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DISTRIBUTION OF SEA SURFACE TEMPERATURE IN THE AREA OF THE ANGRA DOS REIS POWER PLANT: FINAL REPORT FOR MISSIONS 1, 2 AND 3

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12. Revised by

José Luis Stech

9. Authorship *Merritt R. Stevenson*
Héctor M. Inostroza V.
Carlos A. Steffen

Responsible author Merritt R. Stevenson

13. Authorized by

Nelson de Jesus Parada
Director General

14. Abstract/Notes *This Final Report presents results from a cooperative study between CNPq/INPE and CNEN, to monitor spatial and temporal variations of sea surface temperature (SST) in the vicinity of the Angra dos Reis power plant. This report discusses results from the Angra-01, Angra-02 and Angra--03 Missions, with SST's derived from a boat, an aircraft and satellites, surface currents and turbulent mixing in the upper 1-2 m of water. Temperature data from the GOES-5 satellite were used to provide coverage for the Angra area. These SST's possess a thermal resolution of 0.5°C and a spatial resolution of about 10 x 5 km for the study area. Temperature data were also obtained from the polar orbiting satellite NOAA-7. Data from NOAA-7 possess a spatial resolution as small as 1 x 1 km. These uncalibrated data were subsequently converted into SST's with a thermal resolution of 0.3°C. Surface currents were estimated from displacements of dye and oil patches, placed in the water at the start of the experiments. During Angra-02, the currents were to the southwest at 5.5 cm/sec and to the southwest to southeast at 2.5 - 15.4 cm/sec in Itaorna and Piraquara de Fora Bays, respectively. The dye patches were also used to estimate turbulent mixing. For Itaorna Bay $K = 8.6 \times 10^3$ cm^2/sec, for Piraquara K was $4.4 - 7.8 \times 10^3$ cm^2/sec. A comparison was also made between SST anomalies (ΔT's) obtained during a testing cycle of the power plant and a hydrodynamic model used for determination of areal coverage of these anomalies.*

15. Remarks

ACKNOWLEDGMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

This Final Report reviews the most important activities and summarizes the results of a series of three field missions. The objective was to measure sea surface temperature in the area of the Angra dos Reis power plant, using aircraft, boats and satellites. PROJECT ANGRA is a research project undertaken by CNPq/INPE in collaboration with the Comissão Nacional de Energia Nuclear (CNEN), and FURNAS, CENTRAIS ELÉTRICAS. The Angra-01 Mission was made on December 19, 1980; the Angra-02 Mission was completed during the interval of 6-22 October, 1981; and the Angra-03 Mission was done during the period of 22-25 March, 1983.

As originally conceived, PROJECT ANGRA was to be executed in three phases. The first phase was to determine surface temperature conditions before the power plant began its operations. The second phase was to begin when the power plant (Figure 1) began its testing cycles. This phase is characterized by pulses of heated water entering Piraquara de Fora Bay, as the power plant was sequentially turned on and off. The third phase of PROJECT ANGRA was to occur when the power plant was in continuous operation for a period of some days, at a level of power of between 50% and 100%, that is, when the power plant was in normal or commercial operation. The first two phases of the project were completed and are represented in this Final Report. The conclusions contained in this report are based then on the first two phases of the project. A new contract between CNPq/INPE and CNEN has been approved which will enable INPE scientists to complete the third and final phase of research, as originally planned. The results from this final phase will be presented in mission reports and a final report, after completion of the corresponding field missions.

During each mission an attempt was made to obtain the needed field data from three platforms: that is, from an aircraft, a boat and from two types of meteorological satellites. Because the weather is often cloudy over the Angra area, several days must be allowed to complete a mission, in order to allow for at least one good cloud-free day. Even so, it is often difficult to determine which day will be cloud-free; a necessary condition for the aircraft flights and data acquisition from the satellites. Although a several day period was allowed for each mission, weather conditions can get worse during the time of the mission so that the mission must be postponed to a later date (for example, during Angra-02 Mission), or the aircraft flight aborted, as was done during the Angra-03 Mission. In spite of the various problems with weather, it was possible to obtain a considerable amount of material from the three missions. These data are discussed and the methods used to obtain them are detailed in several reports: Stevenson et al (1982) and Stevenson et al. (1983a,b and c).

The same boat was used to provide direct surface measurements for the three missions. Data from the Advanced Very High Resolution Radiometer (AVHRR) system aboard the polar orbiting satellites NOAA-6 and NOAA-7 were requested for the three missions. Also, data were obtained from the Visible and Infrared Spin Scan Radiometer (VISSR) aboard the SMS-2/GOES-5 satellite. The best of these satellite images are discussed in this report. Although rhodamine-B, a fluorescent dye was dispersed in the two bays adjacent to the Angra power plant during the second and third missions, the results of these sub-experiments were reserved for this final report.

Prior to each mission, project scientists used the UAI-1, a real time monitoring system for the SMS-2/GOES-5 satellite. Because a digital image can be received and displayed on a video screen every half-hour, the UAI system was found to be very useful in following the day-to-day changes in weather over the Angra area.

Because PROJECT ANGRA used different platforms to make the observations, it is informative to provide a brief look at the different methods used to obtain the measurements. The boat "Boa Esperança", provided by FURNAS, was used in the three missions. The high speed capability of the boat (Figure 2) was considered necessary in order to be compatible with the rapid changes required in time and position between the flightlines of the aircraft.

Fig. 1 - Aerial view of the Angra dos Reis Nuclear Power Plant Facility, taken on 22 October 1981, during the Angra-02 Mission (Frame Number 4550).

Fig. 2 - The "Boa Esperança" coming up to the dock in Piraquara de Fora Bay.

The boat was used in each mission.

During each mission, the boat moved along 18 lines, corresponding to the 18 predetermined flightlines of the aircraft. Boat navigation was accomplished by visual sightings of prominent landpoints, using a specially modified sextant (Figure 3) and referencing to a prepared table of bearings. After each mission (for example Angra-01 and Angra-02), the actual position of the boat at each station was accurately determined from aerial photographa taken from the aircraft during each overflight.

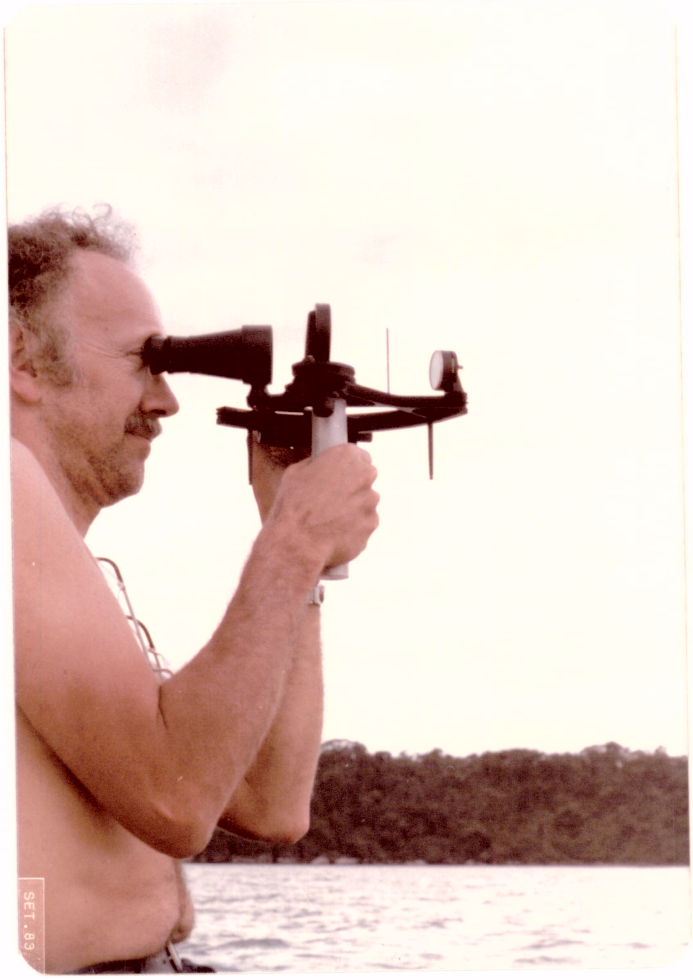


Fig. 3 - Determination of a hydrographic station position using a modified sextant during an Angra Mission.

During each Angra Mission, various measurements were made. Surface water temperatures were obtained from readings of a precision mercurial thermometer (Figure 4).

Fig. 4 - Measurement of surface water temperature using a calibrated thermometer.

Note that a surface water sample is first obtained with bucket and then temperature is determined.

Surface wind measurements were also made. During the Angra-01 and Angra-02 Missions, a handheld anemometer was used to determine wind speed. Wind direction was determined from comparison with the bow of the boat, referenced to a magnetic compass. During the Angra-03 Mission, a more accurate anemometer was used to determine wind speed and direction, relative to the boat (Figure 5) and its compass. Because atmospheric water vapor influences sea surface temperature measurements made from aircraft and satellites, a psychrometer was used during each mission to obtain estimates of surface relative humidity (Figure 6)

Fig. 5 - A handheld anemometer being used at a hydrographic station during the Angra-03 Mission.

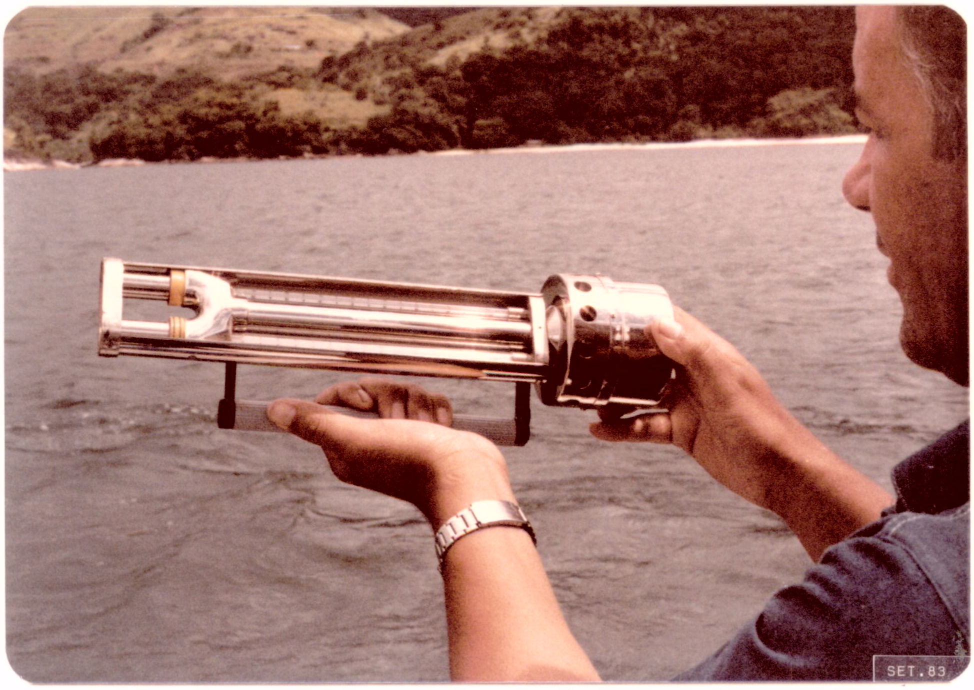


Fig. 6 - Spring motor-driven psychrometer being used to obtain dry and wet bulb temperatures for estimation of relative humidity.

Rhodamine-B dye solutions were used in both Itaorna and Piraquara de Fora Bays (Stevenson et al. 1983b and 1983c). At the time and location of dispersal, the dye filled balloons were gently placed into the water after which they were broken (Figure 7). The initial size of a dye patch was taken to be about 1 m^2.

Fig. 7 - Photograph taken at the instant a dye filled balloon is broken using a pellet gun.

Distance from balloon to boat is about 3 m.

The dispersal point of the dye patch shown in Figure 7 is in Piraquara de Fora Bay. Nearby is the discharge barrier (Figure 8), the location of the output of the cooling water used by the power plant.

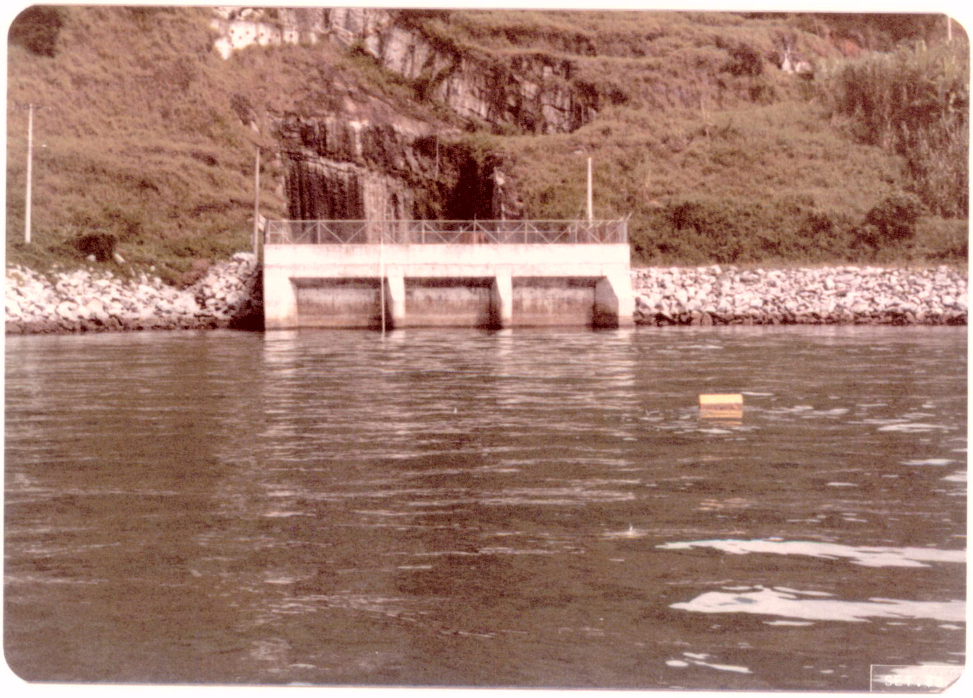


Fig. 8 - The discharge barrier seen here is the point of entry of the heated water into Piraquara de Fora Bay.

Piraquara de Fora is a small bay, measuring about 3 km^2 in area. As previously noted, weather conditions varied considerably from day-to-day during the three missions. During the Angra-03 Mission, for example, only the boat and satellites collected data. Because the sky was cloudy at the start of the operation, it was decided to make surface measurements, while waiting for the weather to improve. As a result, surface data were obtained on 22, 23, 24 and 25 March 1983. The power plant was making tests and operating at about 25% of capacity, so heated water was being discharged into Piraquara de Fora Bay (Figure 9). The weather was very good on 25 March as seen from Figure 9 and the best data were collected by boat and satellite on that day.

Fig. 9 - View overlooking Piraquara de Fora Bay about one hour after completion of the Angra-03 Mission.

INPE's twin-engine, propjet aircraft (Figure 10) was scheduled for use in the three missions. Normally, the aircraft was flown at an altitude of about 915 m over the Angra area. At the conclusion of the predetermined flightlines, the Bandeirante made an aerial sounding to obtain photographs and sea surface and air temperatures at progressively higher altitudes. For the Angra Missions, the aircraft carried a camera (RC-10 with 23 x 23 cm film size), a Barnes precision radiation thermometer (PRT-5) and a prototype instrument for measuring and recording dry and wet bulb air temperatures.

Fig. 10 - INPE aircraft used to obtain data during the Angra-01 and Angra-02 Missions.

Aerial soundings were made to 6100 m altitude to collect temperature data.

The RC-10 Metric Camera (Figure 11) contributed to the project in various ways. Initially, the high quality film images were used after the Angra-01 and Angra-02 Missions, to determine aircraft and boat positions to a high degree of accuracy. Film frames were also used to study the dye and oil patches in the two bays, to extract information on water motion and turbulent mixing in the upper 1-2m of the water column. Photographs were also taken with a matched set of 4-70mm Hasselblad cameras (Figure 12) during the Angra-01 and Angra-02 Missions, to study spectral characteristics of the oil patches, as part of a separate study.

Fig. 11 - Phototechnician making final adjustments on RC-10 Camera prior to photographing a target.

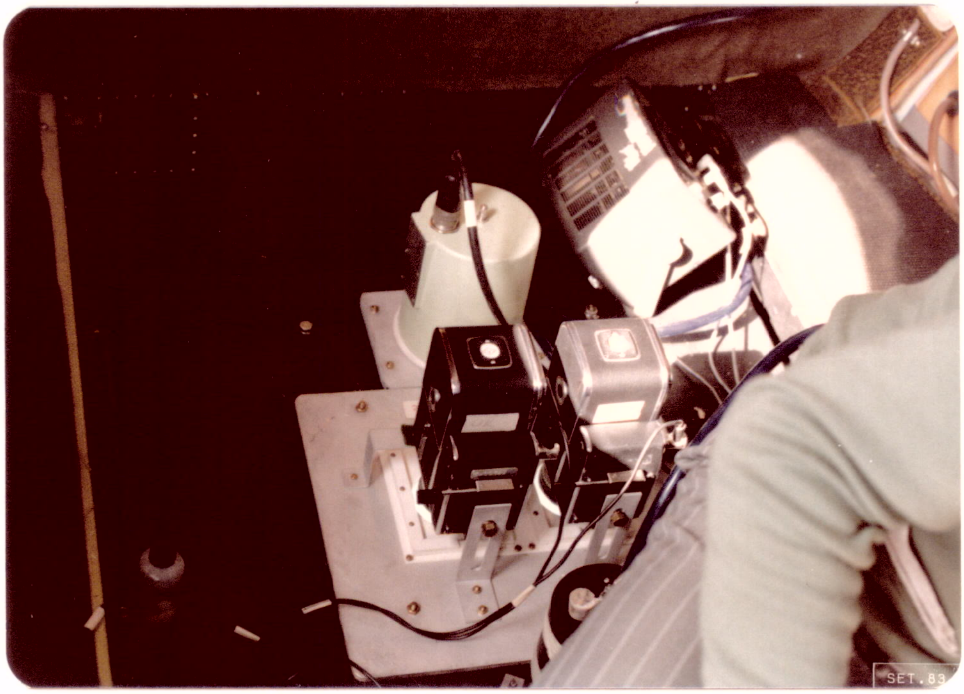


Fig. 12 - View of Hasselblad cameras (in foreground) used to study spectral characteristics of oil patches.

Cylindrical shape behind cameras is the sensor head of the Barnes PRT-5 instrument used to measure sea surface temperatures.

Sea surface temperatures (SST's) were measured with a Barnes PRT-5 instrument and recorded continuously on a 2-channel stripchart recorder. An observer made notations about landpoints beneath the aircraft and the corresponding times at frequent intervals (Figure 13).

As previously noted, the RC-10 Camera was used to observe the Rhodamine dye and oil patches (Figures 14 and 15). Figure 14 was taken at the start of the Angra-02 Mission. A dye patch (No. 3) appears on the left side of the photographs as a reddish color. The discharge barrier is seen in the upper center of the photograph and may be compared with Figure 8. The boats, visible in the center of the figure, are typically 3m in width.

Fig. 13 - Observer marking the time of passage over a landpoint seen by the technician using the RC-10 Camera.

The dispersals and analyses of two small quantities of oil in the Bays were not considered a part of Project ANGRA. The photographs from the RC-10 Camera, however, were found to be very useful in locating and tracking the movements of the oil patches (Figure 15). These data were combined with similar data from the dye patches, to infer circulation of the surface water of Piraquara de Fora Bay.

Because most of the field measurements have already been discussed in earlier Project ANGRA data and technical reports, the rest of this report will consider measurements and results from SST's derived from satellite data. Water circulation and turbulent mixing in the upper 1-2m will also be estimated, based on displacements and dispersals of dye and oil patches. Surface temperature anomalies, determined from Angra-03 data and thermal anomalies, derived from a hydrodynamic model, will be compared in the Results Section.

Fig. 14 - View of the discharge area in Piraquara de Fora Bay during the Angra-02 Mission.

Flight altitude was about 915 m.

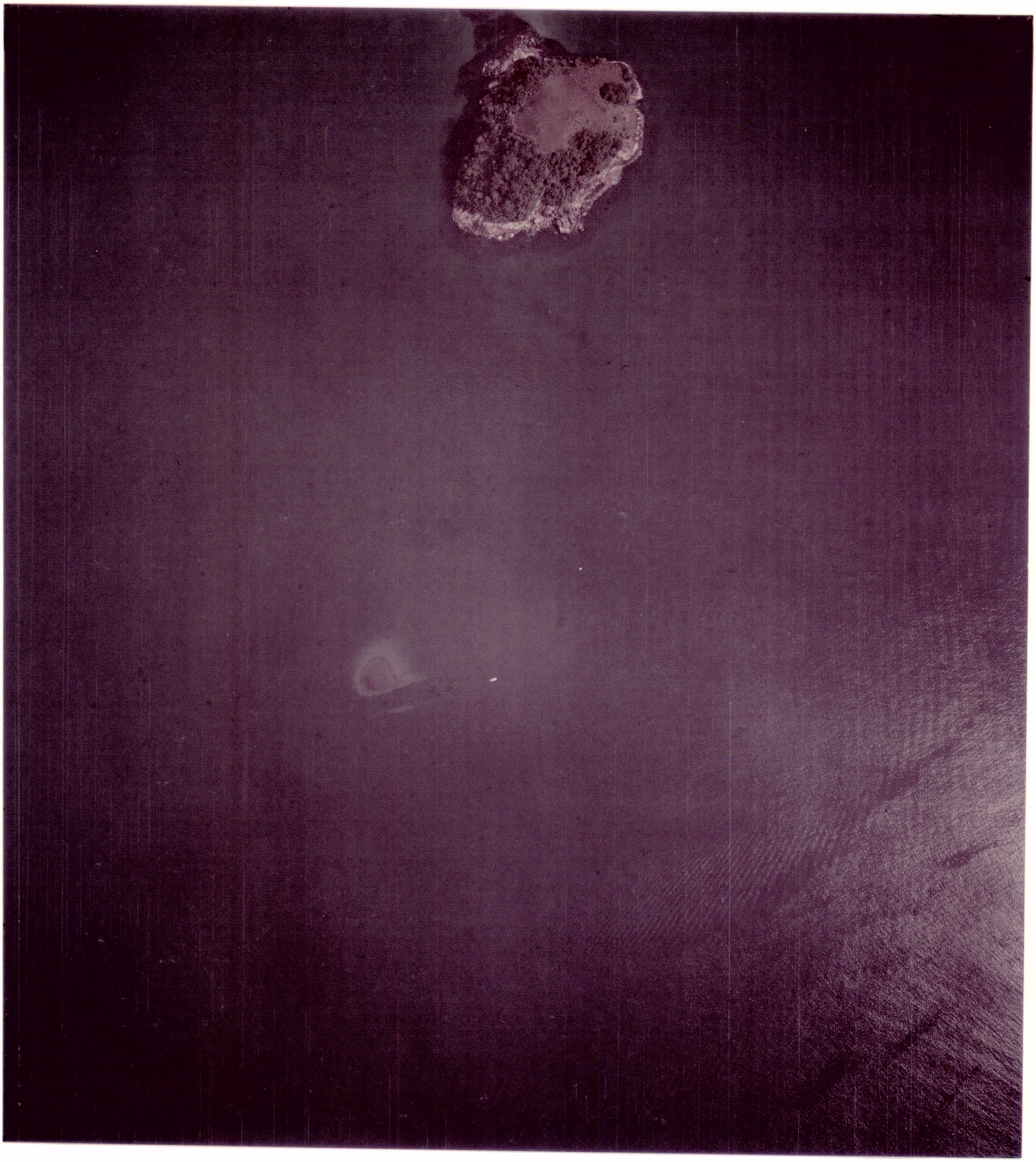


Fig. 15 - View of oil patch No. 2, near the center of the photograph, in Piraquara de Fora Bay.

The "Boa Esperança" is a short distance to the right of the oil patch, at a hydrographic station.

2. DATA AND METHODOLOGY

In this Section, only material related to satellite imagery and data related to the Rhodamine-B dye and oil patches will be included. Detailed discussion of all other measurements has been provided in previously published Data and Technical Reports of Project ANGRA.

2.1 - THERMAL INFRARED (IR) IMAGES FROM THE GOES-5 SATELLITE

IR images were obtained for the area of the Angra dos Reis Power Plant during both Angra-02 and Angra-03 Missions. A bit-shift problem was present in the new software used to record the imagery for Angra-03, so discussion of GOES data in this report will be limited to the image obtained on 22 October 1981, during the Angra-02 Mission.

In practice, the magnetic tape was first read into the General Electric Image-100 System located at INPE, São José dos Campos. The IR data is read into one of the display channels and the accompanying geographic grid is read into a second channel. Several small training areas were then selected and these areas tested for data quality. A histogram listing showed the data to be usable. A similar test was then made over the area of interest to obtain the interval of gray levels (or digital counts) present. As part of this process, temperatures lying outside a selected range; $6.5^{o}C<T>16.5^{o}C$, were rejected. The temperature range bounded by these limits was then separated into 7 thermal intervals, or themes. An eighth theme was reserved for the geographic grid and identification of the different themes. A different color was then assigned to each theme and the resulting false color temperature map shown in Figure 16 was produced. In addition to the color map, an enlarged digital map was constructed using the computer line printer. To assist in the construction and interpretation of the hardcopy output, separate listings of the geographic grid and the thematic map were produced and are shown in Figures 17 and 18. A temperature scale has been included in the upper lefthand margin which relates temperature to digital number and to the thematic symbols used in the map. The areal extent of individual pixels or the distance from one scanline to the adjacent scanline is readily seen in Figure 17. The area covered by a single scanline and the effective width of a single pixel is shown in the Angra dos Reis area by the small scale grid over that area. The individual IR pixels have a rectangular field of view, of example 8 km x 4 km in a north/south and east/west direction at the equator, and beneath the GOES satellite. Because of this geometry, only alternate pixels are actually included in this printout, in order to retain an aspect ratio of approximately 1:1.

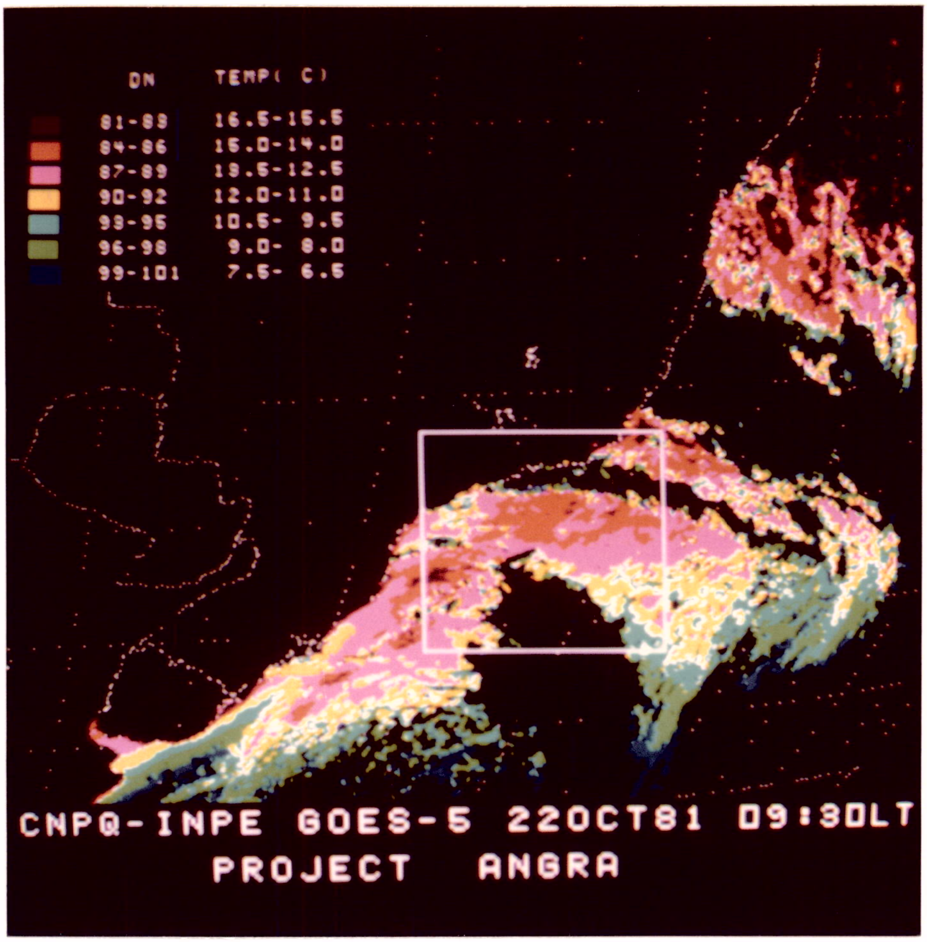
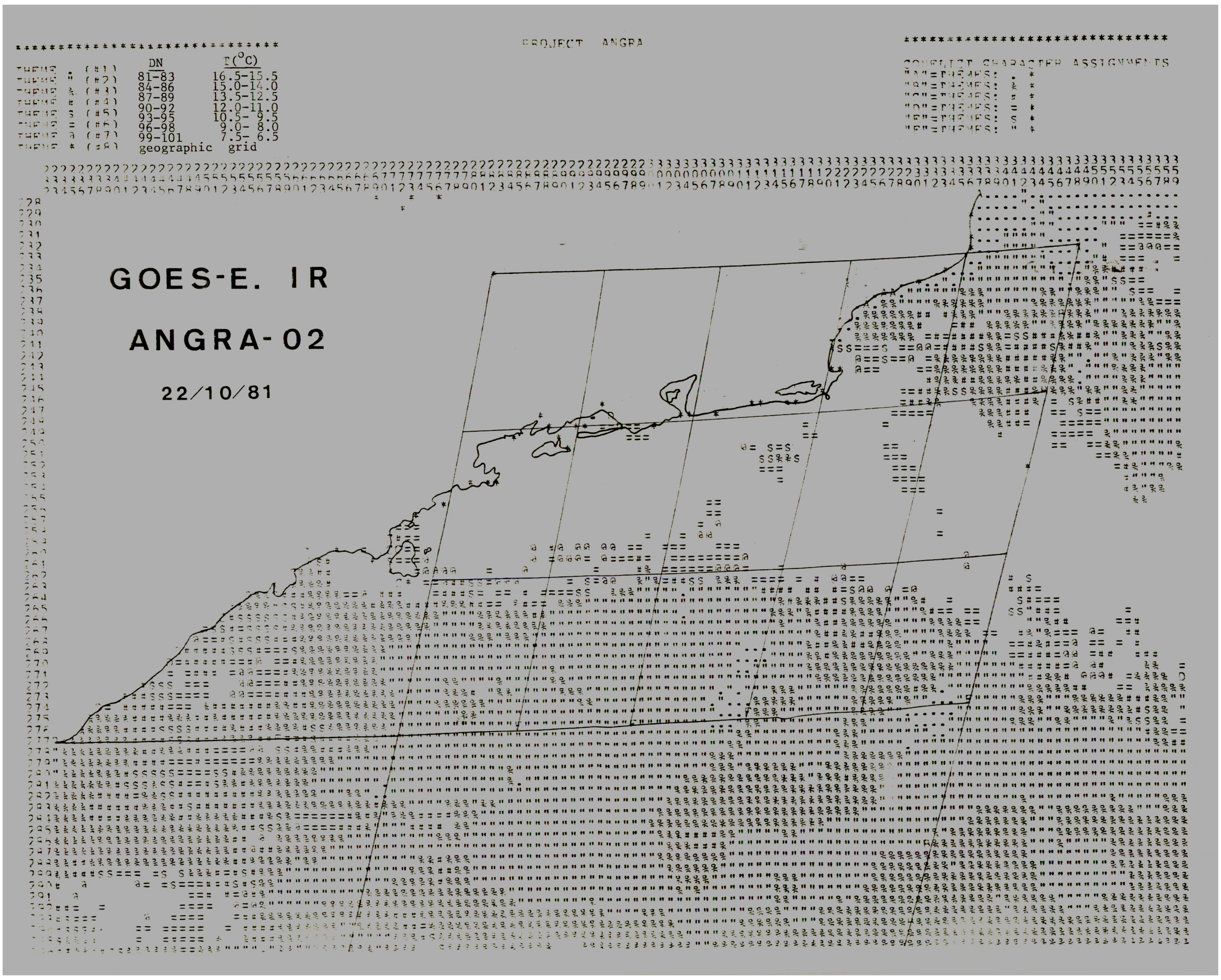


Fig. 16 - False color display of sea surface temperature (in ^{o}C) for the Angra-02 Mission.

Fig. 17 - Digital printout of Brazilian coastline and geographic grid for 22 October, 1981.

Fig. 18 - Digital printout of sea surface temperature for 22 October, 1981.


PROJECT ANGRA
THEME . (#1) 81-83 16.5-15.5
THEME " (#2) 84-86 15.0-14.0
THEME % (#3) 87-89 13.5-12.5
THEME # (#4) 90-92 12.0-11.0
THEME S (#5) 93-95 10.5- 9.5
THEME = (#6) 96-98 9.0- 8.0
THEME @ (#7) 99-101 7.5- 6.5
THEME * (#8) geographic grid
DN
T(°C)
CONFLICT CHARACTER ASSIGNMENTS
"A"=THEMES: . *
"B"=THEMES: % *
"C"=THEMES: # *
"D"=THEMES: = *
"E"=THEMES: S *
"F"=THEMES: " *
GOES-E. IR
ANGRA-02
22/10/81

2.2 - IMAGES FROM THE NOAA-7 SATELLITE

A two channel digital image over the Angra study area was successfully obtained on 25 March, 1983 during the Angra-03 Mission. The data from the visible channel (Ch 1) of the Advanced Very High Resolution Radiometer (AVHRR) was read into channel 1 of the I-100 System (Figure 19) and the thermal IR data (Ch 4 of the AVHRR System) into channel 2 (Figure 20). No geographic grid, similar to the GOES data, is transmitted with the AVHRR image. Because the visible channel data represent an excellent opportunity to screen out the clouds present in the field of view, 1 or more training areas were first selected and tested to determine the digital level corresponding to the unobstructed ocean surface. An example of such a histogram distribution for the visible channel and the corresponding IR channel is shown in Figure 21. Note that there are 140 counts (71% of the test area) with a count of 15. Because the unobstructed surface of the ocean has a low albedo (small digital dount), it is obvious that pixels prossessing digital counts larger than,say 16, represent a view partially contaminated by clouds and or land. For the AVHRR image of 25 March, a critical count of 16 was adopted and considered to represent the limit of unobstructed water. In processing this image, all digital counts greater than 16 were alarmed. The visual array of data, thus modified, was then mapped into the IR data array. Those IR pixels associated with the alarmed pixels were not used (not assigned a theme). The resulting enhanced false color map is shown in Figure 22.

Because the AVHRR IR data are not calibrated and directly convertible into temperatures like the GOES data, it is necessary to obtain reference SST temperatures from independent field data. The method used herein was to match selected SST's obtained from ships in the area, to spatially corresponding IR pixels. Three data pairs were available and these were used to obtain a regression curve. The resulting equation in turn was used to obtain the temperature scale shown in the upper lefthand margin of Figure 23. The grid included in this high resolution digital map was constructed from intercomparison of several maps of the area, with prominent features in the AVHRR data field. The three conventional temperature measurements, used to calibrate the AVHRR data, are seen in the figure as small circles: two circles south and east of Cabo Frio and the third circle near the coast and north of Ilha Grande.

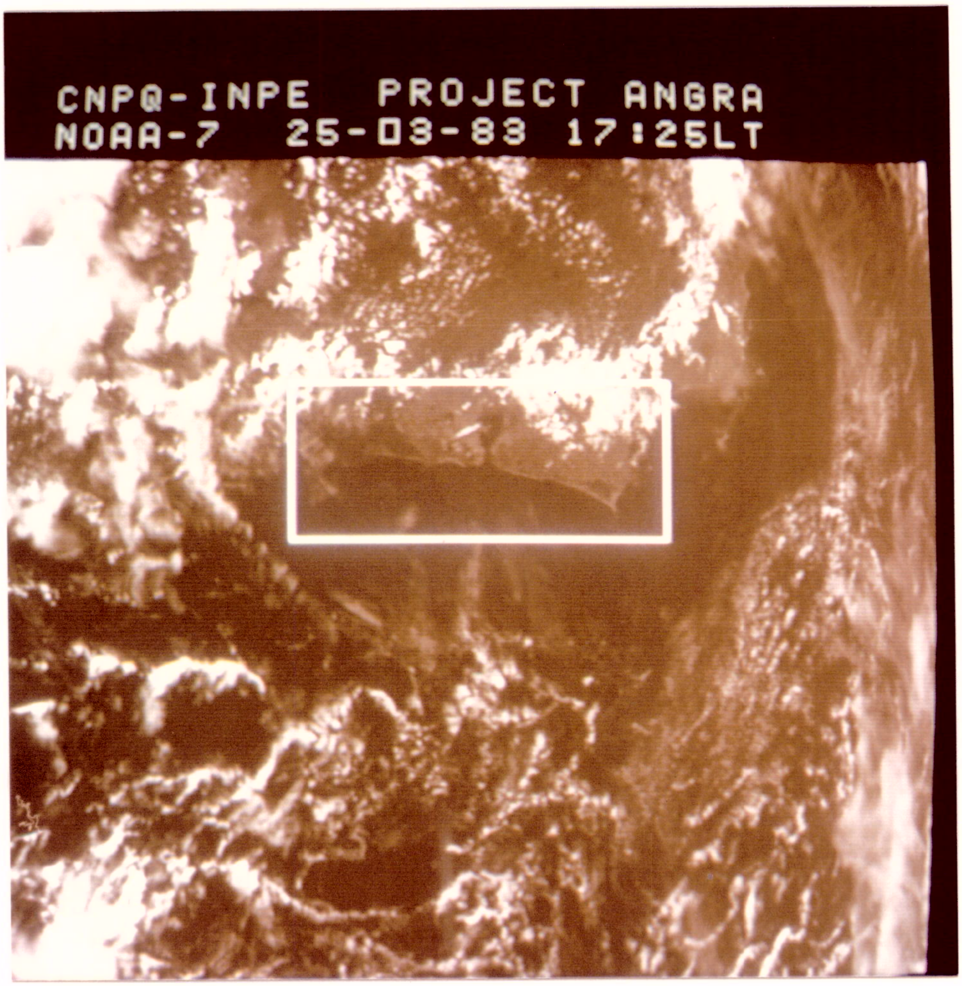


Fig. 19 - False color display of the visible channel of an AVHRR image for the Angra-03 Mission.

The rectangular box includes the Angra dos Reis area and represents the area of Figure 23.

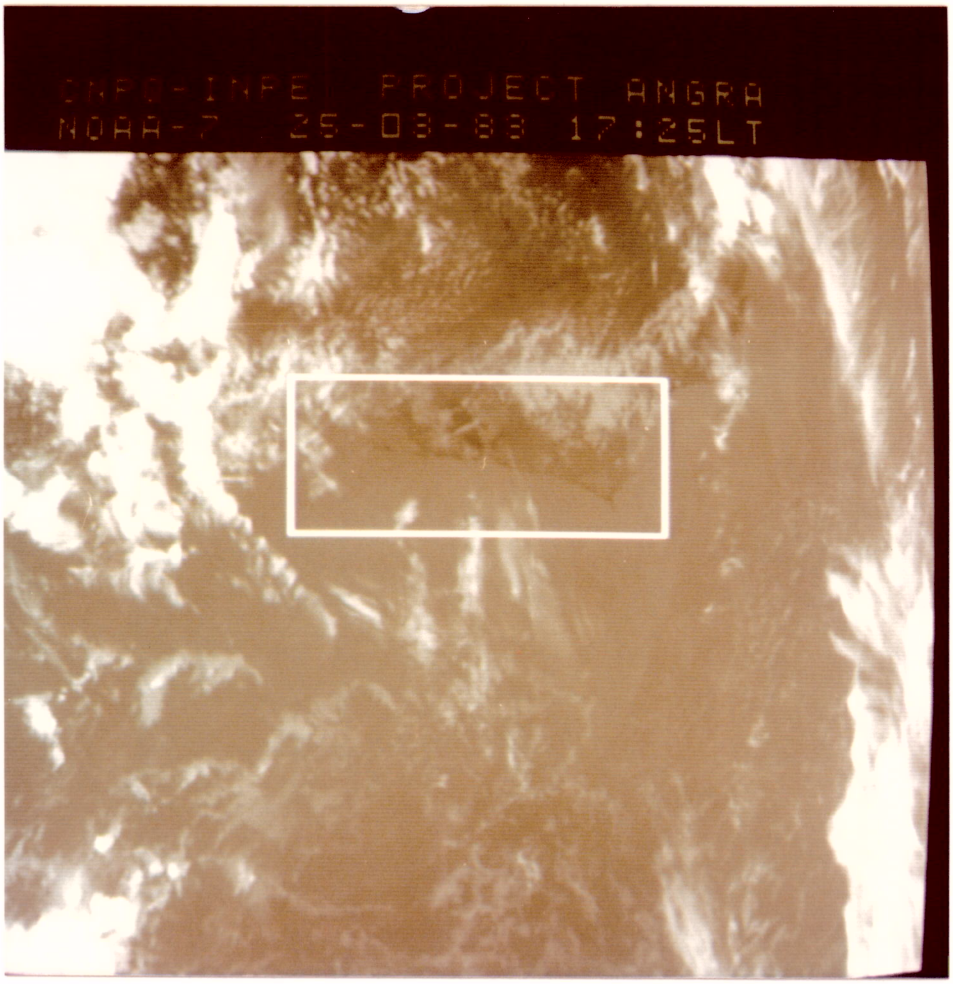


Fig. 20 - False color display of the thermal infrared channel of an AVHRR image for the Angra-03 Mission.

The rectangular box includes the Angra area and represents the area of Figure 23.

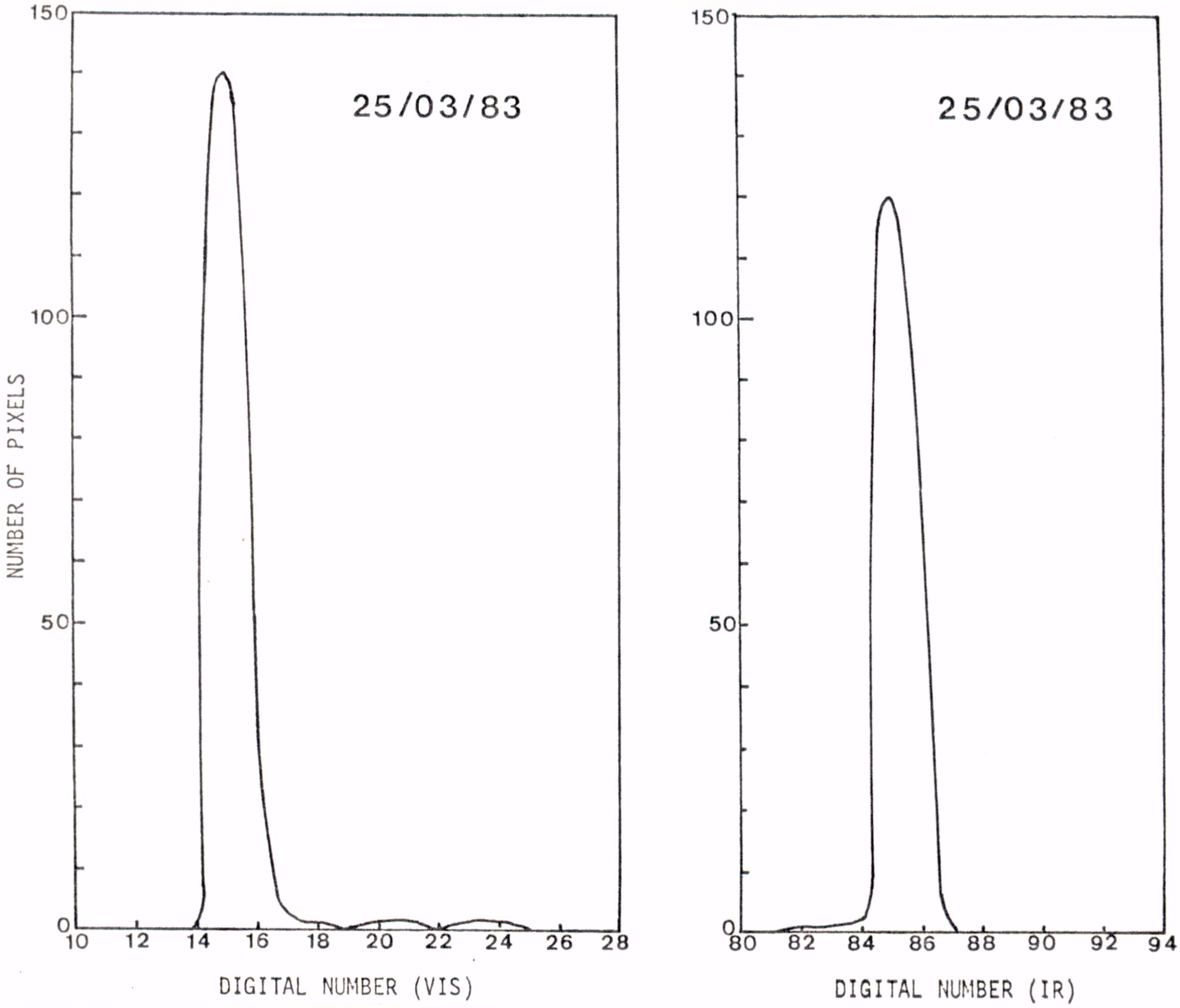


Fig. 21 - Histograms of a training area for the visible (No.1) and thermal infrared (No.4) channels of the NOAA-7 AVHRR.

Data from Figures 19 and 20, respectively.

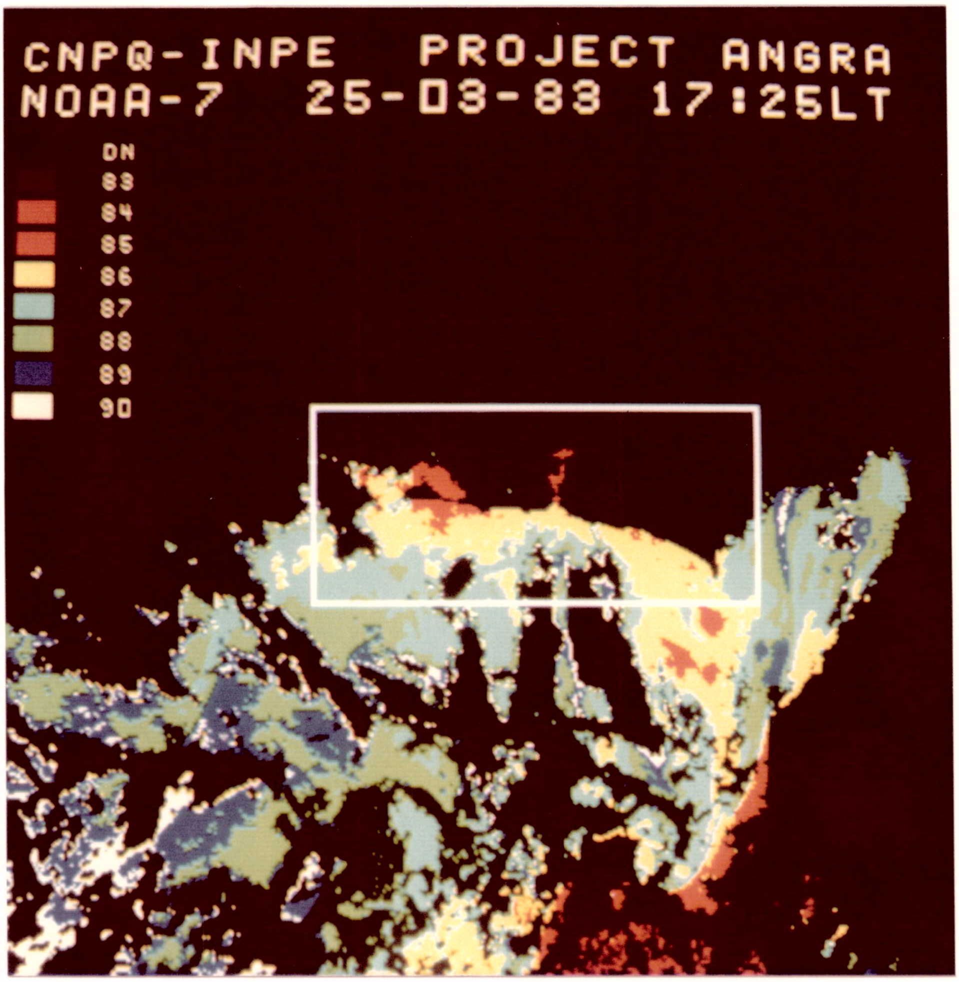
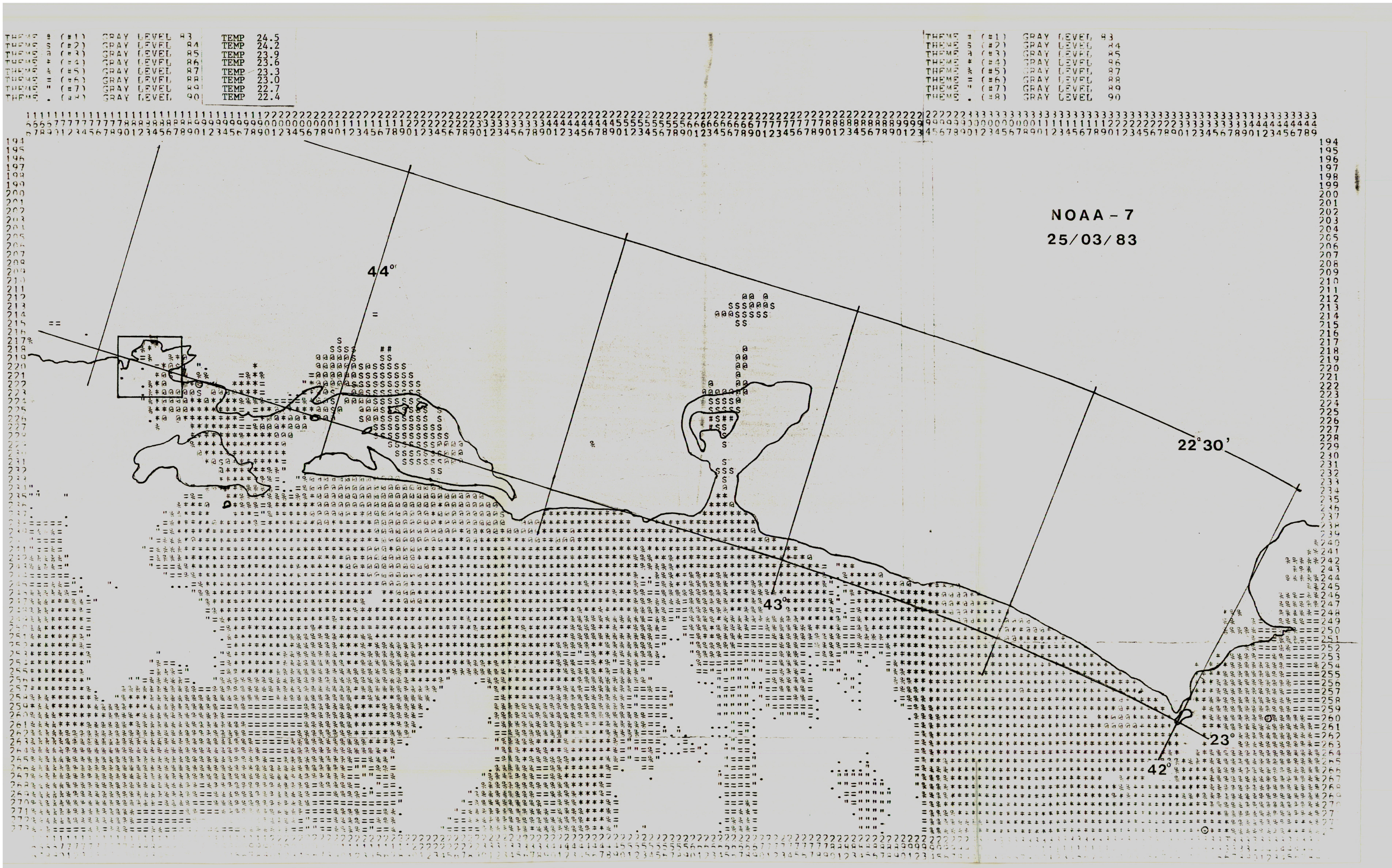


Fig. 22 - False color thematic map for the Angra dos Reis area based on the data in Figures 19 and 20.

Fig. 23 - Digital map of sea surface temperature for the Angra area during the Angra-03 Mission.



THEME # (#1) GRAY LEVEL 83 TEMP 24.5
THEME $ (#2) GRAY LEVEL 84 TEMP 24.2
THEME @ (#3) GRAY LEVEL 85 TEMP 23.9
THEME * (#4) GRAY LEVEL 86 TEMP 23.6
THEME & (#5) GRAY LEVEL 87 TEMP 23.3
THEME = (#6) GRAY LEVEL 88 TEMP 23.0
THEME " (#7) GRAY LEVEL 89 TEMP 22.7
THEME . (#8) GRAY LEVEL 90 TEMP 22.4
NOAA - 7
25/03/83
44°
43°
42°
22°30'
23°

2.3 - FILM IMAGES OF DYE AND OIL PATCHES

Rhodamine-B, a fluorescent dye commonly used to estimate advection and turbulence in the ocean, was used during the Angra-02 and 03 Missions. The inability of the aircraft to obtain film images during the third mission, however, limited our filmed images of the dye patches to the Angra-02 Mission. The basis for using aerial film images to obtain quantitative information about surface advection and turbulent mixing is discussed by Ichiye and Plutchak (1966) and Valerio (1981). A rhodamine/alcohol solution was dispersed at three locations: one patch at the entrance to Itaorna Bay and patches at the entrance and near the discharge barrier of Piraquara de Fora Bay. Two small oil dispersals were also made, one for each Bay. The dispersal in Piraquara de Fora was successful but the sample for Itaorna Bay was rapidly dispersed by strong local action of currents and wind.

Prior to the Angra-02 Mission, Rhodamine-B dye in powder form was carefully divided and weighed into three portions, each consisting of approximately 100 g of dye. Each portion was then dissolved in methanol and brought to a volume of 1 liter; the resulting specific gravity was 0.89 at $23^{o}C$. Shortly before the field work, each dye solution was in turn put into an Erlenmeyer flask and pumped into rubber balloons. The filled balloons were then placed into plastic buckets and the buckets sealed for the travel to Angra dos Reis. At the time of dye dispersal, the boat proceeded to each dispersal point and a filled balloon gently released into the water. After the boat moved away from the balloons a few meters, the balloons were quickly burst by a pellet from a pellet gun (Figure 7). The same dispersal method was used for the two oil dispersals.

The original plan for analysis of the film images of the dye and oil patches was to digitize the film image using the vidicon scanner, connected to the I-100 system. This method has the advantage of directly digitizing the filmed image, using 8 bit words for the gray levels of the film. Unfortunately, the vidicon tube of the scanner possessed electro-optical problems that resulted in nonuniform digitizing of the field of view, so this method was not used.

A much simpler alternative was to use a small optical comparator and to determine the areal extent and center of the patches. In this instance, the areal extent was limited by the threshold visibility of the edges of the dye patches as recorded on the film. The comparator contained a reticle (grid) with 0.5 x 0.5 mm divisions and an optical magnification of 4X. The centers of the individual patch images were visually estimated, and the areal extent of the patch image was determined by graphical integration. To estimate the reliability of the graphical integrations, several patches were integrated a second or third time. The fluctuations in computed areas varied from 0.3% to 3.8% of the computed areas, with the majority of estimates varying by $\leq$ 2%. Estimates of areas for the dye and oil patches are given in Table 1.

The centers of the patches were converted into geographical coordinates by plotting the positions of the dye on high resolution maps (Figures 24 and 25), on which a detailed coordinate system was drawn. With the optical comparator and the 23 cm x 23 cm aerial film, it was possible to readily resolve the position of an object to within about 3m or 0.1" of arc. The positions of the dye and oil patches are also given in Table 1.

It was possible to obtain estimates of mean velocity for the 3 dye patches and 1 oil patch, using the method of least squares. After the geographic positions of the centers of the patches were determined, the least squares method was used separately for the meridional and zonal displacements, with time. These components were then combined vectorially to obtain the mean velocity determinations shown in Table 2.

Fig. 24 - Locations of dye patch (No.1) determined from different film frames, in Itaorna Bay during the Angra-02 Mission.

The three numbered lines in the water represent the successive positions of a surface foam line.

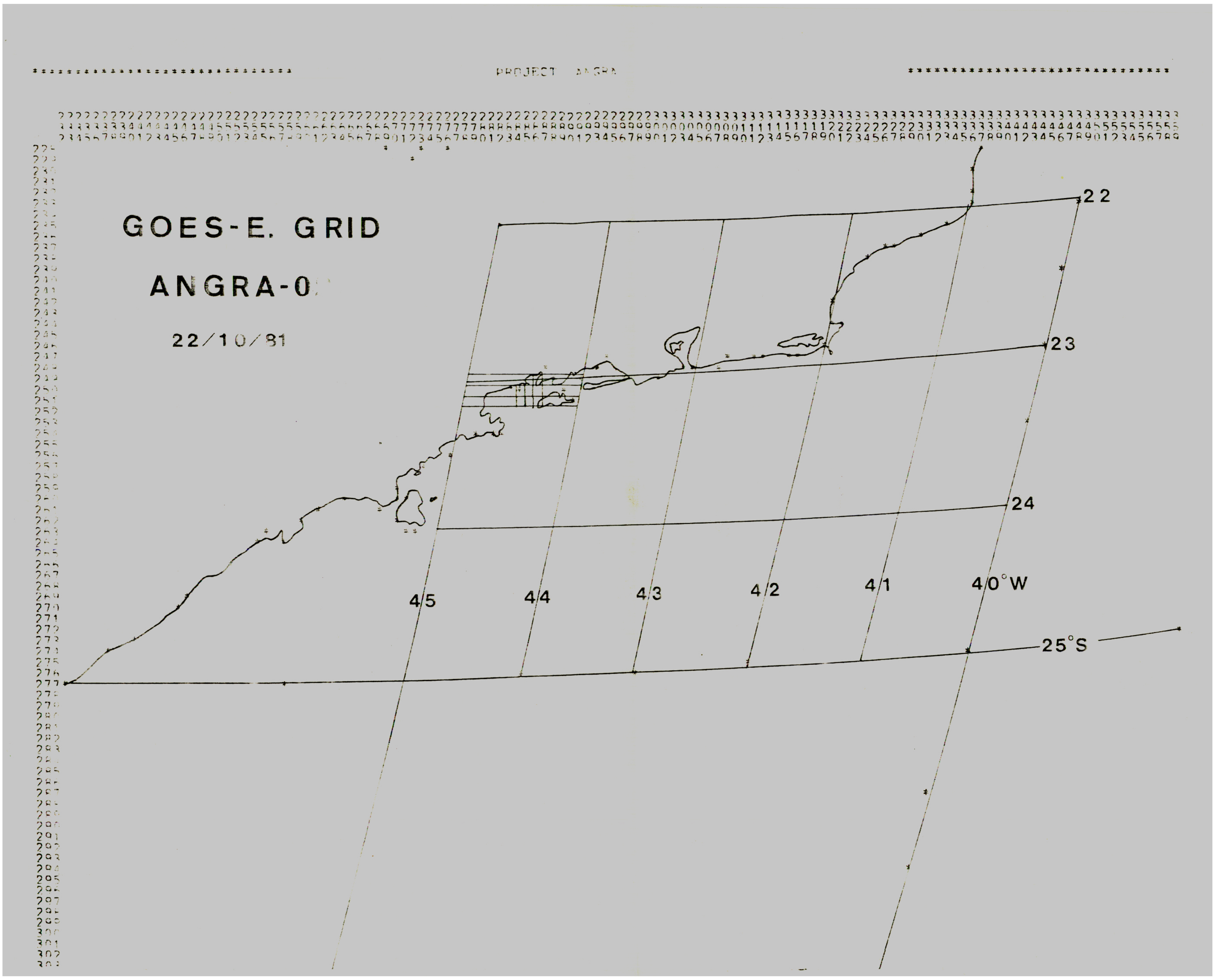

PROJECT ANGRA
GOES-E. GRID
ANGRA-0
22/10/81
22
23
24
25°S
45
44
43
42
41
40°W

Fig. 25 - Location of dye patches (Nos. 2 and 3) and oil patch (No.2) from different film frames, in Piraquara de Fora Bay, during the Angra-02 Mission.

The three numbered lines on the right side of the figure represent different positions of the same foam line.

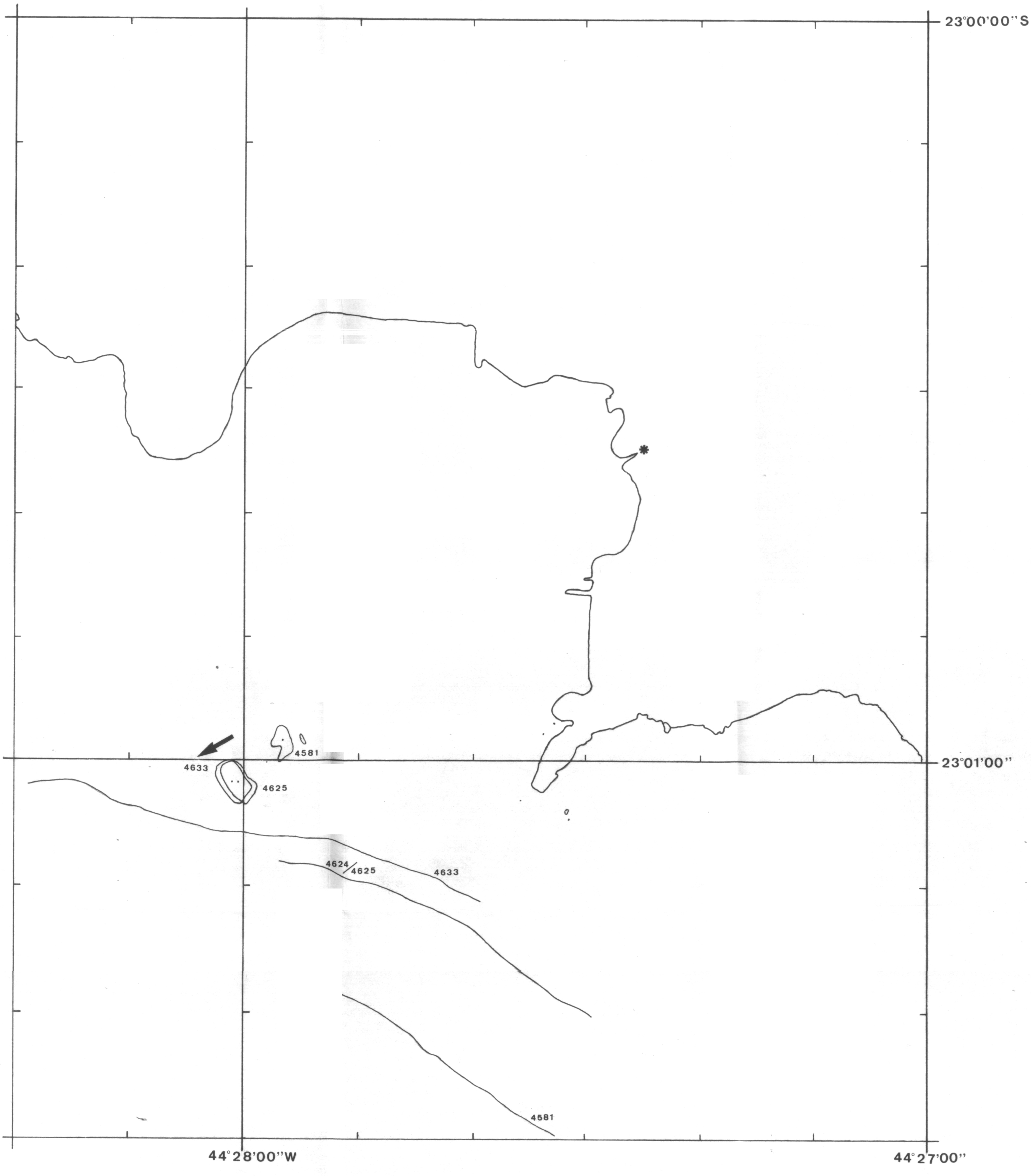

23°00'00"S
23°01'00"
44°28'00"W
44°27'00"
4581
4633
4625
4624
4625
4633
4581

TABLE 1

LOCATION, SIZE AND TIME OF OBSERVATION OF DYE AND OIL PATCHES

IMAGE NUMBER	PATCH NUMBER (DYE)	AREA m^2	LOCAL TIME HR:MIN:SEC	CENTER OF PATCH °	'	"S	°	'	"W
4581	01	2831	08:45:53	23	00	58.3	044	27	56.9
4625	01	5081	09:33:36	23	01	01.9	044	28	00.5
4633	01	5859	09:42:37	23	01	01.8	044	28	01.2
4553	02	1413	08:09:50	23	00	32.8	044	25	07.1
4575	02	2178	08:40:10	23	00	36.8	044	24	59.4
4610	02	7839	09:12:37	23	00	39.3	044	24	54.0
4551	03	1368	08:09:26	23	00	43.9	044	26	35.4
4555	03	1674	08:16:11	23	00	44.2	044	26	35.1
4556	03	1665	08:16:19	23	00	44.3	044	26	35.1
4561	03	1908	08:21:08	23	00	44.6	044	26	35.0
4580	03	2889	08:45:33	23	00	45.6	044	26	34.5
4586	03	3276	08:49:45	23	00	45.8	044	26	34.4
4593	03	3573	08:54:42	23	00	46.0	044	26	34.4
	(OIL)								
4552	02		08:09:37	23	00	24.1	044	25	52.7
4564	02		08:25:25	23	00	26.3	044	25	51.0
4568	02		08:30:40	23	00	26.2	044	25	49.6
4587	02		08:50:00	23	00	27.7	044	25	50.0
4592	02		08:55:26	23	00	28.6	044	25	49.6
4599	02		09:01:27	23	00	29.8	044	25	50.5

TABLE 2

DISPLACEMENT OF DYE AND OIL PATCHES

PATCH (NO.)	QUANTITY	LOCATION OF PATCH	MEAN VELOCITY SPEED (cm/s)	DIR (^{o}T)
Dye	Mass (g)			
01	90	Entrance to Itaorna Bay	3.2	239
02	92	Entrance to Piraquara de Fora Bay	15.4	118
03	95	Near Discharge Barrier in Piraquara de Fora Bay	2.5	156
OIL VOLUME (1)				
02	02	Middle of Piraquara de Fora Bay	5.5	159

3. RESULTS

3.1 - SEA SURFACE TEMPERATURES OBTAINED FROM SATELLITES

The temperatures, obtained from the GOES VISSR data, have an inherent thermal sensitivity of 0.5°C, which is fixed by the NOAA standard equations for conversion of digital counts to temperatures. The area close to the power plant during the Angra-02 Mission was at least partly cloudy at the time of data acquisition. It is recalled that the distance across Itaorna and Piraquara de Fora Bays is 1-2 km respectively, while an individual IR pixel is about 10 km x 5 km for the VISSR data in the study area. This means that any VISSR IR pixel covering either Bay will also contain some coastal margin. In this instance it is difficult to detect the difference between slightly warmed water, and a pixel which includes some (slightly warmed) beach area. A pixel located just outside either Bay, however, could indicate a temperature to within about 0.5°C of the adjacent pixel. Radiosonde measurements were available and discussed in the Technical Report for the Angra-02 Mission. There, Stevenson et al.(1983b) noted that there was a temperature offset of about 3 °C due to water vapor in the atmosphere above the Power plant area, of about 2 cm of precipitable water. The warmest temperatures seen in Figure 18 are 15.5-16.5°C which is 5-6 °C, cooler than the actual temperature. There is still 2-3 °C in temperature offset unaccounted for and this temperature difference attests to the presence of some clouds in the area, smaller in spatial resolution than the area covered by a single pixel.

Due to the presence of several ships in the local field of view, it was possible to calibrate the AVHRR IR data from the NOAA-7 Satellite during the Angra-03 Mission. The 3 data pairs provided the conversion equation

$$T_{sfc} = 0.30DN + 49.43 \quad , (r=-0.93),$$

where the temperature is in ^{o}C. The thermal sensitivity obtained was about $0.3^{o}C$/DN count. From Figure 23, the AVHRR SST for the Angra area is 23.0-23.3^{o}C, reasonably close to the 26^{o}C, actually observed on site, earlier in the day. Some clouds may have moved into the area after the actual mission took place and these clouds could have provided the temperature offset that is observed.

3.2 - ESTIMATION OF SURFACE CURRENTS AND TURBULENT MIXING

Surface currents were computed for both Itaorna and Piraquara de Fora Bays using the dye and oil patches. For Piraquara de Fora Bay, where we have three well-separated patches, it is also possible to infer the general circulation at the time of the experiment. The water movement is readily seen for the two Bays in Figures 24 and 25. For Piraquara de Fora Bay, the circulation was generally from North to South, with slight variations due to location (Table 2). Distinctive surface foam lines were observed in each Bay and are included in the two Figures.

The dye solution possessed a specific gravity of 0.89 (from Anonymous, 1953), whereas the local sea water was estimated from LaFond (1951) to have been 1.023 (for T=23^{o}C; S=33.62 $^{o}/oo$). Because the dye solution is much less dense than the sea water, it is reasonable to expect the dye solution to remain in the upper 1-2 m of the water column, due to the relative buoyancy of the dye solution. The foam line in Piraquara de Fora Bay exhibited a southward motion of 6.5 cm/sec, at the same time the nearby dye patch was moving to the southeast at a speed of 15.4 cm/sec.

A most interesting interaction between the dye patch and the foam line occurred between film frames 4575 and 4610, when the foam line crossed over the dye patch! This was unexpected since it was thought that both the foam line and the dye patch were in the surface layer. The foam line was in fact, on the surface of the water, whereas the dye patch had diffused and was present in the upper 1-2 m of the water column. The change in shape of the dye patch after the crossover also shows the effect of localized horizontal and vertical current shear.

Because oil is immiscible in water, we cannot treat size or area changes of an oil patch as representing an equivalent parcel of water, for estimating turbulent mixing. In terms of advection, however, it is reasonable to use the change in oil patch position as indicative of surface currents. No measurements of the area of the oil patch have been included in Table 1.

Information about surface currents is more limited for Itaorna Bay, where there is only one dye patch. A small oil patch was also created near 23°01'20"S, 44°27'00"W. Unfortunately, a combination of local shear in the currents and perhaps wind, dispersed the small patch into a ribbonlike stain which quickly became difficult to observe. As a consequence, no data are provided for oil patch No.1. The surface current was to the Southwest at 3.2 cm/sec, near the entrance to Itaorna Bay. Between the last two film images, the patch velocity decreased. A foam line was also observed in the area of the dye patch, and during the same period possessed a northward velocity of 10.4 cm/sec. The foam line also decreased in velocity during the final observational period and did not cross over the dye during our set of observations.

The magnitude of turbulence can be estimated from dye dispersal studies. For this reason dye solutions were dispersed during both Angra-02 and -03 Missions. For reasons of economy and relative simplicity in interpretation, the dye solutions were released as point sources, rather than as continuous dye sources (see Okubo 1962 and Okubo 1976 for theory). Determination of the size of the dye patches with time, provides the basis for estimating the intensity of turbulence in the surface water. As mentioned in the Data and Methodology Section, an optical comparator was used to determine both the centers of the images of dye patches and the areal extent of each patch (Table 1). The areal extent of an image of a dye patch is defined as the visual threshold of the outer perimeter of the patch. This limit is dependent upon various factors including clarity of the water, solar angle, sea state, water depth,etc. Since the film images extended over only about 1 hour, there was little change in solar angle. Also, the patches were not advected over large distances in this interval of time. The water clarity was good in both itaorna and Piraquara de Fora Bays during the Angra-02 Mission. Since the manual comparator was used instead of the vidicon scanner, our interest was to obtain the area of a threshold concentration rather than an absolute concentration for the dye patch. While photodensitometric measurements are more accurate and elegant, various researchers have reported that the simple method used in this study are sufficient to obtain useful information about turbulence.

For each dye patch, the initial diameter of the patch at the time of dispersal was taken as 1 m^2. The dispersion of the dye patch in Itaorna Bay (Figure 26) will be considered first. Two time scales are shown along the abscissa: an elapsed time scale starting when the first film image was taken of the patch; and a local time scale in hours, shown from the time the dye was placed in the water. Best fit curves are given for the interval of the filmed patches and for the duration of the experiment. The equation obtained for the 3 filmed images is very useful, because the slope of this equation represents the coefficient of turbulence or diffusion during that time. For this patch, the coefficient is 51.31 m^2/sec, or $8.6x10^3$ cm^2/sec. It is evident that a linear fit is not adequate if the initial point of the experiment is to be included (06:58 LT). Many researchers have reported that, in reality, the diffusion coefficient is not a constant but changes with the scale length of the experiment. The simple exponential equation shown provides a reasonably good fit except for the data point at 08:46 (LT). Because the time interval between the first and last filme image was short (about 1 hour), the scale length has not greatly changed and the diffusion coefficient can be reasonably considered to have been more or less constant.

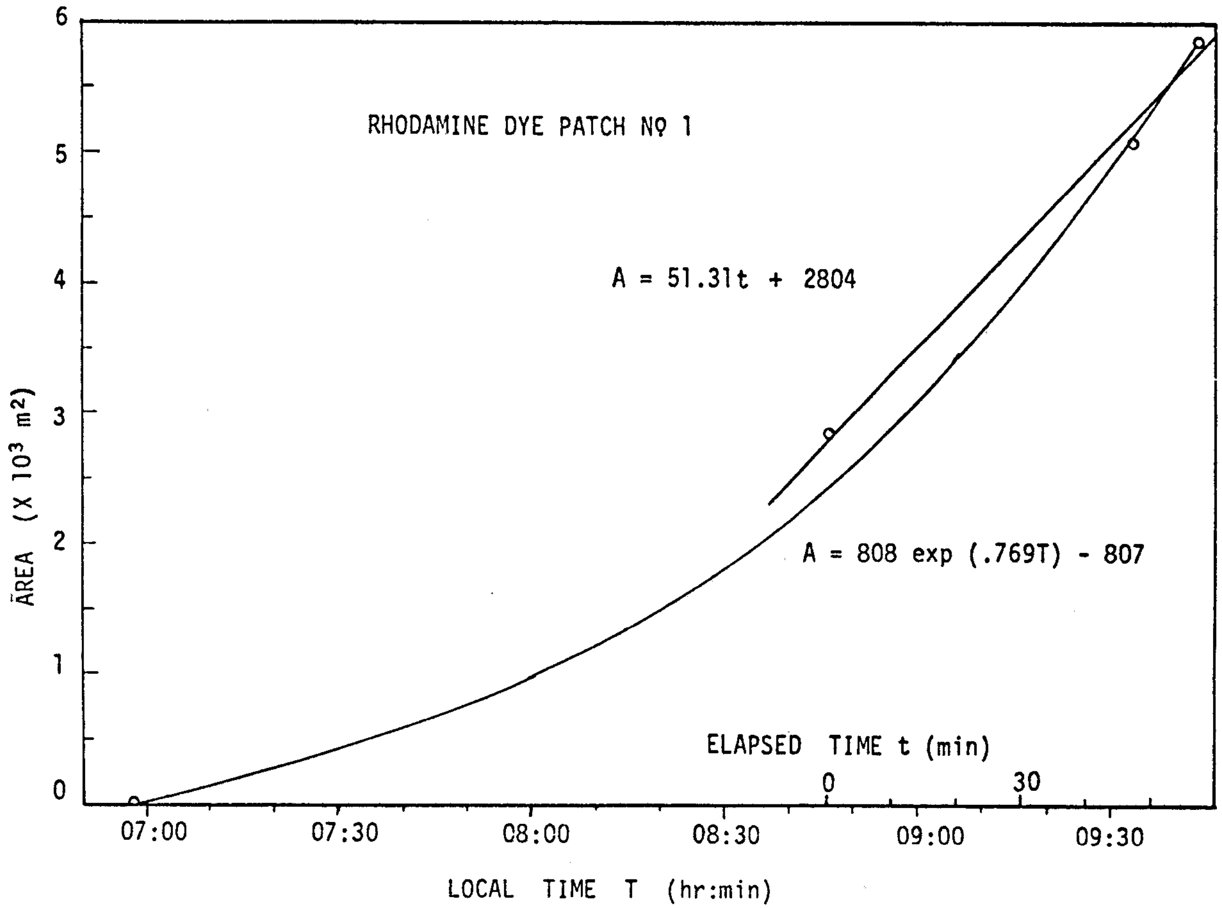


Fig. 26 - Dispersion diagram of dye patch in Itaorna Bay during the Angra-02 Mission.

The interpretation of dye patch number 2, is more complex. Dispersion of the second patch, at least initially, is seen to have been relatively smooth (Figure 27). After 08:30 (LT), however, the patch suddenly underwent a very large increase in size. A quick comparison with Figure 25 will show that the surface foam line crossed over the patch at this time. The sudden increase in patch size and geometry, is then, not particularly due to the usual turbulence, but rather due to horizontal and vertical current shears present during the crossover time. The slope of the two curves is different by almost 7 times, since turbulence is generally considered in the literature as representing a kind of continuum of energy dissipation, it is unlikely that turbulence only was responsible for the sudden size increase of the patch. The lower curve and equation estimate the turbulent mixing to have been 4.4×10^3 cm^2/sec.

The third dye patch was located near the discharge barrier of the power plant. Because a number of flightlines crossed over this area, there were a much larger number of filmed images of this dye patch (Figure 28). For the purpose of simplicity, a simple linear regression fit was made to the points, starting at about 08:09 (LT). While the fit is very useable, it is apparent that the relation between area and time becomes nonlinear toward the end of the observational period. The diffusion coefficient for this patch is $7.8 \times 10^3 cm^2/sec$, intermediate to the first and second patches. The range in diffusion coefficients for Itaorna and Piraquara de Fora Bays is $4.4\text{-}8.6 \times 10^3 cm^2/sec$, with the largest value found for Itaorna Bay, a bay with relatively open water.

Very few other dye diffusion experiments have been reported for this coastal region of Brazil. Ikeda and Stevenson (1982) using point sources of Rhodamine dye obtained $3.5 \times 10^3 cm^2/sec$ and $9 \times 10^3 cm^2/sec$ for a small bay on the east side of Ilha Grande and for open water east of the Island, respectively. Their experiments also took about 1 hour. Variations in dye concentration with time were measured with a fluorometer instrument aboard a small boat, as compared to the film images used in the present study. The similarity of their

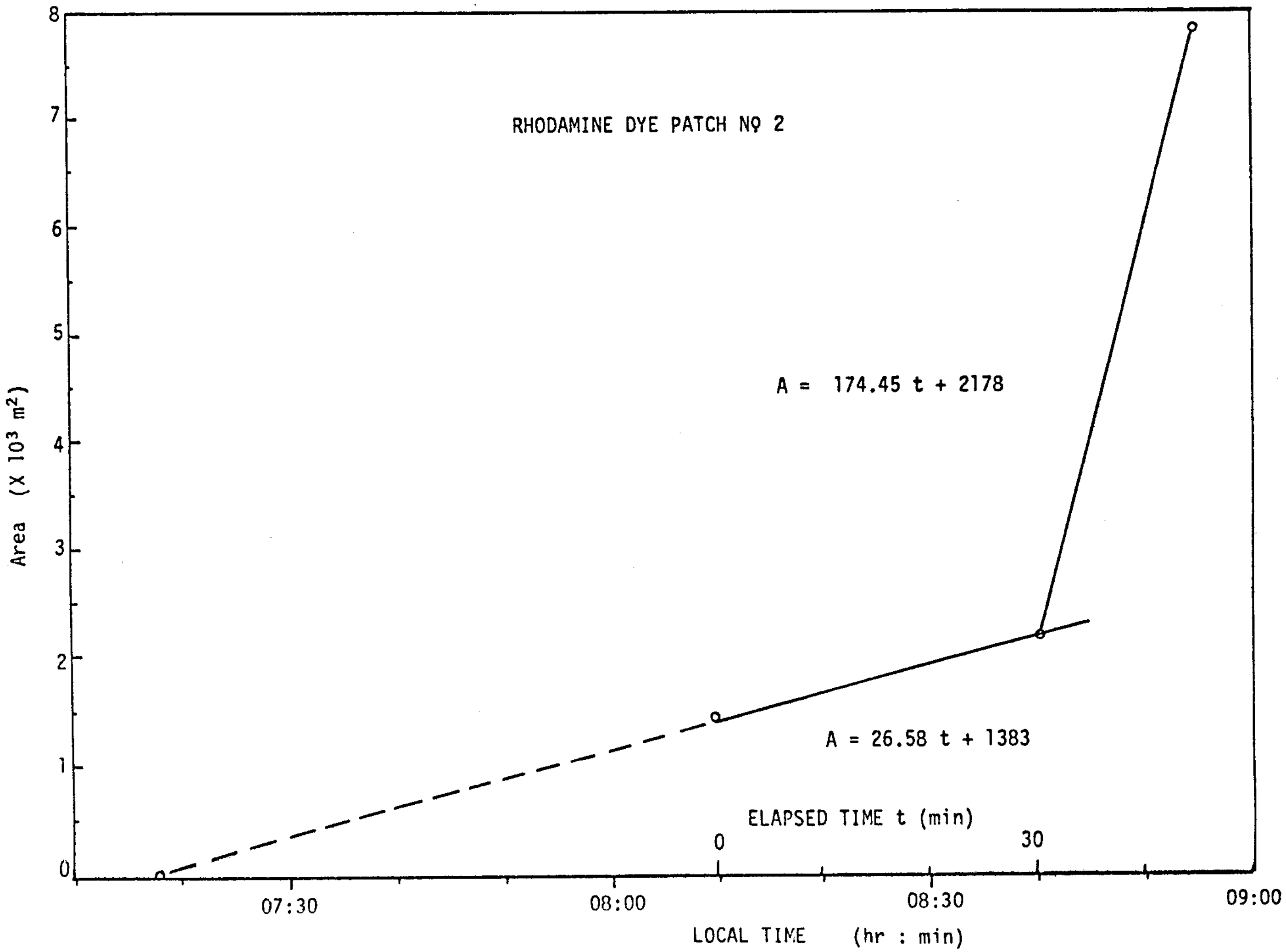


Fig. 27 - Dispersion diagram of dye patch located near entrance to Piraquara de Fora Bay during the Angra-02 Mission.

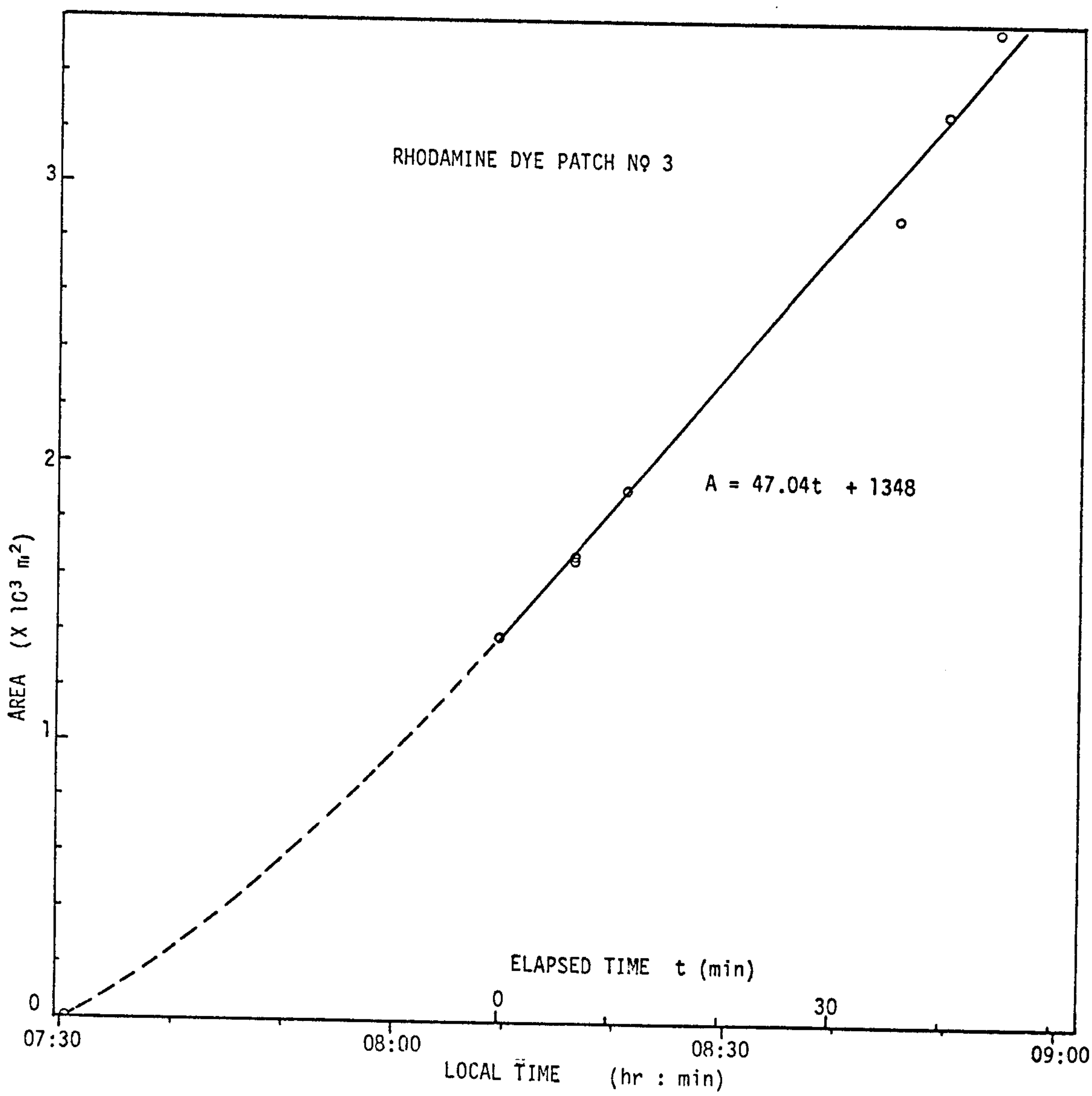


Fig. 28 - Dispersion diagram of dye patch located near discharge barrier in Piraquara de Fora Bay during the Angra-02 Mission.

measurements with Project Angra measurements, and also with other published estimates of the magnitude of the diffusion coefficient, gives increased confidence in the Project Angra measurements.

Various diffusion models have been discussed in the literature (Okubo, 1962). Because of the short time intervals of the Angra experiments, we will limit our consideration of diffusion models to a simple Fickian-type diffusion model (Okubo, 1962). For simple, symmetric two dimensional diffusion in the absence of a surface current, the concentration of dye at a particular point, relative to the dye center, at time t is given by:

$$S = \frac{M}{4\pi Kt} \exp \left[- \frac{R^2}{4Kt}\right] ,$$

where M is the mass of the dye, K is the diffusion coefficient and is considered constant, R is the radius of the circular dye patch and t is the elapsed time, from the start of the experiment. Since there is almost always a current present, it is more useful to include a simple horizontal motion term. For a spatially homogeneous velocity field we obtain (Stevenson, 1966):

$$S = \frac{M}{4\pi Kt} \cdot \exp \left[(-(x-ut)^2 - (y-vt)^2)/4Kt\right] ,$$

where u and v equal the water velocity in component form, and x and y represent a position in space, referenced to the initial point of dispersal. The model in this form is useful to predict the concentration of dye at different points in time and space after placement in the water. Because the model assumes an infinitely wide space for purposes of diffusion, the model can only be used until the concentration level of dye at the shoreline becomes appreciable.

When the power plant operates its cooling system and discharges water into Piraquara de Fora Bay at a rate of 37 m^3/sec, it is expected that the diffusion coefficient for that Bay will increase somewhat, due to the injection of kinetic energy, represented by the flux of heated water.

3.3 - COMPARISON OF OBSERVED SST's AND SST's PREDICTED BY NUMERICAL MODEL

Verification of models used to predict the SST field near the release point of heated water from the Angra Power Plant is important. When a model is shown to accurately predict the spatial and temporal distributions of the heated water, the model may be used with reasonable confidence for analysis of various environmental conditions. Because the Angra-03 Mission occurred during a testing cycle of the power plant, when heated water was present, it is possible to compare the observed SST field with surface temperatures obtained from a hydrodynamic model of the type employed by BIOTEC (1974), called the Model.

In order to efficiently compare observed temperatures with predicted temperatures, it was necessary to convert the SST charts from the Angra-03 Mission (Stevenson et al, 1983c) into temperature anomaly charts. Figures 29, 30, 31 and 32 give the surface Δt for Piraquara de Fora Bay, referenced to the SST for Itaorna Bay. It is important to note that on 22, 24 and 25 March, there were negative ΔT's in the Northeast corner of the Bay. The $-\Delta T$'s were probably caused by cool water that was locally upwelled around the landpoint in that area.

Aircraft observations were not available from the Angra-03 Mission, so surface temperature data are limited to those measurements taken within Piraquara de Fora Bay. The area of the Bay was enclosed by running a line between the two outermost landpoints associated with the Bay, as seen in Figures 29-32. The areas between adjacent ΔT isotherms ($\Delta T \geq 0$) were then determined by planimeter for each day's experiment, and are listed in Table 3. Some uncertainty is present in the areal integration because there was limited coverage very near the discharge area in the Bay. Even so, the general distribution of isotherms is considered reasonable for purposes of comparison with the Model. Some differences between the data and Model are expected, since the Model used 100% output capacity, while the actual data represent

25% of the output capacity of the power plant. Model data used for the comparison were taken from Table 2 of the BIOTEC Report, which assumed a wind speed of 2.5 m/sec. The average wind speed during the 4 days of the Angra-03 Mission varied between 1.2 and 2.3 m/sec.

The Model provides results for the seasonal extremes of April and August. The ΔT anomaly curves for these two months are shown in Figure 33. The ΔT curves for the days of the Angra-03 Mission are also included in the figure. The left-hand Y-axis is used with the Angra-03 curves and the right side is for the Model curves. The areal limit of Piraquara de Fora Bay is shown for each scale on the Y-axis. Curves extending above this reference line represent water extending outside of the Bay.

TABLE 3

SURFACE WATER TEMPERATURE ANOMALIES PRODUCED BY DISCHARGE FROM THE ANGRA POWER PLANT

Date	Itaorna Temp. Tsfc (°C)	Piraquara Temp. Δt (°C)	Area* (km^2)	Mean Wind Speed
22/03/83	26.0	0-1 1-1.8 ≥1.8	1.03 1.44 0.47	1.2
23/03/83	26.0	1-2 2-3 3-4 4-4.9	2.02 0.71 0.09 0.06	2.3
24/03/83	25.0	0-1 1-2 2-3 3-4 4-4.9	0.41 2.06 0.41 0.11 0.06	1.8
25/03/83	26.0	0-1 1-2 2-3 3-4	2.47 0.15 0.12 0.07	1.7

* The area of Piraquara de Fora Bay is considered to be 3.05 km^2, exclusive of islands.

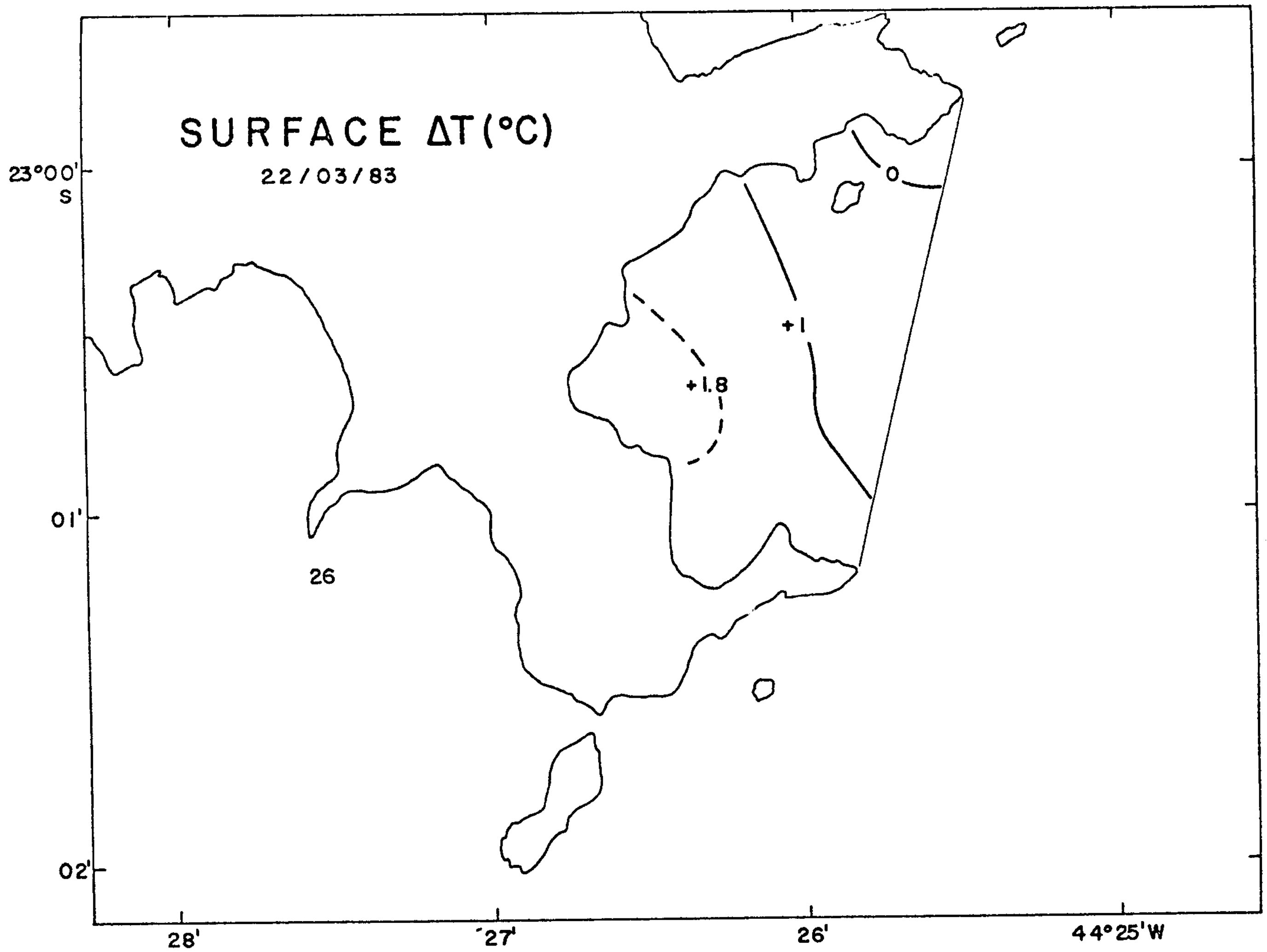


Fig. 29 - Surface temperature anomaly (ΔT) for Piraquara de Fora Bay referenced to average surface temperature of Itaorna Bay.

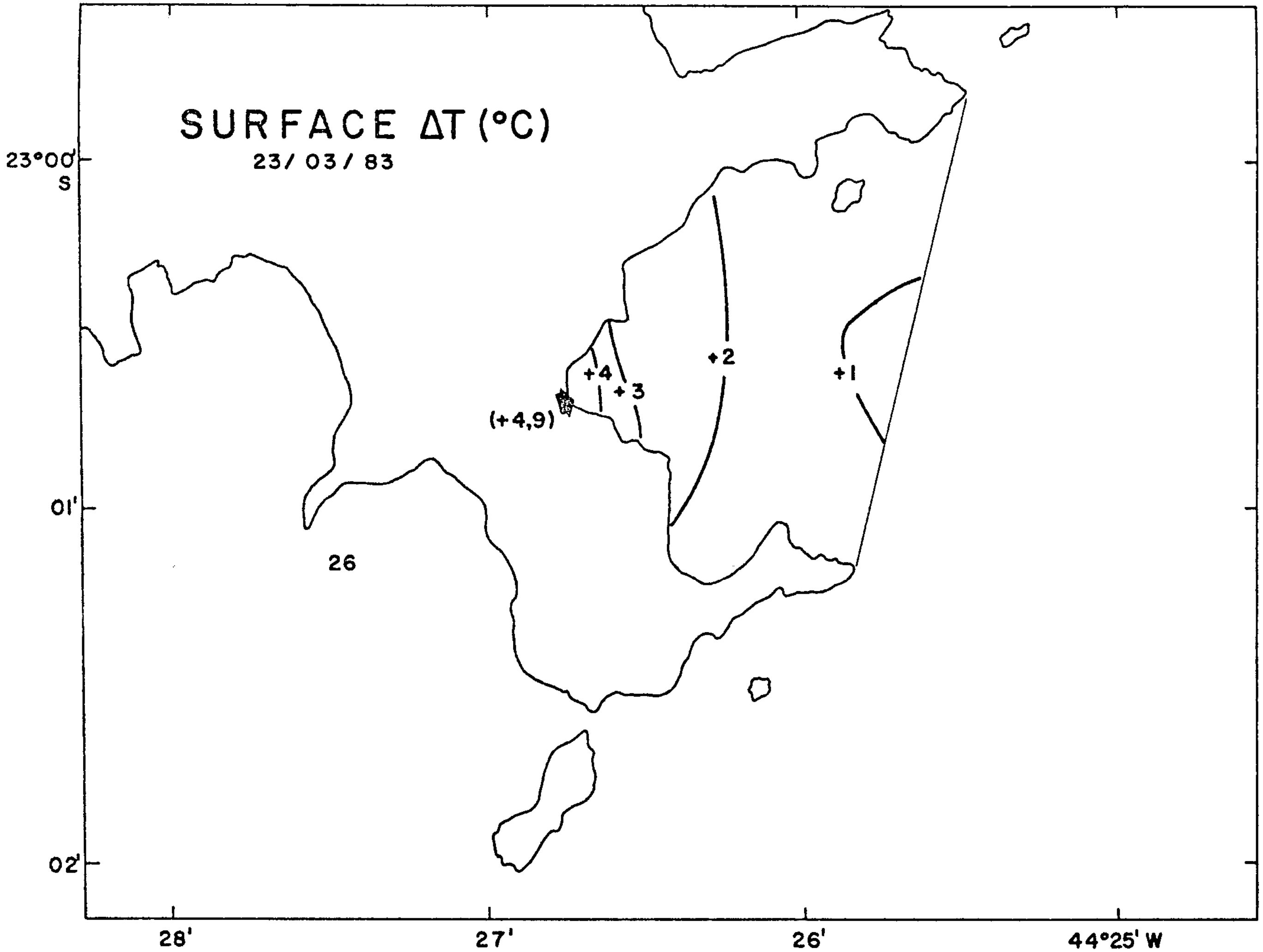


Fig. 30 - Surface temperature anomaly (ΔT) for Piraquara de Fora Bay referenced to average surface temperature of Itaorna Bay.

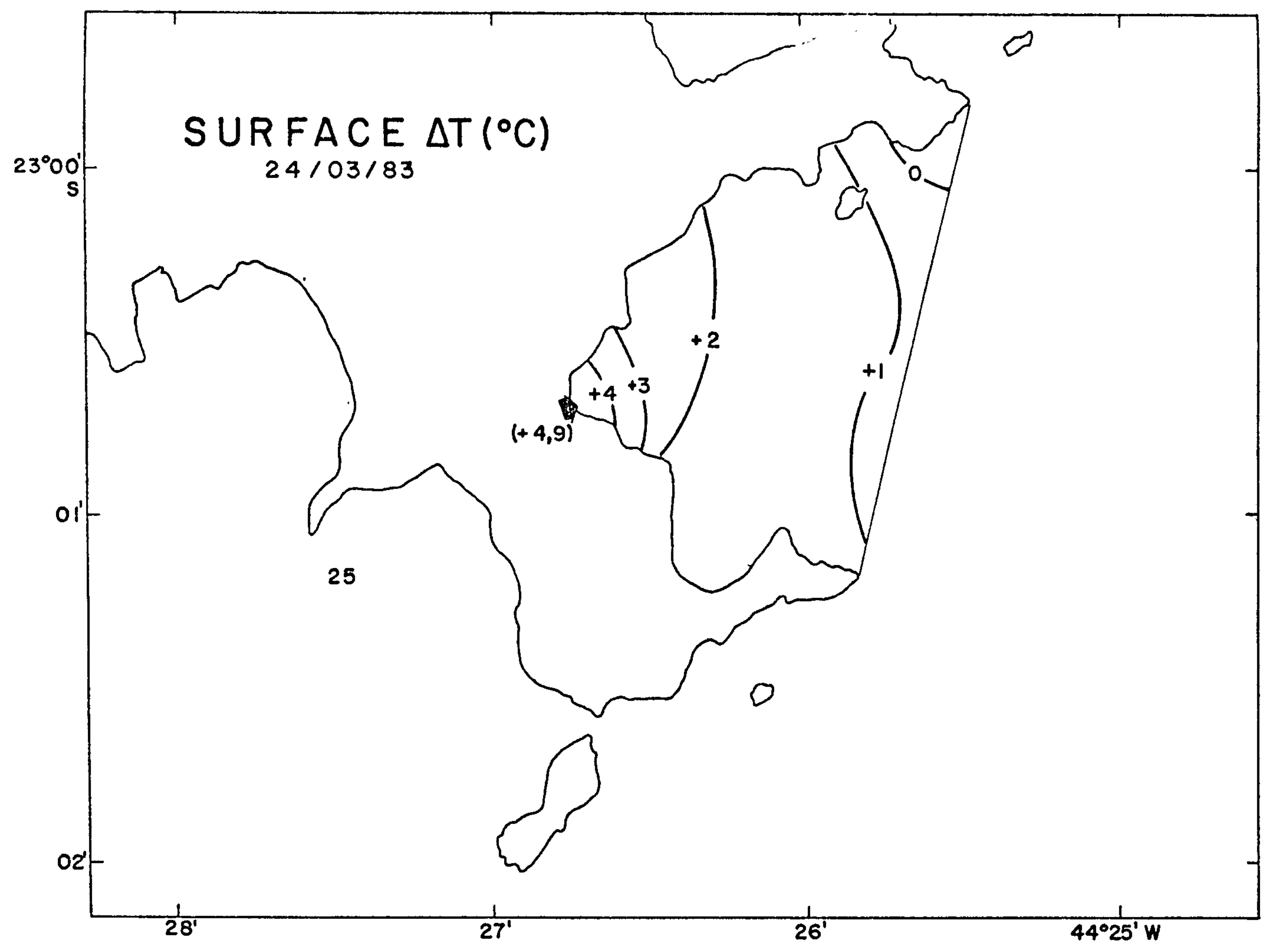


Fig. 31 - Surface temperature anomaly (ΔT) for Piraquara de Fora Bay referenced to average surface temperature of Itaorna Bay.

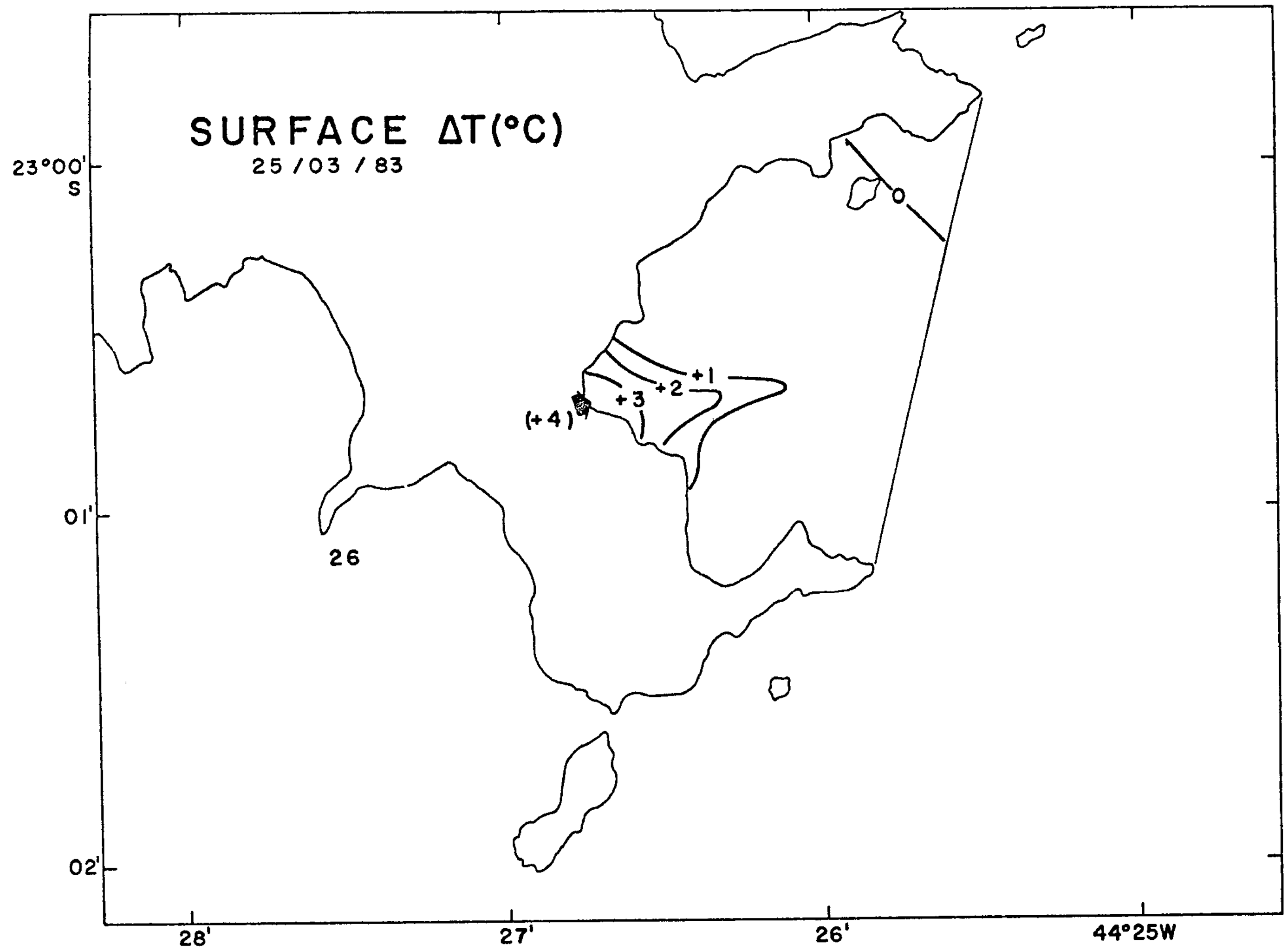


Fig. 32 - Surface temperature anomaly (ΔT) for Piraquara de Fora Bay referenced to average surface temperature of Itaorna Bay.

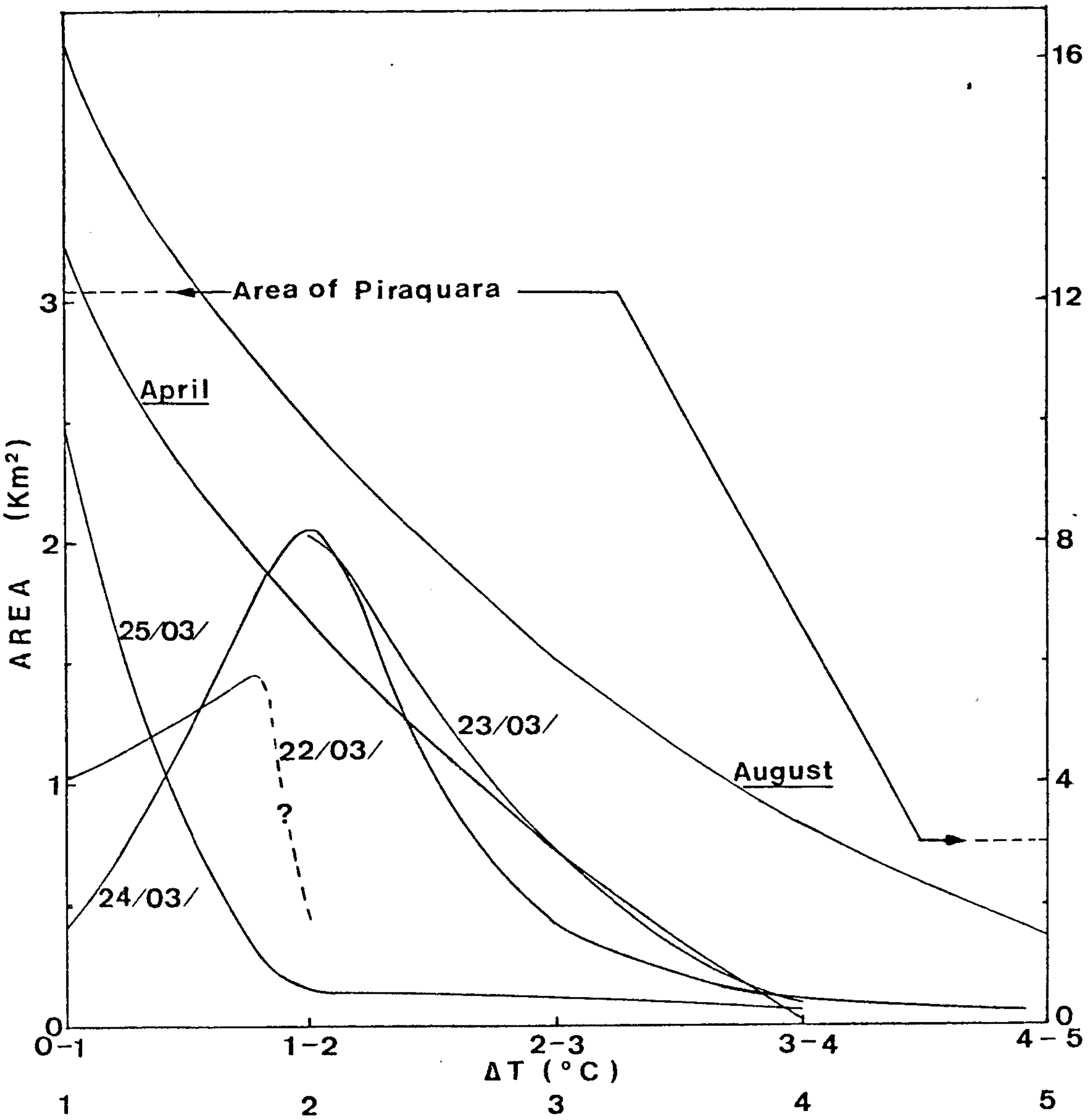


Fig. 33 - ΔT anomaly curves for Angra-03 and the BIOTEC Model.

The X-axis also has a double scale: the upper scale is used with the Angra data and the lower scale is for the Model. The X-axis represents the area associated with increasingly warmer water. It is evident from Figure 33 that both the amount of area occupied by warm water and the size of the ΔT itself, increased from 22 to 24 March. The line for 22 March is broken, due to incomplete data near the discharge barrier. From 24 to 25 March, we see a marked reduction in the area occupied by warm water. The 22-24 March curves suggest an increase in heat output from the power plant, followed by a reduction in output on the 25th of March. It should be remembered,however,that environmental factors such as a change in wind and/or current direction may alter these curves by promoting or impeding the movement of warm water out of Piraquara de Fora Bay.

At first glance, it appears that the area covered by warm water is much greater for the BIOTEC Model than for our results. The power plant, however, was only operating at 25% output capacity during the third Mission, whereas the Model used a 100% output capacity for the power plant. If there is a correspondence between the percent output and the amount of heat output, expressed as ΔT, it is useful to compare the two sets of curves.

Because the Angra-03 Mission was toward the end of March, we would expect the most similarity between Model and real curves to occur for the April Model curve. The curves for the 23rd and 24 th of March do lie reasonably close to the April curve for $\Delta T's \geq 2^{o}C$. It is to be remembered that the Model curves represent a more or less steady state output of the power plant. The Angra curves were based on a testing cycle of the power plant and do not represent a steady state condition.

Within the limitations noted herein then, the BIOTEC Model appears to be a useful tool for predicting the area of coverage of heated discharge water. Variations in winds and currents may cause a considerable departure from a simple steady state condition.

A new contract between CNPq/INPE and CNEN has been approved to conduct two more field missions. These missions will be made during normal or commercial operation of the power plant, after the plant has been operating at the same level (for example 100% capacity) for a number of days. In this future phase of research, it is planned to make another comparison of field data with the BIOTEC Model.

4. CONCLUSIONS

Based on results discussed in previous Project ANGRA reports (Stevenson et al. 1982, 1983b and 1983c) and the present report, the following conclusions are made:

1) The surface temperature conditions in both Bays prior to the operation of the Angra power plant were largely isothermal, ($\sigma=\pm0.1^{o}C$) with only localized thermal gradientes within the Bays. From the field missions made prior to operation of the power plant, there appears to be little difference in the surface temperatures of the two Bays.

2) The thermal difference between either of the Bays and Buzios Island in the Ilha Grande Bay was about $1.5^{o}C$.

3) SST's obtained from airbone radiometer (i.e. a Barnes PRT-5 instrument) appear very suitable for mapping SST's with a precison of about $\pm0.2^{o}C$.

4) The accuracy of remotely sensed SST's is affected by varying amounts of atmospheric water vapor, located between the sea surface and the sensing instrument.

5) Local radiosonde soundings or aerial soundings with an aircraft, can obtain the needed vertical air temperature and humidity profiles. For cloud-free conditions the aircraft may fly at >4000 m altitude, to be above most of the water vapor.

6) Based upon radiosonde data and SST's determined from an airborne radiometer, it was possible to obtain a significant relation between the atmospheric water vapor (ΣH_2O measured in cm of precipitable water) and radiometric temperature (^oC):

$$T_{sfc} - T_{prt} = 1.8\ (\Sigma H_2O) - 0.84.$$

More of these determinations are necessary in order to place much confidence in their general usage for the Angra area.

7) When radiosonde soundings are not available at Angra, the soundings made at Galeão Airport in Rio de Janeiro, offer a reasonable substitute if weather conditions are similar at the two locations, at the time of the sounding.

8) When relatively cloud-free conditions exist over the Angra area, it is possible to use the thermal infrared data from either the geostationary satellite GOES-5 or the polar orbiting satellites NOAA-7 and 8, to obtain regional SST coverage around the Angra area.

9) Very useful information on the surface water motion in both Bays was obtained from the dispersal of small quantities (~100g) of Rhodamine-B dye. Due to the accuracy of the aerial photographs used in the analysis of the dye patches, the velocities are considered good to within ± 0.1 cm/sec. During the Angra-02 Mission the surface current was 5.5 cm/sec and 2.5--15.4 cm/sec to the Southwest and Southwest-Southeast, for Itaorna and Piraquara de Fora Bays, respectively.

10) Filmed images of dye patches in both Bays were also used to estimate the magnitude of turbulent mixing. For Itaorna Bay $K=8.6 \times 10^3\ cm^2/sec$ and for Piraquara de Fora Bay, the value is $K=4.4\text{-}7.8 \times 10^3\ cm^2/sec$.

11) During a testing cycle of the power plant, it was possible to calculate the area occupied by the heated water, in terms of average temperature anomaly (ΔT), referenced to Itaorna SST:

$\overline{\Delta T}$ (^{o}C)	Area (km^2)
4-5	0.06
3-4	0.09
2-3	0.41
1-2	1.42
0-1	1.30

12) Comparison of 4 individual ΔT anomaly curves obtained for March, with a ΔT curve obtained from a hydrodynamic model used by BIOTEC, showed the rescaled Model curve for April to be in reasonable agreement with the Angra-03 data.

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