The role of the thermal infrared in the framework of remote sensilng techniques applied to the environment quality control

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SUMMARY. This paper describes the characteristics, the limits and capabilities of the thermal infrared, applied to the environment quality control, in order to give an idea of the complexity involved in the thermal data interpretation. Everybody who desire to be introduced into remote sensing studies has to know perfectly the basic laws of the electromagnetic radiant energy.
Some examples in several fields of application are given, as well as some handlings the original data.

Key words: radiant power, scanner, emissivity, reflectivity.

1. REMOTE SENSING TECHNIQUES

The observation of objects and the judgement of the quality of the images which represent them has always been conditioned by the limits within which the human eye and brain function.

The beginning of an instrument-aided vision of the world coincided with the birth of photographic technique, along with the capacity of various types of optics, which have vastly extended our possibilities of << viewing >> things. As everyone knows, the human retina is sensitive to electro-magnetic (e. m.) radiations which go from approx. 0.4. to approx. 0.7. micron of wavelength (these limits vary somewhat from one person to another), and hence that section of the electromagnetic spectrum is called visible, or the visible spectrum (Graph 1). It should be added that apart from the so called band limits, the retina is also limited in its non-linear response, that is to say, it is less sensitive to short wavelengths (0.4 micron violet light) and long ones (0.7 micron dark red) than it is to the intermediate ones (0.58 micron yellowy orange).

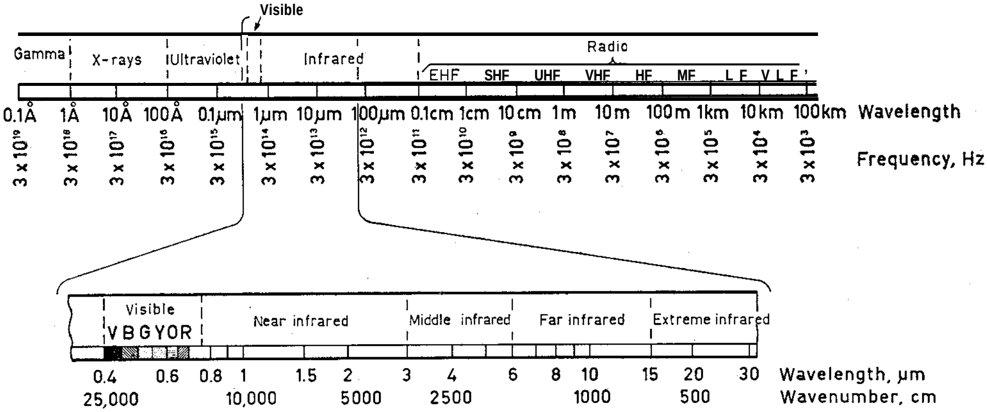
Two other characteristics of the human eye limit its possibilities in a << metric >> sense. In the first place, the fact that there is a sort of automatic light control (the variation in the diametre of the pupil according to the brightness of the light falling on it), which forbids any undifferentiated comparison of dissimilar lights, and the variation of chromatic sensitivity according to the surrounding light: as is well known, capacity for detecting colours decreases rapidly in dark environments.

As to the view-angle of the human eye, it should be noted that although it is physically constant, by means of moving the eye-balls it can in fact be increased, whilst the brain's concentration on any particular detail can have the effect of reducing the general view-angle to the which comprises the detail.

Thus the eye does not only see but it *looks.*

The techniques of remote sensing (R.S.) are in general definable as that group of tools and interpretative instruments which allow the extension and improvement of the perceptive capacities of the eye, supplying the brain with information on distant objects which would otherwise be beyond perceptibility. Remote sensing is thus a discipline which involves the collection of data by means of systems which are not in direct contact with the objects or phenomena under investigation, and their relative interpretation.

Normally a limitation is adopted with respect to the data << carrier >> remote sensing deals with only electromagnetic energy.



Graph 1. The electromagnetic spectrum.

There are four main ways of operating: that is, by employing active, passive, imaging and nonimaging systems. These can also be variously combined.

R.S. is called active (imaging or nonimaging) when the object of the investigation is illuminated by a source of e.m. energy.

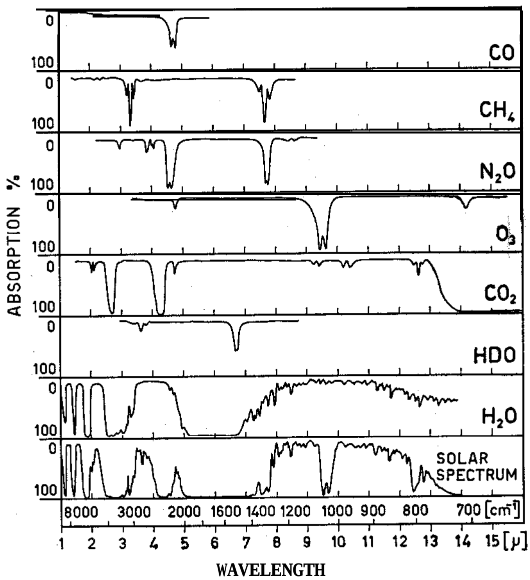
R.S. is called *passive* (imaging or nonimaging) when the object itself is a source of the measured e.m. energy.

R.S. is called *imaging* (active or passive) when the data are shown in an image, be it in real time or not.

R.S. is said to be *non-imaging* (active or passive) when the data are local measurements giving us numbers instead of images.

Three platforms are normally employed: on ground, airborne and spaceborne. The detection and identification of the various objects by means of R.S. techniques depends on the correct use of the distinguishing characteristics of the e.m. radiation patterns, either reflected from or emitted by the particular object of interest: these distinguishing characteristics may be of a spectral, a geometrical or a temporal nature. For instance, the e.m. energy to be detected may be reflected sun energy, in which case the radiation is placed mainly in the visible and near infrared wavelengths (from approx. 0.35 to 1 micron). On the other hand the e.m. energy to be detected may originate from a body at 300 °K (27 "C), and in this case it is convenient, as we will see later on, to stay around the 10 micron wavelength.

Often it is not possible to use the complete spectrum of wavelengths for R.S. applications: in fact atmospheric absorption and scattering restrict the application to a considerable extent. The technique can thus only be used where atmospheric transmission is good, in the so-called << atmospheric windows >> (Graph 2). In the thermal infrared (from 2 to 1000 micron) there are two useful atmospheric windows, roughly speaking, from 3 to 5 and from 8 to 14 micron; the most common available instruments usually work within these two bands.



Graph 2. The atmospheric transmission.

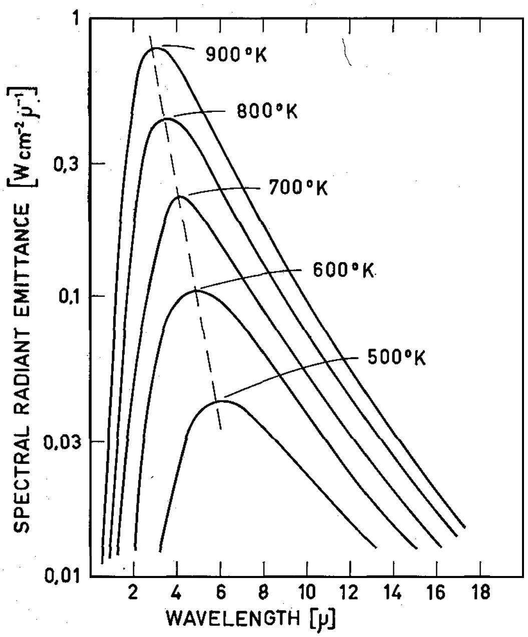
Theory of radiation. Any body, whose temperature is above zero, emits e.m. radiations which depend on the body's temperature and the nature of its surface, whilst it reflects, absorbs or can be crossed by e.m. radiations coming from outside.

Emission, reflection and absorption are closely connected, as we shall see. The general law of e.m. emission was formulated by Planck and states that, for a black body and for a $\lambda_2 - \lambda_1$ wavelength interval

$$P = \frac{1}{\pi} \cdot \int_{\lambda_1}^{\lambda_2} \frac{C_1 \lambda^{-5}}{\exp C_2/\lambda \cdot T - 1} \cdot d\lambda \quad \left[W\ cm^{-2}\ ste^{-1} \right]$$

is true, where C_1 and C_2 are constants, λ the wavelength and T the absolute temperature.

The equation, represented parametrically in T, thus appears in the form:



Graph 3. **The** Planck's law.

Let us define black body as that surface which is able to absorb all the e.m. radiations which are incoming and to emit e.m. energy continuously on the complete spectrum. The degree of << blackness >l of a real body indicates the extent to which the behaviour of the real surface differs from that of the black body. Let us define emissivity s as the ratio between the e.m. energy emitted by a surface of a real body at temperature T and the energy which would be emitted by an equal surface of black body at the same absolute temperature:

$$\varepsilon = \frac{\text{real P (T)}}{\text{black body P (T)}}$$

with $\varepsilon \leq 1$ in all cases, and $\varepsilon = 1$ for black body; furthermore ε is a function of the wavelength, and its value for real bodies is obtained experimentally ($\varepsilon = \varepsilon(\lambda)$). A real body differs from a black body also because its surface reflects a part of the incoming e.m. radiations.

Let us define the reflectivity p of a surface as the ratio between the energy to which it is exposed and that which it reflects

$$\rho = \frac{\text{P reflected}}{\text{P incoming}}$$

where $\rho \leq 1$ in all cases and $\rho = 0$ for all black bodies.

ρ is furthermore a function of the wavelength, that is: $\rho = \rho(\lambda)$

For opaque bodies the following relationship is also valid:

$\varepsilon + \rho = 1$ and thus
$\rho = 1 - \varepsilon$ also called << albedo >>.

Two other laws of radiation can be useful to us at this level for a better understanding of the phenomena. One is the Stefan-Boltzman law:

$$P = \varepsilon\sigma T^4 \quad \text{(real bodies)}$$
$$P = \sigma T^4 \quad \text{(black body)}$$

which tells us that the total power emitted by a surface on the entire spectrum depends on the emissivity and the fourth power of the absolute temperature. The other law we are going to introduce is that of Wien, which says that the highest point on the emission curve of Planck's law shifts towards higher wavelengths for diminishing temperatures obtained from the emitting surfaces. That is

$$\lambda_{max} = \frac{2890}{T}$$

For example, the sun, whose surface temperature is around 6000 °K, has its maximum emission around 0.5 micron (yellow-green light), whilst bodies at approximately environmental temperature (around 300 °K will be more inclined to emit at around 10 micron.

2. THE THERMAL INFRARED

As is described above and as can be understood from the laws describing the behaviour of em. radiations, the choice of wavelength to be used depends entirely on what is to be observed. If the aim is to enquire into the temperature itself of the surfaces, it is convenient to use instruments which work on wavelengths where the thermal emission, fog the range of temperatures involved, is maximum.

Thus it is clear that, of the two available bands (3/5 and 8/14 micron), the first rather than the second will be used for objects of a higher temperature. As it happens, the instruments which work on the 8/14 micron band are so far more expensive than those which work between 3 and 5 micron, such that it is unfortunalety not always possible to carry out research work with the most appropriate instrument.

It should, however, be underlined that in fact the instruments do not take direct tem*peruture* measurements, but rather measure the *radiant power,* this latter being connected to the temperature in a non-linear way, by Planck's law. The variations in the grey or coloured tones which are to be found in the thermographs thus *do not represenf vuriafiom of temperature,* even though they do describe the thermal behaviour of the surfaces observed. It should be borne in mind that a correct interpretation of a thermograph in terms of temperature must also take the emissivity and the reflectivity of the surfaces into consideration.

In general thermographs are obtained with scanning devices, either quick or slow, according to whether they are to give a real time image or not (thermocamera and scanner): normally speaking, thermocameras are used on the ground, whereas scanners are set up on aeroplanes or satellites.

In both cases the thermographs are made **up** of an ordered group of scan-lines which are generated by the electric signals coming from the detector. The electrical signals, suitably treated, allow the reconstruction of the thermal image of the object's surface viewed on a monitor or on film.

3. INFORMATION PROCESSING

When the information available comes from only one band of the thermal infrared, the following simple treatments can be carried out:

a) *Level slicing.* In this process the information is subdivided into a fixed number of intervals; each interval contains all and only informations included in a certain range of incoming energy. The information thus << quantified is then described on the final image >> either with different colours or with clearly differentiated tones of grey.

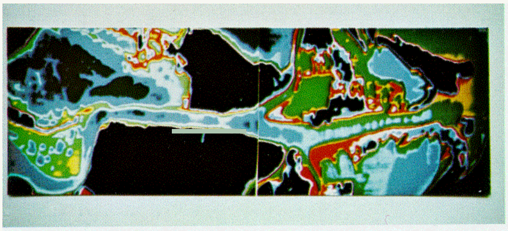


Fig. 1. Po river Delta: a level slicing showing different radiating powers has been performed. The instruments were setted for describing water information, blanking everything else. Band 9/l 1 micron; flight altitude 1500 m **a.5.1.**; slicing step 0.5 "C; courtesy by Rossi Ent.

In Fig. 1 a level slicing technique is applied in the case of water temperature control of a large area. While the emissivity of the non-polluted water is constant (about 0.97), the description of the isoradiating levels is also a description of isothermal areas; in this case the thermography taken from aerial platform jointly with a level slicing technique, allow the comparison of thermal manifestation of some water bodies.

From this document it is easy for instance to study the water dynamic behaviour, by assuming that where the surficial temperature is higher, there probably the water velocity is lower then in other places, because of sun's radiation heating effect.

In Fig. 2 the level slicing technique was employed in order to evaluate the thermal balance of the plume in respect to its envi-

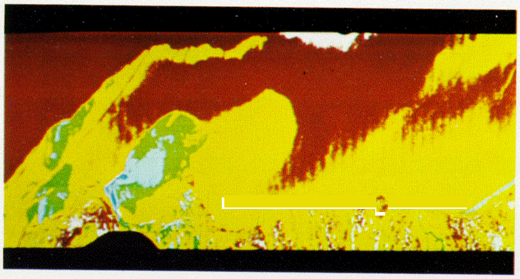


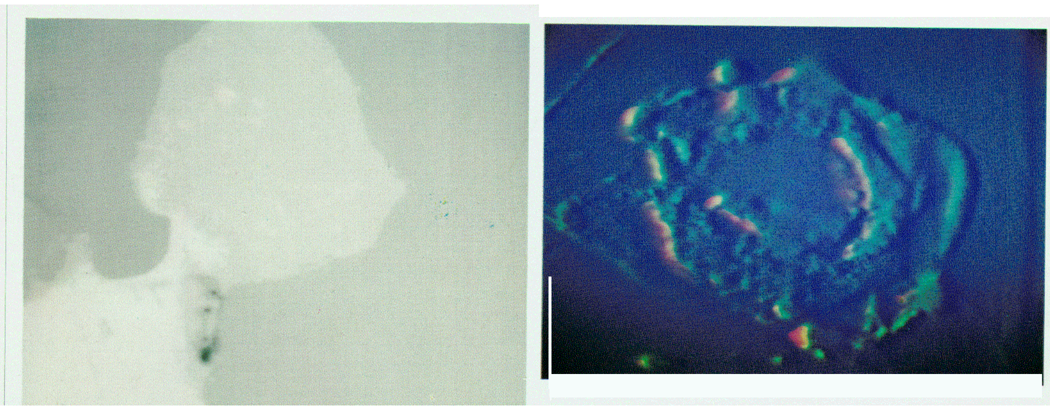
Fig. 2. The blue and the green plumes are the thermal manifestation of some fresh water spring upwelling in the sea (red colour) because of salinity contrast. It was possible to evaluate the mass of fresh water coming into the sea per second. Cefalfi area (north Sicily); 9/11 micron band; flight altitude 1500 m a.s.1.; slicing step 1 °C.

ronment, looking at a quantitative evaluation of the fresh water spring flowing into the sea.

In Fig. 3D the level slicing technique was utilized in order to compare in a quantitative way the surveys on a volcanic area performed in different times. Practically speacking it is possible to follow each year the mouvements and the changes of the isoradiating areas: this methodology is a good approach for the volcanic activity control.

In Fig. 4A-B the level slicing was employed just to have an idea of the extention and the amount of an anomalous thermal phenomenon. In a few words the level slicing is the basys of the quantitative image interpretation.

b) *Gradient function.* The electric signals, coming from a scanning analysis. can also be considered as functions of time, and treated as normal mathematical functions: for example, if the derivative function is applied to information describing the distribution of temperatures, it is possible to obtaining the de-



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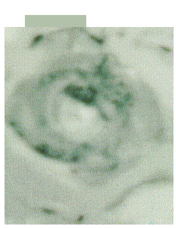

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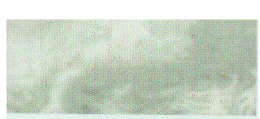


Fig. 3. A) Part of Vulcano island surveyed by means of thermal scanner: this area is controlled each year with << infrared >> flights in order to follow the thermal behaviour of the crater and the surrounding area. 4.5/5.5 micron band; flight altitude 1000 m a.s.1. (black-hot; white-cold). B) Derivative function of the survey shown in Fig. 3A. Here only the crater area is described.

scription of the distribution of the thermal gradients.

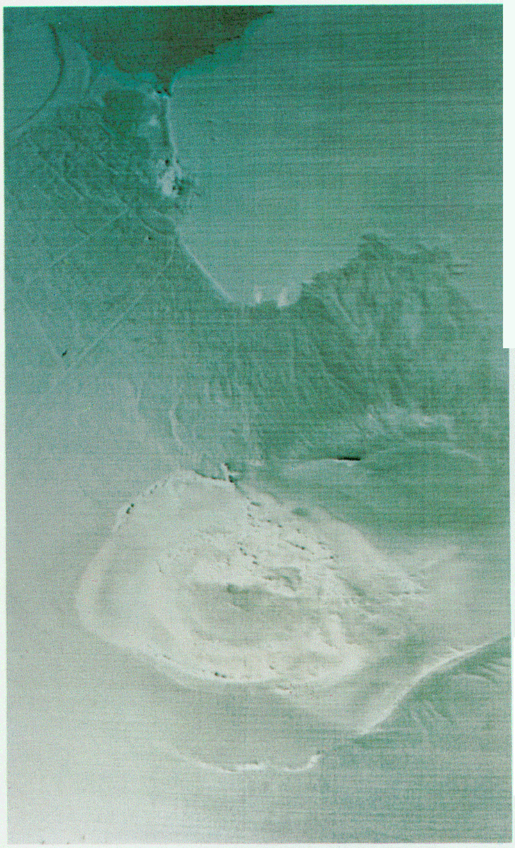
In Fig. 3B is shown an example of the derivative function applied to a thermal signal: in this case it is easy to study the thermal-gradient function of the Vulcan0 crater. The thermal gradients are a very important parameter for the geologic description of this area.

c) A third treatment consists in extracting from a thermal survey information describing the *geormtry of the tlzerrrml nzcrrzifest~rtion~:* in effect, instead of analysing the amplitude of the electrical signals as in cabe (a), we examine them in the temporal domain. Given that normally the scanning takes place at a constant speed, the time analysis coincides with the space analysis. In this case the rcsuiting image no longer contains anything of its original temperature meaning, but rather describes the thermal roughness or thermal texture.

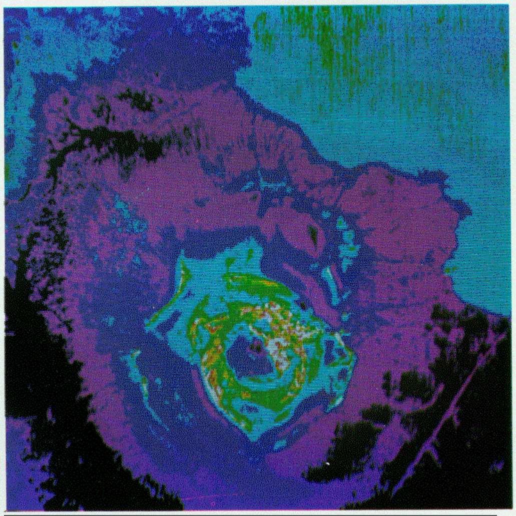
In Fig. 6 an example of thermal geometry investigation is shown. As it is very easy to see in the upper part of the image, every changes in surficial temperature is strongly enhanced, giving the possibility to study the water dynamic in a syntetic view.

On occasions when information is available from two thermal channels, for instance ones working on 3/5 and 8/14 micron wavelength, there are two elementary types of processing which, setting out from thermal information, allow us to obtain data pertaining to the nature of the surfaces.

a) *Difference.* The mathematical difference is computed between electrical signals coming from two separate explorations on different wavelengths, in one of which the effect of solar energy reflected from the surfaces under examination is particularly marked, whereas in the othpr it is not.

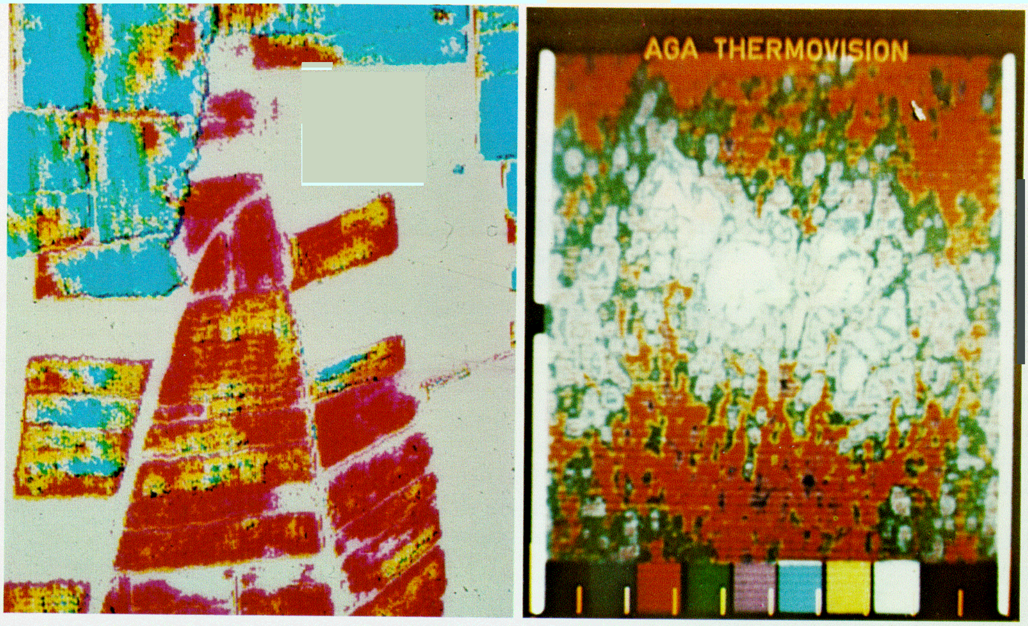


C



D

Fig. 3. C) Difference between the 9/l 1 and 4.5/5.5 micron channels: as it was said in the text the surface is described more accurately than using only one band. D) Level slicing of Vulcan0 island: it is easy to bee that the anomalous thermal manifestations (yelluw and red levels) are present only in the Vulcano crater, where it is easy to control the geographical distribution.



A B

Fig. 4. A) Rice fields affected by a disease: this disease causes a rising in the leaves temperature. as it is clearly shown in yellow areas compared to the red (healty) ones. Level slicing of the band 9/11 I micron; flight altitude 800 m a.s.1. B) Same Fields: this thermogram was taken from a cherry picker 25 m high with an AGA thcrmocamera and a 45° inclined gold mirror. The area shown in white is the diseased, while the red one is the hcalty one. Because of the scale was setted at 0.5 Y° per step the thermal contrast between the healty and diseased rice is 2.5 °C approximately. Hand 2.5/5.6 micron: AGA Thermovision Camera mod. 680.

$$P_{3/5\,\text{collected}} \cong \frac{\tau}{\pi} \cdot \left[\rho_1 \cdot k \cdot \int_3^5 \frac{C_1\ \lambda^{-5}}{\exp\ C_2/\lambda T - 1} d\lambda + \varepsilon_1 \int_3^5 \frac{C_1\ \lambda^{-5}}{\exp\ C_2/\lambda T - 1} d\lambda \right]$$

$$P_{8/14\,\text{collected}} \cong \frac{\tau}{\pi} \cdot \varepsilon_2 \cdot \int_8^{14} \frac{C_1\ \lambda^{-5}}{\exp\ C_2/\lambda T - 1} \cdot d\lambda$$

where

- τ = atmospheric transmission
- k = constant to have the radiating power of the sun referred to the earth surface
- ρ_1 = reflectivity of the surface in 3/5 micron band
- ε_1 = emissivity of the surface in 3/5 micron band
- ε_2 = emissivity of the surface in 8/14 micron band
- T_2 = sun's absolute temperature
- T , = surface's absolute temperature

In this case $P = P_{3/5} - P_{8/14} = P_{3/5}$ sun reflected, given that the contributions of the Pemitted in the two channels can be considered pratitally equal. Thus the possibility exists of observing and evaluating the reflexive behaviour of the surfaces in the 3/5 micron band.

In Fig. 3C an example of the function << difference >> of two channels is given. The advantage of this enhancement of the original data is to describe the surfaces in such a manner that it is possible to distinguish the nature of different surfaces better than in other ways.

b) Ratio. The mathematical ratio is computed between electrical signals coming from surveys on two different wavelengths; the resulting electrical signal obtained is, by dcfinition, adimensional. Practically speaking the thermal information disappears leaving its place to the description of the variations of relative etnissivity of one band with respect to another, such that here again it is possible to inquire into the physical characteristics of the surfaces under investigation. The treatments described above are extremely simple, but should be undertaken with maximum care in order to avoid gross errors of interpretation. Other, highly intricate treatments also exist, and these involve the use of complex mathe-

Fig. 5. Skylab satellite image taken on the venetian lagoon: on the right it is possible to see the discharge surveyed by means of a thermal scanner and described in Fig. 6.

matical algorithms. which cannot be fittingly dealt with here. The important thing is to appreciate how, from a basically thermal information, a quantity of not strictly thermal information can also be derived.

When speaking of surveys or measures in the infrared thermal domain, we are always speaking of surface manifestations: in fact, almost all objects with which we can normally come in contact are opaque as far as wavelengths above 3 micron are concerned, including glass and water.

4. APPLICATIONS OF THERMAL INFRARED TO THE ENVIRONMENTAL BEHAVIOUR STUDIES

a) *Soil's surface control*. I.R. thermal surveys from aeroplanes or satellites are extremely useful for controlling water pollution, be it thermic << in sensu strictu >> deriving from power plant discharges, or chemical. In both cases the signal processing techniques seen above can be employed, mainly by means of difference and ratio of two thermal channels. It is also possible to make an indirect control of air pollution as a survey of its noxious effects on the vegetation; this case also permits a survey of the course of the dominant winds.

b) *Hydrology*. The use of I.R. thermal surveys for the study of the course of both river and marine currents is now universally accepted. Here the temperature is used as a tracer of the preferential courses of the waterbodies. This method also lends itself very well to in-

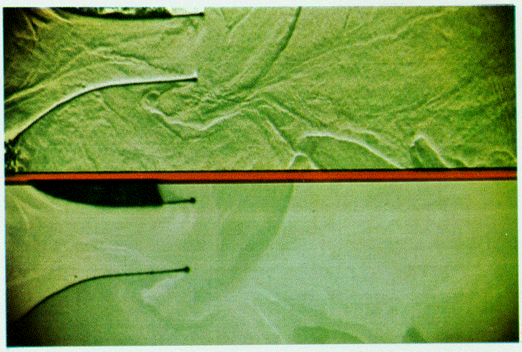


Fig. 6. Discharge from the Venetian lagoon: the thermal information (down) was studied in thl time's domain, in order to extract at best the geometry of the surficial thermal texture, as it is clearly shown (up).

dividuating Fresh water sources in the sea as well as offering a good idea of their dimensions (Figg. 1, 2, 6).

c) Geology. In geology I.R. thermal surveys are often used in thermically anomalous areas, such as volcanic and geothermal areas (Figg. 3A, B, C, D). The control of the thermal manifestations of volcanoes is widely accepted as one of the most indicative ways of keeping watch on their progress. The study of glaciers, of soil moisture, of terrain texture, of the heat capacity of soils are some of the other applications of this method in the geological field.

d) *Agriculture and forestry*. There is no doubt that plants in stress situations manifest anomalous thermal behaviour: the temperature of the leaves (or rather, their radiant power) which is closely linked with the metabolism is also easily measured by means of thermocameras. Clearly it would be scarcely, if at all, possible by means of a conventional thermometre (Fig. 4, A-B). With I.R. control it is also possible to detect the beginnings of forest fires; in fact in some countries it has already been adopted for this purpose.

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