International Hydrographic Review, Monaco, LIV (2), July 1977.

MEASURING THE SURFACE THERMAL STRUCTURE OF THE SEA OFF BRITTANY BY SHIP AND AIRCRAFT

by C. DECHAMBENOY, L. PONTIER, F. SIROU
Laboratoire de Météorologie Dynamique, Palaiseau

and J. LEFLOC'H, J. RAILLARD
Laboratoire d'Océanographie Physique, Brest

INTRODUCTION

During the months of September and October 1975 the "Laboratoire d'Océanographie Physique de l'Université de Bretagne Occidentale" (LOP) and the "Laboratoire de Météorologie Dynamique du C.N.R.S." (LMD) made a joint study of surface temperatures and their variability over the continental plateau off the westernmost point of Brittany.

Between 18 September and 28 October scientists from the LOP made several trips aboard the oceanographic vessel *Capricorne* operating a sonde for in-situ T.S.D. measurements. The LMD utilized an Aries radiometer which they themselves had designed and perfected. This was installed aboard a DC-3 aircraft that also carried pressure, humidity and temperature sensors.

Our two objectives were as follows :

1. To compare the results obtained by two different techniques;
2. To obtain details of certain aspects of the microstructure of the sea surface, in particular over a frontal region.

This paper thus proposes :

a) To compare the results of the bathysonde measurements carried out by the LOP on *Capricorne* with those of a team from the "Centre Océanologique de Bretagne" (COB) embarked in the oceanographic vessel *Cryos* from 16 to 29 September 1975.
b) To present charts derived from radiometric measurements and to compare these charts with previous ones.
c) To present aspects of the fine thermal structure at the surface from a certain number of radial passes with the DC-3.

SURFACE TEMPERATURES DERIVED FROM THE BATHYSONDE MEASUREMENTS

We first present a series of five charts of surface temperatures obtained at different periods in September and October 1975. Charts Nos. 1, 4 and 5 are based on the *Capricorne* measurements, whereas Charts Nos. 2 and 3 are from the *Cryos* measurements taken by the COB team and processed at the University of Brest's Oceanographic Laboratory by M. MAH BU-IL.

Chart No. 1 shows a fairly wide area in order to give a tentative estimation of its general character, and in particular to outline the general aspect of the frontal zone.

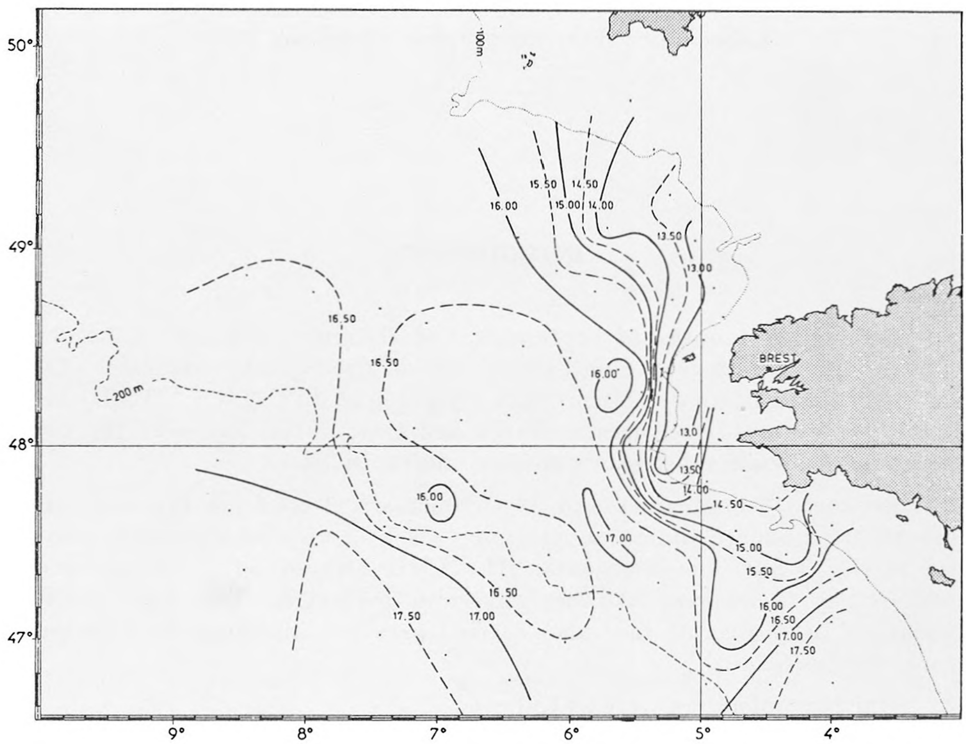

FIG. 1. — CAPRIROISE (1st part.). 18-28 Sept. 1975. Surface temperature.

It should be noted — for comparison purposes with the larger-scale Charts Nos. 2 and 3, both based on a shorter duration of time — that the measurements of Chart No. 1 were obtained from a series of radial passes in the form of a fan around the westernmost point of Brittany. As a result, Chart No. 2 corresponds chronologically to the measurements taken between 18 and 23 September to the south of Lat. 48° N.

This fact led us to draw up Chart No. 6 using the *Capricorne* data to the south and the *Cryos* data for the period 16-19 September. This gives us a picture that is much closer to a synoptic chart than the aspect shown in Chart No. 1 which was based on a wider scale of time and space.

Comparing Charts Nos. 6 and 1, it is seen that they are identical in their southern portion; however although north of 48° N the results are very similar, in the northern sector of the chart the orientation of the

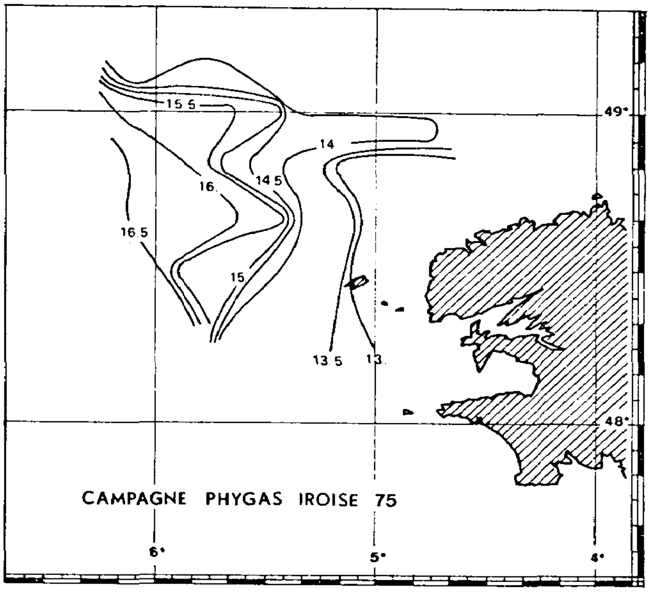

FIG. 2. — PHYGAS IROISE 75 Project. *Cryos*, 16-19 September 1975.

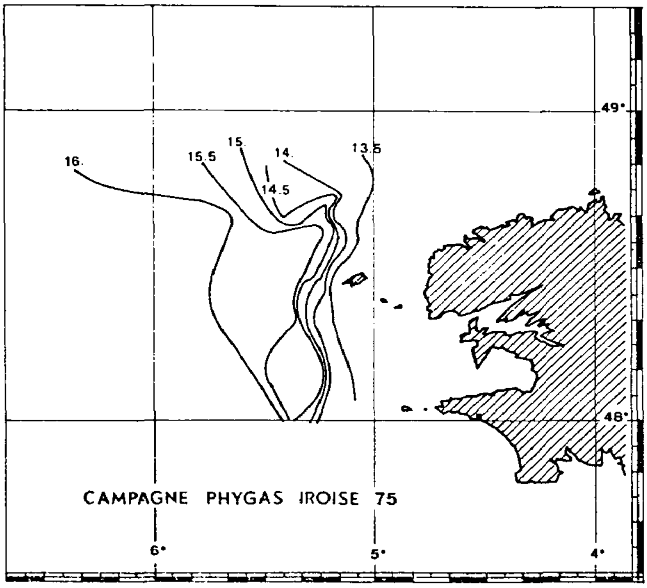

FIG. 3. — PHYGAS IROISE 75 Project. *Cryos*, 24-26 September 1975.

isotherms becomes zonal on Chart No. 6 whereas Chart No. 1 demonstrates a meridional distribution.

This highlights the variability characteristic of the region. Despite this trend it can nevertheless be said that, overall, the results obtained from a relatively long series of measurements are fairly representative; in spite of the fairly complex structure of the records obtained by two different vessels, each using different parameters, they coincide well and lead to very similar results. This was perhaps to be expected, but a verification over this region has been profitable.

In the same way, Chart No. 3 and the northern part of Chart No. 1 can be compared chronologically, and this leads on to Chart No. 7. Although this last has the advantage of being based on measurements over a short period of time (26-29 September), nevertheless it covers only a small area.

This set of charts highlights well the fairly short period variability characteristic of the area, and in particular the distortions of the geometry of the frontal zone. In this respect, and over a longer term, Chart No. 4 shows that the horizontal thermal gradient at the level of the front can decrease considerably, and finally the front disappears completely (Chart No. 5).

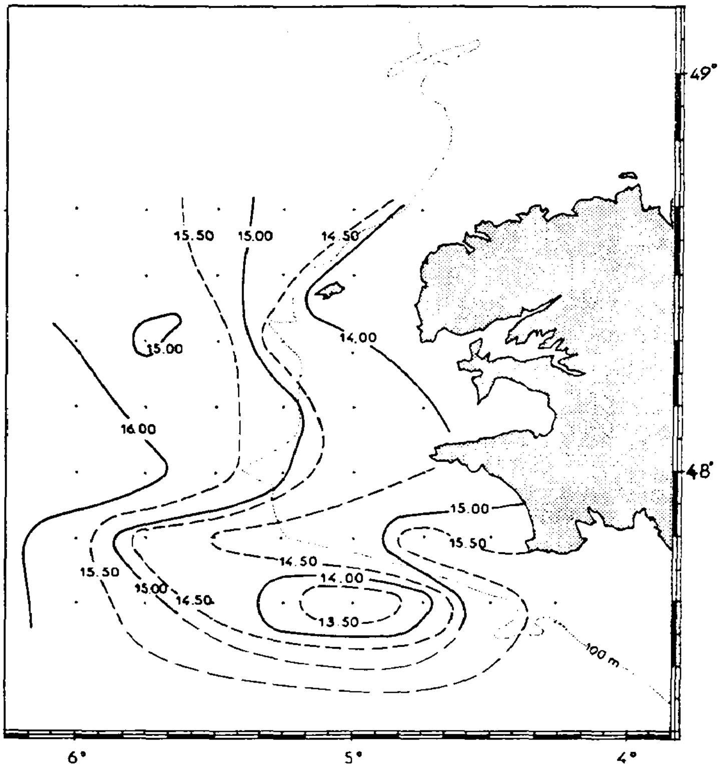

FIG. 4. — CAPRIROISE (2nd part). 1-8 Oct. 1975. Surface temperature.

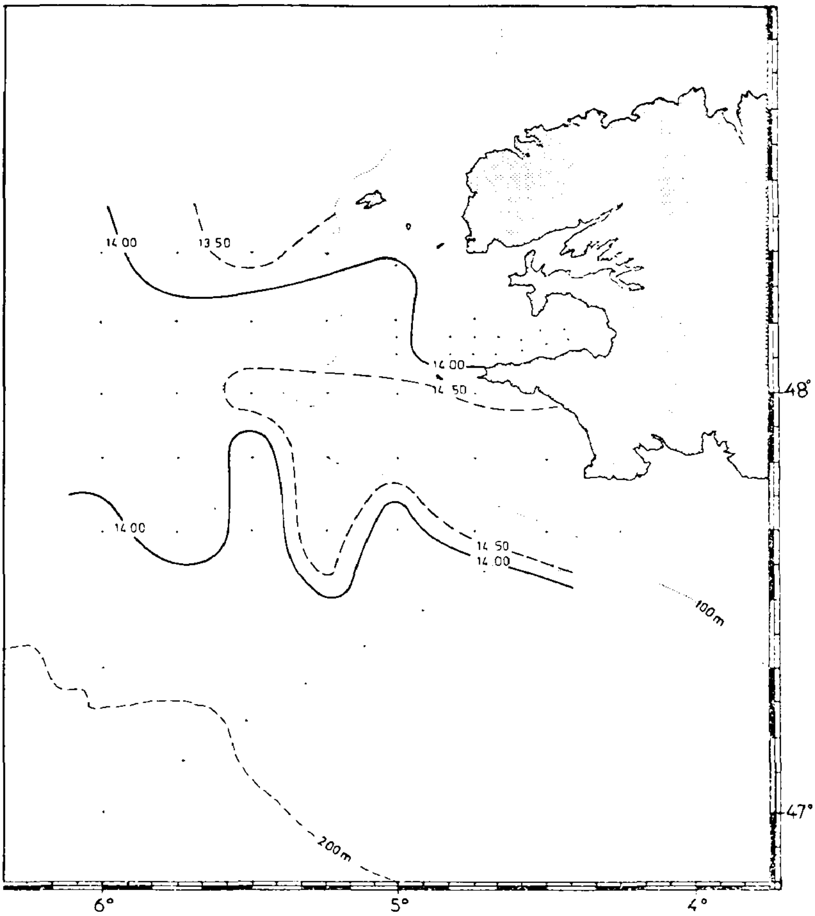

FIG. 5. — CAPRIROISE (3rd part). 20-28 Oct. 1975. Surface temperature.

MEASUREMENT OF SURFACE TEMPERATURES BY AIRBORNE INFRARED RADIOMETRY

Principle

All solid or liquid bodies give off electromagnetic radiation, the total intensity and spectral distribution of which depend wholly on the temperature and surface properties of the body.

This radiation, commonly called thermal radiation, is governed by the well known laws of physics, the PLANCK and KIRCHOFF laws in particular. Thus measurements of radiation utilizing a radiometer permit determination of the surface temperature of the body under scrutiny.

For bodies with temperatures similar to those encountered at the Earth's surface this radiation is essentially in the infrared part of the spectrum, with maximum intensity of about 10-12 μm, Very fortunately, for this part of the spectrum the atmosphere is relatively transparent, and this fact has permitted the development of remote controlled temperature measurements of surfaces by recording their radiation.

Depending on the size of the area to be studied, the radiometer can be carried by an operator, or installed aboard an aircraft or even a satellite.

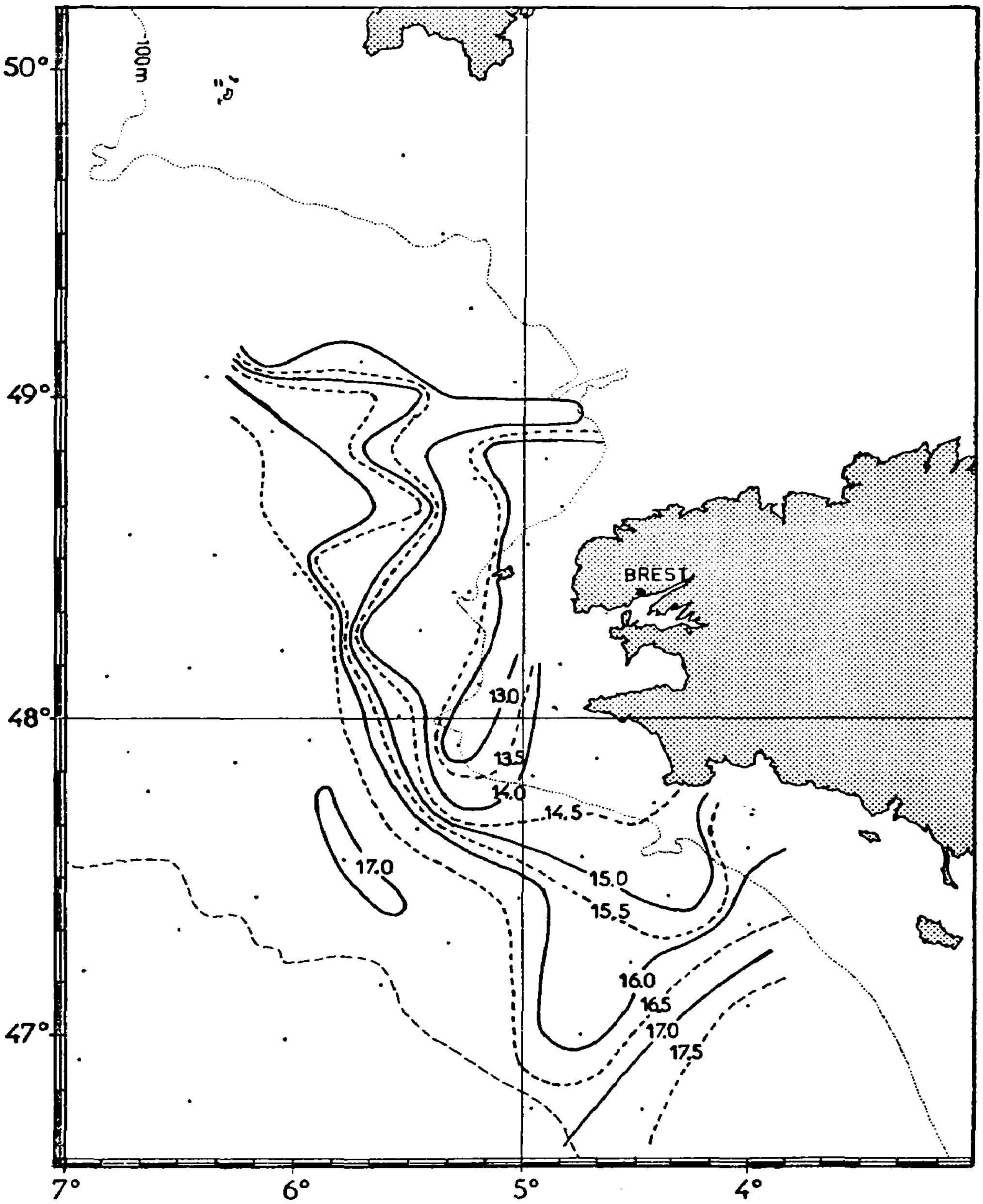

FIG. 6. — Composite chart. 16-23 Sept. 1975. Surface temperature.

In the first of these cases the atmosphere is discounted, as the site and the radiometer are in such close proximity. In the other two cases, however, when the exact temperature of the surface is sought, the influence of the atmosphere must be taken into account as it absorbs a part of the surface radiation and itself gives off its own radiation. In both cases the emissivity of the surface must be known.

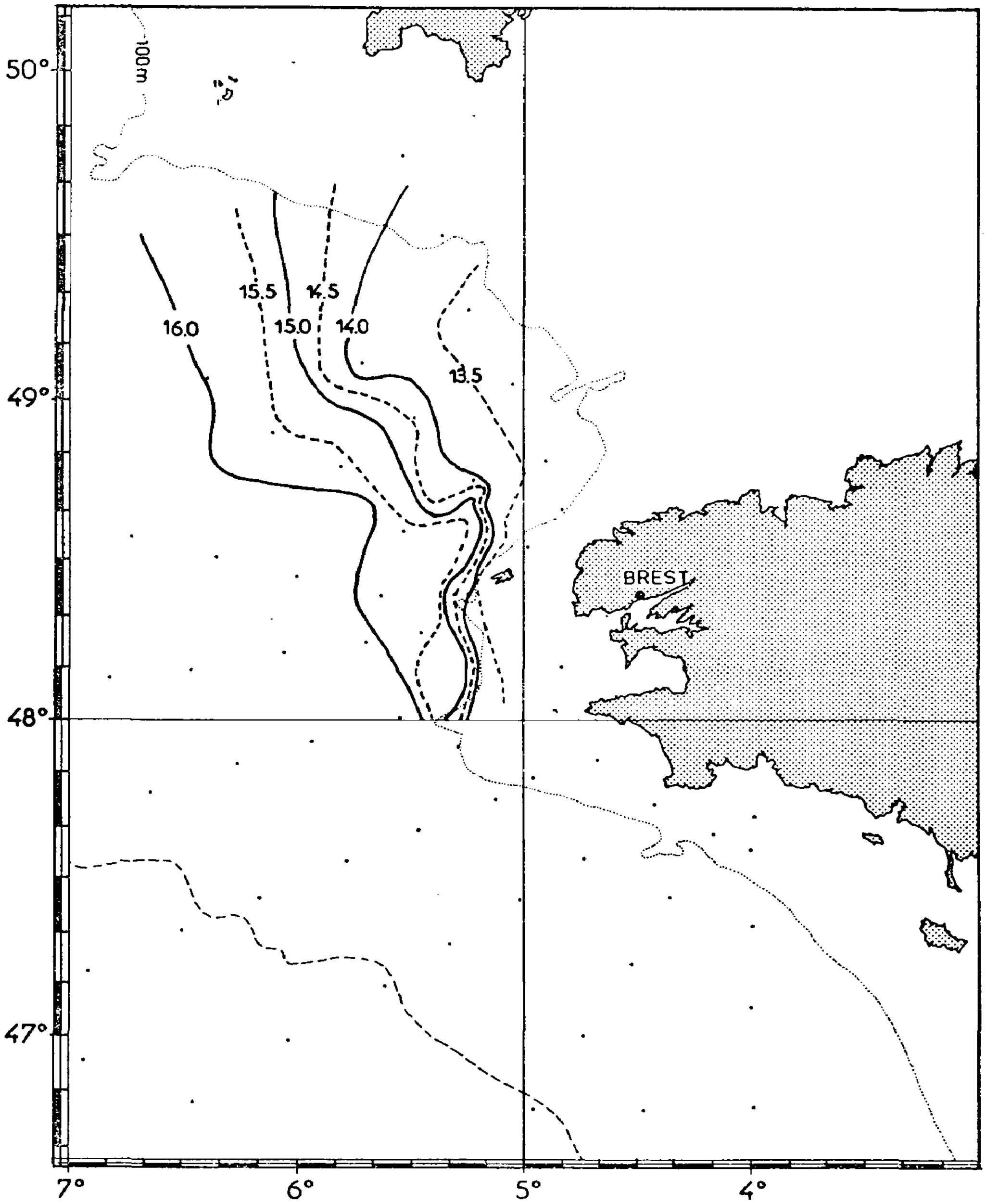

Fig. 7. Composite chart. 26-29 Sept. 1975. Surface temperature.

The radiation that an airborne radiometer receives at distance h from the site is:

$$I(T, \epsilon, h) = \int_{\nu_1}^{\nu_2} R(\nu) \left[\mathcal{T}_\nu (0, h) (\epsilon_\nu B_\nu(Ts) + (1 - \epsilon_\nu) I_\nu \downarrow) + \int_0^h B_\nu(Tz) \frac{\partial \mathcal{T}_\nu(z)}{\partial z} dz \right] d\nu \qquad (1)$$

where:

$I(T, \varepsilon, h)$	=	intensity of the radiation received at the radiometer, at altitude h;
$R(\nu)$	=	spectral response of the radiometer between two limits, ν_1 and ν_2;
$\mathcal{T}_\nu(0, h)$	=	monochromatic transmission of air between the site and the radiometer;
ε_ν	=	emissivity of the surface at frequency ν;
$B_\nu(Ts)$, $B_\nu(Tz)$	=	intensity of the radiation of a black body at frequency ν at temperatures of Ts and Tz;
Ts	=	surface temperature at the site;
Tz	=	atmospheric temperature at altitude z;
$I_\nu\downarrow$	=	monochromatic intensity, at sea level, of the downwards radiation of the atmosphere;
$\mathcal{T}_\nu(z)$	=	atmospheric transmission between altitude z and the radiometer.

The three terms between the square brackets in equation (1) are respectively:

— radiation from the surface, attenuated by the atmosphere between the surface and the radiometer;
— intensity of atmospheric radiation reflected by the surface towards the radiometer;
— radiation of the atmosphere itself between the surface and the radiometer.

It can therefore be seen that in order to determine Ts, we must know the structure of the atmosphere, its radiation in a downwards direction and the emissivity of the surface.

The structure of the atmosphere is determined by pressure, temperature and humidity sensors installed aboard the aircraft carrying the radiometer.

The radiation of the atmosphere down to the sea surface is by estimation. In clear skies at a given place it varies but little, and its value can be estimated to within 25% provided the air temperature near ground level is known. This degree of accuracy is sufficient since the information is only needed for a very small correction: $1 - \varepsilon_\nu \neq 0$ for the case of the sea. On a cloudy day this radiation is equivalent to that of a black body whose temperature is halfway between those of the ground and the cloud base.

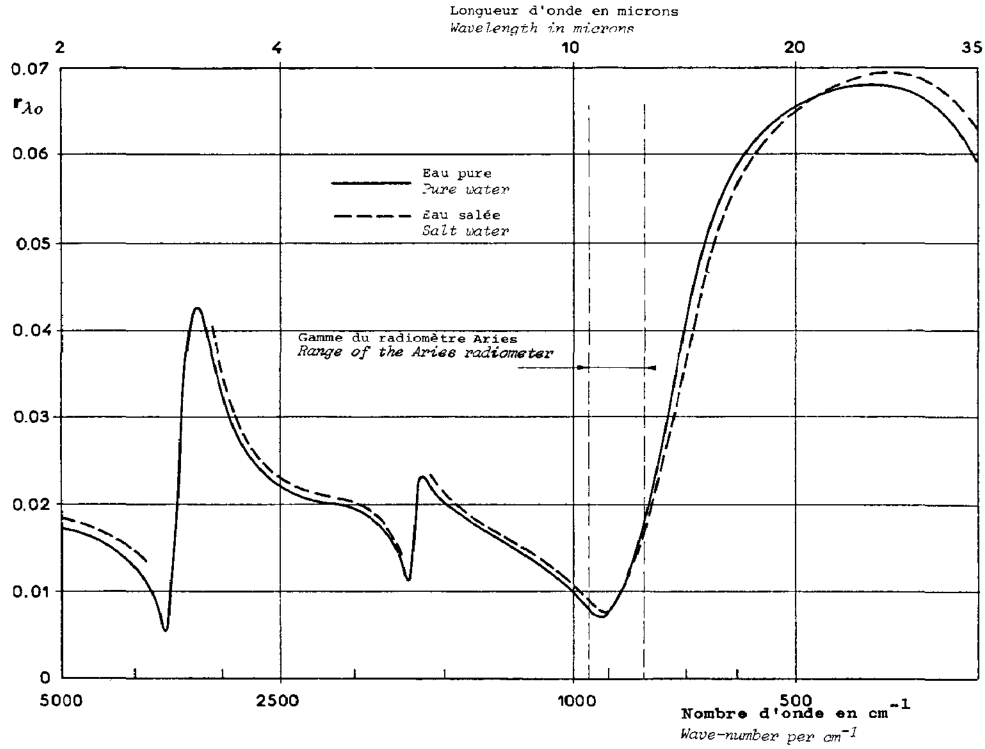

FIG. 8

In the spectral field that we are studying (see fig. 8) the emissivity of the sea is very close to that of pure water. However, if a number of pollutants are present at the sea surface this would obviously not hold good. In the present case emissivity was taken as 0.99, thus very close to 1.

The infrared radiation from the sea comes from a surface layer less than 0.1 mm thick.

Calibrating the radiometer

The radiometer's response $R(\nu)$, a function of frequency ν, is difficult to evaluate accurately since besides depending on transmission through the passband filter it is also a function of the optical system and of reflection by the various mirrors (see fig. 9). The radiometer therefore has to be calibrated, by conversion of the energy registered at the radiometer into an equivalent black body temperature. The procedure is as follows:

The radiometer is placed on a closed tank in the lid of which a small hole has been pierced. The water in this tank is maintained in continual motion in order to homogenize the temperature. The tank lid is maintained at the same temperature as the water. As a result the radiation from the tank is very similar to that of the black body at that water temperature. Thanks to this calibration, the accuracy of surface temperature measurements can be estimated to within a few tenths of a degree.

Correction for atmospheric absorption

The intensity of radiation I (T, ε, h) is evaluated in terms of the equivalent temperature of the black body, and then this temperature is corrected for atmospheric absorption.

In order to make this correction the atmosphere is first divided into horizontal layers of uniform temperature and humidity. Next we calculate the contribution made by each of these layers to the modification of radiation from the site due to partial absorption and to re-radiation from each particular layer.

The spectral interval for the radiometer passband is divided into basic intervals of 25 cm^{-1} for which a mean coefficient of absorption was chosen. The coefficients used are those given by KONDRATIEV (1966) [1].

The corrections obtained were + 0.2° C for 1 October, + 0.25° C for 3 October and + 0.2° C for 22 October.

In this computation the horizontal variations of the structure of the atmosphere are ignored. On account of the length of the tracks flown and the size of the flight area, this is perhaps not entirely justifiable. However, in view of the smallness of the corrections, one can assume that this approximation is closer than any errors of measurement.

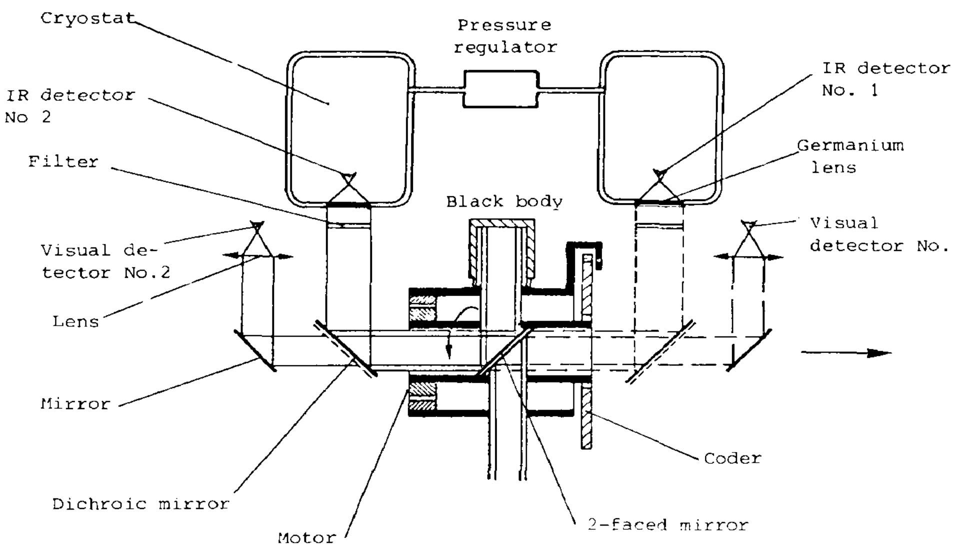

FIG. 9. — Scanning principle of Aries radiometer.

The radiometer utilized

A detailed description of the Aries radiometer was given in a paper presented at the "Journées d'Optique Spatiale de Marseille" by J.L. MONGE, and F. SIROU in 1975 [2], and therefore only its essential points will be given here.

The Aries radiometer is an airborne scanning device operating as follows: longitudinal scanning is effected by the flight motion of the aircraft, in a direction parallel to the scanner axis; while lateral (line) scanning is produced by optical deflection, perpendicular to the axis, of the sighting line. For this, Aries has a double-faced rotating mirror inclined at 45° to the scanner axis and rotating round this axis. This arrangement produces a time multiplexing in both right and left channels, which are entirely symmetrical (fig. 9). On each channel, dichroic mirrors separate the visible from the infrared. The visible is transmitted, the infrared reflected.

In the radiometer's plane of sight there are two black bodies of known temperature, and thus two calibration points at each revolution are obtained. This enables the temperature at each of the points on the scanned line to be determined accurately.

The infrared detectors used are Hg-Cd-Te photo-conductors. They are maintained at the boiling point, at constant pressure, of liquid nitrogen contained in cryostats.

The passband of each detector is defined by an interferential filter. In the present case this band fell within 10.5-12.5 μm.

The instantaneous angle of sighting is 2.8×10^{-3} radians, and the sampling increment 1.75×10^{-3} radians, thus making it possible to record 900 points per line on each channel for a field of $\pm$ 45° from the vertical.

The scanning mirror can rotate at four different speeds: 4.55, 9.1, 18.2 and 36.4 rev/sec.

The values are recorded on a magnetic recorder, digitally for two channels and analogue for the other two. The same tape records simultaneously the parameters of the atmospheric structure.

The data obtained during a series of airborne measurements can be presented in various forms. Immediately after the survey the visible and infrared images of the site can be rapidly scanned by eye. It is also possible to process these same images on high definition film, or else to project them via an interactive console onto a television screen. Finally, the whole series of temperatures in the infrared channels can be delivered as computer print-outs. However, in view of the abundance of the temperature measurements (4100 to 32 800 per second per channel) it is obvious that in most cases the data must be condensed by taking mean temperatures for a group of points chosen according to the purpose of the study. For the present case, the charts were obtained by utilizing the mean temperature at 500 points situated at the centre of the line, and by dividing the lines into groups of 30. The temperature obtained in this way thus refers to an area of about 500 m in the direction of flight by 400-2000 m in the transverse direction depending on the altitude flown.

The computer listing still gave too many points for the charts we wished to plot, and thus we decided to retain only certain of them, i.e. the aircraft positions at regular intervals along each flight track. Intermediate values were only used when they presented significant variations. This was therefore not a question of a smoothing but of an additional manual sampling. However for the charts that follow all the values from the listings have been utilized.

RESULTS OBTAINED, AND COMPARISON WITH PREVIOUS CHARTS

On charts Nos. 10, 11 and 12 showing the results we obtained, the following flight tracks have been plotted:

— Figure 10 : 1 Oct., 1500-1800 local time; Altitude: 410 m; V = 70 m/sec.

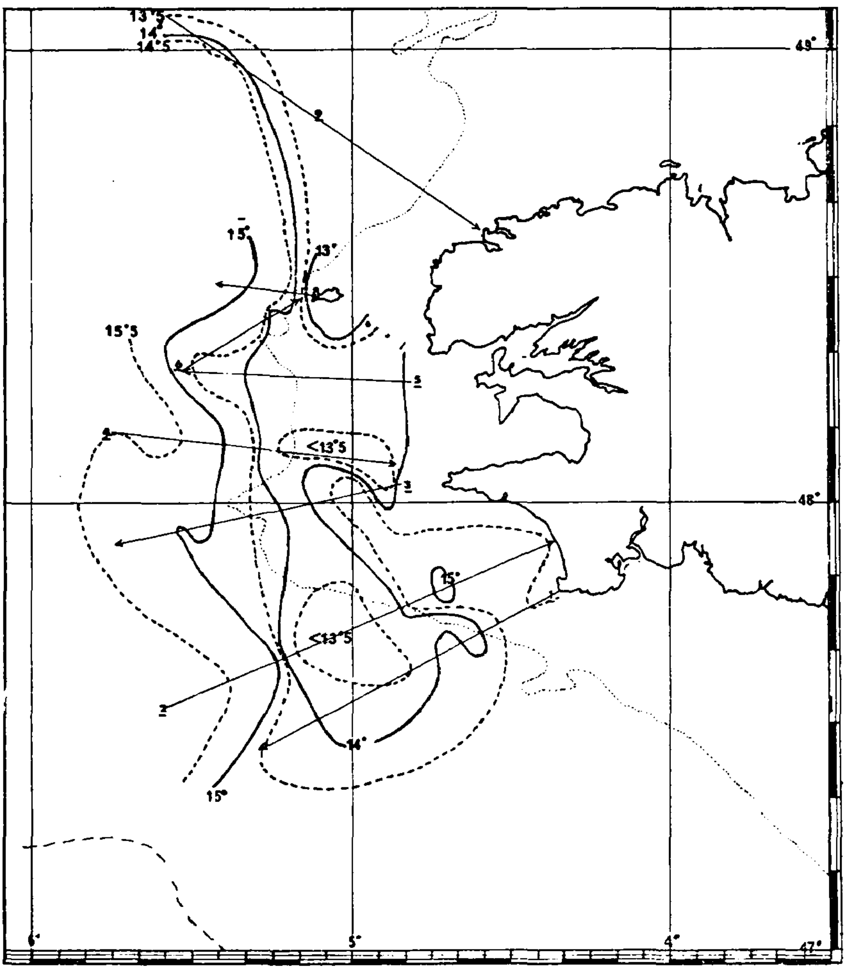

FIG. 10. — Surface temperatures by Aries radiometer. Flight of 1 Oct. 1975.

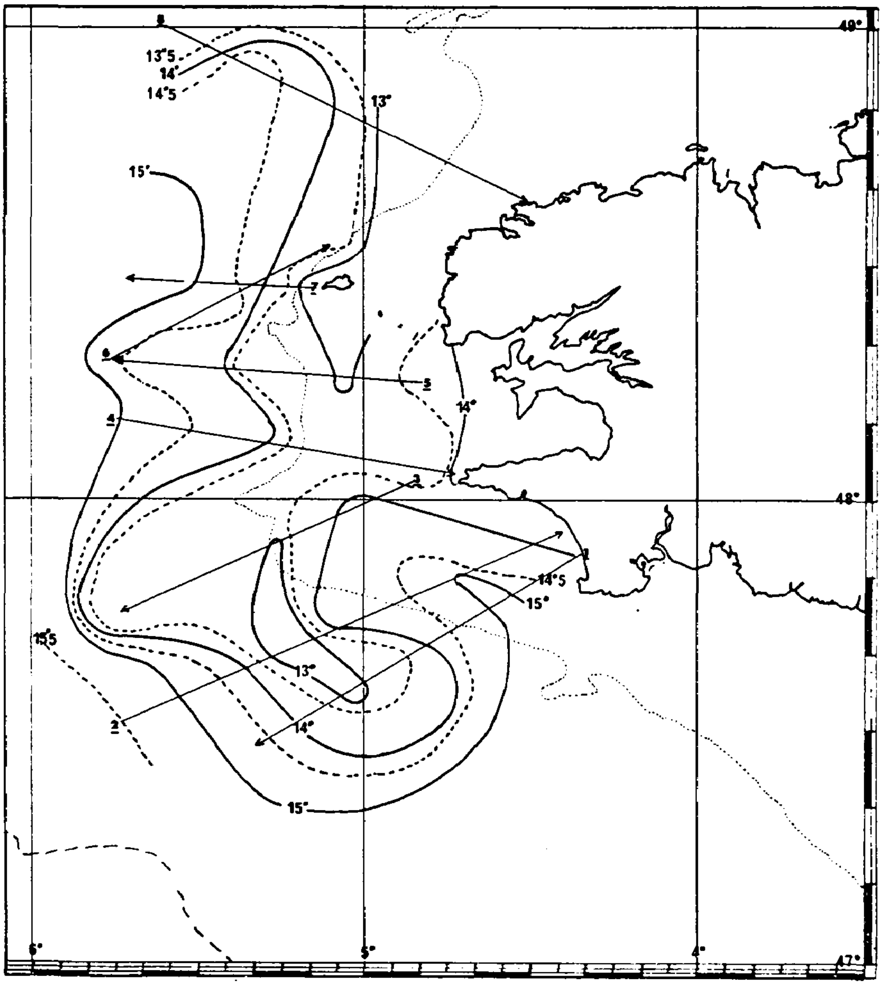

FIG. 11. — Surface temperatures by Aries radiometer. Flight of 3 Oct. 1975.

— Figure 11 : 3 Oct., 0930-1330 local time; Altitude: 550 m; V = 70 m/sec.
— Figure 12 : 22 Oct., 1124-1330 local time; Altitude: 2100 m; V = 76 m/sec.

A further flight on 24 October from 1028-1230 yielded results which were unusable for surface temperature measurement on account of the continuing low cloud base.

When it came to comparing the two series of results certain difficulties arose:

— chronologically, the two types of measurements are at two very different time scales; a matter of a few hours in the one case, and several days in the second;

— physically, they derive from two fundamentally different techniques. Moreover in one case it is the infrared radiation from the surface water film that is measured, and in the second case the measurement is of the mean temperature sampled at a depth of from 1-2 metres. Nevertheless, when the sea surface is choppy, the temperature of the surface layer can be taken as being the same as that of the immediate underlying layer on account of the mixing process.

In both cases, however, the charts must reflect the general aspect of the thermal structure, and this is exactly what they do. It is thus of interest to compare them.

Curiously enough, the northern part of Chart No. 10 (the 1 October flight) shows great analogy with the corresponding area on Chart No. 1, with distortion of the isotherms, the 13° line in particular which stretches less far to the south than on Chart N°. 1. Further southwards, however, (south of 48° N) there is an analogy with the corresponding sector on Chart No. 4 — where the 13.5° isotherm marks the minimum temperature.

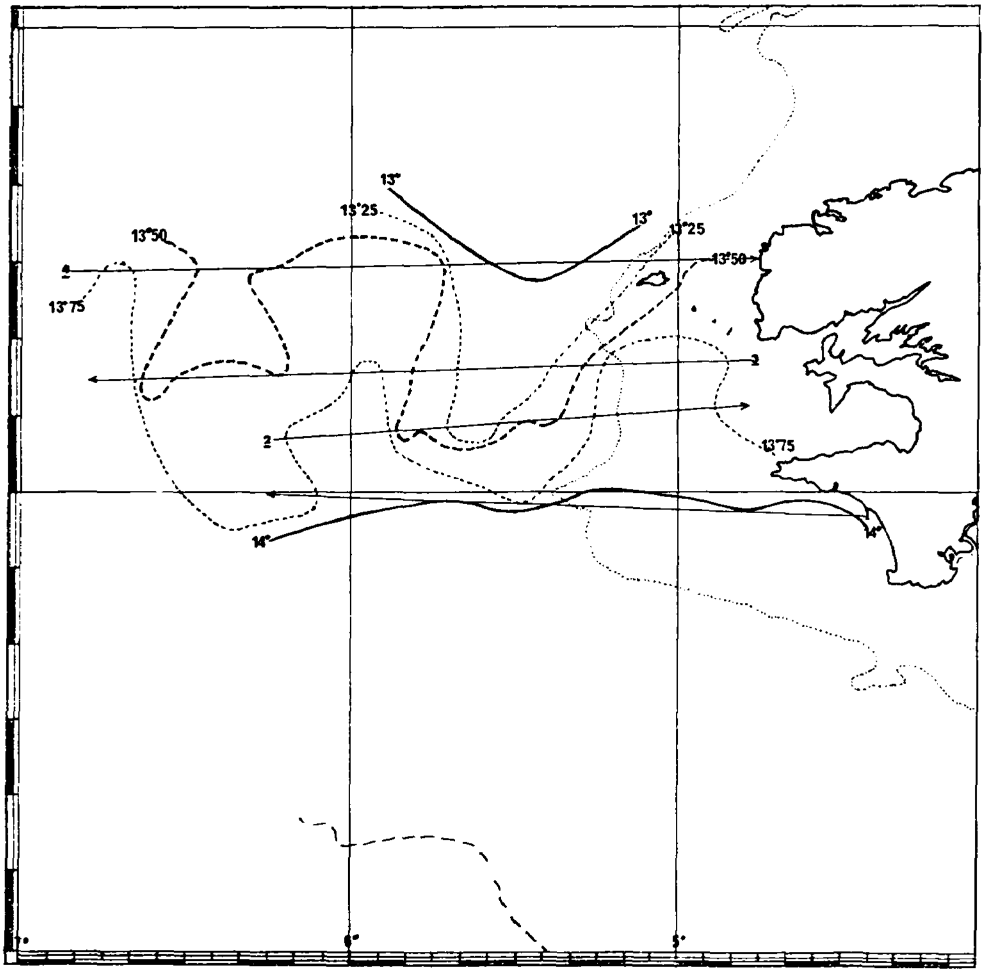

FIG. 12. — Surface temperatures by Aries radiometer. Flight of 22 Oct. 1975.

The general aspect of the isothermal lines over the whole area has marked similitudes to the situation shown on Chart No. 11 which is of the 3 October flight. Here we can note:

— the advance westwards of maximum water temperatures to the south west of the Baie d'Audierne;
— the presence of an isolated pocket of minimum temperature centred on 47°40′ N, 5°15′ W;
— the general orientation of the isotherms north of 48° N.

On Chart No. 12, of the 22 October flight, we note the disappearance of the front and the existence of a surface thermal structure at the end of our campaign that is totally different from the previous one (Chart No. 5). The orientation of the isotherms is this time zonal and no longer meridional.

SOME ASPECTS OF THE FINE SURFACE STRUCTURE

As additional data sampling was necessary for plotting these charts it appeared of interest to portray the variations in temperature of some of the flight passes. What is remarkable on some of these diagrams is the extremely abrupt passage from relatively high temperature waters to cold waters. On flight track No. 2 (fig. 13) of 1 October, for instance, the temperature passes from 15° to 13.5° over a distance of 2.3 miles. In this respect too the lines for flight passes Nos. 4, 6 and above all 8 (fig. 14) are also significant.

On flight pass No. 8 the passage is from 14.5° to 12.5° in only three quarters of a mile. Finally, the presence of certain isolated maximum and minimum temperatures poses the problem of knowing whether we are dealing with isolated pockets or narrow finger-like extensions. This is a matter for a later investigation. It should, however, be noted that we shall be limited by the fact that side scanning can only cover a fairly small width (approximately 1 km) in relation to data acquisition in the longitudinal direction. Thus we shall have to take each flight pass singly, since any comparison between adjacent flight passes is obviously out of the question in view of the spacing between two adjacent passes. The study will therefore be limited to an attempted interpretation at a fine scale.

CONCLUSION

This method of measuring surface water temperatures yielded results which are fully representative, and they have the advantage of having been obtained over a very short period (a few hours only) over a medium sized area. However, this method was not the only one employed during the survey since reference to direct measurements from a vessel was essential for checking the results. Nevertheless, provided the structure of the atmosphere is known, or if differential radiometric measurements are taken, it is likely that the influence of the atmosphere can be minimized before too long. With a good model for atmospheric transmission, errors could then be reduced to a matter of a few tenths of a degree.

As regards the exact nature of the phenomenon measured, the radiometer furnishes the temperature of only a very thin surface layer (less than 0.1 mm), and this obviously cannot be the case where classic measurements from a ship are concerned. Generally speaking, except for

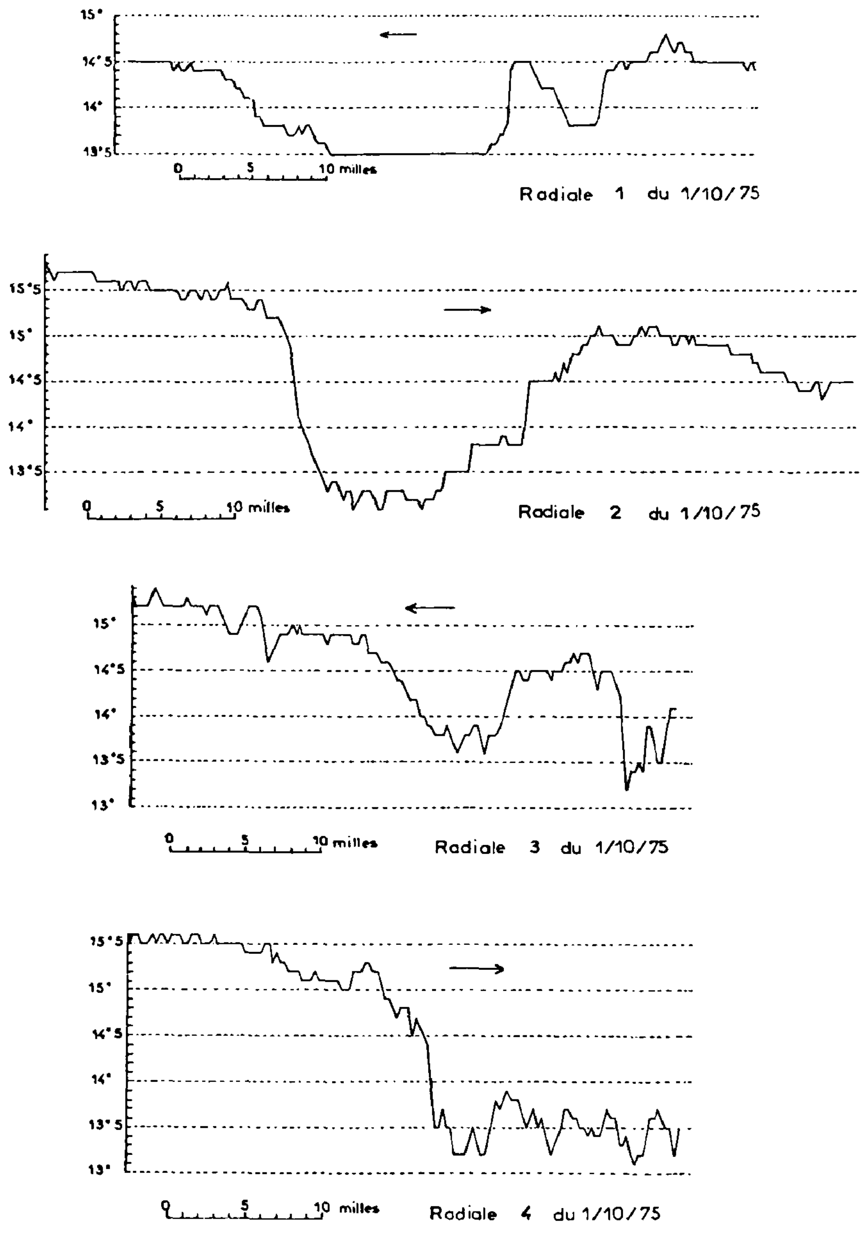

FIG. 13. — Aries temperature profiles, tracks 1-4 (see fig. 10).

periods of flat calm, this is probably not of great importance since the sea surface and its immediately adjacent layers are likely to be homogenized by turbulent mixing.

In the course of our survey the variability of the distribution of temperatures west of Brittany has been highlighted, in particular:

— the short period variability (over one day, by radiometry);

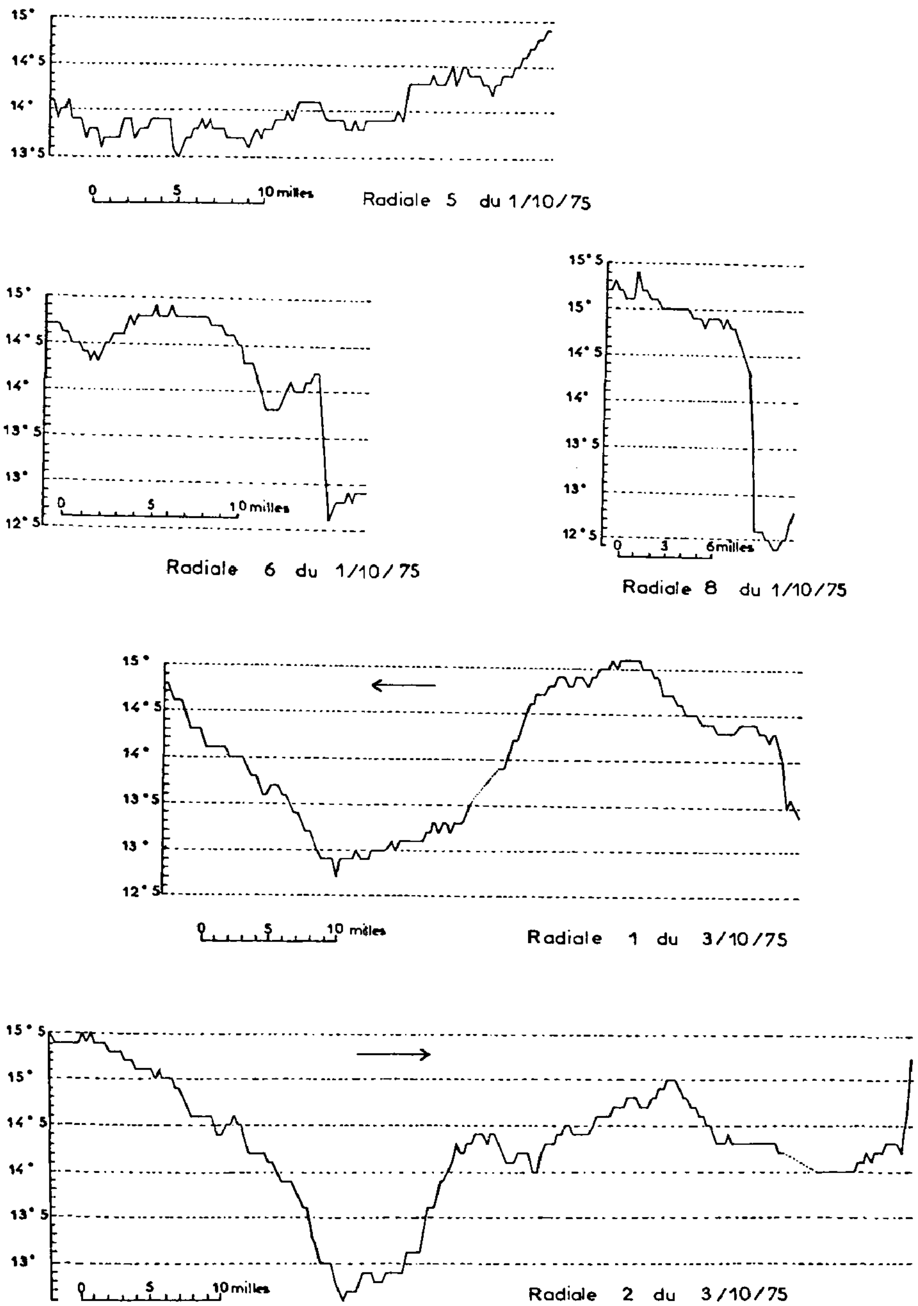

FIG. 14. — Aries temperature profiles, 1 and 3 October (see figs. 10 and 11).

— the longer period variability (over several days, by classical oceanographic measurements).

Radiometric measurements are useful for determining the fine structure and its temporal variation. It is clear that short period variations (in time or in space) cannot be determined by "classical" oceanographic sampling, yet these are of great interest.

Further, it is worth asking, in view of the complexity of the zone studied, whether measurements spaced in time and covering an extensive area had not been affected by considerable distortions by the time they came to be plotted.

Comparison between the results obtained by ship and by aircraft confirms that, for the zone in question, the general structure could be well modelled.

BIBLIOGRAPHY

[1] KONDRATIEV, K. Ya., Kh. Yu. NIILISK, R. Yu. NOORMA (1966) : The spectral distribution of the infrared radiation in the free atmosphere. *Atmos. and Ocean Phys.*, Vol. 2, No. 2.

[2] MONGE, J.L., F. SIROU (1975) : Aries – Un radiomètre multi-canal à balayage. Communication aux 5e Journées d'Optique Spatiale de Marseille. 14-17 Sept.

[3] RAILLARD, J. (1975) : Les zones frontales dans le nord du golfe de Gascogne et en mer Celtique. Sept. 1974. Internal publication, Université de Bretagne Occidentale, Brest.

[4] RAILLARD, J. (1976) : Quelques aspects de la structure thermique sur le plateau continental breton (Thermocline – Front thermique). *Annales Hydrographiques* (to be published).

(Translated from the French)