S2172

UNITED NATIONS

ECONOMIC AND SOCIAL COUNCIL

Distr.
LIMITED

E/CN.14/CART/299
31st October 1972

Original: ENGLISH

ECONOMIC COMMISSION FOR AFRICA

Third Regional Cartographic Conference for Africa

Addis Ababa (Ethiopia) 30 October - 10 November 1972
Provisional agenda item 7(c)

REMOTE SENSING AT IGN*

Submitted by the Government of France

INTRODUCTION

IGN's mission is topographic mapping, that is, the description of the Earth's surface, first by work on the ground, and secondly by aerial photographs which constitute a remote recording of the physical characteristics of the terrain. But topographic data represent only one of the many types of information which can be collected; it is only of the one physical phenomena which can be recorded. Furthermore, light radiations constitute only a small portion of the electromagnetic spectrum which can be used to convey information.

With the rapid expansion of industrialization, urbanization and population, consideration must be given to safeguarding nature, protecting the environment and making an inventory of natural resources; techniques have been developed which make it possible to record the phenomena related to these fields. The study of these phenomena as an extension of the study of the Earth's surface, is part of the mission of IGN just as it is part of the mission of all major world geographical services such as the United States Geological Survey, which is responsible for the survey for the topographical map.

PROBLEMS PRESENTED

The problem of the environment and pollution, although it may be particularly acute today, is, not however, new; Julius Caesar long ago laid down rules designed to ensure the conservation of certain animal species such as hedgehogs, while Horace complained of the infernal noise made by chariots in

---

* By the Institut Géographique National (IGN)

Rome at night. But, of course, the industrialization which has taken place over the last century and the present population explosion, constitute causes of pollution of a much greater magnitude, particularly in view of the degree of urban and industrial concentration resulting in 80 per cent of the world's population being crowded into only 2 per cent of the Earth's surface.

IGN's traditional activities are already enabling it to embark on estimates of natural resources and to contribute to the protection of natural beauty spots through the use of its aerial photographic coverages and of the maps on various scales which can be established from them. Photographs on infra-red sensitive films or on so-called false colour films 1/ provide information on vegetation and the different crops, water resources, coastal areas, forest species, land-use patterns and land-forms. In additinn, the information contained in these documents make it possible to safeguard human populations against natural catastrophies such as avalanches, floods, fire, etc.

Conventional photographic recordings, however, have limitations, in that they are dependent on the transparency and purity of the atmosphere, and on sunlight, and because a large number of the features of the terrain are not discernible on them. It is for this reason that increasing use is being made of remote sensing using various airborne devices known as sensors, which enable phenomena to be recorded by electromagnetic waves with frequencies very different from those of the visible-light spectrum, and extending to the X-band of radar (SHF).

The advantage of these remote sensing methods lies in the wide range of problems that can be studied, it being possible to use one procedure for research of very different types, and also in the rapidity of access to information, laboratory processing generally being minimal. In addition, this rapid access to information makes it possible to describe the environment from in terms of both time and space, enabling the evolution of a phenomenon to be followed by means of a series of sensings carried out at regular intervals over a period of time. Lastly, since these methods are not dependent on the optical transparency of the atmosphere in the visible-light spectrum, or on sunlight, it is possible to operate in over-cast conditions or at night, which has many advantages.

THE REMOTE SENSING PROCESS

The basic elements in remote sensing are the recording devices, or sensors, which are carried on platforms. These platforms may be aircraft, balloons or satellites, and IGN is fortunate in possessing such platforms in its aircraft pool which comprises fifteen aircraft ranging from the Aero Cammander to the Mystére 20 twinjet and including also B.17's and Hurel Dubois. It is, therefore, possible to operate at altitudes from 300m to 13,500 m, at cruising speeds of between 250 km/h and 850 km/h. IGN also has the possibility of participating

1/ For these emulsions, the first layer (non-colour sensitized emulsion, selecting in the blue is omitted, while a third layer is added for selection in the infrared. Further information on this subject can be obtained from the article by Mr. Jean Cruset, Bulletin d'Information de l'IGN No. 12, December 1970.

in a programme of environmental study using the American ERTS-B or EROS satellites, which were specially launched for this purpose, and for which each country can establish a research programme. As a result, IGN will be able to gather information on the development patterns, in terms of both time and space, of snow cover in the mountainous areas of France, by virtue of recordings made at regular 18-day intervals and re-transmitted to the ground. These Earth resources research satellites are termed synchronous because they pass twice daily over the zenith of points of the same latitude, at the same local solar time. To achieve this, they are programmed to follow a near-polar orbit at an altitude of about 910 km. By virtue of the ellipsoidal shape of the Earth, the irregularities of the outer gravity field and planetary influences, the orbits undergo changes which cause the satellites to pass approximately once every 18 days over the zenith of a given point on the Earth's surface at the same local solar time, i.e. in the same position in relation to the sun if the variation in the angle of the sun's declination is not taken into account. If there were no orbital changes, it would be sufficient to programme the satellites to follow a strictly polar orbit at an altitude such that their periods were submultiples of the solar day (e.g. 1,660 km for two hours), so that each day they would pass over the zeniths of the same points at the same solar time.

The first sensors to be brought into service at IGN, and which are still given considerable use were of course conventional cameras which could be used with lenses of different focal lengths, different emulsions and at a variety of flying altitudes and scales, thus providing a wide range of possibilities.

The most interesting instrument which the IGN has at present, however, is a device which enables the temperature of the points on the ground over which the aircraft is flying to be measured to within a fraction of a degree centigrade. While the plane is in motion, the apparatus successively scans narrow strips of terrain to 60° on either side of the line of flight by means of a mirror which rotates at 70 revolutions per second. As the intensity of the signal emitted by the detector cell increase in proportion to the temperature of each point examined, an electrical image of terrain temperatures, or videogramme, is obtained and recorded on magnetic tape. This videogramme may be either transfermed immediately into an optical image on an on-board television screen, on which the details appear brighter in proportion to their temperature, or can be transformed by a laboratory transcription unit into a black and white image on paper, showing the temperatures of the strip of terrain flown over. This apparatus is known as a <u>scanner</u> and the documents obtained are called thermal images. The entire procedure is termed airborne infrared thermography.

PRINCIPLE OF THERMOGRAPHY

The radiation recorded comes partly from the reflexion of solar radiation from the elements constituting the terrain and partly from the radiation emanating from the objects themselves. Between the ground and the sensors, this radiation is modified by atmospheric absorption and diffusion.

The reflected radiation is generally of no interest and can be considered as superfluous radiation which must be eliminated. The simplest way of achieving this is obviously to carry out the photographic coverage by night, but this is not always possible, as for example, when one wishes to study diurnal temperature variations. Mathematical elimination of this radiation is made very difficult by virute of its highly anisotropic nature, (i.e. the energy received depends more on the shape of the figure formed by the

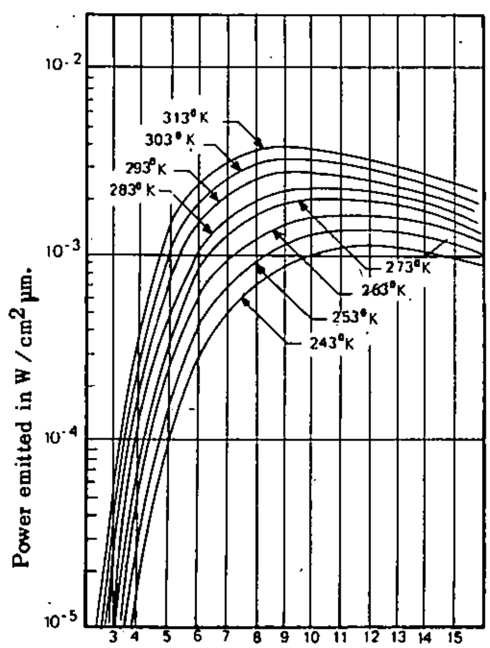


Fig. 1 - Spectral emissivity of black-body radiator at different temperatures

sun, the sensor and the point to be studied than on the nature of this point). Of course, quantitative studies of anisotropy have been conducted on different types of soil and coverings of vegetation, but to use these results in making a correction is at best a laborious procedure, and at worst impracticable for highly heterogeneous areas.

The problem created by reflected radiation can be expressed in terms of the ratio of the energy from this radiation to the energy from the emitted radiation. This ratio is appreciably lower at about 10 microns than at 5 microns, a fact which may influence the choice of the sensor to be used in a given situation.

The important radiation is the emitted radiation, since it enables the temperature to be deduced. In effect, the spectral emissivity curves of a black-body radiator at different temperatures, show that, for those temperatures most frequently found on the ground (about 300°K) the maximum radiated energy is in the region of 10 microns, and that this energy remains appreciable up to

2 microns (Fig. 1). It is therefore tempting to conclude that the ideal arrangement is to have an apparatus sensitive to a band in the region of 10 microns. In practice, the differences of temperature must generally be shown, and a more detailed study shows that the curves become further apart at wavelengths slightly below the maximum wavelength.

In effect, only a very approximate comparison can be made between black-body radiators and actual bodies. In order to make the transition from one to the other, it is necessary to introduce the concept of <u>emissivity</u>. This is the ratio of the energy actually emitted by the body in question to the emissive power of the corresponding black-body radiator at the same temperature. At its maximum, this ratio is equal to 1 (in the case of the black-body radiator) and can vary considerably: between 0.9 and 0.8 for water, according to circumstances, and can fall as low as 0.4 or 0.3 for rocks.

But the atmosphere, too, plays an important part in absorbing and diffusing a certain amount of the radiation. With regard to absorption, there are a number of transmission <u>windows</u> in the atmosphere, as shown in Fig. 2. In the area of concern to us, the following absorption bands are due essentially to transitions in the rotation of molecules of water (vapour) and molecules of carbonic gas. (2,5 microns - 3 microns), (4.3 microns), (5.8 microns - 7.3 microns) and 14 microns - 1 mm). This means that atmospheric absorption does not present any great problem.

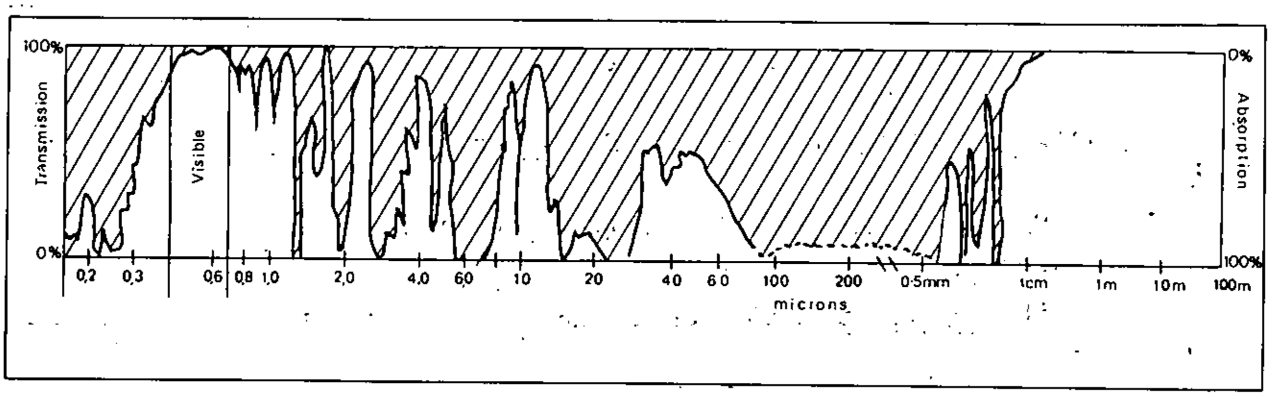


Fig.2 - Atmospheric absorption of the electromagnetic spectrum

Furthermore, theoretical calculations show that diffusion for particles which are small in relation to the wavelength is proportional to -4, where is the wavelength. This phenomenon is therefore very weak in the infrared - less than 1 o/00 of the energy lost by diffusion at 1,000 metres.

In the case of larger particles, the infrared is substantially more penetrating than the visible light wavebands, which is a considerable practical advantage: mists and fine fogs are relatively transparent, which enables photographing to be carried out in mediocre weather conditions. But the size of the particles must not be too great, since the wavelength cannot be increased indefinitely (absorption from 14 microns; beyond this, one comes to the EHF band).

Other phenomena such as the emissivity of the atmosphere may come into play. In the wavelengths which correspond to the absorption bands, the atmosphere behaves like a black-body radiator. In addition, thermal phenomena in the atmosphere, such as temperature inversions, can impair the image of the ground. These questions will be taken up again later in the study of atmospheric pollution.

Finally, there is the question of transparency in liquid or solid media: is it possible to see, or merely detect on a thermograph an object which is sunken below the ground or which is lying on the sea-bottom? There can be no blanket answer to this. Theory shows that the transparency of liquid water, rocks, soils under infrared light is extremely low, in the region, say, a few fractions of a millimetre.

Nevertheless, the answer to this question is not totally negative. The temperature of the surface, or at least of a very fine surface film, is recorded, but this temperature is influenced by deep-seated thermal phenomena. Let us take the case of a homogeneous soil in which an object of a very different specific heat is buried with the whole being subjected to thermal fluctuations. Through thermal conductivity, the soil can be considered as transmitting to the surface, an image of the object; this image may, of course, be distorted. In liquids, convection appears to play the predominant role. An attempt may be made to pinpoint the phenomenon by calculating from models, but as we all know, actual conditions are more complicated than the most complex models. The role which this pseudo-transparency can play will be considered for each type of application (geology, hydrology, etc.).

EQUIPMENT USED

To obtain a thermograph a series of devices must be used. These consist of:

- one or more sensors; infrared scanner, or scanners;
- a recorder;
- a unit for the transcription of the recorded signal on to a sensitive film.

Although the sensor and recorder are installed on board the aircraft, the transcription unit is generally not (it enables the information collected to be processed later).

The sensor: general layout of infrared scanners. The scanner is a device which measures the energy of the radiation received. This is a passive measurement in that it does not call for the emission of a reference radiation and is carried out using the three parts constituting the scanner (Fig. 3).

(a) An optical-mechanical device which collects the radiation emanating from the ground. It consists of a mirror which rotates about an axis parallel to the line of flight and inclined at 45 degrees to it; in this way, the mirror scans the terrain at right angles to the direction of movement of the aircraft. A focusing system enables the energy received to be concentrated onto the detector cell.

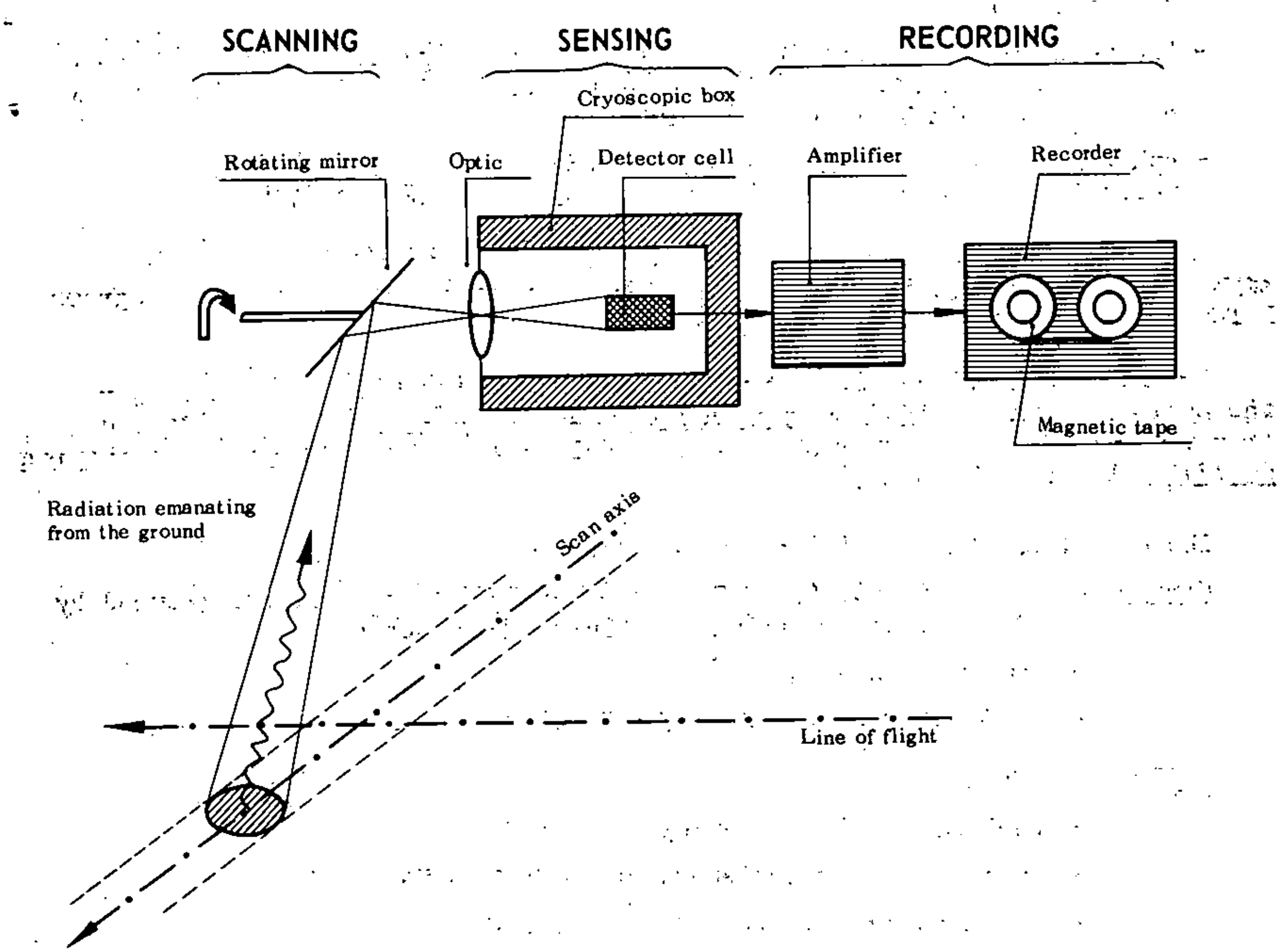


Fig. 3 - Theoretical diagram of a scanner

(b) A cell sensitive to the infrared radiation received, consisting of the detector proper, housed in a cryoscopic box ensuring a good signal-to-noise ratio.

(c) An electronic measuring system consisting basically of an amplifier enabling the signal to be communicated to the recorder.

The first sensors, introduced in 1950, used heat-sensors: the infrared radiation heated a sensitive element, the resistance of which varied in relation to this temperature. The advantage of these was that they could be used at atmospheric temperature, but their response time was very long (several milliseconds). These sensors were replaced by photo-sensors which transform infrared photons into kinetic energy of electrons. These, once liberated, modify the electrical properties of the cell. These devices have a very short response time (less then one microsecond) but can be used only at low temperatures.

The two types of cell mainly used are:

- the indium antimonide (InSb) cell sensitive from 3 to 5 microns at a temperature of 77°K (the sensitivity curve can be shifted towards the longer wavelengths - up to 8 microns by causing a magnetic field to act on the cell);

- the mercury-doped germanium cell (Ge:Hg) sensitive from 8 to 14 microns at the same temperature of 77°K. Fig. 4 shows the relative sensitivity curves of the InSb and Ge:Hg cells;

- other substances may be used as detectors, such as mercury-cadmium telluride (Cd Hg Te) sensitive from 8 to 14 microns at 77°K.

The temperature of the cell is maintained at approximately 77°K in a cryoscopic tank of liquid nitrogen or, for lower temperatures, (a few degrees K for certain Ge: Hg cells), liquid helium.

Further technical details concerning the scanner used in the infrared - the Cyclope of the Société Anonyme des Télécommunications - can be obtained from the article "Le scanner infra-rouge Cyclope", in the Bulletin d'Information de l'IGN, No. 10, March 1970.

The essential characteristics are as follows:

Mirror - speed of rotation: 70 revolutions per second (it was reduced by almost half following the first trials tests)

- scanning angle : 120°
- angle of analysis : 5 milliradians

Cell-type : InSb

- cooling to 77°K by liquid nitrogen
- independent operation time: 5 to 6 hours
- temperatures detected - 30° C to + 60° C
- thermal resolution : 0.25° C.

The electrical signal emitted by the cyclops analysis head does not provide an absolute value for the ground temperature, it provides only a relative indication, so that it is necessary, for accurate interpretation of the measurements, to know the values of certain additional parameters:

- The scanner is coupled to a radiometer, which measures the absolute temperature of the ground along the line of flight. This radiometer consists of a germanium heat-sensor-type cell. The response of this cell, which is sensitive to thermal radiation between 8 and 14 microns, is compared to that for the radiation from a black-body radiator used as a reference, thus enabling the signal values to be converted into temperatures. These temperatures are termed absolute because two points on the ground with the same emissivity and temperature produce the same signal value. Nevertheless, to obtain true temperatures, it is necessary to check the radiometer response against measurements made on the ground.

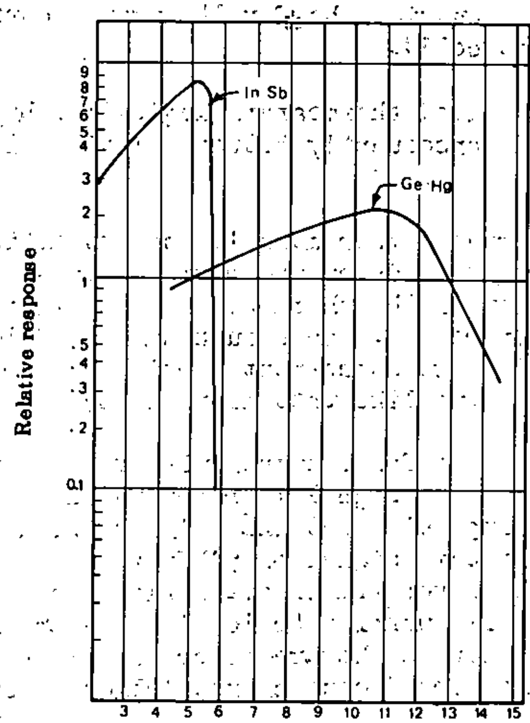


Fig. 4 - Relative spectral responses of InSb and Ge:Hg cells

The radiometer measures radiation in one direction only (it is not possible to conduct an analysis with a rotating mirror because of the excessively long response time of the cell) and in a relatively open cone (the angle of analysis being 2°). It is sensitive to a temperature difference of the order of one-tenth of a degree and permits absolute measurement of about half a degree.

The scanning of the terrain depends to a considerable extent on the movements of the aircraft and determines the quality of the final image for measurements purposes. At present, the flight parameters (heading, position, roll, altitude, etc.) are not recorded; it is possible to envisage the use of sensors which, while measuring these parameters, would be connected to a recorder to allow for better correction during processing of the information given out by the scanner.

<u>The recorder</u> - The signal which comes directly from the detector cell is known as the input signal and the signal recorded from the amplifier is known as the output signal.

The output signal is kept between - 1 and + 1 volts to enable it to be recorded. This calls for two amplification adjustments:

- adjustment of the average level so that the output signal oscillates around a zero average value;

- adjustment of the gain (ratio of the output signal amplitude to the input signal amplitude) so that the output signal is not chopped off when it should have been outside the ±1 volt limits (corresponding to areas which are too hot or too cold).

These two settings provide good thermograph legibility by giving a better rendering of half-shades and consequently better relative discrimination between temperatures.

These adjustments can be made either manually or automatically. In the latter case, the adjustments are made on the basis of the preceding signal values and vary from one point on the thermograph to another, which prevents any direct evaluation of temperature, since such an evaluation can then only be made by taking account of these adjustments, which must be recorded, or by referring to an independent datum like that provided by the radiometer.

At present, signals to be used for measurementspurposes are recorded on an analog basis on magnetic tape (the signal is recorded in a continuous manner, as opposed to digital recording which retains only the signal values taken at regular intervals). A periodic signal of 54kHz is used as a reference and is recorded on one of the seven tracks available. This signal is frequency-modulated for the low signal frequencies (below 100 Hz) and recorded on a second track. Frequencies of more than 100 Hz are recorded directly onto a third track. A fourth track is used for frequency-modulation recording of the signal emitted by the radiometer.

In addition, a "pip" signal marking the beginning and end of each scanning sweep is recorded, thus permitting the two-dimensional reconstruction of the image (see: processing of data). The remaining tracks could be used (up to 14) to record the flight parameters or to check the scanner signal with a view to later processing of the analyzed image for better interpretation. The tapes used are half-inch tapes, 1,100 metres long; these run at a speed of 76cm/s, giving about 20 minutes of recording time.

Other recording systems can be used. It is, for example, possible to store the information and display it on a cathode-ray tube, in order to obtain a real-time image, thus permitting rapid identification and detailed study of the most interesting areas.

The processing equipment, which at present consists of a unit for transcribing the magnetic tape information onto film, is described in greater detail below.

<u>Implementation</u> - Examination of the principles and techniques used in establishing a thermograph demonstrates the importance of the conditions under which the thermograph is made and the data processed to the final interpretation.

There are two factors which determine the methodology to be used: firstly, the choice of the optimum thermographic conditions, not only to show up the phenomena to be studied, but also to check the results obtained (a) in the aircraft, through the use of appropriate additional sensors, and (b) on the ground by the selection of test samples. The conditions which are most suitable depend to a large extent on the result desired, but in general, it can be said that the optimum conditions are those which favour the best differentiation of tempera- tures related to the phenomenon being studied. For example, in looking for fresh-water springs along the coast, the surface thermal effect of these springs must be at its maximum; this means that the sea must be at low tide, that the season must be the one in which the flow of these springs is at its peak and that the scale used must be large enough to show up these springs, which are little more than pinpoints.

It is also necessary to work at night in order to avoid unwanted reflections. Weather conditions can also play a role: thawing snow, for example, favours archaeological exploration.

Processing of data - Having gathered a mass of data, it is necessary to extract from them information of interest to the specialist, who will then interpret the documents produced. At IGN, data processing is carried out by electrophotographic methods, but the future solution will undoubtedly be digital processing by computer. The recorded magnetic tape is read by a transcription unit which reconstitutes the signal emitted by the reading head and uses it to modulate the intensity of a light ray, which, in turn simulates the scanning and produces and image on a 70 mm black-and-white film. This simulation is made possible by the "pip" signals marking the beginning and end of scanning sweeps which are registered during the recording. The film obtained constitutes the thermograph original, and can be reproduced on paper or can be used to produce a positive or negative enlargement.

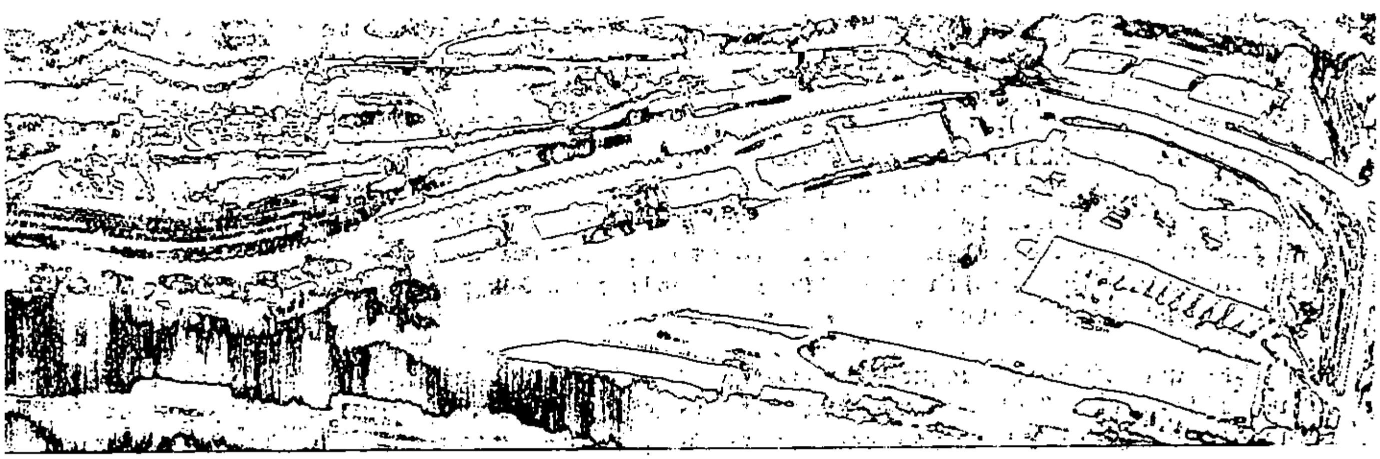
The use of certain special techniques makes it possible to obtain other types of document by filtering the signal, i.e. by letting through only a certain intensity value in order to produce on the film the representation of a line of isodensity (Fig. 5), or by using colour film and filter combinations, to obtain a document resembling a temperature map. The recorded signal is broken down by means of electronic thresholds which select a certain signal pitch interval. Each partial signal is associated with a coloured filter and is translated on the film by a certain colour. Together, the partial signals reconstitute the initial signal, with the different colours making the different shades of this signal more visible.

The use of these documents facilitates interpretation, but does not permit quantification of the phenomena. It is not possible, in this article, to discuss the necessity of recording the ground temperature on an absolute basis. Never- theless, the use of digital methods would make it possible to reduce the unwanted effects produced by the aircraft (geometric corrections) and by the sensor (signal corrections). The final document would be a more faithful image of the terrain and would consequently facilitate interpretation.

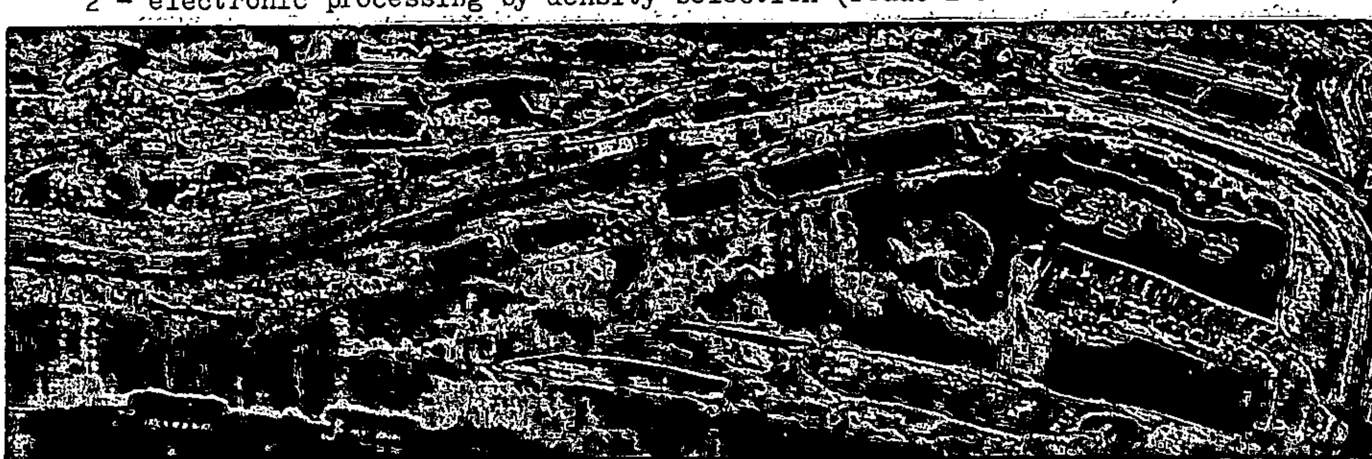
Methodology - The basic principles are the same as for photo-interpretation, i.e. the document obtained from airborne apparatus must be completed by informa- tion collected on the ground;this information has two quite distinct purposes: to"verify" so to speak, the recording in order to permit a fairly detailed interpretation, and secondly to check the validity and the accuracy of this interpretation.

Here the problem is made particularly difficult by the transcience of the parameter being recorded - the temperature. In other words, the appearance of any given area on aerial photographs changes slowly over a period of time, one of the most rapidly changing phenomena being, for example, the appearance of the vegetation at springtime. Even in this case, the change over a few days is negligible. For thermographs, on the other hand, the change over a one-hour period is appreciable. It may therefore be necessary to carry out examinations on the ground which are strictly synchronized with the passing of the aircraft. To avoid the locations of these examinations subsequently proving to have been badly chosen, a real-time visual display of the recording can be very useful.

1 - thermograph of the port of Rouen scale 1:10,000 approx.



2 - electronic processing by density selection (reduction to contour)



3 - processing by colour equidensity method

Fig. 5 - Different methods of processing data received

Notes on Fig. 5

The illustrations above show part of the port of Rouen. The range of the temperatures recorded is of the order of ten degrees centigrade; this range has been transposed into colours in the visible-light spectrum, from the violet to the red, with the lowest temperatures portrayed by the violet and the highest temperatures by the red.

The transposition should be interpreted as follows:

- sheds, covered buildings and metallic surfaces, which are the coldest objects, are shown in violet;
- the ground is in blue;
- the water of the Seine and the tide wave borne in by the rising tide are shown in green and yellow respectively;
- the water in the basins is shown in orange;
- areas of calm water polluted by waste outlets are in red, as are the roads and the warmest objects.

MULTIBAND REMOTE SENSING

A number of such scanners can be used in combination to constitute a multiband device capable of making simultaneous recordings of radiations from the ground in different bands of the spectrum with wavelengths which are not absorbed by atmospheric gases, i.e., the atmospheric transmission "windows". The comparison of the recordings obtained with different wavelengths makes it possible to collect data which would not be discernible on a single document, just as the comparison of photographs of a given area taken simultaneously on normal panchromatic and on infrared emulsions provides more information than a single photograph. In effect, the different radiations received can be subjected to much finer analysis with the aid of airborne spectrometers. These examine the entire spectrum of the radiation received, which is spread out after reception, by measuring the intensity of each individual radiation.

These spectra can comprise up to 17 channels, corresponding to different wavelengths from the ultra-violet to the infrared. The radiations emanating from each point examined by the scanner are directed towards a prism which spreads them into a spectrum. Optical fibres then conduct each of the chromatic bands chosen to separate photo-multipliers so that the energy of each radiation can be measured and the spectral composition of the radiation emitted by the different points on the ground and transmitted through the atmosphere can be determined. To enable these operations to be carried out, the aircraft must remain at an altitude of less than 3,000 m, the most effective flying height being 600 m above the ground surface. Just how the recordings enable the tone signature of a given type of object to be identified, its presence in the biosphere to be recognized, and even its density to be estimated will be seen later.

USE OF RADAR

The use of much longer wavelengths naturally leads to the use of SHF radar bands, which have the advantage of penetrating much denser cloud cover than would be possible with infrared radiations.

Everyone is familiar with the now widespread use of these waves to obtain radar images of the terrain directly below the aircraft, but they are given only limited use in the study of the environment because of the poor image resolution resulting from the minute variations in the reflecting power of the different ground details struck by vertical radar beams and from the small differences in relative distances. If, on the other hand, the beams are directed sideways from the aircraft, the relative distances vary rapidly with the angle of the beam, thus increasing resolution in proportion to the differential coefficient of this distance; in addition, the different details will show highly different reflecting powers, thus giving much better image contrast. Salient features of the terrain, rocky peaks, for example, will diffuse the radar radiation received much more than flat surfaces and will consequently appear as lines, or bright points on the image, thus making it possible to study the morphological, tectonic or structural features of the terrain. Similarly, different crops have different reflecting powers, as do wet and dry rocks, and calm or rough water, which permits detailed interpretation of the documents obtained. This device, known as side-looking airborne radar, operates by sweeping areas situated on either side of the line of flight of the aircraft; the responses provided by the reflected radiation receiver make it possible to establish a document showing the perspective of the terrain adjacent to the line of flight. As, at the same time, the distances between the aircraft and the points on the ground are determined by measurement of the time-delay in the return of the reflected signal, it is possible to rectify these perspective views and to convert them into the form that they would have had if they had been taken vertically, i.e., to make them directly usable for measurement purposes which is obviously of great importance in mapping applications.

THE ROLE OF REMOTE SENSING IN THE STUDY OF THE ENVIRONMENT

The study of the environment can be considered simply as an aspect of physical planning. Its purpose is to prevent such planning from leading to a deterioration in the quality of life in all its aspects, be they physiological, (purity of air and water, conservation and development of natural resources), psychological, (the protection of natural beauty spots and of recreational areas), or intellectual and scientific (protection of flora and fauna). This conception of the environment bring an added dimension into physical planning, which previously has been only a matter of economics.

It should be realized that 80 per cent of the world's human population occupies only 2 per cent of the Earth's surface, and that such a concentration can lead only to a deterioration in living conditions. Even in less densely populated areas of the world, Man's actions can have disastrous consequences for the environment. For example, the practice of burning off accelerates the formation of hard lateritic crusts in tropical regions, and the water in irrigation canals becomes a breeding ground for bilharzia.

We should not, however, make the error of going too far in this direction or of blindly following certain current doctrines which take the form of a sort of manicheism, excessively critical of Man and excessively idealistic in the image of nature which they project, where everything left in its natural state is perfect and everything produced by the hand of Man is depredatory. It is beyond argument that there are also natural phenomena which have devastating effects, that efforts must be made to circumscribe these and that, in any event, it is impossible to revert to a pre-industrial stage of development; we must therefore adjust to the industrialization of the developed countries and to the burgeoning populations of the developing countries, and find means of limiting the damage wrought and of reducing its awesome consequences. This is the role of environmental protection.

IGN now has staff and material resources which it can place at the disposal of the nation for the study of the environment, the management of natural resources, the establishment of inventories of these natural resources, the protection of natural beauty spots and for combatting all forms of pollution. This is the principal role of the Institute's remote sensing facilities.

APPLICATIONS

Geology. In the search for natural resources, the first studies to be carried out must naturally be the geological studies, and this is one of the areas to which thermography can be most successfully applied.

Generally, the best recordings are obtained at night, or more precisely, at the end of the night. This observation can be interpreted as meaning that, during the daytime (quite apart from the effects of reflection) and the evening, temperatures are too variable locally, depending on the topographical details (area illuminated by the sun, are a in shadow, area protected from the wind, vegetation, etc.), whereas, at night, temperatures become uniform over larger areas, mainly according to the thermal properties of the sub-soil.

Faults or fractures are easily visible on the recordings, often by virtue of the hydrological network (see below: hydrology). Of course, almost the same thing could be said of photographs. But - and this is perhaps one of the effects of the pseudo-transparency referred to above - the relative importance of the topographical features is shown more clearly. This is a great advantage to the tectonics specialist, who is considerably hampered by the jumble of minor features when studying aerial photographs.

As far as differentiation between different types of rock is concerned, thermography gives excellent results. Broadly speaking, it can be said that the greater the differences between the specific heats, the easier it is to distinguish between the various types of rock. In sedimentary formations therefore, it is possible to have a reference level of extreme specific heat which can be followed over considerable distances, or - and this is more usual - a succession of a number of layers in which the alternance of specific heats is characteristic and easily discernable with the naked eye. As far as the identification of the nature of the rock is concerned, once the dividing lines between the different rocks have been established, quite obviously a ground survey is often essential (see above: methodology).

In geology, pseudo-transparency appears to be a significant factor. A fairly homogeneous area pierced by an eruptive rock, which does not, however, protrude above the surface, or by a salt dome, are instances in which a certain transparency caused by thermal conductivity is discernible. An interesting case was pointed out in the course of the study of earth resources organized by the Centre national d'études spatiales in 1970-71. Thermographs taken in the late hours of the night gave an impressive representation of the core of the Bray anticline. 1/

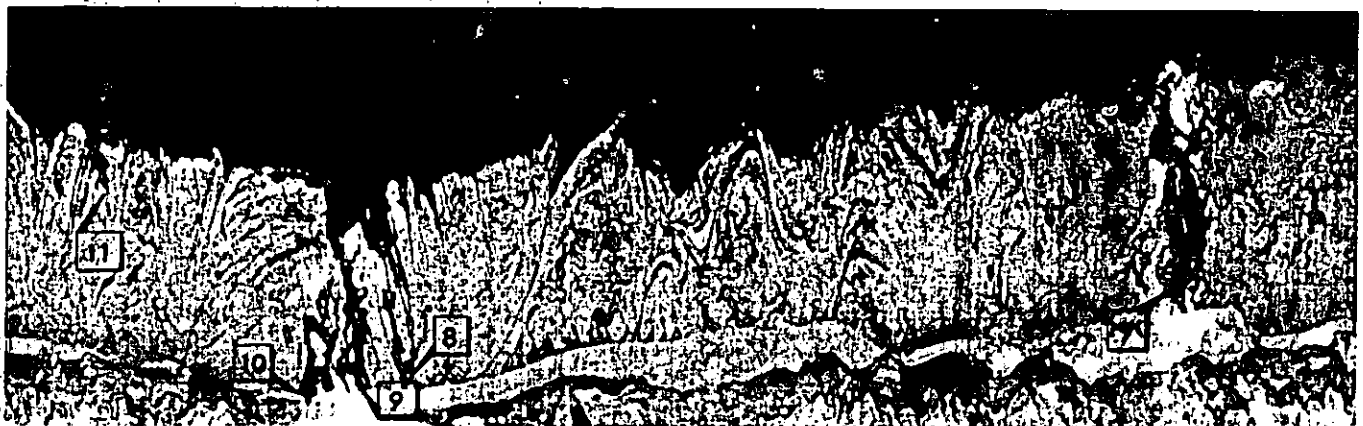
A very natural idea is to use thermographs to look for thermal phenomena of geological origin, such as symptoms of current volcanic activity. So far, research into volcanos in France has not yielded any very clear-cut results, but some success has been achieved with regard to thermal springs. Studies carried out abroad in areas of substantial volcanic activity have demonstrated the advantages of thermographs to the vulcanologist. Furthermore, geophysicists will perhaps find answers to some of their questions by examining recordings made by satellites.

Hydrology. It is in the fields of hydrology or hydrogeology that thermography has so far given the most valuable results. The subject can take on two rather different aspects according to whether one is studying a large body of water (sea, lake, river), or simply traces of water (humid areas). Generally

---

1/ Lecture by Mr. Weecksteen, Bureau de recherches géologiques et minières, October 1971.

speaking, the detection of the presence of water is made possible by the fact that any given material - soil, rock, etc., possesses thermal properties (specific heat, thermal conductivity) which differ considerably according to whether it is dry or wet. The search for traces of humidity often involves both geology and pedology - geology because the particular way in which the



Scale 1:10,000 (approx.)

Fig. 6. Exploration for fresh-water springs on the coast near le Havre.

The springs marked 7, 9 and 10 have a temperature of between 9°C and 11.5°C; they are fresh-water springs and with a flow of some tens of thousands of m^3 a day. The sources marked 8 and 11, on the other hand, are salt-water, cold (7°C) and constitute only tidal drainage channels; they are of no interest.

humidity is distributed often indicates the disposition of geological features, fractures, faults and interfaces between rocks of different types, and pedology, firstly because pattern of water circulation in the soils is clearly shown, and secondly because differences in the nature of the soils may correspond to differences in humidity.

In the specific case of exploration for drinkable water, which is becoming increasingly urgent at the present time, the thermograph is proving extremely useful. The fact that the features of the local geology are shown in great detail on the recordings, combined with the effect of pseudo-transparency referred to above, can, to a certain extent, enable the circulation of underground water to be followed or permit the limits of the ground water to be demarcated. It should be emphasized, however, that if the thermograph is used in conjunction with geophysical measurements on the ground (measurements of resistivity, seismic soundings), the efficacity can be very considerable. These two procedures are in effect complementary, and, although each one, taken individually, produces limited results, when used in conjunction they can produce extremely impressive results. Here again, note should be taken of the constant necessity in photo-interpretation or remote sensing of conducting ground surveys, however rapid, at certain points, or along well-chosen routes, if one wishes to obtain positive and reliable conclusions. There is one instance of thermography being used without geophysical measurements, and with very limited ground coverage. A sizable French town, close to the sea, was meeting with no success in its search for drinking water. Examination of the area showed that the geological features were oriented in such a way that the rain falling on the area ran off in the "wrong direction" towards a certain part of the coastline. The only apparent solution was therefore to look for springs near the shore, in the area so defined. This search, however, was difficult, since indications of the presence of a spring in the area did not necessarily mean that the spring was potable, and in fact many were resurgences of sea water. The thermograph's sensitivity to temperature enabled the problem to be solved without any loss of time; the date on which the thermograph was to be taken having been carefully chosen, the differences of a few degrees between the different types of water made it possible to distinguish the "good" springs. It was even possible to make an estimate of the flows (Figure 6).

Where large bodies of water are involved, the problem generally boils down to discriminating between different types of water in a river, lake or sea. Experience shows and this is the basic property being put to use, that bodies of water of different temperatures will not mix, and consequently remain homogeneous and separate for considerable periods of time. This initial assertion should, of course, be qualified somewhat, as the phenomenon depends on the difference in temperature between the two masses of water and, in particular, on their relative volumes. Where the difference in volume is very considerable, the results observed have varied widely, the pattern being either a very rapid dilution of the smaller mass, or a distinct stability, in accordance with the principle outlined above.

The uses to which the technique can be put vary according to the scale used. When applied to oceanic bodies of water, thermographs can be very valuable to the oceanologist or the fisherman; meteorological satellites provide recordings on a very small scale, but with improvements in the resolving power of on-board apparatus, the results are becoming increasingly informative. Itos I for example, has provided, among other things, remarkable images of the Gulf Stream.

Over smaller areas, coastal currents and the movements of sediment are shown very clearly. Periodic phenomena such as tides are particularly well noted and illustrate the fineness of the results obtained; the tide in the Mediterranean, for example, shows up very clearly on a thermograph, even on a small scale (Figure 7).

Here again, we come up against the question of transparency: is it possible to detect a mass of water which does not come to the surface? Once again, it is impossible to give a cut and dried answer. In general, because of the principle of non-miscibility and homogeneity, the pseudo-transparency phenomenon is of very little importance, so that a mass of water must reach the surface in order to be discernible; examples of this have been provided by research into resurgence on river -, lake- and sea-beds. So far, the results obtained have been varied and more thorough research is required, but it appears that the most successful recordings have been made in cases where the water from the resurgence actually reached the surface; an immersed solid, however, can be detected, because of the convection movement which it provokes. The practical importance of this is considerable in that it permits location of under-water pipelines, etc.

Once this first stage in the differentiation of masses of water has been completed, the next step is generally the study of currents. Repeated thermographic recordings are often essential, particularly if phenomena which change over a period of time are involved. Although assessment of the speed of the current is a difficult undertaking, the geometric description of it (topographical position, extent, etc.) together with some mechanical characteristics such as laminar or turbulent flow, are apparent on the thermograph.

One related problem which often arises is that of the movement of sediment. Repeated thermographic recordings, used in conjunction with natural colour photographs, give excellent results. But here too, the thermograph often contains a greater wealth of information than the photograph, even when the latter is in colour.

Pollution. The preceding studies naturally lead to consideration of the question of pollution, which is perhaps the most worrying problem of our time. The need to safeguard marine life (plancton, fisheries), and the activities of the coastal waters (oyster and mussel farming, recreational activities) entails keeping a close watch on ocean pollution. The same applies to bodies of fresh water, with the added necessity of determining water resources and managing them properly, and detecting new sources to meet the ever-increasing needs of the population, agriculture and industry.

The causes of water pollution are many. The discharging of raw, untreated sewage brings an increase in nutrient salts; this in turn leads to over-expansion of the animal and plant populations, which subsequently die because of lack of sufficient quantities of oxygen. This is the process of eutrophication. In addition, pathogenic bacteria are discharged with this sewage, and not all are destroyed by the ultra-violet radiation of the sun; certain species, such as coli bacilli, are even accumulated by molluscs. In eastern Canada, for example, half of the mollusc-breeding areas have already had to be closed as a result of pollution by sewage.

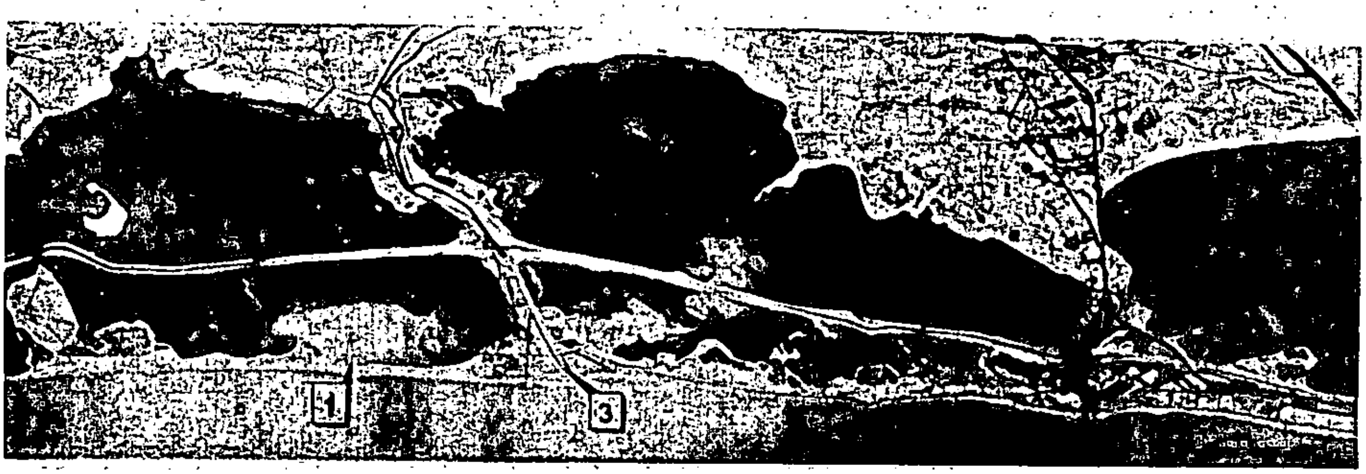
Industrial effluents carry noxious Hg, Pb, Zn, Ni, and Cl salts.

Petroleum products are deposited as a result of the cleaning of tanker holds, or even worse, from collisions, between tankers, and from the operation of off-shore wells, the number of which is due to increase in the next few years. An example of such pollution is the spillage that occurred a few years ago off Santa Barbara, California, which proved difficult to stop. It is estimated that between 1 million and 10 million tons of petroleum products are discharged into the sea each year. The most dangerous of these are the aromatic hydrocarbons, which are more or less soluble in water and possess carcinogenic properties.

Non-bio-degradable pesticides can accumulate in living organisms. Some of these, such as arsenic salts and organic compounds of mercury are highly toxic, and recently, the United States and Sweden had to dump considerable quantities of canned tuna because the mercury content was found to be too high. 1/

1/ This mercury pollution is a cause of particular concern to the countries on the Baltic sea where the water at depths of more than 70 or 80 metres is not renewed, leading to a build-up of pollutants.

1 - recording made 22/7/1970 at 15.00 hrs. scale 1:100,000 (approx.)



1 - recording made 21/7/1970 at 00.46 hrs. scale 1:100,000 (approx.)

Figure 7. Thermograph for a study of the shoreline

These two recordings are of the Mediterranean coast in the Palavas area. Flying altitude was 1,700 m, the temperature at this altitude was +22°C for strip I and +16°C for strip II; the difference between the high tide (strip II) and the low tide (strip I) was 26 cm.

Examination of the documents shows that in general during the day (strip I) the water surface temperature is the same for the pools and for the sea, while the land surface is warmer (shown darker on the recordings). At night (strip II), this situation is reversed, with the pools remaining warmer than both the land surface and the sea.

The following detailed observations can also be made:

- 1 : exchanges of water between the sea and the pools are not visible by day, since the temperatures of the two bodies are equal; they become clearly visible on strip II where a considerable inflow of cold sea-water into the pool can be seen, carried in by the high tide;

- 2 : communication between the two pools separated by the Rhone canal at Sète; there is a relative temperature reversal between the canal water and its banks from daytime to night-time;

Notes on Figure 7 (cont'd)

- 3 : no trace of outflow from the "le Lez" waterway beyond the dikes at its mouth; the temperatures are the same on strip I; on strip II, the tide can be seen rising up the waterway;

These examples give an idea of the help which aerial thermographs can give in studies of coastal areas; exchanges between the sea and the pools in relation to the tide, studies of sedimentation, transport, pollution phenomena, etc.

Other forms of pollution, such as thermal pollution, are more localized. The raising of the water temperature in a bay, for example, through the discharge of water from power station cooling plants, even if this involves a rise of only a few degrees, can have considerable effects on the fauna and flora, and on the local ecology. In effect, the temperature range in which a given marine species can exist and - above all - reproduce is generally quite narrow, and many species may be unable to withstand even the slight rise in temperature involved.

Similarly, the discharge of large quantities of inert solid waste, which settles on the sea bottom, also constitutes local pollution. A case in point is the red mud discharged into the Mediterranean by the aluminium plants in the Cassis of Cap Corse areas. By increasing sedimentation on a massive scale, this waste eliminates all the organisms which normally live on the sediment or in its upper layers. An unexpected result of this pollution of the sea is that it upsets fish behaviour patterns which depend, as we all know, on chemical stimuli. As a result of such chemical attraction, lobsters make for oil slicks, instead of moving away from them, and die, while small doses of DDT are sufficient to completely disrupt salmon runs in rivers.

Some research has been conducted into the behaviour of polluted water discharged into rivers, lakes or the sea by industrial plants or sewerage systems. Often in such cases, the differences in temperature are considerable and the polluted water can travel very easily in a body over long distances. But even when there is no difference in temperature, pollution may result in a change in emissivity (generally a reduction).

The importance of such work is not limited to the field of environmental protection; it can also be of use to industry. A study of the currents, for example, might show that an industrial plant is pumping in the same water that it has discharged. These various types of pollution can be detected by remote sensing, since any change in the physical or chemical characteristics of water produces a change in temperature which can be detected by the sensors, even though it may be a change of only a fraction of a degree. This is obvious in the case of industrial effluents, but it should not be forgotten that the specific heat of petroleum products and their emissivity differ from those of water and that, as a result, they acquire a different temperature and a different radiation; the same is true for dissolved chemical salts, for small, solid bodies in suspension, for mud and for plancton; and the fermentation of organic substances also produces a discernible rise in temperature.

The data provided by remote sensing make it possible to pinpoint the exact location of sources of pollution and trace their development over a period of time, and consequently to devise ways of protecting ourselves from them and of remedying them.

Certain forms of pollution do not produce temperature changes and consequently cannot be detected by thermographic techniques. Changes of transparency or colour, for example, may be indications of contamination. It is in such cases that the techniques of spectrography and monochromatic recording come into play. Radiations of 600 nanometers are those which penetrate water most easily and make it possible to study, and even to map, the sea bed at depths of up to 60 metres in the case of the clearest waters of the Mediterranean or around coral reefs; this penetration, however, is quickly reduced in the presence of suspended impurities or dissolved salts, thus making transparency tests a very sensitive method of detection. The colour of the water itself, produced either by reflection or transmission, from a sandy bottom, for example, is a factor which indicates the degree of purity, and our photographs, whether they are in natural or false colours, constitute an excellent means of detection.

By using an airborne spectrometer to study the emission from chlorophyll, the maximum of which is in the region of 443 nm, it is possible to estimate the abundance of algae and coastal vegetation, and above all, to detect the presence in the water of nitrates, phosphates, mercury compounds, DDT, etc., by the effects which they produce on the chlorophyll spectrum.

Atmosphere. Remote sensing methods have shown themselves to be particularly effective for the study of atmospheric pollution. This pollution is caused by the presence in the troposphere of dust particles and gases discharged by industrial plants, domestic fires and vehicles.

Dust particles, in particular, are shown up on photographs, since they reduce the contrast of the terrain directly beneath, sometimes obscuring it completely. Even more important than detection is the fact that, by repeated photographings at regular intervals, it is possible to determine the direction and speed of movement of these pollutant masses, and consequently to take steps to protect centres of population from them.

But smoke and dust play only a secondary polluting role. The most important task in the control of atmospheric pollution is the detection of SO_2, NO_2, NO, CO_2, CO, O_3, H_2O and Cl molecules in the troposphere. A comparative study of the different bands of the spectrum - ultra violet, visible light, infrared, EHF and SHF, shows the superiority of the infrared. There are two reasons for this. Firstly, using this band, it is possible to make observations by day or by night; secondly, and most important, the absorption-emission bands of normal pollutants show up most clearly and distinctly in this portion of the spectrum. The clearest is CO_2 at 4.6 nm, followed by SO_2 at 7.4 nm, NO_2 at 6.3 nm, NH_3 at 10.8 nm and O_3 at 9.5 nm.

It is interesting to note that, according to the findings of an American comprehensive survey conducted in 1970, the main pollutants discharged into the atmosphere were present in the following proportions:

- CO : 53%
- SO_2 : 18%
- NO + NO_2 : 7%
- Various types of dust : 22%

The same survey gives the origins of these impurities as:

- Transport : 60% - Power stations : 13%
- Industry : 18% - Heating and incineration : 9%

Generally speaking, one of the most serious problems is that of carbon monoxide, which comes almost entirely from vehicle exhausts, the main contribution of industry and power stations to pollution being sulphur dioxide and dust.

The multiband remote-sensing apparatus required for sensing these bands is of rather a special kind and will be studied in greater detail in another article.

Surface pollution. Surface pollution by urban and industrial waste is discernible directly on normal colour and false colour aerial photographs, and even on thermographs because of the rise in temperature produced by the fermentation of organic substances. It is mainly by periodic aerial coverages that it is possible to record accurately urban encroachment on forested lands, crops and green spaces, and also to detect the disappearance of animal and plant species, together with the damage caused by erosion and the disruption of the ecological balance. Using these same aerial photographs, maps derived from them, or orthophoto maps which can now be produced quite rapidly, it is then possible to work out protection measures on a rational basis, by determining the areas to be protected and demarcating nature reserves and natural park areas, for which IGN has recently drawn up a number of special maps.

Agriculture and pedology. Although studies in this field are not yet very far advanced, remote sensing can provide data on vegetation and its development.

The reflectance of different plant species depends on their atomic and physical structure, which gives them a special tone signature. The data obtained in a number of wavelengths enable crops to be differentiated from one another, particularly if one has a series of recordings made at different dates, since the tone development pattern is not the same for all plant or tree species. In this way, it is possible to detect conifers infested by insects through changes in reflectance, and the United States agricultural services use thermographs made at an altitude of 600 m to detect diseased citrus crops.

As far as recognizing plant species is concerned, thermographs are more difficult to interpret than photographs since appearances change according to the time of day (Figure 8). There are a considerable number of parameters involved, so that finding keys to interpretation will undoubtedly be a lengthy process. In the field of plant physiology on the other hand, thermographs provide valuable information on the phenomena of evaporation and transpiration, and on temperature changes. Research is being conducted into these questions, and may lead to new methods of forest- and crop-health surveillance.

As far as pedology is concerned, as was mentioned earlier, humidity and circulation of water in the soils are clearly visible on thermographs. It is believed that qualitative information can be obtained on this subject to a depth of about fifty centimeters (for man-made elements, such as drains, transparency can be appreciably greater). It should also be noted that the extent of temperature change during the day is directly related to the water content of the soil.

The beginnings of forest fires can be detected in this way, with the centre of the fires, which have a temperature of approximately 600°C, showing maximum emission between 3,000 and 6,000 nm, and an incipient fire can be located well before it gives off smoke visible from a watch tower.

A further important advantage of the data provided by remote sensing lies in the synoptic character of the recordings, which cover large areas of the Earth's surface simultaneously and can be repeated at regular intervals, thus enabling the incidence of the various phenomena in time and space to be studied. In the United States, plans are even being made for satellite interrogation of seismographical stations distributed over the whole of the Earth's surface; the data collected in this way will be relayed to a central recording station, which by virtue of these synoptic measurements, will be able to provide forecasts of seismic activity.

Other applications. Thermographs can be of great assistance in the field of archeaology. The effectiveness of the process has until now, been limited, however, because of a major technological problem. Since most archeaological sites cover only a small area, a very low flying altitude is called for, which is not very compatible with night flights, for obvious safety reasons. At the same time, as has already been explained, daytime reflections greatly impair results.

The thermographic technique can be applied to any thermal phenomenon. Thermal study of urban areas, for example, appears to be extremely informative. The nature (and even the age) of buildings can be determined, and actual urban micro-climates can be detected.

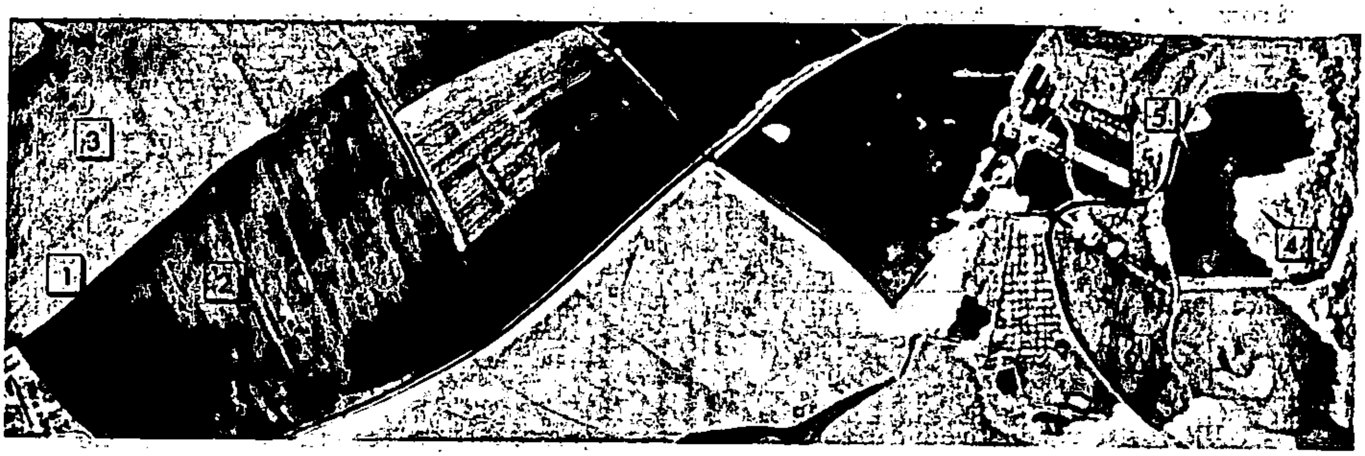
Furthermore, low-altitude recordings (from an Aero Commander, for example) enable phenomena such as traffic density, parking patterns in the streets of towns, parking changes, width and gradient of streets, access to buildings, amount of waste discharged, etc., to be studied at different times of day.

Using thermal recordings made at night, it is even possible to detect parked vehicles by their different temperature, and those which are in motion by the hot gases which they emit and which remain detectable long after the vehicles has departed.

Finally, it is possible to use the thermal images to study urban micro-climates created by atmospheric pollution, and to determine the effect of a polluted atmospheric cover on a region as a whole, to determine the albedo of a soil and to calculate air-ground and air-sea energy exchanges, all of which are elements of the greatest importance to human and animal ecology.

As was said at the beginning of this paper, all these documents, whether they be photographic or thermographic, enable steps to be taken to protect populations against natural calamities such as avalanches, floods, fires, storms and inclement weather. Photogrammetry also makes it possible to measure the height of the groundswell at sea, to determine the movements of cloud masses, to measure the rise and fall of bodies of water, to identify slopes which, by virtue of their gradient and exposure, might give rise to avalanches. It was in this way that IGN was recently able to produce avalanche maps showing dangerous areas and subsequently participated in the proceedings of a Committee devoted to the study of such areas.

I - recordings made 25/5/1970 at 20.00 hrs. scale 1:10,000 approx.



II - recordings made 26/5/1970 at 8.00 hrs. scale 1:10,000 approx.

Figure 8. Thermograph for a study of vegetation

Recordings conditions: flying altitude: 175 m, for strips I and II; Meaux region.

A comparison of these two documents calls for the following observations on the most salient features:

- 1 : winter wheat;

- 2 : ploughed field with maize beginning to show above ground. There is a distinct temperature difference between the earth and the vegetation;

- 3 : note the present of a herd of cows in a meadow;

- 4 : the wood shown here, and, in general, all the trees visible on these two recordings, are warmer in the evening than in the morning, the shade being darker the higher the temperature;

- 5 : a ploughed field, unplanted, is almost indistinguishable from the adjacent woodland, the two temperatures being very close. In the morning, on the other hand, it is very clearly distinguishable from the colder wood. Temperature variations can be seen within the field itself; these are related to the nature of the topsoils;

- 6 : grasslands, with dense grass covering about 40 cm high, in both cases remain colder than ploughed fields.

Notes on Figure 8 (cont'd)

These examples illustrate the importance of aerial thermography in studying the patterns of development of vegetation, its exchanges with the surrounding environment and evaporation-transpiration phenomena.

CONCLUSION

It can be seen that important results have been achieved, principally in the fields of geology and hydrology. Progress is still to be made - and on the face of it appears possible - in many other fields of application and also in the theory of data processing and interpretation.

To permit more complete interpretation of thermographs, considerable advances will be needed in our knowledge of the heat exchanges of natural environments. Calculation of models is a field which has been developing over the last few years, guided and verified by photographic coverages of experimental polygons, and it is possible that their use will expand rapidly. With t he establishment of the basic principles, new fields of application will be opened up to thermography. Accordingly, new specialists must be trained, who will be able to establish a methodology for the utilization of data and will be capable of deriving the maximum information from the various recordings obtained. IGN's research in this field is conducted in collaboration with the Centre national de la recherche spatiale and various university bodies, and major studies have already been undertaken such as the study of the Etang de Berre, where thermographic recordings are enabling currents, water circulation systems and ecological patterns to be studied.

IGN is already producing two series of special maps for the study of the environment, covering the whole of the national territory. These are: a map of land-use patterns on the scale of 1:100,000, in 8 colours, showing the exact location of river and marine hydrography, vegetation, crops, woods, forests, heathlands, fallowlands, meadows, orchards, vineyards, marshlands, salt marshes, oyster and mussel beds, fisheries and also fresh-water springs, industrial areas, etc.; a general infrastructure map also on the scale of 1:100,000, showing on a simple geomorphological base map, all current development projects and, in particular, road, rail, air and port facilities, electricity, gas, water and fuel transmission and distribution networks, drainage and sewage treatment plants, telecommunications networks, the main urban and rural structures already existing or in the process of development, etc.

IGN long ago improved its mapping methods, graduating from ground surveys to aerial surveys using increasingly sophisticated instruments and methods and increasingly experienced personnel. This progress is still continuing, but it is necessary to take account of developing needs and techniques and to turn to the new methods such as remote sensing, which will become more and more important as time goes on. IGN will certainly improve its methods of aerial photography, but we must not be like candle-makers who manufacture better and brighter candles without regard for the fact that electric-light bulbs already exist. It is for this reason that IGN is turning resolutely to remote sensing techniques for all environmental studies.

A. Baudoin, A. Decae, P. Demathieu

BIBLIOGRAPHY

A. Alouges et R. Tessier: Principes généraux de la détection à distance, Séminaire du CNES et de l'Université du Michigan, novembre 1969.

P. Anding et R. Kauth: Estimation of sea surface temperature from space, Remote sensing of environment, Vol. 1, n° 4, December 1970.

C.P. Bastuscheck: Ground temperature and thermal infrared, Photogrammetric Engineering, Vol. XXXVI, n° 10, October 1970.

Dr. Lorenz: Zur Problematik der Fernerkundung der Erdoberfläche mit Hilfe der thermischen Infrarotstrahlung, Bildmessung und Luftbildwesen, November 1971.

V.I. Myers et M.D. Heilman: Thermal Infrared for Soil Temperature Studies, Photogrammetric Engineering, Vol. XXXIII, n° 9, September 1967.

V.V. Salomonson et W.E. Marlatt: Airbone Measurements of Reflected Solar Radiation, Remote Sensing of Environment, October 1971.

E.W. Wolfe: Thermal Infra-Red for Geology, Photogrammetric Engineering, Vol. XXXVII, n° 1, January 1971.

Le scanner infra-rouge Cyclope, Bulletin d'information de l'Institut géographique national, n° 10, mars 1970.

Proceedings of the Seventh International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, May 1971.

La télédétection des ressources naturelles, Journées d'études du CNES, Paris, 26-27 octobre 1971.

- - - - -