Review of Oil Spill Remote Sensing Technologies

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Abstract

Remote-sensing for oil spills is reviewed. The technical aspects of sensors are given and the benefits and limitations of each sensor are noted. The use of visible techniques is ubiquitous; however it gives only the same results as visual monitoring. Oil has no particular spectral features that would allow for identification among the many possible background interferences. Cameras are economical and useful to provide documentation. In daytime oil absorbs light and remits this as thermal energy at temperatures 3 to 8 K above ambient, this is detectable by infrared (IR) cameras. IR cameras are also economical; however they suffer from deficiencies similar to visible sensors such as the inability to discriminate oil on beaches, among weeds, debris or sediment. The use of visible and IR cameras on platforms such as aerostats and drones will result in providing much useful tactical information.

Laser fluorosensors are useful instruments because of their unique capability to identify oil on backgrounds that include water, soil, weeds, ice and snow. They are the only sensors that can positively discriminate oil on most backgrounds. The laser fluorosensor also can discriminate between oil types. Radar detects oil on water by the fact that oil will dampen water-surface capillary waves under low to moderate wave/wind conditions. Radar offers the only potential for large area searches, day/night and foul weather remote sensing. Many oil look-alikes are also detected. Satellite-borne radar sensors are useful for mapping large spills or assisting in ship and platform discharge monitoring. Today, the strategic remote sensing requirements can largely be satisfied by the use of radar data from satellites. Many areas of the world have multiple radar passes per day and these can be used to provide daily oil pollution maps. The use of ship-borne radar can supply much of the local tactical information necessary.

Equipment that measures relative slick thickness is available at this time in the form of passive microwave. Passive microwave has been studied for several years, and has recently emerged as a commercial technology.

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1 Introduction

Remote sensing plays an increasingly important role in oil spill response efforts. Through the use of modern remote sensing instrumentation, oil can be monitored on the open ocean on a 24-hour basis. With knowledge of slick locations, response personnel can more effectively plan countermeasures. A strong role for remote sensing has also been the detection of illegal discharges, especially in view of the large seabird mortality associated with such discharges (O'Hara et al., 2013).

It is important to divide the uses of remote sensing into the end use or objective, as the utility of the sensor is best defined that way (Fingas and Brown, 2011). Oil spill remote sensing systems used for routine surveillance certainly differ from those used to detect oil on shorelines or land. One tool does not serve for all functions. For a given function, many types of systems may, in fact, be needed. Further it is necessary to consider the end use of the data. The end use of the data, be it location of the spill, enforcement or support to cleanup, may also dictate the resolution or character of the data needed.

There are several broad uses of remote sensing:

1. Enforcement of ship discharge laws,
2. Surveillance and general slick detection,
3. Provision of evidence for prosecution,
4. Mapping of spills for various reasons,
5. Direction of oil spill countermeasures, and
6. Determination of slick trajectories.

There are several generic problems in oil spill remote sensing including:

1. There are no cheap commercial off-the-shelf sensors that provide ready, remote sensing capability for oil,
2. Thickness information is not present in many sensors currently used. Only very thin slicks show a few visible indications of oil, but this may not be useful,
3. Some of the sensors and sensor outputs require extensive processing to make the data useful for the many purposes or use described above, and
4. All of the highly-useful sensors to be mounted on aircraft, require extensive aircraft modifications which are both costly and time-consuming.

Several general reviews of oil spill remote sensing have been published (Fingas and Brown, 2014). These reviews show that there is progress in oil spill remote sensing, however that progress is not necessarily moving at the speed that technology itself moves. These reviews show that specialized sensors offer advantages compared to off-the-shelf sensors.

2 Visible indications of oil

In the visible region of the electromagnetic spectrum (approximately 400 to 700 nm), oil has a higher surface reflectance than water, but does not show specific absorption/reflection tendencies. Oil generally manifests throughout the entire visible spectrum. Sheen shows up silvery and reflects light over a wide spectral region down to the blue. As there is no strong information in the 500 to 600 nm region, this region is often filtered out to improve contrast (Fingas and Brown, 2014). Overall, however, oil has no specific characteristics that distinguish it from the background (Fingas and Brown, 2014). It has been known for some time that oil on the water surface is better viewed with polarized lenses. Several workers have noted the polarizing effects of oil on water and have proposed methods to use this phenomenon to distinguish oil. Sun glitter is a particular problem in visible remote sensing. Sun glitter can sometimes be confused for oil sheens. Several workers have found ways to reduce or to deal with sun glitter. Visual oil observations often remain as the final confirmatory step in the process of identifying and confirming a slick.

3 Optical sensors

3.1 Visible

Video cameras are often used in conjunction with filters to improve the contrast in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. With new light-enhancement technology, video cameras can be operated even in darkness. Tests of a generation III night vision camera showed that this technology is capable of providing imagery in dark night conditions (Fingas and Brown, 2014).

Hyperspectral imaging is a growing area in remote sensing in which an imaging spectrometer collects hundreds of images at different wavelengths for the same spatial area (Gonzalez et al., 2013). Hyperspectral images are extremely complex, and require advanced processing algorithms to satisfy near real-time requirements in applications such as, mapping of oil spills and chemical contamination, etc.

Data in the visible has been subject to many efforts to use mathematical techniques to help distinguish oil from water. At this time no automatic processing algorithms are used in the oil spill industry. Overall, the visible area remains an active research area as well as a practical means of monitoring oil spills.

3.2 Infrared

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8 to 14 µm region. Thus infrared is a case where one is measuring the emissions from the oil. In infrared (IR) images, thick oil appears hot, intermediate thicknesses of oil appear cool, and thin oil or sheens are not detected. The thicknesses at which these transitions occur are poorly understood, but evidence indicates that the transition between the hot and cold layer lies between 50 and 150 µm and the minimum detectable layer is between 10 and 70 µm (Pinel and Bourlier, 2009). The reason for the appearance of the 'cool' slick may be that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, thereby reducing the amount of thermal radiation emitted by the water. This would yield a destructive interference onset of about 16 to 20 µm to about 4 wavelengths or about 32 to 40 µm. The destructive or 'cool' area is usually only seen with test slicks, which is explained by the fact that the more rapidly-spreading oil is of the correct thickness to show this phenomenon. Slicks that have been on the water for a longer period of time usually are thicker or thinner (i.e. sheen) than 16 to 40 µm. The onset of the hot thermal layer would in theory then be at thicknesses greater than this or at about 50 µm.

Most infrared sensing of oil spills takes place in the thermal infrared at wavelengths of 8 to 14 µm. Specific studies in the thermal infrared (8 to 14 µm) show that there is no spectral structure in this region (Fingas and Brown, 2014). Nighttime tests of IR sensors show that there is detection of oil (oil appears cold on a warmer ocean), however the contrast is not as good as during daytime. Further, on many nights no difference is seen due to weather conditions.

The relative thickness information in the thermal infrared can be used to direct skimmers and other countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, however, as several false targets can interfere, including seaweeds, sediment, organic matter, shoreline, and oceanic fronts. Infrared sensors are reasonably inexpensive, however, and are currently the prime tool used by the spill remote sensor operator. Infrared cameras are now very common and commercial units are available from several manufacturers.

3.3 Ultraviolet

Oil shows a high reflectance of sunlight in the ultraviolet range. Ultraviolet sensors can be used to map sheens of oil as oil slicks display high reflectivity of ultraviolet (UV) radiation even at thin layers (<0.1 µm) (Fingas and Brown, 2014). Overlaid ultraviolet and infrared images were used in the past to produce a relative thickness map of oil spills. This technique is largely not used today as the thicknesses are not relevant to oil spill countermeasures. Thicknesses of 0.5 to 10 mm are needed for countermeasures purposes these are almost 1000 times greater than those indicated by infrared (Fingas and Brown, 2014). Ultraviolet data are also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material.

4 Laser Fluorosensors

Laser fluorosensors are sensors that use the phenomenon that aromatic compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum (Brown, 2011). Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. Natural fluorescing substances, such as chlorophyll, fluoresce at sufficiently different wavelengths than oil to avoid confusion. As different types of oil yield slightly different fluorescent intensities and spectral signatures, it is possible to differentiate between classes of oil.

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 308 to 355 nm (Brown, 2011). The fluorescent response of crude oil ranges from 400 to 650 nm with peak centers in the 480 nm region.

Most fluorosensors use a technique to open their detectors just at the time when signals return from the surface. This technique is called 'gating'. This vastly increases sensitivity and selectivity. Some fluorosensors are capable of gating their detectors to look below the target surface and some also to look at above the target surface. Work has been conducted on detecting oil in the water column such as occurs with the heavy oil-in-water product, Orimulsion (Brown , 2011). This was carried out with a gated fluorosensor which looked at signal returns below the target surface. This work shows that gated laser fluorosensors are capable of detecting oil in the water column as deep as 2 m and easily at 1 m.

The laser fluorosensor is a sampling instrument. The repetition rate of the laser and the ground speed of the aircraft are important in the sampling rate of the surface where the oil contamination is being observed. At ground speeds of 100-140 knots at a laser repetition rate of 100 Hz, a fluorescence spectrum is collected approximately every 60 cm along the flight path. This decreases if the instrument is scanning.

Laser fluorosensors have significant potential as they may be the only means to discriminate between oiled and unoiled seaweeds and to detect oil on different types of shorelines. Tests on shorelines show that this technique has been successful.

Laser fluorosensors have shown high utility in practice and are now becoming essential sensors in many remote sensing packages. The information in the output is unique and the technique provides a unique method of oil identification. The method is analogous to performing chemistry in flight. The typical fluorosensor can provide an abundance of information to the user as shown in Figure 1.

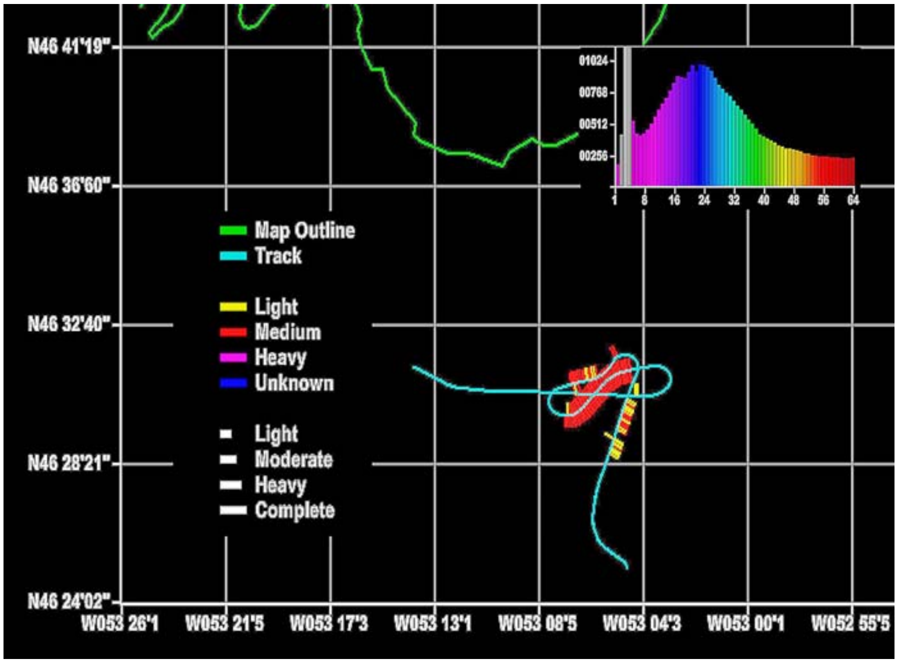

Figure 1 Portions of a real-time fluorosensor output display. The oil detections are shown as bars along the mapped flight path. The color of the bars shows the type of oil measured. The length of the bar shows the aerial coverage. At each point along the flight path the spectrum of the target is also displayed (From Environment Canada)

5 Microwave Sensors

5.1 Radar

Capillary waves on the ocean reflect radar energy, producing a 'bright' image known as sea clutter. Since oil on the sea surface dampens capillary waves, the presence of an oil slick might be detected as a 'dark' sea or one with an absence of this sea clutter (Fingas and Brown, 2014). Unfortunately, oil slicks are not the only phenomena that are detected in this way. There are many interferences or false targets, including fresh water slicks, wind slicks (calms), wave shadows behind land or structures, shallow seaweed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm. Even with extensive processing, false hits on SAR imagery could be as high as 20%, that is 20% of the images reported as oil are still look-alikes. Figures 2 to 3 illustrate some of the many slick look-alikes which appear in radar displays. Despite these limitations, radar is an important tool for oil spill remote sensing because it is the only sensor that can be used for searches of large areas and it is one of the few sensors that can detect anomalies at night and through clouds or fog.

The two basic types of imaging radar that can be used to detect oil spills and for environmental remote sensing in general are Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR). The latter is an older, but less expensive technology, which uses a long antenna to achieve spatial resolution. Synthetic aperture radar uses the forward motion of the aircraft to synthesize a long antenna, thereby achieving very good spatial resolution, which is independent of range, with the disadvantage of requiring sophisticated electronic processing. While inherently more expensive, the SAR has greater range and resolution than the SLAR (Fingas and Brown, 2014). SLAR has predominated airborne oil spill remote sensing, primarily because of the lower price. Experimental work on oil spills has shown that X-band radar yields better data than L- or C- band radar. Several different polarizations exist based on vertical (V) and horizontal (H) electromagnetic wave propagation. Typically transmission and reception are in the same polarity, i.e. VV or HH. But, there are actually 4 poles available: HH, VV, HV and VH. Use of all four of these is designated as quadrupole. Some workers noted that VV polarization tends to be more suitable for oil pollution detection when winds are strong and HH when winds are light although this was observational (Fingas and Brown, 2014). Generally the VV image is better for detecting oil spills.

Search radar systems, such as those frequently used by the military, cannot be used for oil spills as they usually remove the clutter signal, which is the primary signal of interest for oil spill detection. Furthermore, the signal processing of this type of radar is optimized to pinpoint small, hard objects, such as periscopes. This signal processing is very detrimental to oil spill detection.

The ability of radar to detect oil is limited by sea state (Fingas and Brown, 2014). Sea states that are too low will not produce enough sea clutter in the surrounding sea to contrast with the oil and very high seas will scatter radar sufficiently to block detection inside the wave troughs. Indications are that minimum wind speeds of 1.5 m/s (~3 knots) are required to allow detectability and a maximum wind speed of 6 m/s (~12 knots) will again remove the effect. The most accepted limits are 1.5 m/s (~3 knots) to 10 m/s (~20 knots). This limits the environmental window of application of radar for detecting oil slicks.

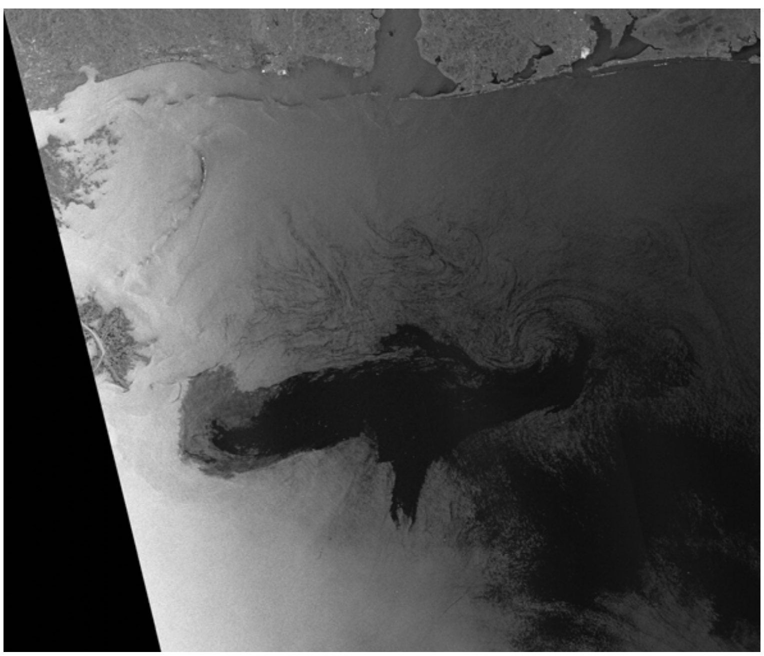

Figure 2 The Deepwater Horizon as imaged by Radarsat (EOSANP).

5.2 Satellite Radars

Currently many different radar systems exist, giving scientists a choice of configurations, bands and polarizations.

5.3 Ship-mounted Radars

Ship-borne radar has similar limitations to airborne and satellite-borne radar and the additional impediment of low altitude, which restricts its range to between 8 and 30 km, depending the height of the antenna (Fingas and Brown, 2011). Ordinary ship radars can be adjusted to reduce the effect of sea clutter de-enhancement, however specialized units perform much better for oil slick detection. Ship-borne radar successfully detected many slicks and at least eight commercial systems are now available. Ship-borne radar is now an important tactical tool for guiding vessel-mounted skimming systems to oil slicks in the vicinity.

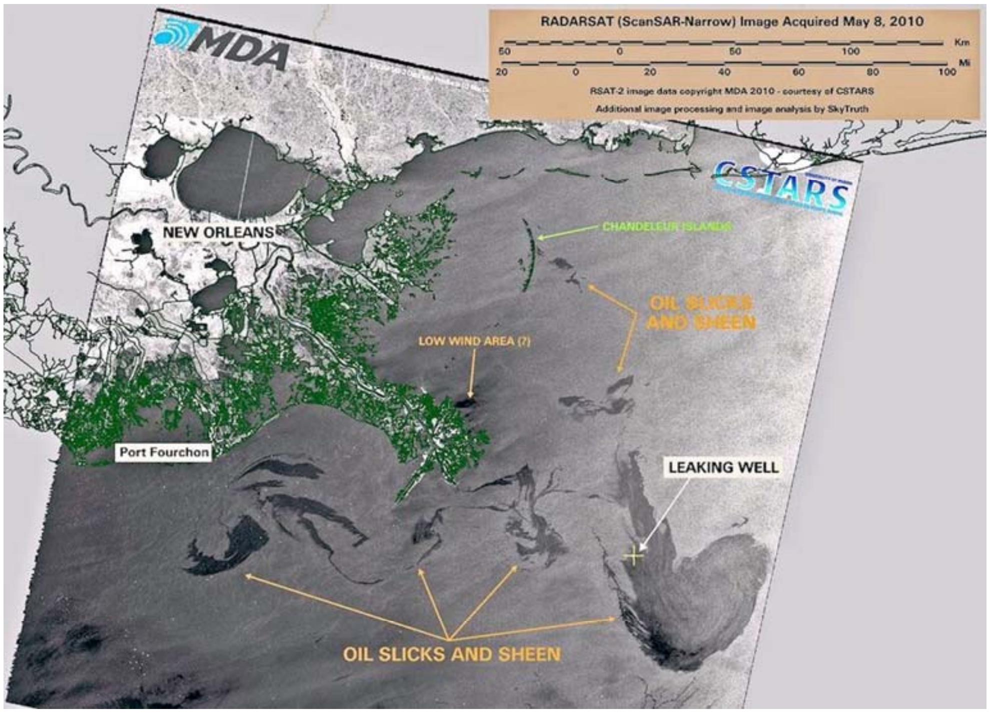

Figure 3 A RADARSAT image of the Gulf Oil spill. The annotation on this image provides information on the scenes. The land is imaged by visible satellite. (Photo from MDA website http://sm.mdacorporation.com)

6 Slick thickness determination

6.1 Passive microwave

Passive microwave uses ambient microwave radiation from space to measure oil thickness (Fingas and Brown, 2011). The microwave signal itself is reflected within the oil layer creating a resonance that can be detected. As the signal is cyclical with respect oil thickness, more than one frequency must be measured to measure oil thickness. The systems require calibration, usually carried out by sensing plastic sheets of the appropriate thickness. Currently passive microwave instruments are the only ones being used for oil thickness measurements. Figure 4 shows the output from a processed set of images of a slick.

6.2 Other systems

There have been several systems proposed over the years. Many of these systems have failed to provide slick thickness data.

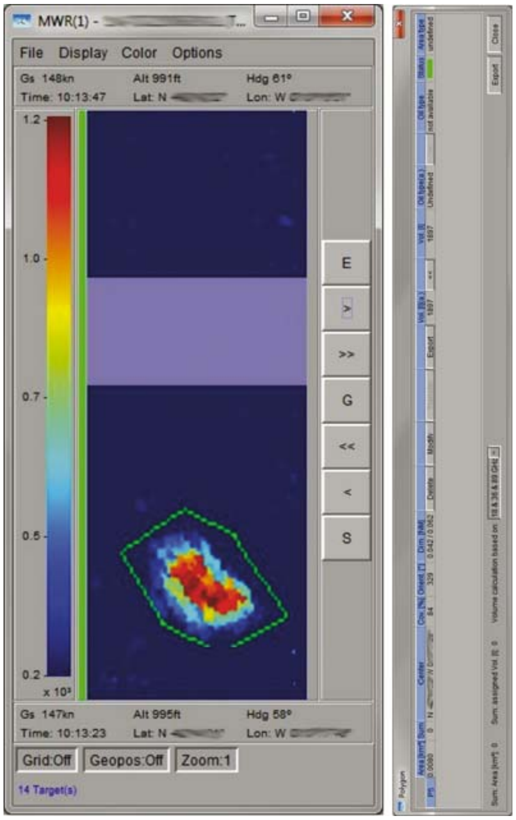

Figure 4 An image of a slick characterized by microwave (Communication from Nils Robbe, Optimare, 2013). The colors of the image represent thicknesses and the scale is on the left hand side of the image display (ranges from 0.2 to 1.2 mm in this case). This is an image from the usual aircraft display and several pieces of information are normally available including location, area of slick (here this is 0.008 km^2, yielding a volume of 1897 L). The data were measured using a 3- band passive microwave imager operating at 18, 36 and 89 GHz.

7 Small remote-controlled aircraft (and drones)

Several parties have suggested remote-controlled aircraft to provide more economical solutions for response personnel (Fingas and Brown, 2014). In fact, remote-controlled aircraft have been used by a number of parties for monitoring a variety of pollutants since the 1970's.

Belgium employs a UAV of the B-Hunter class to routinely monitor its portion of the North Sea (Donnay, 2009). This is a large UAV which has visible and IR camera systems aboard. The unit has 10-hour endurance over the targets.

A variety of commercial platforms are now available which can provide a platform for small sensors such as visible and IR cameras. Further, automatic navigation technology has now made these units, especially helicopters, very much easier to fly than in previous years. These ‘drones’ can now be programmed to fly on their own. Further, gyro-stabilized cameras are available to take the ‘jitter’ out of the images by either electronic or even by direct camera stabilization. This makes imaging capability much more useful to the user. In the future it is believed that drones and sensors mounted on them will constitute an important tactical remote sensing capability.

8 Dirigibles

Similar to drones, the use of aerostats has proven to provide a good tactical means for dealing with oil spill imagery. Also similar to drones, the images can be geo-stabilized. There are existing systems with visible and IR camera systems.

9 Summary

The last decade has seen great strides in some areas. For offshore oil spills, the use of satellite radar has expanded very rapidly. The availability of data from several satellites has greatly increased the utility of this technique. Despite the limitations of winds and presence of look-alikes, the technique of satellite radar has predominated the detection and mapping of offshore spills. This trend is likely to continue and expand for some time to come.

There is little development for near-shore and land spills compared to that for offshore spills. The technology is still similar to that of a decade ago. A similar situation exists for sub-surface spills and for oil-in-ice situations.

Two specific sensors that show potential are the passive microwave radiometer for measuring thickness at sea, and the laser fluorosensor for a variety of sensing applications. Both sensors require extensive commercialization.

In terms of strategic remote sensing at sea, more and more reliance is being placed on the use of satellite remote sensing data. In terms of tactical remote sensing at sea, the use of ship-mounted radar will grow and the use of drones with camera systems will be the future.

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