Recent Developments in Airbor

With Military & Environmental Applications to the Fore!

Infra-Red (IR) imagers have been used by military air forces for the last 25 years. However the last few years have seen some quite dramatic developments in the technology, together with its introduction and widespread adoption in the civilian domain. The first part of this article will review the new IR technology, while the second part will cover some of the numerous applications that have been implemented, especially in the area of environmental monitoring and mapping.

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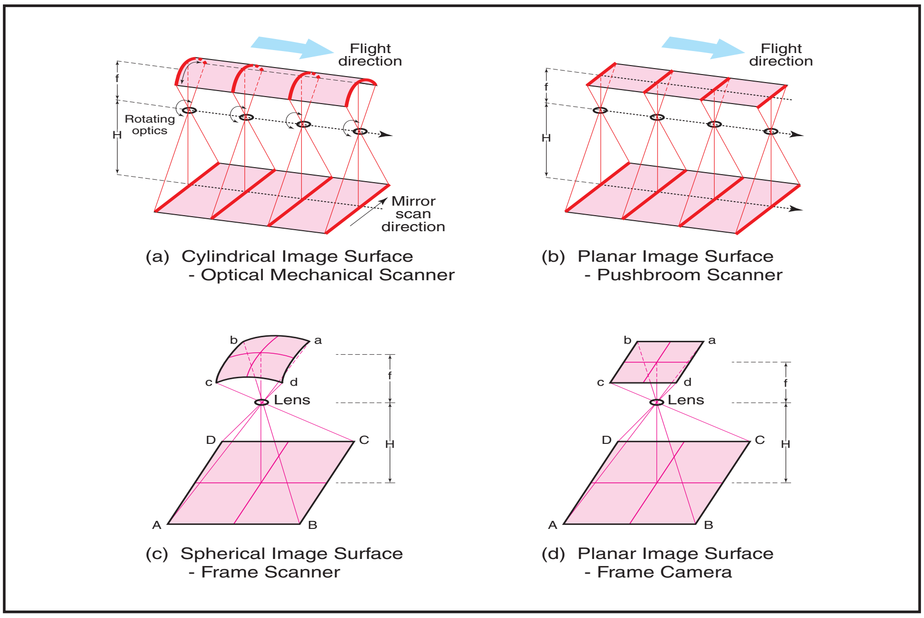
IR Spectrum

Usually four different regions of the infra-red (IR) spectrum can be distinguished. (i) The near infra-red (NIR) region lies adjacent to the visible (VIS) part of the spectrum and covers the wavelength (λ) range between 0.7 and 1 micrometre (µm). (ii) The short wave infra-red (SWIR) region covers the range λ = 1 to 2.5µm. In both cases, the main source of illumination of the terrain comes from reflected solar radiation. Thus the imagers operating over these shorter wavelengths must operate in daylight conditions. (iii) The medium wave infra-red (MWIR) comprises the range λ = 3 to 5µm, while (iv) the long wave infra-red (LWIR) or thermal infra-red occupies the range λ = 8 to 14mm. In stark contrast to the shorter IR wavelengths, the radiation used by imagers operating in these two longer wavelength regions is that emitted by the terrain objects themselves. This latter characteristic allows the terrain to be imaged at night, as well as during the day. The use of imagers operating in the MWIR and LWIR regions also offers the capability of improved visibility through smoke, haze and dust. This article will be mainly concerned with airborne imagers operating in the MWIR and LWIR regions.



Basic image geometries of airborne IR imagers. (a) Optical-mechanical scanner producing a continuous strip image with a cylindrical surface. (b) Pushbroom scanner producing a continuous strip image with a planar surface. (c) Frame scanner producing discrete frame images with a spherical surface. (d) Frame camera producing discrete frame images with a planar surface. (Drawn by M. Shand)

Detectors & Sensors

The detector materials that form the basis of the sensors that will detect radiation from the terrain and produce an image in most parts of the IR spectrum are quite esoteric. Consequently they are extremely difficult and expensive to manufacture and to fabricate into imaging sensors. This results in low yields of these detector materials and places considerable restrictions on the number of detectors and the size of the sensor arrays that can be produced and used in an IR imager. Thus many IR imagers utilize scanning mechanisms to provide the required coverage of the terrain from an airborne platform. In the case of the MWIR region, photon detectors are mainly used. These are usually made of indium antimonide (InSb) or platinum silicide (PtSi). These materials only work efficiently as radiation detectors if they are cooled to a low temperature: 196K (-77°C). In the LWIR region, the detectors that are commonly used are made from compounds or alloys of cadmium and mercury telluride (CMT) or lead and tin telluride (LTT). The CMT material can also be used to detect radiation in the MWIR region. The operating temperature of detectors made from these materials is 77K (-196°C). Older types of IR imager used liquid nitrogen in a Dewar flask as the cooling medium for their detectors. Nowadays, small Joule-Thomson mini-coolers using the cooling effect from a high-pressure gas escaping to the atmosphere through a tiny opening are often used for the purpose. Alternatively tiny micro-cooling engines based on the Stirling cycle may be used instead. A major commercial supplier of these specialist cooling devices that are used in airborne IR imagers is the Hymatic Engineering group based in Redditch in the West Midlands of England.

Focal Plane Arrays

Over the last four or five years, considerable attention has been paid to the development of a new "uncooled" IR detector technology. This comprises areal arrays or focal plane arrays (FPAs) of detectors made

ne Infra-Red Imagers

(a) Barr & Stroud IR-18 frame scanner with five alternative lenses giving different magnifications and fields of view. (b) Agema ThermoVision 1000 frame scanner equipped with an internal lens turret allowing either narrow (5°) or wide angle (20°) fields of view.

of lead zircon telluride (PZT) or other materials that operate in the LWIR or thermal part of the spectrum. When thermal IR radiation is focused on these detectors, their temperature changes in a direct relation to the amount of radiation that they absorb. In turn, this causes a change in certain electrical properties of the detector that are proportional to the incident energy. This change in these properties is measured for each detector by a tiny micro-bolometer. The prime advantage of this technology is that it operates at ambient temperatures without the need for the extreme cooling required by the other detectors mentioned above. Much of the research effort into the development of "uncooled" FPA technology in the USA and UK has been funded from military sources - in the case of the U.K. by DERA (Defence Evaluation & Research Agency). The technology is already being used in a wide range of applications - including missile guidance; early warning systems; infantry weapon sights; driver vision in military vehicles; etc. - besides airborne imaging systems. Europe's largest centre for the production of IR detectors is the plant belonging to BAE Systems located in Southampton - formerly owned by GEC-Marconi Infra-Red Ltd. This produces both "cooled" and "uncooled" detectors for use in airborne and spaceborne IR imagers. The Sofradir company in France also produces a range of IR detectors and sensors.

Optical Aspects

When considering the optical characteristics of infra-red imagers, the main point to note is that the familiar silicon-based optical glass used in frame cameras and scanners in the VIS/NIR region is opaque to and cannot transmit radiation at MWIR and LWIR wavelengths. The most common material used for optical components at these longer wavelengths is germanium. To an observer unaccustomed to IR imagers, it comes as a shock to see that a germanium lens looks like a piece of black tar. Yet it is in fact transparent and will transmit radiation at MWIR and LWIR wavelengths.

Airborne IR Imagers

As noted above, the small size of IR detector arrays has meant that some form of scanning is often necessary to obtain images of the terrain and ground objects from an airborne platform such as a manned or unmanned aircraft or a helicopter. However frame-type images also exist, albeit often using small-sized areal arrays.

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• (i) Line Scanners

Typical of the early types of airborne IR imager were the military infra-red line scanners (IRLS) - e.g. those made by EMI (U.K.) and Texas Instruments (U.S.A.) and the civilian Daedalus (now Sensystech) scanners used for thermal heat loss surveys. These employed optical elements rotating at high speeds to scan the terrain in the cross-track direction. This allowed image data of the terrain to be obtained on a pixel-by-pixel basis sequentially along a single line over the ground. The forward motion of the airborne platform on which the line scanner imager was mounted then allowed successive lines to be acquired to build up a continuous strip image of the terrain. Many of these early scanners are still in operational use today. Imagers such as the Daedalus 1268 Airborne Thematic Mapper (ATM) were multi-spectral scanners recording several channels in the VIS/NIR region, besides two in the SWIR region and one in the LWIR or thermal region. A modern version is the Sensystech Airborne Bispectral Scanner (ABS) which uses two channels - typically one operating in the LWIR region and the other either in the SWIR or the VIS/NIR region. A built-in differential GPS inserts positional/navigation data into the imaging record. Typical of current military airborne IRLS imagers is the Type 8220 VIGIL built by W. Vinten Ltd. of Bury St.Edmunds in Suffolk. This employs a "cooled" detector operating in the LWIR region and a three-sided scanning prism rotating at 12,000 rpm, giving 600 line scans per second.

• (ii) Pushbroom Scanners

Linear arrays of hybrid CMT and CCD detectors with 768 and 1,024 elements that form the basis of pushbroom scanners have also been produced by the Southampton plant of BAE Systems. Several of these linear arrays can be multiplexed together to form TDI (Time Delay and Integration) channels in the scan direction to give improved radiometric sensitivity. So far, they have mainly been used in military IR imagers. However the pushbroom approach has also been used in a Rank Taylor Hobson Talytherm frame scanner that has been modified in-house to a pushbroom arrangement by the NRSC mapping company and used in its airborne heat-loss surveys. This imager acquires a 700 pixel wide swath over the ground and can record its data either in the MWIR or in the LWIR region. The UK-built military IR imagers that utilize CCD linear arrays in a pushbroom mode are the Type 8010 and 8042 EO (Electro-Optical) imagers built by Vinten. However these operate over the range $\lambda = 0.5$ to $0.95\ \mu m$ - i.e. in the VIS/NIR region - rather than in the thermal (LWIR) region. Basically these EO imagers are intended to replace Vinten's well known reconnaissance cameras equipped with 70mm and 5 inch (125mmm) wide film respectively. Both of these imagers are fitted with gyros to measure the tilts of the imager for every scan line that is acquired. Scan rates of 1,800 lines per second are typical with these imagers.

• (iii) Frame Cameras

Because of the difficulties experienced in constructing large areal (or staring) arrays of IR detectors, most IR frame cameras have quite a small format. Typical of these are the small hand-held cameras built in Sweden by Agema (now part of the American FLIR group). These include the Model 550 with its "cooled" InSb detectors operating in the MWIR (λ = 3 to 5μm) region and the Model 570 with its "uncooled" FPA operating in the LWIR (λ = 8 to 14μm) region. Their respective areal arrays are only 320 x 240 pixels in size - which has meant that they have been used mainly for ground-based condition monitoring within buildings and the inspection of electrical, mechanical and refractory equipment. However they have also been flown in helicopters, usually to record images of specific point targets rather than execute the systematic coverage of large areas of terrain. Similar imagers using "cooled" detectors operating in the MWIR and LWIR regions have also been produced by the Avionics Group of BAE Systems located in Basildon, Essex in the U.K. These mainly form the basis of FLIR (Forward Looking Infra-Red) imagers used for in-flight navigation and head-up displays (HUDs) or for military target detection, identification and tracking. However the most startling recent development in this field is the CA-265 Millennium IR framing camera from Recon Optical in the U.S.A. This military reconnaissance imager utilizes a much larger-format "cooled" PtSi array operating in the MWIR region producing 2k x 2k = 4 Megapixel images in combination with a 2.5 per sec. framing rate.

• (iv) Frame Scanners

In order to produce the wide field of view required in many military applications, especially airborne operations, the small sensor arrays that have been available have been used as the basis for another form of imager - the frame scanner. These employ a scanning mechanism in conjunction with a very small areal array to produce frame images of the ground. This mechanism has two optical scanning elements operating at right angles to one another in combination with the main imaging lens or telescope. The first of these elements is the so-called frame-scanning element - which scans the ground line-by-line; while the second element is the line scanning element - which scans each line pixel-by-pixel. The resulting frame image forms a spherical surface with all points on the image equidistant from the perspective centre. This image is of a relatively high resolution in IR terms outside the NIR region - 525 x 690 pixels in the case of the Barr & Stroud (now Pilkington Optronics) High Definition Thermal Imager (HDTI) and 565 x 450 pixels in the case of the Agema ThermoVision 1000. Increased sensitivity to the incident radiation is achieved through the use of small strips of the CMT material in the so-called SPRITE (Signal Processing In The Element) detector. This performs the same function as a row of detectors but with the Time Delay and Integration (TDI) taking place in the CMT strip itself. Typically a set of 5 to 8 SPRITE elements form the small sensing array that is used to carry out the scanning of the ground using the imager's dual optical scanning elements.

Video Displays & Recording

The recording, display and storage of the monochromatic (black and white) images captured by infra-red imagers is mostly implemented using analogue video signals and technology. Video Tape Recorders (VTRs) are in widespread use for the recording of the images generated by infra-red imagers, both in the field and during airborne operations. Professional grade U-matic VTR machines provide high-quality recording on $^{3}/_{4}$ inch (19mm) wide magnetic tapes, while Super VHS (S-VHS) VTR machines give an adequate quality using $^{1}/_{2}$ inch (12.5mm) wide tapes. These VTRs utilize the formats and standards (PAL, NTSC) that are currently in use in standard broadcast TV. Whenever real-time imaging and viewing is required - as in fire-fighting, surveillance, monitoring and military operations - the images will also be displayed directly on small video display screens that often

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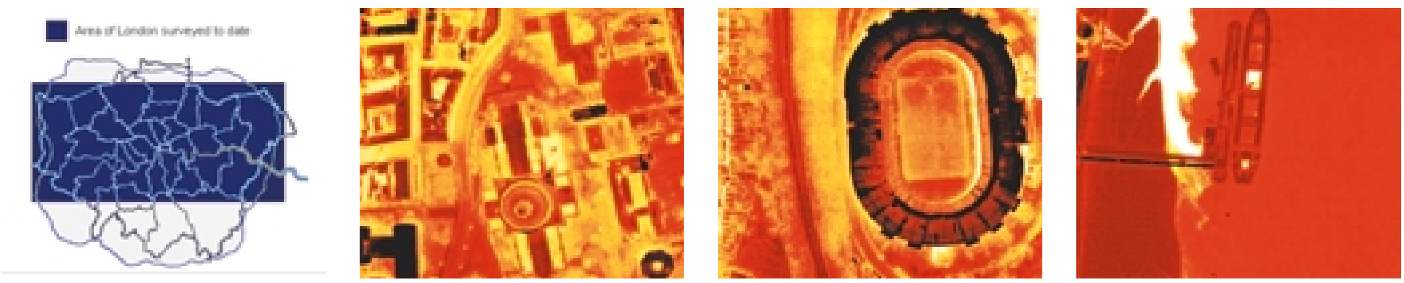
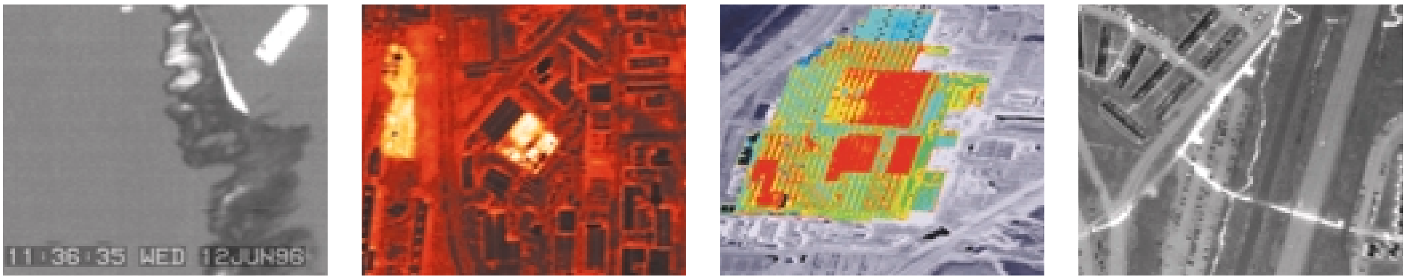
form an integral part of the imager. For the final processing, measurement and analysis of airborne infra-red images, the recorded images will normally be played back using a suitable VTR. Often large-format video monitors will be used to display and view the imagery, more especially in a laboratory or office situation. The video-based images will often need to be converted to digital form for processing and measurement purposes - especially for mapping and GIS operations. This video-to-digital conversion is carried out by a frame grabber mounted in the PC used for the post-flight processing and analysis. Some modern IR imagers can also record their data directly in digital form in-flight on 8mm tape .



London Thermal IR Mapping. (a) Map showing the area of the city covered to date. Thermal IR images of (b) St. Paul's Cathedral and (c) Wembley Stadium. (d) Hot water being discharged into the River Thames. (Source: Horton Levi)



(a) An oil spill shows up clearly as dark patches against the grey background image of the sea water. N.B. An oil boom has been set behind the spill control vessel, both showing up as bright objects on the image. (b) The bright yellow buildings (displaying excessive heat loss) comprise a block of flats from the 1960s and a small foundry. (Source: Sight Unseen) (c) Great differences in heat loss show up across a large factory. (Source: NRSC) (d) The heating pipeline crossing an American college campus shows up clearly on this thermal IR image.

Military Reconnaissance

Since the developments in IR imaging technology have largely been driven and fuelled by military requirements, obviously it is used extensively by military air forces for reconnaissance purposes. The imagers are either fitted directly into dedicated reconnaissance and patrol aircraft or into removable pods that are slung below the aircraft. Increasingly they are also being used in unmanned drone aircraft, as well as a wide range of combat aircraft and helicopters. The ability to undertake reconnaissance missions at night or in hazy conditions using imagers operating in the MWIR and LWIR regions is a major advantage. The characteristics of the imagers allow them to be used both when travelling at low altitudes and high speed and at high altitude, often standing off to image the target area using long-focus, high-resolution lenses. The images can either be recorded directly on board the aircraft or transmitted directly to a ground station using an air-to-ground data link. Corresponding developments have also taken place in the workstations that have been built to allow analysts to rapidly exploit the information gathered by the airborne IR imagers. Needless to say, the IR images can be readily processed, manipulated and enhanced in these workstations with rapid geo-referencing and overlay of the imagery on digital map data and the measurement of the coordinates of ground targets or features that are of interest to the analyst.

Heat Loss Surveys

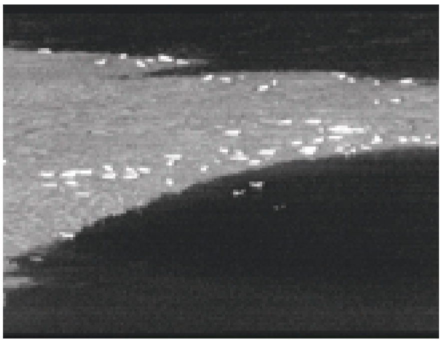
Heat loss surveys are one of the major civilian applications of airborne thermal IR imaging. In the U.K., several commercial companies - e.g. Horton Levi, Sight Unseen and NRSC - specialize in this activity. Other smaller companies specializing in ground-based condition monitoring may also undertake airborne surveys on request when the opportunity arises. Recently a major survey covering most of London has been carried out by Horton Levi and its associated company, Thermal Mapping Ltd., both of which are based in Norwich in East Anglia. So far, 40,000 frame images have been acquired to ensure this coverage of London. The images have been taken using the Barr & Stroud IR-18 frame scanners operated by the company. One of these imagers has been converted to give direct digital recording on tape in the aircraft which was flown at 2,000ft (610m). These IR-18 imagers have produced a continuous series of frame images with a swath width of 420m over the ground. The data sets are being made available to industry, central and local government agencies and the general public over the Internet. As well as London, Norwich has also been covered in a similar manner and the intention is to provide thermal IR image coverage of a number of other towns and cities in the U.K. Besides these large systematic surveys, many smaller individual surveys are carried out on contract for local authorities and large industrial companies all over the U.K. by all three of the companies mentioned above. For example, NRSC has carried out surveys of the London boroughs of Hackney and Bexley on this basis.

• Energy Conservation

A major objective of all of these heat loss surveys is energy conservation. In particular, under the UK's Home Energy Conservation Act (HECA), all local authorities must assess the energy efficiency of their existing housing stock. Within this context, the thermal IR images are being used to check the integrity of house insulation and to identify individual buildings or parts of large public buildings (schools, hospitals, etc.), office blocks, factories, warehouses and industrial plants that are poorly insulated and are suffering heat loss. Remedial measures may then be taken to rectify this situation and so save energy and cut costs. Also the exact location of the underground hot water pipelines used in district heating schemes can be determined and any breaks in the insulation or leaks in the pipes resulting in ground saturation or thermal plumes can be pinpointed with a view to their repair.

• Flying Operations

With regard to the acquisition of the image data, the flying for heat loss surveys is normally carried out at night during the winter when the outside air temperature is at a minimum, buildings are being heated and any heat loss will be most easily seen on the imagery. Sight Unseen, based in Southport, Lancashire, uses twin-engined aircraft to fly over urban areas. These are supplied and operated by Cooper Aerial Surveys - which is also the main flying contractor for the Millennium Mapping orthophoto project described in the April/May 2000 issue of GeoInformatics. Like Horton Levi, Sight Unseen also utilizes Barr & Stroud IR-18 frame scanners for its thermal IR surveys and mapping operations. The in-flight navigation of the aircraft at night is carried out using the Computer Controlled Navigation System (CCNS) supplied by the German IGI company, which is in widespread use throughout the aerial survey and mapping industry. The CCNS package is also used for the flight planning of the surveys. GPS is used for the positioning and in-flight navigation of the aircraft, the coordinate values being continuously recorded by the CCNS system. Differential GPS is not necessary, especially now that the Selective Availability (S/A) feature has been switched off. The accuracy achieved with the simple non-differential GPS is quite appropriate for the purpose of airborne thermal imaging and mapping. Horton Levi has also experimented with the simultaneous use of its two IR-18 imagers with each being tilted slightly to the left



Harbour seals show up clearly as white objects against the rocks and seaweed of the coastline. (Source: Sea Mammal Research Unit, Univ. of St.Andrews)

and right of the flight line respectively to increase the ground swath covered by the imagery.

- **Mapping Operations**

In some cases - especially if cost is a major consideration - the client may be quite happy with the supply of the image data on video tape, with certain parts supplied on a CD-ROM and selected images produced in hard copy form. However many local authorities require the image data to be geo-referenced since they use GIS systems for the storage, display and analysis of all the map-based information held in their databases. Thus the images resulting from a heat loss survey may be required to fit this other information whose geographical location is usually based on Ordnance Survey (OS) digital map data. Both Horton Levi and Sight Unseen use the ERDAS Imagine package for this purpose. The frame images are rectified and mosaiced using ground control points (GCPs) that have been identified and extracted on-screen from OS Landline data. This is a fairly labour-intensive operation since the overall mosaic will often be formed from a very large number of quite small-format images. In this respect, the IR-18 images acquired from the commonly used flying height of 2,000ft (610m) may only cover an area of 120 x 275m - though the actual coverage will of course depend on the specific lens that is fitted to the imager for use on a particular survey. Given the comparatively low ground resolution of the images and the fact that normally a quantitative analysis will be carried out on the image data rather than high-precision photogrammetric measurements, no attempt is made to remove the relief displacements resulting from terrain elevation differences or building heights. Frequently individual images that are of particular interest will be converted from the grey level values of the basic (monochrome) thermal IR imagery to a false-colour representation in order to accentuate and pick out temperature differences. This colourized representation is often easier for a non-specialist to interpret. Almost invariably, the interpretation of thermal IR imagery is carried out manually and visually on-screen by specialist interpreters or by the client - who may need some prior training for the purpose. Automated machine-based classification techniques are seldom used in thermal mapping and heat-loss surveys.

Environmental Applications

Airborne IR imagery is also used in a wide range of environmental applications. Thus, for example, the extent of flooding and water damage - which currently is a matter of great concern over much of Europe - may be determined rather readily from MWIR and LWIR airborne imagery. At the other extreme, surveys are often conducted along water supply pipelines to locate damage to and leakage from such pipes. This is a matter of considerable concern in those areas experiencing droughts and water shortages. Airborne IR imagery has also been used to detect and locate effluent being discharged into rivers, canals, lakes and reservoirs. Still other surveys are being carried out to study the flow and dispersal of hot water being discharged into the sea or rivers from power stations and the water circulation patterns that are present in cooling ponds. Other matters of strong environmental concern involve the use of airborne IR imagery to carry out the monitoring of landfill sites to determine thermal anomalies and the possible build-up of methane gas or the leakage of pollutants. The monitoring of underground fires in abandoned coal workings has also been carried out using airborne IR imagery, as has the location and extent of forest fires - where the smoke penetration capability of longer wave IR imagers is an important attribute. Another application of airborne IR imagery is the location and monitoring of oil spills from ships at sea. British, Dutch, Norwegian and Swedish coastguard aircraft are all equipped with Daedalus and/or Talytherm IR imagers, often in combination with SAR imagers, for this purpose. Yet another task for helicopters fitted with IR imagers is the routine monitoring of electrical power distribution networks to locate hot-spots on cables, insulators and transformers which may signify potential faults.

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Animal Censuses

Still in the environmental area, an important application of airborne IR imagery is the undertaking of censuses of certain animals. Thus, for example, the Sea Mammal Research Unit at the University of St. Andrews in Scotland has been undertaking regular surveys of the seal populations that live along the Scottish coastlines. Use is made of a Barr & Stroud IR-18 frame scanner mounted in a helicopter. The surveys are carried out at low tide while the seals are hauled out of the water during their annual moult in August. The heat from their bodies makes them appear conspicuous and easy to identify and count on the thermal IR imagery - whereas at visible wavelengths they are well camouflaged against the rocks and seaweed of the coast. The information gained from the resulting data has been used to help define Special Conservation Areas under the EU's Habitat Directive.

Conclusion

Given the present day concern with environmental issues, now that airborne IR imaging technology has matured and has come more fully into the hands of civilian users, it should find widespread application in the future.

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