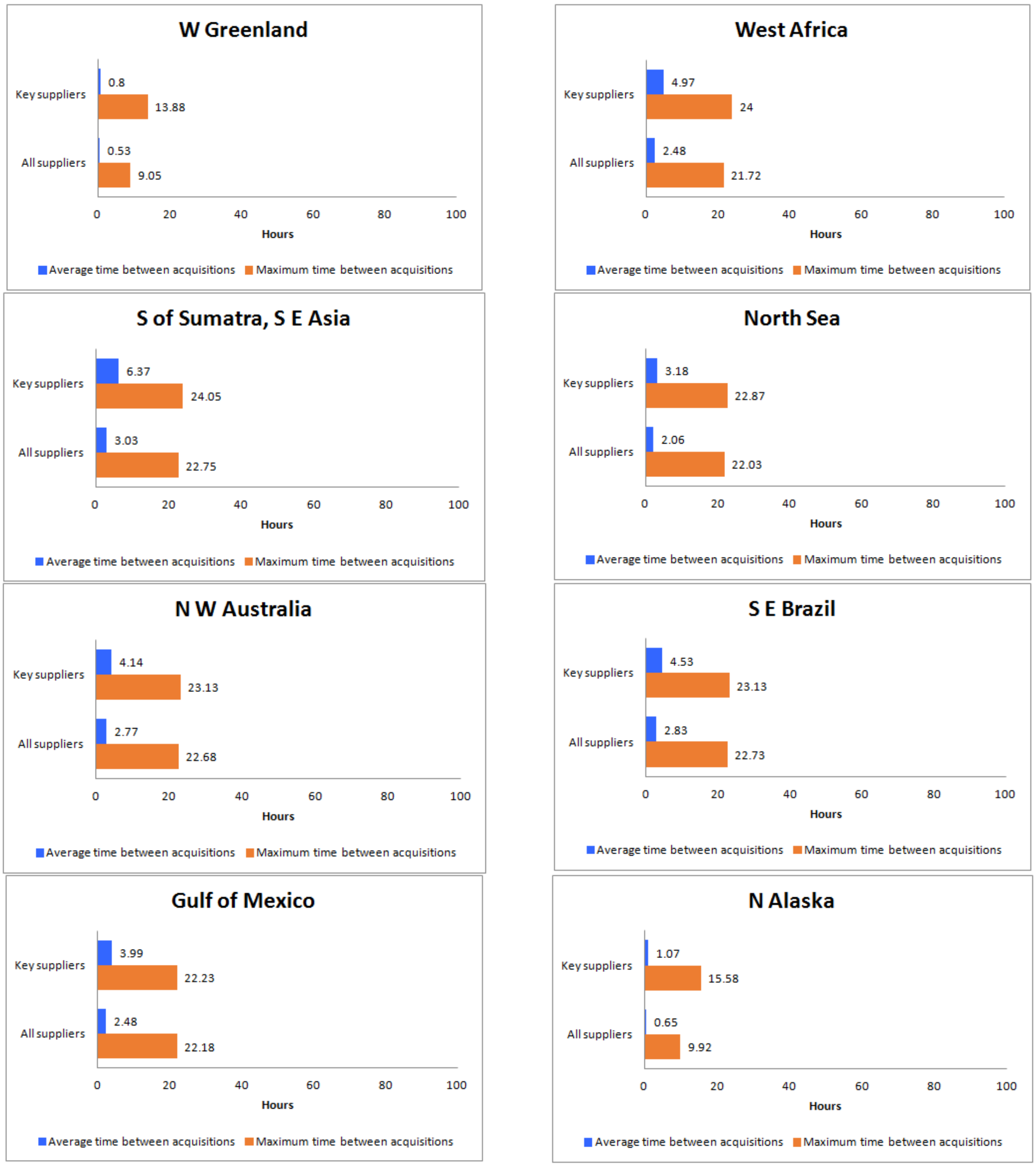
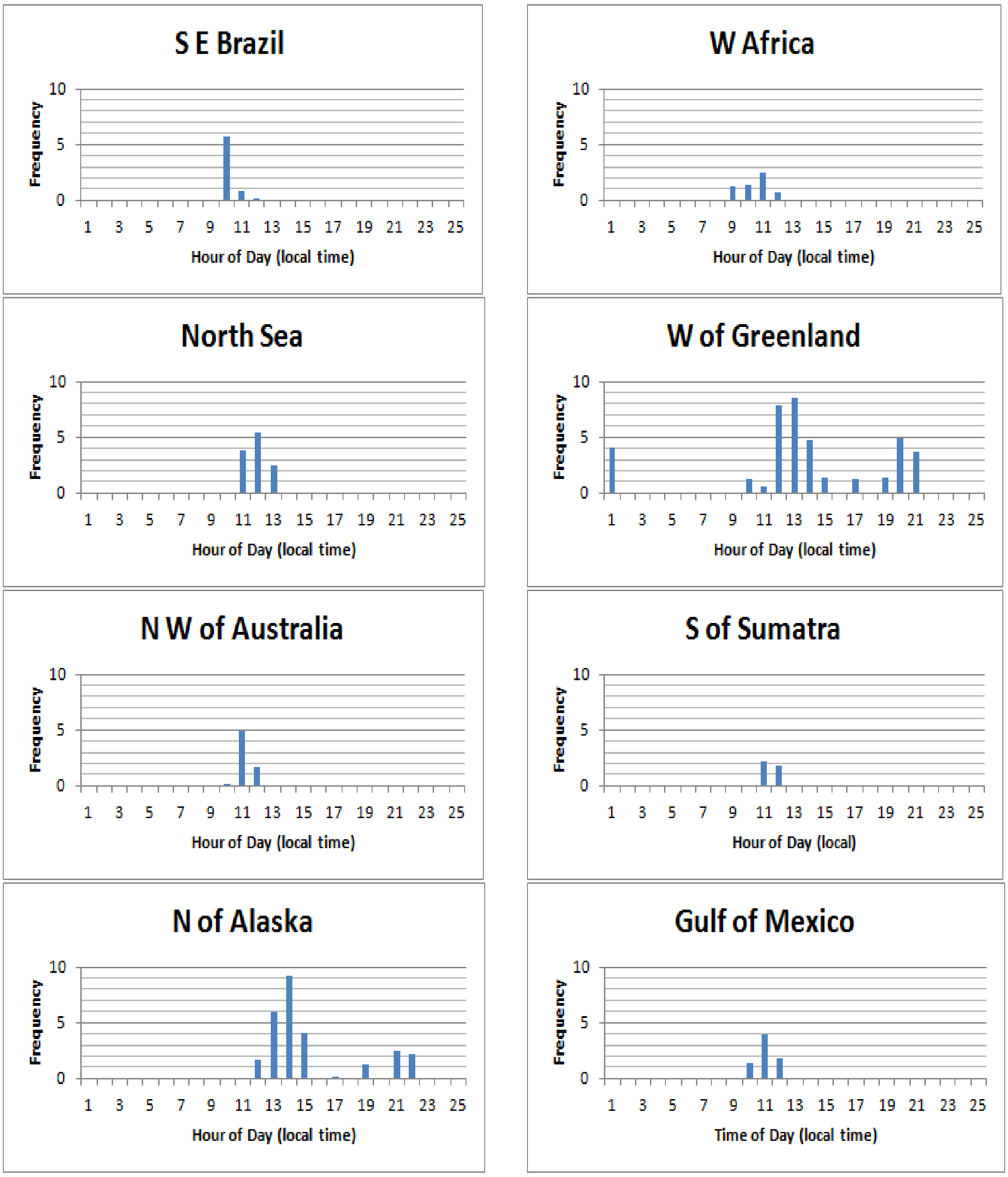


Figure 20 shows the diurnal sampling of high resolution optical imagery for the eight sample areas. It can be seen that optical data tends to be acquired later in the morning than SAR data. Again, the spread of data acquisition times increases with latitude so that West Greenland, for example, has a reasonable spread of acquisitions during daylight, while equatorial regions are more limited.

Figure 20. Average numbers of high resolution optical image acquisitions per hour of day from Astrium, DigitalGlobe and RapidEye. Acquisitions with solar zenith angle greater than 80° are rejected (the time of year was arbitrarily selected as July).

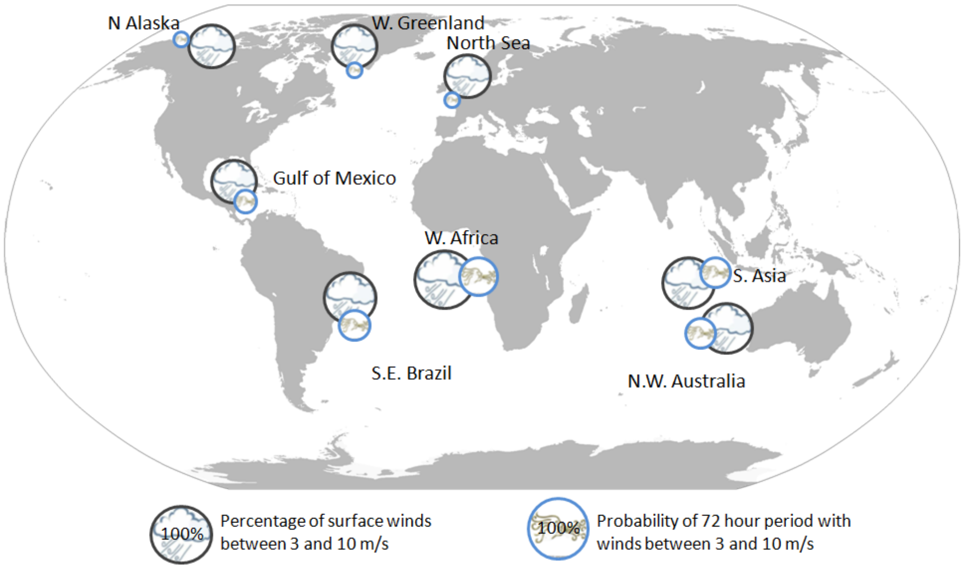


8.4. Environmental Considerations

8.4.1. General Considerations

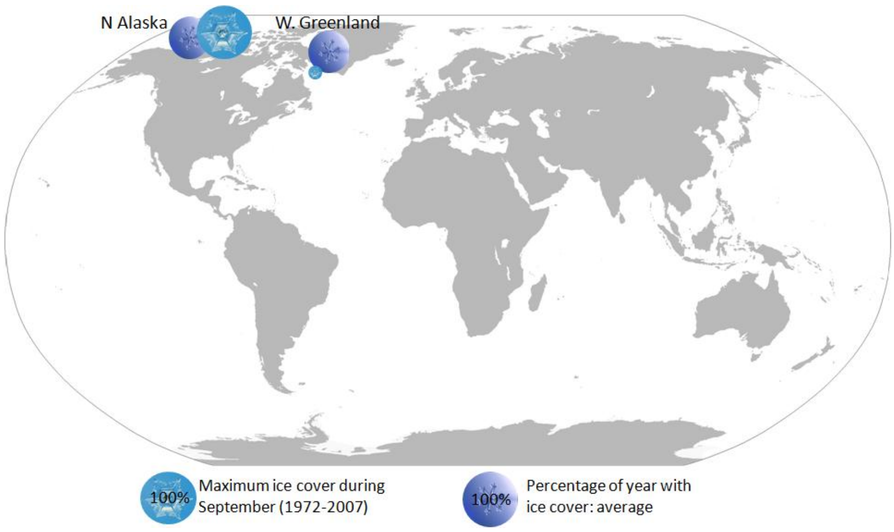
The availability of effective SAR data for offshore OSR depends not on cloud or daylight, but to first order on the presence of open water and surface wind speeds that are, ideally, between 3 and 10 m/s (to afford backscatter contrast between open water and the spill), or at least between 2 and 14 m/s (*Figure 21*).

Figure 21. Surface winds statistics for the eight sample areas [17].



Open water is reduced by the presence of sea ice, which above an area concentration of about 30%, tends to dampen the oil-water contrast and to directly mask the oil signature. Ice cover is a challenge in some areas. Note that for both Harrison Bay, Alaska, and West Greenland, ice can occur in any month of the year (*Figure 22*), compromising oil spill detection and monitoring (some types of young ice can appear similar to oil spills in SAR imagery).

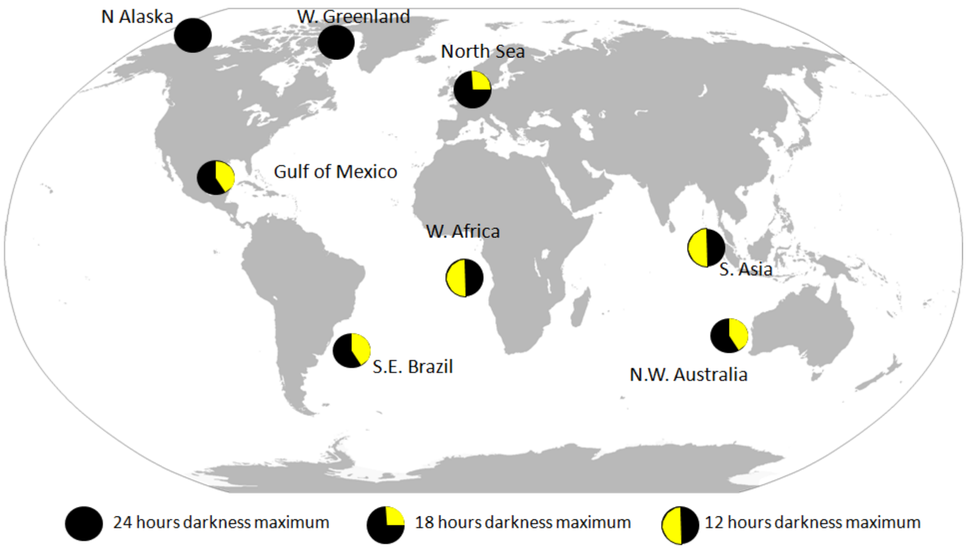
Figure 22. Sea ice statistics for two of the eight sample areas affected by ice [18].



8.4.2. Considerations for Optical

It is clear from that daylight impacts are optical data are significant, even in summer. In many of the eight sample areas, one of the two daily sampling periods are lost due to lack of natural light. Other areas, such as Alaska, are able to be optically imaged at any time of day during mid-summer, although conversely Alaska has complete darkness during mid-winter (*Figure 23*). Unlike VIS and NIR bands, SWIR is able to image during dawn and dusk, and TIR can image during day and night, so there is value to checking whether TIR in particular is available for night-time imaging. It is worth noting, however, that TIR and SWIR are not available for high resolution optical imaging.

Figure 23. Maximum daily duration of darkness for the eight sample areas.



The revisit potential of optical data is affected by cloud, and very few regions of the Earth do not suffer from significant cloud cover at least during part of the year. Infrared frequencies are able to see through some minor cloud (e.g. SWIR can image through haze and fog), but thick cloud is opaque to all optical frequencies, and so limits the effective optical revisit times substantially in many areas. Cloud statistics exist which can be used, in principle, to estimate the potential revisit capability for optical sensors in particular areas.

Figure 24. Global mean cloud cover fraction from 28 years of AVHRR [19] .

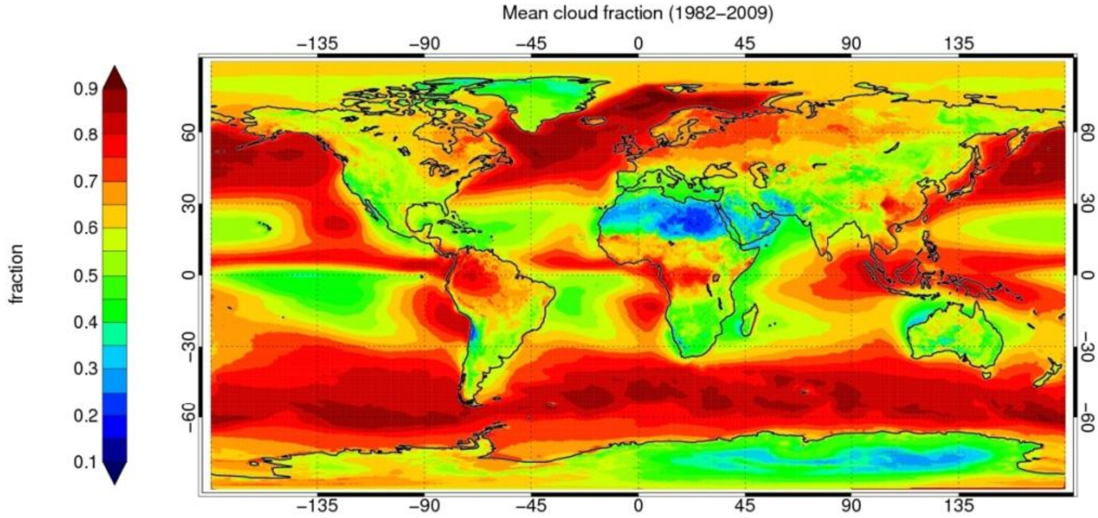
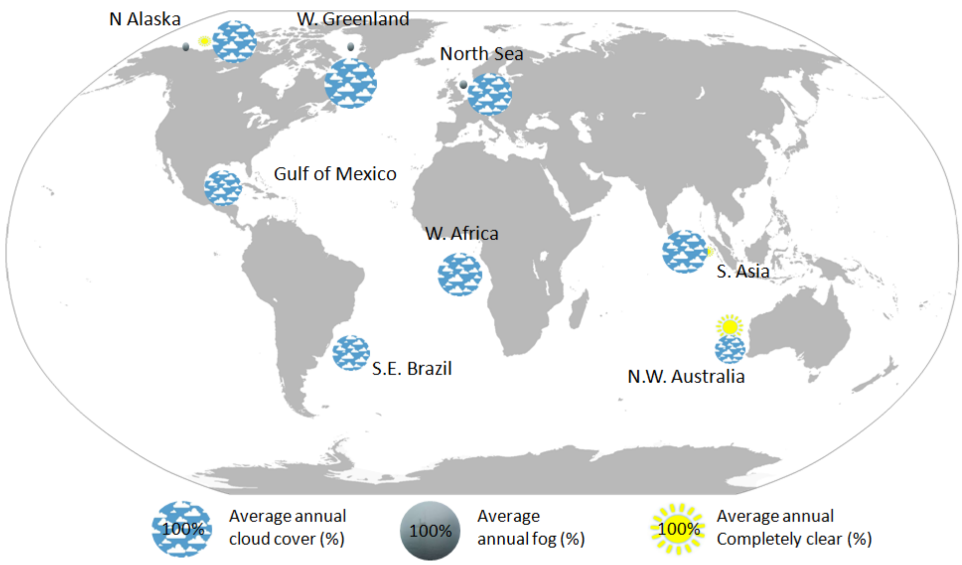


Figure 25. Cloud cover statistics for the eight sample areas.



Finally, optical imaging is also impacted by surface wind speed. For oil spill detection using VIS and NIR, the optimum surface wind speed is < 10m/s, or at least < 14 m/s (*Figure 21*).

9. Challenges for the use of Satellite Remote Sensing

Satellite remote sensing data has significant value for OSR, but comes with a number of sensing constraints. These include false alarms, data quality constraints, technology development, and dealing with the large (and increasing) number of satellites and sensors.

9.1. False Alarms

The technology also has constraints in the form of false alarms, and there are a wide range of sources of these. They can be ubiquitous across many areas and are summarised in *Table 7*.

Table 7. Sources of false alarms from satellite sensor surveillance for OSR.

	Microwave	**Optical**			
	Active (radar)	**Passive**			**Active (lidar)**
Band	SAR	TIR-MWIR	NIR-SWIR	VIS	VIS-NIR
	2.5-30cm	3-14μm	0.7.4-3μm	0.4-0.74μm	~0.47-1.1 μm
Biological	Biogenic slicks; mineral oils		Biogenic slicks; mineral oils; weed and kelp beds, etc.		Phytoplankton, weed and kelp beds, etc.
Oceanographic	Fresh water plumes, fronts, internal waves	Upwelling, water inflows, fronts			Suspended sediment
Bathymetry	Shallow water modulation			Shallow water feature	
Atmospheric	Variable surface wind stress; rain cells; wind shadows			Cloud shadow	
Man-made	Turbulent ship wakes	Man-made heat sources			

A strategy for dealing with false alarms is to **have available multiple contemporaneous data sources from different sensors**. This can be very effective at discriminating oil spills from features such as wind shadows. Another strategy for dealing with false alarms is to build up a picture of patterns of false alarms in advance of an oil spill, using baseline monitoring.

Figure 26. Complex ocean surface features, including internal waves and wind shadows, around the Strait of Gibraltor. Some of these features could be erroneously classified as oil spills, from the ESA ERS SAR missions © ESA.

9.2. Data Quality

There are various limitations related to the quality of satellite data for OSR. These are listed as follows:

- Positioning accuracy. The COP may require a minimum positioning accuracy for the imagery that is not met for the following reasons:
    - Use of preliminary orbit may result in positioning uncertainties for the imagery that can be as large as ~700m for the case of near real time imagery. This will depend on the particular satellite and vendor.
    - If there is no land in the image, then locational accuracy can be limited if sensor pointing accuracy is limited and again, this depends on the sensor.

  In either event, it will be necessary to meet the requirements of positioning using whatever additional information is available, e.g. known positions of infrastructure.

- Radiometry. The radiometry relates to the pixel values and their accuracy and precision, both in terms of spatially random properties and spatially correlation properties that can create artefacts in the data. Artefacts are defined here to be features in the imagery that derive from properties (or limitations) of the instrument rather than of features on the Earth's surface.
    - SAR can come with a number of artefacts including scalloping and range ambiguities which can compromise, although not normally seriously, the interpretation of the data.
    - The signal to noise ratio is particularly important for oil spills because in SAR data they can generate such small backscatter that it can approach or even be below the noise level. A result of this can be the more obvious presence of artefacts across the oil spill such as a residual antenna pattern.
    - Optical data can also have banding and streaking present in the data. Again, these are normally minor artefacts, but potentially significant nonetheless.
    - The dynamic range of the data can be an important factor in its utility. Many high resolution optical sensors are now 11 or 12-bit which supports a much wider dynamic range than 8-bit data.

10. Emerging Capabilities of Satellite Remote Sensing

10.1. Data Capabilities

10.1.1. Data Types

There will be a continuation of high resolution optical sensors with spatial resolution as low as 0.31m (Table 14). Innovations, in the case of DigitalGlobe's Worldview-3, include additional SWIR bands and atmospheric correction sensors that will improve the range of atmospheric conditions under which surface imaging may be carried out effectively (e.g. through haze and thin cloud).

There is notable innovation at moderate spatial resolution (10-100m), with the advent of new hyperspectral spaceborne sensors (Table 15) and multispectral sensors with multiple SWIR and NIR bands (with expected oil absorption sensitivity). The hyperspectral sensors will provide an excellent resource for research with a view to future operational use in OSR and/or optimisation of the design of new multispectral sensors for OSR. The planned multispectral sensors include Sentinel-2, which has 2 SWIR bands, and from which the data will be available "for free" (see Section 10.2.1).

In terms of SAR, some of the new missions have enhanced polarimetric data (such as compact polarimetry with the Radarsat Constellation mission, and full polatimetry available with the Cosmo-Skymed follow-on mission), which may help with reduction in false alarms and even perhaps oil spill characterisation. The availability of data at L band (e.g. SAOCOM and ALOS-2) and S band (NovaSAR) as well as C and X bands may also help with elimination of false alarms, such as those generated by atmospheric artefacts.

Some satellite missions now have AIS available with remote sensing imagery, thus providing integrated information on vessel identifications, which may be very useful for OSR.

10.1.2. Platforms

Some ventures have been established recently to exploit the commercial potential and advantages of very small satellite platforms. Small satellites can be launched in significant numbers to enhance sampling of the surface significantly. PlanetLabs expects to launch 28 platforms by July 2015 (with spatial resolution of 5m). The Skybox platform, from Skybox Imaging, is also small, and there is a plan to launch 24 of these by 2017 (with spatial resolution of about 1m). The advent of large micro-satellite constellations may well radically alter both the cost of satellite imaging, and the sampling.

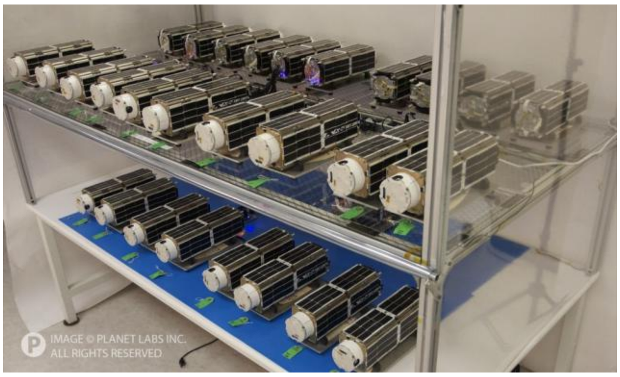


Figure 27. Satellites from PlanetLabs, ~5kg in weight, each PlanetLabs is one of the suppliers of a new generation of micro-satellites (image provided courtesy of PlanetLabs).

The International Space Station (ISS) is also now being exploited for commercial sensors. This limits the latitudinal range of observations to 51°N/S, but the “piggybacking” is cost effective. Urthecast is deploying a 5m resolution camera and 1m resolution video, while TBE are deploying a four sensor platform on the ISS called MUSES, which will initially host both a multispectral and a hyperspectral sensor.

10.1.3. Coverage and Revisit

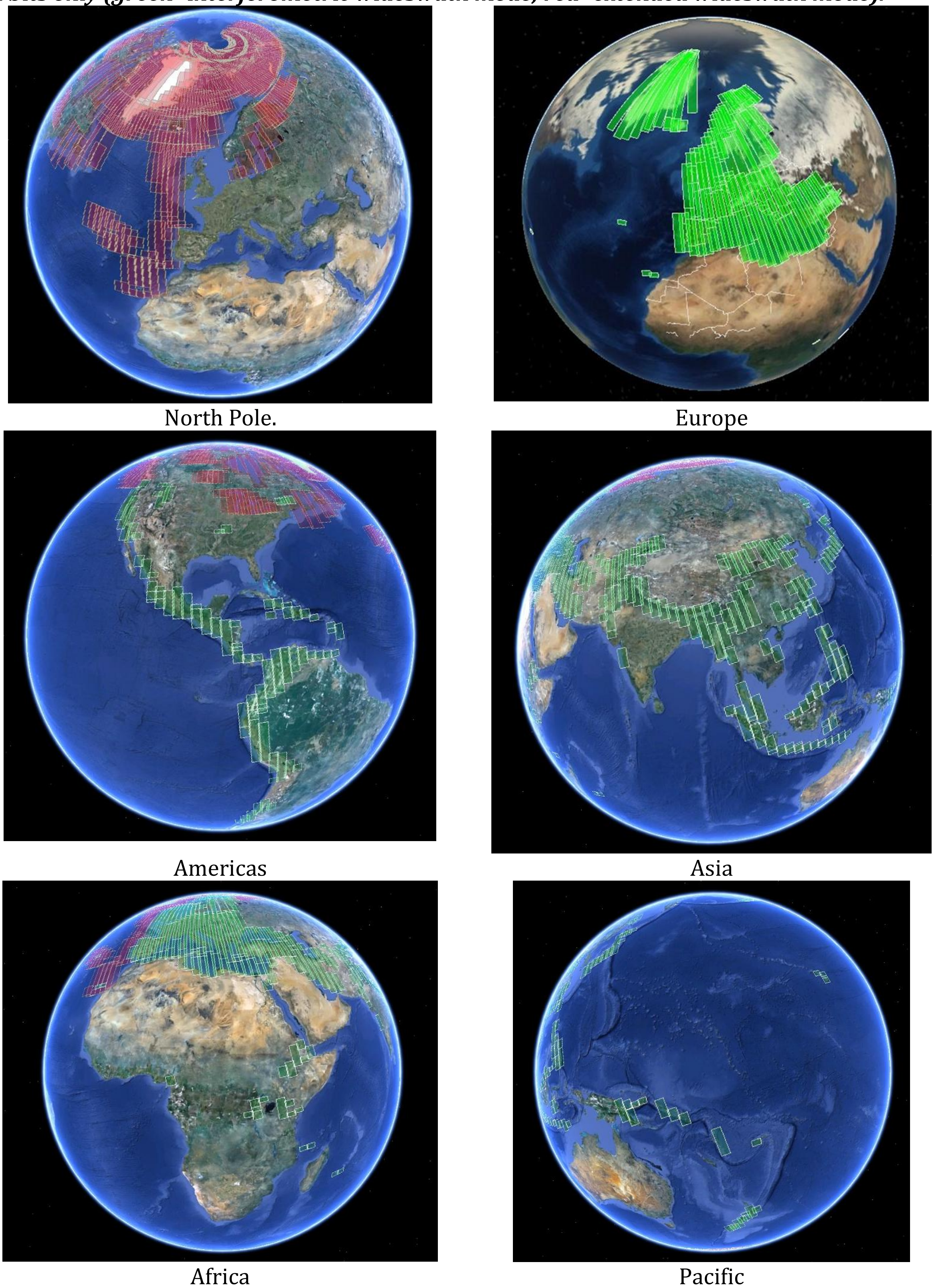
One effect of a growth in constellation missions will be to enhance the overall revisit capability. Guaranteed daily coverage available from SAR data will be augmented by potential daily revisits from high resolution optical imagery, subject to atmospheric and lighting conditions.

Not all suppliers will achieve daily revisit capability at all locations using their own satellites alone, but several suppliers have been establishing “virtual constellations” of linked satellite missions from more than one image supplier, with a view to achieving significantly enhanced combined revisit and coverage capabilities. Examples include the SIASGE constellation (Italian Argentinian Satellite System for Emergency Management) incorporating Cosmo-Skymed current and follow-on missions, at X band, and SAOCOM, at L band, which will provide revisits every 12 hours on average anywhere on the Earth. The Italian Space Agency also has an MoU in place with JAXA for cooperation between the ALOS-2 and Cosmo satellite missions. The TerraSAR-X, TanDEM-X and PAZ SAR missions will provide combined X band monitoring, while the Sentinel-1 and Radarsat Constellation Missions will provide coordinated C band monitoring, with particular coordination in terms of maritime coverage.

In the case of Novasar, innovative combinations of orbital inclinations within the satellite constellation will be used to enhance revisit times in key areas. Novasar will combine a high and low inclination orbit to achieve both good polar coverage and relatively high revisits in equatorial latitudes.

In the case of the Sentinel-1 SAR satellites, the coverage will be pre-determined not by the orbit and sensor imaging geometry, but by the pre-selection of areas for sensor acquisitions covering a range of thematic requirements for SAR data [20]. The preliminary coverage maps are shown in the following figure. Europe, including surrounding seas, is well covered. Some other areas are also well covered, such as the Southern Ocean and areas around Canada (including to the east of Harrison Bay, Alaska) and Greenland (including West Greenland). Outside these areas, there is significant coastal coverage, but many areas are not planned to be covered at all and none of the other test areas identified in this report are likely to be directly covered (although areas “coastward” of some of the test areas are covered).

Figure 28. Sentinel-1 preliminary planned SAR coverage over a 12 day period, ascending orbits only (green=interferometric wideswath mode; red=extended wideswath mode).



10.1.4. Lead Times and Latencies

Improved data turnaround times are anticipated as a result of more ground stations (including in Alaska, recently upgraded to support Pleiedes data from Astrium, for example), portable ground stations (such as the Skybox Skynode system) and satellite data relay (e.g. the European Data Relay System which will be used to relay data from the Sentinel satellites). Improvements to the fixed ground station network, and satellite data relay, will reduce the maximum data latency values significantly. Portable stations can in some case be used both for tasking and downlink (and processing) of satellite data, providing advantages in terms of both lead time and latency.

10.2. Data Access

10.2.1. Data Access Plans

As competition increases in the market, there are opportunities for new methods of purchasing, and guaranteeing access to, satellite data. There are opportunities available to pre-purchase data at a favourable rate per image in return for guaranteed priority for data acquisitions. This type of arrangement is being offered for NovaSAR data. In effect, the purchaser is paying for some of the capacity of the instrument and mission and helping to support mission financing in the process. Other providers, such as DigitalGlobe, offer a subscription-type purchase model that also offers advantages over a “pay as you go” purchasing arrangement.

There is also a particular development of note in Europe in terms of the new EU Copernicus programme, incorporating the Sentinel satellites, which has a “free and open” data policy. Acquisitions from the Sentinel satellites will be available “for free”, albeit pre-planned. Thus, there is an opportunity, at least for some areas of interest, to ensure very cost effective baseline access to SAR data that can serve a “monitoring” function for oil spills, but also potentially post-spill surveillance. However, a result of this free and open data policy is that ESA are not taking responsibility for the processing and distribution of these data beyond a very basic level of processing. The industry therefore needs to take actions, via collaborative agreements, to ensure that they have effective near real time access to processed data for their areas of interest. It will then be possible to build commercial data acquisitions around these planned “free and open” data acquisitions.

Note that there are plans for some suppliers to provide satellite imagery “for free” for research purposes, in some cases where the data are not near real time, thus providing a potentially useful data resource for research by the industry.

10.2.2. Tasking

Tasking is conventionally carried out by contacting an image supplier and providing an order for imagery covering an area of interest and time period. A number of developments are taking place that provide more options compared to this traditional model, as follows:

- No tasking. In some cases, such as that of the Planetlabs and ESA Sentinel satellites, there is no tasking of the sensors. In the case of the former, the sensors are continuously operating, despite being high resolution, and so tasking is not required. In the case of the latter, the SAR acquisitions are fully pre-planned, so that there is virtually no scope for any third party tasking requests (major disasters being one exception).
- Direct access user tasking. It is possible with some planned missions for the user to carry out tasking requests themselves using a ground terminal which supports direct tasking uplinks. This is associated with satellite constellations where there is scope for distributed tasking that can be allocated amongst multiple satellites.

10.2.3. Delivery

The conventional method of data delivery via a fixed ground station, possible processing at an additional site, and the delivery on an image-by-image basis, is being augmented by more innovative approaches, as follows:

- Routine and continuous refresh of data, for example from PlanetLabs, is being planned, as in a "near real time Google Earth" type of product, that will be web-based.
- Streaming of data direct to the web is being planned for video from the ISS, for example from Urthecast.
- Direct reception at a local portable ground station is potentially available, for example from Skybox Imaging and their Skynode station.
- ESA in particular is moving towards a decentralised strategy for processing of data. In the case of data from Sentinel-1, ESA is committed to generating level 0 SAR data within 10 minutes of acquisition, and within either 1 or 3 hours for level 1 data covering some pre-selected areas, but other organisations are taking on responsibility for serving specific sets of users and/or specific geographical areas. ESA has established a collaborative agreement with EMSA, for example, to provide data for them in near real time from pre-planned acquisitions. Entities in Canada and the US are taking responsibility for near real time delivery of data in their respective areas of interest.

The industry should therefore consider the options that are available for delivery of data and should plan ahead to ensure that appropriate infrastructure is in place, along with collaboration or contractual agreements.

11. Findings

A number of key findings arise from the work described in this report.

11.1. Organisation and Planning

Because the use of satellite surveillance for OSR is challenging in terms of technology and operational issues, is global in application, and requires agreements with image suppliers, it is recommended that **a centralised, operational oil and gas industry facility for coordinating planning of satellite surveillance for OSR be established**, with the following characteristics:

- The facility has clearly defined responsibility for OSR in terms of global satellite surveillance with single point of contact and well proven protocols for robust and effective response (a partial model might be provided by the Disaster Charter facility, [21]);
- The facility acts as a repository of experience and expertise with respect to oil spill satellite surveillance;
- The facility provides effective coordination of global assets and capabilities and links to global network of OSR organisations;
- The facility acts to ensure compliance of satellite remote sensing with the Common Operating Picture;
- The facility provides a strong negotiating position for satellite data with vendors, including those with innovative business models;
- The facility communicates its satellite data needs and issues with relevant remote sensing organisations and agencies.

There are now many remote sensing satellites and sensors, indeed it has been estimated that the number of launches of remote sending satellites is expected to double over the decade from 2013, to 360 [22]. The vast majority of these fall outside the range of useful configurations for OSR, but the number of suppliers and range of technologies still represents a challenge to the industry. Some 39 future satellites of potential direct value to OSR are listed in the appendices as being approved for launch (*Table 13* to *Table 16*), building on the 57 identified that are already in orbit (*Table 8* to *Table 12*). Some 17 commercial image suppliers are identified (*Table 17*). It is recommended that the satellite surveillance facility **carry out a regular horizon scan, extending 5 years, to ensure that they are aware of upcoming satellite remote sensing technologies and data**.

Fundamentally, there is the opportunity to treat the large number of earth observing satellites are a virtual constellation for OSR, albeit supported by several suppliers. The advantages of this are as follows:

- Several suppliers now offer their satellites are a constellation in which they can optimise sampling of an AoI;
- Some suppliers are now offering interoperability of missions, such as PAZ and TerraSAR-X/TanDEM-X, and Cosmo-Skymed and SAOCOM missions. Interoperability refers to the use of coordinated planning and operations, with benefits in terms of more efficient sampling and the synergistic use of complementary data sources (e.g. to support false alarm detection).
- Some remote sensing data from future sources will be nominally free-of-charge (Copernicus data from the European Space Agency Sentinel series of satellites) and these data should be incorporated into planning to optimise the planning of commercial data;
- Any part of the imaging tasking, acquisition and processing of data is subject to failure, and suppliers tend to streamline this workflow to make it as efficient as possible. A failure during OSR might create a temporary unavailability of data, and hence having more than one supplier available (in advance) is important.

It is important to convey to image suppliers the necessity of data continuity to justify operational investments and commitments.

To exploit data from multiple satellites and sensors, and to support effective multi-sensor integration as recommended by many of those involved in the Deepwater Horizon oil spill, **<u>software should be available with which to identify suitable data for OSR from among the plethora of data sources</u>**. This should take into account the following:

- Multi-satellite orbits, sensor geometries and planning constraints;
- Pre-selected sensor configurations for the best data sources for OSR, incorporating intelligence on imaging mechanisms, remote sensing and environmental factors;
- Ancillary information to support planning, e.g. weather forecasts and COP information (e.g. spill trajectory forecasts and asset positions);
- Pre-planning information where available, such as from Sentinel-1.
- Suitable visualisations to aid with decision-making;
- Ability to order data direct from the planning tool;
- Internet connectivity to facilitate communication of plans;

This software could be used to help **<u>generate local satellite surveillance plans for OSR, incorporated within Field Development and Emergency Response Plans</u>**. These satellite surveillance plans would effectively be customised for the particular environmental and operational challenges of each local area, and could then be used as one input to assess the need for airborne assets on standby.

This evaluation can then be used to ensure that the industry puts in place appropriate contracts with image suppliers and value-added organisations, covering such issues as appropriate priority for data if and when required for OSR, access to data for exercises and tests, access to data for background monitoring (if appropriate), multiple user licensing for the data, guaranteed data ordering lead and delivery times, data backup and compliance with the Common Operating Picture (COP) for product delivery. With sufficient planning and negotiation for long term data access, it may be possible to give the image suppliers sufficient justification to invest in infrastructure to support delivery standards for data.

Once the data requirements have been defined and suitable contractual vehicles put in place to support these requirements, then covering each area, **a satellite image acquisition plan should be maintained and refreshed in real time so that, in the event of a spill, the plan can be executed without delay**. Such planning is feasible through the use of multi-mission planning tools that are maintained in an operational environment. Such tools should incorporate information on anticipated data delivery times, latencies, etc., to support operational planning including effective coordination with airborne assets. Such a plan should also take into account pre-planned, and/or nominally "free", data that may be leveraged for OSR.

Part of this forward planning is a recommended **programme of baseline satellite monitoring at key industry locations**, with the following benefits:

- Early detection of oil spills;
- Availability of a resource of data that can be used for training, evidence and understanding the local environment;
- Familiarity with data interpretation, to support readiness when an emergency occurs, including elimination of false alarms, and training;
- Monitoring the performance of image suppliers and "ironing out" any problems in relation to planning and delivery of timely and good quality data;
- Providing support to industry Geomatics teams in promoting the use of satellite surveillance data internally for OSR;

Collaborations with other organisations, such as EMSA, should be considered as a means of cost effective monitoring.

11.2. Research and Development

The oil and gas industry should be pro-active in ensuring that research and development is being actively steered towards the goal of effective OSR. This will be facilitated by effective communication of industry needs to relevant satellite remote sensing communities and organisations, such as the Oil and Gas Earth Observation (OGEO) portal established by the European Space Agency [23].

- **Ensuring that design criteria are available that define satellite sensor characteristics of value to OSR**, and communicating these to satellite mission planners and designers. In some cases, OSR may be enhanced significantly by relatively modest tradeoffs in instrument design. An example would be designing adequate signal to noise ratio at key frequencies, sufficient dynamic range in the signal, designing optimised imaging modes for OSR sampling, or identifying minimum acceptable positioning accuracies for preliminary orbits. This might also include a requirements for integration of AIS with remote sensing, linking together positioning of assets with oil spill and other information from remote sensing, would be extremely useful, within the context of the COP. Some satellite missions are already offering this.

- **Encouraging the development of promising new instrument and measurement concepts**. Academic research may provide some embryonic concepts that can be explored for oil spill response, for example to detect oil on land or in sea ice, or to estimate oil thickness or to map the application of dispersant. Some space agencies are actively developing some of the more innovative and promising remote sensing instrumentation ideas, such as the European Space Agency Earth Explorer Programme (which is currently developing a P band SAR mission, [24]). By communicating the main challenges to the broader academic community, some promising new concepts may be forthcoming. It would be useful for sample (historical) oil spill datasets involving remote sensing imagery to be made available to researchers, along with ancillary data.

- **Being open to innovative satellite platform options for OSR surveillance** that may enhance capabilities significantly. Geostationary satellites offer continuous monitoring of the Earth's surface, and are being proposed for ocean colour and atmospheric composition. These offer excellent vehicles for OSR surveillance sensors, providing the ability to detect and monitor oil spills conditions during any breaks in cloud cove, as well as aerosols. Such capabilities are being planned by ESA, KARI and NASA [25]. Communications satellites have also offered hosting capabilities for remote sensing instruments (Iridium), and small satellite constellations are changing the economics of space. Where a new game-changing opportunity becomes available, the industry should be prepared to be pro-active in exploring how this can be leveraged.

There should be ongoing research focused on SAR, as the primary satellite sensor for synoptic surveillance of oil spills. There are several developments here that are of interest for OSR:

- L and S band SAR sensors will be available in the coming years, and may even become similar to C and X band in terms of availability, yet familiarity with these data for OSR is lacking. The potential and limitations of these imaging frequencies should be evaluated for OSR in terms of detection capability as a function of surface wind speed, incidence angle and false alarms.

- New capabilities of operational polarimetric SAR imaging modes should be evaluated, which may ultimately have value to oil spill characterisation as well as detection, for example to help discriminate between sheens and thicker oil, or perhaps to be sensitive to oil in ice (at L and S as well as C and X frequencies). Compact polarimetry in particular may have potential.

Although optical sensors are limited by atmospheric conditions and the availability of natural light, where clear skies are available, optical data can be very useful, with the potential to provide information on the characteristics of oil spills as well as their presence. In order to exploit this, **a programme of research should be focussed on the optimum configurations for optical sensors for oil spill detection, and the potential of planned optical satellite missions**, including the following:

- Spectroscopic techniques and their practical application to space-borne sensors. There are useful developments in terms of optical imaging frequencies that are expected to be particularly useful for OSR, including through hyperspectral sensors which are now approved for deployment on satellites (and the International Space Station). Research on the capabilities of critical absorption frequencies would be useful, such as the red edge of NIR. There is a need to leverage, or where appropriate, encourage laboratory and field-based research in spectroscopy towards the goal of fingerprinting oil type, condition and concentration from space-based hyperspectral sensors. There should be an applied aspect to this research that takes into account the ultimate goal of near real time information.

11.3. Exercises

It is recommended that **the industry should incorporate satellite data routinely into OSR exercises**. Historically, such exercises have tended to focus on ground-based and airborne activities, but satellite technologies should be included. The following benefits will accrue from such exercises:

- Early assessment of new satellite data sources or value-added products to OSR;
- Validation and refinement of more mature techniques and products;
- A framework for linking together researchers and operational users to provide a route for development of products and capabilities;
- A means to test and, where required, improve operational practices prior to a real emergency;
- A means of providing training, not only "in the field", but in terms of satellite image planning, delivery and analysis.
- A way to carry out tests in less familiar environments, such as the Arctic.

Such exercises should involve the actual acquisition and delivery of satellite imagery. This does not need to involve collection of all the imagery that would be collected in a real oil spill, but it could involve collection of random sample images to validate data turnaround times and delivery. This would be particularly important where a source of data has not been used for OSR before, or there is new infrastructure involved, such as a new ground station or processor. As well as ordering satellite imagery to test operations, this would also help enable research, particularly if relevant other data were collected simultaneously to support interpretation.

12. Conclusions

Satellite remote sensing is now an accepted and integral component of effective OSR. The capabilities of the technology have developed significantly over the last decade to the point where the technology is now genuinely meeting useful industry needs in terms of spatial and temporal sampling and timely response. Unlike airborne or in situ platforms, satellites are routinely available and are particularly useful for wide area synoptic coverage that can be used to deploy airborne assets both efficiently and, in some cases, safely. It remains the case that satellite remote sensing covers only part of oil spill surveillance requirements, but it is now an effective and essential part. At the same time, there is disruptive development of the technology in terms of capabilities and commercial offerings, and the number and range of sensors and suppliers continues to grow. In order to make effective use of the technology, it is necessary to plan well ahead for the use of satellite surveillance for OSR, and to be aware of longer term technologies, data sources and related opportunities. In the past, the industry has tended to operate locally and reactively in responding to oil spills with satellite surveillance. In future, the industry should be operate pro-actively with globally coordinated satellite surveillance, in order to optimise effectiveness.

Appendix A. Satellite Remote Sensing Sensors

This appendix provides detail on the sensors and their suppliers.

The information on available sensors is obtained from the following two sources:

- CEOS handbook or information on agency-led satellite missions (see [26]);
- Earth Observation Portal for information on both commercial and non-commercial satellite missions (see [27])

Note that we do not include the following sensors in this survey:

- PAN-only sensors;
- Military satellite missions without a civilian element;
- Student-designed and operated satellite missions;
- Satellite missions that are not formally approved.

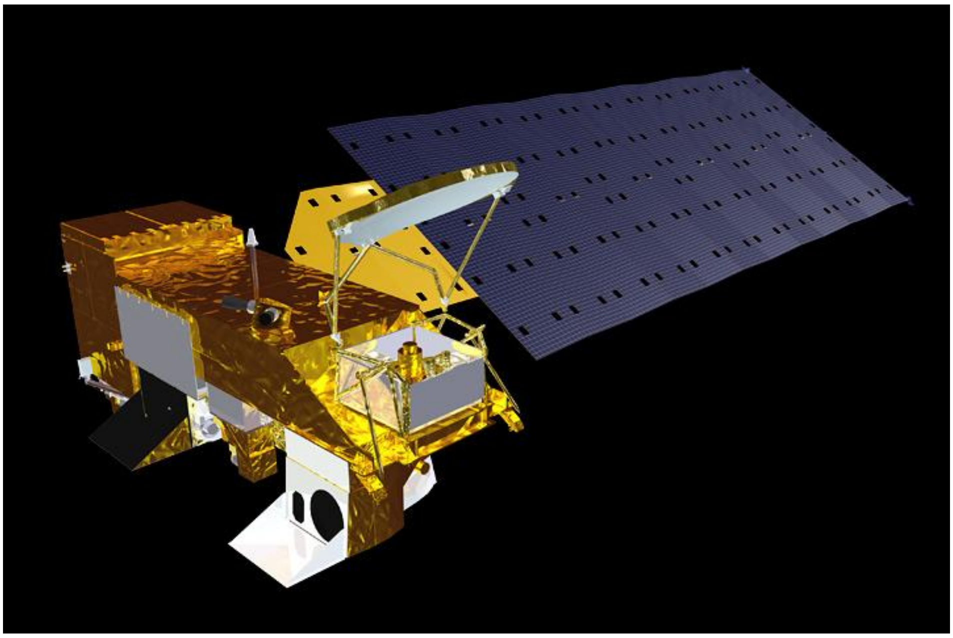


Figure 29. Artist's impression of NASA's AQUA satellite, which has been operating for a decade with multiple sensors on board, including MODIS which was used to monitor the Gulf of Mexico oil spill.

The information is provided in the form of tables which relate to the following categories of remote sensing sensors:

- Satellite SAR sensors;
- High resolution optical sensors;
- Broad band moderate resolution optical sensors (multi- and hyperspectral);
- Lidars.

A1. Current Sensors

Table 8. Current SAR satellite sensors

<table>
<tr><th colspan="6">Satellite and Source</th></tr>
<tr><th>Mission</th><th>Source</th><th>Launch</th><th>Band</th><th>Resolution range</th><th>Coverage range</th></tr>
<tr><td>TERRASAR-X</td><td rowspan="2">Astrium</td><td>2007</td><td>X</td><td>1-40m</td><td>5-270km</td></tr>
<tr><td>TANDEM-X</td><td>2010</td><td>X</td><td>1-16m</td><td>5-100km</td></tr>
<tr><td>COSMO SKYMED 1</td><td rowspan="4">E-GEOS</td><td>2007</td><td rowspan="4">X</td><td rowspan="4">1-100m</td><td rowspan="4">10-200km</td></tr>
<tr><td>COSMO SKYMED 2</td><td>2007</td></tr>
<tr><td>COSMO SKYMED 3</td><td>2008</td></tr>
<tr><td>COSMO SKYMED 4</td><td>2010</td></tr>
<tr><td>RADARSAT-2</td><td>McDonald Dettwiler Associates</td><td>2007</td><td>C</td><td>1.6-160m</td><td>8-500km</td></tr>
<tr><td>RISAT-1</td><td>Indian Space Research Organisation</td><td>2010</td><td>C</td><td>3-50m</td><td>30-240km</td></tr>
<tr><td>HJ-1C</td><td>China Centre for Resources Satellite Data and Application</td><td>2010</td><td>S</td><td>20m</td><td>100km</td></tr>
<tr><td>KOMPSAT-5</td><td>Korea Aerospace Research Institute</td><td>2013</td><td>X</td><td>1-20m</td><td>5-100km</td></tr>
</table>

Table 9. Current satellite lidar sensors

<table>
<tr><th colspan="5">Satellite and Source</th></tr>
<tr><th>Mission</th><th>Source</th><th>Wavelengths</th><th>Spatial resolution</th><th>Vertical resolution</th></tr>
<tr><td>CALIPSO</td><td>National Aeronautics and Space Administration</td><td>532 nm, 1064 nm</td><td>330m</td><td>~60m</td></tr>
</table>

Table 10. Current high resolution optical satellite sensors (1 of 2).

Mission	Source	Spatial resolution (PAN)	Swath	Number of channels (excluding PAN)				
				TIR	SWIR	MWIR	NIR	VIS
ALSAT-2	Algerian Space Agency	10m (2.5)	17.5km				1	3
Kompsat-3	Korea Aerospace Research Institute	4m (0.8)	15km				1	3
DubaiSAT-1	Satrec Initiative	5m (2.5)	20km				1	3
Geoton	Rosmosmos	1-3m	30km				1	3
HiRi	Centre national d'études spatiales	0.7m	20km				1	3
LISS-IV	Indian Space Research Organisation	5.8m	70km				1	2
Kompsat-2	Korea Aerospace Research Institute	4m (1)	15km				1	3
Kanopus-V1	Roscosmos	10.5m (2.1)	20km				1	3
MSI	German Aerospace Center (DLR)	6.5m	78km				1	4
LAPAN-A2	National Institute of Aeronautics and Space	5m	12km					3
MSS	State Space Agency of Ukraine	8.2m	46.6km				1	2
ZY-02C	China Centre for Resources Satellite Data and Application	10m (5)	60km				1	2
THEOS	Geo-Informatics and Space Technology Development Agency	15m (2)	90km				1	3
RASAT	Tubitak	15m (7.5)	30km					3
RazakSAT	Satrec Initiative	5m (2.5)	20km				1	3
RESURS-DK	Roscosmos	2.5-3.5m	28km					3
SSOT	Agencia Chilena del Espacio	5.8m (1.5)	10km				1	3
SICH-2	State Space Agency of Ukraine	8.2m	48.8km				1	2
Ikonos-2	DigitalGlobe	4m (1)	11km				1	3
NigeriaSAT-2	DMCii Ltd	5-32m (2.5)	20km				1	3

Table 11. Current high resolution optical satellite sensors (2 of 2).

Mission	Source	Spatial resolution (PAN)	Swath	Number of channels (excluding PAN)				
				TIR	SWIR	MWIR	NIR	VIS
RapidEye 1	RapidEye	6.25m	70km				1	4
RapidEye 2		6.25m	70km				1	4
RapidEye 3		6.25m	70km				1	4
RapidEye 4		6.25m	70km				1	4
RapidEye 5		6.25m	70km				1	4
Formosat-2	Astrium	8m	24km				1	3
SPOT-5		2.5m	60km		1		1	2
SPOT-6, SPOT-7		6-10m (1.5-2.5)	60km				1	3
Pleiedes-1A, 1B		2.8m (0.7)	20km				1	4
Ikonos	DigitalGlobe	4m (0.8)	11km				1	3
Quickbird		2.4m (0.6)	16.5km				1	3
Worldview-1		0.5-0.55m	17.6km				2	6
GeoEye-1		1.56m (0.41)	15.2km				1	3
Worldview-2		2m (0.9)	16.4km				2	6
VNRedSAT-1	Space Technology Institute	10m (2.5m)	17.5km				1	3
ZY-3A	China Centre for Resources Satellite Data and Application	5.8m	51km				1	3

Table 12. Current broad band moderate resolution optical satellite sensors.

Mission	Source	Spatial resolution (PAN)	Swath	Number of channels (excl PAN)				
				TIR	MWIR	SWIR	NIR	VIS
ALI	National Aeronautics and Space Administration	30m (10)	185km			2	8	
ASTER		15-90m	60km	5		6	3	
Hyperion		60m	600km	8				
			185km		260			
EO-1		30m (10)	185km			3	6	
HICO/ISS	Naval Research Laboratories	90m	50km				~102	
HRG	Centre national d'études spatiales	10m (5)	60km			1	1	2
HRVIR		10-20m	117km			1	1	2
LISS-III	Indian Space Research Organisation	23.5m	141km			1	1	2
LandSAT-7	National Aeronautics and Space Administration	15-60m	185km	1		2	4	
LandSAT-8		230m (15)	185km			2	1	4
MTI		5m	12km	2	1	2	4	3
AQUA /MODIS		250-1000m	2330km	8	8	2	7	11
TERRA /MODIS								
MTI		20m	12km	2	1	2	4	3
Resource SAT-2	Indian Space Research Organisation	56m	740km		1		1	2

A2. Future Sensors

Approved future satellite remote sensing missions in the following tables.

Table 13. Approved future microwave satellite sensors for OSR

Mission	Source	Launch	Band	Resolution range	Coverage range
SAOCOM-1A	Comisión Nacional de Actividades Espaciales	2014	L	10-100m	20-350km
SAOCOM-1B		2015			
SENTINEL-1a	European Space Agency	2014	C	5-100m	80-400km
SENTINEL-1b		2015			
ALOS-2	Japan Aerospace Exploration Agency	2014	L	3-100m	25-350km
RADARSAT-C1	Canadian Space Agency	2018	C	3-100m	20-500km
RADARSAT-C2		2018			
RADARSAT-C1		2018			
MeteorM-N3	Roscosmos	2015	X	1-500m	10-750km
CSG	Agenzia Spaziale Italiana	2015	X	2-35m	40-320km
CSG		2015			
PAZ	Hisdesat	2014	X	1-15m	5-100km
NovaSAR	DMCii Ltd	2015	S	6-30m	20-140km
NovaSAR		2016			

Table 14. Approved future high resolution optical satellite sensors for OSR

Mission	Source	Launch	Spatial resolution	Swath	Number of channels				
					TIR	SWIR	MWIR	NIR	VIS
ALOS-3	Japan Aerospace Exploration Agency	2015	5m	90km				1	3
ALSAT-2B	Centre National des Techniques Spatiales	2014	6-10m (1.5-2.5)	17.5km				1	3
ASNARO-2	Ministry of Economy, Trade, and Industry (Japan)	2014	2m (0.5)	10km				6	
DMC-3 DMC-3 DMC-3	Twenty-First Century Aerospace Technology Co. Ltd.	2014	4m (1)	23km				1	3
DubaiSAT-2	Satrec Initiative	2013	4m (1)	12km				1	3
HISUI	Ministry of Economy, Trade, and Industry (Japan)	2015	5m	90km				4	
Kanopus-VN2	Roscosmos	2013	10.5m (2.1)	20km				1	3
Ingenio	Centre for Industrial Technological Development	2015	10m (2.5)	55-60km				1	3
GeoEye-2	DigitalGlobe	On hold	1.36m (0.34)	14.5km				1	3
SeoSAT	Hisdesat	2015	10m (2.5)	55km				1	3
MUSES	Teledyne Brown Engineering	2015	4m	50km					
Venus	Centre national d'études spatiales	2014	5.3m	27.5km				12	10
Worldview-3	DigitalGlobe	2014	1.24m (0.31)	66.5km		8		2	6
Doves constellation	PlanetLabs	2013 (4) 2014-15 (24)	3-5m	16km				1	4
Camera / video	Urthecast	2014	5m (camera 1m (video)	60km					3
Skysat constellation	Skybox Imaging	2014-17 (24)	2m (0.9)	8km				1	4

Table 15. Approved future moderate resolution wider band optical satellite sensors for OSR

Mission	Source	Planned Launch	Spatial resolution	Swath	Number of channels: TIR	SWIR	MWIR	NIR	VIS
ALOS-3	Japan Aerospace Exploration Agency	2015	30m	30km		128		57	
CBERS-3	National Institute for Space Research	2013	10-80m (5)	60-866km	1	2		1	3
CBERS-4		2015							
EnMAP	German Aerospace Center (DLR)	2015	30m	30km		136		96	
HISUI	Ministry of Economy, Trade, and Industry (Japan)	2015	30m	30km		128		57	
Sentinel-2	European Space Agency	2014	10m	290km		2		2	6
MUSES	Teledyne Brown Engineering	2015	30m	50km		200			
Worldview-3	DigitalGlobe	2014	3.7m SWIR	66.5km		8		2	6
Prisma	Agenzia spaziale italiana	2014	30m	30km		171		66	

At the present time, only one satellite lidar mission is approved for launch, with similar characteristics to Caliop.

Table 16. Approved future satellite lidar sensors for OSR

Mission	Source	Launch	Wavelengths	Spatial resolution	Vertical resolution
ICESAT-II	NASA	2015	532 nm, 1064 nm	66m	n/a

A3. Satellite Mission Contacts

Satellite mission contacts are listed in *Table 17* and in *Table 18*.

Table 17. Commercial satellite mission contacts

Ref	Organisation	Nation	Name	Email	Telephone
[1].	EADS Astrium	DEU	Lutz Petrat	lutz.petrat@astrium.eads.net	+49 7545 8 3389
[2].	DigitalGlobe	USA	Casey McCullar	Casey.mccullar@digitalglobe.com	+1 303.684.1597
[3].	DMCii Ltd	BGR	Martin Philp	m.philp@dmcii.com	+44 1483 804299
[4].	E-GEOS	ITA	Paola Nicolosi	paola.nicolosi@e-geos.it	+39 334 680 2012
[5].	Hisdesat	ESP	Juan Ignacio Cicuendez-Perez	jcicuendez@hisdesat.es	+34 914490149
[6].	ImageSAT International	ISR	Alex Imas	imas@imagesatintl.com	+972-3-796-0627
[7].	MDA Corporation	CAN	Bob Dams	BDAMS@mdacorporation.com	613-727-1087 ext.248
[8].	Satreci Initiative	KOR	KyoungJin Jung	kjjung@satreci.com	+82-70-7006-6057; +82-10-2764-0519
[9].	Urthecast	CAN	Wade Larson	wlarson@urthecast.com	+1 (604) 669-1788
[10].	Antrix Corporation	IND	K. Radhakrishnan	unknown	+91-80 -2341 6273
[11].	Beijing Space Eye Innovation Technology Co	CHN	Kimy Cheng	bsei@bsei.com.cn	+86 10 822 57160
[12].	RapidEye	DEU	César Santos-González	csg@rapideye.net	+(49) 30 609 8300-100
[13].	Teledyne Brown Engineering	USA	Dr. Mark S. Whorton	mark.whorton@tbe.com	+1 256-726-1924
[14].	Deimos Imaging	ESP	Aurelio Marti Ferrer	Unknown	+34 983 54 89 23
[15].	Twenty First Century Aerospace Technology Company Ltd	CHN	WANG Xiaoming	Unknown	+86 10 62929966
[16].	PlanetLabs	UK	Matthew Waldram	matthew.waldram@planet-labs.com	+44 781 628 1968
[17].	Skybox	USA	Mr. Ching-Yu Hu	Sales@skybox.com	unknown

Table 18. Non-commercial satellite mission contacts

Ref	Organisation	Nation	Name	Email	Telephone
[18].	Naval Research Laboratories	USA	Jeff Bowles	jeff.bowles@nrl.navy.mil	+1 202 404 1021
[19].	European Space Agency	n/a	Gordon Campbell	Gordon.campbell@esa.int	+39 06 941801
[20].	National Aeronautics and Space Administration	USA	Mike Corson	Unknown	Unknown
[21].	Agenzia spaziale italiana	ITA	Cristina Ananasso	cristina.ananasso@asi.it	+39 06 8567 1
[22].	Comisión Nacional de Actividades Espaciales	ARG	Patricio J. Obcowski	pjo@conae.gov.ar	+54 11 4331 0074
[23].	Indian Space Research Organisation	IND	V.V. Ganesh	ganesh_vv@nrsc.gov.in	+91-135-2524105
[24].	National Institute for Space Research	BRA	Carlos Alexandre Wuensche	ca.wuensche@inpe.br	+55 (12) 3208 6000
[25].	National Oceanographic and Atmospheric Administration	USA	Jennifer Belge	jennifer.belge@noaa.gov	*+1 301-683-1408*
[26].	National Space Organization	TWN	Guey-Shin Chang	Unknown	+886-3-578-4208
[27].	State Space Agency of Ukraine	UKR	Borys Atamanenko	Unknown	+380442816200
[28].	German Aerospace Center (DLR)	DEU	Uta Heiden	uta.heiden@dlr.de	+49 8153 283282
[29].	Japan Aerospace Exploration Agency	JPN	Shimada Masabobu	shimada.masabobu@jaxa.jp	Unknown
[30].	Geo-Informatics and Space Technology Development Agency	THA	Jirawan Chareonratch	'jirawan@gistda.or.th'	+66(0)-2141-4470
[31].	Research Center for Earth Operative Monitoring	RUS	Unknown	ntsomz@ntsomz.ru'	+7 (495) 925-0419
[32].	Geo-Informatics and Space Technology Development Agency	THA	Ms. Jirawan Chareonratch	jirawan@gistda.or.th	+66(0)-2141-4470
[33].	Space Technology Institute	VIE	unknown	vanthu@sti.vast.vn	(84-4) 37914746
[34].	Hisdesat	SPA	Juan Ignacio Cicuendez	jicicuendez@gmail.com	+91 449 01 49

Appendix B. References and Sources

[1]. OGP/IPIECA, "An Assessment of Surface Surveillance Capabilities for Oil Spill Response using Airborne Remote Sensing", Polar Imaging report, ref. PIL-4000-38-TR-1.0, 10th April 2014.
[2]. American Petroleum Institute, "Remote sensing in support of oil spill response: planning guidance", API Technical Report 1144, September 2013.
[3]. http://www.opengeospatial.org/projects/initiatives/ogpoilspill.
[4]. National Aeronautics and Space Administration, Science Mission Directorate, 2010, Introduction to the electromagnetic spectrum, retrieved June 23, 2013, from Mission: Science website: http://missionscience.nasa.gov/ems/01_intro.html.
[5]. Alliance for Coastal Technologies, 2008, "Hydrocarbon sensors for oil spill prevention and response", ACT workshop of developers, deliverers and users of technologies for monitoring coastal environments report, ref. CBL 08-095., April 8-10, Seward, AK.
[6]. Alliance for Coastal Technologies, 2011, "Use of, satisfaction with, and requirements for in situ hydrocarbon sensors", http://www.act-us.info/Download/Customer_Needs_and_Use/Hydrocarbon/files/act_cnua11-01_hydrocarbon.pdf
[7]. Liefer, I., Lehr, W., Simecek-Beatty, D., Bradley, E. Clark, R., Dennison, P., Hu, Y., Matheson, S., Jones, C., Holt, B., Reif, M., Roberts, D., Svejkovsky, J., Swayze, G. And Wozencraft, J., 2012, "State of the art satellite and airborne marine oil spill remote sensing: application to the BP Deepwater Horizon oil spill", Rem. Sens. Env. Vol. 124, pp. 185-209.
[8]. Nir A., Shechter, E., 2011, "Lessons learned in emergency remote sensing and BP response during Deepwater Horizon", ASPRS 2011 Annual Conference, Milwaukee, WI, May 1-5, 2011.
[9]. Brovey, R., "Applicability of current remote sensors, platforms and image exploitation strategies to the reconnaissance needs of operational event responders", draft document 68pp.
[10]. Goodman, R., 2009, "Under ice oil detection", Exploration and Production, vol. 7, issue 2, pp 142-147.
[11]. Jha, M., Levy, J. And Gao, Y, 2008, "Advances in remote sensing for oil spill disaster management: state of the art sensors technology for oil spill surveillance", Sensors 2008, 8, pp. 236-255.
[12]. Lewis, M. D., Gould, R. W., Ladner, S., Gallegos, S., Jolliff, J., Bennert, E., and Li, R. -R., "Spectral and Spatial Analysis of the Gulf of Mexico Oil Spill Using Satellite and In Situ Data", in Ocean Optics XX Conference, held in Anchorage, Alaska, 25 SEP-01 OCT 2010, 9 (2011)
[13]. Lan, Guoxin; Ma, Long; Li, Ying; Liu, Bingxin, Mechanism and look-alikes analysis of oil spill monitoring with optical remote sensing, MIPPR 2011: Remote Sensing Image Processing, Geographic Information Systems, and Other Applications. Edited by Liu, Jianguo; Tian, Jinwen; Sang, Hongshi; Ma, Jie. Proceedings of the SPIE, Volume 8006, article id. 800628, 7 pp. (2011).
[14]. http://www.taitussoftware.com/savoir
[15]. Clark, R.N., Swayze, G.A., Leifer, I. Livo, K.E., Kokaly, R., Hoefen, T., Lundeen, S., Eastwood, M., Green, R.O., Pearson, N., Sarture, C., McCubbin, I., Roberts, D., Bradley, E., Steele, D., Ryan, T., Dominguez, R., and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Team, 2010, A method for quantitative mapping of thick oil spills using imaging spectroscopy: U.S. Geological Survey Open-File Report 2010–1167, 51 p.
[16]. http://www.arcticresponsetechnology.org/
[17]. Surface wind speed climatology. http://nomads.ncdc.noaa.gov/las/getUI.do, NOAA/OAR/PMEL, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, Phone: (206) 526-6239 ~ Fax: (206) 526-6815, Email: oar.pmel.contact_ferret@noaa.gov.
[18]. Sea ice climatology. National Ice Center. 2006, updated 2009. National Ice Center Arctic Sea Ice Charts and Climatologies in Gridded Format. [indicate subset used]. Compiled by F. Fetterer and C. Fowler. Boulder, Colorado USA: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5X34VDB.

[19]. Karlsson, Karl-Göran; Riihelä, Aku; Müller, Richard; Meirink, Jan Fokke; Sedlar, Joseph; Stengel, Martin; Lockhoff, Maarit; Trentmann, Jörg; Kaspar, Frank; Hollmann, Rainer; Wolters, Erwin (2012): CLARA-A1: CM SAF cLouds, Albedo and Radiation dataset from AVHRR data - Edition 1 - Monthly Means / Daily Means / Pentad Means / Monthly Histograms. Satellite Application Facility on Climate Monitoring. DOI:10.5676/EUM_SAF_CM/CLARA_AVHRR/V001. http://dx.doi.org/10.5676/EUM_SAF_CM/CLARA_AVHRR/V001.

[20]. European Space Agency Earth Observation Program Board Sentinel High Level Operations Plan, ESA/PB-EO(2013)1, 21 January 2013.

[21]. International Charter for Space and Major Disasters, http://www.disasterscharter.org/home.

[22]. Euroconsult, 2012, Satellite-based earth observation: market prospects to 2021.

[23]. http://www.ogeo-portal.eu

[24]. http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers

[25]. J. Fishman, L. T. Iraci, J. Al-Saadi, K. Chance, F. Chavez, M. Chin, P. Coble, C. Davis, P. M. DiGiacomo, D. Edwards, A. Eldering, J. Goes, J. Herman, C. Hu, D. J. Jacob, C. Jordan, S. R. Kawa, R. Key, X. Liu, S. Lohrenz, A. Mannino, V. Natraj, D. Neil, J. Neu, M. Newchurch, K. Pickering, J. Salisbury, H. Sosik, A. Subramaniam, M. Tzortziou, J. Wang, and M. WangTHE UNITED STATES' NEXT GENERATION OF ATMOSPHERIC COMPOSITION AND COASTAL ECOSYSTEM MEASUREMENTS Nasa's Geostationary Coastal and Air Pollution Events (Geo -Cape) Mission, Bulletin of the American Meteorological Society, October 2012, pp. 1547-1566.

[26]. Committee on Earth Observation Satellites handbook, at http://database.eohandbook.com/, 2012 version.

[27]. Information resource for satellite missions, http://www.eoportal.org/.