Smarter Regulation of Waste in Europe
(LIFE13 ENV-UK-000549)
LIFE SMART Waste Project

Action B8:
Remote sensing – Phase 1 (Research)

Final Report

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Foreword

Key to the future use of remote sensing (RS) in the waste crime sector will be showing that this form of monitoring works, that it offers something new to regulatory bodies (or be better than existing methods) and that the cost is viable. In the invitation to tender, we were required to:

(1) Identify current applications and emerging developments in the field of RS and earth observation (EO) data acquisition and processing techniques and, where appropriate, an assessment of how successful the application of these technologies has been to environmental regulation and, more specifically, to identifying waste and other environmental crimes.

(2) To explore the opportunities for pro-active detection of emerging waste crime circumstances (i.e. before they become fully established).

(3) To assess the potential of innovatively using and overlaying RS technologies, EO technologies/techniques and Geographic Information Systems (GIS); and combining these through novel procedural approaches to help detect waste crime (emerging and established).

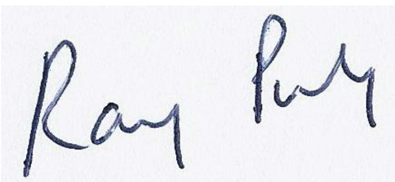
(4) Identify if particular waste streams emit unique signatures which would allow for proactive identification of illegal stockpiling and disposal.

(5) Recommend pilot projects (and provide an outline design of these) that will test:

- The innovative use and overlaying of RS technologies, EO technologies/techniques and GIS; and
- How they can be combined through novel procedural approaches to produce intelligence products and fill intelligence gaps to better detect waste crime activities (emerging and established) associated with challenging waste streams at a local, regional, national and/or international scale.

(6) To provide a cost benefit analysis of recommended pilot projects along with an assessment of potential added-value to regulators

This report provides answers to the above questions. We consider it to be the most comprehensive international examination of the viability of a future operational case for using RS technologies in waste regulation, undertaken yet. The material in this report demonstrates that RS could be very important and useful to many working in environmental regulation, and the pilots which are proposed for Phase 2 will assist in providing further evidence of this.



Raymond Purdy
Director, Air and Space Evidence

Acronyms

API	Application Programmeing Interfaces
ARCHER	Airborne Real-Time Cueing Hyperspectral Enhanced Reconnaissance
ARPA	Agricultural Risk Protection Act
ASM	Angular Second Moment
BI	Brightness Index
BAI	Burned Area Index
CAP	Common Agricultural Policy
CASI	Compact Airborne Spectrographic Imager
CCDs	Charged Coupled Devices
CEOS	Committee on Earth Observation Satellites
CHRIS	Compact High Resolution Imaging Spectrometer
CSCDA	Copernicus Space Component Data Access
CTBO	Comprehensive Nuclear-Test-Ban Treaty Organization
DEM	Digital Elevation Model
DIS	Dissimilarity
EA	Environment Agency (England)
EFTA	European Free Trade Association
EM	Electromagnetic
EMSA	European Maritime Safety Agency
ENT	Entropy
EO	Earth Observation
ESA	European Space Agency
EU	European Union
GIS	Geographic Information System
GLCM	Gray Level Co-occurrence Matrix
GloVis	Global Visualisation Viewer
GMES	Global Monitoring for Environment and Security
GSR	Geospatial Reference
HA	Hectare
HI	Hydrocarbon Index
HOM	Homogeneity
IBAMA	Brazilian Environment Agency
ICSU	International Council for Science
INPE	National Institute for Space Research (Brazil)
InSAR	Interferometric SAR
INS	Inertial Navigation System
IPR	Intellectual Property Rights
KM	Kilometres
LAI	Leaf Area Index
LIDAR	Light Detection and Ranging
LWIR	Long Wave Infra Red
M	Metres
MARISS	Maritime Security Service
MARS	Monitoring of Agriculture with Remote Sensing
MAX	Maximum Probability
MIVIS	Multispectral Infrared Visible Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPF	Federal Public Prosecutor (Brazil)
MT	Mega Tonnes
MWIR	Mid Wave Infra Red
NDRE	Normalised Difference Red Edge Index
NDVI	Normalised Difference Vegetation Index
NGOs	Non-Governmental Organisations
NIR	Near Infra-Red
OLAF	European Anti-Fraud Office

OPCW	Prohibition of Chemical Weapons
PCA	Principal Components Analysis
PRI	Photochemical Reflectance Index
PSRI	Plant Senescence Reflectance Index
RI	Redness Index
RIPA	Regulation of Investigatory Powers Act
RIPSA	Regulation of Investigatory Powers Scotland Act
RMA	Risk Management Agency (USA)
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SEPA	Scottish Environmental Protection Agency
SFSI	Short-Wave Infrared Full Spectrum Imager
SMA	Superintendency of the Environment (Chile)
SSP	Satellite Sentinel Project
SWIR	Short Wave Infra-Red
TM	Thematic Mapper
UAV	Unmanned Aerial Vehicle
UCL	University College London
UK	United Kingdom
UN	United Nations
US / USA	United States / United States of America
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VHR	Very High Resolution
WDS	World Data System
WV3	Worldview 3
3DEP	3D Elevation Programme

1.0 Executive Summary

Waste crime is a major crime sector. Illegal waste activity costs the United Kingdom (UK) up to £1 billion per year in lost revenue to legal businesses, lost taxes and high clean-up costs. Unlawful waste sites present significant environmental and social hazards. Remote sensing (RS) data offer a way of contributing to the detection and monitoring of unlawful waste sites on a regular basis. Such data have not been used extensively in the waste crime sector: this report examines the use of the data so far and explores how the data can be used effectively in tackling waste crime.

Satellite RS data have been used in many environmental monitoring applications, including the identification of illegal vegetation clearance in Australia, checking agricultural subsidy claims within the European Union's (EU) Common Agriculture Policy, identifying oil pollution in European waters, monitoring agriculture fraud in the United States of America (USA) and mapping illegal forest logging in Brazil. RS data have been used as formal evidence in courts in cases concerning insurance fraud, boundary disputes and property litigation. Given that waste crime sites have an environmental impact then there is the potential for RS to assist with monitoring waste crime. The experience of using RS data in the waste crime sector so far has shown that mapping vegetation, vegetation change, changes in surface minerals and changes in surface height are key indicators of waste crime sites. RS data in the optical, infrared and radar parts of the electromagnetic spectrum have been shown to be useful for waste crime site identification, plus the potential value from LIDAR and hyperspectral RS. In the cases studied in this report, RS data have been used in several countries to identify illegality at legal, exempted and unlawful sites using a wide range of different types of RS data.

Based upon existing applications of RS in environmental monitoring plus the use of RS data in waste crime monitoring, there is a role for the technology in providing information to assist in waste crime prevention. The data can be most effectively used as part of an intelligence-led approach to waste crime detection where the RS data make one contribution to waste crime mapping, typically in a Geographic Information System (GIS), and as part of a wider strategy to tackle waste crime. Already the smallest pixel size from satellite RS is 0.31m from DigitalGlobe satellites. While this pixel size will not diminish significantly in the future, there will be more satellites with very high spatial resolution sensors. Such very high resolution data do carry relatively high costs, but there are also open data that are free of charge that can contribute to providing information for the waste crime sector.

Given the early stage of development of RS in waste crime there is great merit in exploring the following four pilot projects proposed in the report.

- An operational 'live' case (based on historical data) to analyse RS and related geospatial data of a known illegal site.

- A case study of monitoring waste tyre piles by using RS data to examine compliance and potential licence breaches.

- A behavioural case to assess changes in compliance with and without knowledge of satellite surveillance.

- A test of the detection of unknown sites using RS data to examine the success rate of detecting unlawful waste crime sites.

These different styles of pilot projects will provide a variety of information to evaluate the role of RS data in the waste crime sector, including producing behavioural change in offenders, and so help develop effective strategies for tackling waste crime.

The following report was produced for Phase 1 (Research) of Action B8 in the LIFE SMART Waste project (LIFE13 ENV-UK-000549). The aim of Action B8 is to develop innovative remote sensing techniques, pilot them and produce evaluation and intelligence reports.

2.0 RS in the environmental crime sector and lessons-to-date

Section 2.0 provides demonstrative examples of the use of RS in the environmental crime sector and outlines the significant lessons learnt to date.

2.1 Overview

Satellite monitoring of laws is on a basic level, often more theoretical than applied, and its use in regulatory strategies is still very much in its infancy worldwide. To date, there have been only a few instances of practical regulatory applications. The lack of empirical evidence on operational experiences and costs available to regulatory bodies has meant that there has been a poor level of the use of satellite technologies in regulatory strategies, relative to its full potential.

This work package catalogues experiences, providing examples of the extent to which this form of monitoring is being used and in what applications. A number of international associations (specialising in knowledge exchange in environmental compliance and space law) were consulted during this cataloguing process and these are listed in Annex 1.

2.2 Key regulatory applications

2.2.1 Illegal vegetation clearing – Australia	
Why and how it is used	The clearing of native vegetation from much of Australia's prime agricultural land has emerged as a serious issue in land management, causing widespread fragmentation of natural ecosystems, reducing their viability and threatening maintenance of flora and fauna and the ecological processes upon which productive rural landscapes depend. Australian regulators (at State level) use satellite imagery to check legislative compliance (which prohibits clearing without a licence), by analysing it to determine whether and when vegetation was cleared. The regulators look for relative changes in vegetation response between two satellite images of the same location with different capture dates. Comparative images can show that the vegetation clearing took place between the first image date and the second. If the satellite image shows that an offence might have occurred, regulators can then take a decision as to whether to direct resources to further investigations. Australia has been using satellite data in a regulatory context for over fifteen years.
What it offers that's different to what already exists	Australia is at the cutting edge in terms of experience with using satellite monitoring in a regulatory context. The main reason for this is that satellite monitoring is the only feasible way to get land cover information over very large areas. Aerial photography is considered too expensive to obtain land cover information over physically large areas, because of the large number of fly-overs required. Regulators are also not able to adequately monitor vegetation changes in physically extensive rural areas from the ground. An estimated 417 million hectares, or 54% of Australia's landmass, was used for agricultural activity in 2008. Most of the terrain is too big, too rough and it is far too resource intensive to send inspectors in on the ground to investigate each rural landholding. It can sometimes take inspectors two days or more to drive to and investigate some rural properties. In one investigation, a team of six forestry officials took four months to map one property on the ground. Ground based monitoring in this context can, therefore, be a major logistical exercise with high associated costs. One Government official in Australia estimated that in the time it would take inspectors to survey 20 hectares on the ground, a RS

2.2.1 Illegal vegetation clearing – Australia	
	team can potentially look at 2.5 million hectares using satellite imagery.
Use in court	Australia has seen numerous prosecutions and other forms of administrative sanctions where satellite data has been successfully used as evidence to demonstrate vegetation clearance (at least 50 times to date). Australia has probably tested satellite evidence in courts more than any other jurisdiction in the world (except perhaps the United States (U.S.)).
Imagery used	Optical satellite data is used. Most Australian States acquire Landsat data of the whole of their States, because it is relatively cheap (virtually free), well-documented, well-archived and secure. Some have a programme of then buying ad-hoc high resolution imagery (SPOT, Ikonois, Digital Globe) to corroborate evidence from Landsat imagery, either to take a closer look if they find something suspicious, or especially if they think that it could lead to a prosecution in court. There is a strong belief that data from high resolution satellites will be better for use in court, as judges will understand it better. New South Wales have a state-wide programme of tasked monitoring using high resolution SPOT imagery.
Legislation	Legislation concerning vegetation clearing in South Australia and New South Wales does not mention 'satellite imagery' or 'remote sensing' anywhere in their provisions. The view of these States is that they did not need to expressly mention satellite imagery, because they have general investigatory powers under environmental legislation and it was considered another form of evidence subject to general laws of evidence. Queensland has special provisions governing the use of data that is 'remotely sensed' (a 'remotely sensed image') under the Vegetation Management Act 1999 and the Land Act 1994. Including these terms in the legislation was not originally done out of a perceived legal necessity. However, their later legislative approach, aimed at improving the admissibility and reliability of RS data, meant that it became necessary to expressly mention these terms in their legislation.
In-house or out-sourced	Some Government departments run their programmes using in-house analysts, and others use a mixture of in-house and out-sourced processing/ ortho-rectification experts. The South Australia monitoring programme employs only one satellite data analyst, Queensland averages six permanent RS scientist positions, and New South Wales had the largest scientific programme and has employed up to twenty full time analysts.
Costs	As New South Wales, has a state-wide high resolution programme, this costs about (AUS) $2.5 million a year. There are also costs associated with the recruitment and training of analysts, as well as purchasing computer hardware and data storage facilities. In New South Wales their overall monitoring programme costs approximately (AUS) $6,500,000 a year. However, the South Australian programme, which has less staff and fewer imagery costs (Landsat is free, so they only ad-hoc purchasing of high resolution imagery), costs in the region of (AUS) $2,000,000 a year. This illustrates that satellite monitoring will in some ways be as expensive as a regulator wants it to be.
Parallels with waste crime	There is no significant temporal dimension to the monitoring – in terms of requiring an immediate reaction. Once the regulators have an image in their possession there are time limits in which they must bring a prosecution, but these are generally years. There is no real need to respond quickly because they can always cross reference data to identify the owner of the land (and land does not move).

2.2.1 Illegal vegetation clearing – Australia

Headline impacts	As Queensland has the most established and longest running satellite monitoring programme, it is the most useful for impact analysis. In 1999, illegal vegetation clearing levels in Queensland were at 758,000 hectares a year (ha/yr.). A decade later they were at 123,000 ha/yr (for 2007-2008) and 12,500 ha/yr. (2009). This represents a massive decrease in clearing over ten years and also a decline in greenhouse gas emissions of an estimated 60 mega tonnes (Mt) of emissions in 2003-2004, to an estimated 24Mt in 2007-2008. However, declines in vegetation clearance have not been as dramatic in New South Wales, for example, and have stabilised over the same time period.

Figure 1. Two images showing 'before and after' clearing in New South Wales (trees in the middle have been removed) [Copyright: CNES. Distribution Spot Image].

Figure 2. Two images showing 'before and after' clearing in Queensland (two trees on the right-hand image have been removed) [Copyright: [left] Queensland State Remotely Sensed Image Library [right] GeoEye Inc. 2009].

2.2.2 Oil pollution monitoring in Europe

Why and how it is used	CleanSeaNet (established 2007) is a European service which offers a near real time satellite based oil spill monitoring and polluter identification service. It supplies over 3,000 satellite radar images a year to 27 Coastal States (23 EU coastal Member States, 2 EFTA [Iceland and Norway], plus Montenegro and Turkey). Services are also being delivered on a project basis via the EU's SafeMed Project to five beneficiary countries (Algeria, Israel, Jordan, Morocco, and Tunisia). RS radars are used to identify objects and landscapes through the transmission of pulsed microwave (radio wave) beams. The beams bounce off, and are altered by, objects and surfaces they come into contact with (termed backscatter). The backscatter is transmitted back to the satellite, and the strength and origin of these returning reflections is captured by sensors. The resulting data can be analysed to provide information of varying kinds, for example whether a sea surface area has an unusual texture which may be due to spilt oil. Even very thin oil films, some measuring just micrometres, can be visible from space. Nevertheless, it is important to note that CleanSeaNet does not detect "oil spills" but "possible oil spills". Discrimination between oil spills and look-alikes require more information and most often on site verification (with a boat or plane). Moreover - as oil spills can evaporate, dissolve in the water column or be dispersed by drift and wind - it is critical that the verification activities are done shortly after the satellite acquisition. Synthetic Aperture Radar (SAR) imagery used for oil spill analysis also allows vessel detection since they are able to measure the reflection of bright targets against the sea background. This results in ships appearing as bright dots on the sea surface. The SAR images,

2.2.2 Oil pollution monitoring in Europe	
	results of oil spill and vessel detection analysis, and relevant auxiliary data (wind and swell detection, vessel traffic information, nautical charts, meteorological, oceanographic information and oil drift modelling results) are all made available to Coastal States through a web based user portal. The service can provide aggregated products on possible oil spills, potential polluters, pollution alerts and related information to the operational maritime administrations within 30 minutes after satellite acquisition, to enable effective follow up activities.
What it offers that's different to what already exists	Surveillance coverage is required over a very wide area; an area of more than 1 billion km2 per year is monitored. Aerial coverage of the same area would require about 50,000 flight hours. Satellite monitoring to cover wide and/or remote areas has been estimated by the European Maritime Safety Agency (EMSA) to be up to 10 times cheaper than aerial surveillance. The surface area covered by CleanSeaNet would have cost at least €30 million to monitor by aircraft alone. As time is critical for confirming a possible spill and catching polluters in the act, the shortest possible delay between satellite detection and alert is essential for a rapid response by coastal states. CleanSeaNet is a near real time service. Detection results are reported to the affected coastal state approximately 30 minutes after satellite image acquisition (the exact time varies according to the size of the image). Coastal States often plan to use their assets in conjunction with the CleanSeaNet service to improve efficiency, i.e. the patrol operations of aircraft are timed to coincide with the satellite overpass so that they can quickly follow up on the detection of possible pollution.
Use in court	It is not always possible, legally or technically, to prosecute the offender for the pollution observed on the satellite image alone. CleanSeaNet can show the dimensions of a possible floating pollution but SAR satellite images cannot discriminate the type of pollution (mineral oil, fish or vegetable oil, other look-alikes). Consequently, best practice is for satellite images to be combined with supporting information about the spill when prosecuting a case, but the images themselves can be admitted as primary evidence in prosecutions. Satellite images can be used as direct evidence to prove the link between the vessel and the spill, or the location of the vessel when it was discharging. Satellite imagery from SafeSeaNet was used in a successful prosecution in the UK in 2012 to show that an oil slick was inside the 12-nautical mile zone from the shore (which the vessel, the Maersk Kiera, denied), and that the discharge was illegal. This was the first-time satellite imagery had been used in Europe in an oil spill case. There has been a least one more case in Europe since.
Imagery used	The service is based on radar images obtained from synthetic aperture radar (SAR) satellites. Satellite images are acquired in segments of up to 1600km and swaths of up to 500km. The service is based on radar images obtained from synthetic aperture radar (SAR) satellites. Currently the service can provide products from the European Space Agency (ESA) satellite Sentinel-1, the Canadian Space Agency's RADARSAT-2 satellite and the commercial satellite

2.2.2 Oil pollution monitoring in Europe	
	TerraSAR-X. By using several satellites CleanSeaNet is able to cover European waters several times per day according to the needs of each individual coastal State. Additionally, optical imagery can be used in support to Member States' efforts to combat large accidental spills.
Legislation	The European Parliament and Council Directive 2005/35/EC of 7 September 2005, as amended by Directive 2009/123/EC of 21 October 2009 on ship-source pollution, which established CleanSeaNet, states that the European Maritime Safety Agency (EMSA) shall: (a) 'work with the Member States in developing technical solutions and providing technical assistance …in actions such as tracing discharges by satellite monitoring and surveillance.' In an international context, the MARPOL convention (International Convention on the Prevention against Pollution by Ships), has expressly defined the possibility of using RS data to detect oil spills (APERTURE). The OSPAR Commission, North Sea Manual on Maritime Oil Pollution Offences also permits the use of satellite monitoring in identifying oil slicks.
In-house or out-sourced	The information is collected and made available via a web application. Day-to-day operational support is handled by EMSA. Coastal states define in advance their service coverage requirements. In cooperation with the users, EMSA plans and orders satellite images to meet these requirements. Despite evidence supplied by the CleanSeaNet service, there is still a relatively low level of enforcement through follow-up actions at national level and limited feedback on the measures taken by national authorities more generally.
Costs	Coastal States using the service in European waters do not pay a direct cost, but support the service through the national contribution to the EU budget. CleanSeaNet satellite services costs are roughly €3 million per year.
Headline impacts	The levels of oil pollution in the waters that are monitored are very difficult to measure. Evidence from beached bird and tar ball surveys in the EU indicate that levels of oil pollution have dropped considerably over recent decades, although levels remain above what is legally permitted. Evidence from satellite surveillance indicates that over the past decade illegal discharges from vessels have been reducing in volume in across Europe. CleanSeaNet statistics for example show a steady decrease each year in the number of possible spills detected; from 10.77 possible spills identified per million km2 monitored with satellite images in 2008, to 7.61 in 2009, 5.68 in 2010, 5.08 in 2011, 4.53 in 2012, 3.89 in 2013, 3.42 in 2014, and 2.32 in 2015. However, this trend is in practice unevenly distributed, and the reduction is more evident in some sea basins than others. Generally, CleanSeaNet has increased the likelihood that illegal discharges from vessels are detected and EMSA considers that there has been a clear deterrent effect from using the service which is difficult to measure directly.

Figure 3. EMSA oil slick detection [Copyright: ESA / EMSA 2009, and Irish Coast Guard].

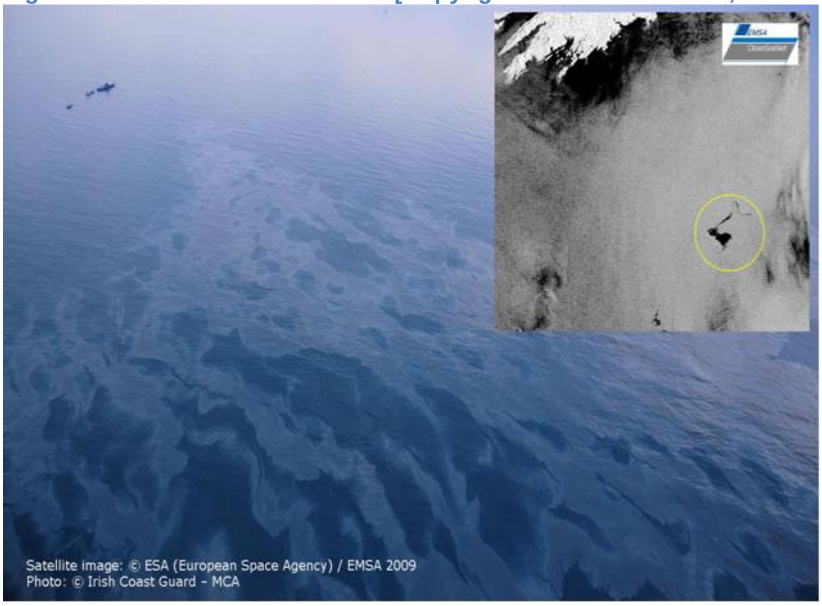


Figure 4. Area covered by satellite versus area covered by aircraft during one flight hour [Copyright: EMSA – Addressing Illegal Discharges in the Marine Environment (2009)].

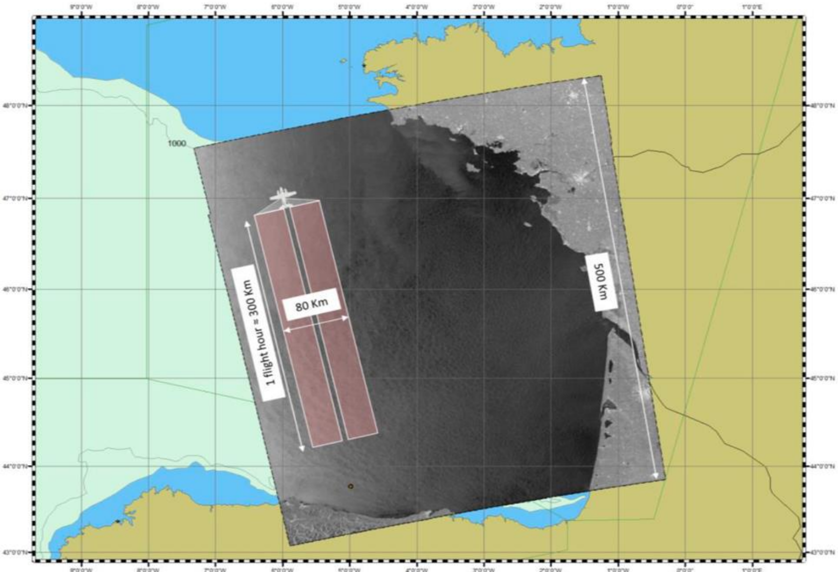
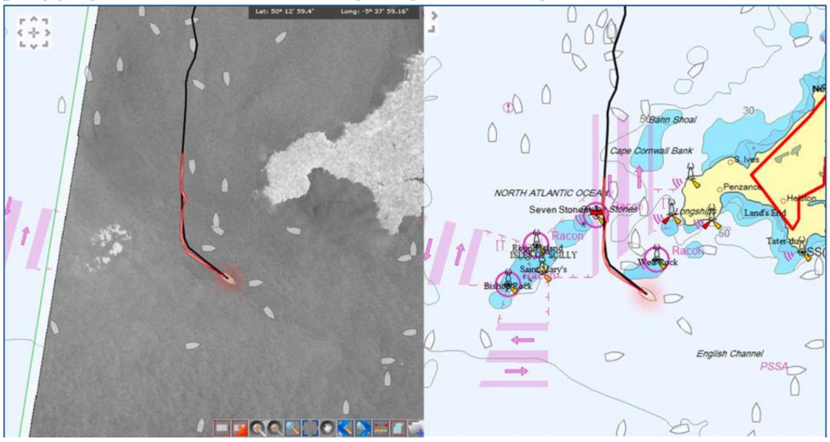


Figure 5. CleanSeaNet evidence that a discharge took place within 12 nautical miles off the coast [Copyright: EMSA – Addressing Illegal Discharges in the Marine Environment (2009)].



2.2.3 Agricultural subsidy monitoring – European Union (EU)	
Why and how it is used	There have been European programmes dedicated to using satellite data for agricultural purposes since 1973. Early interest resulted from a need to have a reliable source of data on agricultural surfaces and the potential of production. The EU spends between 40% and 50% of its budget on agriculture subsidies, and whether farmers are declaring everything correctly can be checked through satellite data. The Monitoring of Agriculture with Remote Sensing (MARS) programme, which uses space technologies for a more effective and efficient management of the Common Agricultural Policy (CAP), especially in the field of subsidies granted according to the area farmed, started in 1988. Almost all EU countries now use satellite technology, which can produce accurate maps of the size of agricultural parcels (ensuring farmers are only claiming subsidies for genuine farmland), and to check if claimants are complying with certain environmental conditions attached to subsidies (e.g. farmers have to keep their land in "good agricultural and environmental condition" to qualify for subsidies, so images can reveal whether a farmer is complying with the rules on hedges and ponds, say, or buffer strips around arable fields).
What it offers that's different to what already exists	The use of satellites came about because of two reasons. Firstly, there were concerns about the safety of inspectors on the ground (there had been high profile incidents in some EU countries). Secondly, it makes sense, to use satellite monitoring in the agricultural sector, as it enables large areas of agricultural land to be monitored relatively easily, sometimes with significant cost savings. There are approximately 5 million farming businesses declaring more than 50 million agricultural parcels; claiming up to Euros 59 billion each year on EU subsidies. Satellites are the best way to rapidly cover such a huge area in detail (Commission studies found they were a cheaper method than aerial photography). In 2012, about 70% of the total required controls on farm payments in the EU were done by satellites, which photographed more than 210,000 sq. km (81,000 sq. miles) of land in all. Scanning a farm in the UK with a satellite costs about one third as much as sending an inspector on a field visit - £115 rather than £310.
Use in court	The satellite images collected are not normally used as evidence in courts in EU countries and are most often used to provide advance notification to the authorities of potential fraud. The actual evidence of the illegal act is normally ascertained from subsequent ground inspections. Also, some offenders receive administrative sanctions, rather than facing formal criminal sanctions. However, there have been a small number of cases, however, where satellite imagery has been used as evidence (e.g. Germany, Netherlands.
Imagery used	Optical satellite data (low resolution and high resolution) is used. These can cause issues in some European countries: (1) the shadows cast by very mountainous terrain sometimes make satellite images inaccurate; (2) weather conditions in countries experiencing a lot of cloud-cover. In 2015 the UK Government funded a project examining how Copernicus Sentinel-1 data could be used in fulfilling Defra's monitoring requirements for CAP

2.2.3 Agricultural subsidy monitoring – European Union (EU)	
	compliance.
Legislation	Satellite monitoring has existed in the agricultural sector in the EU for over 20 years. Legislation gives all Member States the option of using satellites to monitor farm subsidy payments under agricultural cross compliance schemes. Commission Regulation 796/2004/EC lays down detailed rules for the implementation of cross-compliance, modulation and the integrated administration and control system provided for in Council Regulation 1782/2003/EC establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers [2004] OJ L141. Under this legislation Member States must check a minimum of 5% of these claims in their own countries, and can use satellite data to enable them to do these checks.
In-house or out-sourced	The responsibility to interpret the satellite data is with the individual Member States. Some Member States do this work in-house and others, like the United Kingdom (UK), outsource this work to commercial operators.
Costs	While the monitoring responsibility is with the individual Member States, the EU provides them with satellite imagery free of charge to assist them in fulfilling this requirement. Commercial satellite operators are paid approximately €6.5m euros annually by the European Commission for supplying satellite images. EU member states pay for the image processing and analysis. This varies from country to country, but overall it is estimated to cost approximately €40m euros annually (for all countries).
Parallels with waste crime	Unlike waste crime monitoring, the surveillance is specifically targeted. The regulators know which parcels of land they are checking, rather than doing blanket surveillance across a whole region of land. The imagery used is specifically tasked. There is no significant temporal dimension to the monitoring – in terms of requiring an immediate reaction. The satellite data will be used to demonstrate whether the subsidy application from the owner of the land (who can be easily identified) was correct or not. This is not very time-sensitive. It is essentially a catalyst for an on-the-ground follow-up inspection in the future, rather than immediately.
Headline impacts	According to data from the European Anti-Fraud Office (OLAF), fraud accounted on average for just 0.02% of the CAP's budget in 2006-10.

Figure 6. Image showing the existence of oil trees in a subsidy application [Copyright: Space Imaging / Ikonos].

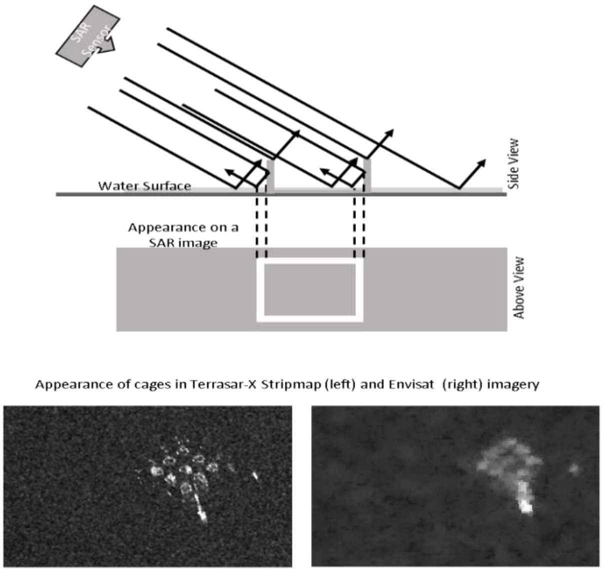
2.2.4 Aquaculture enforcement - Chile	
Why and how it is used	Chile's aquaculture industry is very large – and there are a large number of fish farm facilities related to farming, fattening and processing of hydro-biological resources (mostly salmon and mussels). Licensing is very important because of the environmental impact of these activities (e.g. decreased oxygen concentration in water column, oxygen-reduced sediment affected by faecal material and unconsumed food pellets, structural solid facilities - i.e. fish cages, nets, pontoons and others) and use of chemical substances for cleaning, sterilizing and disease control. Because of the issues above, an environmental impact assessment has to be carried out. Where projects are authorised, each authorization is defined by the vertexes of the permitted activity area. Any projects located in a different area, to where the licence was granted (and impact assessment conducted) are prohibited because they potentially have an environmental risk. Chile's Superintendency of the Environment (SMA) has responsibility for environmental compliance in the regulation of the aquaculture industry. To accomplish that task, they use satellite imagery to map aquaculture facilities and locate unlawful aquaculture projects. In the images, water will be very dark because it absorbs most of the electromagnetic signal transmitted by the radar and because calm water (which Patagonia's fjords have) presents a flat surface, the signal bounced once and points at one straight direction, while the structures (cages, network lines, boats, ships, pontoons, silage, etc.) will shine in contrast with the water, since edges of these structures will bounce the signal several times and in several directions. The monitoring is done periodically.
What it offers that's different to what already exists	SAR allows for low-cost monitoring in the geographical region where most of the aquaculture industry is based. 1,500 km2 of land can be captured in each SAR image. Eighty percent of aquaculture activities (approximately 4,000 facilities) are clustered within two administrative regions of southern Chile, specifically in Coastal Patagonia, which covers 240,000 km2 and is geographically composed largely by islands, channels and fjords. The intelligence from the SAR data allows the SMA to operate a more efficient inspection programme (basing the ground resources on anomalies discovered by the SAR imagery).

2.2.4 Aquaculture enforcement - Chile	
Use in court	Satellite data has been successfully used as evidence in the Chilean courts. In the one case where it was successfully used to prosecute, in relation to an aquaculture facility (operating outside a permitted boundary), the court found the data to be reliable and permitted it to be entered as an enforceable document. In 2017 the Legal Affairs Division in the SMA will examine the legal impacts of RS use, in areas like admissibility, probative value, custody chain, and weight of proof, etc.
Imagery used	SMA use Synthetic Aperture Radar (SAR). SAR is used (instead of optical data) because it is not affected by the cloudiness of the troposphere, a common meteorological condition in Coastal Patagonia. 1,500 km2 of land can be captured in each image. They are currently working on the automatization of algorithms to trigger alerts when a fish farm moves outside its permitted boundaries.
Legislation	There is no legislation which expressly mentions the use of RS. The State Agencies (SERNAPESCA and SMA) in charge of monitoring activities use their general enforcement powers.
In-house or out-sourced	The monitoring and analysis is done in-house. The analysts in the Programme of Territorial & Environmental Monitoring team do not work solely on aquaculture monitoring and also work in other fields of Government regulatory interest (e.g. wetland monitoring). In 2017, they plan to recruit more staff so there is a dedicated aquaculture monitoring section in the team.
Costs	The satellite data programme (including imagery analysis) cost US$450,000 to monitor the whole region, using Terrasar-X Stripmap imagery. They have since found that, if they use Sentinel-1 Stripmap, imagery costs US$75,000 to monitor the whole region.
Parallels with waste crime	There are numerous parallels with waste crime monitoring. One is that it is using SAR data. Secondly, they are in part just monitoring areas where illegal activity might be taking place, rather than undertaking targeted surveillance. The key difference to waste crime monitoring will probably be the response times required e.g. I suspect that most illegal fish farms will operate over a significant time period (at least weeks if not months), whereas waste crime in many cases requires immediate follow-up checks before the criminals move on.
Headline impacts	Immediately after the prosecution, where satellite imagery was used, the SMA found that many permit-holders started to regulate their boundaries compliance, and in some particular cases, they even moved aquaculture farms which were operating outside the boundaries of the law. News of the satellite monitoring in the programme was well publicised by industry and the media (including industry publications) and this had a positive impact. However, aquaculture is a very dynamic industry in Chile and in recent years there have been two major infectious salmon anemia virus outbreaks, forcing the Government to make permit adjustments to protect the wider production. Because many permits have been modified, relocated, and resettled in other aquaculture districts this has meant that non-compliance rates have not diminished as quickly as expected

2.2.4 Aquaculture enforcement - Chile

	after the introduction of the satellite monitoring programme.

Figure 7. Using SAR imagery in aquaculture monitoring in Chile [Source: Superintendency of the Environment, Chile].



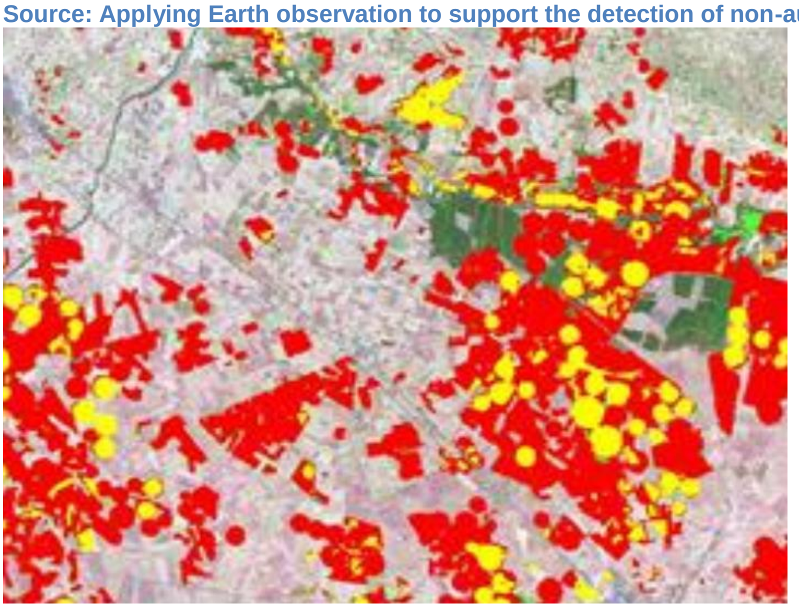
2.2.5 Groundwater abstraction – Spain

Why and how it is used	Like the majority of semi-arid Mediterranean basins, some parts of Spain are often subject to drought and floods, making the balance between water supply and demand very fragile. Some areas of Spain had seen increasing water demand for irrigation, which caused a drop-in groundwater levels, threatening the conservation of water resources. Groundwater was considered a private good until legislation (The Water Act) was passed in 1986 in Spain, making it a public good. Spanish Water Law, states that the Water Administration Authority has to give water abstraction permits to farmers, based on what the farmers claimed that they were irrigating in 1985. This permit is required to irrigate within the registered parcels and using the registered water volumes. The Government needed a technological solution to regulate and to monitor water use sustainably. Some water administration authorities (e.g. in La-Mancha, Upper Guadiana) have used historical satellite imagery and GIS data since 1992 to check the truthfulness of farmer's declarations e.g. whether the farmers claiming for water rights, had indeed irrigated the land they stated in 1985, and how much water they had historically used. They monitor and control abstractions based on the identification of crops with similar water requirements by means of a sequence of EO images and subsequent assignment of water volumes per class (m^3).

2.2.5 Groundwater abstraction – Spain	
What it offers that's different to what already exists	EO is used because the groundwater monitoring is often required over vast areas. E.g. the Irrigation User Association, "Junta Central de Regantes de la Mancha Oriental", is in charge of managing the aquifer Mancha Oriental. This is one of the largest aquifers in Spain which covers an area of 10,000 km2, and holding about 100,000 ha of irrigated land. "The system based on satellite data allows for a more efficient use of water resources, while also enhancing transparency and participation." [Francisco Belmonte, President of the Central Irrigation Board of La Mancha Oriental]. There are also significant cost savings. In La Mancha Oriental, the cost for mapping irrigated areas, covering 25%-50% of the irrigated area (i.e. 50,000ha) by field inspection only is €406,250 per year (to achieve a sampling of more than 25% of the area). The satellite monitoring programme (24 images per year, each for an area of about 180 km by 180 km) costs €150,000 per year (for 100% of the irrigated area). This figure includes images, EO staff and a field team for validation and calibration with in-situ data. This cost doesn't include the field inspection itself which is however much reduced as it can be targeted at the most suspicious plots. In summary, this EO-based service provides maps of irrigated plots at a fraction (around 40%) of the cost of the field-inspection-only mode while covering the whole area (i.e. 100,000 ha).
Use in court	The classification process to identify and measure irrigated areas based on satellite imagery was recognised as good evidence by the Spanish Supreme Court in 2012. There have been numerous court cases where satellite imagery has been used as evidence (where farmers had disputed the findings that certain fields were not irrigated before 1986, or the water volumes which had been calculated). Most significantly, the use of satellite data in court to show irrigation rights under Spanish water legislation is one of the few examples where the conflict between a prosecution satellite image and evidence from an individual defendant has directly been in issue. The Spanish courts have favoured evidence from satellite technology over human corroboration.
Imagery used	A variety of EO sensors/platforms using visible and NIR bands (Deimos 1, Sentinel 2, RapidEye, Landsat 5, SPOT 5) are used to create a time series of reflectance, vegetation indices, and colour composites – to create maps of irrigated areas. Landsat 8 and ASTER thermal band are used to create a time series of canopy temperature. Crop water requirements can be obtained either directly from visible and near-infrared bands or through the surface energy balance from additional thermal bands.
Legislation	The Water Framework Directive (2000/60/EC), introduced in the EU in 2000, aims to ensure the long-term sustainable use of clean water across Europe by reaching the objectives of good ecological and chemical status for all water bodies by 2015. One of its key aims, as set out in Article 1, is the promotion of sustainable water use (e.g. sufficient quantity of water and good quantitative status in groundwater that should ensure sufficient recharge of groundwater systems). All Member States have to implement basic measures (Article 11.3) *inter alia* to promote an efficient and sustainable water

2.2.5 Groundwater abstraction – Spain	
	use; and to control water abstractions from groundwater and surface waters through the maintenance of registers and a requirement of prior authorisation for abstraction. There is no specific mention of the use of satellite technologies.
In-house or out-sourced	The work is done in-house. The monitoring programme for the aquifer Mancha Oriental has two staff. The image processing, product generation and upload to SPIDER webGIS requires one senior RS and GIS expert, plus one other expert in image processing, classification and GIS for 12 months. They also receive basic SPIDER support.
Costs	Mapping and monitoring the aquifer Mancha Oriental based on temporal sequences of 12-24 images per year, for an area of about 180 km by 180 km (size of one Landsat scene) the cost is €35,000 /year (including Landsat at no cost). Image processing, product generation and upload to SPIDER webGIS requires one senior RS and GIS expert over 12 months, plus one expert in image processing, classification and GIS for 12 months, plus basic SPIDER support. It also requires a field team for validation and calibration with in-situ data with a cost of €32,500 a year. The total annual cost is €150,000 (including images). This cost doesn't include the field inspection itself which is, however, much reduced as it can be targeted at the most suspicious plots.
Parallels with waste crime	There are few similarities.
Headline impacts	Extensive assessments of costs of field measurement approaches alone, compared to their combination with Earth observation show that the cost of Earth observation services in Spain was significantly lower than the cost of field measurement and inspection.

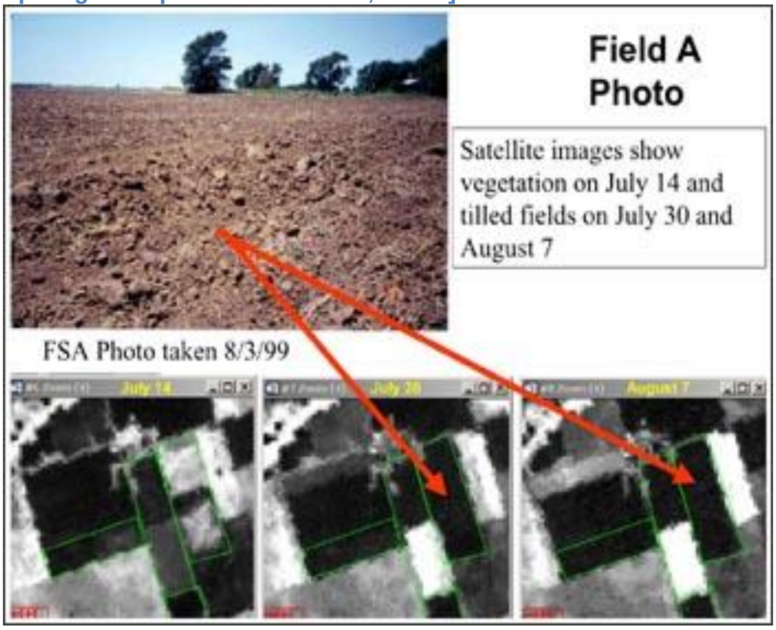
Figure 8. Example of annual map of irrigated areas in La-Mancha Oriental aquifer (Spain). Parcels in yellow indicate irrigation before 1984 (in contrast to parcels in red indicating irrigation after 1984). Source: Applying Earth observation to support the detection of non-authorised water abstractions (2014).



2.2.6 Agricultural fraud monitoring – United States	
Why and how it is used	The Risk Management Agency (RMA) of the Department of Agriculture in the United States has about 1.3 million policies and sending agents out to confirm each claim is simply not feasible. They have used optical satellite data for nearly seventeen years to monitor field crop data through their Federal Crop Insurance Programme. Satellite imagery is typically employed when a field investigator determines that claim-verification is warranted. Data mining — coupled with satellite imaging — also pinpoints about 1,500 farms annually that are put on a watch list for possible crop fraud. Initially it was not used for 'fishing', but for following up suspected cases of fraud. More recently, it is also used in spot-checks. If the satellite image does not support a farmers' insurance claim, then it is used as the basis for legal action against the farmer.
What it offers that's different to what already exists	Firstly, it enables monitoring over very large areas. The RMA use an average of 600 Landsat scenes per year (each covering a geographic area of 7.6 million acres) for investigative purposes. Secondly, with agricultural fraud there normally won't be any other evidence, or enough evidence to prosecute, so the satellite data can show them what a certain piece of land (and crop growth) looked like historically. Landsat "stops time," as one investigator has put it, giving investigators the data they need to prosecute for fraud. Thirdly, farm insurance fraud costs the Government millions of dollars. According to the RMA, the spot-check-list project alone has resulted in savings of $975 million in unjustified claims payments from 2001 through 2012. What's more, it is estimated that the programme has saved $2.5 billion in cost avoidance. Fourthly, it also provides clear evidence of the extent of the problem. The RMA have said that "what we're doing is bringing more and more empirical evidence into the crop insurance programme so that those naysayers who claim that it's rife with waste, fraud and abuse won't have a leg to stand on."
Use in court	There have been a large number of instances where it has been used as evidence in court to show false insurance claims (as of 2012, just under 100 cases). One out-sourced expert witness alone (specialising in imagery analysis) testified as an expert witness 26 times, saving the Government over $50 million. In a recent RMA case, it was found to be: "impressive to the jury to have this presentation about this eye in the sky and satellite imagery and a trained expert," said Richard Edwards, the assistant U.S. Attorney in North Carolina. "In our case it did not make the case, but it sure helped and strengthened and improved the case."
Imagery used	The RMA use Landsat 8 imagery from the USDA imagery archive (there is a regular image acquisition schedule, so there is a fantastic archive).
Legislation	Congress passed the Agriculture Risk Protection Act of 2000 (ARPA),

2.2.6 Agricultural fraud monitoring – United States	
	which mandated the use of a data warehouse and data-mining technologies to improve crop insurance programme compliance and integrity. There does not appear to be any specific mention of satellites and RS.
In-house or out-sourced	The image investigation is mainly performed for the RMA by Tarleton State University's Centre for Agribusiness Excellence. It is also sometimes contracted out to a private RS expert.
Costs	The programme draws data from more than 170 data sources, including 3 terabytes of RMA policy information that has been connected to 120 terabytes of weather, satellite and other RS data collected by the university. Between 2001 and 2012 the United States Department of Agriculture spent $50.68 million on the programme. That averages at about $4.6 million per annum.
Parallels with waste crime	There are not many parallels. The imagery is not tasked, but instead taken from archives to provide historical context (or evidence). Also, there is no significant temporal dimension to the monitoring – in terms of requiring an immediate reaction, as they already have information concerning the owner of the land.
Headline impacts	The agency says its spot checklist generated by the satellite data has saved taxpayers between $71 million and $110 million a year in fraudulent crop insurance claims since 2001. This has resulted in total savings of $975 million in unjustified claims payments from 2001 through 2012. Additionally, it is estimated that the programme has saved $2.5 billion in cost avoidance. Typically, about half of the sites subject to fraud checks by satellite monitoring support a farmers' insurance claim and half indicate fraud. "Landsat has played a major role in shifting the tide of fraud cases." "More importantly, the criminals now know they are being watched," on EO analyst working on the programme has surmised. In regions where EO experts have testified, the number of claims has dropped, the number of appeals has diminished, the overall number of fraud cases has declined, mediation settlements have increased, and farmers have even come into USDA offices to admit guilt. "After notifying the farmers [of the satellite monitoring programme], we saw pretty drastic behavioural changes in the producers and in their claim rates," said the deputy director of strategic data acquisition and analysis at RMA in 2012.

Figure 9. The use of satellites to detect crop fraud [Source: Rocchio, L. Saving Millions in Government Dollars: Landsat Helps Fight Crop Insurance Fraud, NASA].



2.2.7 Illegal logging - Brazil	
Why and how it is used	As of 2015, 750,000 km2 of Brazilian rainforest has been lost since 1970. About 90 percent of Brazil's deforestation is illegal, much of it carried out by organised groups clearing land for agriculture. The Brazilian National Institute for Space Research (INPE) has used satellite imagery to make a systematic study of Amazon deforestation since April 1989. INPE's projects related to Amazon, namely PRODES and DETER, include the use of remote sensing satellite images for deforestation assessment. The Brazilian Environment Agency (IBAMA), have used the satellite data in a regulatory context for about 13 years. Today, IBAMA has access to data from four satellites monitoring illegal activities in the Amazon.
What it offers that's different to what already exists	The Amazon is the world's biggest rainforest and a huge area to monitor; it is impossible to do so from the ground. IBAMA relies on two intelligence methods. Firstly, information from networks of indigenous people. Secondly, satellite imagery enables IBAMA to target their ground-based monitoring with more precision; "Before [satellite data] we were looking blindly". When satellites detect large-scale forest clearing, IBAMA (armed) inspectors are deployed to hard-to-reach sites via helicopters.
Use in court	In 2009, the Federal Public Prosecution (MPF) and the Brazilian Institute for the Environment (IBAMA) presented 20 lawsuits against ranchers that had caused 157,000 hectares of deforestation in the Amazon. In these lawsuits, the deforestation has been validated in accordance with the satellite data from the PRODES project. Brazilian courts have been accepting data from PRODES, because this Project has been the official parameter established by the Brazilian Government to provide deforestation assessment in Legal Amazon. So, when data from PRODES is questioned, the burden of proof has been on those who claim.
Imagery used	Initially the Brazilian Government only used Landsat data to identify illegal logging. Before 2010 only visible light satellite images from Landsat were

2.2.7 Illegal logging - Brazil	
	taken. Those involved in illegal logging came to know that the satellites monitoring of this type could only be done in daylight hours and was poor in cloudy conditions. This meant that operating in the night, or under cloud cover, could provide a shield for their activities. The Brazilian Environment Agency is now also using radar satellite surveillance which means that the ‘felling of trees can be spotted from space, rain or shine, day or night.’
Legislation	N/A
In-house or out-sourced	N/A
Costs	N/A
Parallels with waste crime	There are a number of key similarities with a waste crime monitoring programme. Firstly, the monitoring is not targeted; it is fishing for potential illegal behaviour. Secondly, the monitoring system now uses radar data. The key difference is probably going to be response times. We envisage that there won’t be the same urgency getting to illegal loggers, as they could be in the same area for an extended period of time i.e. days or weeks (although this is just an assumption). With waste crime, there is probably going to be a shorter window to respond to the satellite data.
Headline impacts	The rates (of deforestation) have over time mainly come down because of the impact of satellite technology (and other policies). E.g. deforestation rates were 27,000km2 in 2004 and between 5000-6000 km2 in 2010. Since 2003, Brazil reduced its deforestation rate by more than 70 percent (by 2016). However, satellite images show that the rate increased again in 2015 by 24% compared to 2013, Brazil's National Space Research Institute (INPE) found. Satellite monitoring has had a massive impact but satellite analysis still recorded about 100,000 incursions into the forest in 2015 (with Brazil losing the equivalent of two football fields of rainforest every minute). In 2015, IBAMA made more than 4,000 arrests, seizing 91 trucks, 115 chainsaws and the equivalent of 2,000 truckloads of wood. “It is clear that Brazil’s efforts to curb deforestation are working in respect to large illegal logging, but small-scale illegal logging is – proportionally speaking – on the rise”. Hard-to-detect small-scale clearance of Amazon rainforest now makes up half of country’s deforestation rate. This has an impact on ground-based resources for following up the satellite intelligence. Brazil’s advanced satellite monitoring system, coupled with increased law enforcement, was responsible for nearly 60 percent of the 101,000 square kilometre-drop in deforestation observed between 2007 and 2011, argues a new study published an international think tank. CPI concluded that 59,511 sq. km of the 101,073 drop in deforestation that would have otherwise occurred could be attributed to satellite-based monitoring and increased law enforcement. It estimated that had there been no law enforcement at all, some 164,290 sq. km of forest might have been cleared.

Figure 10. Landsat 5 image of the Rondonia region of Brazil. The horizontal pattern in the right of the image has been created by the systematic, linear deforestation of part of the Amazon rainforest [Copyright: Landsat].

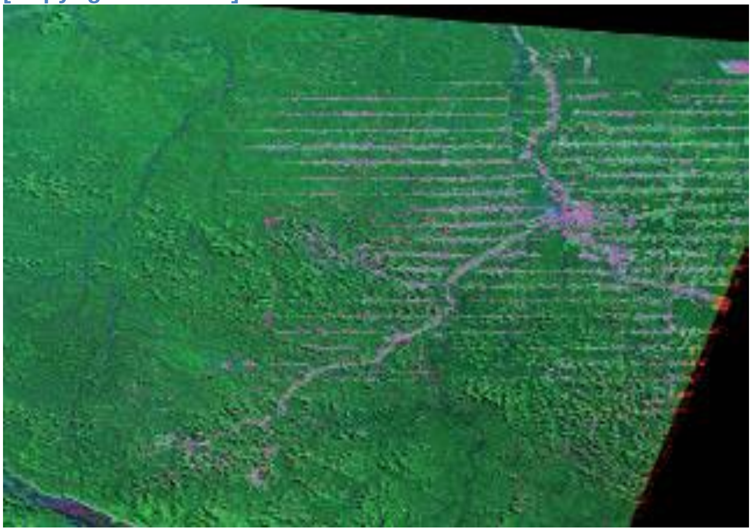
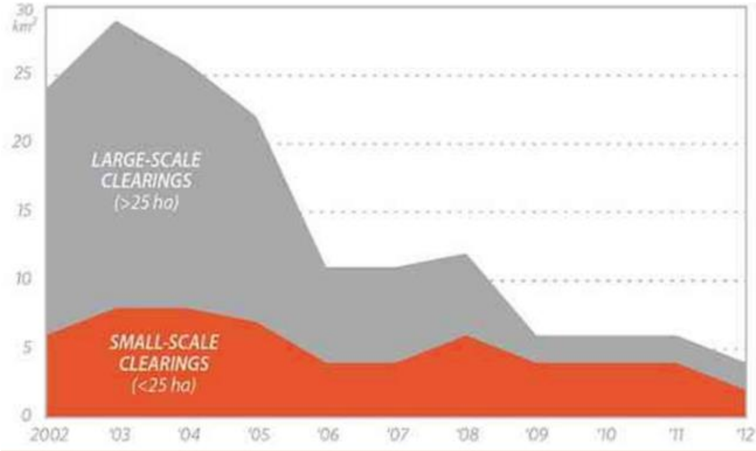


Figure 11: Brazilian Amazon Annual Deforestation [Source: Climate Policy Initiative].



2.3 Other monitoring programmes

2.3.1 Property taxation – Spain

In Spain, the municipalities collect a local tax (similar to council tax) based on property bands. Some municipalities have monitoring programmes using optical satellite imagery, whereby they look to see changes in properties e.g. extensions, additions of swimming pools and cross reference this to what has been authorised – e.g. with planning permission. If planning permission was not given they can either taken enforcement action for illegal building, or they can ask the owners for an increase in their local taxes (if the property is deemed to have moved into a higher band).

2.3.2 Human rights monitoring – Sudan

An organization fronted by the actor George Clooney, called the Satellite Sentinel Project (SSP), has been using satellite data to provide daily evidence on war crimes in Sudan. More specifically it uses information from satellites to help prevent humanitarian disasters before they happen – rather than reporting the aftermath of a conflict. Near real-time satellite data, provided free by one of the world's biggest commercial satellite operators, DigitalGlobe, is used to deter atrocities and to monitor military movements along the troubled border of Sudan and South Sudan, enabling responses that avoid civilian casualties.

The SSP originally used very high resolution optical images. Awareness of the satellite programme meant that attacks switched to only happening "at night or under cloud cover," when the satellite cannot see what is happening. This led to a change of tactics. The counter-counter response from the SSP team was to switch to infrared satellite monitoring that would pick up activity in the dark.

2.3.3 Nuclear and chemical weapons monitoring – international

Satellite imagery has long been used for the verification of international obligations and the strengthening of international security. Bodies that use it in monitoring programmes include the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and the Organization for the Prohibition of Chemical Weapons (OPCW). Both these organizations have exchanged knowledge about inspection activities and discussed procedures for the use of satellite imagery.

The CTBO and OPCW use satellite data in the framework of their well elaborated systems of international verification. Nuclear facilities in suspected proliferant states have frequently been identified by satellite imagery, including high resolution commercial satellite imagery, although the analysis often includes information from other intelligence sources, or the IAEA directly. Satellite imagery is potentially able to provide information that might shed light on disarmament and weapons control (it’s expressly mentioned in the Comprehensive Nuclear-Test-Ban Treaty), identify a nuclear weapon production facility, progress in the construction of a facility and increase in the number of buildings at a site.

However advanced satellite technologies are, the actual interpretation of the photographs can be wrong or used by those with certain agendas. A significant element of the US case against the Iraqi regime in the UN Security Council in 2003 centred on satellite photos claiming to show the existence of chemical weapons sites and associated equipment used for transporting weapons of mass destruction. Checks on the ground still provide the best answers.

Figure 12. Image of North Korea Missile facility [Copyright: CNES 2016. Distribution Airbus DS / Spot Image].

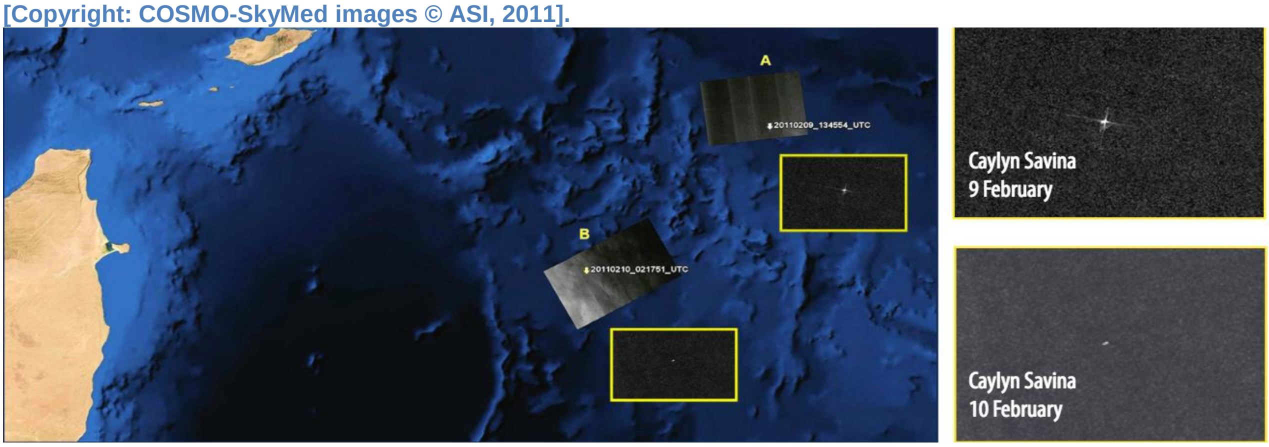
Figure 13. Human Rights Abuses in Sudan [Imagery Copyright (above): © DigitalGlobe Inc.; Analysis: The Satellite Sentinel Project].

2.3.4 Piracy detection

The techniques to rapidly locate and track ships in open waters have been developed and operationally delivered by the Copernicus MARISS (Maritime Security Service) network. COSMO-SkyMed was fully supporting these initial monitoring services.

MARISS provided satellite-based maritime surveillance services. It used rapid integration of satellite based vessel detection with conventional information streams to extended surveillance information to a range of coast guards, police forces, navies, customs and excise agencies, border guards and intelligence services.

Figure 14: Tracking the oil tanker Caylyn Savina, pirated in the Indian Ocean on February 8th 2011 [Copyright: COSMO-SkyMed images © ASI, 2011].



2.3.5 Aid auditing – disaster relief

Another area of verification is presented by assessment of the flow and effectiveness of disaster aid from government funds. Satellite derived information has been used for this purpose by the Netherlands, following the Tsunami.

2.3.6 Forestry management – Portugal
Legislation was introduced in Portugal to enable the National Authority (DGF) to implement management strategies for forest burnt areas. Some landowners were burning certain tree species and replacing them with faster growing and more profitable species e.g. pine to eucalyptus stands. Legislation was implemented which sought to prohibit this, by requiring the forest owner to seek permission from the DGF if they wanted to replant after a fire and requiring the same species be planted which was there before the fire (for up to ten years following the fire). However, the Government Agency was faced with landowners claiming that the original species before the fire occurrence was the faster growing tree species, and there was difficulty disputing this. Satellite imagery is used to identify the species composition of the forests before being burned, and to supervise on an annual basis the burnt areas in order to check if the forest owners are in compliance with the Portuguese legislation on burnt areas.

2.3.7 Fisheries – international
There have been, and continue to be, a number of pilot programmes looking at using satellite data to enforce illegal fisheries. These include Project Scale (INTERPOL), Safari Project (GEO), MESA (EU), Detection and Characterisation of Illegal, Unlicensed and Unreported Fisheries Activity in West Africa (European Space Agency). Radar data is used to detect vessels that are illegal fishing. The Satellite Applications Catapult in the UK also conducted trials in 2016 in Reunion. Satellites were tested operationally, but it appears there have not yet been any convictions based on the satellite data (the satellite data is used to trigger Government vessels to intercept the vessel which is suspected of fishing illegally).

2.4 Other applications where satellite imagery has been successfully used as evidence

Application	Country	Details
Insurance Fraud Investigation	US	A couple in New Orleans were prosecuted for insurance fraud after satellite images taken immediately after Hurricane Katrina revealed that the damage to their house actually occurred after the hurricane. Images were purchased after investigators considered that the damage did not look like other hurricane damage and appeared to be human-made.
Boundary Disputes	International	In international litigation, satellite imagery showing demarcation changes in boundary dispute cases has been offered as evidence many times before the International Court of Justice. EO images, taken over a period of years, have been entered as evidence showing changes over time in the locations of villages and other installations, in agricultural use, in river courses and the erosion or accretion of coastlines.
RAMSAR Wetland	Chile	The Chilean Government brought a case against a permit holder (a mining company) in northern Chile for breach of licence. This was in connection with illegal water extraction from wells located in a RAMSAR designated wetland's watershed. In this case SAR (radar) satellite data was accepted by the court as evidence and the prosecution was successful.
Water Irrigation	Australia	State Governments sometimes use satellite imagery in water resource prosecutions. The South Australian Government brought one prosecution after satellite

Application	Country	Details
		imagery showed that an irrigator was taking water in contravention of his water allocation licence (which allowed the defendants to irrigate an allocated amount per hectare). Satellite images indicated they were irrigating double the area they were permitted to. The defendants were successfully prosecuted in a criminal court and the Government also won a civil action. The Queensland Government have also successfully prosecuted an unlicensed irrigator, who had been detected via satellite imagery. The New South Wales Government have also used satellite data in prosecutions, for the purpose of showing farm dams that were oversized, i.e. taking more water than they are allowed too.
Nature Protection	Australia	Satellite imagery has been used in a number of Australian Federal Government prosecutions on nature protection, including some concerning threatened endangered species, and another on damaging a protected wetland area. Some Australian State Governments have also used satellite imagery in court to show that houses were illegally built in reserves/listed wetlands areas.
Jurisdiction – Maritime accident	US	Satellite images were used in a case to determine whether a barge accident occurred in Illinois or Iowa waters, thus determining which court had jurisdiction.
Drugs	Australia	The Australia Federal Police and some State police forces have used satellite data to detect the illegal growing of drug crops.
Human Rights Abuses	Africa and Asia	NGOs have, for a number of years, widely used satellite technologies to show evidence of human rights abuses in places such as Burma, Darfur and Zimbabwe. The Office of the Prosecutor of the International Criminal Court now how has its own in-house expert satellite team, as so many NGOs now provide evidence from satellites. The Office of the Prosecutor does not proactively monitor countries where human rights abuses are suspected. Instead they rely on historical evidence where human rights abuses are suspected of taking place. This sometimes involves asking international bodies like UNISAT to search satellite archives, or confirming the providence of the imagery that has been supplied to them by the NGOs. Only multispectral (optical) satellite imagery has been used as evidence to date, not radar imagery.
Property Litigation	Greece	In Greece, it is common for litigants to provide the court with satellite photos (which are available to the public by the Geographic Agency of the Army) in civil cases concerning property law. In Greek law this evidence is considered incontestable and very efficient in resolving litigation (concerning for example borders of the plots or constructions, or vegetation related to a very specific time spot). It is often used to prove timings of developments (which can be critical in law).
Environmental Impact	Philippines	The Environmental Law Alliance Worldwide became aware of plans for the construction of a waste landfill site

Application	Country	Details
Assessment		in the Philippines. The Alliance considered the site to be in an environmentally sensitive location because it was in a low-lying coastal area that was extensively covered with mangroves. The environmental examination report of the company that was proposing to create the landfill site made no mention of the loss of mangroves, so the Alliance used satellite images in court to provide evidence that an extensive canopy of mangroves would be illegally cleared if the landfill were constructed.

2.5 Lessons learnt from other satellite monitoring programmes

We have identified twelve important lessons learnt from other existing operational satellite monitoring programmes.

1 It is likely that a satellite monitoring programmes will catch more people than conventional inspections

Satellite monitoring can be a very pro-active method of enforcement. It has been demonstrated numerous times that it will probably detect a lot more possible offences (than would be detected by conventional checks). A common outcome is that satellite monitoring programmes can reveal far more breaches of the law than the regulator was expecting, and which they have at the outset resources to investigate. E.g. in one satellite monitoring programme examined, the regulator could only investigate approximately 150 out of 2000 flagged cases of potential illegality each year. This equates to only 7.5% of all suspected illegality being followed up on.
Advance thinking is required on strategies to handle this, if the above situation occurs. Governments might have to substantially increase the numbers of on-the-ground staff in the early days if they want to respond to all suspected offences that are detected and make compliance decisions. Otherwise it will appear that an expensive monitoring programme isn't working all that effectively. If they cannot carry out on-the-ground follow up inspections to the same level of intensity on all of the activities falling within the scope of control, risk assessments will have to be developed. Most of the current satellite programmes seem to base the risk assessments on those which pose the highest environmental or public safety risk, or whether those investigated are repeat offenders.

2 The satellite monitoring programme is likely to be required on an on-going basis.

Most satellite monitoring programmes see very significantly positive results. However, this does not always mean that the regulatory body running the programme becomes less busy, and that they can spend less money on it over time. What appears to often happen in practice is that they go from investigating large cases of potentially illegality to investigating smaller potential breaches. In other words, compliance programmes generally do not reduce all cases of smaller illegal behaviour – mainly the larger breaches.

There is also a suspicion that many of the positive impacts of satellite monitoring programme are caused because the programmes are effective (i.e. at detecting illegality), and this has a deterrent impact. If word got around that a satellite monitoring programme had finished (because it had been hugely successfully in stopping crime) it is possible that the illegal activity might resume again. Therefore, funding a satellite monitoring programme could be a long-term commitment.

3 The success of satellite monitoring programmes will often depend on the time required to respond to the data.

In many investigations undertaken in a satellite monitoring programme, once the Government have the alert from the satellite they will then do additional research, before undertaking ground inspections. E.g. they might undertake desk top analysis to see if there were permits, whether exemptions applied under the legislation, or whether other supporting evidence was available. Of the cases that Governments decide to investigate following the risk assessment process, many will turn out to be a breach – in part because of this stringent additional analysis. Government departments will often be reasonably sure from all of the evidence that there has been illegal behaviour before deciding to investigate further. That is not to say that such systems are fool-proof – they are not - and investigators can still find that site inspections reveal issues that they had not anticipated. But it holds true that the more time a regulatory body has to collect other evidence, the greater the likelihood of the success of the overall monitoring programme.

With waste crime, enforcement officials may have to respond quickly before the waste crime activity ceases at that site. Other satellite monitoring programmes also require using the information from the data quickly e.g. oil pollution. Generally, however, the quicker the data is needed the greater the emphasis on the ground based available to respond quickly. A quicker regulatory response is likely to result in more false-positives at ground-level. Therefore, regulators should examine whether supporting evidence, such as permits, can be electronically linked to the satellite monitoring programme, and quickly and easily searchable to discover whether the activity being scrutinized had a permit or not.

4 There are advantages and disadvantages to running the satellite monitoring programme in-house, or contracting the work out externally.

Having well-trained and competent staff is one of the most important, but often least talked about component of a satellite monitoring programme. Different satellite monitoring programmes have different approaches to whether the satellite analysis is done in-house, or not. Part of the decision-making for deciding which route to take concerns whether regulators (or other parts of Government) have the institutional knowledge and expertise in: (1) sourcing and obtaining satellite imagery; (2) analysing the data; (3) ensuring that the data is fit for court. Staff can be recruited, but to get an operational programme up-and-running will be easier with institutional knowledge. A second consideration is whether external satellite companies or third party analysis companies can offer a very reactive service. The data might need to be processed and interpreted by an analyst very quickly (i.e. so the regulator can be made aware of the illegal site and intercept the criminals in the act, and before its economic and environmental impact increases. A third consideration is regulatory budgets.

There are advantages and disadvantages which can be derived from both the in-house and contracting approaches.

Advantages of in-house expertise:

- The data doesn't have necessarily to be moved about between external and internal sites.
- There are costs associated with the recruitment and training of analysts, but this is probably not going to be as expensive paying for external analysis and expert witnesses.

Disadvantages of in-house expertise:

- Buying the satellite data is not the only significant expense of a satellite monitoring programme. There are also costs associated with purchasing computer hardware and software, and data storage facilities.
- Government staff might be away from the office for long periods if they are frequently called to be expert witnesses in prosecutions.

5 Anticipating adaptation by those they are monitoring

Those being monitored by satellites can become wise to the limits of satellite monitoring programmes and exploit weaknesses. There has often been a pattern of move, counter-move and counter-counter-move when satellite images are used in monitoring programmes. There are a number of examples of this:

(i) EU subsidies to Italian olive growers were supposedly greatly reduced after a European Commission satellite monitoring programme was introduced to detect fraud, then inexplicably started growing again. It is said that some farmers began planting cheap umbrellas which looked like olive trees on the satellite images to make it look like they were growing more than they were.

(ii) The Satellite Sentinel Project (SSP), used satellite monitoring to deter atrocities and to monitor military movements along the troubled border of Sudan and South Sudan, enabling responses that avoid civilian casualties. This satellite programme has led to a change of tactics. Attacks went from occurring in day light hours to deliberately happening "at night or under cloud cover," so there was less chance of detection. The counter-counter response from the SSP was to switch to infrared satellite monitoring that would pick up activity in the dark.

(iii) There is evidence to suggest that shipping fleets became aware that if they discharged oil into the sea whilst the water was choppy, this would not be visible on satellite imagery.

(iv) When satellite monitoring programmes were introduced in Australia to detect illegal land clearance (i.e. deforestation) many landholders in Australia were deterred from clearing land illegally. However, some landholders worked out the limits of the risk-based enforcement programme. Realising that the authorities prosecuted the landholders who cleared the most land first, and determining the numbers of prosecutions brought, they decided to continue clearing small to medium amounts of land, knowing that they would not be selected for further investigation. Some farming bodies offered assistance as to the limits which would stay beneath the regulators' radar so they could get away with repeatedly breaking the law. Even if some repeat offenders cleared huge areas of land in total over lots of years these escaped sanctions, because of statutory time limits for bringing prosecutions, which made it impossible to prosecute for cumulative clearing over a long period of time.

The above shows that anyone wishing to implement a satellite monitoring programme should never underestimate the cunning of those that they regulate. Before implementing any satellite monitoring it is a useful exercise to anticipate how waste crime offenders might adapt to continue rule breaking.

6 Satellite monitoring can have a deterrent impact

Satellite monitoring programmes can have a higher deterrent effect than some other enforcement approaches, because they are, by their nature, covert. Regulators could have an instrument by means of which the regulated can be made aware that they may be being watched at any time, but they cannot actually tell when, or whether, they are in fact being monitored. Regulatory bodies could create the impression of a substantial capability and threat of enforcement with a small regulatory resource commitment.

It is clear from earlier research studies that those being monitored generally do not know the extent of the monitoring capability. A UCL survey of Australian landholders about monitoring under a Government satellite monitoring programme designed to catch illegal land clearance, asked them to estimate the percentage of how many farms in their States were monitored by satellite and the frequency of this monitoring, many farmers massively underestimated the true extent of the satellite monitoring programmes. In practice, every farm in each of the States examined was monitored annually. It was clear that a large number of Australian farmers surveyed did not know this. Less than half of all farmers surveyed thought that they were monitored at least once a year. In an earlier UCL survey, UK farmers massively overestimated the true extent of the satellite monitoring programme (which is used in the UK to check for agricultural subsidy fraud). Only 14% of the farmers thought that less than 10% of farms were monitored annually, with significant numbers believing that the answer was over 50%. 43% of UK farmers also thought that there was satellite monitoring at least once a year. The truth is that approximately 5% of UK farms are monitored each year, with each farm in the UK actually having been monitored on average once every 23 years. This perception of more substantial monitoring than was the case appeared to substantially improve compliance levels with the legislation and reduced fraud in the UK. An important finding of both the above surveys was that those regulated did consider that the satellite monitoring was having an effective deterrent impact. Nearly two-thirds agreed that the fact that they were being watched by satellite was acting as a deterrent.

Satellite monitoring was clearly having an impact on behaviour of Australia farmers, although compliance levels could be better still if there was higher awareness of true monitoring levels.

One observation is that many existing satellite monitoring programmes are low-key. In other words, Governments have not gone out of their way to publicise them. It is understandable that the UK Government would not want to publicise their true satellite monitoring rates, because of the perception of farmers of more monitoring than was the case. Conversely, there is a strong argument that if other satellite monitoring programmes have very frequent satellite monitoring (e.g. bi-annually), then the true levels of monitoring should be communicated to those being regulated. Communication about a satellite monitoring programme might lead to the programme being more effective than it might otherwise be. Generally, if a satellite monitoring programme is undertaken, it is clearly in the interest of Government to let those who may be monitored know that this is happening. Knowledge of monitoring on the part of regulated communities is likely to alter their behaviour, potentially towards enhanced compliance. Any monitoring programme requires advance thinking about an information dissemination strategy.

7 How you will measure operational effectiveness should be considered at the outset.

It is preferable to have some form of determinable impact of a satellite monitoring programme because it will often be an expensive outlay and will require budgetary justification over time. However, although there is a lot of evidence that a satellite monitoring programmes can have significant impacts, it can be difficult to measure the precise impact that satellite monitoring might directly have had in terms of compliance. A combination of issues, including policy changes, legislative changes and the satellite monitoring could have influenced any statistical changes.

Measuring the success of satellite monitoring is also often difficult because it does not produce instantly quantifiable results. The image analysis or follow-up investigations might be done months after the offence occurred and prosecutions can take place years after the illegal act occurred. This can cause long time lags between the offence being committed and knowledge of the prosecution within the regulated community. It can similarly take a while for the impact of regulatory action to filter through to the statistics.

However, it would be good to have some form of indicators in a waste crime satellite monitoring programme. Government could do this in one of three ways (or all of them):

- Compiling records of the numbers of suspected waste crime sites each year.

- Compiling records of the number of sites that were found to be illegally operated.
- Compiling records of the levels of waste entering the legal chain (and the levels of tax income).

8 Industry is likely to support the monitoring programme.

Research has shown that there can be high levels of industry support for the use of satellite technologies, in that they are more likely to provide a level playing field (e.g. some normally law-abiding companies argue that they are forced to break the law to compete with other companies that are habitually breaking the law). In respect of waste crime, one impact might be an increase in revenues to legitimate companies (as more illegal operators are deterred or caught). Governments wishing to adopt satellite programmes might consider emphasizing 'supports' when publicizing a monitoring programme.

9 Satellite monitoring requires a strategic regulatory approach from the outset

Satellite monitoring is going to be a new thing to most Government departments who adopt a monitoring programme. There will be a lack of experience and understanding in how the technology works and its probity as evidence. One of the key challenges in using satellite data in a regulatory environment is to prevent the monitoring programme becoming too "technically led". Ideally there needs to be a lot of thought before the programme is adopted as to how to build good working interdisciplinary relationships within Government. In order to understand the challenges of each other's needs, there has to be an evolving process of collaboration between different disciplines.

At the outset of a monitoring and enforcement programme where satellites are used, most Government lawyers will have little knowledge or experience with digital evidence. They will in most instances not completely understand the science of satellite imagery, or its limitations and strengths as evidence. The lawyers need to ask the Government scientists (or the sub-contracted body) these questions before prosecutions commence in order to understand the vulnerabilities of the technology. Without communication, some lawyers will not be clear about what the satellite image has actually shown (and they might play an important role in convincing a court why the image can be relied upon).

Similarly, Government scientists responsible for remote sensing will, in the early stages, have little knowledge of legal procedure and the wording of the legislation. They will also be unlikely to have experience of preparing reports, affidavits and other documentation to a standard that is required for court. Many will also have not appeared in court before, and could have limited experience of aggressive cross-examination by defence lawyers. They will require briefings from lawyers as to how to prepare the evidence, and what to expect in court.

Experience in other countries shows that there has not always been good understanding and communication between the technical and legal groups (which has had a detrimental impact on the monitoring programme). A disconnect between different actors in the regulatory process has directly resulted in some prosecutions collapsing in court. In some satellite monitoring schemes examined, Government scientists commented that there had been cases where they had received no briefing from a lawyer/prosecutor at all before court, or if this had taken place, it had been less than ten minutes long and on the courtroom steps. This had sometimes resulted in the lawyers showing an ignorance or lack of understanding about the evidence and the issues in court. Sometimes, their questions had even been counter-productive and made the evidence more vulnerable. One Government scientist remarked to me that a lack of communication increased the prospect of a lawyer making the satellite data seem more complicated in front of the judge. If there had been better liaison and communication between these different groups from the start, then better outcomes might have been achieved.

Satellite monitoring programmes require a far more strategic regulatory approach than conventional approaches. Lawyers and satellite specialists would be required to work together as a team. It is, therefore, not just evidence that is an issue when satellite data is used in court, staffing and regulatory structures can sometimes be overlooked, even though these can be equally as important. Regulatory agencies must, from the beginning of adopting a satellite monitoring programme, collectively understand their overall delivery aims, their individual roles within the programme, and how these varying Government functions will interact and work together. This might create deeper issues to resolve if there is out-sourcing of support networks.

There should be dedicated personnel in each of the interdisciplinary groups appointed to work closely together and to provide communication and liaison between different arms of Government. Regular meetings, training events and published guidance should also be undertaken to foster interdisciplinary understanding and cooperation. It takes a lot of energy to bring these groups together, but this is necessary, to enable them to understand each other's needs. Otherwise, there is the danger that satellite monitoring and enforcement programmes become disjointed or scientifically/technically-led. There is no point detecting and catching people if there is no positive end-result (e.g. a conviction).

10 Sanctions can be key

The existence of a satellite monitoring itself is not always the major factor in taking the decision whether to break the law. A significant factor in deterring breaches of the legislation is the actual penalties for non-compliance (a credible sanction). The risk of being caught via the satellite (and then ground inspection) and the potential cost of fines, versus the economic outcome has meant that in some satellite monitoring programmes the deterrent impact of the fine is key.

11 Have an evidential plan at the outset

There are systems and protocols that can be put in place to enable satellite data to be a more effective form of legal evidence. For example, there is now greater emphasis on showing the chain of custody and events from the raw data, through processing, to the product that is used in court. There are existing standards that can be followed that might give lawyers and judges greater confidence in the use of the technology and can also inform technical experts as to how to best manage digital data. It is preferable to develop an evidential plan at the outset of a monitoring programme e.g. affidavits can be collected from external image suppliers to demonstrate authenticity.

12 Satellite imagery won't always be used as evidence.

Satellite data is most effective when it is used in combination with other forms of evidence. It is essentially one jigsaw piece in a jigsaw puzzle. In most cases evidence from satellite technologies does not appear to have reached a stage yet where it should be used alone as evidence (and some legal systems like Scotland require corroborative evidence). It is recommended that, wherever possible, it should always be accompanied by other forms of corroborating evidence, such as witness statements from ground inspections, GIS data, and anything else that helps support its findings, so as to give a young technology more credibility in the eyes of the judiciary and the public.

3.0 Improving awareness, knowledge and understanding of RS in the regulatory sector

Section 3.0 addresses improving awareness, knowledge and understanding in the regulatory sector of RS by: reviewing the current capabilities of RS and other identified technologies; reviewing data acquisition and processing techniques; and collating an easily understandable list of applicable sources and datasets.

3.1 Introduction

The discovery of an illegal waste site that was previously unknown or unsuspected is a key challenge when applying remote sensing techniques in the waste sector. The image in figure 15 shows a waste site near Kiev, Ukraine as imaged by the QuickBird remote sensing satellite: it would be ideal to use this type of remote sensing technology to detect illegal waste sites quickly and easily.

Figure 15. A QuickBird remote sensing image of a municipal waste site near Kiev, Ukraine [Source: Aristov, 2008. Copyright: QuickBird © DigitalGlobe].

The image is a combination of a multispectral colour image with a pixel size of 2.44 m and a panchromatic image with a pixel size of 0.61m.

The state of the art in remote sensing of illegal waste sites does not allow us to carry out such detection with a high degree of confidence yet because automated detection systems have not been developed to pinpoint illegal waste sites and to allow the refinement of potential sites by the visual inspection of images. However, progress has been made in recent years to improve the use of remote sensing to detect and characterise waste sites.

This report reviews the scientific and other literature on remote sensing of waste sites and summarises the applicable remote sensing technologies. The review will allow the identification of the most likely routes to the successful use of remote sensing technology to detect illegal waste sites and therefore contribute steps forward to reach the ideal solution that is illustrated by figure 15. The review will improve awareness, knowledge and understanding in the waste regulatory sector of current and developing remote sensing and related technologies.

The review includes applications of remote sensing of waste sites in the 13 countries and 23 regions listed in table 1. A wide variety of remote sensing systems have been used in the applications summarised here. Table 2 lists the satellite missions and the instruments that have been used in the studies. The terms *satellite remote sensing* and *Earth observation* are generally regarded as synonyms.

Table 1. The countries and regions reviewed here that have used remote sensing and related technologies in waste site detection and analysis

Country	Region	Country	Region
Australia	Queensland	Spain	Andalusia Madrid
Canada	Ottawa	Taiwan	
Greece	Athens	Turkey	Konya
Italy	Apulia Caserta Naples Rome Veneto Venice	Ukraine	Kiev
Japan		UK	Bedfordshire Sheffield
Kuwait		USA	Missouri Pennsylvania South Carolina Southern California
Palestine	Ramallah		

Table 2. Satellite Earth observation missions (and aerial photography) used for waste detection and analysis in the studies reviewed here

Aerial photography	Cosmo-Skymed	Hyperion	QuickBird
ALOS AVNIR	Envisat ASAR	Ikonos	Resource-F
ALOS PALSAR	ERS-1/2 SAR	IRS 1C/1D	SPOT
ALOS PRISM	Formosat	Landsat	WorldView
CHRIS Proba	GeoEye	LISS	

3.2 Structure

This section consists of the following sub-sections:

- A summary of the types of remote sensing technology and data typically used in waste site detection;
- A review of the applications of remote sensing to detect waste crime;
- A summary of the applications, focusing on the pros and cons of remote sensing technology for detecting waste crime;
- A representative summary of the costs of the remote sensing data used in the applications reviewed.

In addition, the chapter examines LIDAR remote sensing and hyperspectral remote sensing. Both are relatively new technologies in remote sensing and there have been few cases where these data have been used in waste detection and analysis. However, both hold promise and are included in this report to indicate potential.

3.3 Summary of remote sensing technologies

3.3.1 Electromagnetic radiation

All remote sensing instrument sensors are sensitive to energy in a part of the electromagnetic (EM) spectrum and the sensitivity to energy of the sensor is recorded and translated into digital data (Harris 2012). Different sensors operate in different parts of the EM spectrum and this section summarises the main parts of the EM spectrum used in remote sensing of waste sites: visible, near infrared, thermal infrared and radar. Data from sensors operating in these principal parts of the EM spectrum are used later in this report when discussing applications of remote sensing to detection and analysis of waste sites.

3.3.2 Visible

The most common part of the electromagnetic spectrum used in remote sensing is the visible wavelength range where the wavelength is 0.4 – 0.7 μm[1]. This is the light that we can see with our eyes and has been used in remote sensing since cameras were used in the early hot air balloons. Visible wavelength sensors capture electromagnetic energy that is *reflected* by the surfaces beneath the sensor, so they rely on solar radiation as the main energy source. The visible wavelength sensors are typically charged couple devices (CCDs) such as are found in ordinary digital cameras. These devices collect visible wavelength data for each of the pixels in an image. The energy collected may be for the whole visible wavelength range or for parts of the range. For the whole of the visible range (i.e. 0.4 – 0.7 μm) then each pixel has a single data value. Alternatively, the visible range can be divided and data collected for each part: commonly the visible range is divided into blue, green and red parts[2] and data collected for each part measured by the sensor. Sensors that capture data over the whole visible range produce monochrome (black and white) images and sensors that capture data for parts of the visible range produce colour images when the different parts of the visible wavelength range are combined together in a single image.

A very important element of remote sensing sensors of all wavelengths is the pixel size. This is the individual element in a digital image and is usually presented as the equivalent area on the ground to which a pixel in the sensor corresponds. In early Landsat images the pixel size was 79 m for the Multispectral Scanner sensor and for later Landsat missions the pixel size was 30 m for the Thematic Mapper sensor. In the last decade sensors with pixel sizes as small as 0.31 m have been operated, for example on the satellites operated by DigitalGlobe. Table 3 summarises the changes in the smallest pixel size available from land remote sensing satellites since the 1970s.

Table 3. The changes in pixel size from satellite remote sensing since the launch of Landsat 1 in 1972.

Time period	Pixel size (m)
1970s	79
1980s	30
1990s	10
2000	1
2001	0.6
2007	0.5
2015	0.3

It is not unusual for the term ‘pixel size’ to be synonymous with the term ‘spatial resolution’. While for most practical purposes this presents no real problems, the spatial resolution of a remote sensing sensor depends on the information content in a scene as well as the electronics of the sensing instrument. In a Landsat Thematic Mapper image with a 30 m

[1] 1 μm = 10^{-6} m or one millionth of a metre.
[2] Broadly speaking blue light has a wavelength range of 0.4 – 0.5 μm, green light has a wavelength range of 0.5 – 0.6 μm and red light a wavelength range of 0.6 – 0.7 μm.

pixel size, a black tarmac road crossing a white sand desert will be clearly visible. The road is not 30 m wide, but the contrast of the road with the surrounding desert allows the road to be visible on the image, especially if it is straight. By contrast, a winding gravel road crossing a desert of brown sand will probably not be visible at all on a Landsat Thematic Mapper image because (1) there is little contrast between the road surface and the desert surface and (2) our eyes see linear features on images much more easily than they see meandering features. Spatial resolution also depends on atmospheric conditions at the time of data capture: a clear atmosphere will produce a better effective spatial resolution than a misty or dusty atmosphere.

A recent development in satellite remote sensing has been the launch of very high resolution (VHR) sensors (Toutin 2009) that produce images directly comparable to aerial photographs and have similar spatial resolution. The best spatial resolution sensor operating at the moment on a remote sensing satellite is the DigitalGlobe WorldView-4 satellite which has a pixel size of 0.31 m. VHR images are typically the easiest to interpret as they are familiar to us, either through the use of aerial photographs in everyday life or through the experience of flying in an aeroplane. For waste sites, VHR images offer the opportunity to see in detail what is happening at a waste site. Figure 15 is an example of a VHR satellite image and it allows us to see the extent of the waste site near Kiev and its internal structure. The image is from the QuickBird satellite and has a smallest pixel size of 0.61 m.

3.3.3 Near Infrared

The wavelength range of the near infrared is approximately 0.7 – 1.1 μm and near infrared sensors are commonly found in association with visible wavelength sensors. Near infrared sensors respond to reflected energy and near infrared energy behaves in physical terms like visible light. We cannot see near infrared radiation because our eyes only respond to visible light and they stop being sensitive beyond 0.7 μm. However, remote sensing sensors have been commonly constructed to measure near infrared wavelength energy along with visible wavelength energy and normally with the same pixel size.

The near infrared wavelength range allows the construction of false colour composite images, images that show land surface vegetation strongly and are very common in Earth observation applications. The basic logic of false colour composite images is shown in table 4.

Table 4. The correspondence between real wavelength ranges and the colours shown on a false colour composite image.

Wavelength range	Real colour or name	Colour shown on a false colour composite image
0.5 – 0.6 μm	Green	Blue
0.6 – 0.7 μm	Red	Green
0.7 – 1.1 μm	Near infrared	Red

Images that we can see are normally produced from three colours, namely blue, green and red. When a near infrared wavelength is used in a remote sensing image it is typically portrayed as a red colour, the real red wavelength is portrayed as a green colour and the real green wavelength as a blue colour, although these assignments vary depending on the application. The reason for this pattern is to emphasise the vegetation areas in the image because vegetation has a high reflectance in the near infrared but a low reflectance in visible wavelengths. In simple terms areas of vegetation appear red in false colour composite images, which at first sight is counter-intuitive but by combining near infrared and visible wavelengths together vegetation areas are emphasised and the contrast with other areas sharpened.

Figure 16. A Landsat 8 Thematic Mapper false colour composite image of the area around Southampton [Source: US Geological Survey].

Figure 16 shows a Landsat 8 false colour composite image of the area around Southampton: the red areas are the healthy vegetation areas.

3.3.4 Thermal infrared

The near infrared part of the EM spectrum is in the domain of reflected radiation. The term infrared energy often brings to mind heat energy, although this is strictly the domain of the thermal infrared with a wavelength range of around 8.5 – 12.5 μm[3]. Thermal energy is *emitted* by a surface not reflected. This means that thermal infrared sensors can be used day and night because the energy emitted by a surface does not rely on the reflectance of energy from the sun. The pixel size of thermal infrared sensors is normally around four times larger than the pixel size of visible and near infrared sensors: for example, the Landsat Thematic Mapper (TM) has a 30 m pixel size for its visible and near infrared wavebands and a 120 m pixel size for its thermal infrared waveband. The reason for the larger pixel size is that there is much less energy emitted by the Earth's surfaces than reflected by those same surfaces, so the detectors in the remote sensing sensors have to be larger to capture the lower quantities of energy in the thermal infrared. Larger detectors at the Earth observation instrument mean larger pixels on the ground.

Thermal infrared data have been used extensively in remote sensing for energy balance modelling, and have also been used to identify heat anomalies such as in nuclear power stations or other industrial plants. Waste sites are often warmer than their surroundings and can sometimes be detected using thermal infrared sensors. When remote sensing instruments are used in situ on the ground the use of the thermal infrared waveband is well known for identifying the growth of cannabis plants in greenhouses because the greenhouses are kept warm at night and therefore have a high thermal infrared signal.

3.3.5 Radar

The visible, near infrared and thermal infrared wavelengths all have one limitation for the observation of the surface of the Earth: they are all affected by cloud cover. In the presence of cloud cover there is no possibility of collecting data at these three wavelengths for the surfaces beneath the cloud. The answer to this problem is to use radar sensors. Radar operates in the microwave portion of the electromagnetic spectrum with a wavelength range of approximately 1 – 30 cm. A key feature of this wavelength is that it is not affected by cloud. Radar is an active sensor, which means that it transmits a beam of microwave energy from the radar to the surface and then records the radiation returned to the radar sensor. By contrast, remote sensors operating in the visible, near infrared and thermal infrared wavelength ranges are passive sensors in that they record the energy reflected from or emitted by surfaces and do not themselves send our radiation.

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[3] The wavelength range of thermal infrared sensors varies considerably but most fall in the range 8.5 – 12.5 μm. Some thermal infrared sensors start at around 10 μm and some detect energy up to around 14 μm.

Within the radar wavelength range of 1 – 30 cm there are three wavelengths commonly used in radar remote sensing:

- X-band, 2.4 – 3.8 cm wavelength
- C-band, 3.8 – 7.5 cm wavelength
- L-band, 15 – 30 cm wavelength

The first space borne radar was Seasat launched by the USA in 1978. This was followed by imaging radars on board several NASA Space Shuttle flights and then by the ERS-1 mission of the European Space Agency in 1991 and Envisat in 2002. There have also been imaging radars launched by Japan, Canada, Italy and Germany. The pixel size of imaging radars has decreased from around 25 m for Seasat to around 1 m for TerraSAR-X[4], bringing radar images to a pixel size comparable to very high resolution visible wavelength sensors (see figure 17).

Figure 17. A TerraSAR-X radar image of the agricultural area near Dessau, Germany created by combining three dates of data and assigning each image to one of red, green and blue colours on the display [Source: Airbus Defence and Space and Satellite Imaging Corporation].

Radar images are not easy to interpret. The radar signal transmitted by an antenna on the satellite down to the Earth's surface is *backscattered* by that surface and part or all of the signal is recorded back at the antenna on the satellite. This backscatter is influenced by two main features of the surface, the roughness of the surface and the electrical conductivity (or dielectric constant) of the surface. Rough surfaces will backscatter more radar energy back to the satellite radar antenna while smooth surfaces will backscatter much less or even no energy back to the satellite radar antenna. The second influence on radar backscatter is the electrical conductivity (dielectric constant) of the surface, which is directly related to the moisture content of the soil. A high moisture content means a high backscatter; and a low moisture content means a low backscatter, even to the extent of radar being able to see through the sand of hyper-arid desert areas to the solid rock beneath.

For operational information systems, imaging radar has the major benefit of reliability. It operates day and night and in all cloud cover conditions. However, because of the speckle

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[4] TerraSAR-X has a best spatial resolution of 0.25 m in spotlight mode, although this is uncommon. The TerraSAR-X web site is at http://www.intelligence-airbusds.com/terrasar-x/

created as part of the data collection process, radar images are more difficult to interpret than images in the visible, near infrared or thermal wavelength parts of the EM spectrum.

Radar is becoming more widely used because of improved spatial resolution and also because of the techniques of interferometry (Hanssen 2001). Interferometry allows the creation of maps of the height of the surface in an image. This has allowed the creation of digital elevation models[5] for most of the land surfaces of the Earth and also the identification of land movements and of buildings that have been destroyed or damaged in earthquakes. Radar interferometry was used extensively after the Haiti earthquake of 2010 to assess the extent of land surface deformation in the area of Port au Prince. Interferometry has also been used in the UK to assess the extent of land subsidence above former coal mines in connection with insurance claims.

3.4 Applications of remote sensing to detect waste crime

3.4.1 Visual interpretation of aerial and satellite images

Aerial photography has been a useful source of information about waste sites for over 40 years: the first scientific paper on the use of aerial photography for waste site characterisation is usually attributed to Garofolo and Wobber (1974). Erb et al (1981) used a sample of the archive of aerial photography for the USA at a scale of 1:20,000 to examine the changes at selected landfill sites over time. In a similar fashion de Wet (2016) used aerial photography of Lancaster County, Pennsylvania, USA to identify and characterise waste disposal sites.

Satellite remote sensing images have been used in a similar way to aerial photographs for visual interpretation. Purdy (2009) gives examples of using QuickBird images to show an illegal waste site at a farm in Chelmsford, Essex between November 2004 and October 2005 and illegal operations at a scrap yard in Sheffield between May and June 2005. In Japan Yonezawa (2009) illustrated the use of QuickBird images and images from the Japanese ALOS PRISM, AVNIR-2 and PALSAR instruments to identify different types of waste, including tyre dumps, at the Ishidumori landfill site.

3.4.2 Multispectral analysis

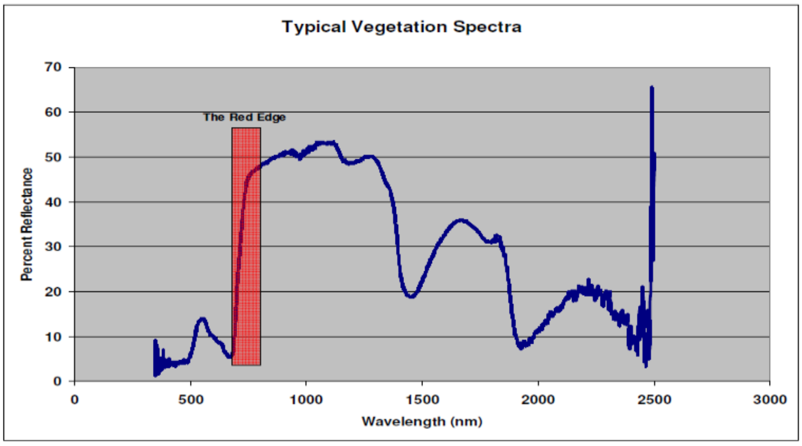
Multispectral analysis is the analysis of remote sensing data for several wavebands, typically across the visible and near infrared parts of the EM spectrum. Johnson et al (1993) used Landsat Thematic Mapper (TM) multispectral data (30 m pixels) to analyse seven landfill sites in south west and central Missouri for the period April 1984 to May 1989 with the purpose of examining the ability of the data to delineate these landfill sites. They found that the most useful Landsat TM band for detecting landfill sites was band 7 (2.08 µm – 2.35 µm) and that a combination of bands 4 (0.76 µm – 0.90 µm) and band 7 also detected the landfill sites well. Johnson et al (1993) also used a clustering algorithm to produce a map of similar land cover categories in order to try and identify a map cluster that was directly associated with landfill sites. They used a minimum distance to means classifier to produce a map of 12 classes of land cover, but found that landfills occupied more than one class and so there was not a consistent association of any one land cover category with landfills.

Reflectivity across several wavebands is at the core of multispectral analysis. Old landfill sites are often covered by vegetation and such vegetation is usually not as vigorous as the more mature vegetation of surrounding areas that is the vegetation is under stress because of the underlying waste site. Stressed vegetation can be detected on multispectral imagery by the reduction in the near infrared reflectance and the increase in the visible reflectance.

[5] The Shuttle Radar Topography Mission was specifically designed to create digital elevation models of most of the land surfaces of the Earth. This has been followed by the TerraSAR-X and TanDEM-X missions to create improved digital elevation models. See http://www.infoterra.de/terrasar-x

Slonecker et al (2010) use an analysis of the 'red edge' to detect vegetation stress as part of a review of remote sensing of hazardous waste sites. The red edge is the steep increase in reflectance from the red portion of the EM spectrum to the near infrared portion of the EM spectrum (see figure 18). Healthy vegetation has a higher concentration of chlorophyll and the red edge shifts to longer wavelengths (in the range 0.68 µm – 0.76 µm) while stressed vegetation has a lower concentration of chlorophyll and the red edge shifts to shorter wavelengths. Vegetation on old landfill sites may be detected by a lowering of the red edge.

Figure 18. Typical vegetation reflectance across visible and near infrared wavelengths showing the red edge which is a steep increase in vegetation reflectance. The units on the X-axis (wavelength) are in nanometres, where 1 nm = 1000 µm. So, the visible wavelength range is 400 – 700 nm or 0.4 – 0.7 µm [Source: Slonecker et al 2010].

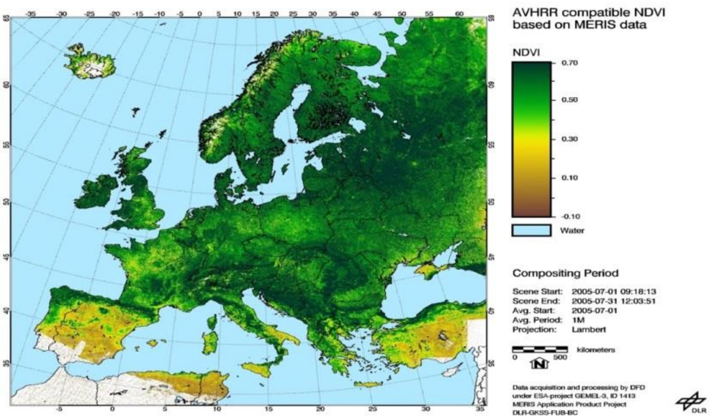


There is a common tool used in remote sensing which takes advantage of the high reflectance of vegetation in near infrared wavelengths, the Normalised Difference Vegetation Index (NDVI). The equation for the NDVI is commonly:

$$NDVI = \frac{NIR - R}{NIR + R}$$

For any pixel, the value of NDVI is calculated by subtracting the red (R) reflectance value for that pixel from the near infrared (NIR) reflectance value. For a pixel with a high quantity of vegetation (for example a mature crop) this difference will be large, while for a pixel with no vegetation (for example the bare surface of an active landfill site) the difference will be zero or a small number. The denominator in the equation above normalises the values to account for variations from image to image. Figure 19 shows an NDVI map for the whole of Europe for the month of July 2005. The darker green areas show active vegetation while the brown areas show low or no vegetation.

Figure 19. A Normalised Difference Vegetation Index (NDVI) image of Europe for the month of July 2005 calculated from data from the MERIS sensor [Source: DLR, the German space agency].



The NDVI is the most common example of a vegetation index. Other variants of vegetation indices are also used, for example the soil-adjusted vegetation index. The creation of NDVI images is potentially useful for waste site monitoring because vegetation growing on former waste sites typically shows a less vigorous growth than vegetation growing on nearby normal soils because of the poor soil quality of the landfill site. Calculation of NDVI values for waste site detection has been used by Aristov (2008) in Ukraine, Ishihara et al (2002) in Japan and Notarnicola et al (2004) in Italy, but in these cases the results were poor except for the largest waste sites because waste sites appear to be bare soils rather than being a distinctive class.

Cadau et al (2014) extended the NDVI idea by using a soil-adjusted vegetation index and combining it with the local texture of an image at the waste site. They proposed a Dump Detection Index (D):

$$D = SAVI \times Entropy$$

Where *SAVI* is a modification of the NDVI to take account of vegetation density (Huete 1988) and *Entropy* is a measure of image texture calculated for the pixel values around a target pixel (Haralick et al 1973).

In Kuwait, Kwarteng and Al-Enezi (2004) showed how Landsat and Ikonos images captured between 1977 and 2000 could be used to map the extent and the development of the Al-Qurain area. The area had been used as an illegal waste site and when a new housing development was constructed on it there were fires and foul odours caused by gases leaking upwards from the approximately 5 million cubic metres of waste.

Also, working in Kuwait, Faisal (2011) used Landsat TM thermal infrared images with 60 m pixels as input to a land surface temperature model. The results of the model showed that temperatures were 5°C higher in the target landfill area than in the surrounding area, and the model was then used to identify five suspicious waste sites by their higher temperatures. A similar study was reported in Italy by Persechino et al (2010) who measured temperatures of 30° - 40°C in illegal waste sites, in their case using thermal infrared images from drones and airships. Similar results are reported by Zilioli et al (1992) from ground-based thermal sensors.

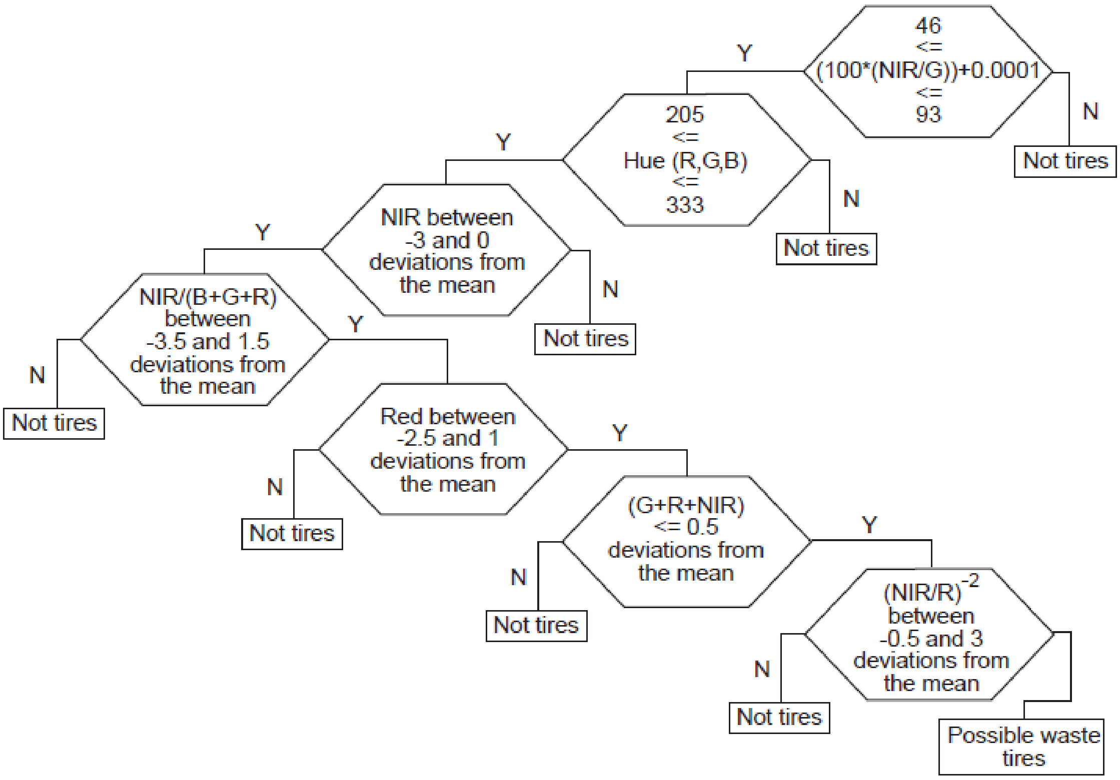
Notarnicola et al (2004) explored an alternative statistical approach in the search for a distinctive classification of landfill sites on remote sensing images. They used Principal Components Analysis (PCA) which creates new variables from the original wavebands: each new variable accounts for a successively lower proportion of the variance of the data set. Typically, the first Principal Component (PC1) is a general measure of the overall brightness of the image across all the wavebands analysed. Notarnicola et al (2003) found that Principal Component 3 showed many of their target waste sites in their analysis of Landsat Thematic Mapper data of the Apulia region of southern Italy for the period May 1994 to May 1995. On the PC3 image there was some confusion with bare soils and urban areas but the authors found that visual inspection of the PC3 image results aided the ability to identify waste sites. In a study of olive oil waste sites in Crete, Agapiou et al (2016) found that the Principal Component 1 image was useful in detecting the waste sites, mainly because the sites were darker features on the satellite imagery and the PC1 image is a general brightness image.

There are two types of classifications of remote sensing data often used to produce summary land cover maps: unsupervised classification; and supervised classification. In unsupervised classification, each pixel is assigned to one class as the result of an algorithm which simplifies the multispectral data set by clustering the data. Johnson et al (1993) used this approach for waste sites in Missouri and Aristov (2008) used the approach for Ukraine. Supervised classification consists of three stages. First, test sites are used to calibrate a classification model that contains (say) 15 land cover classes. A common classification model is a maximum likelihood model. Second, the data for all the pixels in the image are then classified into one of these 15 classes based upon the model. Third, a test is performed using validation data to assess the performance of the supervised classification model.

Silvestri and Omri (2008) analysed Ikonos image data for the period June - July 2001 for the Veneto region of northern Italy. They used a maximum likelihood supervised classification approach for the initial recognition of possible waste sites, followed by visual interpretation of the data and the use of ancillary geographical data. They identified 2944 possible illegal waste sites in an area of 1969 sq. km from their initial analysis which was then reduced to 1199 sites by using visual interpretation and ancillary geographical data. The locations of these 1199 sites were then reported to the local authorities responsible for waste crime. For a test site in a forested region north of Tokyo, Japan, Ishihara et al (2002) analysed Landsat TM and ASTER data using the NDVI and then a supervised classification approach to map waste sites through detecting the changes in land cover over time. They found that their approach yielded poor results for waste sites less than 2000 sq. m in size but better results for waste sites larger than 5000 sq. m in size.

Remote sensing imagery has been used for the specific case of identifying piles of waste tyres in the USA (Quinlan 2012). Imagery from the multispectral sensor (2.44 m pixels) and the panchromatic sensor (0.61 m pixels) of Ikonos were analysed to identify illegal tyre waste dumps in the Sonoma and San Bernardino regions of southern California. Four hundred images on 40 dates in the period November 2005 to November 2007 were analysed. In general waste tyre dumps appear as dark tones on remote sensing images, but there is confusion with other persistently dark features such as water, shadows, asphalt, rusted metal or black plastic used on farms. Quinlan (2012) used a decision tree approach to attempt to isolate the tyre waste dumps on the Ikonos imagery. The decision tree is shown in figure 20.

Figure 20. The decision tree used by Quinlan to identify the possible sites of waste tyres on Ikonos imagery [Source: Quinlan (2012)].



The approach of the decision tree is to ask a series of questions each with a yes/no answer about the characteristics of the remote sensing data in individual bands or combinations of bands. The results of the analysis were 76 sites identified as potential tyre dump sites which required field inspection. Of the 76 sites, 66 contained waste tyres and only 3 sites were false positives.

3.4.3 Remote sensing and GIS

Several of the studies reviewed here have found that using remote sensing data alone does not produce good enough results because of the confusion of waste sites with other bare or near-bare surfaces. So, some authors have turned to using other geographical data in combination with the remote sensing data as a means of filtering out likely illegal waste sites.

For example, the Wastemon project by Planetek Italia (Drimaco 2012, Planetek 2016) analysed WorldView-2 image data of a test site south east of Bari in southern Italy to detect waste sites. The Wastemon project is part of the European Copernicus programme. They found it beneficial to include information about: (1) the distance from a road of a potential waste site because lorries and trucks carrying waste need road access; and also (2) the distance from existing waste sites as illegal waste sites are often found in connection with legal waste sites. This addition of geographical information is performed in a Geographic Information System (GIS) that enables the combination of a variety of spatial data. Biotto el al (2009) list a set of criteria that they found useful when analysing Ikonos data of the area around Venice, Italy to map landfill sites. They built a GIS of their test area around Venice that included the following geographical variables:

- Road network accessibility;
- Population density;
- Land use classes;
- Former quarries;
- Proximity to authorised landfill sites;
- Industrial sites.

From this analysis, they produced a map of the probabilities of illegal waste sites based upon a set of 20 calibration sites and 19 validation sites. They found that 16 of the 19 validation sites fell into the high probability category, and only one of the 19 validation sites fell into the low probability category.

Chu et al (2013) used a test area of 105 sq. km in central Taiwan to develop a probability map of likely illegal waste site locations. They used Formosat-2 multispectral data (pixel size 8m) together with other geographical data for 27 test sites of illegal dumping for the period 2008 – 2009: 18 sites were used as calibration and 9 sites as validation of the approach. The geographical variables they used in addition to the Formosat image data were the distances to: dykes, rivers, idle land, factories, roads, residential areas and commercial areas. Their probability map allowed them to identify about 12% of the study area where the likelihood of illegal waste dumping was very high. A similar approach has also been examined by Jorda-Borell et al (2014) for the Andalusia region of Spain.

The use of additional data was taken further by Persechino et al (2013) who, based upon the use of remote sensing and GIS data of the Caserta region of Italy to identify illegal dumping, added the analysis of texts from news report, technical reports and private sector investigations to refine the methodology to map possible illegal dumping sites.

Stephenne et al (2013) developed a GIS database called *Terrils* for the Walloon region of Belgium in response to the EU Mining Waste Directive 2006 that requires all member states to create and maintain an inventory of closed waste facilities that cause negative environmental impacts or a serious threat to human health. As part of the database they included information for 591 waste heaps and the GIS allowed each one to be assessed in relation to distance from water courses, the location of settlements and the proximity of Natura 2000 sites.

3.4.4 Radar

As noted earlier, radar offers the opportunity to collect remote sensing data on a regular basis because the sensor is an active one that works during both the day and the night and also independently of cloud cover. The normal form of radar instrument carried on remote sensing satellites is a Synthetic Aperture Radar (SAR) and this type of instrument has been flown on the ERS, Envisat, Sentinel, Radarsat, Cosmo-Skymed and TerraSAR missions, amongst others.

SAR images show the backscatter of the surface, affected as noted earlier by surface roughness and soil moisture. Figure 17 earlier in this report is an example of a SAR amplitude image and it shows different agricultural fields that have different backscatter characteristics. The image was created from three different image dates and then combined in a colour composite. Such images show similar surface features to multispectral remote sensing in the visible and near infrared wavebands, although are always characterised by speckle because of the nature of the image creation process. SAR images such as this can be used to identify waste sites in a way similar to multispectral images.

A relatively new development in SAR data processing is the production of interferometric SAR (InSAR) images. These images use the phase information present in SAR backscatter data and show the height of a surface or the changing height of a surface. InSAR images may be useful for waste site detection because they can show the change in height of a waste site as the result of new waste being added.

In his PhD thesis at Cranfield University, Ottavianelli (2007) examined the use of SAR data for landfill monitoring in the UK. He used SAR data from ERS-1, ERS-2 and Envisat for the period 1995 – 2006 supported by analysis of CHRIS Proba, SPOT and Landsat data. His test sites were at the Brogborough and Stewartby landfill sites in Bedfordshire. He analysed images of SAR amplitude, SAR coherence and InSAR data for his test areas. He concluded the following for the optimal use of SAR data for landfill monitoring:

- Pixel size of 4 m or less;
- L-band (15 – 30 cm wavelength) with full polarimetry;
- Interferometric pairs of images with a maximum temporal difference of 24 hours.

These characteristics were not available in the SAR data sets he used at the time, but are now available through newer SAR systems such as Cosmo-Skymed, TerraSAR-X, TanDEM-X, Radarsat and Sentinel-1. Cadau et al (2014) have subsequently analysed Cosmo-Skymed SAR data in order to examine the evolution of landfill volumes in waste test areas around Naples and Caserta, Italy.

Karathanassi (2012) used digital elevation models (DEMs) created from InSAR data to detect changes in height at the Liosia II landfill site near Athens, Greece: the input data were from the Envisat SAR for the two time periods of May-June 2004 and October-November 2004. NPA (2016) report on the measurement of sinkholes at a test site in Wink, Texas. They used InSAR analysis on data from ERS (1993 – 2000) and ALOS PALSAR (2007 – 2011) and showed that subsidence rates of up to 80 cm per year were happening at the sinkholes in Wink and that this subsidence can continue for more than 35 years after the formation of the sinkhole. In the case of the Wink test site the sinkholes were created as a result of sub-surface oil and gas exploration, but similar subsidence can also result from collapsing voids at landfills.

3.5 Summary of the applications

The published material on the use of remote sensing data for detecting legal and illegal waste sites is not very extensive and certainly not as extensive as (say) crop monitoring, but from the material reviewed here a number of conclusions can be drawn.

- Remote sensing data have been widely used for examining the characteristics of vegetation and especially of reduced or changed vegetation health. Old waste sites may be characterised by vegetation growing on the site, but with poor quality vegetation because of the poor substrate of the waste site or the production of waste gases at the site. The use of the normalised difference vegetation index can help in identifying zones where vegetation health is poor.

- Classification of remote sensing image data is a common tool for producing land cover maps. The published work so far shows no clear class in a classification map produced from the analysis of remote sensing data that can be associated directly with waste sites. There is always an overlap between waste sites and other, similar land cover features. However, classification can narrow down the search for probable illegal waste sites.

- A further tool for narrowing down the location of probable sites is the use of ancillary geographical information in a Geographic Information System (GIS). Where it is known that waste sites normally have particular geographical attributes (for example, distance from a road or distance from a legal landfill site) then this information can be built into a GIS along with the remote sensing data as an aid to reducing the number of sites that are to be visited for field inspection.

- Targeting specific types of illegal waste has been successful in the case of tyre dumps in the USA. The dark reflectance tones are on the one hand a distinguishing feature but on the other hand it is easy to confuse dark tyres with other dark features. However, there do seem to be tools to help distinguish various dark features and such an approach could be useful for targeting (say) dark plastic coverings of hay bales.

- Radar provides a reliable source of remote sensing data. The cloud penetration capability is particularly useful in Scotland. Direct detection of waste sites is possible with radar, although the use of supporting GIS data will enhance the information level. The use of InSAR to map height and height change seems attractive because landfill sites do change in height over time as more waste is added. However, the use of SAR still needs extensive experimentation and testing: SAR applications are not as mature as visible and near infrared remote sensing applications.

3.6 Costs

Since the 1970s the spatial resolution of remote sensing systems has improved dramatically. Now it is possible to acquire satellite remote sensing images with a spatial resolution of 0.3 m which make them directly comparable with aerial photographs. For radar the best spatial resolution is now of the order of 1 m. This means that it is now possible to examine the spatial details of waste sites. Data from the high spatial resolution systems have a much higher cost than the medium and low spatial resolution data.

Table 5 shows the cost of satellite remote sensing data sources for an example set of commonly used systems. The highest resolution systems have a cost associated with acquiring the data, while the medium resolution systems such as Landsat and Sentinel are free of charge.

Table 5. A summary data prices for a selection of commonly used remote sensing satellite data [Source: NPA/CGG, 2015].

Satellite system	Spatial resolution Panchromatic/Multispectral	Archive price per sq. km	Minimum order (sq. km)
DigitalGlobe WorldView-4	0.31 m / 1.24 m	US$ 17.50	25
GeoEye-1	0.41 m / 1.64 m	US$17.50	25
QuickBird	0.61 m / 2.44 m	US$17.50	25
SPOT-7	1.5 m / 6 m	€3.80	100
Sentinel-2 XS	10 m	Free of charge	
Landsat OLI	15 m / 30 m	Free of charge	
Sentinel-1 SAR	20 m	Free of charge	
Envisat ASAR	30 m	Free of charge	

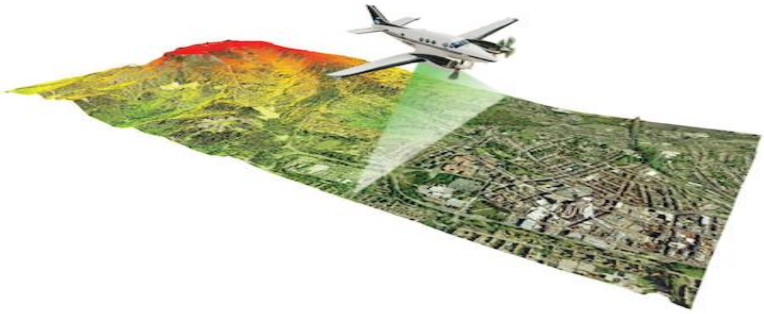
3.7 Remote sensing technology developments

This report has so far reviewed the main sources of satellite remote sensing data and the applications of these data to waste site monitoring. This section of the report examines two relatively new remote sensing technologies that show potential for waste site monitoring and waste crime detection but for which as yet there are few relevant applications, namely LIDAR and hyperspectral remote sensing.

3.7.1 LIDAR

LIDAR is an acronym for Light Detection and Ranging. It uses lasers to send a beam of light in the visible to near infrared wavelength range (typically 0.5 µm to 1.7 µm) to a target and then measures the response. Airborne LIDAR altimetry is the technique of obtaining surface elevation data from a LIDAR on an aircraft platform (Wallace et al 2003).

Figure 21. A schematic illustration of an airborne LIDAR in operation [Source: www.renewableenergyworld.com].



As illustrated schematically in figure 21, a laser pulse is transmitted to the ground target area in a scanning pattern and the pulse is reflected and returned to the receiver where it is measured. The receiver measures the travel time of the pulse and the distance travelled by the pulse is determined by solving the equation (Jaboyedoff et al 2012):

$$2 \times d = c \times \Delta t$$

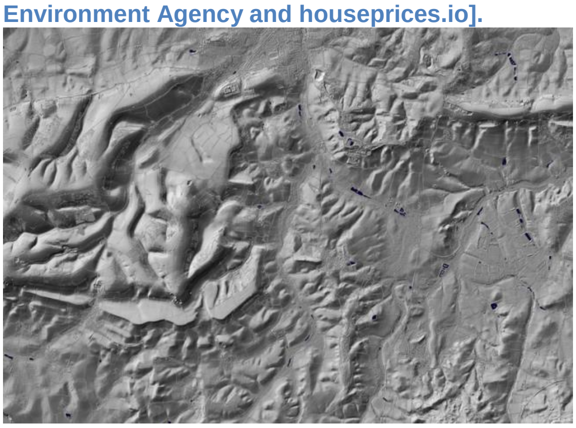
Where d is distance, c is the speed of light and t is time.

The position of the aircraft is determined using the Global Positioning System (GPS) and the Inertial Navigation System (INS) which allows the position and orientation of the laser pulse to be calculated. By combining the information on the geometry of the LIDAR with the GPS and INS data, the x, y and z locations of the ground points scanned can be calculated. This is normally referred to as a 3D point cloud because it is the laser point returns from the surface below the aircraft in three dimensional space, i.e. the x, y and z coordinates. From these laser point returns a digital elevation model of the surface can be produced. Data accuracy is typically 15 – 25 cm in the vertical and 50 – 75 cm in the horizontal. Digital elevation data created from LIDAR data can often be more accurate than ground surveying because (1) there are many more data points and (2) the inherent error is lower (Garcia-Quijano et al 2008).

The Environment Agency (EA) has created a data set of LIDAR data for England and Wales. The data were collected from LIDAR flight campaigns over a 17-year period and cover 72% of England and Wales with spatial resolutions between 0.25 m and 2m. The data are provided free of charge and available from the Environment Agency web site[6].

Figure 22 is an example Environment Agency LIDAR image of the central part of the Isle of Wight: the data are at 1 m spatial resolution and have been contour shaded to emphasise relief[7]. The data are often used for flood risk management in England and Wales, as is also the case with LIDAR data for Scotland used by the Scottish Environment Protection Agency[8].

Figure 22. A 1 m spatial resolution LIDAR data set of the central Isle of Wight, shaded for relief [Source: Environment Agency and houseprices.io].



The United States has taken a similar approach. The US Geological Survey (USGS) embarked in 2014 on an eight-year programme to collect LIDAR data for the conterminous United States, Hawaii and the US territories in order to create a national digital elevation model[9]. This 3D Elevation Programme (3DEP) primarily uses LIDAR data to create the elevation data plus also radar data for the state of Alaska where cloud cover is high. The elevation data have a 1 m spatial resolution and a vertical accuracy of approximately 18 cm (Witt 2016).

There are several commercial operators of airborne LIDARs. One such company is Firmatek which is based in Texas, USA and offers a LIDAR mapping capability for mine mapping, landfill mapping and stockpile inventory. Fugro in Europe has a similar capability.

There has been some published research on the use of LIDAR data for waste detection and analysis. De Wet (2016) examined three sites in Lancaster County, Pennsylvania to search for abandoned waste sites that had been active in the 1940s to the late 1960s. He used aerial photography for the period from 1940 onwards to provide baseline information and LIDAR data from flights in 2004 for height information. The LIDAR data had a 1 m spatial resolution and a vertical accuracy of 15 cm. De Wet inspected the aerial photographs and

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[6] See https://data.gov.uk/dataset/lidar-composite-dsm-1m1
[7] Source: houseprices.io
[8] https://www.sepa.org.uk/environment/water/flooding/developing-our-knowledge/
[9] See https://nationalmap.gov/3DEP/

the LIDAR images of potential landfill sites, characterised the appearances of former landfill sites on the two types of imagery and then used the two data sets to estimate landfill thickness.

In a similar way Witt (2016) used a comparison of LIDAR data and aerial photography to map the height change at probable former mine waste piles in Missouri. For probable waste sites, he used a base height polygon calculated from the US National Aerial Imagery Programme[10] and then overlaid on this base the digital elevation model data obtained using LIDAR data through the USGS 3DEP programme. This allowed the calculation of the volume of the waste pile and from this volume of waste he estimated the residual amount of lead and zinc using historical data on unrecoverable metal concentrations.

Stephenne et al (2014) used LIDAR data to estimate landslide risk on coal waste tips in the Walloon region of Belgium. They used 1 m spatial resolution LIDAR data to create a digital elevation model of a waste tip which was then assessed for slope stability from the slope angle and the internal friction angle of the waste material.

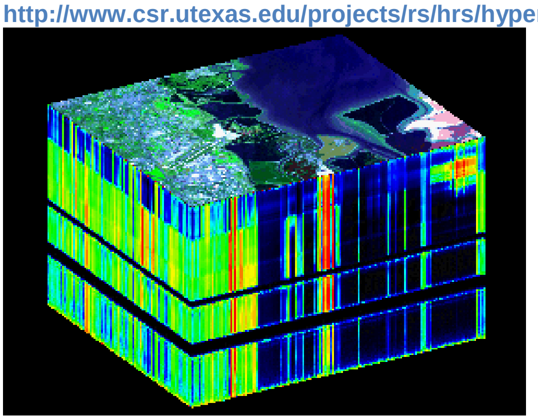
Torno et al (2010) used a digital elevation model created from LIDAR data for a landfill site in Cudillero, Asturias, Spain. Their purpose was to use the elevation model to then model airflow in and around the landfill site to identify areas that were either sources or sinks of particles and therefore of air pollution.

3.7.2 Hyperspectral

The first French SPOT Earth observation satellite had just three wavebands in the visible and near infrared. The first Landsat Earth observation satellite had four wavebands in the visible and near infrared. Therefore, much of the early work with satellite Earth observation was working with just three or four values of reflectance for each pixel. This was regarded by many as inadequate and consequently now Landsat 8 has eight wavebands in the visible and near infrared.

A recent development in remote sensing has been the use of sensors that have many more wavebands to measure the spectral characteristics of specific surface cover types. These sensors are termed *hyperspectral* sensors or imaging spectrometers because they sense in many wavebands, typically in tens or hundreds of wavebands (Eismann 2012). Because they have so many wavebands the width of each waveband can be narrow, typically measured in nanometres (nm)[11] rather than in µm. Because the use of nanometres is normal in hyperspectral remote sensing, this section of the report uses nm rather than µm.

Figure 23. A representation of the data produced by hyperspectral remote sensing. The same area is measured many times at slightly different wavelengths [Source: http://www.csr.utexas.edu/projects/rs/hrs/hyper.html].



[10] See https://www.fsa.usda.gov/programmes-and-services/aerial-photography/imagery-programmes/naip-imagery/index

[11] 1nm = 10^{-9} m, or 1000 µm. For example, 0.5 µm = 500 nm.

Figure 23 (above) shows a representation of the data created by hyperspectral remote sensing: it shows a data cube in which the target area (shown in the top layer) has measurements of this same area across many wavebands. It is the same principal as with multispectral remote sensing, but with many more wavebands. Often hyperspectral remote sensing data are used in combination with laboratory spectrometer data which produce spectra of "pure" samples of the surface collected in the field (Lothode et al 2014).

Hyperspectral data have been used in geology to detect specific surface minerals, in agriculture to detect specific crop types or crop diseases and in oil spill detection such as the Deepwater Horizon marine oil spill.

Hyperspectral remote sensing has been carried out mainly using airborne platforms, with some also on space borne sensors. The first significant airborne hyperspectral system was AVIRIS[12] which was developed and first flown in 1987 by the NASA Jet Propulsion Laboratory (Riaza and Muller 2010). The AVIRIS instrument has 224 wavebands each of 10 nm bandwidth operating in the range of 400 – 2500 nm. A widely used commercial system is HyMap[13] which has 128 wavebands in the wavelength range 450 – 2500 nm and bandwidths of 15 – 20 nm.

The use of hyperspectral sensors in space has not been as successful as planned. The first space borne hyperspectral sensors were HIS and LEISA which flew on the NASA Lewis spacecraft in 1997 but was lost shortly after launch (Wilkinson et al 2002). A similar event occurred for the hyperspectral instrument on the OrbView-4 satellite which was destroyed on launch in 2001. The Hyperion instrument on the EO-1 satellite mission has been successful. It has 220 wavebands in the range 400 – 2500 nm and was launched in 2000 as a one year technology demonstrator and it is still in operation. The CHRIS hyperspectral instrument[14] on the ESA Proba mission was launched in 2001 also as a technology demonstrator and is also still in operation. The CHRIS instrument has 15 wavebands in the range 450 – 1050 nm, bandwidths of 1 – 10 nm and a pixel size of 25 m. The most widely used satellite hyperspectral sensor is MODIS[15] which has 36 wavebands from visible through to thermal infrared wavebands, but the pixel size at 250 – 1000 m is too large for waste detection applications.

Much of the work that has been done on hyperspectral data relevant to the waste sector has been in identifying surface minerals (Wallace et al 2003). Carbone et al (2005) used a hyperspectral sensor operating with 52 bands in the wavelength range 500 – 1100 nm and with a bandwidth of 11.5 nm to examine possible contamination of mine waste and leachate seeps in southern Missouri. They were able to detect concentrations of hematite, residual lead and residual zinc in mine waste tailings as well as evidence of lead dust and leachate seeps from waste ponds. Their efforts at using hyperspectral data for identifying tyre dumps were not successful.

Riaza and Muller (2010) used airborne AVIRIS and HyMap hyperspectral data of a test site at Sotiel in south west Spain to identify sulphide deposits on mine waste which in turn allowed them to predict surface water quality, estimate acid drainage and detect metal contamination in soils. They compared the hyperspectral data with laboratory spectra of the sample target materials (Lothode et al 2014) and were able to identify areas of melanterite (the first sulphate to form) and hematite (formed when dehydration and oxidation are complete). They noted though that the presence of vegetation can interrupt accurate mineral mapping and that their results were not general but varied from image to image.

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[12] AVIRIS : Airborne Visible/Infrared Imaging Spectrometer, see http://aviris.jpl.nasa.gov/index.html
[13] HyVista Corporation operates a HyMap hyperspectral scanner manufactured by Integrated Spectronics Pty Ltd, Australia, see http://www.hyvista.com/technology/sensors/hymap/
[14] CHRIS : Compact High Resolution Imaging Spectrometer, see https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/proba
[15] MODIS : Moderate Resolution Imaging Spectroradiometer, see https://modis.gsfc.nasa.gov/about/

Belviso et al (2011) used airborne MIVIS[16] hyperspectral data to detect red muds and red dust in the soils surrounding the waste area of an aluminium plant in Montenegro. Red mud and red dust can be highly alkaline and can contaminate natural environments and be dangerous to humans. They were able to identify iron oxides and phyllosilicates and consequently were able to map soils containing a high concentration of red dust with an accuracy of 86%.

Peters et al (2001) used two hyperspectral sensors to identify minerals in the waste dumps around a smelter site in Utah. They used data from a CASI[17] instrument operating in the range 403 – 914 nm (the visible and near infrared) and from a SFSI[18] instrument operating in the range 1220 – 2320 nm (the short-wave infrared). Using these data together with in situ portable spectrometer measurements of the target minerals they were able to identify gypsum, calcite, copper sulphates and acid drainage and also the impact of the emissions from the smelter smokestack on reduced vegetation health.

In a doctoral thesis, Winkelman (2005) used airborne hyperspectral data to detect soils contaminated with hydrocarbons. He used HyMap hyperspectral data with 126 bands in the wavelength range 457 – 2480 nm, a bandwidth of 10 – 20 nm and a pixel size of 5 m. One tool that was used was a hydrocarbon index (Kuhn et al 2004) that exploits certain spectral features where reflectance by hydrocarbon materials is low (e.g. plastics, roofing materials). The hydrocarbon index (HI) is:

$$HI = {}^{2}/_{3}\,(R_c - R_a) + R_a - R_b$$

Where R = radiance at wavelengths a, b and c.

For their experiments with HyMap hyperspectral data for the detection of surface hydrocarbons, Kuhn et al (2004) used the following wavelengths for
a, b and c: a = 1705 nm, b = 1729 nm and c = 1741 nm.

While much of the work on hyperspectral remote sensing related to waste has been concerned with identifying indicator surface minerals, there has been some work on identifying vegetation stress as an indicator of waste below the surface. Slonecker and Fisher (2014) used hyperspectral airborne data from the ARCHER[19] system with 52 wavebands in the range 500 – 1100 nm and 1 m pixels to examine 16 hazardous waste sites in Pennsylvania. Their focus was on vegetation stress as an indicator of soil contaminants, especially lead and zinc and they were able to detect some areas of dead vegetation that were not visible from ground observations. They proposed a Photochemical Reflectance Index (PRI) as a technique of measuring stress in vegetation. The PRI equation is similar to both the NDVI and the hydrocarbon index:

$$PRI = \frac{R_a - R_b}{R_b + R_b}$$

Where R is radiance at wavelengths a and b. In the Slonecker and Fisher (2014) study a = 531 nm and b = 570 nm, both in the green part of the spectrum.

Im et al (2011) also examined vegetation stress as an indicator of hazardous waste. Their two test sites were uranium mill tailing sites in Utah and Arizona and they used HyMap hyperspectral data together with in situ measurements of Leaf Area Index (LAI). They analysed the hyperspectral data by vegetation indices, the red edge position (see figure 4

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[16] MIVIS : Multispectral Infrared Visible Imaging Spectrometer; 102 wavebands in the range 430 – 12700 nm
[17] CASI : Compact Airborne Spectrographic Imager
[18] SFSI : Short-Wave Infrared Full Spectrum Imager
[19] ARCHER : Airborne Real-Time Cueing Hyperspectral Enhanced Reconnaissance

above), machine learning, decision tree modelling and matched filtering, but concluded that there are few techniques that provided unequivocal information about vegetation stress created by hazardous waste in hyperspectral data. Their most successful technique was decision tree modelling which had an accuracy of 85%.

3.7.3 Summary of LIDAR and Hyperspectral Applications

There has been little literature on LIDAR and hyperspectral applications in the waste sector. Both technologies are applied mainly from airborne platforms which means that they are useful for targeting specific sites. By contrast, data from satellite remote sensing platforms provide a general overview.

1. LIDAR is mainly used for measuring surface height and the derivatives of surface height such as height change over time, the volume or thickness of a deposit and the slope characteristics of a site.
2. Hyperspectral remote sensing has been mainly used for identifying the detailed spectral characteristics of surface minerals, which can themselves be indicators of waste at or below the surface.
3. The work so far on the use of hyperspectral data for vegetation stress analysis has not been particularly successful for waste sites. The very large number of wavebands may cause a problem of selecting which waveband combinations are generally useful. Two possible ways forward are: (1) the uses of standardised indices such as a version of the Hydrocarbon Index; and (2) the exploration of Principal Components Analysis to reduce the number of wavebands and pick out the main features of data sets.

4.0 Opportunities for innovation

4.1 Regulatory problems to which remote sensing could contribute

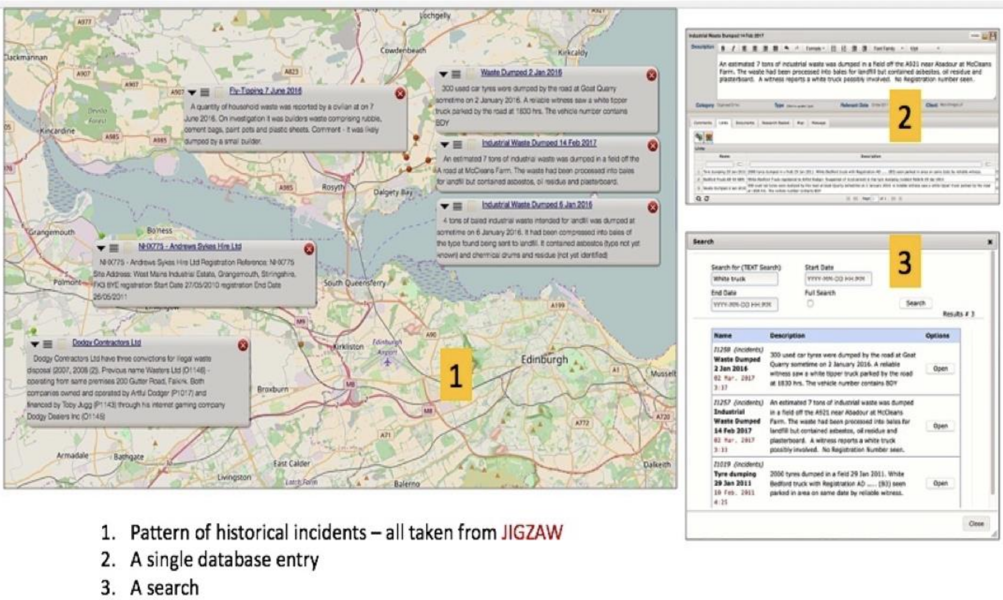
4.1.1 Introduction

A regulatory body will need the best practicable picture of the environment it is responsible for protecting. A common integrated GIS/ Intelligence database is thus a prerequisite. Adding/building in a capability of including RS allows incorporating/combining this with the kind of wide area / real time ground truth which must be able to add significant capability for the regulator to monitor (and be seen to monitor) and intervene if necessary, across a whole range of responsibilities for land use, habitat protection, water resource management, developing incidents, man-made spillages, or flood defence response strategies.

But it is in the key and increasingly sensitive area of illegal waste dumping that RS can, perhaps make the most immediate and effective contribution. Examining opportunities for innovation requires: firstly, getting a better understanding of the problems and intelligence needs; and secondly, allowing for the collection and consideration of information about the characteristics of waste crime in a structured way, using a systematic process (e.g. data on timings, size, waste deposited, and locations of known sites, illegal operators and past history). The greater quantity of information we have on characteristics and prior examples of illegal waste cases, the more focused and useful this scoping exercise and our analysis will be.

For unlawful sites, which have already been historically identified by the regulator, the challenge is exploring what evidence these technologies can provide to regulators that is beyond what they already know. This can encompass the true extent of site, operational timing (e.g. to provide data to see if a crime had been going on longer than was previously thought when considering a Proceeds of Crime application).

Figure 24. What, Where, When information on a common GIS format [Source: Jigsaw].



So, there are real opportunities for innovation in the field of RS and EO in providing intelligence on waste crime at regional, national and international levels. It can contribute the basis of a system that can link events, locations, companies and people together, display results and permit complex search and display. This is fundamental to supporting analysis and the context of real-time data from remote sensing. Live data without context can result in poor decisions. RS data presented as a comprehensive package can, therefore, be useful in different circumstances and offers much more than just monitoring.

A clear value of EO data is providing evidence where the temporal dimension of what happened is important. Systematic archiving of imagery is a fundamental approach in the intelligence process to enabling interpretation of changes over time. Data streams provide historical evidence that would often be otherwise unavailable. This can enable a regulator (and ultimately a court) to have a better (and more accurate) understanding of what took place, where, and at what time and in particular, what information informed operational decisions at the time.

We should also have a pro-active detection element, identifying opportunities for tasked regular monitoring programmes to catch operational unlawful sites.

4.1.2 Why waste?

The conventional approach to environmental regulation is to set conditions and issue licences to operate, inspect against these conditions, and if necessary take measures to ensure compliance and prosecute if not implemented. The Stirling Report on the economics of waste crime assumes this model and costs the resources needed to service this routine, with no comment on its effectiveness (Simpson and de Vries, 2014).

This works only if the businesses involved are focused on producing outputs and the costs in any fines, legal fees, compensation, image, etc. are considered to be too much to contemplate. Such operations can then be inspected regularly to assure the regulator that all is well. Indeed, the first environmental Inspector, Angus Smith, made it a point of encouraging / showing the industry how to be both more efficient in operation and in obeying the law by guidance notes on best practice, etc.

The problem is that regulating the waste industry is very different from this idealised model. While there is inevitably a wide range of observed behaviours by the different companies, from exemplary to subversive, the distribution is very definitely skewed towards the lower part of the curve. Many factors contribute to this from historical “rag and bone man” origins to the low legal profit margins obtainable and generally undemanding skill sets needed to operate, in this sector. This together with the exponential rise in the awareness of health effects and the greatly increased sophistication of control of toxic chemicals (e.g. REACH), has meant that the growth of activity by organised crime to cash in on the quick profits to be realised from circumventing these expensive and extensive controls has been second only to their exploitation of the drug trade in recent years.

All this renders the classic inspection regime practically useless for this sector. Just to highlight one anomaly – which site do you inspect? This is a classic intelligence requirement; the purpose being to refine the search using intelligence-led processes to identify inspection locations and specified inquiries in a proactive manner. A basic intelligence database, supported by a simple system that supports logical analysis is thus essential to getting value from the inspection process. This, like the drug trade, is an international organised crime activity. The poisonous dioxin from the Seveso incident near Milan, Italy was tracked through Rotterdam, to Houston and trans-continentally shipped over to southern California before being dumped in Mexico. Imagine what profit margin is needed to fund such an illegal operation.

The approach needed is the same as the response to drugs; intelligent, cooperative policing. But the key to success is effective intelligence led enforcement. So specifically, and particularly in this waste crime area, RS can play a decisive part in completing/ complementing this intelligence picture. As with most criminal enterprises, the judgements made tend to be risk/reward. So, the higher we can raise the risk of being caught, and the proportional scale of sanctions ensuing, the better; as the rewards, as pointed out in the Stirling Report, are significant (Simpson and de Vries, 2014).

4.1.3 Characteristics of waste crime

A vital part of this intelligence picture must be an understanding of the nature of waste crime. Disposal of wastes has become a much bigger problem as the cost and expectation of disposal options has changed. "Everything to landfill" is now expensive and limited; while the cheapest forms of recycling tend to consist of clandestine dumping in quiet, remote, rural sites. This is not the ever-present "normal" opportunistic or antisocial fly tipping behaviour we have come to expect around our large conurbations, but the deliberate and organised large scale operations with carefully planned target sites for big money clients (aware or not). The sophistication of end product has also now moved on to pseudo black plastic haylage bales and as groundwork construction materials for golf courses etc. So, while the wide area surveillance of areas of Scotland can discover previously unknown incidents, there needs to be a much more intelligent focusing on key areas around known activities, and coordination with activity reports to be effective. So, we need to build up a database of the characteristics of these sites, the type of wastes, modes of disposals and the human 'players' involved.

4.1.4 Examples of waste crime

Annex 2 gives some 80 examples of waste crime drawn from the public record. An extensive analysis of the issues they raise has been summarised later in this section. This introductory section, concentrates on the bigger picture, or context, in which innovation is needed. But a few examples are outlined below for illustrative purposes.

From: Environment, 9 September 2016 - "Waste being illegally dumped on land in rural North East locations.

- Last week at Bishop Auckland in County Durham, approximately 40 tonnes of general mixed waste were illegally tipped out the back of a waggon and into a field.
- A second lorry was prevented by Durham Police from tipping its waste and has been seized by Durham County Council pending further investigation.
- A second case near Sadberge, near Darlington, saw old processed waste that had been wrapped in 80 black plastic bales dumped on land without the landowner's permission. Figure 25 illustrates what this looks like.
- And on Wednesday, 7 September, 20 bales of old processed waste wrapped in plastic were found to be dumped at a farm near Northallerton."

Figure 25: Waste disguised as fodder [Source, Environment].

From these few examples, we can see that identifying opportunities for innovation requires close collaboration between the project team and SEPA: firstly, to get a better understanding of the problems and intelligence needs; and secondly, to allow for the collection and consideration of information about the characteristics of waste crime (e.g. data on timings, size, waste deposited, and locations of known sites). The greater quantity of information we can access on the key characteristics and prior examples of illegal waste cases in Scotland, the more focused and useful this scoping exercise and the analysis will be.

One way of utilising the RS dimension would be to look at an automated detection model to detect illegal landfill sites, using signature systems. This will require analysis of issues such as common chemical signatures in waste sites (and their concentrations, which will be critical) such as gaseous methane and ammonia to heavy metal and ammonium salts. But a key consideration is to look at actual cases to assess whether such an approach could have been successful.

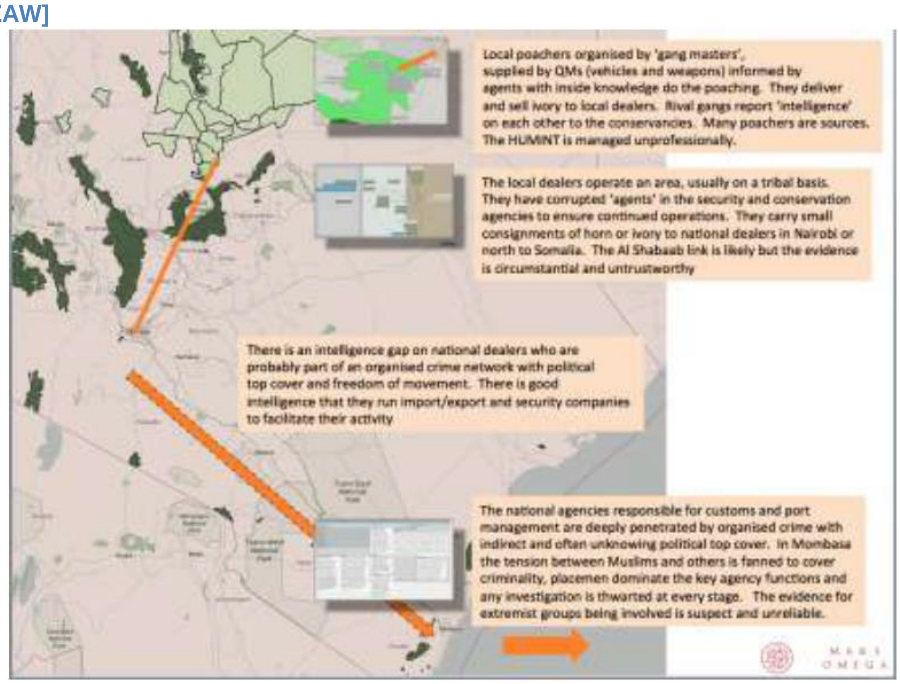
4.1.5 Intelligence needs

If we are adopting an intelligence-led approach, then we need to look at the different uses of this intelligence, particularly as these illegal [waste] practices are ever-changing and are not easily visible. There will thus be a need to categorise and prioritise areas of interest. It will be critical to be able to utilise RS both proactively and retrospectively in organising evidence for potential enforcement and prosecution needs.

There will clearly be an historic legacy, where known sites have been operating. RS could contribute to continued surveillance on current behaviour, offering a capability to maintain a historical database to provide evidence for how these sites have evolved and over what period.

But the crucial needs of intelligence are in the proactive mode. As we have seen in other work packages, the earlier we can make interventions, the more cost effective the regulation. Here we are not looking at known sites necessarily and the combination/coordination that can arise from a common GIS database which can link/display/prompt on-the-ground intelligence with observational data on events, changes, with focused areas of interest with tasked observations, etc. An example of this combination has been successfully deployed in anti-poaching operations in Africa.

Figure 26. An example of a combined GIS/Intelligence database used for anti-poaching activities [Source:JIGZAW]



So, we would also need to examine the potential to combine RS imagery with GIS technologies and other geospatial data and techniques. Comparison of existing data on volumes of waste processed at individual sites, with the estimated waste generated within the catchment, may identify anomalous volumes of waste or processing. We should be able to provide land use change maps and height change maps identifying suspect locations, local difference in waste volumes along with critical infrastructure and mapping to determine the degree of the potential health and environmental threat.

4.2 Nature of remote sensing data as evidence

Whilst remote sensing seems to have great promise in the waste crime field, technological solutions to waste crime, using remote sensing techniques, have not been successfully demonstrated to the required degree (for regulators to adopt them) as yet (or at least have not resulted in significant regulatory waste monitoring programmes). The literature review in part one of this study revealed that whilst there had been a lot of analysis, much of this was theoretical, or focused on specific elements of a monitoring system rather than an all-encompassing review of monitoring possibilities. There is a notable lack of awareness, knowledge and understanding in the environmental regulation sector as to what opportunities for innovation in waste crime monitoring the technology can precisely offer.

In determining opportunities for innovation in remote sensing, having a good understanding of the problems and intelligence needs is key. The literature review revealed that whilst there had been a lot of analysis on potential technical solutions, this wasn't always tied up with what the actual problems were, other than an examination by remote sensing of buried waste or illegal waste dumps on the land surface. There is an obvious lack of literature on specific waste crime problems in European Union (EU) countries, and the extent of these problems. We consider that to solve the problem, you need to scope the problem, which we believe no one has properly done (in terms of the application of remote sensing to waste crime).

One of the key elements of this project research phase is to dig much deeper as to the actual characteristics of the waste crime problems being experienced, and to combine the analysis of that with an assessment of where remote sensing data can contribute to detecting certain waste crimes (and at what types of sites). A lot of attention has been given by us to information on characteristics and prior examples of illegal waste cases, to make our analysis more focused and relevant to the work of environmental regulators. It is therefore expected that this research exercise on innovative methods will correspond to reality (and regulatory problems) rather than loose assumptions. However, this analysis comes with a caveat that different countries (or even regions) might experience different forms of waste crime with different characteristics.

Generally, there is a broad range of opportunities that remote sensing technologies can offer and three specific uses in particular can be highlighted:

(i) historical evidence;
(ii) targeted enforcement;
(iii) untargeted monitoring.

4.2.1 Historical evidence

Remote sensing data can be useful in different circumstances than just monitoring. Archiving of satellite images could in theory provide environmental regulators, or a court, with a relatively impartial snapshot of any location at a time in the past, providing accurate evidence that would often be otherwise unavailable.

Figure 27. High resolution imagery demonstrating historical evidence of waste burning [Source: Copyright: DigitalGlobe].

Figure 27, above, contains imagery illustrating how historical evidence from satellites might work in a waste crime context. In 2006, there was a prosecution in the UK for an offence relating to an illegal waste landfill site. This was a major criminal operation and the rubbish that was burnt caused a mound of ash that was 3 metres thick and measured 260 metres in circumference. It was calculated that by burning wastes and hazardous wastes to this extent, the offender would have received an annual turnover of approximately £40,000. At trial, the Environment Agency stated that this offence took place between May 2005 and January 2006. The two images at the top of Figure 27, dated October 2005, appear to show, in the circled area, the burning of waste on this land during the already known time of the offence.

The two images at the bottom of Figure 27, dated June 2004, were taken nearly a year before the Environment Agency believed the offence was committed. These appear to show a large burned area on the land at this time and might be evidence that the illegal activity had been ongoing for a longer period of time than the investigators previously thought.

PRO'S	• Historical imagery can be used to show the length of time an illegal activity was taking place. This can be particularly useful in the case of sites where burning has taken place, and the length of the activity (or proceeds of crime payment) cannot be easily calculated. • Historical imagery can be used to detect illegality in other places on the land (or other properties connected to the offender), that are not known about. • Relatively inexpensive to purchase historical archived imagery for major cases.

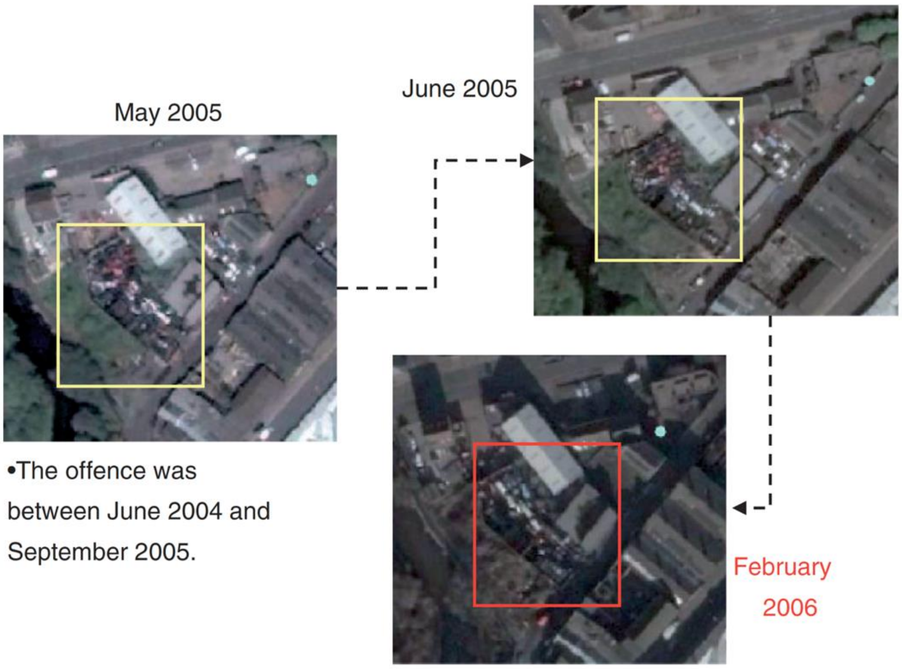
CON'S	• Archives can be hit and miss. There can be no guarantees that there will be data matching the date requirements of a case. • Optical imagery might be purchased and then found to have cloud cover over the area in question (rendering it useless). • The imagery might be purchased and show that the illegal operation had not been operating for a much longer time than thought (rendering it redundant in an evidential context). • Archived imagery has limited evidential value if the offender cannot be identified. i.e. it will just show there was a problem on the site that was longer that initially though, not who was actually committing the offence. • This form of monitoring might be seen as being reactive not pro-active.

4.2.2 Targeted Enforcement

Satellite imagery can also be used as part of a targeted enforcement strategy to monitor specific companies or places. A key example where they might have a strong compliance value is monitoring individual sites or areas where environmental offences have been known to occur historically.

In another case in the UK, in 2005, a defendant was found guilty of keeping approximately 50 scrap vehicles in an illegal scrap-yard without a waste management licence. The offence was originally discovered by the Environment Agency following a ground inspection. The offence above occurred between June 2004 and September 2005 and the offender was given a set-period of time in which to comply with a court order to remove the illegal vehicles from the scrap-yard.

Figure 28. High resolution imagery showing an illegal waste site [Source: Copyright – DigitalGlobe].



The satellite images in Figure 28 (above), dated May and June 2005, show that there were scrap cars stored on the site during the time of the offence. If this method of monitoring had been used in the first place, then cross-referencing with records on waste management licensing might have alerted the Agency as to whether an offence was taking place.

Of greater interest in the compliance context is the satellite image taken of the site on February 2006, after the date for compliance with the court order. This image, on the bottom right of Figure 28, shows that the vehicles appear not to have been removed from the site and that the court order might not have been complied with. A closer examination of the image also reveals that the illegal activity might have actually intensified, as it appears there are more cars on the site.

Remote sensing might, therefore, under certain conditions, be used by regulators to check legal compliance as part of a risk-based enforcement strategy. Sometimes, those committing environmental offences will not change their behaviour even if caught and fined. This targeting checking could include monitoring sites with a high-risk of offending or a defendant's performance after a successful prosecution; for example, checking on any subsequent clean-up operation. Or if there are resources everyone could be checked.

Possible groups that could be monitored this way, include:

i. **Focused targeting**

- Licensed waste facilities where there have been historical breaches, or owners with any previous waste, or other,) criminal convictions.
- Unlicensed sites where there have been historical breaches.

It might be possible to have a licensing regime, whereby if certain licence breaches have taken place (i.e. major ones or an accumulation of many small breaches), then more money is collected off the licence holder to pay for future satellite monitoring of the site over a certain time period.

ii. **More general targeting**

- Certain high-risk companies (e.g. skip hire companies).
- Licenced waste facilities (all).
- Sites with waste exemptions.

PRO'S	• Targeted monitoring means that illegal activity could be picked up quicker. Greater likelihood of catching people in the act before situation gets too bad. • Could be cheaper than sending boots on the ground (if one satellite image can be used to analyse multiple sites). • Can base monitoring programme to a certain degree on risk-based regulation. • Could have deterrent impact.

CON'S	• Satellite imagery will not be able to detect all forms of waste crime. • Could be costly (depending on how much imagery is needed frequency of monitoring required, and extent - over what geographical area). • Criminal behaviour might be modified to hide the activities from satellites. • There would have to be strong linkages between what site permits or exemptions allow, and the analysis of the imagery – to get a better understand whether there is a compliance problem. This is particularly relevant in terms of whether monitoring is done in-house, or by an external contractor.

4.2.3 Untargeted Monitoring

Remote sensing technologies have already been used systematically to monitor compliance (that is not yet known about) as part of a targeted enforcement strategy. Examples of this were given in section 2 above.

Untargeted monitoring would work by enabling enforcement bodies to rely on satellite checks to alert them to any suspicious behaviour that is taking place, before conducting ground inspections. This would be mainly focused on illegality at unlawful sites, which the regulator does not yet know about (e.g. unlicensed sites).

The key issue with the above is that in trying to find an illegal landfill in a large area of a country, the satellite analyst is looking for a needle in a haystack. They have two options to make this work:

- Look for the needle.
- Remove as much as the haystack as possible to make the detection easier.

To do the above, algorithms might be developed to detect illegality. The analysts and the regulators will also have to work closely together to consider the locations of site with permits and exemptions (removing the haystack).

PRO'S	• Give the regulator a better indication of the true extent of illegality (as this is currently unclear). • Targeted monitoring means that illegal activity could be picked up quicker. Greater likelihood of catching people in the act before situation gets too bad. • Specific areas where illegality is suspected to occur can be targeted periodically – adjusted to suit the resources of the regulator.

CON'S	• Requires a lot of cooperation between analysts and regulators in terms of information exchange (i.e. the more information available the greater the chance of finding the 'needle'). • The number of false positives generated by the algorithms from the satellite checks are unknown, and might need to be subject to technical adjustments over time. • Potentially very expensive (depends whether open data or commercial data is used, and how many analysts will be required).

4.3 Characteristics of the problem

Environmental regulators cannot expect to just ask remote sensing specialists to monitor waste crime, without providing them with a thorough assessment of the problem. There will be a lack of awareness, knowledge and understanding in the remote sensing sector as to what the actual waste crime problems are that environmental regulators are experiencing.

More generally, there is a notable lack of literature on the specifics of waste crime problems in European countries. Our assessment is that at first sight it is not precisely clear:

- The form of waste crime that are the problems (and which are the most serious).
- The key characteristics of the waste crime problems.
- Who is it that is breaking the law, requiring monitoring?

To solve the problem (with the use of remote sensing), there has to be serious attention paid to scoping the problem in Europe, which it seems like that no one has properly done to date. Obviously, different countries might also be experiencing different waste crime problems.

Generally, though, the more information that can be given to the satellite experts, the more focused the analysis and better resulting answers. In seeking to get a more accurate understanding of the key issues connected with waste crime, and attempting to place these findings in the context of monitoring possibilities via satellite technologies we looked at all of waste crime stories in the ENDS reports (a UK environmental magazine) between March 2014 and March 2017 (3 years). We found detailed reports of approximately 80 stories of cases involving serious waste crime. From these 80 cases, we sought to consider details about what types of waste crime were committed, so we knew more about the problem we were trying to solve.

Using the information, we had picked up in the ENDS reports we also searched the British press for each of these 80 cases, in search of photographs of the sites, where offences had occurred. Photographs enable visual assessments of the problem (i.e. it is quite hard to picture what 400 waste tyres might look like in an illegal site, but a photograph will enable to much more accurate assessment of what can be seen from a satellite).

We realise this approach is not wholly scientific, but in the absence of any other data on specific waste crime cases provided, this will enable us to base our analysis on evidence. Most of the assessment is UK derived, but many of the problems might be common. Annex 2 contains the case studies (with photographs) that we complied.

4.4 Types of waste crime and their ability to be monitored by satellite

4.4.1 Illegality at legal sites

There are a number of different ways that landfill operators can operate illegally at lawful sites, and these are considered in table 6 below.

Table 6. Illegality at legal sites

ILLEGALITY AT LEGAL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
1.	Misclassification or blending of waste types at legal landfill sites.	This is tax fraud. Waste is either misdescribed, or mixed to disguise parts of the load which would attract higher landfill taxes, when entering legal landfill sites. This will often be perpetrated with the aid of rogue employees working at the landfill site (although sometimes depending on the extent of the blending it might be done with the landfill sites knowledge).	N/A	Misclassification/blending is very hard to differentiate visually on the ground. It appears that this would be even more difficult to identify from a satellite image. We can only think of two ways this would work: (a) If there are obvious materials that should not be in the site that can be detected e.g. metals. However, this would still depend on the type of metal. Metals can also be tricky optically and spectrally because they can give so much reflection that it saturates the sensor. (b) If the misclassification of higher rated material results in a very obvious change in ambient temperature at a landfill. Generally, on-the-ground checks should result in the most reliable checks of misclassification. This would be by drilling holes in landfill sites and taking samples on the types of waste in there. This would enable regulators to work out which landfill sites are acting illegally if they find any higher rated material. However, it is possible that sites which breach other permit conditions might be more likely to misclassify waste, meaning that a remote sensing analyst could look for the former, and leave the rest for a site visit.

ILLEGALITY AT LEGAL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
2.	Operating outside of permit at legal landfill sites. Excess waste.	Exceeding the amount of waste allowed to be stored at the site.	Case 8, 9, 10, 16, 19, 38, 65, 78	Detection by satellite depends on how much waste was permitted and how much excess waste there was. For example, in case 65 the company had 37 times more waste than permitted, which would be more easily detectable than those only slightly going over there permit allocations. The analyst would need to have background information as to what the permit allowed An analyst could also make estimates of volume changes if they compared DEMS from two different dates. Reliability would be dependent on the availability of elevation data.
3.	Operating outside of permit at legal landfill sites. Waste not permitted.	Storing waste that was not covered by the permit (e.g. hazardous waste). Or storing it for longer than was allowed.	Case 34, 36, 45	Misclassification/blending is very hard to differentiate visually on the ground. It appears that this would be even more difficult to identify from a satellite image. We can only think of two ways this would work: (a) If there are obvious materials that should not be in the site that can be detected e.g. metals. (b) If the misclassification of higher rated material results in a very obvious change in ambient temperature at a landfill. The analyst would need to have background information as to what the permit allowed.
4.	Operating outside of permit at legal landfill sites. Operating in an unpermitted area.	Operating on another part of the site that is not covered in the permit. There have been numerous cases where operators at lawful landfill sites have been	Case 9, 20, 25, 34, 45, 57, 67, 78	This would be a really good area for analysts to offer insights. Obviously, the results of the analysis depend on the size of the illegal operation, and where the permitted area was, but in most cases, this could be detected by a satellite.

ILLEGALITY AT LEGAL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
		found to have been operating some other illegal activity on the site – in some instances the legal site has been a cover for an illegal operation.		For example, some companies were not permitted to store waste outside. The analyst would need to have background information as to what the permit allowed.
5.	Operating outside of permit at legal landfill sites. Keeping waste in a way that could cause pollution, damage to human health.	Keeping waste in a way that could cause pollution. E.g. failure to control leachate (into accidental or pumped into neighbouring fields).	Case 1, 12, 31, 34, 39, 45, 58	Major leaks, as can be seen in case study 1 might be detectable, but otherwise it will be hard to detect pollution. There are lots of variables to this, and it is difficult to identify a hard and fast solution to a changing problem.
6.	Operating outside of permit at legal landfill sites. Manner waste is stored.	E.g. stacked too high. Or stacked in a dangerous place. Keeping waste on a site in a way that risked fire.	Case 8, 10, 16, 27, 36, 71, 78	Height analysis might be possible by satellite, via DEM generation. Analysis can also be done in some cases by simply measuring a shadow. Several of the case studies concerned the storage of waste dangerously next to transport infrastructure e.g. railway lines, which might be possible. The analyst would need to have background information as to what the permit allowed.

ILLEGALITY AT LEGAL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
7.	Registering a lower amount of waste for landfill than had been taken in.	Landfill tax fraud by taking in greater quantities of waste than legally registering.	N/A	Our assessment is that it would probably not work using satellites. However, this could work through a drone monitoring programme. Volumetric analysis is perfectly possible, although it is unclear whether this problem is a volumetric analysis issue or a weight issue (as whether there has been fraud at the weighbridge at the landfill site). Presumably, the volumetric analysis comparisons might indicate fraud, although this would have to be examined in a much more scientific manner in terms of how waste behaves when stored in a landfill site.

4.4.2 Illegality at exempted sites

If a waste activity is considered to be small scale and/or low risk, then a person storing waste can sometimes register with the environmental regulator for an exemption. There is often very little oversight from the environmental regulator that the exemption holder is sticking to the conditions attached to the exemptions. There is a suspicion that people sometimes do exceed storage limits, or undertake activities which are not within the conditions of the exemption. This was notably widely seen in many of our case studies in Annex 2.

There can often be tens of millions of tonnes which are exempted (people often apply to the end of the upper limit), and no one has an accurate handle on how much of the exemptions are actually used. Because there is an extremely low level of monitoring, crime activity goes undetected and unreported and remote sensing technologies could in theory play a key role here. Table 7, below, gives more information on illegality at exempted sites.

Table 7: Illegality at exempted sites

ILLEGALITY AT EXEMPTED SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
1.	Exceeded their exemptions	The types of problems with exemptions mirror in many ways the problems at legal sites. The main issue seems to be though a massive intensification of their activities and the amount of waste stored at the sites.	Case 5, 17, 38, 40, 41, 53, 63, 70	Satellite monitoring could be used to detect illegal behaviour amongst exemption holders. It would be more likely that larger breaches are more obvious, than only very minor cases of non-compliance.

4.4.3 Illegality at unlawful sites

Illegal sites are problematic to environmental regulators, mainly because they fall outside of regulatory inspections. If the regulator does not know that an unpermitted activity is happening it might take place over a long time before detection, or might never be detected. Similarly, if a site does not have specific permits, the activity in questioned might not be taking place in a safe or controlled manner. Illegality in unlawful sites is covered in Table 8 below.

Table 8: Illegality at unlawful sites

ILLEGALITY AT UNLAWFUL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
1.	Illegally stored waste on ground or in skips	High numbers of cases involved waste simply dumped in large piles on ground, or stored in vast numbers of skips.	Case 3, 4, 6 7, 11, 13, 19, 21, 22, 23, 25, 28, 29, 30, 35, 40, 41, 46, 47, 48, 49, 51, 56, 60, 62, 64, 68, 69, 72, 73, 74, 79	Large piles of mixed waste are evident from high resolution optical imagery. SAR based change detection would identify the arrival of large amounts of mixed waste, and particularly angular metal containers like skips. However, confirmation of the assessment would be required from optical imagery. The SAR based assessment would only allow the identification of a large amount of material arriving.
2.	Buried waste	We only came across three sites where waste was buried (although one of them – the one in Northern Ireland was the largest illegal site in the UK, with over one million tonnes of waste).	Case 26, 44, 75	Multiple techniques may identify activity at the location including SAR based change detection, analysis of vegetation and comparative elevation model analysis. High resolution optical would also be necessary for confirmation.

ILLEGALITY AT UNLAWFUL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
3.	Burning of waste	There seemed to be a significant number of cases where waste was burnt on site – meaning there is no record of it being there – except via ash and burnt areas.	Case 8, 13, 15, 18, 21, 28, 29, 31	Satellites can potentially identify sites where waste is illegally burnt outside (e.g. major bonfires). We know that they can validate sites where burning has historically been known to have occurred. It is more difficult to identify what are large bonfires on farms, and what are waste burning sites. If the same vegetation stress is present on a site over long periods, this might indicate a criminal operation. Satellites cannot identify sites where incinerators are illegally burning waste (often inside a building).
4.	Mixing waste with soil and depositing it on land	There were a number of types of illegality here. Some cases involved plastic elements or household waste being mixed together with soil to be distributed on a topsoil. This was often for land raising or developments (such as golf courses). There were also cases where waste was mixed with fertiliser. This is sometimes legally allowed, but the types of waste used were not always allowed.	Case 50, 52, 54, 59, 70	Soil indexes derived from multispectral sensors are a potential method to identify bare or disturbed earth. Spectral analysis in the SWIR part of the spectrum might identify plastic components. This would be complicated by the chemical composition of the waste and the substrate. It would also depend on the mixing ratio and the spatial and spectral resolution of the sensor SAR based change detection should identify a change in the surface conditions. Changes in elevation may be possible to identify from comparative analysis from high resolution DEM, such as airborne LIDAR.

ILLEGALITY AT UNLAWFUL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
5.	Storage inside building.	There were two types of issue. One was criminals filling up warehouses with waste and then abandoning it. These might have been short-term leased or broken into. This also encompassed waste which was stored in the criminals own buildings.	Case 8, 20, 30, 33	The options for purely internal storage are limited for EO techniques.
6.	Silage bags / bales of waste	We came across a small number of cases where waste was stored in bales, presumably to disguise it (particularly on farm-land).	Case 35, 61, 80	Bulk storage of large amounts of plastic covered bulk waste storage would be an easier target for multispectral and hyperspectral identification. World View 3 has a SWIR mode which may have a utility to identify bulk plastic storage. The optical mode could then be used to look for signs of waste related activity. Monitoring the growth of the bulk storage with reference to the agricultural cycle could indicate a typical use.
7.	Back handers at sites being cleaned up (to allow more waste to be illegally added to the pile).	This type of illegality was not found in the case studies, but was considered to be widespread by members of the waste industry that we consulted.	N/A	Routine monitoring using high resolution optical imagery to ensure compliance.

ILLEGALITY AT UNLAWFUL SITES				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
8.	Non-compliance with clean-up orders or enforcement notices.	Sometimes the regulatory bodies would give sites acting in breach of their permit, or even illegally, time to rectify their problem (e.g. clearing up the land, complying with the permit). We came across numerous examples of where enforcement notices, or clean-up notices, were not complied with – sometimes over very significant time periods.	Case 22, 36, 37, 58, 78	Routine monitoring using high resolution optical imagery to ensure compliance.

4.4.4 Illegal export of waste

There is a growing black market of illegally exporting waste each year, from the UK to third world countries (ENDS, 2017). Sometimes the exports are not disguised, but are misdescribed in the shipping notes. Other times they are hidden amongst types of waste that are permitted to be exported. The illegal export of waste is covered in Table 9 below.

Table 9: Illegal export of waste

ILLEGAL EXPORT OF WASTE				
No.	**Type**	**Information**	**Case Studies**	**Assessment**
1.	Shipping containers containing WEEE (going to other countries)		Case 2, 24, 53, 55, 76	In one UK case eleven shipping containers were used to illegally export WEEE. If these containers were stored on land connected with the waste industry, then they might have been identified. They would not be able to be identified by satellite if (1) they were stored inside a building at the site before leaving the site or (2) once leaving a waste site. 15 million tonnes of waste are exported each year from the UK (ENDS, 2017). So, satellite technology cannot distinguish between legal and illegal exports, only that there is potentially a shipping container on the site.

4.4.5 General Conclusions

Analysis of known sites is preferable for analysis of remote sensing data. It allows the analyst to focus on a specific known area and its surrounds using higher resolution data sets. Searching for unknowns is more problematic due to the volume of data to be analysed and the cost of the data. These factors make it more likely that lower resolution sensors would be used, decreasing the likelihood of conclusive analysis.

One point to note about the above analysis (and the results of our case studies) is that many of the problems encountered were multiple – particularly at legal sites. Therefore, whilst the satellites cannot spot all forms of illegality, they might be able to spot one type – which should trigger an on-the-ground inspection, which might then also reveal others at ground inspection.

An analysis of the issues above suggests that waste crime is varied and a dynamic issue. So, what waste crime looks like now, might look very different in 3 years. E.g. following Brexit, the currency changes might mean that there is greater export to and from other countries. In any monitoring programme, it would be wise to:

- Regularly update analysis on what the problem areas are;
- If possible try and anticipate what tomorrows problem will be.

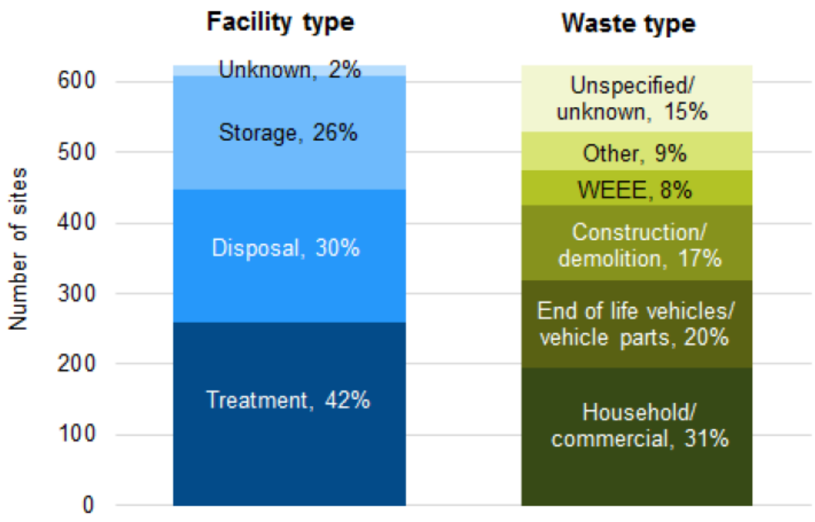
Other changes are social and economic. For example, landfills are shutting down. 50-60% will be closing in the next few years – so waste won't be going there. Where will it be going – incinerators, export? Intelligence on incineration capacity might also be useful.

4.5 The types of waste being dumped and their ability to be detected by satellite

The type of illegal facility and waste types in the UK are shown in Table 10 below. The top three types of waste found at illegal sites in 2015 to 2016 in the UK were household and commercial waste, end-of-life vehicles and construction and demolition waste. These waste types made up more than two-thirds of the waste types found on sites still active in March 2016.

In 2015 to 2016, the Environment Agency dealt with 125 large, serious and organised illegal dumping of waste incidents, the majority of which involved household and commercial waste (31%), end of life vehicles (20%) or construction/demolition and excavation waste (17%) (Environment Agency, 2016). It is likely that these waste types are typical in most illegal landfill sites (although further research would have to be done in other countries).

Table 10. Facility type and waste type at active illegal waste sites in the UK, March 2016. Waste type "other" contains scrap metal, hazardous waste and tyres [Source: Environment Agency, 2016].



We also conducted our own analysis of what types of waste were being dumped (from Annex 2), and this is contained in Table 11 below.

Table 11: Visible waste

VISIBLE WASTE No.	Waste Form	Case Study	Assessment whether can be detected by satellite
1.	Mixed Waste in skips	Cases 3, 4, 6, 7, 19, 25, 32, 35, 47, 62	Note skips not full of waste were often stacked. Can distinguish that way between one's full and one's empty. Empty skips will probably be more highly reflective on SAR imagery depending on orientation. High resolution optical may be the only way to confirm although SAR methods could highlight activity.
2.	Wood recycling	Case 9, 13, 17, 31, 40, 41, 42	High resolution optical imagery would be applicable. There may be a spectral option if it is large homogenous piles. Could be complicated by solvents coating the wood.
3	Mattresses	Case 5, 79	High resolution optical imagery would be applicable. Potentially a viable target for hyperspectral imaging.
4	Tyres	Case 8, 39, 40, 49, 60, 69, 79	High resolution optical imagery would be applicable. Potentially a viable target for hyperspectral imaging.
5	Waste vehicles	Case 6, 14, 22, 37, 46, 57, 73	High resolution optical imagery would be applicable. A strong SAR signal would be expected with complex metal structures.
6	Construction and Demolition waste (Inc. stone, tarmac, concrete pipes, trommel fines).	Case 6, 14, 18, 27, 40, 41, 43, 47, 48, 56, 62, 63	High resolution optical imagery would be the applicable. A strong SAR signal would be expected from manmade material if stored chaotically or stacked closely in large regular piles.
7	Oil drums / plastic containers	Case 23, 33, 40, 53, 79	High resolution optical imagery would be the applicable. A strong SAR signal would be expected from manmade material if stored chaotically or stacked closely in large regular piles.

VISIBLE WASTE No.	Waste Form	Case Study	Assessment whether can be detected by satellite
8	Hazardous waste (asbestos roof tiles, liquids)	Case 25	If mixed and loosely piled, like in case 25, then high resolution optical imagery would be applicable. A strong SAR signal would be expected from manmade material if stored chaotically or stacked closely in large regular piles.
9	Road sweepings	Case 40	SAR change detection would highlight the arrival of the material. It may be difficult to confirm from high resolution optical imagery due to its mud like appearance. Repeated monitoring may be needed to establish that it is not an element of a building process.
10	Commercial/Industrial	Case 29, 30, 32, 40, 44, 64	High resolution optical imagery would be the applicable. SAR change detection would highlight activity but would require confirmation.
11	Electrical	Case 29, 64, 73	If part of large piles of mixed waste, then high resolution optical imagery would be applicable. SAR change detection would highlight activity as would comparative DEM analysis but both methods would require confirmation.
12	Household	Case 30	If part of large piles of mixed waste, then high resolution optical imagery would be applicable. SAR change detection would highlight activity as would comparative DEM analysis but both methods would require confirmation.
13	Food waste	Case 32, 59, 77	If part of large piles of mixed waste, then high resolution optical imagery would be applicable. SAR change detection would highlight activity as would comparative DEM analysis but both methods would require confirmation.
14	Municipal waste	Case 44	If part of large piles of mixed waste, then high resolution optical imagery would be applicable. SAR change detection would highlight activity as would comparative DEM analysis but both methods would require confirmation.
15	Scrap metal and End of life machinery	Case 68, 73	High resolution optical imagery would be applicable. A strong SAR signal would be expected from manmade material if stored chaotically or stacked closely in large regular piles.

4.6 Signs of illegal activity

We also conducted our own analysis (via interviews with environmental regulators) of what the signs of illegal waste crime activity might be, and this is contained in Table 12 below. Linked case numbers are given if relevant.

Table 12. Signs of potential illegal activity

SIGNS OF POTENTIAL ILLEGAL ACTIVITY			
No.	**Type**	**Case number**	**Assessment whether can be detected by satellite**
1	Vegetation stress or change/increased growth (in the case of an organic waste).	-	In a fixed location with high resolution spectral data then it may be possible based on the extent and severity. Over larger area with uncertain location it would be more difficult to identify due to the natural changes in the agricultural cycle of different crops.
2	Dead trees.	-	There has been some spectral work on senescence in trees. The key factors would be the extent. Small patches of dead trees are part of the natural cycle of a forest and are also an indicator of disease. Factoring in the naturally cycle for the trees would be important collection parameter.
3	Litter.	-	Extent of the litter would be the key factor.
4	Lorry track marks.	-	Can be detected with high resolution optical data. Would be a complementary indicator of suspicious activity rather than the key identifier.
5	Heavy machinery (used to dig holes or empty lorries e.g. forklifts, diggers and compactors to compact its cubic size. One sophisticated site had a shredder to disguise the origin of the waste	Case 11 (digger can be seen on google earth image)	Can be detected with high resolution optical data. Would be a complementary indicator of suspicious activity rather than the key identifier.
6.	Pollution pathways.	Case 1 (huge puddles of contaminated surface waste)	Unusual discolouration in association with unhealthy vegetation would be an indicator of pollution and should be visible on high resolution optical imagery dependent on size.

4.7 Who needs to be monitored (who is breaking the law)?

In any monitoring programme, it is beneficial to know who might be breaking the law. This enables the monitoring to be more targeted and risk-based. Obviously, the primary motivation is to monitor the actual waste crime rather than the people breaking the law, but if we have a better idea of who is breaking the law this will enable a remote sensing analyst to consider focusing on certain groups.

People who break the law also make risk-based decisions – they compare the maximum money that can be made with the minimum risk. Offenders can be sophisticated, varied and adaptable and we have to ensure we chase the right rabbit. Table 13 presents our assessment of the groups that are breaking the law, and whether they might be monitored by satellite.

Table 13. Types of offenders

WHO IS BREAKING THE LAW?			
No.	**Type of person**	**Details**	**Can they be monitored by satellite?**
1	Serious organised crime gangs	There are an estimated 5 or 6 gangs in each UK country. They would seek to adapt – e.g. hide, conceal, divert. Waste crime earns them a lot of money – but is also linked to other types of crime they commit. E.g. waste crime is an excellent cover for other activities – people smuggling, drugs smuggling.	Hard to detect these. The hard-core criminals are less likely to be caught as more careful (though depends on attitudes towards risk). This is probably reflected in the fact that we only came across one serious organised crime gang in our case studies (although this might not be indicative that there wasn't organised crime influence in the other cases). One method would be to give priority to monitoring sites to persons with prior criminal convictions – both for waste offences, and also for other offences. If they have broken other laws then they would be higher risk to break waste laws.
2	Rogue waste traders.	There are some skip hire companies, waste hauliers, and recycling companies that make a conscious decision to break the law to maximise their profits. They are not as organised as serious crime gangs, but can still have organised hard-to-detect illegal operations.	At least a quarter of the case studies we examined in Annex I involved illegality amongst the registered waste industry. Primarily this was skip hire companies (13/80 cases). One method of innovative monitoring could be to remotely sense the premises of all registered skip hire companies. Or at the very least those skip hire companies that had been subject to warnings or sanctions in the past.

WHO IS BREAKING THE LAW? No.	Type of person	Details	Can they be monitored by satellite?
3	Rogue employees in well-established legitimate companies	Even in the big well-established waste companies there is some bad behaviour and criminality. There are dodgy individuals or teams and this is known.	These will be extremely difficult to identify via satellite monitoring. Rogue employees can only get away with things that are not easily identifiable e.g. the misclassification of waste. Drone monitoring can reveal volumetric problems – which might alert a company/regulator that there is a rogue employee, but satellite monitoring will probably not be able to detect crimes like misclassification.
4	Legitimate sector chancing their arm.	Sometimes legitimate companies might make isolated decisions to break the law e.g. if they see a major waste site being cleaned up, they might ask if they could pay a bit of money to add their waste to the pile.	Again, if the non-compliance is sporadic and done on impulse, it would be very difficult to build this into a monitoring strategy.
5	Accidental criminals.	Many people set up waste companies with the idea to make money. They often start off with what seems like a good idea, get a permit, get a licensed site and then things don't go to plan. The business model does not work, or a problem occurs. E.g. one company started a waste carpet processing business. They would make money out of separating the waste and then selling it to energy to waste plants. Unfortunately, they couldn't find anyone to buy the flammable bits of carpet and could not afford to dispose of these without making a loss. The numbers of these kept stacking up to a huge level – and in the end, became an unlawful landfill site on the site of the licensed premises. They eventually caught fire and they were prosecuted. These people don't start as criminals, but get problems through poor judgement.	Because some of these would have been subject to inspections it is reasonable to assume that some warnings or concerns might have been flagged up. Sites where concerns have been raised can be subject to priority monitoring to check compliance. There were also a high number of sites that massively exceeded their exemptions that could be potentially monitored by satellite.

A list of risk factors could be compiled and modelled in a geospatial database which would show locations of high and low risk but also inform a collection strategy for air or space based platforms.

4.8 Regulatory requirements

4.8.1 Monitoring Frequency

The revisit frequency that might be operationally needed is very hard to estimate, because it has to be primarily based on the end user's needs and budget. We do not have an accurate picture of either of these to be able to provide an accurate assessment (and this will differ from country to country). What is clear is that the greater the frequency of the monitoring the more expensive it will be. Direct costs will be data analysis and data costs. Indirect analysis will be utilising boots on the ground to respond to red flags raised by the data.

Interviews with four environment agencies suggest that the monitoring frequency envisaged is three of four times a year (although it is unclear whether that would be monitoring high-risk areas or the whole of the country itself). From an analysis perspective, the size of the monitoring task can be in-part solved by the number of analysts that are employed.

4.8.2 Temporal Needs

The temporal needs of environmental regulators are going to vary. Generally, anything that raises standards, identifies bad practice, and stops people breaking limits at legal (or exempted) sites is a good thing. However, timing is probably going to be more of an issue for sites where there is less of a property connection with the offender (e.g. illegal waste disposal at an abandoned quarry). For sites with a property connection an offender might be more quickly identified. Looking at the issue more widely though, both illegal sites and illegality at legal sites, can both cause environmental damage and lost tax revenues. A key selling point of remote sensing is that might detect this quicker in some circumstances than conventional forms of monitoring. Who and what is targeted by remote sensing might vary considerably depending on the circumstances and the service which is deemed a priority by the regulator.

4.8.3 Communication

As was noted in section 2, satellite monitoring appears to have a strong influence on the compliance behaviour of those being monitoring, particularly as they cannot tell when or whether they are being watched. In some circumstances, it might act as a smart deterrent method to be utilised by Governments.

People's compliance behaviour is sometimes influenced by perceptions of whether their neighbour is 'getting away with it' as well as whether they agree with the law. Often cited in this context, Bowles considered that 'twenty percent of the regulated population will automatically comply with any regulation, five percent will attempt to evade it, and the remaining seventy-five percent will comply as long as they think that the five percent will be caught and punished' (Bowles, 1971).

Satellite monitoring might have limited success as a deterrent if those who are being monitored do not know about it, or do not know enough about it. There are two ways of promoting the regulatory use of remote sensing technology, to those that might break the law:

(i) Publicising big wins in the court. This can be in major newspapers, TV and overall sends out a powerful message.
(i) Letting the legitimate waste industry know via information on the permits, through direct contact (e.g. letters) or waste trade bodies (e.g. CIWM magazine).

As well as having a deterrent effect, knowledge of a remote sensing programme might also lead to criminals changing the way they operate, to counter the threat of being detected by satellite. Therefore, a communication strategy would need careful consideration before a remote sensing programme became operational.

5.0 Technical assessment of remote sensing data sources for waste crime detection

5.1 Introduction

This part looks at recorded waste crime identified in the previous section and attempts to detail techniques that may be appropriate for its identification. Waste crime is a broad problem set, which varies depending on the specifics of the territories and locations. This is true in the sense that different legal and regulatory pressures, along with different local circumstances will affect the nature and scale of the crime. The nature of the crime along with the local topography, including the climate and vegetation of an area will also affect the optimum method of observation.

Remote sensing (RS) technologies can offer a powerful tool in the identification and monitoring of conditions at the Earth's surface. People have traditionally interpreted aerial photography by interpreting the features of an image along with its contextual environment.

A digital image however, in its most basic form, is a grid of numbers. This grid is a record of the radiation collected at the sensor which can be processed to estimate the elements of radiation reflected and/or emitted from the Earth's surface. This allows us to not only interpret the picture but to analyse the data behind the picture. Most RS data is geographically registered allowing easy interaction between different types of data sets within GIS architectures. This enables the use of multiple datasets both corroboratively and comparatively, creating additional datasets for specific needs, and using different statistical methods to understand the relationships between features.

This section of the report briefly summarises appropriate technologies for the analysis of waste crime (identified in the previous section).

5.2 Analysis of contextual features in optical imagery

Optical sensors capture radiation reflected from the sun through a lens. There is generally a trade-off between the footprint of an image (the surface area it covers) and its GSR (Geospatial Reference)[20]. The larger the footprint, the coarser the resolution. Freely available medium resolution imagery such as Landsat or Sentinel 2 can be leveraged for large area searches, however at 15m and 10m resolution respectively, identification of contextual features associated with waste crime are unlikely to be achievable. The footprint of Landsat 8 is 185 km x 185km.

Advances have been made in the GSR of satellite optical imaging sensors resulting in the availability of 30cm resolution from commercial vendors. The footprint for these sensors is much smaller at only 13km wide (the length can be variable). This is comparable to some airborne imagery capabilities, which is more flexible and determined by the altitude of aircraft when imagery is acquired. Drone based optical sensors are now widely available and allow for the acquisition of imagery at sub 10cm GSR.

A high resolution approach with an airborne sensor is practical in predetermined areas. The two images below in Figure 29 are of an illegal waste site in southern UK. The image on the left is likely to be from either a helicopter or drone and shows quite clearly piles of waste. The image on the right is aerial imagery from a light aircraft but is comparable to the highest GSR achievable from satellite sensors.

[20] The Geospatial Reference provides the geographic coordinate system for all surveying and mapping applications. It comprises two primary components - a physically monumented system and a satellite positioning reference system. Both systems provide compatible coordinates.

Figure 29. Illegal waste site in UK (1) [Source: Eastnews Press Agency]

Figure 30. Illegal waste site in UK (2)

The image on the right in Figure 30 is from a date after the site has been cleaned up although some elements of the waste remain in a more consolidated pile. It is still visible from the imagery but no longer as clear given the difference in clarity.

The unlawful site in the image above has an area of 0.03 km^2. To give an example, England has a surface area of 130,279 km^2 some four and a half million times this area. In order to purchase the requisite amount of satellite imagery at 30 cm resolution then over 1300 satellite images would need to be purchased at a cost of approximately $4.5 million US dollars. No efforts to conceal the waste are evident and it would be relatively easy to identify this site if directed to it. Simple “eyeball” analysis of this type however, would not necessarily be sufficient to identify smaller concealed locations.

The previous section detailed 80 of some the most recent cases of illegal waste crime activity (see Annex 2). The clear majority of these offences would have been visible from contextual imagery analysis from high resolution aerial or satellite sensors. Mixed waste of the kind above is quickly recognisable and is often accompanied by other features, such as:

- An enclosed yard or storage area for the waste (not always hidden from public view);
- Earth moving vehicles or skips;
- Extensive vehicle tracks;
- Large lorries or vans capable of moving sufficient waste.

It is not currently practical to attempt to purchase or analyse whole countries with high resolution imagery. The previous section highlighted that the same companies or people are often repeat offenders. Certain businesses also tend to be involved in unlawful waste storage. They include skip and plant hire companies - organisations that have the equipment and space to allow movement and storage. Mapping the relevant businesses and register of former offenders and their associated enterprises would highlight vulnerable locations and provide a guide for collection.

Monitoring licenced sites to ensure compliance with conditions would also be appropriate with high resolution imagery. In many cases, high resolution imagery should be tasked to corroborate findings from other methods.

5.3 Texture analysis

Texture analysis is a method of analysing variations in groups of pixels across a grayscale image. In this case, image texture means spatial changes in tone of the pixels across the image. A field of homogenous crops, for example, will have a consistent tone, until it reaches the hedge. Here a change in tone - from the hedge, the shadow of the hedge, and potentially a new set of crops or a change in land use on the other side of the hedge - will have a significantly different texture. Spatial information in the form of texture features can be useful for image classification. Texture analysis involves the information from neighbouring pixels which is important to characterize the identified objects or regions of interest in an image.

The Gray Level Co-occurrence Matrix (GLCM), proposed by Haralik et al is one of the most widely used methods to compute second order texture measures (Haralik R, 1973). Several texture features can be computed from the GLCM matrix, e.g. angular second moment, contrast, correlation, entropy, variance, inverse difference moment, difference average, difference variance, difference entropy, sum average, sum variance and sum entropy. The features can be categorized into three groups, i.e. contrast group, orderliness group and statistics group.

(i) Contrast Group Features:

- Contrast
- Dissimilarity (DIS)
- Homogeneity (HOM)

(ii) Orderliness Group Features:

- Angular Second Moment (ASM)
- Maximum Probability (MAX)
- Entropy (ENT)

(iii) Statistics Group Features:

- GLCM Mean
- GLCM Variance
- GLCM Correlation

Texture analysis, therefore, has the potential to identify tonal changes resulting from large irregular piles of mixed materials, areas of disturbed earth and tonal shifts in soil composition. This method is available with any single band of imagery, and is equally applicable to SAR or derived spectral products.

5.4 Visible and infrared spectrum

Figure 31: Visible and IR portion of the EM spectrum

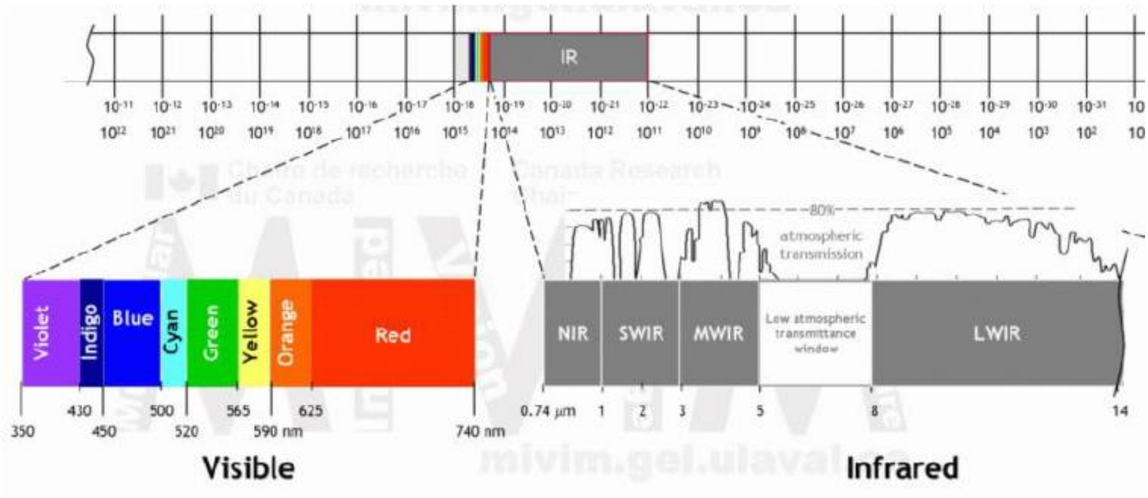


Figure 31 (above) shows the visible and IR parts of the electromagnetic spectrum. NIR and Short Wave Infra Red (SWIR) are reflected energy outside of the visible component of light (unless at very high tempretures). Long Wave Infra Red (LWIR) is also known as thermal IR and is emited radiation. Mid Wave Infra Red (MWIR) can be both reflected and emited radiation. The grey line above the IR spectrum shows atmospheric transmission at those wavelengths. Transmission is affected by atmospheric components such as water vapour at particular wavelengths. Reflected IR radiation happens exactly like visible radiation, with different materials absorbing and reflecting wavelengths in various quantities. Although this is beyond our visible range it can be recorded and displayed to distinguish beween materials.

5.5 Multispectral capabilities

Most optical sensors have a multispectral component. The radiation is collected in discrete bands which can be viewed independently, or in combinations as required. Colour imagery is usually a combination of three spectral bands, blue, green and red. A near infra red band is also common with most optical sensors. This band is just beyond the visible component of the EM spectrum and leaf structures are strongly reflective at this wavelength, as such it is a vital component in land use estimations, detailing vegetative coverage and health, but also indicative of other landforms such as deserts or urban environments.

Multispectral sensors like most imaging sensors, have a trade off between GSR and footprint, however, there is an additional complicating factor. There is also a trade-off between spatial and spectral resolution. A high spectral resoltion decreases the spatial resolution due to less data being collected for each pixel, as it is recorded separately (Landsat 8 has a panchromatic band at 15m resolution, compared with 30m for most spectral bands). To combat this many multisprectral sensors collect a higher resolution panchromatic band that combines the red, green and blue band into one higher resolution band. These bands can then be registered together, in a process called pansharpening, which gives spectral bands with higher resolution.

Multispectral capabilities have traditionally concentrated on analysis of vegetation. Spectral imaging increases the flexibility of the data by allowing analysis of bands in combination or independenly. NIR false colour composites, NDVI and the concept of the “red edge” were introduced in the Phase 1 report. All are methods of assessing vegetation charteristics. More modern sensors have added additional bands within the red edge area to better analyse vegetation charecteristics, including chlorophly and nitrogen content of plants (Eitel et al. 2007).

Table 14 below compares Sentinel 2 and Landsat 8 (two medium resolution freely available multispectral sensors) with Worldview 3 (WV3), the state of the art in comercial optical remote sensing.

Table 14: Comparison of freely available multispectral sensors

Sentinel 2 Bands	GSR m	Landsat 8 Bands	GSR m	Worldview 3 Bands	GSR m
Band 1 Coastal aerosol	60	Band 1 Coastal aerosol	30	Panchromatic	0.31
Band 2 Blue	10	Band 2 Blue	30	Band 1 Coastal	2
Band 3 Green	10	Band 3 Green	30	Band 2 Blue	2
Band 4 Red	10	Band 4 Red	30	Band 3 Green	2
Band 5 Red Edge	20	Band 5 NIR	30	Band 4 Yellow	2
Band 6 Red Edge	20	Band 6 SWIR 1	30	Band 5 Red	2
Band 7 Red Edge	20	Band 7 SWIR 2	30	Band 6 Red Edge	2
Band 8 NIR	10	Band 8 Panchromatic	15	Band 7 NIR 1	2
Band 8a Red Edge	20	Band 9 Cirrus	30	Band 8 NIR 2	2
Band 9 Water Vapour	60	Band 10 Thermal Infrared TIRS 1	100	WV 3 also has 8 SWIR bands	7.5
Band 10 SWIR	60	Band 11 Thermal Infrared TIRS 1	100		
Band 11 SWIR	20				
Band 12 SWIR	20				

Figure 32. Landsat 8 and Sentinel 2 comparison [Source: NASA Landsat Science]

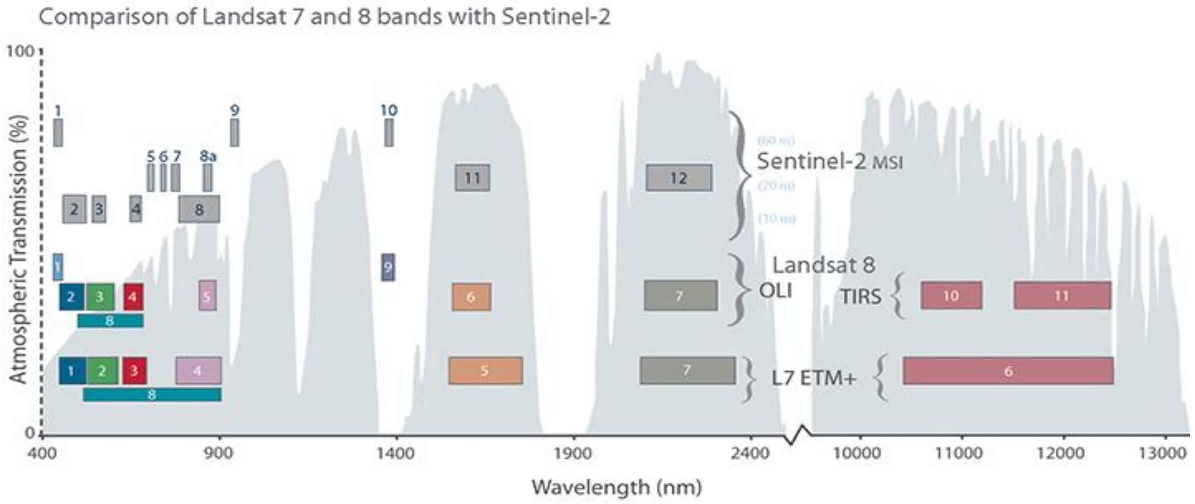
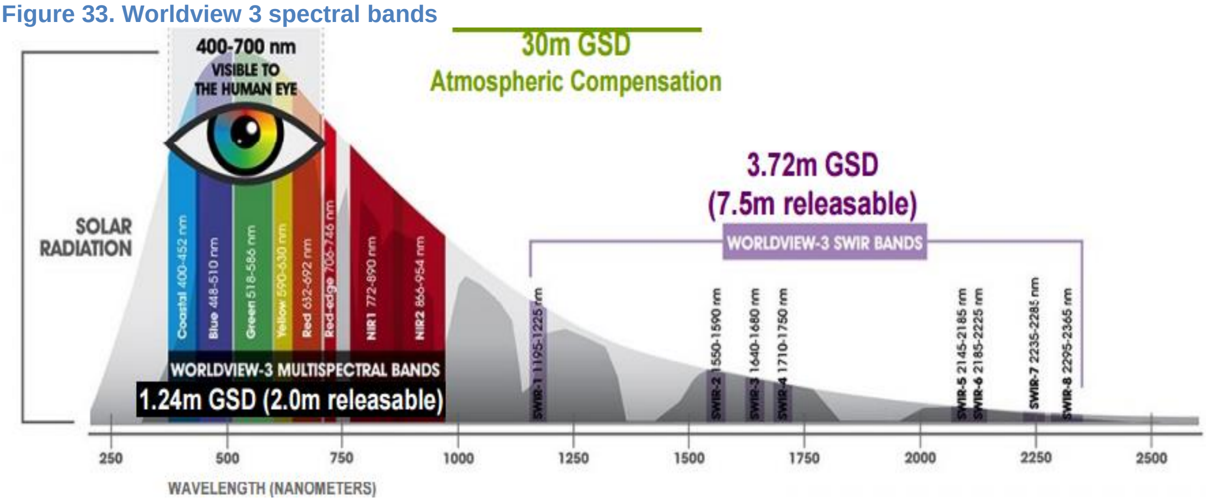


Figure 33. Worldview 3 spectral bands



WV3 is a high fidelity platform both spatially and spectrally giving access to high resolution contextual imagery analysis but also detailed spectral data.

5.6 Vegetation indices

Vegetation stress may be a viable indicator of waste buried for concealment or soil contamination due to leachate leaking from an improperly secured landfil site. There are a wide array of vegetation indices which can be investigated to highlight stressed vegetation including the NDVI and MSAVI mentioned in the Phase 1 report. Other indicies merit further investigation. Two of particular interest in investigating vegetation stress are the Plant Senescence Reflectance Index (PSRI) and the Normalised Difference Red Edge Index (NDRE).

PSRI is designed to maximize sensitivity of the index to the ratio of bulk carotenoids (for example, alpha-carotene and beta-carotene) to chlorophyll. An increase in PSRI indicates increased canopy stress (carotenoid pigment), but also the onset of canopy senescence, and plant fruit ripening.

$$\mathbf{PSRI} = \frac{\boldsymbol{Red - Blue}}{\boldsymbol{Red\ Edge}}$$

NDRE is similar to NDVI but substitutes the red band for red edge.

$$\boldsymbol{NDVI} = \frac{\boldsymbol{NIR - RE}}{\boldsymbol{NIR + RE}}$$

Vegetation stress may be indicative of buried waste, or a breached or incomplete lining at a licensed landfill. The rhythms of the agricultural cycle need to be factored in before planning this analysis.

5.7 Other spectral indices

There are also specific indices for analysis of soils. The Brightness index (BI) and Redness index (RI) both highlight bare soils, but can also be used to detect presence of salts in the surface and variations in soil colour.

The burned area index (BAI) which works by emphasizing the charcoal signal in post-fire images.

$$\boldsymbol{BAI} = \frac{\mathbf{1}}{(\mathbf{0.1} - \boldsymbol{Red})^{\mathbf{2}} + (\mathbf{0.06} - \boldsymbol{NIR})^{\mathbf{2}}}$$

Soil indices may have utility against redistribution of soils and the mixing of waste in a soil substrate. The BAI help to identify areas where the waste is routinely burned.

5.8 SWIR analysis with Worldview 3

WV3 is the most advanced satellite imaging sensor in terms of spatial resolution. It also has an 8 band multispectral capability in the SWIR element of the IR spectrum. This allows the distinction of materials based on material properties rather than colour or texture. The Digital Globe produced white paper the benefits of SWIR shows differentiation between visually similar coloured rooftops made of plastic or polymer materials based on SWIR characteristics.

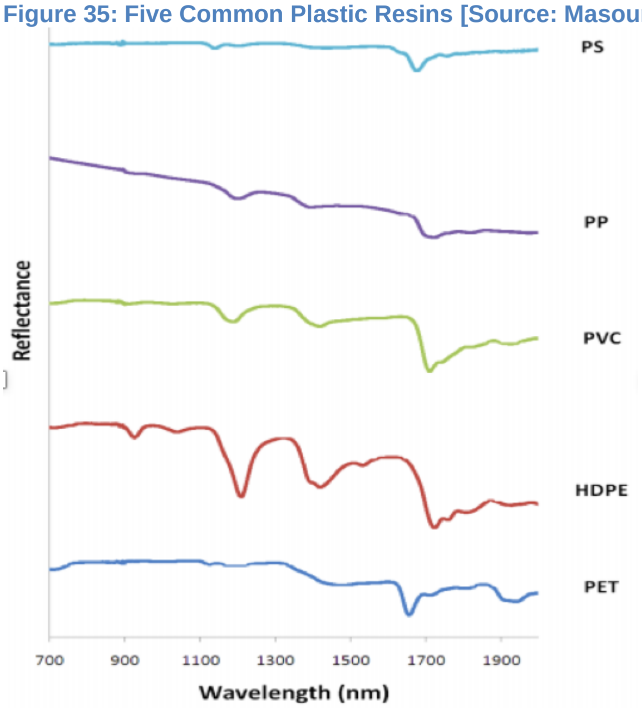
Figure 34. WV3 SWIR image composite

Due to the unique way that materials reflect data in the SWIR wavelengths, it is often possible to discriminate between materials that look similar to the naked eye. In the image on the right, rooftops made of plastic or polymer materials are shown in yellow and orange and clearly differentiated from green vegetation and blue/grey asphalt and dirt Looking at the band combinations on concert with 5 of the most common plastics shows absorption features in the range of SWIR bands 1, 3 and 4. Table 15 below shows the wavelengths of the WV3 SWIR spectral bands.

Table 15. Five common plastic resins, offset to distinguish spectra.

Band	Wavelengths
SWIR 1	1195–1225 nm
SWIR 2	1550–1590 nm
SWIR 3	1640–1680 nm
SWIR 4	1710–1750 nm
SWIR 5	2145–2185 nm

Figure 35: Five Common Plastic Resins [Source: Masoumi et al, 2012].



The SWIR component of WV3 has a GSR of 7.5m. There is potential for WV3 to detect locations of bulk mixed plastics in open waste storage sites. The site can then be viewed contextually with the high resolution optical component, for corroboration of the detected facility and analysis of legality. It is also a potential method for the monitoring of waste disguised as plastic covered hay-bales.

Small plastic components mixed with a soil substrate would be more difficult to assess, as the spectral information would be a mix of soil and plastics. There is, however, potential that varying mixes can be modelled to allow background subtraction of the soil element. Most soil spectra are almost featureless which means that the absorption features may still be present in a mixed pixel. There is little literature available of identification of plastics using WV3 and no literature was available on sub pixel identification of plastics.

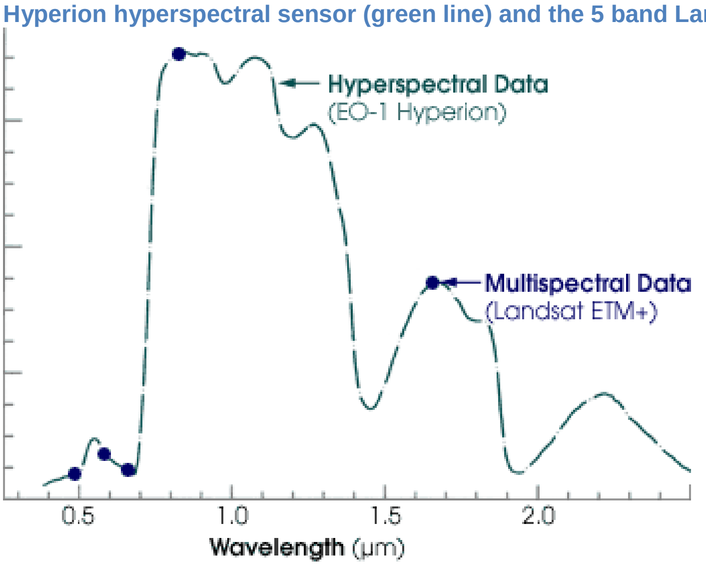
5.9 Hyperspectral capabilities

Hyperspectral techniques were briefly documented earlier in this report, and work in a similar manner to multispectral techniques. The primary difference is the quantity and the bredth of spectral bands.

Hyperion is a satellite borne sensor operated by Nasa and was used mainly for geological functions. It has a GSR of 30m. There are however increasing amounts of airborne sensors which would have GSR in the range of 1m, dependent on altitude.

Spatial resolution is important in hyperspectral remote sensing. Each pixel has a reflectance spectrum that can be compared with known spectra in a spectral library contained within the relevant software package. The recorded reflectance for each pixel is a mix of all the materials present in that pixel. The smaller the GSR the more likely a pixel is to be of a single material, which would result in a clear and distinct spectral match against the library, enabling material identification. The most widely used hyperspectral software is ENVI, which has a set of tools designed to detect specific target signatures and enable sub pixel analysis by comparing multiple spectra and listing the statistically most likely combinations of known spectra resulting in the target spectrum.

Figure 36: A representation of the different spectral representation of vegetation from the 220 band Hyperion hyperspectral sensor (green line) and the 5 band Landsat ETM Blue dots.



Hyperspectral analysis requires significant inputs in terms of trained staff and software, along with high data storage requirements and processing power. Both the Environment Agency Geomatics (Casi - VNIR) team and the Airborne Research & Survey Facility (Eagle and Hawk VNIR and SWIR) have an airborne hyperspectral capability. There are also commercial operators such as APEM and 2Excel Aviation.

This capability is far from an off the shelf solution but it may have potential for future detection of mixed plastics indicative of waste dumped in the open, or even sub pixel detection of plastics mixed with soil. Large scale contiguous features such as plastic wrapped haybales would be a good target with hyperspectral sensors, allowing much more detailed analysis of the surrounding environment.

As the technology matures identification of leachate chemicals may be an area to exploit. There are also hyperspectral sensors which utilise LWIR, enabling distinction of materials which are not reflective in SWIR, including some gasses. LWIR identification is more difficult due to poorer signal to noise ratios, so small quantities of gaseous may be impossible to detect.

5.10 Change detection techniques

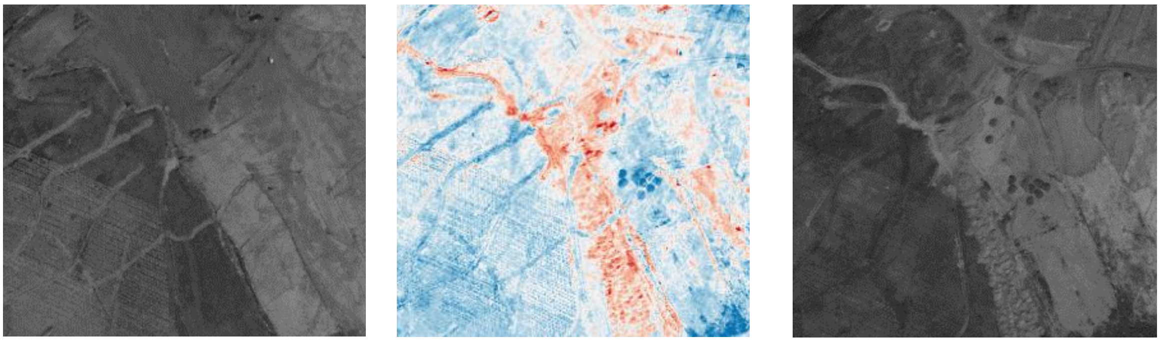
Change detection is a common method used to identify change over time, in the same location. Band math applications in GIS and imagery exploitation software allow you to perform mathematical operations on individual, or combinations of bands. Co-registration of imagery layers allows for the creation of additional datasets.

Change detection is a common method used to identify change over time in the same location. Band math applications in GIS and imagery exploitation software allow you to perform mathematical operations on individual, or combinations of bands. Co-registration of imagery layers allows for the creation of additional datasets.

Figure 37. Images from 2 dates are co-registered

A simple method of measuring change between two data sets is to subtract one from the other, resulting in a separate data layer which details the strength of the change between the two original data layers. The image on the right in Figure 38 is subtracted from the left. Where the pixel values are the same the resulting value is zero (displayed in white) changes produce both positive and negative values with stronger change showing stronger colours.

Figure 38. Measuring change



All digital imagery products can be manipulated this way, including derived data sets such as vegetation indices and texture analysis. This allows detailed discrimination of particular features over time.

The concept of Synthetic Aperture Radar (SAR) was introduced earlier in this report, but is worth re-emphasising as it is particularly effective. Most Remote Sensing uses reflected solar radiation or emitted thermal IR. SAR generates its own radiation which it then collects as it scatters back towards the sensor. If the collection geometry (the location of sensor in relation to the target) is consistent, then highly accurate measurments between separate data sets can be derived, as vairables are minimised.

The images below show part of an ongoing construction of Belarusian construction facility co-located with a small scale material extraction site for use in the construction. The top image is optical imagery. The bottom image is SAR ampltude change detection made from two SAR images. Green indicates a new object on the second date, red indicates an object present on the first date that is absent on the second date. Yellow is diffuse low level change between the two dates and blue/grey indicates no change. The car park in the top left corner shows both red and green where cars have come and gone, but also yellow in places where a vehicle is in the same spot on different dates. In the area to the left a new track has been graded, highlighted in green and there are several areas where earth has been moved depicted in red. The vegetated areas are yellow due to growth, weather or wind changing conditions or position of the vegetation.

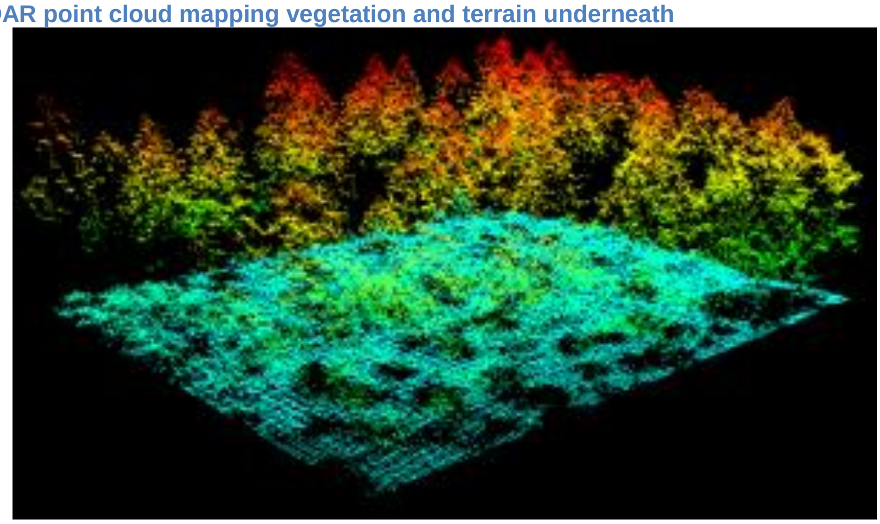
Figure 39: Images of Belarusian construction facility [Source: Astrium].

These types of changes are not always evident from high resolution optical data. It is therefore an appropriate tool for waste crime where both the illegal activity and the background shows lots of variability

Digital elevation models (DEM) are raster images of a sligtly different form. Rather than representing reflected light or radar backscatter the pixel represents a value of elevation against a reference point. DEM can be generated from various sources but the most common methods of generation are from LIDAR, Steroscopic optical imagery and SAR.

LIDAR was introduced earlier in this report. It is generally flown from light aricraft and uses laser pulses and calculates the distance of objects from the response time. These responces for a point cloud from which a dem can be derrived.

Figure 40. LIDAR point cloud mapping vegetation and terrain underneath



LIDAR tends to be the highest fidelity data available and can be 15 – 25 cm in the vertical, and 50 – 75 cm in the horizontal. Digital elevation data created from LIDAR data can often be more accurate than ground surveying because: (1) there are many more data points; and (2) the inherent error is lower (Garcia-Quijano et al 2008). Canopy penetration is another advantage of LIDAR, allowing both an assessment of the tree cover but also mapping the terrain underneath.

Stereoscopic imagery collects data of the same area from at least two viewpoints and uses photogrammetric methods to extract 3D information. Airbuses Pleiades sensors use three collections and advertise 1.5m vertical accuracy and 1m horizontal accuracy. Hu et al found the accuracy of stereo imagery from WV3 to be 1.61m and the 2.16m horizontal accuracy. Stereoscopic imagery from airborne sensors can have improved accuracy however it is harder to quantify due as it is affected by altitude and aircraft movement.

The most accurate SAR generated DEM are formed from Terrasar-x and Tandem-x part of the Airbus constellation of satellites. They can collect in a bistatic mode where 2 sensors work in tandem, from slightly different orbits. One sensor transmits and both receive. The resulting DEM has 5m vertical accuracy and 10m horizontal accuracy. Lower fidelity SAR DEM can be created from repeat pass single sensor; however the change in conditions both in the atmosphere and at the surface can create inaccuracy.

SAR and optical satellite based methods have the larger footprints than airborne methods; however, airborne sensors have greater flexibility. SAR and LIDAR can both collect in overcast conditions (as long as the flying conditions are appropriate for the airframe).

DEM can be used to as a base layer over which imagery is draped to give a 3d perspective and increase understanding of a location. They can also be used in products such as flood and landslip modelling.

Change detection processes can be used with multiple DEM and can highlight change where it would not necessarily be identified otherwise. The products from different sensors are compatible to a degree but work best with the same collection method.

Applying this to waste crime then has potential for identification earth removal, waste burial and subsequent redistribution of soil. Mixed waste either stored at an unlicensed site or dumped in the open would be evident as the topology of the surface changed. A determining factor in method selection would be whether a specific site was targeted, or a more speculative area search was required.

A low-cost method of targeting specific sites could be the use of a drone based photogrammetric sensor. These can have the accuracy of centimetres rather than meters and would be much more cost effective.

5.11 Emerging capabilities

Earth observation, has changed significantly in the last few years. Commercial imaging satellites, particularly high resolution satellites have traditionally required huge capital investments in cutting edge technology with a significant risk of loss of the asset during launch and deployment. They have had a limited customer base. Digital Globe is the largest commerical imaging satellite company and in 2015 made 63.7 % of its revenue from the US Government.

More recently, there has been new entrants to the market with startups building much smaller, cheaper satellites, for deployment in large constellations. Planet (fromerly Planet Labs) recently launched 88 small satellites to enhance its existing constellation of over 100. These sensors are not as capable as the more advanced sensors offered by Digital Globe and Airbus having a GSR between 5 and 3 meters and limited to four spectral bands but the amount of platforms gives a flexibility which allows repeated daily monitoring. Subscription pakages of routine monitoring can be ordered along with one off purchases.

A similar company is Blacksky which is planning a constellation of 60 satellites at 1m GSR.

A newer concept embeded within these companies is ease of customer use. Rather than receiving the imagery data from the vendor, the analysis can be performed by the customer in a web based platform with a selection on application programmeing interfaces (API), available for users to process the information. More established companies are incresingly looking to provide “insights” or processed information, rather than just the imaging data.

Artificial Intelligence is increasingly being applied to satellite imagery in a process where computers are trained to recognise certain classes of objects, which can then be applied to larger volumes of data for automatic recognition. How soon this can be applied on a large scale and to a problem as diverse and complex as waste crime is a different story.

An interseting use of this training method is Urthecasts Optisar concept. Here an optical and SAR sensor image are used in tandem. The analysed optical data will then be used to “train” a more comprehensive and useable output from the SAR sensor, allowing clearer understanding of SAR data imaged at night or in clouded areas. The information gained may also be applied to other SAR sensors, allowing enhancement of their capabilites.

Satellites are not the only thing that is getting smaller with RS capabilities from drones being a lower cost alternative to satellite observation. Not only are they competitive on price, but they can capture a higher standard of data, although with a much smaller footprint. With the ability to capture extremely high resolution spectral, thermal and elevation data they are a great option for the acquisition of data against a predetermined target.

5.12 Summary of key findings

- The sites in Annex 2 had connecting factors and could possibly be flagged as susceptible to waste crime from three main factors: Type of business, licence conditions, and personnel with recorded breaches of conditions. This would make it possible to target specific locations rather than searching countrywide. It is possible that these are the “low hanging fruit” and there are also more clandestine operations that are not routinely identified.

- Most of these locations detailed in Annex 2 would be evident from high resolution optical imagery.

- Texture analysis may highlight locations of open mixed waste.

- Multispectral imagery can be processed to produce various indices highlighting vegetation stress, distinctions in soil classes and evidence of fires.

- Worldview 3 may be used to detect plastic materials in bulk but potentially also mixed in with a soil substrate.

- Airborne hyperspectral sensors can detect specific materials from their reflectance spectra. A significant investment would be needed to operationalise this technique.

- Change detection is a useful technique for detecting unusual activity that can be missed from single source analysis. Particularly if tasked to identify an undefined activity in an undefined location.

- Changes in land elevation can also be indicative of waste crime.

- There is a trade-off between area coverage and image quality.

- In some areas, it may be more effective to look at airborne remote sensing rather than focus solely on satellite sensors. Many aircraft carry multiple sensors allowing simultaneous collection of high resolution imagery and LIDAR. Drones give high resolution results at cost effective prices but can only target known locations, rather than search out potential new targets.

6.0 Access to remote sensing data: archives and tasking

6.1 Introduction

Archives of data are useful in the waste crime sector to allow the investigation of the extent of waste crime in the past. When a waste crime event has been discovered on the ground then it is useful to be able to look back in time to discover the length of time an event may have been in existence. Alternatively archives of satellite remote sensing data can be examined to identify possible waste crime sites that can be investigated further on the ground.

Tasking a satellite is useful for the waste crime sector because evidence can be pro-actively collected for specific sites of concern. Typically tasking doubles the price of the data. The benefit of satellite tasking for the waste sector is to collect image data for a specific place and specific time where there is suspected waste crime.

This section of the report examines the practical access to satellite remote sensing data through both archive access and through satellite tasking. At the request of the client the bulk of the material can be found in Annex 3 which covers the following topics.

- Landsat and the evolution of data archives
- Very high spatial resolution data
- High to medium spatial resolution data through Geostore
- European radar and related optical data
- Other data sources

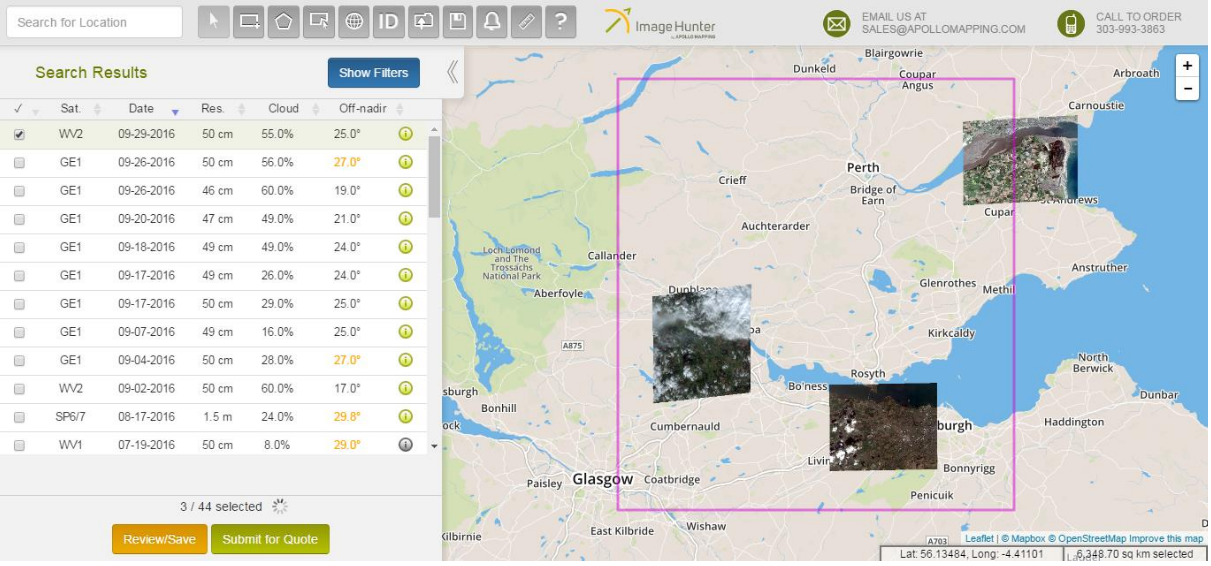
This section of the report covers two important points related to data access. Firstly, how cloud cover is dealt with in data archives and satellite tasking, and secondly the data policy considerations that govern access to remote sensing data.

6.2 Cloud cover

In the visible, near infrared and thermal infrared wavebands cloud cover presents a problem for the use of remote sensing data. Where there is cloud cover then there is no information about the land surface below the cloud. Satellite remote sensing data archive systems offer information about the percentage cloud cover in a scene as part of the archive search.

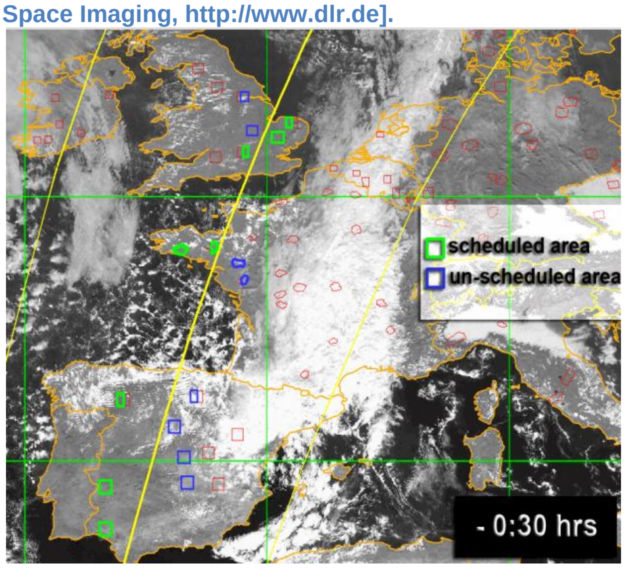
An example is shown in figure 41 which is the user interface to the Apollo Mapping data archive system. The rows on the left side list the images that correspond to the search criteria set up at the start of the search. For each scene, there is information about the satellite source, the date of image acquisition, the resolution or pixel size, the percentage cloud cover and the pointing direction of the satellite instrument. The percentage cloud cover figure is an estimate of the amount of cloud cover in the image.

Figure 41. The results of a search for very high spatial resolution data of central Scotland [Source: https://apollomapping.com]



One way to work around the cloud cover problem is to use weather forecasts and weather satellite imagery to plan satellite tasking so that imaging is carried out when and where clouds are not present. Figure 42 shows an example of using weather satellite imagery to help plan Ikonos very high resolution data acquisition. The areas shown in red are target areas where very high resolution data could not be collected mainly because of cloud cover. The areas shown in green are areas where it was scheduled to collect very high resolution images and image acquisition was possible. The blue areas are target areas that were originally un-scheduled but were included in the tasking plan because the weather satellite imagery and the weather forecast showed that the areas would be cloud-free at the time of satellite overpass.

Figure 42. An illustration of the use of weather satellite images to help change tasking plans for very high resolution image acquisition [Source: Zevenbergen A, Benefits of local satellite tasking and real-time data downlink, European Space Imaging, http://www.dlr.de].



second way to work around the cloud cover problem is the use of a constellation of satellites. According to the 2017 Smallsat Symposium[21] there will be over 400 Earth observation satellites of 50 kg and above planned for launch by 2025 and over 1000 Earth observation satellites that weigh less than 50 kg flying in constellations by the same date. Constellations

[21] http://smallsatshow.com/

of Earth observation satellites increase the probability of cloud-free data acquisition of any one site because there are more attempts because there are more satellites.

Radar images have no cloud on them because radar penetrates cloud. Therefore, radar image data archives do not carry information about cloud cover for each scene. Tasking a radar satellite to acquire data does guarantee image acquisition because the sensor operates day and night and independently of cloud cover.

6.3 Data policy

6.3.1 Scope

Alongside the technical characteristics of remote sensing data such as spatial resolution and sensor wavelengths there are also important data policy issues to consider in access to and use of the data. These data policy issues include ownership, copyright, pricing policy and licences. This section presents briefly the data policy issues that are relevant to the use of remote sensing data in the waste crime sector. This summary gives the general data policy characteristics for satellite remote sensing data: each data set has its own set of data policies that set out the rules for the use of the data.

6.3.2 Ownership

The ownership and intellectual property of Earth observation data lies with the creator of the data, i.e. the space agency such as ESA or the private sector company such as DigitalGlobe. Users who purchase a digital image purchase a licence to use the data and do not purchase the data set itself. The licence conditions associated with a data set provide the rules for the use of the data by a user.

In general, intellectual property rights (IPR) extend to the stages of data processing where the original image data are recognisable, particularly for very high resolution data. When derived products are generated from the image data or from a combination of image data plus other data, for example a road network map, and when there is no longer a recognisable image present then the IPR may pass to the creator of the derived products.

6.3.3 Copyright

There is no copyright in US federally-produced data. This means that Earth observation data produced by the US federal government, such as Landsat data, can be copied and used with no constraints. There are no licences associated with US federally-produced data.

Sentinel data have copyright protection and also require licences to be agreed before the data are used, but the licences allow reproduction, distribution, adaptation, modification and combination with other data sets[22]. Sentinel data are owned and protected by ESA but wide use is encouraged through the licence conditions.

In other cases, for example the SPOT satellite[23], Earth observation data come with a copyright restriction, that is they can only be used for the purpose for which the licence was granted and cannot be copied and distributed further.

6.3.4 Licences

Most satellite remote sensing data sets, except those of the US federal government, are provided with a licence. The owners of the remote sensing data grant a licence to a user and

[22] <https://sentinel.esa.int/documents/247904/690755/Sentinel_Data_Legal_Notice>
[23] <http://www.intelligence-airbusds.com/files/pmedia/public/r5053_9_eula-spot1-7_sicorp_january_2015.pdf>

that licence has specific characteristics: a licence may be a single user licence or maybe (say) a licence for 1-5 users. For example, DigitalGlobe has four types of licence:

- Internal use licence
- Group licence
- Subscription services licence
- Evaluation licence

A common approach is for users to sign an End User Licence Agreement that sets out all the terms and conditions for data use. Such End User Licence Agreements are normally available on the web sites of the satellite data providers, for example DigitalGlobe and Cosmo-Skymed.

Licence conditions normally exclude any warranty or liability of the data owner regarding the availability, quality, accuracy and fitness for purpose of the data provided.

In almost all data purchase agreements the name, address and intended use of the data have to be stated with the order. This is especially the case with very high resolution data that originate in the USA. The stated use of Earth observation data by a purchaser should be wide in scope so that the data can be used internally by an organisation without constraint. There have been cases where data purchased by one part of an organisation cannot be used by another part of the same organisation because of the restrictive licence conditions.

If satellite remote sensing data are to be used as evidence in a court case, then it is necessary to give copies of the data to the opposing side (i.e. normally the defence) during evidential disclosure. This is to enable the defence to challenge, if they wish, whether the processing, analysis and interpretation steps followed are correct and follow accepted procedures. Giving the satellite data to the defence may break the terms of the original data licence and so this potential eventuality should be considered at the time the data licence is agreed at the outset.

6.3.5 Open data

There is a trend in society at large to open data, particularly data that has been collected by government. The basic principle is that once the costs in collecting data have been incurred then the maximum value in the data can be subsequently achieved by the widest use of those data. An example of a basic open data policy for government data is the G8 Open Data Charter[24] agreed in 2013 as a plan to orientate all of the G8 member state governments' data to a position of openness by default.

There is no single agreed definition of open data. In the UK, the Open Data Institute[25] defines open data as:

> "… information that is available for anyone to use, for any purpose, at no cost. Open data has to have a licence that says it is open data. Without a licence, the data can't be reused."

In Europe, the European Union Open Data Portal[26] defines open data as:

> "Data are free to use, reuse, link and redistribute for commercial or non-commercial purposes."

[24] Open Data Charter. Improving the transparency and accountability of government and its services. UK Cabinet Office, 17 June 2013. The text can be found under <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/207772/Open_Data_Charter.pdf>

[25] <http://theodi.org/guides/what-open-data>

[2626] https://open-data.europa.eu/en/data/

There is a trend in Earth observation to open data[27]. This is the case for medium and low spatial resolution data including all Sentinel data. The Copernicus data policy has the objective of free of charge, full and open access to information produced by Copernicus services and data collected through Copernicus infrastructure, subject to relevant international agreements, security restrictions and licensing conditions[28].

The Earth observation data sets that are not open and free of charge are in general the very high spatial resolution data.

For some so-called open data sets, for example the ESA Third Party Mission data, there is a distinction between data used for scientific research and data used for commercial or operational purposes. The data used for scientific research are more easily accessible and can be used with fewer restrictions than those used for commercial or operational purposes.

The combination of copyright and open data can be accommodated in Creative Commons licences[29]. Such licences enable the free distribution of otherwise copyrighted work and then protect the onward distributor from concerns about copyright protection. The minimum requirement in Creative Commons licences is attribution and share-alike. The data in OpenStreetMap, for example, are made available under the Open Data Commons Open Database Licence.

[27] Harris R and Baumann I (2015) Open data policies and satellite Earth observation, *Space Policy* 31, 44-53.
[28] Regulation (EU) No 377/2014 of the European Parliament and of the Council of 3 April 2014 establishing the Copernicus Programme and repealing Regulation (EU) No 911/2010.
[29] https://creativecommons.org/licenses/

7.0 Costs of data and implications for regulatory monitoring

7.1 Open data

As mentioned earlier in this report, remote sensing data can be obtained free of charge from high quality ‘open data’ portals. Open data sources include United States Landsat imagery, and image data from the Sentinel missions of the European Space Agency. Some third-party mission data is also available free of charge via the European Space Agency Earth Online. Much of this data can be made freely available to environmental regulators relatively quickly after capture.

Given the austerity agenda which is affecting many environmental regulators across Europe, open data remains a highly attractive option (in regulatory monitoring). Earlier in this report there was analysis about what open data can achieve in terms of monitoring waste crime, especially when considered in direct comparison to commercial satellite data (i.e. data that requires payment). Our conclusion was that in general terms, open data tends to have a smaller spatial resolution than the best commercially available data, which can sometimes make it less relevant in a law enforcement context. Many factors are at play, such as, for example, whether the pixel sizes are large enough to be able to detect, or distinguish individual landfills. In terms of detecting waste crime, more evidence is required to determine the value of open data in a waste crime context (hence the value of the trials that SEPA will be conducting later in 2017).

7.2 Optional sub-sections

Commercial data will certainly be less attractive to regulators, in comparison to ‘open data’, because of the costs; although imagery prices have come down a lot in recent years, main due to increased competition, which has made high resolution data more affordable. For example, some very good commercial high resolution optical imagery (one scene) can now be obtained for less than £500. However, the cost of the most recent very high resolution data at thousands of dollars per scene can be prohibitive for use in a regulatory context.

The price of satellite data varies enormously. Below are example costs for single user licences for a selection of the most common high resolution satellite imagery (as of December 2016), and these should be used as a guide only. Prices can be liable to change without notice and so (from experience) a formal quotation is necessary each time for current and accurate pricing. Multi-user licences, rush programmeming and other custom processing, format and product options are also possible, which can impact on pricing. The costs below also reflect standard image costs, which exclude standard processing – which will cost more money.

7.2.1 Optical and Radar Satellite Data Cost

Example data prices for three selected very high spatial resolution data sets for archive and tasking products and examples are shown in Table 16. The prices are per sq. km for archived data and for data that result from a tasking request and are subject to minimum order and licensing conditions.

Table 16. Example data cost for optical data

	WorldView-2/3		GeoEye-1		Pleiades	
	Archive	Tasking	Archive	Tasking	Archive	Tasking
Panchromatic	$14.00	$24.00	$14.00	$24.00	$10.00	$17.00
Panchromatic plus 4 band multispectral	$17.50	$27.50	$17.50	$27.50	n/a	n/a
8 band multispectral	$19.00	$29.00	n/a	n/a	n/a	n/a

The prices of the TerraSAR-X radar products are given in Table 17. For each of the three main product types there is a price for archive data and a price for new acquisitions that have been tasked. The new acquisitions resulting from tasking are roughly twice the price of the archive data.

Table 17. Example data cost for radar data

TerraSAR-X mode	Pixel size (m)	Scene size (km)	Price archived data (euros)	Price new acquisitions (euros)
SpotLight	1 - 2	10 x 10	2125	4250
StripMap	3 - 6	30 x 50	1475	2950
ScanSAR	16	100 x 150	875	1750

There are many numbers of satellites, with a wide variety of costs. Annex 4 demonstrates the costs of all commercial satellite data (as of February 2017). Table 1 of Annex 4 contains prices for optical imagery; Table 2 of Annex 4 contains prices for radar imagery.

7.2.2 Video Satellite Data Cost

At the current time, only two companies are collecting data using video satellites. There are ongoing issues about obtaining this data commercially, so no reliable figures can be given at the moment. Video data is sometimes possible to get hold of but it is generally extremely expensive (in the past we have been given estimates of around €4000 for a small scene that was approximately 90 seconds in time, at 1 metre resolution).

7.3 Costs of a monitoring programme

Different satellite monitoring programmes cost different amounts of money. The analysis in section 2 showed that governments in New South Wales (vegetation clearing), the EU (agricultural fraud, oil pollution), and US (crop fraud) spent annually over a million pounds on data for their monitoring programmes. Whereas other monitoring programmes, in countries such as Chile (fish farm monitoring) and Spain (La-Mancha and Upper Guadiana regions) (water abstraction) spent considerably less than half a million pounds.

We have tried to work out the potential cost of very high spatial resolution imagery for satellite monitoring. To take an example of the country of Scotland, Scotland has a surface area of 80,077 square km. The cost of buying Digital Globe optical data (40cm) from archived data that have already been captured, for the whole of Scotland, would be US$ 19.50 per sq. km x 80077 sq. km = US$ 1,561,502 [currency exchange = £1,280,154 on 7/3/2017].

The cost of buying CosmoSkyMed radar data (1m) for the whole of Scotland from an archive would be – €3000 euros per scene of 10 x 10 km = 100 sq. km which means that the data cost is €30 euros per sq. km. So, €30 euros per sq. km x 80077 sq. km= €2,402,310 euros [currency exchange = £2,082,803 on 7/3/2017].

Note that we gave the upper costs limits in our calculations above, but this demonstrates that the best commercial satellite imagery (with that pricing) is not going to be affordable to most regulators. But as the cost analysis in Annex II shows, there are many different satellites with a wide variation in data costs. Therefore, the cost of satellite monitoring will be, in some ways, as expensive as a Government wants it to be.

When considering costs, it is also not necessary to cover a whole country for monitoring purposes. It is likely in practice that only (say) 10% of Scotland would have to be covered by Earth observation data to cover a lot of areas where waste crime is experienced. A 10% sample of Scotland is reasonable, because of the mountains and the remote northern and western areas. Obviously, in practice it will depend on where waste crime is actually happening in Scotland. 10% of the sample costs given above will be far more affordable to regulators (e.g. £128,015 for 40cm optical data from Digital Globe; and £208,280 for 1m radar data from CosmoSkyMed)

The imagery that is required and how it is used, can on the one hand be specifically tailored to individual needs and affordability, but on the other hand it also depends on the requirements of what the person buying the imagery wants to achieve and at what cost.

Table 18 below considers some of the key variables that should be examined when considering purchasing data for a satellite monitoring programme.

Table 18. Key variables to consider for a monitoring programme

The regulatory budget.	Perhaps the most important aspect is the money that will be made available to fund a monitoring programme. If there isn't sufficient funding to buy the best very high resolution data then, data will have to be purchased that matches budgets.
The size of the area that is to be monitored (size of the image in sq. km).	It is going to be a lot more expensive to monitor larger areas (e.g. a whole country), so strategies might need to be developed to get imagery based on risk assessment or operational needs.
What kind of data you are going to use?	As can be seen from the tables above, generally radar satellite data is a lot more expensive than optical data. However, which type of used will depend upon the characteristics of evidential needs.
The frequency of the monitoring.	A further trade-off (when considering costs) is the frequency of the monitoring. The key advantage of satellite monitoring in waste crime will be detecting illegality quicker, but very frequent monitoring might not be possible if costs are too high.
The spatial resolution of the data.	The cost of the data is often linked to the spatial resolution and the detail that is necessary to be shown. A thorough examination of waste crime characteristics will be required to identify operational needs, which can enable informed decisions on which spatial resolution would suit the monitoring programme.
Use of archived data or tasking.	Generally tasked data is twice the price of archived data. Therefore, there needs to be examination of whether there is sufficient and timely archived data to enable a monitoring system to work, or whether it would be more beneficial to ensure that it is specifically ordered in the future through tasking (to exactly match regulatory requirements).
Cost-benefit analysis.	A further consideration is cost benefit analysis, in the sense that if better spatial resolution catch's more illegality and results in significantly better economic results (e.g. reclaimed tax), then this might provide a more compelling case for investing in better data.
On-the ground resources.	A key variable is whether the regulatory body has the resources to react to the data. For example, if imagery is collected very frequently of a substantial area (e.g. the size of Scotland, but if the regulator doesn't have the manpower to follow up the satellite reports then it probably should not develop such an ambitious data collection programme.

More generally, the cost of purchasing satellite data can also depend on two further things, which are given in Table 19 below.

Table 19. Other cost variables that are often forgotten in monitoring programmes

The location of the area of interest where the imagery is required.	Often there is no uniform price for the whole of the world and some companies charge different prices in their catalogues based on geographical location. Sometimes there are permanent pricing structures, and in some instances, either special offers or additional costs may apply in some geographical regions.
Exchange rate fluctuations.	Most imagery is purchased in US dollars or Euros (although some is available in Chinese Yen). Currency fluctuations in markets can mean that imagery prices can sometimes change by significant sums if the currency trading changes (e.g. following Brexit). Therefore, unless a regular monitoring programme has got a long term fixed price agreement then costs could unexpectedly change by 20-30%, having major impacts on budgets if not in a country's currency's favour.

7.4 Innovation in data costs

7.4.1 Targeting Resources

On the whole, the costs of acquiring very high resolution and high resolution data image data are high if you want to monitor very large areas (e.g. an entire country regularly). The regulators could either choose to look at selection of random areas (e.g. like EU subsidy monitoring, which is about 5% of the whole of the land-mass in the UK). Alternatively, a regulator could buy data of areas that are experiencing the most problems (e.g. if the problem is worst in the Highlands then they could start by targeting their resources on that area). We don't have data that shows where waste crime is believed to be happening most in Scotland, but this would be useful in determining potential costs.

It is also not necessary to buy whole images. Data can be purchased for any polygon shape. So, data can be purchased in a polygon shape covering certain areas where, for example, serious illegality is known to have occurred before.

7.4.2 Negotiating Prices

The data prices in the tables in the Annexes were indicative prices of buying small quantities of data. Most satellite operators would be open to negotiate bulk discounts for purchases of substantial amounts of imagery, especially for a regular monitoring programme. In our experience, even in regular monitoring programmes the price of the imagery can be constantly re-negotiated.

Costs can also be split. For example, the imagery used by New South Wales in their vegetation clearing programme, has in the past come at a discounted price by sharing the data costs with Google Earth.

7.4.3 Multiple Uses for the Data

Purchasing satellite data is more cost-effective if it can also be used by other government agencies, or used for multiple purposes (subject to the relevant licensing authorisation). In terms of other activities this might encompass other uses such as: monitoring fish farms, monitoring illegal house building (without necessary permissions), or monitoring protected areas like SSSIs.

Regulatory bodies considering purchasing data for monitoring programmes could establish a coordination body to champion and support activities where such images might be used elsewhere in their organization (Purdy, 2010). This might enable regulators/governments to get more bang for their buck, obtain discounts for bulk buying, and/or make sure that the same or similar imagery is not purchased over and over.

If multiple uses are envisaged it will be important to be consider in advance how the data is going to be used and who will need to be covered under the licence (e.g. some environment agencies are executive non-departmental bodies – so, for example if one arm of the Government gave them data to use, because the licence allowed only Government bodies to use the data, this could potentially be in breach of licence).

7.4.4 Payment by Results

To ensure that a satellite monitoring programme will be a success, then regulators might consider paying for a commercial service from a third party (e.g. satellite vendor), where payment is based on actual results (e.g. payment based on numbers of unlawful landfills detected). This could potentially be an attractive model, which offers regulators a certain degree of protection.

7.4.5 Recovery of Costs

Regulatory bodies sometimes look to recover their investigative costs from the defending party. This might be harder to do in respect to an ongoing monitoring programme, but would certainly be possible if ad-hoc imagery was purchased in relation to a specific investigation.

Some environmental laws contain a provision that allows the recovery of 'reasonable costs' for preparing the prosecution of an offence. In Queensland, they have legislation which specifically states that an example of a reasonable cost is those involved in 'obtaining and analysing remotely sensed images' (Purdy, 2010). The Queensland Government recover the cost of purchasing images via this provision, although it is unclear this applies to satellite data purchased in bulk, or just ad-hoc acquisitions of data which are used in the specific case.

If an enforcement agency was relying on a satellite image from one provider in a case, and the other party challenged this, it seems that the agency could potentially purchase further archived imagery, taken of the same time period, from another provider (if this was available). This could be used to corroborate the earlier evidence and, if the agency wins the case, they could recover the costs of buying this additional imagery. It might just be a sufficient deterrent to a frivolous challenge from the other party for Government to tell them that if they did intend to contest the imagery, they would buy additional, better quality, high resolution imagery to prove their case. There is a question of fairness in such methods, but research has found that parties relying on weak arguments do sometimes back down if faced with the prospects of further costs.

A regulator wishing to use satellite imagery might, therefore, wish to introduce a legislative provision that allowed for the recovery of reasonable costs involved in obtaining data, additional or otherwise.

7.5 Other costs

Purchasing the satellite data is not the only significant cost in establishing a satellite monitoring programme. Section 2 revealed that New South Wales, who have one of the most expensive monitoring programmes, internationally, spend approximately (AUS)

$6,500,000 a year on their monitoring programme. However, only (AUS) $2,500,000 of this figure is costs. Those considering using this technology in a regulatory context need to consider other costs in detail (with a view to avoiding under-budgeting).

7.5.1 Staff

Employing spatial experts to process and interpret the data can be a significant expense. These have to be specialised, highly skilled professionals. There is normally only a smallish pool of such graduates who are qualified to work on specialist monitoring programmes. As such, demand is high and they will require reasonable remuneration (and in the civil service salary costs have to go up over time). Employing and training analysts can take a long time and cost significant sums of money.

Some environmental regulators will have experts with remote sensing and GIS experience, but there can be additional cost implications if they need to recruit additional experts, or out-source processing and ortho-rectification to experts, because they don't have the expertise in-house.

From a technical point of view, it might be possible over time to increasingly moving towards being systematic, so the analysts would be needed less and less. However, we are not yet at a stage where we can completely automate sophisticated satellite monitoring programmes, and some human input will also be required. Humans will always be required to at least review and check certain stages of the remote sensing data before compliance decisions are taken, and might be needed to present the data (and more importantly its significance) in a court if necessary.

7.5.2 Equipment

Spatial data requires tools for computer analysis. There are software licensing costs and hardware costs. In respect of the latter, if regulators wish to be at the leading edge of the technology, computers and other hardware have to be periodically updated. This can be expensive. Satellite imagery in large quantities can also require serious data storage facilities.

8.0 Recommendations for pilots

8.1 Pilot 1 (the operational 'live' case)

8.1.1 Description

The brief in this trial is to offer operational support to an environmental regulator in a 'live' case. A 'live' case will enable a better evaluation as to the evidential usefulness of RS and UAVs to those working in a waste crime enforcement context. As well as examining the usefulness of the data, it will also look at both practicalities and any potential barriers in using the data, as it is beneficial to understand operational realities. Pilot 1 would encompass the following four core aspects.

Firstly, the contractor would use archived EO data to show what an unlawful waste site, which had recently been discovered by an environmental regulator, had looked like historically, focusing on the timing of the unlawful activities taking place on the site. There would also be an examination of other areas of the site (depending on size) to see if any unlawful activity had historically taken place across multiple locations on the site. This could be important (in some jurisdictions) in respect to demonstrating the size of the case, which could be a factor in terms of what court the case is heard in and the penalty level imposed.

Secondly, the above analysis will be combined with GIS data obtained from other sources, which we believe would be operationally useful to an environmental regulator. This would include an analysis of relevant information such as: the proximity to population, proximity to watercourses and historical land-use of the unlawful waste site. It would also include a map of local waste operators, licensed landfill sites, and sites which held exemptions for waste storage.

Thirdly, the contractor would also assess how regulatory bodies might like to receive the data, and their expectations as to what an expert report accompanying the data might look like. The contractor would also assess licensing issues to do with purchasing the data (in respect to potentially having to disclose it to the defence in the event of a prosecution), and the applicability of rules concerning investigatory powers / search warrants (e.g. the Regulation of Investigatory Powers Act (RIPA) in England and the Regulation of Investigatory Powers (Scotland) Act (RIPSA) in Scotland.

Finally, the contractor would also be expected to use a UAV to estimate the volume of waste contained at the unlawful site, if appropriate (i.e. if the waste is on the surface, rather than buried).

8.1.2 Justification

(i) Operational Examination

This trial is intended to both examine the usefulness of the data collected and to flesh out operational needs. The trial would benefit from this being a current active regulatory investigation, but this could be a 2016/2017 post-prosecution case if there were any *sub judice* implications. If a post-prosecution case was chosen it would be preferable for any illegally deposited waste, or evidence of burning, to still be visible on the site. The contracting body should make the final decision on whether this trial can be part of an active investigation after the contract has been awarded.

(ii) Historical Analysis

EO technologies could be extremely useful to environmental regulators in providing historical evidence. A major benefit with EO technologies, and one that is unique in its scale and timing, is the fact that images be stored and archived in archive data banks, which can be purchased. Systematic archiving of satellite images could in theory provide environmental regulators with a relatively impartial snapshot of any location at certain times in the past, providing accurate evidence that would often be otherwise unavailable. An increase in numbers of operational satellites means that there is growing access to more historical data at a cost-effective price.

8.1.3 Trial Design

(i) Use of Archived Data

There are five things that this trial should flesh-out, so environmental regulators can get a better understanding as to the value of EO data as historical evidence:

- What kind of evidence can be potentially created? That is, can the imagery identify what was taking place over time on suspect sites; can it make an estimation of the size of the unlawful waste site (height/width); can it identify the type of waste materials; or can it give an estimation of waste volume?
- At the outset of the trial the environmental regulator will provide a date as to when they believe that the activity started. The contractor will then see the length of time that imagery shows the activity had been taking place (i.e. how big a case it is). This might have implications in terms of what court the case is heard in, which might also affect the penalty imposed.
- The contractor should also examine whether there were possible multiple burial locations or burnt locations on a site, and to see whether the regulator was aware of all of these.
- An estimate of the cost of the imagery and the analysis, so regulators can understand the cost implications.
- Finally, the contractor should hold discussions with the regulator (i.e. SEPA) and/or the Crown Office and Procurator Fiscal, to discuss the usefulness of these images and whether they offer anything different, supplementary or superior than what is used under current investigatory approaches, e.g. usefulness in relation to sentencing, tax evaluation or the extent it provides pictures of sites that a judge/jury could better relate to (particularly in respect to scale).

(ii) Other GIS Data

A second element of the trial will be to see how the EO data can be combined with other GIS and mapping data to create a “problem profile” that could be useful to environmental regulators. Information which might be collected would include: proximity to population, land-use and proximity to watercourses. This would enable regulatory bodies to see what impact or damage might result from the site, so they can tailor any reaction accordingly, and also so that this data can be potentially used in court if it had a bearing in terms of the seriousness of the offence and sentencing. The key indicators will be determined through discussions with the regulator after the award of the contract.

(iii) Data usage issues

It is feasible that an external contractor might be employed by an environmental regulator to do the EO analysis, as some regulatory bodies will not have the internal experience to be able to do that. Therefore, this trial will also contain analysis as to how an environmental regulator might like to receive the data and an expert report from a third-party expert. This will encompass how satellite data is transferred and their expectations of what an expert report might look like and what it contains.

Secondly, if an environmental regulator uses EO data as evidence then this data will have to be disclosed by the prosecution. The contractor should, therefore, examine the licencing implications of this and how this might affect costs.

Thirdly, whilst an environmental regulator will have some powers to enter premises, occupants at unlicensed or illegal sites may refuse entry, and the investigating officer might need to get a better understanding of the permissions required to look at a site using EO or UAV data. Permission might also be needed before some form of investigations if there was deemed to be any form of privacy impact. Trial 1 also requires an examination as to whether there are any barriers in terms of the rules laid out in investigatory powers legislation (e.g. RIPA in England and RIPSA in Scotland), or if privacy impact assessments are required and in what circumstances they could apply.

(iv) Volumetric analysis by UAV

Volumetric analysis of illegal sites by UAVs can test whether an accurate calculation can be made of the financial benefit of waste crime. Tax can be applied retrospectively to illegal landfills in some countries (including Scotland), so there should potentially be real value in doing this.

This element of the trial should provide an estimation of volume and type of waste materials, and provide an assessment of the accuracy of this calculation. UAV’s can collect imagery of much higher resolution than satellite based sensors, enabling more accurate estimates of waste volume and discrimination of waste types. It would be useful if comparisons on waste volume could be made as to what the regulatory body believed was at the site following ground inspections, and also against any satellite analysis estimates (if possible).

8.1.4 Building upon other work

There has been very little published work on the use of historical satellite data to provide evidence of waste crime.

In 2010 Purdy published an article in the Journal of Environmental Law which reported a trial examining the use of archived satellite data (Purdy, 2010). He examined a prosecution in 2006 in England for an offence relating to an illegal landfill site. This was a major criminal operation and the rubbish that was burnt caused a mound of ash that was 3 metres thick and measured 260 metres in circumference. It was calculated that by burning wastes and hazardous wastes to this extent, the offender would have received an annual turnover of approximately £40,000. At trial, the Environment Agency stated that this offence took place between May 2005 and January 2006.

The two satellite images at the top of Figure 43 (below), which were from October 2005, appear to show, in the circled area, the burning of waste on this land during the already known time of the offence.

Figure 43 - Archived Imagery Showing Timing of Waste Site [Source: Copyright: DigitalGlobe].

The two satellite images at the bottom of Figure 43 (above), which were dated June 2004, were taken nearly a year before the Environment Agency believed the offence was committed. These appear to show a large burned area on the land at this time and might be evidence that the illegal activity had been ongoing for a longer period of time than the investigators previously thought. Purdy found that this highlighted the practical function of imagery archives for prosecuting authorities - if they would have had access to such imagery, then they might have used this in court to press for a harsher sentence.

We have also heard of an environmental regulator commissioning a report from an independent drone operator to calculate waste volume, but there does not appear to be any published material on this.

8.1.5 Test Area Size

The test location is unknown at the current time. The regulatory body would be expected to inform the contractor of the location of an unlawful site after the contract has been awarded. The minimum order price for archived data is usually 25 sq km and we would not envisage needing more than that amount of data.

If possible, the regulatory body should give the contractor a selection of sites, in case there are issues such as data availability and cloud cover over one particular site.

8.1.6 Data to be Used

The contractor would use optical satellite data from a mixture of commercial and open data sources. Open data would be used to provide a comparative analysis of the benefits of commercial and open data.

For thorough analysis, very high resolution commercial data would be necessary. Both to fully explore the optimum method for monitoring activity, but also to understand the implications for enforcement bodies and make the analysis accessible for legal proceedings.

Open data can be used as a guide to purchase commercial data in the correct time frame, but lacks the resolution to fully detail any unlawful activity. We envisage this trial using very high resolution optical data that was Digital Globe 0.30 metre (m) or 0.40 m class.

The contractor would need:

- Optical images taken on different dates;
- Drone analysis taking place over two days.

8.2 Pilot 2 – risk based case (monitoring waste tyres)

8.2.1 Description

The brief in this trial is to focus on waste tyre piles and to examine the effectiveness of monitoring potential breaches at licenced sites, which were deemed to be operated by high risk offenders. The contractor would ideally look at sites which had a history of licence breaches (or owners/operators with breaches/convictions at other sites). The focus would be on sites where tyres are stored, because these are high potential for licence breaches in this area.

The contractor would test the following three scenarios at known sites:

- Whether there had been burning of tyres on these sites;
- Whether there had been any potential licence breaches, e.g. how and where the tyres were.;
- Whether it was realistic to assess compliance by examining tyre numbers on the site (by height stacked; comparing imagery; length of shadows).

The contractor will also look at the potential for designing an automated detection model to detect tyre sites which were unlicensed (i.e. searching) for waste tyre piles that have not been so far detected.

8.2.2 Justification

(i) Risk based monitoring

Earlier research in this study concluded that on a basic level there are two methods of undertaking a targeted monitoring programme using remote sensing.

- Firstly, the regulatory body could task a satellite to monitor all of a specific area of land/water. An example of this is that most Australian States purchase imagery and examine the complete (100%) area of land under their control, in their vegetation clearing monitoring programmes.
- Secondly, the regulatory body can task a satellite to monitor certain areas/activities or percentages of land. An example of this is agriculture subsidy monitoring in the EU, whereby Member States must check a minimum of 5% of claims annually in their own countries using satellite data.

A monitoring programme across a whole state is likely to detect more potential illegality, or potential licence breaches. However, it is also likely to cost significantly more money – both in terms of data and staff costs. Public sector resource constraints on environmental regulators suggest that this might not be an option for some. Within the context of budgetary constraints, an increasingly common regulatory response to dealing with contemporary environmental challenges has been to implement the so-called flexible risk-based enforcement strategies.

In line with the Hampton Review of inspection and enforcement in the United Kingdom (UK), risk-based regulation implies using what are often limited resources, in the most effective manner possible, to achieve specific policy outcomes (Hampton, 2005). Rather than carrying out inspections to the same level of intensity on all of the activities falling within the scope of control, calculated assessments are made to target regulatory attention on where the risks are most likely; namely, the higher-risk operators with the worst environmental performance. An effective targeting approach aims to reduce the cost of ensuring compliance. This pilot is intended to assess the utility of using RS to monitor high risk sites, or high risk activities, concentrating on waste tyres.

(ii) Tyres

The World Business Council for Sustainable Development has estimated that approximately one billion end of life tyres are created every year globally and that there are approximately four billion waste tyres in total around the world in stockpiles and in landfills (World Business Council for Sustainable Development, 2010). The number of waste tyres is growing each year. Waste tyre piles can be dangerous, in particular through fires. Once started, fires in waste tyre piles are difficult to control, burn for a long time and can create dangerous gases such as cyanide and sulphur dioxide. Waste tyre piles can be dangerous to animals and can affect soil, vegetation and water quality. They can be a landscape eyesore. Many countries have regulations or rules to control waste tyres. In Europe, the EU Landfill Directive of 1999 banned whole waste tyres from landfills. National legislation in EU Member States provide for the licensing arrangements for waste tyre storage and management (e.g. how many waste tyres are allowed to be stored), but these laws can often in practice be widely abused. Whilst the focus of this trial is on tyres, these have a very similar spectral response to plastics, which would enable a calculated assessment to be made on monitoring other forms of waste crime (such as the mixture of plastic waste in soils).

8.2.3 Trial design

In this trial, the contractor will primarily monitor licensed legal waste tyre pile sites. This is to investigate whether licence conditions on factors such as size and area are being followed correctly and that tyres are not being burnt on the site. In practice, the trials should include sites that are either known to have been historically in breach of the rules, or synthetic sites where the area of tyres is within the rules but it is regarded as exceeding the rules by dividing the waste tyres into two parts, a legal part and an illegal part. The contractor would benefit from being supplied with a GIS map of tyre recycling sites by the regulatory body (with indications of those sites with a history of licence breaches). This would allow the collection strategy to be more informed and intelligent. A further option would be to look at clusters of tyre recycling/storage sites in a specific area (e.g. Lanarkshire in Scotland appears to have a lot of licenced sites).

A second objective will be to examine whether remote sensing can be used to search for waste tyre piles that have not been so far detected (i.e. unlicensed sites). The contractor will also look at the potential for designing an automated detection model to detect tyre sites which were unlicensed (i.e. searching) for waste tyre piles that have not yet been detected by a regulatory body. If time and budget allows the contractor should undertake a small trial looking for unknown sites. In practice, some of the unknown sites will need to be known by the regulatory body, but the locations kept in reserve from those carrying out the data analysis. The contractor would then be set the test of seeing whether they can be detected.

The characteristics set out below summarise the main characteristics of waste tyre sites as they appear on RS image data. The characteristics are examined as a set of options and the choice of the options will depend on the projects budget and priorities.

- A trial should examine measures of the radiation and image texture of waste piles, that is the spatial variation of radiation characteristics across a waste tyre pile.
- Tyre piles are both formal in shape, such as rectangular, and random in shape. A trial could be conducted to examine if it is possible to use pattern recognition to identify common shapes of waste tyre piles against templates of common waste tyre pile shapes.
- A trial should examine whether imagery can identify new tyre piles or increases in tyre pile height. A trial could examine Light Detection and Ranging (LIDAR) data for known waste tyre pile sites to determine the accuracy of height measurements and the opportunity for height change detection.

8.2.4 Building upon other work

Figure 43 - Waste tyre piles west of Sulaibiya, Kuwait seen from space (left side) and on the ground (right side) [Image on the left: © DigitalGlobe via Google Earth].

Large piles of waste tyres can be readily seen on very high spatial resolution imagery. The left-hand image in Figure 43 shows a DigitalGlobe image of the Sulaibiya waste tyre site in western Kuwait, a site that has developed substantially since 2010 to be a major waste tyre site. Each of the rectangular waste tyre areas on the left side of this figure measure approximately 70 metre (m) x 40 m. On the right side of Figure 53 is a ground surface picture of one of the waste tyre piles.

RS imagery has been used by Quinlan and her colleagues to test the ability of high spatial resolution image data to identify tyre piles in California and Mexico (Quinlan 2006, 2009, 2012). Imagery from Ikonos and QuickBird satellites were analysed to identify illegal tyre waste dumps in central and southern California. For the Sonoma and San Bernardino regions of California, four hundred high resolution satellite images on 40 dates in the period November 2005 to November 2007 were analysed. In general waste tyre dumps appear as dark tones on optical wavelength remote sensing images, but there is confusion with other persistently dark features such as water, shadows, asphalt, rusted metal or black plastic used on farms. The results of the analysis by Quinlan were 76 sites identified as potential tyre dump sites which required field inspection. Of the 76 sites, 66 contained waste tyres and only 3 sites were false positives.

So, waste tyre piles can be seen on satellite imagery, but can they be identified unequivocally and consistently? Waste tyre piles are dark in tone in optical wavelengths because of the black rubber, but there is potential confusion with water and shadows which are also dark in tone. There is also the potential for confusion with burned areas which are also dark in tone. A trial to examine the ability of remote sensing to detect waste tyre piles should consider the following issues.

- Dark tones in optical wavelengths. The dark tones of waste tyre piles are useful to detect tyres against a substantially different background such as desert sands in the case of Kuwait or active vegetation in agricultural or woodland areas in temperate countries. The confusion with water, shadows and burned areas can be addressed by using ratios of wavebands and also by exploring the value of short wave infrared wavebands.
- Texture. The surface of waste tyre piles is highly varied because of the tyres themselves, so an analysis of image texture could be valuable. Areas of high texture and dark tones would narrow down the likely locations of waste tyre piles.
- Shape and pattern. As in figure 43, organised piles of waste tyres often show a clear structure and so their appearance may be useful for recognition purposes. This may be useful for checking the spatial extent of known waste tyre sites. Illegal sites are generally characterised by incoherent piles so shape may not be so useful.
- Height. Waste tyre piles may be higher than the surrounding areas so measurement of height change can be useful. Airborne LIDAR will be particularly useful, especially for repeated coverage of known sites because the change in height will be clear. Interferometric SAR could be used to map height change, although this will be at the limits of the practical use of the technology.

Figure 44. Waste tyre piles at the Palabora Mining Company, Phalaborwa, South Africa. The two images have different scales [Source: DigitalGlobe via Google Earth].

Figure 44 (above) shows satellite images of two areas of waste tyre piles at the Palabora Mining Company, Phalaborwa, South Africa and on both images the four features noted above can be seen.

8.2.5 Test Area

The size of the trial areas will be important for reasons of cost and data handling. The minimum area for very high resolution data ordering is typically 25 sq km, so the size of the trial areas should be 5 km x 5 km. This trial will have two test sites.

8.2.6 Data to be Used

(i) Radiation characteristics

The trial should consider the following types of RS data.

- Visible and near infrared. It is likely that this type of data will be the most useful because they are the most readily available and at the highest spatial resolution. Waste tyre sites will appear as dark tones in the visible and near infrared.

- Short wave infrared. Data in this waveband are less common but typically do show more subtle features than visible and near infrared data. They are worth examining but not as the top priority.

- Thermal infrared. These data will show the temperature at the ground surface and so will show waste tyre piles that are either burning or hot enough to be near to burning.

- Radar data have value in areas of persistent cloud cover. There has been no published research on radar data of waste tyre piles and it is not clear what their absolute backscatter will be, but because of the higher backscatter waste tyre piles should appear brighter on radar images.

(ii) Texture

For visible and near infrared data, there are several texture measures found in the main image processing packages such as European Space Agency (ESA) SNAP and ENVI/IDL. Radar data measure the backscatter of the radar impinging of the waste tyre pile. Because of the local height variation in the surface (i.e. the texture) it is expected that the radar backscatter will be higher at waste tyre pile sites that in neighbouring areas.

(iii) Height

A trial could examine LIDAR data for known waste tyre pile sites to determine the accuracy of height measurements and the opportunity for height change detection. The size of tyre piles and the relationship to satellite sensor pixel size will be important in assessing the ability of remote sensing techniques to identify waste tyre piles. As illustrated in figures 53 and 54, very high resolution imagery with a small pixel size can readily show waste tyre piles. The question arises of how effective are different pixel sizes in identifying tyre piles.

Table 20 shows the number of pixels at a range of pixel sizes that can be used in measuring a waste tyre pile. The table gives data for pixel sizes ranging from 30 m (Landsat Operational Land Imager multispectral mode) to 0.31 m (WorldView-4 panchromatic mode).

Two waste tyre pile sizes are included in table 20: first the size of very large tyre piles such as found in Sulaibiya, Kuwait (70 m x 40 m) and second the size of large tyres piles typically found in the USA and Europe (20 m x 20 m, Evans and Evans 2006).

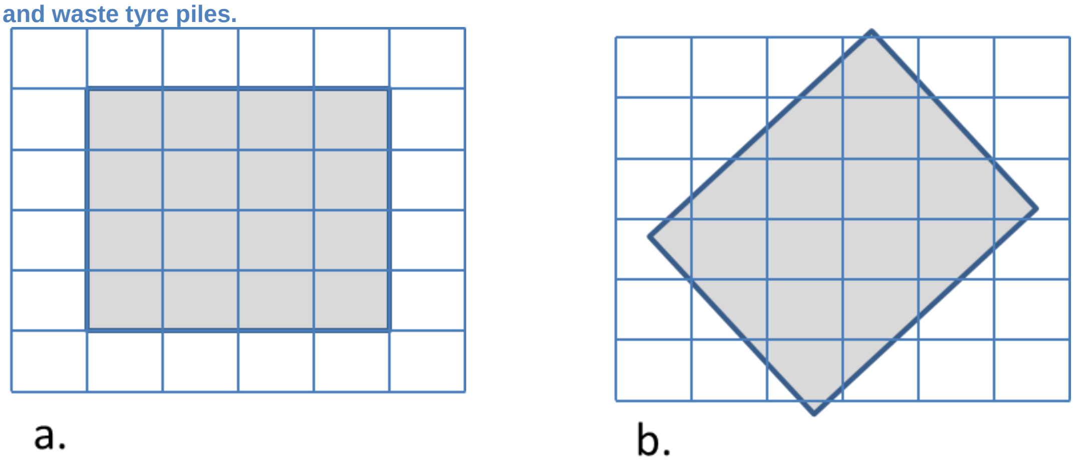
Table 20. The number of pixels at varying pixel sizes for a perfect alignment and a normal alignment with waste tyre piles of 70 m x 40m and 20 m x 20 m

	Waste tyre pile size : 70 m x 40 m		Waste tyre pile size : 20 m x 20 m	
	Perfect alignment	Normal alignment	Perfect alignment	Normal alignment
Pixel size (m)	Number of pixels	Number of pixels	Number of pixels	Number of pixels
30	4	2	1	<1
20	6	3	1	<1
15	8	6	1	<1
10	28	18	4	<1
5	112	91	16	9
1	2800	2584	400	324
0.5	11,200	10,764	1600	1444
0.31	29,128	28,321	4160	3969

For each pile size and pixel size combination there are two assumptions concerning the number of pixels:

- A perfect alignment of the waste tyre pile and the image pixels. This is shown schematically in figure 45a. This would be very unusual and therefore represents the maximum number of pixels possible.
- An estimate of a more normal situation where pixels overlap the edges of tyre piles. This is shown schematically in figure 45b. This is a more realistic assessment of the number of pixels.

Figure 45. A schematic representation of the perfect alignment (a) and a normal alignment (b) of pixels and waste tyre piles.



For very large sites, such as 70 m x 40 m, RS data with a pixel size of 10 m should be adequate for the trials. For large sites, such as 20 m x 20 m, it will be necessary to use data with a pixel size at or near 1m. This rules out using open data. Sentinel 1 and 2 and Landsat data are free of charge, but not very high spatial resolution and are probably of little value for waste tyre pile detection.

Bearing the pixel size requirement in mind, the following data is required:

- Three very high resolution optical images taken of both sites (6 images in total);
- One very high resolution radar image scene, taken on two separate dates (2 scenes in total).

8.3 Pilot 3 – the behavioural case

8.3.1 Description

The brief for this pilot is to get a better understanding of whether the use of satellite monitoring by environmental regulators can have any form of beneficial deterrent impact in relation to waste crime. This trial has some similarities to Trial 2 (waste tyre monitoring), in that it is based on the regulator adopting a flexible risk-based enforcement strategy to waste regulation.

The key difference is that instead of the primary focus being on what the satellite can identify in respect of risk-based checks on permitted sites (in essence its effectiveness as an intelligence tool to target on-the-ground resources), the focus of pilot 3 will instead be on the potential outcomes in actually having a satellite monitoring system. Primarily, what kind of deterrent impact might it have? The contractor will evaluate whether there were any changes in compliance behaviour by those organisations and individuals in the waste industry that were being subject to satellite checks (at waste sites with licence and exemptions). This will be done by examining whether there were any changes on waste sites before and after a regulated group were made aware of the monitoring.

The second part of the brief for Trial 3 will be to examine some of the satellite data collected above to consider whether sites with registered waste exemptions were acting in accordance with the limits of their exemption. Volumetric analysis by satellites will be too expensive as part of their trials. Instead the contractor will just look at see if there are any obvious discrepancies in size of (exempted) waste sites at any of the test sites.

8.3.2 Justification

(i) Deterrent

Environmental compliance is often measured by comparing the number of inspections with the number of enforcement actions, in order to garner insight into the relative success of enforcement strategies. However, this does not paint a full picture as to the success of a given compliance strategy, and probably underestimates environmental performance in practice. Although inspections open up the possibility of non-compliance being detected, it is more likely that it is the actual threat of detection that encourages compliant behaviour. Standard deterrence theory holds that the mere fact of conducting inspections, coupled with the probability of detection being credible, should increase the rate of compliance (Posner, 1993). Often cited in this context, Bowles considered that ‘20 percent of the regulated population will automatically comply with any regulation, 5 percent will attempt to evade it, and the remaining 75 percent will comply as long as they think that the 5 percent will be caught and punished’ (Bowles, 1971).

If Bowles’ assumption is correct, risk-based regulation could mean that the targeting of those who are most likely to seek to evade the law should bring about better overall compliance. However, risk based strategies at a time of pressures on regulatory budgets has also meant that there could be less frequent inspections overall – which might well also have a negative impact on perceptions and compliance behaviour.

Some incidents of non-compliance might be more effectively deterred if those regulated thought that they were being permanently monitored, or monitored a lot more than was the case. This has been argued since Bentham’s Panopticon theories, where he considered that ‘the more strictly we are watched the better we behave’ (Quinn, 2001). With this in mind, it is possible that a regulatory satellite monitoring programme could act as an increased deterrent over conventional inspection approaches, becoming a new creative means to influence potential criminal behaviour in the area of waste regulation.

In earlier work as part of this study, we identified that satellites appeared to be able to have a higher deterrent effect than some other technology-based enforcement approaches, such as speed cameras or closed circuit television (CCTV), because they are by their nature covert. Regulators could have a tool where the regulated can be made aware that they could be watched at any time, but they cannot actually tell whether in fact they are being monitored.

The threat of such monitoring (which might be considered to be both continuous or more advanced than is the case) might provide regulators with a credible deterrence threat, whereby they could create the impression of a substantial capability and threat of enforcement with only very limited regulatory resource commitment (i.e. better results for less spend). Exploiting the gap between 'perception and reality' in this way could enable greater successes when combined with risk-based regulatory approaches.

(ii) Exemptions

In the UK, there can often be tens of millions of tonnes of waste which are exempted (as waste-holders often apply to the end of the upper limit). Regulatory bodies do not appear to have an accurate estimate of how much of the exemptions are actually used. Sites are not currently subject to any form of fixed inspections because they are deemed to be low risk, which has meant that there is less chance of detection of illegality by the authorities. There have been some cases of large scale illegality originating from exempted sites. Remote sensing could potentially be used to check legal compliance and identify obvious large scale illegality at some sites.

8.3.3 Trial design

The consultant will look at a selection of licenced sites, and sites with waste exemptions, in three small areas (Test Site A, Test Site B and Test Site C). RS images will be collected of all three sites at the beginning of the trial. The following will happen after images have been collected of all sites.

Test Site A – The regulatory body will be asked to write to the licenced sites, and sites with exemptions, in Test Site A, telling them (on headed paper) that a trial is going to be taking place in their area, using satellite technologies, over a specified time period in the future (e.g. the trials will take place over 1 month, in 4 weeks' time).

Test Site B – The regulatory body will be asked to write to the licenced sites, and sites with exemptions, in Test Site B, telling them (on headed paper) that they had started using satellite technologies to monitor waste crime in some parts of Scotland. The correspondence would include RS images of the areas covered in the trial to illustrate what can be seen.

Test Site C – these will be unaware of any satellite monitoring as they will not receive a letter or image.

The Consultants will then examine RS images to assess whether there were any changes in activity at Test Sites A, B and C, between dates, to see if there were any non-compliance indicators (e.g. waste piles being moved, items covered up, waste burnt).

A second part of the trial will be to assess whether sites with registered waste exemptions were acting in accordance the limits of their exemption. RS data will be analysed to see if it can show approximate waste quantities at some sites, to see if sites which are clearly not within their exemption can be detected.

We do not yet know how many exempted sites will be situated in the Test Site areas, and it is likely that the consultants will not be able to examine all of them. A selection of sites should be looked at in total across Test Sites.

8.3.4 Building upon other work

There has been little research into whether mere knowledge of being monitored by RS could lead to positive compliance outcomes, in terms of influencing the behaviour of those subject to regulation. At the moment, there is limited compelling evidence.

It is clear from earlier research studies that those being monitored generally do not know the extent of the monitoring capability. Academic research by Purdy found that UK farmers claiming EU agricultural subsidies did not have a clear idea of how regularly they were monitored by satellite, and found that they greatly overestimated both the percentages of farmers monitored this way annually, and the number of actual checks made by satellite (Purdy, 2011). Only 14% of the farmers thought that less than 10% of farms were monitored annually, with significant numbers believing that the answer was over 50%. 43% of UK farmers also thought that there was satellite monitoring at least once a year. The truth was that approximately 5% of UK farms were monitored each year, with each farm in the UK actually having been monitored on average once every 23 years. This perception of more substantial monitoring than was the case appeared to substantially improve compliance levels with the legislation and reduced fraud in the UK.

Another important finding of the above research by Purdy was that those regulated did consider that the satellite monitoring was having an effective deterrent impact. Nearly two-thirds of UK farmers agreed that the fact that they were being watched by satellite was acting as a strong deterrent.

A trial looking at deterrent impact could be of international importance, and would attract a lot of academic and regulatory interest.

8.3.5 Test area size

The contractor would focus on three specific small areas containing a suitable number of companies associated with the waste industry, or using exemptions. It is hoped that these could be in a 5km by 5km area; however a larger area may be necessary to include enough exemption sites to provide a robust dataset. The selection will be made with the cooperation of the regulatory body.

8.3.6 Data to be used

The contractor would use optical satellite data from a mixture of commercial and open data sources. Open data would be used to provide a comparative analysis of the benefits of commercial and open data.

Far more detailed information can be seen from satellites operating at higher spatial resolutions. We envision this trial using high resolution imagery between 0.5m to 2m resolution depending on the area that is required to be imaged.

The contractor would need 3 optical images taken on two different dates - i.e. before and after (total 6 images).

8.4 Pilot 4 – detection of unknown sites

8.4.1 Description

The main brief in this pilot will be to use EO data to identify operational unlawful waste sites, which are unlicensed (i.e. sites that the regulator does not know about).

8.4.2 Justification

EU criminals are short-changing economies, exploiting the high costs of legal waste management, by making substantial profits from unlawful waste landfills. Some governments are overwhelmed with the problem, and struggle to detect the very large numbers of unlawful sites (that have been occurring in some countries) quickly. This is because some sites can be in remote locations, or difficult to see at ground level, and there can be a lack of good timely intelligence. Some will be run by organised criminals who have disguised their operations at ground level.

Sites that are unlicensed are costing countries' economies huge amounts of money in lost tax, clean-up costs and losses to legitimate companies (who are being undercut by rogue operators who avoid the costs of legal disposal). Unlawful landfills are also causing significant degradation and damage to the environment (land, water and air), and can have a very serious detrimental impact on human and animal health.

A key issue is that although significant sums of money is often spent on waste crime the problem can often be dealt with too late. In essence, an intelligence lag. A monitoring system which used EO could be extremely interesting to environmental regulators because it might enable them to be more pro-active and less reactive to the problem. Better targeted intelligence reports could enable them to better deal with the problem before it gets so expensive, potentially saving tens of millions (at a low estimate) by more tax collected, lower clean-up costs, additional revenue to legitimate business, and have wider environmental/societal/health benefits. Regular EO monitoring might also improve the chances of the regulators both catching criminals in the act and prosecuting/fining them; as well as having someone identifiable to recover retrospective waste landfill tax owed (which is possible in some countries, including Scotland).

8.4.3 Trial design

The contractor will have to design a methodology and detection model that can find unlicensed sites.

In the trial five validation sites will be chosen by the regulatory body. These will give the contractor a map with up to five areas, each in either a 25km2 or 80km2 radius. Each circle will contain at least one randomly located unlawful waste site and the contractor must find that site, or sites, within each circle.

Ideally, the validation sites would have the following characteristics:

- These will be waste sites that had been discovered in the last 12 months by the regulatory body.
- They would be sites that were active when discovered, as opposed to abandoned (so the timing of when operational is not unknown).
- Ideally there would be two waste sites contained in each circle (but this is dependent on what the regulatory body have detected).

Five sites have been suggested because the contractor would need a selection of sites because of potential cloud cover issues. In practice, only one site will be examined by the contractor (after imagery availability has been confirmed for those locations).

As it is a 'blind' trial, the true locations of the unlawful waste sites will not be disclosed by the regulatory body to the contractor. The contractor will then produce a report which describes where they think the unlawful waste sites are in two circled areas, and the regulatory body will then disclose the true locations of the illegal waste sites in these areas. This will enable an evaluation of the success of the contractor's methodology and detection model.

The contractor's report should also demonstrate any differences in findings between the use of open data and commercial data.

8.4.4 Building upon other work

There does not appear to be any published work available about the detection of unknown waste sites. There appears to have been a small number of earlier trials that have been conducted, but this data is not publically available.

8.4.5 Test area size

The regulatory body will give the contractor a map with up to 5km by 5km areas. One area will then be chosen by the contractor, after examining imagery availability and cloud cover. Note: more than one test area can be examined, but this is outside the budget envisaged below. The regulatory body could decide to increase the number of test sites in this particular pilot if more money was made available (than envisaged in the budget in Section 7).

8.4.6 Data to be Used

The trial would use VHR optical data and SAR data, from both open and commercial sources.

The minimum following data is required:

- One very high resolution optical image taken of the location (1 image in total);
- One very high resolution radar image scene, taken on two separate dates (2 scenes in total).

8.5 Key challenges

8.5.1 Introduction

This document has proposed four trials to examine the ways in which EO data can be used in the waste crime sector. The four trials are deliberately different in character so that different attributes of the use of satellite data can be assessed. In carrying out these trials there will be some key challenges that need to be considered and this section identifies those challenges under two headings: data availability and data processing techniques.

8.5.2 Data availability

EO satellites dedicated to land applications are mainly placed in polar orbits, i.e. they orbit the Earth crossing the North Pole and then the South Pole. They achieve global coverage by the Earth spinning underneath their sun-synchronous orbit while they travel from one pole to the other. This means that the maximum revisit cycle is twice per day for any one location, i.e. once during the day and once during the night. Applications relevant to the waste crime sector need data from daylight hours, so the maximum revisit cycle is once per day. In practice, the real revisit cycle is much longer than this, typically of the order of weeks because of the swath width of the satellite coverage. It is possible to task some EO satellites to revisit more often than this, but this carries with it extra expense.

Cloud cover is always a problem for optical EO data. In the presence of cloud, no data of the surface can be collected at all. Even with satellite tasking, if there is repeated cloud then there will be no image data capture. One solution to the cloud cover problem is to use radar data because radar can see through cloud and produce image data of the surface. However, the techniques of data processing for radar data are not as mature as for optical data.

Data formats for satellite image data have become more standard in recent years, but it is still necessary to check in advance that the data formats provided by the data suppliers are compatible with in-house data processing technologies.

Very high spatial resolution image data are highly attractive for the waste crime sector, especially given that the smallest pixel size of 0.31 m provides images close in resolution to those from aerial photographs. However, such images do carry high costs for large areas. Previous reports in this series have described the costs: individual images cost of the order of hundreds of euros, but when large areas are considered then the costs are in the thousands or tens of thousands of euros. The research by Quinlan summarised in earlier reports in this series cost of the order of US$250,000 for one study in California to identify piles of waste tyres.

8.5.3 Data processing techniques

There has been some success in the literature for identifying waste sites using a combination of band ratios and texture analysis. The band ratio techniques are well established and in common use, and are used to identify the presence or quality of vegetation cover: in the case of waste sites the target is likely to be a reduction in vegetation over time. Problems may arise when there is insufficient contrast between waste sites and their surroundings. This may happen when illegal waste sites are located in areas where vegetation is sparse and/or highly varied. In the suggested trial of identifying waste tyre piles it is easier to identify tyre piles if they are in an area of highly contrasting surfaces such as bare concrete but more difficult to do if the tyre piles are in or near an area of black tarmac, water or dark vegetation.

Although techniques for the analysis of image texture have been used for decades they are not as mature as those for band ratios. While the main image processing packages do include techniques for analysing image texture (for example the ESA SNAP package), the application of those techniques is still in the development phase. Trials that use image texture measurements are just that, i.e. trials of the data processing chain.

Analysis of radar images is potentially useful but the techniques are still in the development phase. They have been shown to work, and work impressively, in the experimental domain but it is difficult to regard the analysis of radar data as fully operational in the waste crime sector: the data analysis steps are well known but need to be assessed in practice.

LIDAR data can be used for estimating surface height and therefore surface height change over time. The data processing techniques for height estimation are robust for clean surfaces but need to be evaluated in more detail for the highly variable surfaces found at waste crime sites.

8.6 Budget

We have estimated that a budget of £53,990 would be necessary to do the pilot studies, as they are envisaged above. A breakdown is contained in Table 21.

Table 21. Proposed budget for pilots

Item	Price
Earth observation satellite imagery and drone imagery	£22,300 (including VAT)
Data contingency fund *Note: imagery might be affected by cloud cover, which can be quite prevalent in Scotland. Some money has been budgeted to allow the contractor to purchase additional (unforeseen) imagery if necessary.*	£1,500 (including VAT)
Currency fluctuation contingency *Note: imagery is purchased in Euros and Dollars, and the price in pounds can be affected by currency fluctuations (e.g. following elections or referendums). We have allowed for a 5% contingency in case this happens.*	£1,190
Project administration costs	£1,000
Labour costs (20 days allocated per trial; 80 days work in total)	£28,000
TOTAL	**£53,990**

8.7 Cost benefit analysis

At this stage, it is difficult to do a full cost benefit as the actual data required will only emerge after the results of the trial pilot studies are obtained. But each of the trials is designed to tease out how RS might complement, extend or amplify the capabilities of environmental regulators.

Case 1 looks at how effective RS could be in gathering and compiling the evidence/ case for enforcement proceedings. As each case is different this will be best judged by the teams normally carrying out the conventional routines.

Case 2 looks to test how effective, and at what cost, breaches can be detected and documented at known sites. This should be the simplest cost benefit judgement to make.

Case 3 introduces a dimension that is difficult to compare with existing approaches. Nevertheless, if demonstrated successfully, it could be very attractive in today's resource challenged regulatory bodies.

Finally, **Case 4** offers perhaps the potentially most powerful complement to conventional ground bound enforcement efforts. The ability to routinely and systematically sweep large areas is practically not possible to contemplate with current approaches to inspection.

Table 22. Cost benefit analysis of recommended pilots

Case Study	RS Overall Trial Costs	Data Costs	Labour costs	Equivalent Conventional Monitoring / Inspection Costs	Expected Cost saving (Benefit)
Pilot 1 Alternative enforcement evidence provision	£11000	£4000	£7000 (20 days work)	£615,000 (Life 10 ENV UK 2011 SEPA cost estimate)	Possibly 10:1
Pilot 2 Normal Waste Tyre Inspection equivalent	£16000	£9000	£7000 (20 days work)	Typical monitoring and enforcement costs of between £20,000 - £50,000 (Life 10 @2017 prices)	Possibly 2:1
Pilot 3 Behavioural deterrence	£9700	£2700	£7000 (20 days work)	N/A	Essentially low-cost inspection say 10:1
Pilot 4 Unknown site detection	£13,600	£6600	£7000 (20 days work)	Very difficult conventionally – chance or random discoveries	Leverages existing resources in scope and effectiveness. Needs evidence from trial
Total	£50,300	£22,3000	**£28,000** (80 days work)		

In the table above the costs of the plots has been estimated for the different recommended pilots and a notional estimate of what might be expected to emerge from the pilot studies. Full cost benefit analysis will then form the basis for decision making as to whether or not to deploy these remote sensing possibilities routinely as part of an environmental regulators enforcement options.

9.0 Conclusions & recommendations

A key conclusion was that many monitoring programmes using RS have resulted in successful outcomes, which should promote confidence in the opportunities it offers in the context of waste crime. They suggest that there are real opportunities for innovative approaches to using RS in waste regulation applications.

A further conclusion is that it would be beneficial for RS to be seamlessly integrated into a facility (a true relational database) for assembling and displaying its results as part of an interactive, live GIS database to hold terrestrial awareness and surveillance information as well as satellite inputs. It should also have the potential to combine RS imagery with GIS technologies and other geospatial data and techniques. For example, comparison of existing data on volumes of waste processed at individual sites, with the estimated waste generated within the catchment, may identify anomalous volumes of waste or processing.

RS clearly can provide historical evidence that might be useful to regulators (e.g. the timing of the unlawful act). It should also have a pro-active detection element, identifying opportunities for tasked regular monitoring programmes to catch operational unlawful sites. This would encompass further examination of what RS platforms may be able to detect using standard optical, spectral, thermal and Synthetic Aperture Radar (SAR) sensors.

From our case study examination, we found that the sites (in Annex 2) had connecting factors which could possibly be flagged as susceptible to waste crime from three main factors:

- Type of business;
- Licence conditions;
- Personnel with recorded breaches of conditions.

The above would make it possible to target specific locations rather than searching countrywide. It is possible that these are the “low hanging fruit” and there are also more clandestine operations that are not routinely identified.

We also concluded that:

- Most of these locations detailed in Annex 2 (Case Studies) would be evident from high resolution optical imagery.
- Texture analysis may highlight locations of open mixed waste.
- Multispectral imagery can be processed to produce various indices highlighting vegetation stress, distinctions in soil classes and evidence of fires.
- Worldview 3 may be used to detect plastic materials in bulk but potentially also mixed in with a soil substrate.
- Airborne hyperspectral sensors can detect specific materials from their reflectance spectra. A significant investment would be needed to operationalise this technique.
- Change detection is a useful technique for detecting unusual activity that can be missed from single source analysis. Particularly if tasked to identify an undefined activity in an undefined location.
- Changes in land elevation can also be indicative of waste crime.
- There is a trade-off between area coverage and image quality.
- In some areas, it may be more effective to look at airborne remote sensing rather than focus solely on satellite sensors. Many aircraft carry multiple sensors allowing simultaneous collection of high resolution imagery and LIDAR. Drones give high resolution results at cost effective prices but can only target known locations, rather than search out potential new targets.

Other changes are social and economic. For example, landfills are shutting down. 50-60% will be closing in the next few years – so waste won't be going there. Where will it be going – incinerators, export?

Other insights that the report concludes include:

- Once users have gained experience in using RS data archives and tasking web sites then the technical process of acquiring remote sensing data is more straightforward. However, to gain such practical experience can take considerable time.

- The data licence terms and conditions require considerable knowledge and understanding of the implications of the licence.

This may be why more satellite data providers are inviting customers to engage in a dialogue with them rather than for users to try and use a web site that is fundamentally complex, especially for new users or users whose domain of expertise is not in remote sensing. Data brokers also provide good web interfaces to data catalogues so it is still possible to use web sites to research data archives or plan satellite tasking.

On the whole, the costs of acquiring very high resolution and high-resolution data image data are high if you want to monitor very large areas (e.g. an entire country regularly). The regulators could either choose to look at selection of random areas (e.g. like EU subsidy monitoring, which is about 5% of the whole of the land-mass in the UK). Alternatively, a regulator could buy data of areas that are experiencing the most problems (e.g. if the problem is worst in the Highlands in Scotland then they could start by targeting their resources on that area). Having data in the future that shows where waste crime is believed to be happening the most in a country would be useful in determining potential costs.

It is also not necessary to buy whole images. Data can be purchased for any polygon shape. So, data can be purchased in a polygon shape covering certain areas where, for example, serious illegality is known to have occurred before.

The data prices in the tables in Annex 4 were indicative prices of purchasing small quantities of data. Most satellite operators would be open to negotiate bulk discounts for purchases of substantial amounts of imagery, especially for a regular monitoring programme. In our experience, even in regular monitoring programmes the price of the imagery can be constantly re-negotiated.

Purchasing satellite data is more cost-effective if it can also be used by other government agencies, or used for multiple purposes (subject to the relevant licensing authorisation). In terms of other activities this might encompass other uses such as: monitoring fish farms, monitoring illegal house building (without necessary permissions), or monitoring protected areas like SSSIs.

Key to the use of RS in the waste crime sector will be showing if this form of monitoring works. This document contains recommendations for four pilot projects, which if taken forward will enable important new evidence to be collected on the viability of a future operational case for using RS technologies in waste regulation.

The four pilots which were recommended in this document are:

1.	**An operational 'live' case**	• Test the use of archived satellite data to provide evidence of timing and locations of unlawful waste sites. • Examine the usefulness of integrating satellite data

		with other GIS data. • Assess how the regulator might like to receive the data, and consider licensing issues (in the event of being used in court) and the applicability of investigatory powers. • Consider the viability of using UAVs to estimate the volume of waste at an unlawful site.
2.	**Monitoring waste tyre piles**	• Test monitoring licence breaches at licenced waste sites (with a focus on tyre piles). • Examine the potential of designing a detection model to detect changes at unlawful tyre sites.
3.	**A behavioural case**	• Assesses whether satellite monitoring might have a beneficial deterrent impact in relation to waste crime. Test whether there were any changes on waste sites after a regulated group were made aware they were being monitored. • Examine whether sites with registered waste exemptions were acting in accordance with the limits of their exemption.
4.	**Detection of unknown sites**	• Test whether EO data can identify operational unlawful waste sites which are unlicensed (that the regulator doesn't know about).

The pilots are deliberately different in character so that different attributes of the use of satellite data can be assessed. The pilots also deliberately differ in terms of difficultness (in undertaking) and cost (we have attempted to extract the most 'bang for buck' possible). These pilots are intended to demonstrate the effectiveness of different forms of RS and UAV when used in various different types of waste regulation – from checks at licenced waste sites to detecting illegality at unlicensed sites.

The designs of the four pilots, described in this document, are written with a strong recognition that these are being done to support the activities of environmental law enforcement - in line with end user needs. It is expected that the range of the trials will enable environmental regulators to determine whether RS can offer something new to them (or whether it is, in some way, better than existing regulatory methods), and to provide a calculation as to cost – so they might determine whether its viability in certain situations.

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Annex I - Consultees

Bodies consulted

- Chilean Superintendency of the Environment [Chilean Aquaculture monitoring]
- European Maritime Safety Agency (EMSA) [European Oil Pollution monitoring]
- Joint Research Centre (JRC), European Commission [EU Agricultural monitoring]
- North Sea Network of Investigators and Prosecutors [European Oil Pollution monitoring]
- Maritime and Coastguard Agency, UK [European Oil Pollution monitoring]
- Office of the Prosecutor of the International Criminal Court [Human rights monitoring]
- Risk Management Agency (RMA) of the Department of Agriculture in the United States [Agricultural fraud monitoring]
- Scottish Environmental Protection Agency

Bodies contacted

- Association of European Administrative Judges, Environmental Law Group (AEAJ)
- Australasian Environmental Law Enforcement and Regulators Network (AELERT)
- East African Network for Environmental Compliance and Enforcement (EANECE)
- EnviCrimeNet
- European Centre for Space Law (ECSL)
- European Network of Prosecutors for the Environment (ENPE)
- European Union Forum of Judges for the Environment (EUFJE)
- European Union Network for the Implementation and Enforcement of Environmental
- Law (IMPEL)
- Europol
- International Association of Prosecutors (IAP)
- International Institute of Space Law (IISL)
- International Law Association – Space Law Committee (ILA)
- International Network for Environmental Compliance and Enforcement (INECE)
- Interpol

Annex II – Case studies

Case Study Number	Brief Facts	Photograph
1	Cornwall. Landfill leachate overflowed from a deep extraction well at legal site. Unauthorised methods of disposal in an attempt to remove large volumes of contaminated surface water from the site, pumping it onto adjacent fields.	  <https://www.gov.uk/government/news/suez-to-pay-505000-for-pollution-at-cornwalls-largest-landfill>
2.	Illegal export from recycling company in Warrington. Eleven shipping containers full of WEEE were found by EA destined for Nigeria, Ghana and Tanzania.	 http://resource.co/article/fine-illegal-weee-export-after-panorama-sting-10664

3.	Illegal waste operation in Shropshire (no permit). Site had a large number of skips containing a variety of waste	 http://www.expressandstar.com/news/crime/2017/01/27/firm-and-boss-must-pay-30000-over-skips-of-waste-with-130000-bill-to-clear-site-up/
4.	Storing waste on land in Wakefield with no environmental permits in place for the operation. Piles of waste and skips (was a skip company).	  http://www.examiner.co.uk/news/west-yorkshire-news/sam-hunter-court-over-illegally-12519289

5.	Mountain of mattresses in Kent, built up recycling firm. Failed to comply with waste exemptions and enforcement notices.	  http://www.dailymail.co.uk/wires/pa/article-4189178/Rogue-recycler-given-suspended-jail-term-Kent-mattress-mountain.html
6.	Site in Shotts (organised crime gang) stored waste there contrary to exemptions registered for the site. Unsegregated mixed waste contained in skips: construction and demolition waste, tyres, plastic, polystyrene, bales of municipal solid waste, food waste, cathode ray tube monitors, metal, wood, soil, rubble, liquid waste, car batteries, an end of life vehicle, packaging, carpets, furniture, road planning's.	 http://media.sepa.org.uk/media-releases/2016/former-company-director-sentenced-to-undertake-200-hours-unpaid-work-for-breaching-environmental-legislation/

7.	Skip hire operator (with no permit) using his farm in Oxfordshire to store large quantities of waste (household and hazardous) illegally. Stored in skips and dumped on land.	  https://www.mrw.co.uk/latest/skip-operator-gets-suspended-sentence/10015696.article
8.	Scottish tyre disposal company breached waste management licence at five sites. Exceeded the maximum permitted storage height for tyres, stored a quantity of tyres without the authority of a waste management licence at some sites, kept tyres on other sites for a period exceeding three months. Sites had 6,900 – 15,000 tyres on. One site had burnt tyre residue. Not clear how many stored inside and how many outside.	 http://resource.co/article/businessman-fined-34000-waste-tyre-recycling-offences-11551
9.	Teeside wood recycling company kept wood in a way likely to cause pollution or harm to human health. They exceed the size of allowed wood piles (making combustion highly likely) and ignored the specified fire breaks recommended. They also illegally deposited 8,200 of wood waste on an adjacent site they leased.	 https://www.mrw.co.uk/latest/teesside-wood-recycler-fined-after-blaze/10015194.article

10.	London waste transfer station failed to comply with conditions of permit. The permit required the waste to be stored in a building and to a limit of 2.5m in height. Neither was being done. They also had an excessive quantity of waste on site, being stored outside, and at risk to fire.	 https://www.gov.uk/government/news/london-waste-company-fined-for-breaching-permit
11.	Skip company operated an unlicensed landfill on public land (behind a Glasgow industrial estate). Left thousands of tonnes of waste. Satellite images on Google Earth – taken before DC Skips left the site – show a digger operating at the site.	 http://www.eveningtimes.co.uk/news/13260514.Illegal_Glasgow_dump_could_cost_taxpayers___500_000/
12.	Rubbish stored at a Swindon recycling site caught fire, and company was prosecuted for keeping and disposing of waste in a manner likely to harm environment or human health.	 http://www.itv.com/news/westcountry/2016-10-27/averies-recycling-brothers-sentenced-over-tip-fire-which-burned-for-two-months/

13.	Illegally deposited mounds of wood at a site near a busy dual carriageway in Kent. Burnt waste at the site.	  http://www.kentonline.co.uk/canterbury/news/two-men-fined-after-dumping-114743
14.	Unlicensed site in Kent containing masses of construction waste, old tyres and scrap vehicles	 https://www.businesswaste.co.uk/kent-waste-crook-given-curfew-and-electronic-tag/

15.	Offender in Eastleigh operated by offering to dispose of waste for businesses in the area before taking it to an illegal site where he would sort through it, removing all valuable materials and burn as much as he could of what was left.	  http://www.dailyecho.co.uk/news/14742806.VIDEO_AND_PHOTOS__Notorious_flytipper_jailed_after_dumping_waste_across_Hampshire/#
16.	Bromley recycling company had been stacking flammable materials 12 times higher than legal limits. Company left 18,000 tonnes of waste on site. £2.7 million clean-up cost (being done by Veolia). EA paying most and Bromley council 10%.	

		 http://www.newsshopper.co.uk/news/14834029.Waste4Fuel__First_trucks_ready_to_move_on_vermin_ infested_rubbish_dump/#
17.	Breach of permit exemption in Sussex. Was allowed to store 500 tonnes of wood waste but stored 1200 tonnes on leased land and did a flit when asked to remove it.	 https://www.gov.uk/government/news/jail-for-sussex-waste-boss-who-illegally-stockpiled-over-1200-tonnes-of-wood
18.	Deposited construction waste at a builder's yard in Aidrie and burnt mixed construction and demolition waste, including pallets, treated doors, plastic, glass, barrels and wooden roof trusses. Increase in illegality even after warnings.	 http://media.sepa.org.uk/media-releases/2016/airdrie-builder-fined-for-depositing-and-burning-waste https://www.gov.uk/government/news/bradford-waste-firm-ordered-to-pay-27420-for-environmental-offences

19.	On one site Yorkshire repeatedly stored too much waste than allowed in permit (allowed 10 tonnes and stored 75 tonnes). Another site was illegal (had 82 skips – half contained plastics, glass, uPVC frames, furniture, pallets, rubble and garden waste).	 http://www.walesonline.co.uk/news/wales-news/skip-firm-dumped-huge-mountain-11705339
20.	Mountain of waste dumped inside a skip hire company's warehouse. Also, a lot of filled unsecured skips outside which were not in the sites designated zone for storage.	
21.	Operating a waste facility without a licence in Murton. Recycling company. Also, evidence of a fire at the site.	 https://www.gov.uk/government/news/man-jailed-for-running-illegal-waste-site http://www.chroniclelive.co.uk/news/north-east-news/crushed-vehicles-cost-one-northumberland-11649049
22.	Stored scrap vehicles at a former colliery in Morpeth without a permit. Discovered and then failed to clear the site by date required.	 http://www.chroniclelive.co.uk/news/north-east-

		news/crushed-vehicles-cost-one-northumberland-11649049
23.	Ran illegal waste cooking oil storage and processing plant in the Dorset countryside (without exemption or permit). 60,000 litres of mixed oils and food products were being stored. Oils were stockpiled on pallets and on bare unmade ground. Resulted in groundwater and river pollution. The site was also being used for the illegal production of bio diesel fuel.	  https://www.gov.uk/government/news/dorset-man-narrowly-escapes-prison-for-running-illegal-waste-oil-site
24.	Recycling fraud. Falsified WEEE evidence notes (to defraud government backed recycling scheme).	 http://www.businessgreen.com/bg/news/2465163/electric-waste-operator-jailed-over-gbp22m-recycling-fraud
25.	Skip company in Cotswolds. Stored piles of waste including asbestos, loose tyres and hazardous liquid outside a permitted area at one site (in accordance with permit). Also, operated a waste operation without a permit at another site. The latter had 18 skips full of mixed waste.	

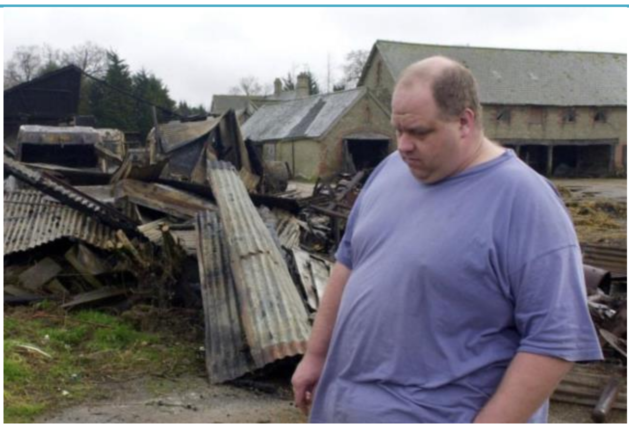
		http://www.worcesternews.co.uk/news/14616082.Skip_hire_director_disqualified_and_fined_over_hazardous_waste/
26.	Over one million tonnes of waste was deposited in an illegal landfill in Mobuoy. The majority of the waste had been buried in sand and gravel pits that had been excavated by a quarrying operation run by a company on the adjacent site, Campsie Sand and Gravel. Next to the illegal site there was a small legal operation (well planned operation).	 http://resource.co/article/1m-tonnes-waste-illegally-dumped-mobuoy-10672
27.	Waste Products company illegally dumped thousands of tonnes of waste in County Durham site. Building waste was piled 27ft (8.2m) high. Breached permit and failed to comply with enforcement notice.	 http://www.sunderlandecho.com/news/crime/waste-boss-who-allowed-rubbish-to-blow-across-country-park-ordered-to-do-litter-picking-as-punishment-by-judge-1-7942351
28.	Recycling company in Kent dumped lorry loads of waste wood on farmland, which was then burned.	 http://www.kentonline.co.uk/kent-business/county-news/ashford-firm-fined-fly-tipping-96392/

29.	A Somerset builder dumped and burned illegal waste in an unlicensed field he owned (including rubble, timber, electrical items and various mixed and commercial waste).	 https://www.gov.uk/government/news/somerset-builder-prosecuted-for-dumping-and-burning-waste-near-crewkerne
30.	Illegal waste site in Shildon. Offender had been running a waste transfer facility on the land – illegally depositing, sorting and storing mixed household and industrial waste. Proceeds of Crime Act proceedings. Waste stored outside and inside warehouse.	 http://www.ciwm-journal.co.uk/wordpress/wp-content/uploads/2016/05/Hackworth-image-1.jpg
31.	Illegally burnt wood waste on Teesside site, next to where corrosive, flammable and toxic substances, which were stored outside (falling outside of permit). There was no concreted surface to prevent chemicals from spilling into the ground, no bounded area to contain a spill and no sealed drainage. The illegal wood waste fire spread causing a major fire where 1,600 litres of formaldehyde spilled into the ground.	 http://www.gazettelive.co.uk/news/teesside-news/huge-chemical-fire-started-because-12190866

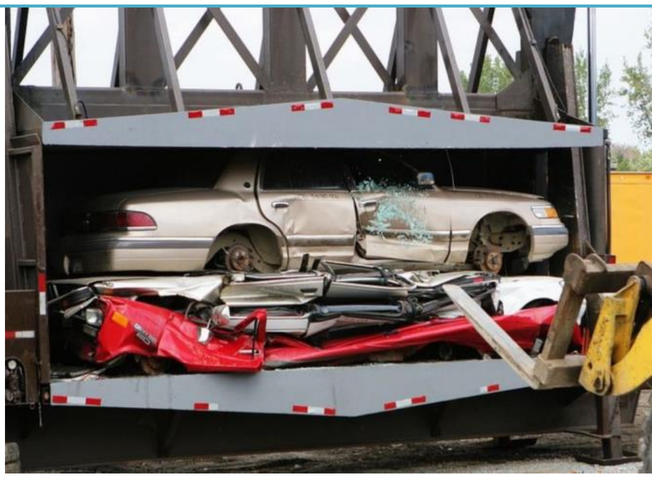
32.	Skip hire company in Blackpool was paid to collect out of date food waste from a Blackpool food distribution company. Then kept a total of 42 skips site at Roseway which contained building materials, household waste, sandwiches, fruit juice, meat and dairy products all of which had expired between one to two months. Some of the waste food was being fed to pigs on the site. Note: skips that weren't full of waste were stacked.	 http://www.blackpoolgazette.co.uk/news/crime/skip-firm-boss-guilty-of-illegal-collections-1-7895985
33.	Company produced Hazardous Waste Consignment Notices (HWCNs) containing false information to customers from whom he collected waste oils. They then transported the oils to the site pending re-sale. Had over 3,000 litres of waste oil being illegally stored in plastic and metal containers. There were no measures in place to prevent the oil from reaching open water drains nearby in the event of a leak. Note: appears stored inside.	 https://www.gov.uk/government/news/kidderminster-man-sentenced-for-running-illegal-hazardous-waste-site
34.	Failed to comply with permit at some sites. Waste at Derbyshire sites was stored for longer than permitted and seen to be engulfing the outside storage bays. The odorous nature of some of the waste resulted in fly infestation. Waste was also stored in such significant quantities, that it posed a fire risk. One site was not permitted.	

		 http://www.cheaperwaste.co.uk/ward-recycling-fined-for-derbyshire-breaches/
35.	Waste and asbestos was dumped on two areas of farmland in Carmarthenshire by skip company (for five years). Dumped on ground, in skips and looks like maybe silage bags.	   http://www.bbc.co.uk/news/uk-wales-south-west-wales-35153007

36.	Cornish company pleaded guilty to 5 offences of permit breaches and one offence of failing to comply with an enforcement notice. The quantity of combustible material on site posed both a pollution and fire risk. Inadequate sealed drainage system. Accepted hazardous waste (not permitted to do so).	 https://www.gov.uk/government/news/torpoint-waste-management-company-fined-14000
37.	Cornish company breached a permit by depolluting vehicles, illegally storing and handling waste, including plasterboard, wood, green waste and trommel fines. They also failed to comply with an enforcement notice, which required the reduction of waste on the site by 500 tonnes. Also, later on knowingly permitting the carrying on of a waste operation without the benefit of an environmental permit.	 https://www.gov.uk/government/news/waste-site-owners-ordered-to-clear-site-within-18-months
38.	Legal waste site failed to comply with permit, creating a mountain of rubbish at their Birmingham site. Vastly exceeded amount that was allowed to be stored.	 http://www.birminghammail.co.uk/news/midlands-news/company-hit-100000-cost-after-11192532

39.	Waste company in Gateshead which collected tyres had registered an exemption for temporary storage of tyres. But they expanded way over exemption and illegally stored up to 30,000 tyres – created fire hazard next to railway line.	 http://www.chroniclelive.co.uk/news/north-east-news/company-fined-illegally-storing-up-11127148
40.	Skip hire company stored and disposed of waste at two sites which didn't have a permit. They had an exemption but this did not permit them to treat waste, deposit it on site, or store such a large amount. These had waste material ranging from wood, old tyres and waste batteries along with construction type soil and mixed commercial waste. They also had oil drums lying upside down and industrial oil had leaked out onto the ground. Picture on right is dumped road sweepings they had collected.	 https://www.gov.uk/government/news/company-and-director-to-pay-over-30000-for-waste-offences
41.	Illegal waste site at farm in Norfolk – construction and wood waste. Waste dumped in piles on land.	 http://www.edp24.co.uk/news/crime/waste_operator_jailed_for_running_illegal_site_1_4460932

42.	Two wood recycling sites in Gloucestershire exceeding their exemptions. Supposed to store up to 500 tonnes by stored 4000 tonnes. Not separated and no fire breaks so risk of fire.	 https://www.gov.uk/government/news/man-handed-8800-penalty-for-operating-illegal-waste-sites-in-gloucestershire
43.	Metal recycling company in Wiltshire was running an illegal waste operation - taking in piles of chalky stone, tarmac road planning's and concrete pipes on farmland.	http://www.wiltshiretimes.co.uk/news/14290189.Suspended_jail_term_for_Wiltshire_scrapyard_boss_who_ran_illegal_waste_operation/
44.	Illegally buried waste in a former quarry in Worcestershire. Industrial and municipal waste. Also, operated site beyond extent of permit.	 https://waste-management-world.com/a/six-guilty-of-illegal-waste-disposal-at-worcestershire-quarry
45.	Devon company (one company was a skip business and one was a top soil business) stored waste including hazardous asbestos roof tiles at an unlicensed site. 2,600 tonnes of hazardous waste (due to the presence of asbestos) had been mixed and then deposited at a site that was only licensed to accept inert wastes. A large pile of mixed waste was also being stored outside the permitted area in close proximity to an electrical sub-station.	 https://www.gov.uk/government/news/company-fined-for-illegal-waste-offences

46.	Cornish scrap company kept and broke vehicle waste without a permit (at multiple sites).	 http://www.piratefm.co.uk/news/latest-news/1873209/cornish-car-scrap-owner-fined/
47.	Illegal waste business at Penyrheol farm. Dumped and sorted 150 skips of mixed waste without a permit. Skips contained plasterboard, scrap metals, plastics, and general builders and household rubbish. Also, significant amount of demolition and builders waste — including plasterboard, wood, carpets and plastics — being piled up behind an agricultural building.	  http://www.southwales-eveningpost.co.uk/man-given-ultimatum-pay-160k-months-jail-illegal/story-28666518-detail/story.html#1

48.	Unlicensed site in Ludlow with large mounds of mixed waste including plastic, construction and demolition waste.	 https://www.gov.uk/government/news/man-ordered-to-pay-over-16800-for-waste-offences-in-ludlow-shropshire
49.	Various illegal waste operations took place at an Oxfordshire farm – which let multiple tenants operate waste crimes there. In particular, a skip hire business operated illegally from the site, and there was also another company who deposited large quantities of tyres.	 https://www.gov.uk/government/news/oxfordshire-company-guilty-of-allowing-waste-crime
50.	Spreading illegal waste on land in County Durham. 26 tonnes of waste which should not have been used for land spreading on farm. They did have a permit to spread waste on land as fertiliser, but the type of wastes accepted did not match those on the permit.	http://www.bbc.co.uk/news/uk-england-birmingham-24090869
51.	The rubbish at an illegal tip in Brierley Hill reached a height of 42ft (13m).	 http://www.bbc.co.uk/news/uk-england-birmingham-24090869

52.	A Plant and Haulage company transported over 5000 tonnes (in 4 months) of waste soil and stones to a site in Motherwell without a permit.	 http://www.recyclingwasteworld.co.uk/news/lanarkshire-businessman-given-community-pay-back-order-for-unlicensed-waste-carrying-offences/111260
53.	Unlawful handling and export of hazardous waste. Despite the Yorkshire site not having an environmental permit or planning permission for a waste facility, the firm received hazardous waste for export. Illegal activities were discovered when found dead fish in a pond fed by the River Ryburn. A discharge of foam in the watercourse was traced back to the site where more than a hundred, 1,000-litre plastic containers were found stored. Some containers had holes drilled in them, and liquids were seen leaking onto the ground before entering the water.	https://www.gov.uk/government/news/man-handed-jail-term-over-illegal-waste-operation
54.	Illegal dumping of some 60,000 tonnes of waste on two farms in Cornwall. Had a much smaller exemption. Collusion between farmer and hauliers. Demolition and construction waste. Land raising using excavation spoil – but this slipped into stream.	 https://waste-management-world.com/a/hefty-fines-for-illegal-dumping-of-66-000-tonnes-of-waste-in-cornwall
55.	Illegal export case. 11 shipping containers full of electrical waste destined for Nigeria, Ghana and	http://www.ciwm-journal.co.uk/waste-crime-couple-fined-for-illegal-exports-man-sentenced-to-prison/

	Tanzania. 40-foot containers, each with about 15 tonnes of e-waste inside, had wrapped items at the front, which were made to look like working products. However, further back the container included hazardous cathode ray televisions and broken fridge freezers which were described as second-hand goods but didn't work. Containers loaded at a site in Warrington.	
56.	Man, in Ballynahinch had 2,000 tonnes of mixed waste illegally on his land. It included building materials, plastics, timber, carpet and textiles.	  http://www.bbc.co.uk/news/uk-northern-ireland-34871436
57.	A vehicle breakers yard after it over-spilled on to land it was not allowed to use. The company was legally permitted to operate on the former airfield but after running out of room began to use three unlawful sites including the former runway.	http://www.edp24.co.uk/business/vehicle_breakers_fined_for_overspill_at_shipdham_airfield_industrial_estate_1_4257738

58.	Keeping treated tyre waste in a manner likely to cause harm to human health and pollution of the environment and failing to comply with a waste removal notice. Fire. Illegally stored thousands of tyres.	 http://www.southwales-eveningpost.co.uk/natural-resources-wales-have-had-concerns-about-port-talbot-tyre-centre-for-some-time/story-29509100-detail/story.html
59.	Waste from cheese factory was spread onto land in breach of permit condition.	https://www.gov.uk/government/news/parkham-farms-cheese-factory-in-devon-fined-for-pollution
60.	Had no permit, but stored large quantities of waste tyres (1500) on a site in Newcastle. Created a fire hazard.	  http://www.chroniclelive.co.uk/news/north-east-news/newcastle-second-hand-tyre-business-9845975
61.	Avonmouth company collected compacted bales of waste wrapped in plastic. Found 200 split bales, some with waste and "brown" liquid oozing out causing a "nauseating, putrid smell." Fly infestation affecting local	http://www.bristolpost.co.uk/waste-company-boomeco-fined-thousands-avonmouth/story-27515919-detail/story.html

	properties.	
62.	Skip hire company in Surrey operated a waste facility without permit. Stored 4000 tonnes of construction and demolition waste, and also 17 skips of builder's waste.	https://www.gov.uk/government/news/surrey-waste-site-ordered-to-pay-19000
63.	3,000 tonnes of non-hazardous trommel fines were deposited at a Mushroom farm by a waste company. Did not comply with exemptions.	 https://brownfieldbriefing.com/46641/powerday-fined-1m-for-waste-offences
64.	Illegal landfill site on farm near Lochgelly held (stored) an estimated 85,500 tonnes of unlicensed waste material. Filled between 2006-2012. Various wastes (household, commercial and industrial) were kept on the land, included rusting cookers, polypropylene bags and sheets, polythene, railway sleepers, plastic parts, metal gauze, a hand saw, polystyrene, foam sheets of wall insulation, damp course membrane, wood, a rotary air dryer, plastic drainage pipe, aerosol cans and car seat springs, roofing slates, bricks, concrete blocks, metal parts, plastics, paving slabs, wooden doors and corrugated iron sheeting. These materials were not permitted to be stored over that length of time without a waste management licence being in place.	http://www.bbc.co.uk/news/uk-scotland-edinburgh-east-fife-33443191

65.	Plant hire business in Norfolk stored more than 37 times more waste than permitted. Allowed 50 tonnes to be stored and stored nearly 2000 tonnes.	http://www.derehamtimes.co.uk/news/company_fined_for_storing_37_times_more_waste_than_allowed_at_its_dereham_site_1_4091807
67.	Recycling company. Prosecuted for the deposit and storage of 420 tonnes of mixed municipal waste in the company's yard on Everite Road outside their permitted area. Flies neighbouring properties.	 http://www.letsrecycle.com/news/latest-news/fly-infestation-sees-centrol-recycling-fined/
68.	Site in Ballynahinch containing a substantial quantity of controlled wastes in the form of end-of-life plant and machinery was deposited (without a licence.	http://www.enviro-solutions.com/dailynews2/270415-niea-waste-96k.htm
69.	114,000 tyres illegally stockpiled, without a waste management licence in Motherwell. Tyres were stacked haphazardly and there was insufficient access to the site for fire trucks. Tyres were stacked too high and too close together. A licensed site would be required to store tyres with fire breaks of at least 15 metres. At this depot, some tyres were stacked 20 feet high with gaps between piles of only a metre.	 http://www.motherwelltimes.co.uk/news/crime/tyre-boss-jailed-over-illegal-dump-1-3708913

70.	The limit under the exemption was 5,000 tonnes of aggregates – company records showed that 94,000 tonnes had been taken to the site in Norfolk. Piles of various wastes which included soil, rubble, asphalt, and aggregate fines. Treated controlled waste without a permit and sold some of it on – e.g. formed a golf course.	 https://www.gov.uk/government/news/company-hands-over-almost-250000-proceeds-of-crime
71.	Edinburgh company pleaded guilty to failing to carry out water spraying of stockpiles containing dry, crushed and screened waste materials in order to prevent particulate emissions to air, and also having stockpiles of waste exceeding three metres in height. Permit breaches.	http://www.ciwm-journal.co.uk/edinburgh-waste-firm-fined-4000-for-dust-and-storage-breeches/
72.	Despite having its permit revoked and 2 enforcement notices and 2 breach of condition notices, a skip company took in even more waste at its site in Lincoln. Took in 20,000 tonnes of waste when only allowed 1100. The waste was 7 to 8 metres high in places, breaching planning conditions.	 https://www.gov.uk/government/news/lincoln-waste-company-director-sentenced-to-prison
73.	Businessman and his scrap metal firm were dumping waste illegally at their premises in Ballymena. 80% of the eight-acre land at the firm's site was covered in scrap metal, cars and car parts. Also, consisting of scrap lorries, trucks, cars, fridges, bed springs, batteries and cans. 20,000 tonnes of waste treated on site.	http://www.bbc.co.uk/news/uk-northern-ireland-25094365

74.	A skip operator in Cambridgeshire ran an illegal waste dump at multiple sites (some in his name, others in his wife's).	 http://www.wisbechstandard.co.uk/news/skip_hire_man_who_ran_an_illegal_rat_infested_waste_site_in_march_must_pay_47_000_court_rules_1_3829256
75.	Waste recycling company hid tonnes of waste under soil at a former colliery in West Lothian. Two passers-by complained to the West Lothian Council about the mountains of rubbish they could see from the nearby road (before it was buried). Was then excavated.	 http://www.dailyrecord.co.uk/news/scottish-news/recycling-boss-slammed-as-one-of-countrys-1399952
76.	Essex man illegally exported WEEE to West Africa. Broken cathode ray tube televisions and fridge freezers had been found in four containers intercepted at ports by Environment Agency investigators. Kept in building storage area on site.	 http://www.letsrecycle.com/news/latest-news/ca-site-illegal-weee-exporter-jailed/
77.	Devon business collected liquid food wastes and stored them in lagoons prior to spreading on farmland as a soil improver. The lagoons continued to rise, close to overflowing, despite	http://www.devonlive.com/lagoons-food-waste-close-overflowing/story-14228861-detail/story.html

	warnings.	
78.	Dudley waste recycling site had number of breaches including having too much waste on site, and significant amounts of waste tipped outside the permit area. Company also failed to comply with a series of enforcement notices with the lack of action resulting in a number of waste fires.	 http://www.expressandstar.com/news/2014/05/28/dudley-waste-firm-hit-by-fires-ordered-to-clear-site/
79.	Recycling company pleaded guilty to depositing, keeping and treating the likes of waste vehicle tyres, mattresses, metal drums and fuel tanks on a leased site in Airdrie, without a licence.	 http://www.letsrecycle.com/news/latest-news/news-in-brief-583/
80.	Storing waste without permits at multiple sites in Yorkshire. Waste pile was 11,500 bales on some of the sites. The waste contained paper, plastic, carpet, metal, wood, drinks bottles containing liquid, and general waste.	

http://www.letsrecycle.com/news/latest-news/suspended-jail-terms-for-leeds-paper-recycling-pair/

Annex III – Archives and tasking

1. Purpose

The purpose of this section is to examine how in practice it is possible to access remote sensing data through either access to existing data in archives or through requesting a specific data acquisition through tasking.

The web site of the Committee on Earth Observation Satellites (CEOS[30]) lists the public sector Earth observation satellites in current operation. The database section of the CEOS web site[31] covers 60 agencies operating 142 Earth observation satellites. In addition, there are the Earth observation missions operated by the private sector, especially the very high resolution missions such as DigitalGlobe WorldView. The number of Earth observation missions is therefore very large. This appendix will cover the main sources of satellite remote sensing data that are likely to be useful in the waste crime sector and will discuss the overall approaches to archives and tasking rather than attempting to be an exhaustive survey of access to all remote sensing mission data.

This appendix examines the data archives and tasking of the following types of satellite remote sensing data.

- Landsat and the evolution of data archives
- Very high spatial resolution data
- High to medium spatial resolution data through Geostore
- European radar and related optical data
- Other data sources

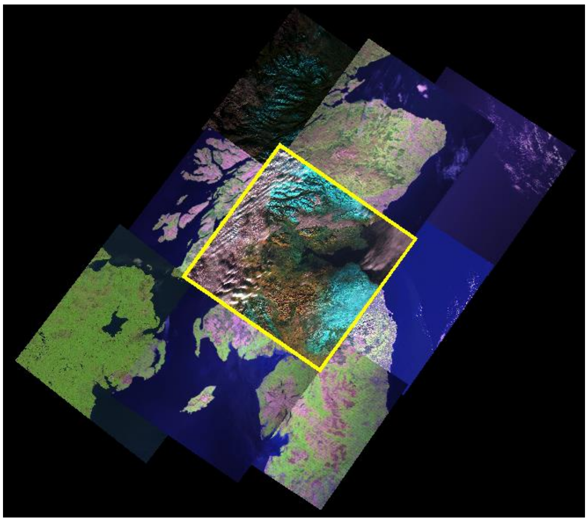
2. Landsat and the evolution of data archives

The first land remote sensing satellite, Landsat-1, was launched in 1972. For several years after the launch of Landsat-1, the Landsat data were the only satellite remote sensing data of the land surface openly available and as the data acquisition structure was simple then access to archived data was also simple. Landsat satellites acquire images of the surface directly below the satellite instrument and correspond to 185 x 185 km on the ground. The area covered by each image is defined as the Path and Row; that is the number of the orbit (the Path) and the position along the orbit (the Row). This gave rise to a fixed pattern of images and so the archive of images, as it was built up, consisted of image dates related to each Path/Row identifier.

An example of the structure is shown in figure 46. It illustrates the Path/Row scenes for most of Scotland and was taken from the US Geological Survey (USGS) GloVis[32] system that gives access to archived Landsat data. The central image is Path 205 Row 21 of the Landsat data system. The Path numbers progress east to west and the Row numbers increase north to south as the satellite travels on its orbit.

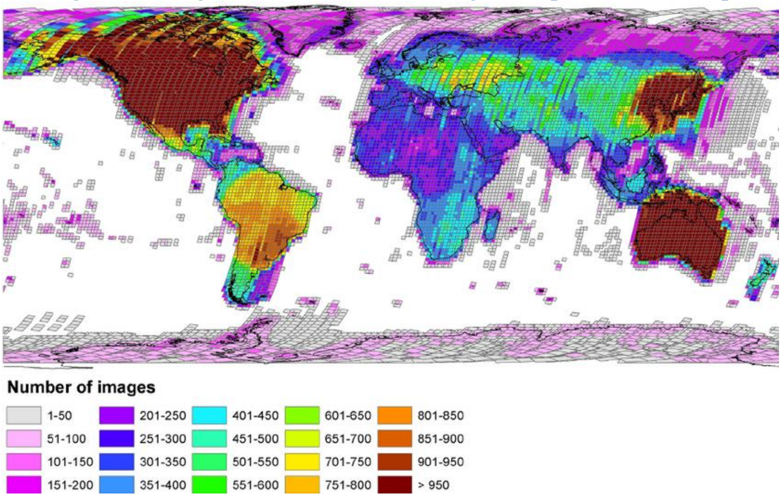
Figure 46. The Landsat Path/Row system for Landsat images over Scotland [Source: USGS Global Visualisation Viewer GloVis].

[30] http://ceos.org/
[31] http://database.eohandbook.com/
[32] GloVis: Global Visualisation Viewer, http://glovis.usgs.gov/



The Path/Row structure for all the land surfaces of the Earth can be seen in Figure 47 which shows the number of images archived by USGS as of 1 January 2015. The boxes are the fixed Landsat scenes and the colours represent the number of images for each box. The USA, Canada, China and Australia are particularly well covered. Western Europe has of the order of 200 – 300 images for each Path/Row scene while Eastern Europe has about twice as many as Western Europe.

Figure 47: The Landsat Path/Row scene structure and the number of Landsat images held in the US Geological Survey archive as of 1 January 2015 [Source: USGS]



Two important factors have resulted in a much more complicated satellite remote sensing data archive picture since the start of the Landsat programme. First, there are now many more remote sensing satellites in operation. Second, many of the newer satellites have the ability to point their instruments to one side or the other of the ground track. This means that there is not a fixed image acquisition structure as is the case with Figure 47. In place of a Path/Row structure of data archives, most Earth observation missions have interfaces to archives that allow searches and data access via geographical latitude/longitude) and time (acquisition date) coordinates.

All Earth observation missions have a basic data acquisition schedule, which is often referred to as the *background mission*. In addition, many satellite missions offer users the opportunity to collect data of a specific location at a specific time that is they offer the opportunity to task the satellite. This has proved very useful in the case of emergencies such as earthquakes or tsunamis and is often used by the International Charter on Space and Major Disasters[33]. The computer systems for remote sensing data archives now often offer

[33] www.disasterscharter.org

both information about the data archives and about the ability to request satellite tasking. Therefore, in this report access to archives and access to tasking are discussed side by side when they occur. In practice, the same interface systems are often used to examine what data already exist and what data could be obtained in the future through satellite tasking.

One important feature of images in the visible to thermal infrared wavelength range is the presence of cloud because cloud obscures the surface. Remote sensing data archive systems for optical data give estimates of cloud cover for existing scenes and tasking allows the specification of minimum cloud cover levels that are acceptable to users when new images are acquired. By contrast, radar can penetrate cloud and so cloud cover estimates are not relevant.

3. Very high spatial resolution data

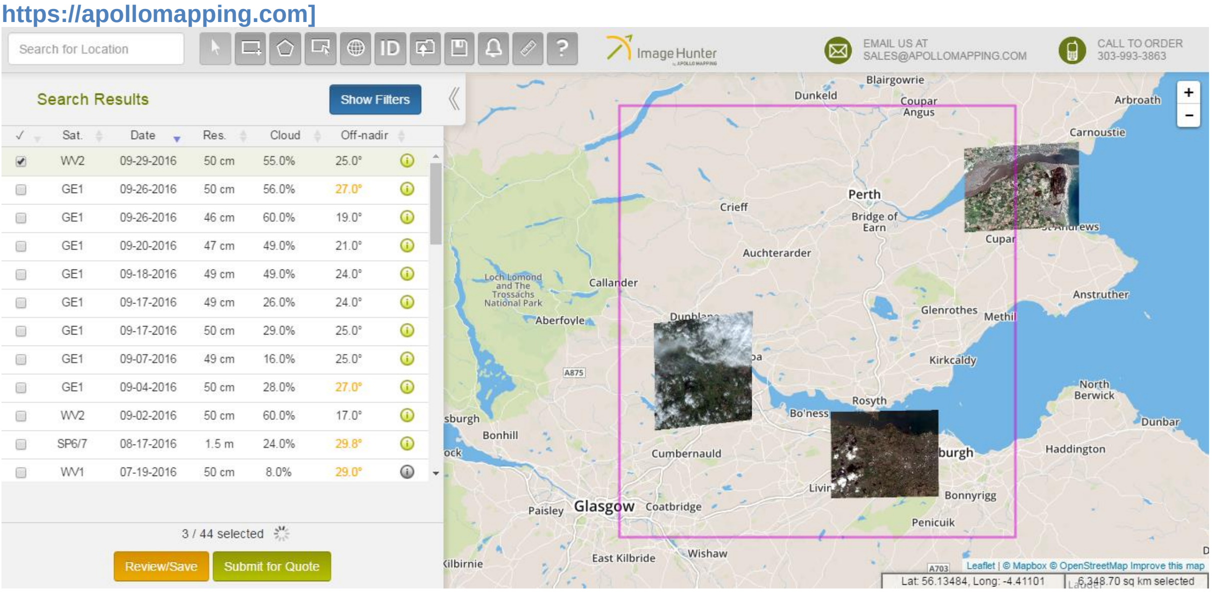
The consolidation of the very high spatial resolution satellite industry has resulted in DigitalGlobe being the dominant data supplier of data at around 0.5 m pixel size. DigitalGlobe is the result of mergers or acquisitions of Space Imaging, Orbimage and GeoEye. DigitalGlobe now offers data from WorldView-1 to 4, GeoEye-1, QuickBird and Ikonos missions. The DigitalGlobe web site invites users to enter a conversation and discuss with DigitalGlobe their data requirements rather than provide users with a tool to assess easily the DigitalGlobe data archives.

Access tools for very high resolution data are provided by data brokers such as Apollo Mapping, Geocento and LandInfo. Apollo Mapping[34] offers data archive searches for the following missions:

- WorldView-1 to 4
- GeoEye-1
- QuickBird
- Ikonos
- Pleiades
- SPOT
- EROS B
- Kompsat
- Triplesat
- Aerial imagery from airborne sensors

The archive search interface is through geographical and time coordinates and an example for central Scotland is shown in Figure 48.

Figure 48. The results of a search for very high spatial resolution data of central Scotland [Source: https://apollomapping.com]



The interface shows on the left side the list of images that meet the search criteria. For each image in the list there is information on the satellite, the date of image acquisition, the pixel

[34] https://apollomapping.com

size, an estimate of the percentage cloud cover in the image and the off-nadir observation angle. On the right side is the overall extent of the data search area and then three example quick-look images that correspond to three of the images from the list on the left side. The Apollo Mapping interface is a common approach for satellite remote sensing data archives and differs from the Landsat archives because there is no fixed scene structure.

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- QuickBird
- Ikonos
- Pleiades
- SPOT
- EROS B
- Kompsat
- Triplesat
- Aerial imagery from airborne sensors

DigitalGlobe offers satellite tasking for its WorldView and GeoEye-1 satellites. It offers three priority categories, a maximum cloud cover level (typically 15%) and the opportunity to specify a time window during which data capture will be attempted. The minimum time period to request tasking is one hour before image acquisition. DigitalGlobe gives limited information about archive data and tasking pricing on their own web site, but the data broker LandInfo does give data prices for archive and tasking products and examples are shown in Table 23.

Table 23. Example prices (US$) for three selected very high spatial resolution data sets offered on the Landinfo web site [Source. http://www.landinfo.com].

	WorldView-2/3		GeoEye-1		Pleiades	
	Archive	Tasking	Archive	Tasking	Archive	Tasking
Panchromatic	$14.00	$24.00	$14.00	$24.00	$10.00	$17.00
Panchromatic plus 4 band multispectral	$17.50	$27.50	$17.50	$27.50	n/a	n/a
8 band multispectral	$19.00	$29.00	n/a	n/a	n/a	n/a

4. Geostore

Geostore[36] is the Airbus Defence and Space search web site for remote sensing data from the Pleiades, SPOT and TerraSAR-X Earth observation missions plus digital elevation data. It provides a single interface to these data sets and the same interface covers archives for the three satellite data sets and tasking for Pleiades and SPOT satellites. The Geostore system allows the interrogation of the archive of data products as follows.

- Pleiades optical archive data, 0.5 m pixels, mono and stereo
- SPOT optical archive data, ranging from 1.5 m to 20 m pixels, panchromatic and multispectral

[35] https://apollomapping.com
[36] http://www.geostore.com/geostore4/

- TerraSAR-X radar data with six options including SpotLight and StripMap (discussed later in this report)

In addition, the Geostore system allows the entry of tasking requests for SPOT and Pleiades data under five schedules or modes that have different criteria on time scale, acceptable cloud cover, size of the target area and failure terms. The tasking plan for SPOT and Pleiades is updated every four hours to accommodate urgent tasking requests.

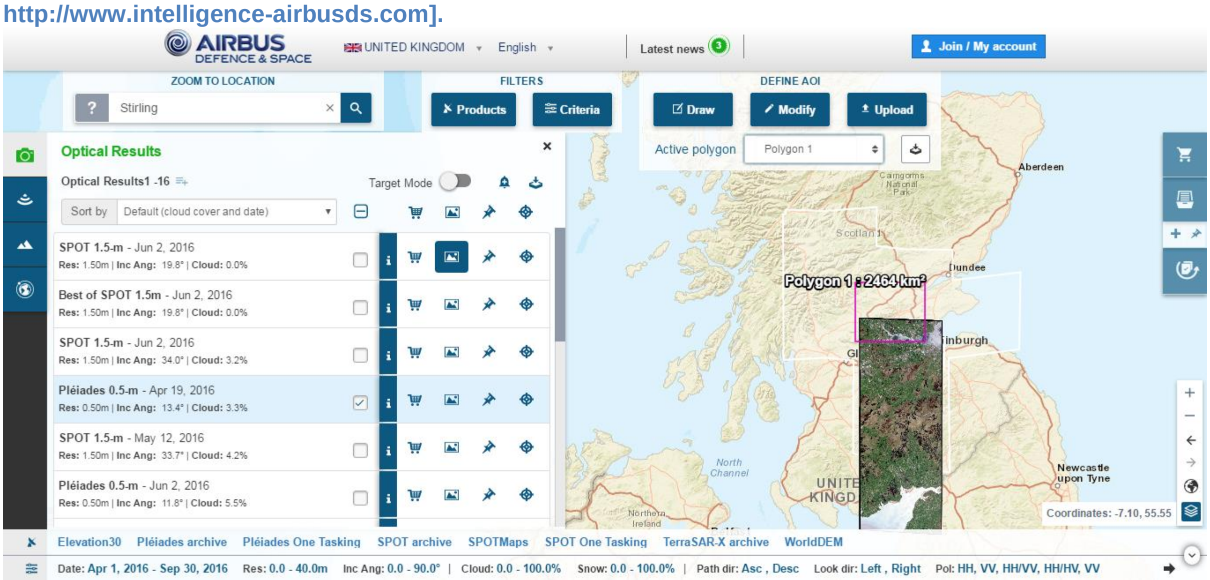
The Geostore system allows users to search the remote sensing data archives with the following criteria.

- Geographical location: point, rectangle, polygon, uploaded file
- Time period
- Spatial resolution of the data
- Incidence angle of the instrument
- Maximum cloud cover acceptable
- Maximum snow cover acceptable

For radar, there are the additional characteristics of orbit direction (ascending or descending), look direction (left or right) and polarisation.

Figure 49 is an example of the Geostore interface and shows a search for Pleiades and SPOT data for part of Scotland for the period 1 April to 30 September 2016. The target search area is shown as a purple rectangle in the centre of the map. On the left side is the list of images that meet the search criteria and overlap the target search area. On the right is the coverage of the images in white plus a quick-look of one image, a SPOT 1.5 m pixel image captured on 2 June 2016 and listed as the first entry in the list on the left side.

Figure 49. The use of Geostore to search for Pleiades and SPOT images of central Scotland [Source: http://www.intelligence-airbusds.com].



5. European radar and related optical data

Copernicus and Sentinels

The main European initiative on satellite remote sensing is the Copernicus programme[37]. Copernicus is led by the European Union (EU) in partnership with the European Space Agency (ESA) and was formally established on 3 April 2014 by Regulation 377/2014 of the European Parliament and of the European Council. The main satellites that are part of Copernicus are the Sentinel satellites which are constructed and operated by ESA. The Sentinel missions are as follows.

- Sentinel-1. Radar for land and ocean monitoring.
- Sentinel-2. High resolution optical for land monitoring.
- Seninel-3. Low resolution for marine observation.
- Sentinel-4. Spectrometer for air quality monitoring.
- Sentinel-5. Also, a spectrometer for air quality monitoring.
- Sentinel-6. Radar altimeter for oceanography.

The main missions relevant to waste crime are the Sentinels 1 and 2. Sentinel-1 is equipped with a C-band radar that produces images at a spatial resolution of 5 – 20 m depending on the operational mode. Sentinel-2 carries a multispectral imager which has 13 wavebands across the visible and infrared bands and a best spatial resolution of 10 m.

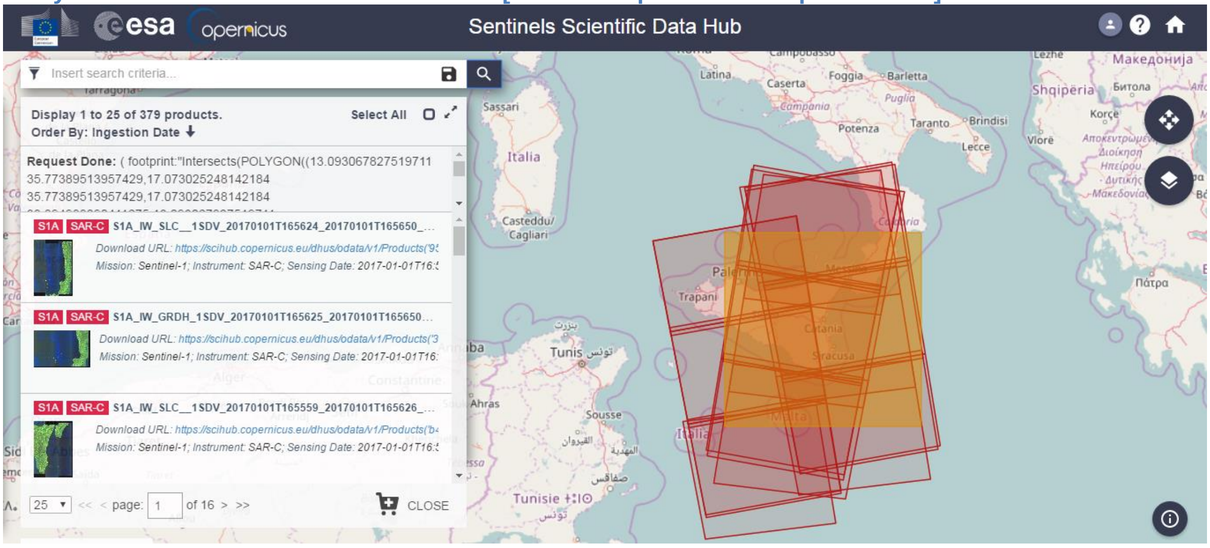
Using Sentinel and other remote sensing data, the Copernicus programme is organised into six thematic areas: land, marine, atmosphere, climate change, emergency management and security. Within these six thematic areas there are a wide range of applications, including environmental protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection and tourism. Waste crime does not have a specific action in Copernicus but it can fit within several of the land applications. Waste crime could benefit from the Copernicus focus on emergency management if there were very urgent waste crime cases in Europe.

There are several ways to access remote sensing data within Copernicus. The Copernicus Space Component Data Access (CSCDA) system[38] provides access to all the Sentinel data and to the Copernicus Contributing Mission data, that is non-Sentinel data that are available via Copernicus such as Envisat and Landsat data. The CSCDA explains the user's eligibility, the data available and the status of data provision, the data access mechanism and support available to users.

It is however simpler to focus on Sentinel 1 and 2 data because they are the most relevant to the waste crime sector. Access to Sentinel data is offered by the Sentinels Scientific Data Hub[39]. Figure 51 shows a search for Sentinel-1 radar images for the region of Sicily for the month of December 2016. The target area is shown as an orange box over Sicily and the red boxes are the extent of the scenes that overlap the target area for that time period. The small images on the left side of figure 50 are the quick-looks for each scene: the quick-looks can be examined further before an image order is created.

[37] Copernicus was formerly known as GMES – Global Monitoring for Environment and Security. The Copernicus web site is at: http://www.copernicus.eu/
[38] https://spacedata.copernicus.eu/
[39] https://scihub.copernicus.eu/

Figure 50. The Sentinels Scientific Data Hub used to identify the Sentinel-1 radar images available for the Sicily area for the month of December 2016 [Source: https://scihub.copernicus.eu].



The Sentinel-1 radar operates for 25 minutes out of each orbit of 100 minutes with a systematic data acquisition schedule. The revisit cycle for Europe for Sentinel-1 is 12 days, which means that all places in Europe are covered by the radar at least once every 12 days.

The approach taken by ESA is to have systematic product generation as follows.

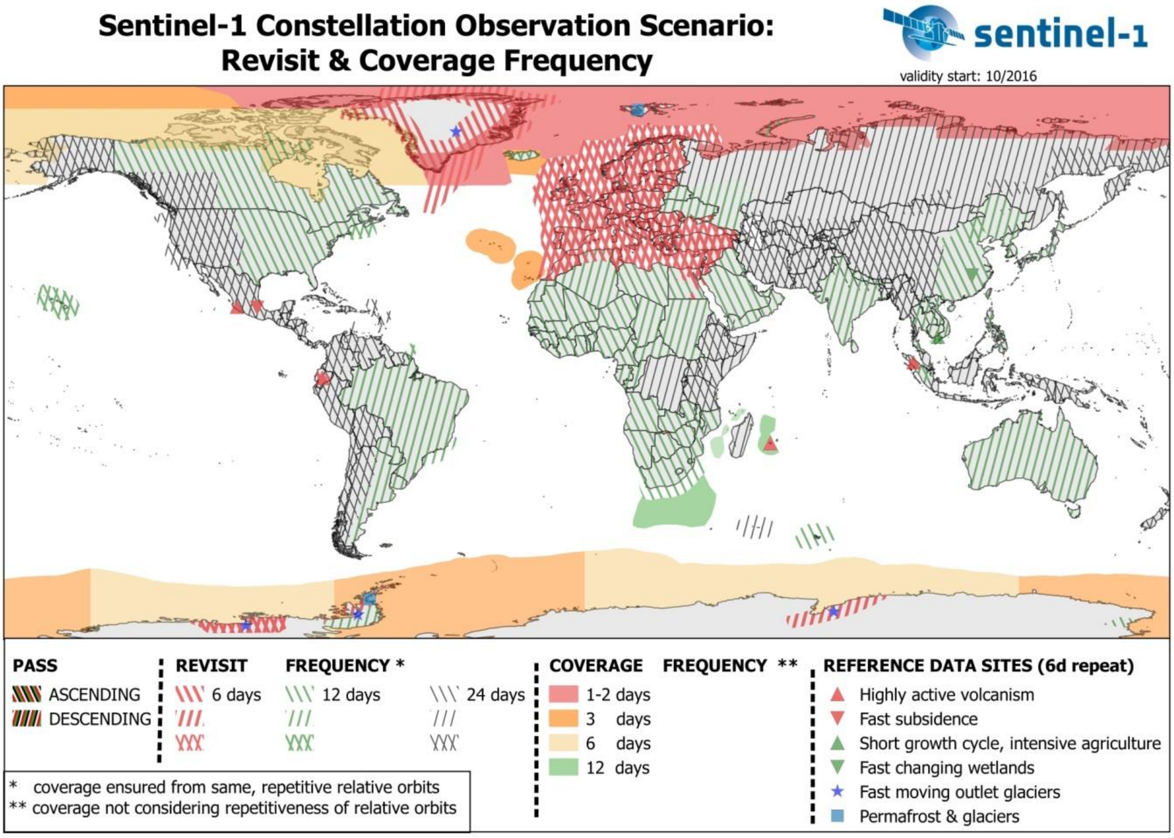
- Systematic near real time within 10 minutes of data capture. This is for basic processing of a selection of products and with the collaboration of ground stations.

- Systematic near real time within 1-3 hours of data capture. This is for a specific sub-set of data products.

- Systematic processing within 24 hours for all pre-defined level 1 and 2 products. This covers most products that are generally useful and in a form that users can use directly. This would include the products of use in the waste crime sector.

Because the Sentinel-1 radar can see through clouds the acquisition of data is guaranteed in the operations schedule. Figure 51 shows the revisit and coverage frequency of Sentinel-1 and it can be seen that there is a focus on data acquisitions over Europe. ESA does not normally offer satellite tasking for Sentinel-1 because the revisit of 12 days for European coverage is enough for most applications. Tasking requests are possible, but only for emergency purposes where the application is made through member states, national services or from the International Charter on Space and Major Disasters.

Figure 51. The revisit and coverage frequency of the Sentinel-1 satellites [Source: https://sentinel.esa.int].



The same data archive search system is used for Sentinel-2 which carries optical instruments. Figure 52 shows an example of a search for optical image data of the Sicily region. The orange zone in the centre is the target area and the green boxes show the extent of each of the Sentinel-2 images that overlap the target area, in this case for the month of August 2016. Figure 53 is the extent of one of the images plus a quick-look image of the selected scene for southern Italy.

Figure 52. A search of Sentinel-2 data for the Sicily region for the month of August 2016 [Source: https://scihub.copernicus.eu].

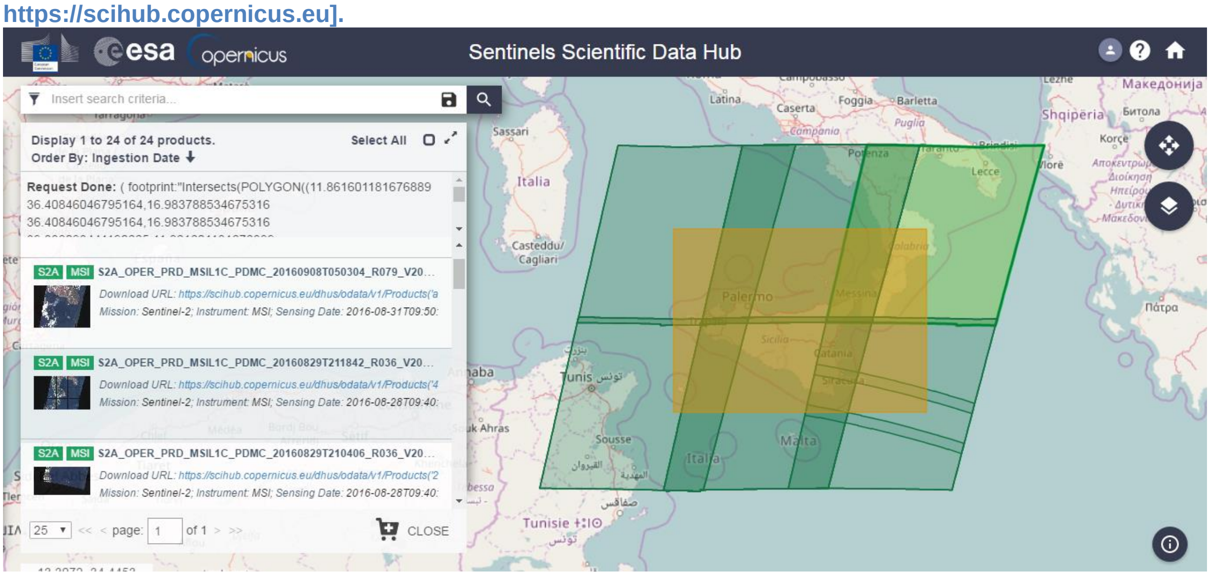
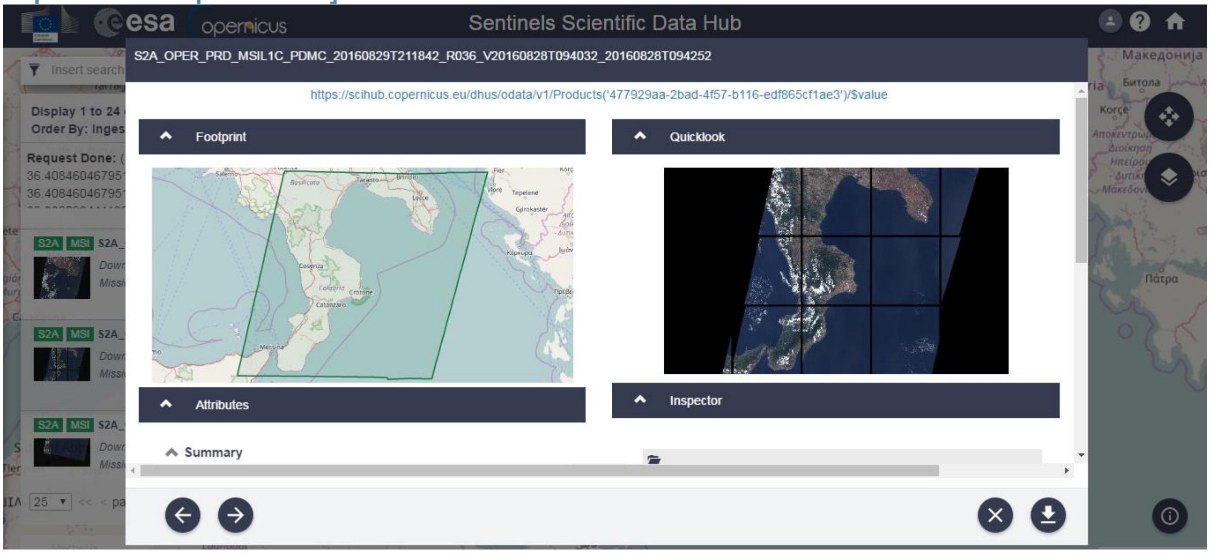


Figure 53. The extent of an image selected from the search shown in Figure 53. This one if for southern Italy and shows the coverage zone on the left side and a quick-look on the right side. [Source: https://scihub.copernicus.eu].



Sentinel data are available to all free of charge under the Copernicus data policy.

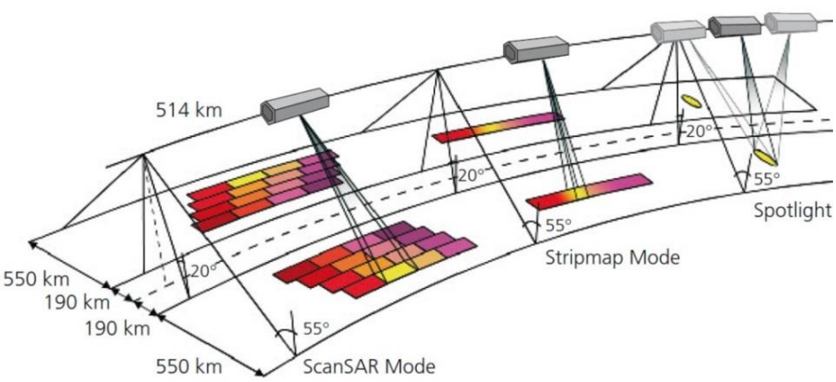
TerraSAR-X

TerraSAR-X is a German Earth observation radar satellite. Its primary payload is an X-band radar sensor (2.4 – 3.8 cm wavelength) with a range of different modes of operation, allowing it to record images with different swath widths, spatial resolutions and polarisations. TerraSAR-X offers three main modes of operation:

- Spotlight mode: pixel size of 1 – 2 m, image area of 10 km x 10 km
- Stripmap mode: pixel size of 3 – 6 m, image strip of 30 km wide
- ScanSAR mode: pixels of 16 m, image strip of 100 km wide

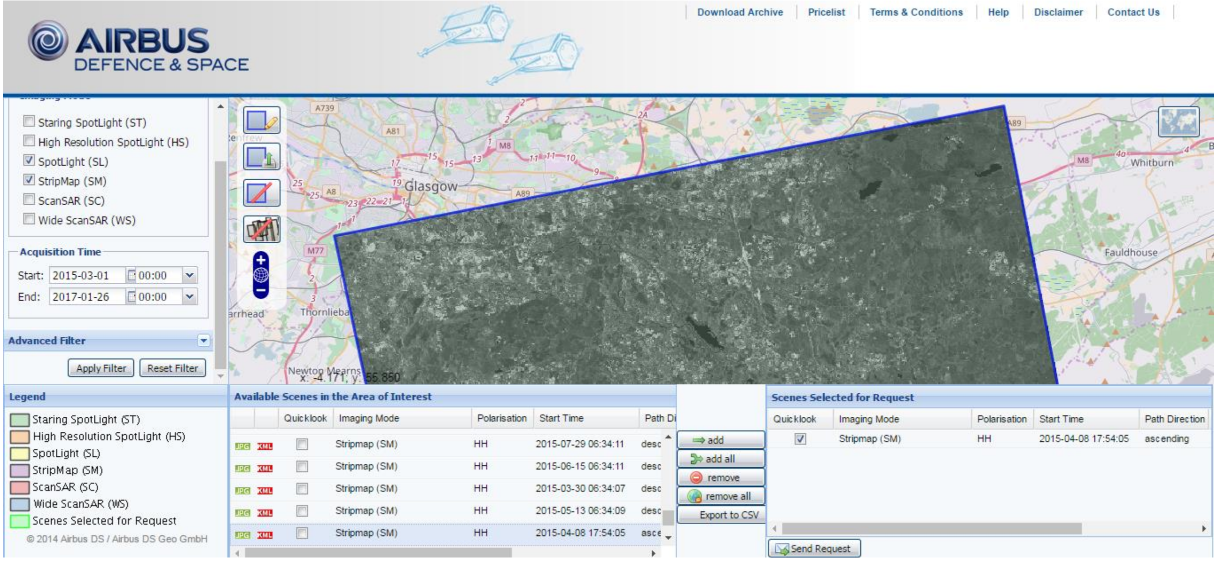
Figure 54 is a schematic illustration of how the three modes operate.

Figure 54. The operation of the three modes of TerraSAR-X [Source: www.dlr.de].



Germany has launched a similar satellite called TanDEM-X that works in a flying formation with TerraSAR-X to allow the creation of digital elevation models (DEMs). Because TanDEM-X is very similar to TerraSAR-X, reference is made in this section only to TerraSAR-X although the same points apply to TanDEM-X data.

Figure 55. A search of the TerraSAR-X archive using the Geostore system. The partial image shown is a StripMap mode (3 – 6 m pixels) for an area south east of Glasgow for 8 April 2015 [Source: http://terrasar-x-archive.infoterra.de/].



Access to the archives of TerraSAR-X data can be performed using the Geostore system noted earlier in this report. Figure 55 (above) is an example of a search for TerraSAR-X data using a version of Geostore offered by Airbus Defence and Space. On the left side are the search parameters. In this case, the search was for the SpotLight and StripMap modes for the period 1 March 2015 to 26 January 2017 and for a region south of Glasgow. Of the scenes identified by the archive search an example of one of these is shown for an area south east of Glasgow.

Because of the high spatial resolution and the modes shown in Figure 55, TerraSAR-X does need to be selective in its operations and therefore the German space agency does offer tasking. The tasking priorities offered are low priority (3 days), medium priority (1 day) and high priority (responding to a deadline). To illustrate the practical tasking system the schedule below describes the time phases of TerraSAR-X tasking.

• Submission deadline each day	0830 GMT
• Development of the tasking plan taking into account all the tasking requests and the satellite's operational schedule	0830 – 1516 GMT
• Uplink the final daily operational plan to the satellite including the tasking plan	1516 – 1801 GMT
• Radar data acquisitions according to the plan	1801 – 0717 next day GMT

The prices of the TerraSAR-X products are given later in this report. For each of the three main product types there is a price for archive data and a price for new acquisitions that have been tasked. The new acquisitions resulting from tasking are twice the price of the archive data.

Cosmo-Skymed

A similar system to TerraSAR-X has been developed by the Italian Space Agency and the Italian Ministry of Defence. Cosmo-Skymed is a constellation of four X-band radar missions. The radars have similar modes to TerraSAR-X as follows.

- Spotlight mode: pixel size of 1 m, image area of 10 km x 10 km
- Stripmap mode: pixel size of 5m, image area of 40 x 40 km
- ScanSAR Wide mode: pixels of 30 m, image area of 100 x 100 km

The orbit cycle of any one mission is 16 days but as there is a constellation of four satellites the revisit time can be as low as 11 hours. Cosmo-Skymed offers satellite tasking with three categories: routine (72 hours data supply), crisis (26 hours) and very urgent (18 hours).

The distribution and marketing of Cosmo-Skymed image products is the responsibility of the company e-geos which also offer remote sensing data from DigitalGlobe, Radarsat and the Indian Earth observation satellites. There is no simple archive search system for Cosmo-Skymed. E-geos offers a user registration process followed by an order form for specific products. Unlike some of the other archive systems reviewed in this report the access to Cosmo-Skymed data is not simple and user-friendly.

6. Other data sources

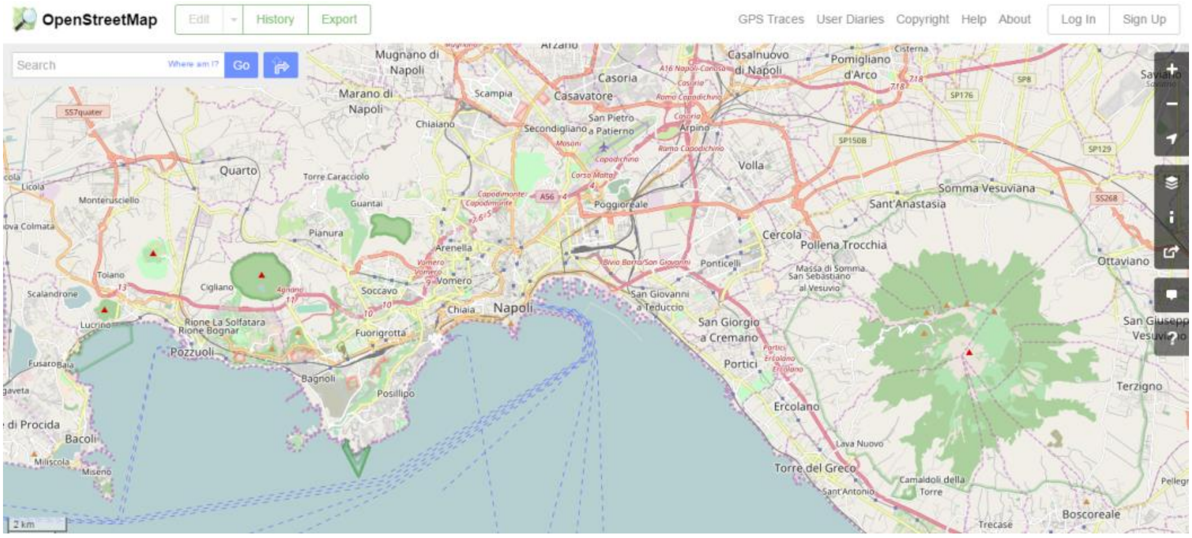
This report has discussed the main archives of Earth observation data that are of value for the waste crime sector. There are other relevant data archives and these are briefly described here.

ESA Earth Online[40] is a web site that gives access to all Earth observation data held by ESA. The ESA Earth Online archive comprises data from earlier ESA missions such as ERS-1, ERS-2 and Envisat plus selected data from 32 Third Party Missions such as Landsat, SPOT, Radarsat, Ikonos and WorldView. ESA Earth Online also provides links to the Copernicus data and ESA campaigns data. In general, the data are intended for scientific research and development (see the data policy section below). The ESA Earth Online web site is not easy to use.

It is likely that for waste crime applications remote sensing data will be used in combination with other geographical data in a GIS. Environmental data for GIS applications is available from many sources. OpenStreetMap[41] provides free of charge a valuable range of environmental data for most of the world. The main categories of OpenStreetMap data are: roads, railways, airports, lakes and land cover including residential, commercial, industrial, forests, heathlands and nature reserves. An example OpenStreetMap map of the area around Naples is shown in Figure 56.

[40] https://earth.esa.int/web/guest/home
[41] https://www.openstreetmap.org

Figure 56. An example OpenStreetMap of the Naples and Mount Vesuvius region [Source: https://www.openstreetmap.org/#map=12/40.8391/14.2815]



In the UK, the web site data.gov.uk gives access to data, including environmental data, collected by UK government departments.

At a European level, much geospatial data is available through INSPIRE. The EU INSPIRE Directive[42] of 2007 established an Infrastructure for Spatial Information in the European Community with the intention of providing to users' seamless access to geospatial data across European boundaries. The INSPIRE Geoportal[43] provides access to many data sets relevant to the waste crime sector such as land use, population, hydrology and vegetation. ESRI, which sells the ArcGIS software, has created ArcGIS Open Data as a portal for users to search, download and visualise open data. The ArcGIS portal has over 23,000 open GIS data sets available.

The International Council for Science (ICSU) has established a World Data System[44] (WDS) that provides trusted data for global science. Data available through WDS include many environmental data sets such as soil type, sustainable development, land cover change, hydrology and agriculture.

7. Trends

Once users have gained experience in using the remote sensing data archive and tasking web sites then the technical process of acquiring remote sensing data is straightforward. However, to gain such practical experience can take considerable time. In addition, the data licence terms and conditions require considerable knowledge and understanding of the implications of the licence. This may be why more satellite data providers are inviting customers to engage in a dialogue with them rather than for users to try and use a web site that is fundamentally complex, especially for new users or users whose domain of expertise is not in remote sensing.

In parallel, new data broker services such as Apollo Mapping have been established to provide good web interfaces to data catalogues so it is still possible to use web sites to interrogate data archives or plan satellite tasking. A further type of data broker is a value-added reseller that can provide information on what remote sensing data are available and

[42] Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007
[43] http://inspire-geoportal.ec.europa.eu/discovery/
[44] https://www.icsu-wds.org/

advice on the licence terms and conditions connected with different data sets. An example of such a value-added reseller in the UK is NPA Satellite Mapping[45]. In Europe, many such organisations belong to the European Association of Remote Sensing Companies[46].

Cloud cover is a problem for optical data acquisition in many parts of the world and especially in northern Europe. One way to work around the cloud cover problem is to use weather forecasts and weather satellite imagery to plan satellite tasking so that imaging is carried out when and where clouds are not present.

Figure 57. An illustration of the use of weather satellite images to help change tasking plans for very high resolution image acquisition [Source: Zevenbergen A, Benefits of local satellite tasking and real-time data downlink, European Space Imaging, http://www.dlr.de].

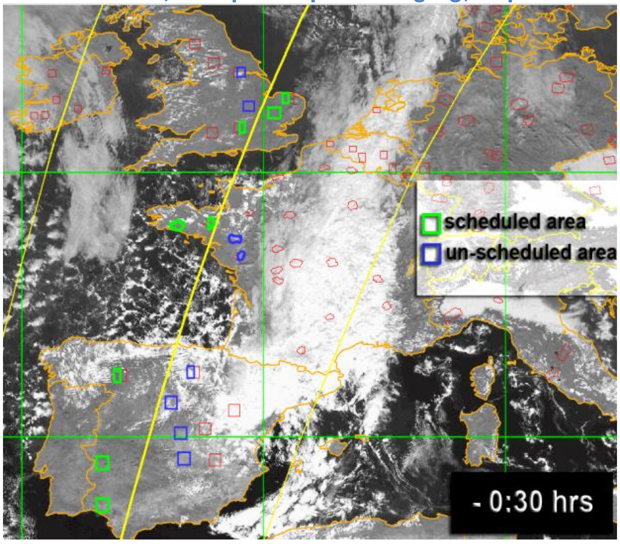


Figure 57 (above) shows an example of using weather satellite imagery to help plan Ikonos very high resolution data acquisition. The areas shown in red are target areas where very high resolution data could not be collected mainly because of cloud cover. The areas shown in green are areas where it was scheduled to collect very high resolution images and image acquisition was possible. The blue areas are target areas that were originally un-scheduled but were included in the tasking plan because the weather satellite imagery and the weather forecast showed that the areas would be cloud-free at the time of satellite overpass.

A second way to work around the cloud cover problem is the use of a constellation of satellites. According to the 2017 Smallsat Symposium[47] there will be over 400 Earth observation satellites of 50 kg and above planned for launch by 2025 and over 1000 Earth observation satellites that weigh less than 50 kg flying in constellations by the same date.

Constellations of Earth observation satellites increase the probability of cloud-free data acquisition of any one site because there are more attempts because there are more satellites. An example of a planned constellation is Hera Systems that is planning a constellation of small CubeSat's with spatial resolutions of the imaging instruments at 1 m and 0.5 m. This very high resolution data will be sold at US$ 1 – 3 per sq. km and be accessible via its Hera GeoSnap app on a smart phone.

[45] http://www.cgg.com/en/What-We-Do/GeoConsulting/NPA
[46] http://earsc.org/
[47] http://smallsatshow.com/

Copernicus is the major European Earth observation initiative and it has its focus on the provision of services. Data services for the waste crime sector seem very suitable candidates for Copernicus services because the waste crime problem is large and growing, the problem is present across all European countries and it is a problem that can be tackled in part by a view from above.

For the waste sector, there are more open data sets available at no cost, especially government data. Many Earth observation data sets are open data and free of charge but the spatial resolution of these data may not be adequate to identify waste sites clearly. The very high resolution data sets, which can identify waste sites more clearly, are not normally open data. One data set that may be useful in the waste sector and is high resolution is the LIDAR data of the Environment Agency (England) which is open data and provided free of charge.

Annex IV – Data costs

1. Cost of imagery from all optical satellites

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
DigitalGlobe 60cm class (Pan)	0.6m	25 sq km	US$14 sq km	100 sq km	US$24 sq km
DigitalGlobe 50cm class (Pan)	0.5m	25 sq km	US$14 sq km	100 sq km	US$24 sq km
DigitalGlobe 40cm class (Pan)	0.4m	25 sq km	US$16 sq km	100 sq km	US$26 sq km
DigitalGlobe 30cm class (Pan)	0.3m	25 sq km	US$19 sq km	100 sq km	US$29 sq km
DigitalGlobe 60cm class (4 Band)	0.6m	25 sq km	US$17.5 sq km	100 sq km	US$27.5 sq km
DigitalGlobe 50cm class (4 Band)	0.5m	25 sq km	US$17.5 sq km	100 sq km	US$27.5 sq km
DigitalGlobe 40cm class (4 Band)	0.4m	25 sq km	US$19.5 sq km	100 sq km	US$29.5 sq km
DigitalGlobe 40cm class (4 Band)	0.4m	25 sq km	US$22.5 sq km	100 sq km	US$32.5 sq km
DigitalGlobe 50cm class (8 Band)	0.5m	25 sq km	US$19 sq km	100 sq km	US$29 sq km
DigitalGlobe 40cm class (8 Band)	0.4m	25 sq km	US$24 sq km	100 sq km	US$34 sq km
DigitalGlobe 30cm class (8 Band)	0.4m	25 sq km	US$24 sq km	100 sq km	US$34 sq km
IKONOS	0.8m / 3.6m	25 sq km	US$10 sq km	100 sq km	n/a
Pleiades	0.5m	25 sq km	€10 sq km	100 sq km	€17 sq km
Triplesat/DMC-3	0.8m	25 sq km	US$10 sq km	100 sq km	US$15 sq km
Kompsat-2	1m	25 sq km	US$4 – 5.50 sq km	100 sq km	US$8 sq km
Kompsat-3	0.5m	25 sq km	US$8-11 sq km	100 sq km	US$16 sq km
Kompsat-3A	0.3m	25 sq km	US$12-16 sq km	100 sq km	US$24 sq km
Orbview-3	1m	25 sq km	free	100 sq km	n/a
Dubaisat-2 4 band	1m	25 sq km	US$6 sq km	100 sq km	US$10 sq km

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
Dubaisat-2 bundle	1m/4m	25 sq km	US$8 sq km	100 sq km	US$14 sq km
Deimos-2	0.75m	25 sq km	US$6 sq km	100 sq km	US$12 sq km
EROS B	0.7m	25 sq km	US$6 sq km	50 sq km	US$16 sq km
Cartosat-2	0.8m	25 sq km	US$ 1515	Scene	US$ 1515
KazEOSat-1	1m	100 sq km	€7 sq km	100 sq km	€11 sq km
SPOT6 /7	1.5m	100 sq km	€3.80 sq km	500 sq km	€4.6
SPOT 6/7	6m	1000 sq km	€0.90 sq km	500 sq km	€1.3 sq km
SPOT 5 3 band	2.5m	1000 sq km	€2.30 sq km	n/a	n/a
SPOT 5 Pan	2.5m	1000 sq km	€1.50 sq km	n/a	n/a
SPOT 5 3 Band	5m	1000 sq km	€1.50 sq km	n/a	n/a
SPOT 5 Pan	5m	200 sq km	€0.90 sq km	n/a	n/a
EROS-A	1.8m	1 scene	US$0.50 sq km	n/a	n/a
Cartosat-1	2.5m	1 scene	€1980.00	1 scene	€1980.00 scene
Formosat-2	2m	1 scene	€1875.00	n/a	n/a
Formosat-2 4 Band	2m	1 scene	€2250.00	n/a	n/a
THEOS	2m	1 scene	US$850.00	1 scene	US$1150.00 scene
THEOS	2m	1 scene	US$1105.00	1 scene	US$1495.00 scene
ALOS PRISM	2.5m	500 sq km	¥50000.00 sq km	n/a	n/a
RapidEye	5m	1 scene	€0.95	3500 sq km	€0.95
Theia	5m	1 scene	US$995.00	5000 sq km	US$1.00
ZY-3 Pan	2.1m	1 scene	US$800.00	1 scene	US$800.00
ZY-3 4 band	2.1m	1/8 scene	US$1600.00	1 scene	US$1600.00
TH-1 Pan	2m	1/8 scene	US$860.00	1/8 scene	US$1585.00
TH-1 4 Band	2m	1 scene	US$1290.00 scene	1/8 scene	US$2015.00 scene

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
ALOS AVNIR	10m	1 scene	£60 / scene	n/a	Archive only
DMC	22m	1 scene	€0.06 / sq km	€ 1,500.00	€0.15 / sq km
ASTER	15m/30m/90m	1 scene	Free	1 scene	Free
ASTER	15m/30m/90m	1 scene	Free	1 scene	Free
Cartosat-2	0.8m	1 scene	US$895 / scene	1 scene	US$1,486 / scene
IRS-P5 (Cartosat-1)	2.5m	1 scene	€2,070 / scene	1 scene	€2,070 / scene
IRS-R2 (Resourcesat-2)	5m	1 scene	€5,175 / scene	1 scene	€5,175 / scene
IRS-R2 (Resourcesat-2)	5m	1 scene	€2,875 / scene	1 scene	€2,875 / scene
IRS-R2 (Resourcesat-2)	20m	1 scene	€3,105 / scene	1 scene	€3,105 / scene
IRS-R2 (Resourcesat-2)	60m	1 scene	€1,840 / scene	1 scene	€1,840 / scene
IRS-P6 (Resourcesat-1)	5m	1 scene	€5,175 / scene	1 scene	€5,175 / scene
IRS-P6 (Resourcesat-1)	5m	1 scene	€2,875 / scene	1 scene	€2,875 / scene
IRS-P6 (Resourcesat-1)	20m	1 scene	€3,105 / scene	1 scene	€3,105 / scene
IRS-1C/1D	60m	1 scene	€1,840 / scene	1 scene	€1,840 / scene
IRS-1C/1D	5m	1 scene	€4,542.5 / scene	1 scene	n/a
IRS-1C/1D	5m	1 scene	€2,932.5 / scene	1 scene	n/a
IRS-1C/1D	5m	1 scene	€2,587.5 / scene	1 scene	n/a
IRS-1C/1D	5m	1 scene	€1,322.5 / scene	1 scene	n/a
IRS-1C/1D	5m	1 scene	€862.5 / scene	1 scene	n/a
IRS-1C/1D	25m	1 scene	€2,760 / scene	1 scene	n/a
IRS-1C/1D	25m	1 scene	€1,725 / scene	1 scene	n/a

2. Cost of imagery from all radar satellites

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
CosmoSkymed Spotlight 10	1m	1 scene	€ 3,000	1 scene	€ 6,000
Cosmoskymed Spotlight 7	1m	1 scene	€ 2,500	1 scene	€ 5,000
Cosmoskymed Stripmap Himage	5m	1 scene	€ 1,500	1 scene	€ 3,000
Cosmoskymed Stripmap Pingpong	20m	1 scene	€ 950	1 scene	€ 1,900
Cosmoskymed ScanSAR Wide	30m	1 scene	€ 825	1 scene	€ 1,650
Cosmoskymed Scansar Huge	100m	1 scene	€ 825	1 scene	€ 1,650
TerraSAR-X Staring Spotlight	0.25m	1 scene	€ 3,475	1 scene	€ 6,950
TerraSAR-X High resolution spotlight	1m	1 scene	€ 2,975	1 scene	€ 5,950
TerraSAR-X Spotlight	2m	1 scene	€ 2,125	1 scene	€ 4,250
TerraSAR-X Stripmap	3m	1 scene	€ 1,475	1 scene	€ 2,950
TerraSAR-X ScanSAR	18.5m	1 scene	€ 875	1 scene	€ 1,750
TerraSAR-X Wide ScanSAR	40m	1 scene	€ 875	1 scene	€ 1,750
Kompsat-5 High resolution mode	1m	1 scene	US$1,650	1 scene	US$3,300
Kompsat-5 Standard mode	3m	1 scene	US$1,000	1 scene	US$2,000
Kompsat-5 Wide swath mode	20m	1 scene	US$800	1 scene	US$1,600
ALOS-1 Palsar	6.25m	1 scene	€ 60	n/a	Archive only
ALOS PGM (Palsar Global Mosaic)	10m	10,000 sq km	¥100,000 / 10,000 sq km	n/a	Archive only
ALOS PGM (Palsar Global Mosaic)	25m	10,000 sq km	¥50,000 / 10,000 sq km	n/a	Archive only
ALOS-2 Palsar Spotlight	3x1m	1 scene	¥500,000	1 scene	¥650,000

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
ALOS-2 Palsar Ultra Fine	3m	1 scene	¥300,000	1 scene	¥450,000
ALOS-2 Palsar High sensitive	6x4.3m	1 scene	¥300,000	1 scene	¥450,000
ALOS-2 Palsar Fine	9x5.3m	1 scene	¥300,000	1 scene	¥450,000
ALOS-2 Palsar High sensitive full Polarimetry	5x4.3m	1 scene	¥300,000	1 scene	¥450,000
ALOS-2 Palsar Fine full polarimetry	8.7x5.3m	1 scene	¥300,000	1 scene	¥450,000
ALOS-2 Palsar ScanSAR nominal (20MHz)	47.5mx77.7m	1 scene	¥150,000	1 scene	¥300,000
ALOS-2 Palsar ScanSAR nominal (14MHz)	95.1mx77.7m	1 scene	¥150,000	1 scene	¥300,000
ALOS-2 Palsar ScanSAR wide (490km)	44.2mx56.7m	1 scene	¥150,000	1 scene	¥300,000
Radarsat-1 all beam modes	All	1 scene	CAD$3,600	n/a	Archive only
Radarsat-2 heritage modes Single pol	All	1 scene	CAD$3,600	1 scene	CAD$4,200
Radarsat-2 heritage modes Dual pol	All	1 scene	CAD$3,800	1 scene	CAD$4,400
Radarsat-2 Spotlight A	1.6x0.8m	1 scene	CAD$6,000	1 scene	CAD$6,600
Radarsat-2 Extra Fine	3.1x4.6m	1 scene	CAD$7,500	1 scene	CAD$8,100
Radarsat-2 Wide Fine	5.2x7.7m	1 scene	CAD$7,500	1 scene	CAD$8,100
Radarsat-2 Ultra Fine	1.6x2.8m	1 scene	CAD$5,400	1 scene	CAD$6,000
Radarsat-2 Wide Ultra Fine	1.6x2.8m	1 scene	CAD$7,800	1 scene	CAD$8,400
Radarsat-2 Fine and Standard Quad Pol	5.2x7.6m & 9 or 13.5x7.6m	1 scene	CAD$5,400	1 scene	CAD$6,000
Radarsat-2 Wide Fine Quad Pol	5.2x7.6m	1 scene	CAD$7,800	1 scene	CAD$8,400

Sensors	Spatial Resolution	Minimum Order Price for Archived Data	Archive Price	Minimum Order Price for Tasked Data	Tasking Price
Radarsat-2 Wide Standard Quad Pol	9 or 13.5x7.6m	1 scene	CAD$7,800	1 scene	CAD$8,400
Radarsat-2 Multilook fine	3.1x4.6m	1 scene	CAD$4,200	1 scene	CAD$4,800
Radarsat-2 Wide Multi-Look Fine	3.1x4.6m	1 scene	CAD$7,500	1 scene	CAD$8,100
RISAT-1 Coarse resolution ScanSAR (CRS)	50m	1 scene	US$660	1 scene	US$1,320
RISAT-1 Medium resolution ScanSAR (MRS)	25m	1 scene	US$660	1 scene	US$1,320
RISAT-1 Fine resolution Stripmap (FRS-1)	3m	1 scene	US$840	1 scene	US$1,680
RISAT-1 Fine resolution Stripmap (FRS-2)	9m	1 scene	US$840	1 scene	US$1,680
ERS-1 SAR	25m	1 scene	Free	n/a	n/a
ERS-2 SAR	25m	1 scene	Free	n/a	n/a
ENVISAT ASAR	25m	1 scene	Free	n/a	n/a
ENVISAT Wide	150m	1 scene	Free	n/a	n/a
JERS-1	18m	1 scene	Free	n/a	n/a
Sentinel-1A/B	5m/20m	1 scene	Free	n/a	n/a