SECTION 100

APPLICATION OF THERMAL RADIATION DATA
TO FISHERY OCEANOGRAPHY

by

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INTRODUCTION

Work on the varied aspects of research related to our SPOC contract has continued since our last report (April - September) in the areas of: Project Little Window-1 and -2, DRIR data conversion, improvements on the APT receiver, equatorial upwelling and the new topic of thermal fronts. Since the Objectives of our contract are noted in the contract they will not be repeated in this report. The Tasks however, represent the means of reaching our goals and because our work is designed around the 4 Task areas they are repeated below:

Task I - Complete studies relating analyses of sea surface temperatures as derived from APT and other satellite data to similar analyses using conventional data as related to Project Little Window.

Task II - Prepare analyses of processed satellite, oceanographic, and meteorological data for selected periods to be determined by investigator.

Task III - Begin preliminary studies on procedures for monitoring oceanographic environmental conditions for fisheries by combining satellite data with conventional sea surface data.

Task IV - Evaluate the results of Task I, II, and III and prepare reports on these results and progress during the one year contract period as set forth in Section 6.0 DOCUMENTATION AND REPORTS of the Contract.

RESEARCH ACTIVITIES

PROJECT LITTLE WINDOW-1

Final preparations were made several months ago on a data report containing the oceanographic and meteorological observations made during LW-1 (14-23 March, 1970) and the report was published as part of the IATTC Data Report (Stevenson and Miller, 1971) in December. Copies of the report for use by interested scientists may be obtained from Commission headquarters in La Jolla.

PROJECT LITTLE WINDOW-2

Much of our effort during the past three months on this particular study has been to make the final preparations on figures and tables of oceanographic and meteorological information collected aboard the R/V DAVID STARR JORDAN (National Marine Fisheries Service, NOAA) and the ALEJANDRO VON HUMBOLDT (National Fisheries Institute, Mexico). These materials along with an explanation, will form the basis for a second data report. Present plans call for the addition of data from research aircraft and HRIR and DRIR data from satellites. Because these data have only recently become available, the additional compilation is expected to take another 2 months of time.

Preliminary Meteorological Results

During Project Little Window-2 (LW-2) meteorological observations were made to determine: 1) the effect of surface winds on ocean mixing; 2) the vertical heat and moisture flux between ocean and atmosphere by measuring the vertical profiles of moisture and temperature and; 3) thermal stability in the marine layer of the atmosphere and its effect on the ocean surface temperature. To accomplish these objectives detailed surface and upper air (radiosonde) observations were made at frequent intervals, particularly during the times of satellite passages overhead. The data taken aboard the R/V JORDAN and 4 Mexican research vessels are being prepared for a data report in tables and horizontal charts.

From May 1 to 4, surface winds became light and variable in direction over the LW-2 area in the Gulf between 24° N and 25.5° N. Over most of this area the surface air and sea surface temperatures were initially in equilibrium; as the winds became lighter (less than 5 kts) the surface water temperatures warmed up creating a highly stratified condition. Because the air in the marine layer was warm and moist (high humidity) during this period, the air-sea exchange of heat was minimal; the winds were too light to induce much mixing of the surface layer in the Gulf. Periodically, high thin cirrus clouds obscured the sun or moon, but the clouds were either absent or very thin during times of satellite passages over the JORDAN.

By May 5 the winds shifted to the south and strengthened and as a weak weather front passed, a narrow band of middle and high clouds moved over the LW-2 area. Fortunately, this happened between a day and night pass of the NOAA-1 satellite. Thereafter, winds shifted to the northwest and strengthened. Significant wind mixing of the surface layers of the Gulf began early on May 5. In addition, colder and drier air from the west was advected over the area creating a condition favorable for an upward flux of heat from the sea surface. Sky conditions remained quite clear after May 5 with only small patches of thin cirrus moving over the area.

Throughout most of the LW-2 Project, the radiosonde data revealed a dry atmosphere (except during frontal passage) with an average integrated water vapor content of 1.5 cm in the air column above the Gulf. Apparently the small amount of water vapor in the atmosphere caused only a slight attenuation of the radiance received by the 11 micron infrared sensor on the spacecraft. Preliminary plots of the thermal infrared data showing sea surface temperatures only slightly colder than those observed seem to confirm this.

Preliminary Oceanographic Results

Information about oceanographic conditions during LW-2 was obtained from temperature measurements made continuously with a towed thermistor (HST), infrared radiation thermometer (PRT), thermo-salinograph and at individual stations with expendable bathythermographs (XBT's) and an <u>in-situ</u> salinometer (STD). Since each of these methods differs from the other methods, an inter-comparison was made of the various data. A check of the bucket thermometer readings with the other data suggests that the bucket temperatures showed more "scatter" than the other methods and may have been due to the presence of a shallow layer of stratified surface water. Under such conditions the manner and location of taking the sample measurements from a vessel is very important. A comparison of the bucket values and the STD data was fairly good ($r = .89$, $p < 0.5\%$) although the bucket temperatures were about 0.2°C above the STD readings. Because the PRT operates on the same principles as the HRIR spacecraft sensors and could serve as a primary means of collecting ground-truth information, data from the PRT were compared with STD and HST temperatures. The resulting relation between the PRT and STD data was good

($r = .93$, $P < 0.5\%$), though the PRT values were about 1.2°C low. The correlation between the HST and the PRT was also good ($r = .93$, $P < 0.5\%$) with the PRT readings about 1.3°C low. From such inter-comparisons then, it appears that about 1.2°C should be added to PRT readings from LW-2 to bring them into agreement with the other measurements. The high degree of correlation between the towed thermistor and the shipboard PRT (during LW-2) provides encouragement for future use of a shipboard PRT in future calibration studies.

Surface temperatures obtained from the towed thermistor (HST) tended to be low on both the east and west sides of the Gulf, with slightly higher values in the central part of the Gulf. Temperatures on the east side of the Gulf increased from 19.9°C on May 1, by about 0.6°C, on May 2. On May 3-5 atmospheric conditions were clear and calm and the temperature increased up to 25.2°C on the east side. By May 6, however, the changing weather brought about a marked decrease in temperature so that surface temperatures were reduced to May 1 values. During the same period the central and western parts of the Gulf underwent similar changes in temperature. The time series collected by the 3 Mexican naval vessels at their anchor stations also show a gradual warming trend from May 1 through May 4, after which increased winds brought about a cooling interval from May 4 through May 6. In addition to the warming and cooling trends, diurnal heating occurred in the surface layer and caused water temperatures to vary by about ±1.2°C. Because this diurnal change is about equal in magnitude to gradients across the Gulf, it appears that a correction for diurnal change may need to be applied to shipboard observations to bring them into alignment with measurements made with airborne sensors and those made from spacecraft instruments.

DIGITIZATION OF INFRARED DATA

During the past several months a number of infrared images on 35 mm and 70 mm film negatives have been photo-scanned on the micro-densitometer* located at the S.I.O. Vis. Lab. Considerable flexibility of the system is provided by an IBM 360/44 interfaced to the densitometer. The 50 micron aperture was used during the scanning operation with 2 exceptions when the 100 and 200 micron window was used to compare aperture induced noise from apertures of different size. The arrays of digital values (8 bit; 0-255 range) resulting from the digitizing process, if contoured at 10 unit intervals, provide maps quite similar to those obtained if the same data were digitized directly by electronic means. Although a contoured map of digitized units can provide considerable information about warm and cool regions, there is a need to convert these

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* (Model Photoscan P1000, Optronics Int., Inc., 7 Stuart Rd. Chelmsford, Mass. 01824)

values into meaningful temperatures. Several schemes are available for converting an array of digitized values into temperatures.

The first method for calibration utilizes the step wedge, a part of every scan line and the bolometer reading (measures the ambient temperature within the spacecraft). The bolometer is used to determine a small correction to the HRIR sensor output because the sensor's voltage varies not only with the incoming radiation but also with the temperature of the sensor. The step wedge is used to provide several reference points for a scan line so that a conversion can be affected between sensor voltage and infrared temperature.

When the infrared image is digitized from a photographic negative, the wedge is also digitized so that a similar relationship of wedge to scan line can be obtained. A different type of problem is added when the incoming signal from a satellite is received by the APT receiver and is passed through a waveform remodulation unit to enhance the "warm part" of the photograph. Whereas the digitization of regular infrared images is linearized with a logarithmic amplifier and the resulting distribution of steps are approximately linear (e.g. the Vis. Lab. densitometer), care must be taken when the signals are processed with the waveform remodulation unit.

After the data have been converted to temperature values, corrections to account for the water and carbon dioxide vapor in the atmosphere, non-blackness of the water and non-zero nadir viewing angle need to be applied. The following section describes some aspects of this scheme for applying corrections to infrared data from NIMBUS IV.

THE NIMBUS IV (THIR) DATA OVER THE EASTERN TROPICAL PACIFIC

In September we began a new phase of our research in which thermal-humidity infrared (THIR) data, received from NASA, are being examined and compared to sea surface temperatures recorded by the NMFS research vessel DAVID STARR JORDAN. Accurate surface temperatures are seldom obtained in the equatorial part of the eastern tropical Pacific because of the limited research cruises in that area; but during March, 1971 the JORDAN, on the SKIPJACK fishery research cruise (March-April, 1971) obtained accurate and detailed oceanographic and meteorological observations (including upper air soundings) from 5°S to 10°N, between 118°W and 120°W an important area of upwelling and marine productivity. Fortunately, the NIMBUS IV satellite passed over the eastern tropical Pacific once each day; and the THIR data was recorded and archived at the Goddard Space Flight Center in formats useful for research.

Analysis of Infrared Data

For the period of February and March, 1971, the NIMBUS Users Group at the Goddard Space Flight Center selected for us several day and night orbits of thermal infrared data covering the eastern tropical Pacific, from 110°W to 140°W and between 30°N and 10°S, when there was 30% or less cloud cover. After the infrared data had been screened from the archived data file they were converted into temperatures (°K) and were plotted on a 1:1 million mercator map projection. At this projection scale each data point consisted of two to five infrared scan points, representing a resolution slightly greater than the resolution of the radiometer.

Initially, we selected two periods, March 11-12 and March 19-20, when sufficient sea surface temperatures were available from the R/V JORDAN in an equatorial area which was relatively free of clouds. The thermal infrared data for March 11 (daytime orbit #4532) have been analyzed in detail; and as soon as maps of the other days have been received from NASA, they will be analyzed to provide continuity in time and space.

Although the temperature patterns revealed by the infrared data for March 11 do not resemble closely those obtained from conventional ship data, the warmer temperatures were located where the NIMBUS IV video (IDCS) photographs showed that the minimum cloudiness occured. In contrast, the cold infrared temperatures corresponded geographically to the cloudy areas of the intertropical convergence zone. Similar results have been observed many times before; but over the eastern torpical Pacific, where research in tuna ecology is carried out extensively, the ability of spacecraft infrared sensors to detect sea surface temperatures will greatly enhance our ability to monitor a region where water temperatures may be outside the range in which tunas may be found in commercial quantities.

Three significant, but not surprising, features evolved from the analysis of the March 11 infrared data. First, sea surface temperatures derived from the daytime THIR data were approximately 11.5°C colder than those observed by the R/V JORDAN or other commercial vessels sailing between 4°S and 4°N along 119°W. A deep, warm and moist marine layer in the atmosphere apparently attributed to a strong attenuation of the radiation received by the infrared sensor. Second, a statistical comparison of sea surface temperatures based on THIR data and observed surface temperatures gave a high correlation coefficient ($r = .85$) and a least-squares fit according to:

$$T_J = .45T_s + 19.13$$

where T_J = sensor temperature referenced to the R/V JORDAN and

T_s = sensor temperature

A third noticeable feature revealed a recognizable pattern of noise superimposed over the thermal radiation received as the satellite passed over. The spurious noise was apparently caused by the spacecraft tape recorder.

Since NASA had not filtered (smoothed) or corrected the THIR data in any way, part of it was processed through the computer with a 2-D filter program which had been successfully used before. The result shown in figure 1a was a more coherent isotherm pattern which retained the essential features displayed in the unsmoothed and uncorrected sea surface temperature analysis (Fig. 1b)

Because extensive cloud cover obstructs the satellite's view of the ocean surface, it was important to accurately outline areas more than half covered by clouds (the resolution of video cameras will not permit the recording of scattered cumulus clouds). From enlargements of video (IDCS) and infrared (THIR) data gridded by computer and recorded on 70 mm film, we transferred recognized cloud patterns and types to the 1:1 million mercator projection with the use of an engineering pantograph. Thus, we were able to superimpose the cloud patterns onto the infrared temperature charts and determine more accurately which areas had minimum cloud cover.

It was possible to recognize cloud types in the eastern tropical Pacific when NIMBUS IV passed over during the daytime. With simultaneous coverage of an area by the video (IDCS) camera and the THIR (11 micron) sensor, we have been able to differentiate low stratus clouds from middle and high cirrus clouds. Over areas covered extensively by low stratus it has been difficult to determine from infrared data alone where the stratus clouds begin or ended and the sea surface was visible to the satellite sensors. This has been particularly true to the west of Baja California and to some degree in the equatorial regions between 5°N and 10°N. The daytime IDCS cloud photographs have been very useful in this respect; but to completely evaluate the thermal temperature field derived from infrared data, it was necessary to process the vertical temperature and moisture profiles of the atmosphere from radiosonde data.

During the SKIPJACK cruise, personnel from the National Weather

Service were aboard the R/V JORDAN to make radiosonde observations. Balloons were released at least once a day in order to obtain representative profiles of moisture and temperature from the ocean surface to heights up to 18 km. Copies of the radiosonde data for this period have been obtained from the National Data Center, Asheville, North Carolina.

From the radiosonde data, temperature and water vapor content have been interpolated at 50 mb. (pressure-altitude)intervals. The preliminary results revealed that the atmosphere in the equatorial region was much warmer and considerably more moist than the atmosphere over the Gulf of California. By comparison, temperatures in the lower half of the atmosphere within 5° latitude of the equator are about 3°C higher in the marine layer than over the Gulf; and the total precipitation near the equator exceeds that in the dry Gulf by a factor of 3 to 4. Thus, the optical path was quite opaque to the NIMBUS IV, THIR sensor; and atmospheric attenuation of outgoing thermal radiation was computed to be nearly the maximum expected for a deep tropical atmosphere.

As mentioned earlier, sea surface temperatures derived from THIR data were about 11.5°C lower than observed by the R/V JORDAN along 119°W. (Fig. 2). Until the radiosonde data had been examined closely, these temperatures seemed to be colder than expected. However, the theoretical, atmospheric attenuation curves computed for NIMBUS III and a moist atmosphere during project Little Window-1 indicate that data from the infrared sensor (11 micron channel) would require corrections greater than 7°C for data in the nadir angle range of 0° to 30°. We are presently attempting to work out a computer program for the radiative transfer equations described by Kunde (1967). When this task is completed we will be able to compute accurate atmospheric attenuation curves for infrared sensors used on either NIMBUS or ITOS satellites. For the present, it appears that the available corrections for NIMBUS III HRIR data are not greatly different than those we will derive from NIMBUS IV data.

If adequate sea surface temperatures were available from ships over the oceans, limb darkening (atmospheric attenuation and ocean surface non-blackness) corrections could be obtained by merely applying the temperature difference between satellite infrared data and ship observations. Unfortunately, this will seldom be possible over large areas; and this direct means of calibrating thermal infrared data can be accomplished only on special projects similar to Little Window 2.

Because most of the eastern tropical Pacific has a moist warm atmosphere throughout the year, it is essential to establish a means of correcting satellite infrared data for atmospheric attenuation. Future satellites will obtain continuous moisture and temperature profiles along the optical and orbital paths. The first IRIS sensor experiment on NIMBUS IV has established this potential. In the meantime, radiosonde data will provide the needed data to determine from the ocean upward the opaqueness of the atmospheric window in the 10.5 to 12.5 micron region.

An important task of our research is to determine the limb darkening corrections over the eastern tropical Pacific where the fishery-oceanography is being conducted. If after applying these corrections to the infrared data over cloud free areas, the surface temperatures agree closely with the ground truth data, we can complete the evaluation of remote sensing of sea surface temperatures. Although it has been established that prominent features such as the Gulf Stream can be detected by remote sensing, there remains much research to be conducted over areas where ocean fronts and upwelling concentrates food for the tuna fishery.

In the introduction to this section we outlined an indirect approach to deriving digital values of sea surface temperatures by scanning photographs of infrared data with a microdensitometer. The principal drawback of this method is related to the large variations in film emulsions or densities and film processing procedures. However, it is possible with an APT satellite receiver to record on the same film strip both the calibration (step) wedge in the sensor housing and the earth scan of infrared data. It is possible also to maintain precise controls in the film processing and apply known calibration step wedge temperatures to corresponding gray-tones in the film which have been converted to numbers with the densitometer. Although this procedure has little ultimate value in working with stored infrared data that has been digitized at data acquisition centers, it is providing us with another approach to evaluating the NIMBUS IV data over the equatorial tropical Pacific.

NASA provides 70 mm film strips of infrared data and corresponding video photographs for daytime orbits to accompany the grid prints of digitized thermal infrared data. Each film strip of earth scanned infrared data is followed by a 10-step, calibration gray scale which is put on the film electronically to show the dynamic (equivalent blackbody temperature) range used to represent radiance from clouds or earth. However, this gray scale is not accurate enough to assign specific temperatures because of variations in film density and emulsions during film processing. Therefore, it is necessary to obtain accurate sensor temperature readings from the original analog data files. Upon request NASA also makes available analog records from the original spacecraft interrogation tape records. The analog data consist of Visicorder oscillograph records of each full (360°) scan with corresponding time/date markings below the analog trace. Selected areas of the infrared films, where ground truth data were available for March 11, 12, 19 and 20, 1971, have been scanned with the micro-densitometer at the Visibility Laboratory, S.I.O. Also the 10-step calibration wedge was scanned from the same strip of film so that the emulsion density characteristics should be known over the entire strip.

Because the individual steps are not exactly uniform, each step can be characterized by a mean value and a standard deviation about the mean (see Fig. 5). Mean values of the steps indicate that the steps are not uniformly spaced, but are compressed at either end of the wedge. In addition, the distribution of observations about each mean value becomes progressively larger with increase in optical density (darkest gray tones).

From selected analog records we have been able to extract equivalent black body temperatures for scan lines which correspond to those on the infrared photographs which have been digitized. Thus, we have been able to assign temperatures to the 10-step calibration gray scale which has also been digitized from the 70 mm film. Finally, working from the step wedge temperatures to the digitized infrared photographs we will be able to convert film density counts to equivalent black body temperatures representing clouds or sea surface. We are presently evaluating this technique by comparing sea surface temperature charts derived by this indirect method with those obtained by the more conventional method described in previous sections.

ALTERNATE METHOD FOR CALIBRATION OF INFRARED DATA

An alternate and more empirical scheme for converting digital values derived from photo-scanned negatives into realistic temperatures requires the use of ground (sea surface) temperature values in a cloud free area within the general region of interest. In order to obtain a reasonable least squares equation from the 2 data sets, it appears necessary to have the digitized density units corresponding to surface temperatures extend over a range of 30 density units or more, to insure a useful conversion over a range of several degrees C. Implicit in the constant of this equation are the several individual correction factors. For most accurate results a variable correction factor resulting from changes in the nadir angle needs to be added after the other correction has been applied.

An example of this statistical conversion is seen in figure 3. The spatial correlation ($r = .92$, $P < 0.5\%$) resulted in a relatively accurate conversion of digital units off southwest Baja California and within the Gulf of California but somewhat low temperatures over land and cloudy regions. If the wedge is used in conjunction with the least squares fit, the calibration can be extended over a considerably larger portion of the thermal range of the instrument.

THERMAL FRONTS

Thermal fronts are usually associated with ocean current boundaries and where two dissimilar water types are in juxtaposition. These boundary regions are either convergent or divergent, depending upon whether the surface layers are approaching or receeding from the zone. Considerable biomass may be concentrated along a convergent frontal zone and this accumulation of forage appears to attract large fish that can then be harvested by fishermen. Also pelagic fish such as tunas may well use thermal fronts for reference in traveling along their migratory routes.

While the average seasonal position of the major surface fronts in the world oceans have been outlined, relatively little is known of the extent and nature of short period displacements of these fronts. Local fronts by comparison are largely unmapped and will remain so until greater use is made of data collected from satellites and oceanographic vessels to make synoptic studies of these features. Because there will probably never be an adequate number of research vessels available to provide the detailed coverage over large regions, the ability of the high resolution infrared sensors to rapidly scan large portions of an ocean in a synoptic fashion provides a method of obtaining these data when atmospheric conditions permit.

Various methods have been developed in the fields of meteorology and oceanography for enhancing frontal zones such as Clarke and Laevastu (1967). Our initial approach has been to evaluate the method of Clarke and Laevastu and to determine how effective it would be in the present situation. In practice a computer program was first written to determine the absolute value of the gradient of the temperature ($|\nabla T|$) and then an array of surface DRIR temperature data was used with the program and the results were compared with the initial temperature field (Fig. 4). This technique produces maximum values corresponding to the central region where the gradient is a maximum. A second program was then written for determining the gradient of the gradient function previously determined ($-\nabla|\nabla T|$). This time by not taking the absolute value of the new function we have three important reference points for a frontal zone; a maximum negative value corresponding to the cold side of the front; a zero value corresponding to the maximum gradient in the zone and a maximum positive value corresponding to the warm side of the front. Further improvements on this method may consist of the addition of a smoothing procedure to be used after the gradient fields have been determined.

REFERENCES

1. Stevenson, M. R. and F. R. Miller. 1971. Oceanographic and meteorological observations for Project Little Window: March 1970. Inter-Amer. Trop. Tuna Comm. Data Report No. 4. [in English and Spanish]. 324 p.

2. Kunde, V.G. 1967. Theoretical computations of the outgoing infrared radiance from a planetary atmosphere. NASA Techn. Note, TN D-4045, NASA, Washington, D. C.

3. Clarke, L. C. and T. Laevastu. 1967. Numerical Methods for Synoptic Computation of Oceanic Fronts and Water Type Boundaries. Int. J. Oc. & Limn. Vol. 1 (1):28-45.

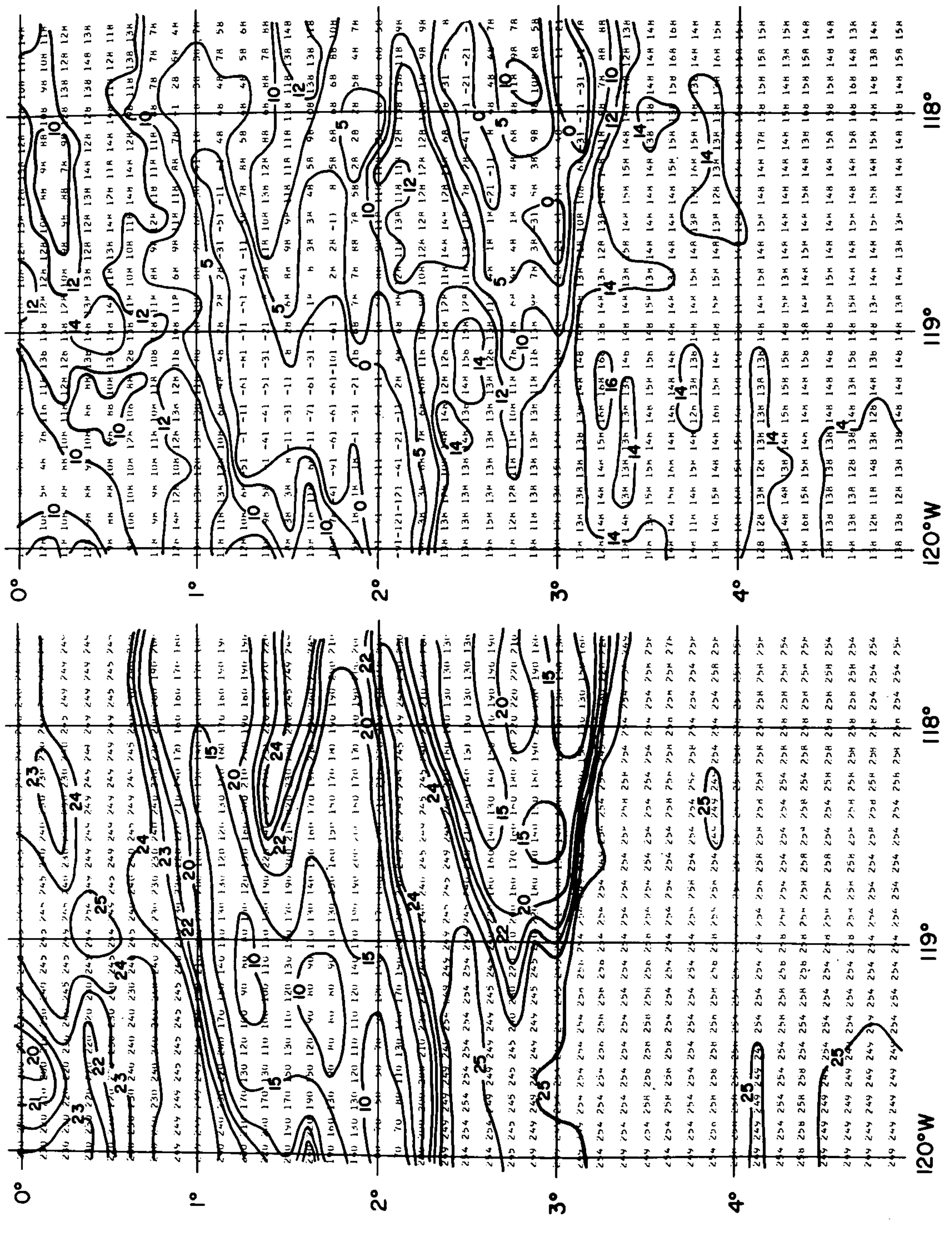

Figure 1. A. Smoothed THIR data (in °C) corrected for ground turth from NIMBUS IV (orbit #4532) for March 11, 1971.
B. Unfiltered THIR data (in °C) uncorrected for ground truth for the same orbit.

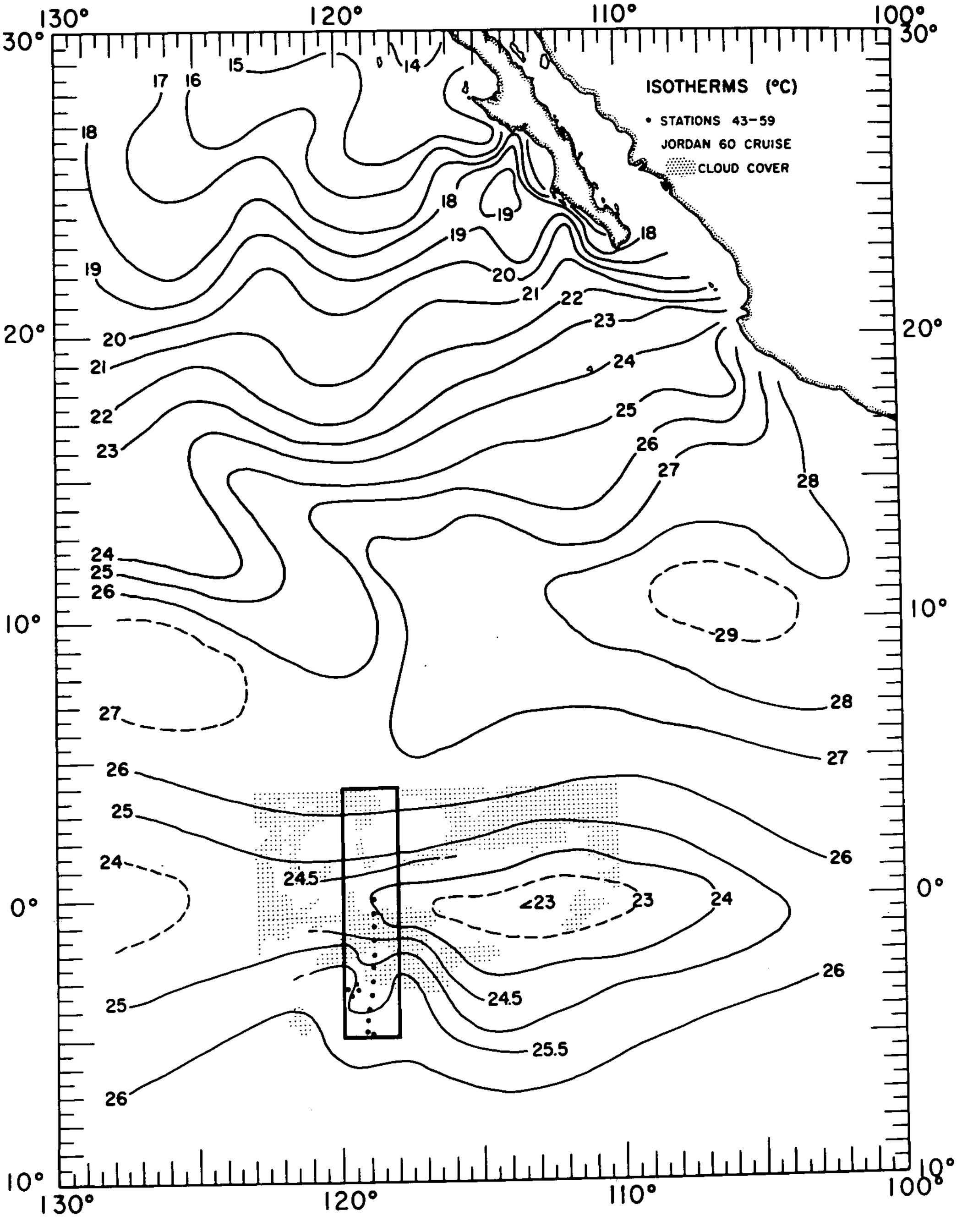

Figure 2. Sea surface temperature (in °C) based on data from R/V JORDAN and other vessels in the ETP for the period March 10-12, 1971. Note that cloud boundaries have been added in the transequatorial area to indicate those areas causing additional attenuation of infrared radiation. The enclosed area (4°N - 5°S) corresponds to the area shown in figure 1a-b.

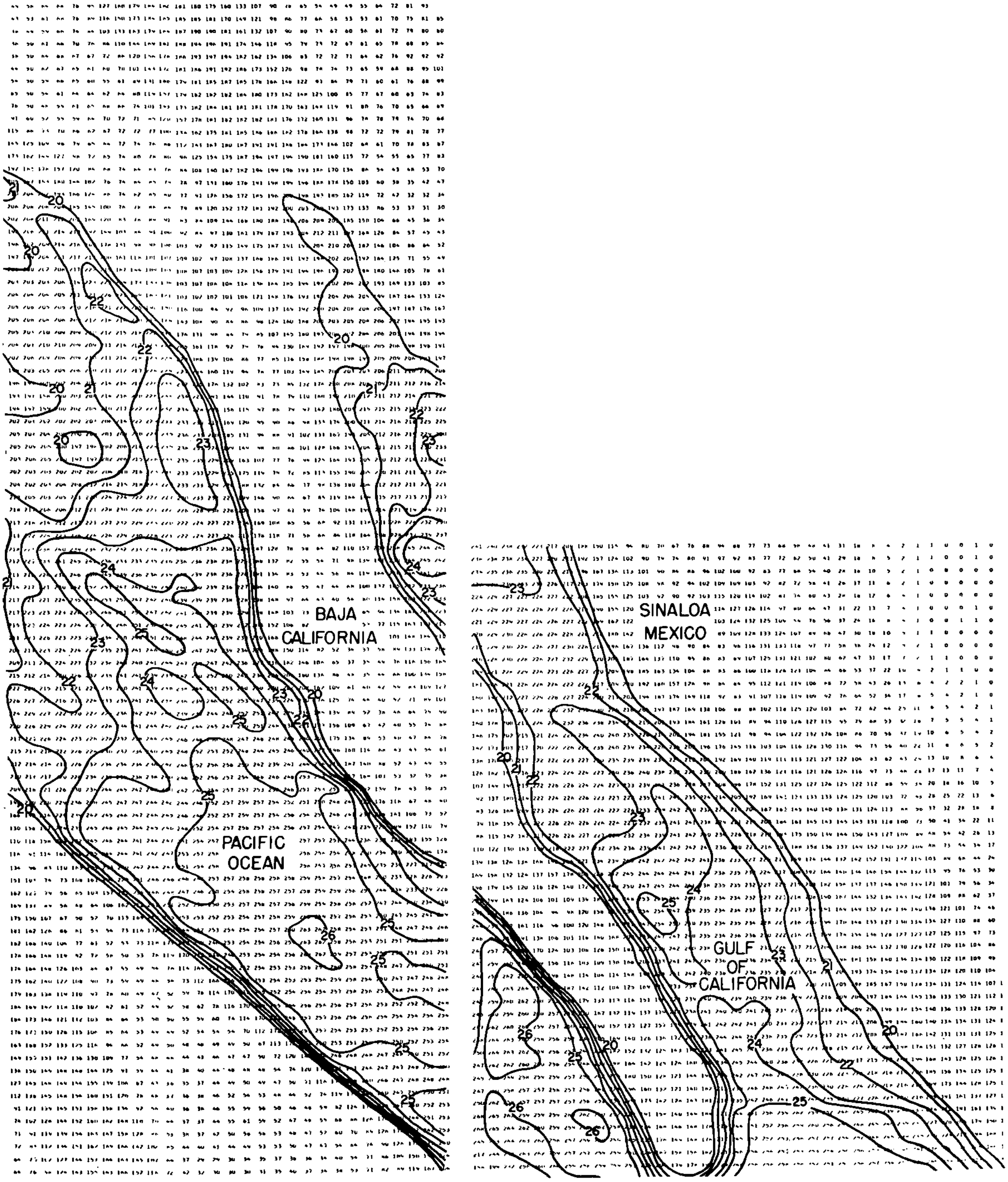

Figure 3. Digitization of DRIR information by photo-scanning and subsequent conversion to temperature (in °C) using a least-squares relation.

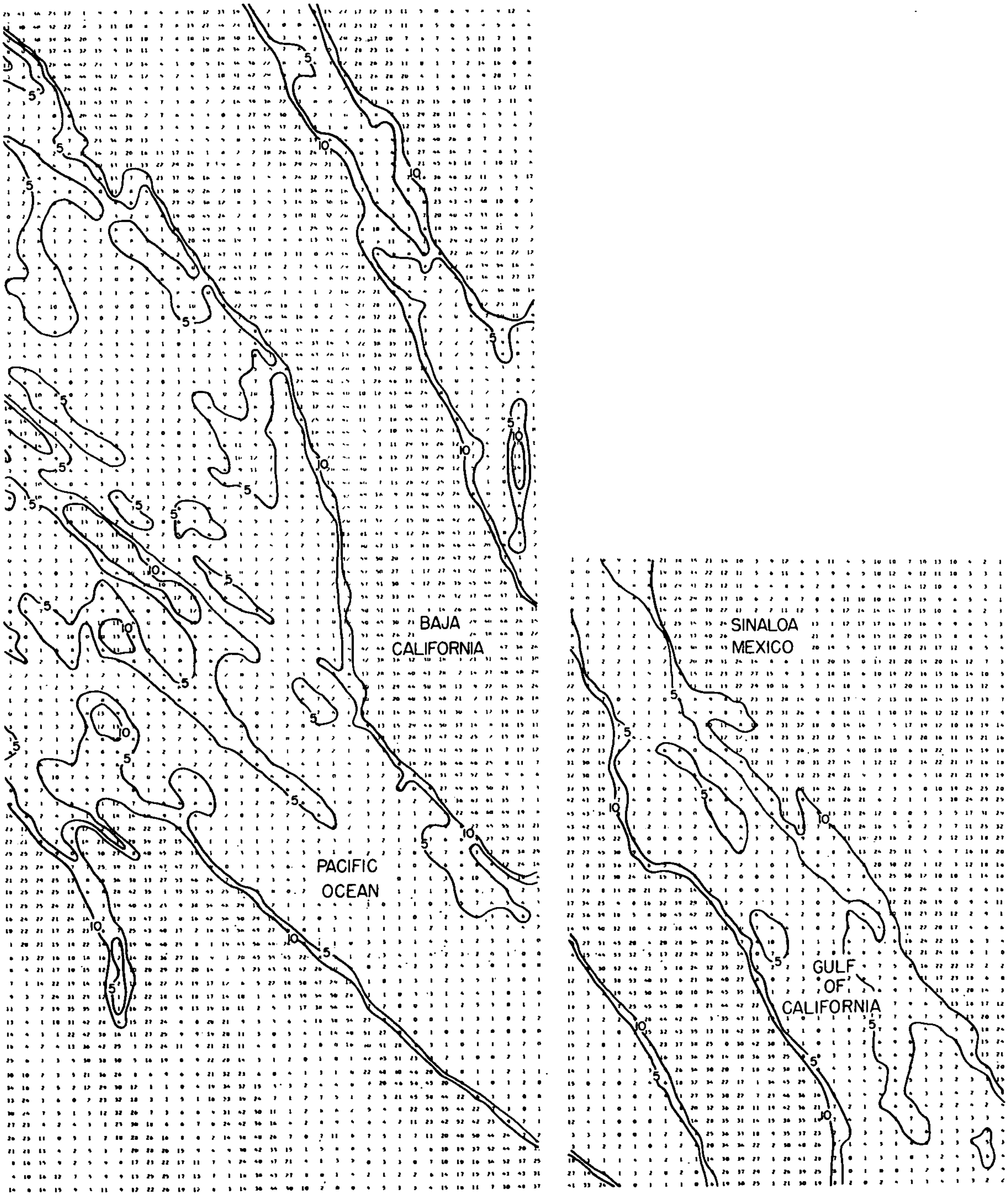

Figure 4. Frontal enhancement of sea surface temperature (in °C, times 0.1); same data sources as for figure 3.

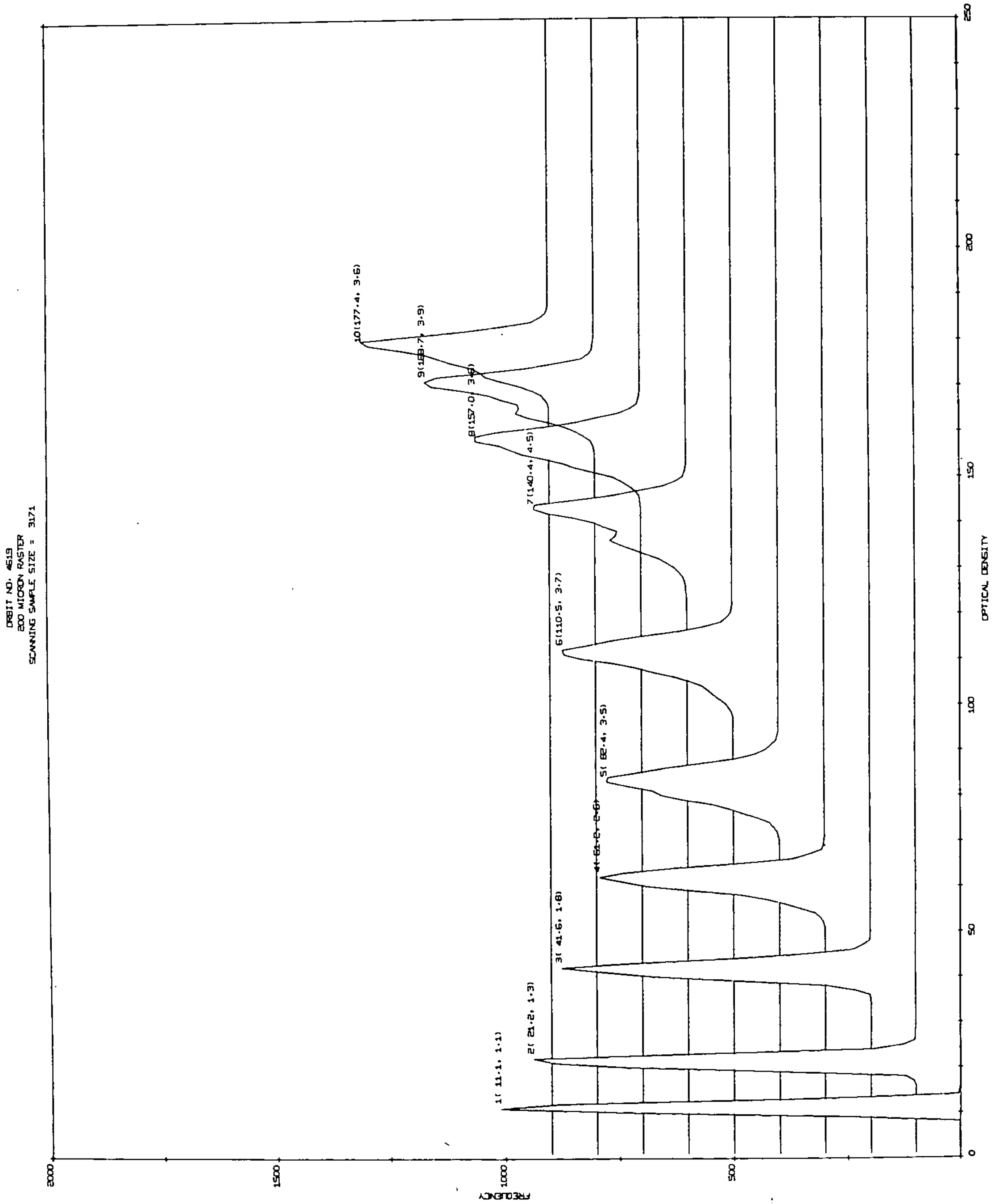

Figure 5. Frequency histogram of individual steps of 10-step reference wedge. Wedge was scanned by a densitometer using a 200-micron raster. Numbers in brackets are the means and standard deviations for each step, respectively. Number of counts per step is given at the top of the figure.