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# Remote Sensing of Oceanic Parameters During the Skylab/Gamefish Experiment



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# REMOTE SENSING OF OCEANIC PARAMETERS DURING THE SKYLAB/GAMEFISH EXPERIMENT

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## SUMMARY

The Earth Resources Laboratory participated in the National Marine Fisheries Service Skylab Experiment 240 by assisting in mission planning, data acquisition, and analysis of remotely acquired data. The surface data were acquired during 3 days in August 1973 in a triangular test area that extended southward from near Destin, Florida; aircraft and satellites surveyed the test area on the third day of the mission. The focus of the work being reported here is the aircraft data, which consist of thermal-infrared measurements, radiance spectra, and supporting photography.

The analysis was directed toward three basic objectives: remote measurement of sea-surface temperature and derivation of chlorophyll-a concentrations and of Secchi extinction depths from water color. The work was in support of the National Marine Fisheries Service effort and was pursuant to the continuing program of the Earth Resources Laboratory to advance the application of remote-sensing technology to marine resources problems. The algorithms used by other investigators for the derivation of chlorophyll content and turbidity were evaluated with the data collected in this experiment. Good accuracy was obtained for the chlorophyll calculation but only fair accuracy for the turbidity computation. Two statistical methods, principal-factor and linear correlation analyses, were used to select optimum radiance data for the remote sensing of chlorophyll and turbidity. Chlorophyll-a concentrations were remotely measured with an accuracy of 0.4 $mg/m^3$ over a range of 0 to 5 $mg/m^3$. Secchi extinction depths were derived from spectral radiance measurements with an accuracy of better than 5 meters over a range of 2 to 30 meters.

The thermal work consisted of applying atmospheric corrections to the aircraft infrared data and combining the data sets from three different sensors on two aircraft. A map of the surface temperature was developed from this composite data set. Varying atmospheric conditions over the test area influenced these data greatly and introduced relatively large errors that could not be corrected by using current techniques.

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# INTRODUCTION

An important goal of the Earth Resources Laboratory (ERL) has been the development of remote-sensing technology applicable to marine problems. The work described in this document is one phase of a cooperative effort of the ERL and the National Marine Fisheries Service (NMFS) National Fisheries Engineering Laboratory to establish the feasibility of using satellite imagery for determining the availability and distribution of living marine resources, specifically gamefish. The stated objectives of the multiphased experiment, designated the Skylab/Gamefish Experiment, were to evaluate the use of remotely acquired data from satellite platforms to improve oceanic gamefish stock assessment, to enhance the capability of predicting the best areas for gamefishing success, and to examine relationships between ocean surface data and gamefish distribution.

The role of the ERL in the experiment was to plan remote data acquisition, to assist in the collection of surface and remote data, to process water samples in the laboratory, and to develop and evaluate measurements of oceanographic parameters from remotely acquired data. The remote data analysis, which was directed toward supplying NMFS with information that could be readily applied to the fisheries distribution analysis, consisted primarily of the computation of chlorophyll-a content and Secchi extinction depth as a measure of turbidity from wavelength-discriminated visible, near-infrared radiometry, and the computation of sea-surface temperature from thermal-infrared radiation measurements.

This report documents ERL efforts toward the continued development and evaluation of techniques for the measurement of three oceanic parameters. Using remote and surface data acquired during the Skylab/Gamefish Experiment, existing procedures for the calculation of sea-surface temperature were applied, existing algorithms for the computation of chlorophyll-a and Secchi transparency measurements of turbidity were applied and evaluated, and modifications made to these algorithms which were then applied and evaluated. The remote measurement of these three oceanic parameters was integral to the NMFS effort to evaluate the use of remote sensing for the assessment and monitoring of the gamefish resources because of the relationship that was found to exist between the distribution of certain species of fish and these parameters (ref. 1).

The author is most grateful for the cooperation of the NMFS in the entire Skylab/Gamefish effort, especially that of Kenneth Savastano, who was the Principal Investigator for the project, and with whom most of the interaction took place. The experiment was initiated by William Stevenson, who served as Principal Investigator until his departure midway through the experiment. James Weldon, formerly of the Earth Resources Laboratory, was principally responsible for the planning of the remote data acquisition mission and of the ERL role in the overall experiment. The surface data acquisition mission was carried out by NMFS, National Oceanic and Atmospheric Administration (NOAA) National Ocean Survey, NASA, General Electric, and Lockheed Electronics personnel.

Jerry Brashier of Lockheed Electronics has been especially helpful in all aspects of the operations and documentation phases of the experiment.

Ronald Holyer, formerly of Lockheed, assisted in the analysis of the data, and his assistance in developing the algorithms for computing the oceanic parameters from the spectrometric data deserves special mention.

As an aid to the reader, where necessary the original units of measure (except for temperature) have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

## BACKGROUND

The 8- to 14-micrometer region of the electromagnetic spectrum is considered the thermal-infrared band and corresponds to an atmospheric transmission window that has become somewhat dirty because of absorption and emission by such atmospheric constituents as water vapor, carbon dioxide, ozone, and aerosols. The measurements of infrared radiation must be processed to remove the effects of the atmosphere so the radiation measurement can be translated into thermodynamic temperature. Boudreau (ref. 2) has developed a theoretical model for atmospheric effects that can be used to correct the radiation measurements or to estimate the effect of different atmospheric conditions on remote measurements.

Evaluation of the remote thermal measurements has been difficult in the past. In 1972, Worthington (ref. 3) performed extensive analyses on thermal data acquired during 13 missions over the Mississippi Sound. After correcting surface measurements for the effects of insolation on the surface waters between the times of surface and remote sampling, he found that the remote measurements were typically within 0.2° C and often within 0.1° C of the adjusted surface temperatures. Occasional errors as large as 1.0° C were observed but could not be explained. For example, in the case of the most deviant data point of his analysis, it is impossible to explain the discrepancy by hypothesizing nonuniform variation of surface temperature with time because the measurements were essentially simultaneous. From his analysis, Worthington reached no conclusion as to which measurement caused the error, and it is possible that the remote measurement may be more accurate than the surface reading. Under ideal atmospheric conditions, the remote thermal measurement may provide synoptic data that are more accurate than surface data acquired over an extended period.

Remote measurement of chlorophyll content and turbidity is more complex than the measurement of surface temperature. The techniques now being explored involve interpretation of water color as measured by spectrometers or multispectral scanning radiometers. The physical phenomena that determine water color are complicated and involve the interaction of many different factors. As a result, extensive efforts have been made to empirically relate these two parameters to aerial and satellite measurements of water color.

Clarke et al. (ref. 4) reported successful discrimination of waters having high, low, and very low chlorophyll content on the basis of spectra of backscattered light from the sea obtained by an airborne spectrometer. The results reported can be expected from the transmission characteristics of the pigment; strong absorption in the blue region of the spectrum results in a negative correlation between chlorophyll concentration and relative upwelling radiance in the blue region, whereas backscattering by chlorophyll-bearing organisms and low absorption in the green region result in a positive correlation of chlorophyll content with relative upwelling radiance in that portion of the spectrum. Analysis of the transmission characteristics of chlorophyll and water considered together (ref. 5) explains the behavior of the blue and green portions of the spectrum with varying chlorophyll content and the lack of variation in the red region of the spectrum.

Scattering of light by suspended particles must be considered together with the attenuation by chlorophyll and other pigments. Chlorophyll-bearing phytoplankton, exclusive of the effects of any pigments, scatter downwelling radiation and thus reduce penetration and simultaneously increase backscattered light. The pigment contained within the cells modifies the scattering, causing it to be wavelength-dependent. The result is a decrease of the scattering and an increase of the absorption of blue and red light. It is thus evident that, whereas increasing numbers of phytoplankton per unit volume of seawater will cause increasing attenuation of blue light because of the chlorophyll pigment, scattering by the plankton will simultaneously increase upwelling light and decrease penetration. Other suspended particles, including bacteria, plant fragments, and inorganic materials, have a scattering effect that is dependent upon the refractive index of the particles and upon the ratio of particle size to wavelength. Coincident variation of size, index of refraction, and number of the various suspended particles varies the backscattering of incident radiation across the spectrum. Scattering from unpigmented particles diminishes the effects of varying chlorophyll content on water color.

Another problem that may seriously affect any calculation based on the color of the sea results from specular reflection of incident solar radiation and skylight from the water surface. This problem may be rather severe, because the radiation emerging from the water (as observed at nadir) has been estimated by Cox and Munk (ref. 6) to be approximately equal to the reflected skylight in intensity, and the specular reflection of sunlight may be an order of magnitude greater. Determination of an oceanographic parameter from water color requires the measurement of small changes in only a small component of upwelling radiance.

The approach used in this experiment, to model the effects of chlorophyll content variation on light backscattered from the sea, is based on previous successful statistical studies of the variation of spectra of upwelling light with changes in chlorophyll content. Weldon (ref. 7) examined experimental data taken at different altitudes over the Mississippi Sound and found that, from the difference of the radiance at two wavelengths divided by the radiance at a third, a linear function could be constructed that describes the chlorophyll content very well in the 1.0- to 5.0-mg/$m^3$ range. Holyer[1] found that the fourth power of a

[1]Holyer, Ronald J. (unpublished report): A Statistical Method for Determination of Chlorophyll Concentration From the Remotely Sensed Ocean Surface Albedo. Lockheed Electronics Co., Inc., Bay St. Louis, Miss., Contract NAS 9-11584, 1973.

weighted sum of the radiance in 56 bands divided by the radiance in a 57th enabled computation of the chlorophyll concentration in a range of 1.2 to 40 $mg/m^3$ with an average error of 15 percent, as opposed to 20 percent using Weldon's technique on the same data set. It should be noted that these accuracies were determined with the data that were used to develop the model and hence do not constitute an independent test.

The selection of wavelengths for use in chlorophyll prediction is discussed briefly by Weldon (ref. 7), who selected 620 and 470 nanometers for the wavelengths at which the difference of radiances was to be computed. This decision was based on the large difference in radiance values at these wavelengths that occurred with changes in chlorophyll concentration and the limitations of the instrument providing the spectral data. He hypothesized that 440 nanometers would be better than 470 nanometers because of the peak in the chlorophyll absorption spectrum at approximately 440 nanometers but, because of spectrometer limitations, could not verify this hypothesis. The radiance at 520 nanometers was used as the divisor because its variance with chlorophyll content was slight.

Also normalizing the radiance at 520 nanometers, Holyer used all data available, even though high correlation of radiance at the different wavelengths resulted in redundancy in the data. He found that nearly 80 percent of the chlorophyll information was contained in the radiance at 22 wavelengths. In general, an effort has been made by investigators (refs. 7 to 9) to use in the denominator of the ratios in their models a wavelength at which the radiance was relatively unaffected by chlorophyll concentration variation but was affected by atmospheric variations and changes in surface reflection.

The technique for inferring turbidity from water color has undergone a development similar to that for determining chlorophyll concentrations. No applicable physical model for turbidity as measured by the Secchi disk has been developed because of the very complicated manner in which numerous factors interact to yield this rather superficially simple parameter. Numerous factors, such as size and number of particles per unit volume, index of refraction of particles, and dissolved and suspended pigments, all affect the Secchi extinction depth; therefore, this turbidity measurement does not describe a unique physical situation. The fact that different combinations of these factors having the same Secchi transparency may affect the water color in different ways suggests that water color is not a good source of data on turbidity. However, because experience has shown a statistical correlation between the Secchi transparency measurement of turbidity and water color, one must conclude that in a given geographical area (at least during a short time) the factors that affect this measurement do combine in a unique manner that enables the inference of this parameter from water color.

Weldon (ref. 7) found that a statistical relationship existed between Secchi transparency measurements and the ratio of radiances measured at 550 and 600 nanometers in his data obtained from the Mississippi Sound. Holyer[1] used a technique similar to that employed in determining chlorophyll content from spectrometer data, using a fourth-power relationship between the Secchi extinction depth and a weighted sum of radiances normalized by the radiance averaged over the entire sensed spectrum (390 to 1290 nanometers). Working only with the same data set, Holyer found that the average error using the nonlinear function of the entire set of spectral data was 15.6 percent, as opposed to 16.8 percent using the ratio of two sets of radiances. This data set was taken in the Mississippi Sound, where Secchi extinction depths were in the range of 1.0 to 3.5 meters.

## OBJECTIVES

The work reported in this document was initiated to assist the NMFS in its efforts to demonstrate the applicability of remote-sensing technology to the assessment and monitoring of the gamefish resource. The approach taken by NMFS in this demonstration is described in figure 1. A direct relationship between the resource and the remotely acquired data (A) was not anticipated, although the possibility of finding a statistical correlation between the two was not ruled out. Emphasis was placed on exploring the relationships that might exist between the oceanographic and meteorological parameters and the resource distribution and abundance using surface measurements of the parameters (C). Simultaneously, the ERL would concentrate on developing remote measurements of oceanographic parameters (B).

Four parameters of interest to NMFS in the gamefish distribution analysis had previously been measured with some success from remote data. Although Thomann (ref. 10) demonstrated that salinity could be measured remotely, the unavailability of instruments prevented remote measurement of salinity in this experiment. Chlorophyll-a, turbidity, and surface temperature were the remaining parameters that could be measured remotely and that were applicable to the NMFS effort. Of these, only the remote measurement of surface temperature is approaching operational status. Measurement of the other parameters required modification and refinement of existing procedures that led to an expanded understanding of the relationship between such oceanographic parameters and the optical properties of the sea as observed from aircraft and satellites.

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[1]Holyer, Ronald J. (unpublished report): Additional Investigations into the Application of Optimal Linear Least-Squares Prediction for Measurement of Ocean Parameters From the Remotely Sensed Surface Albedo. Lockheed Electronics Co., Inc., Bay St. Louis, Miss., Contract NAS 9-11584, 1973.

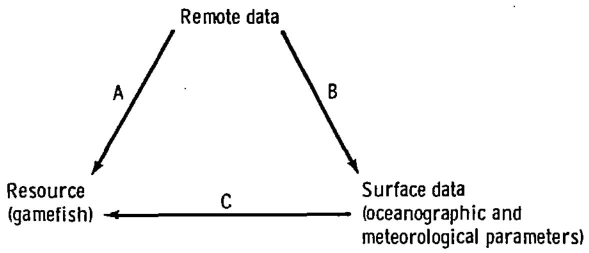


Figure 1.- National Marine Fisheries Service experimental approach.

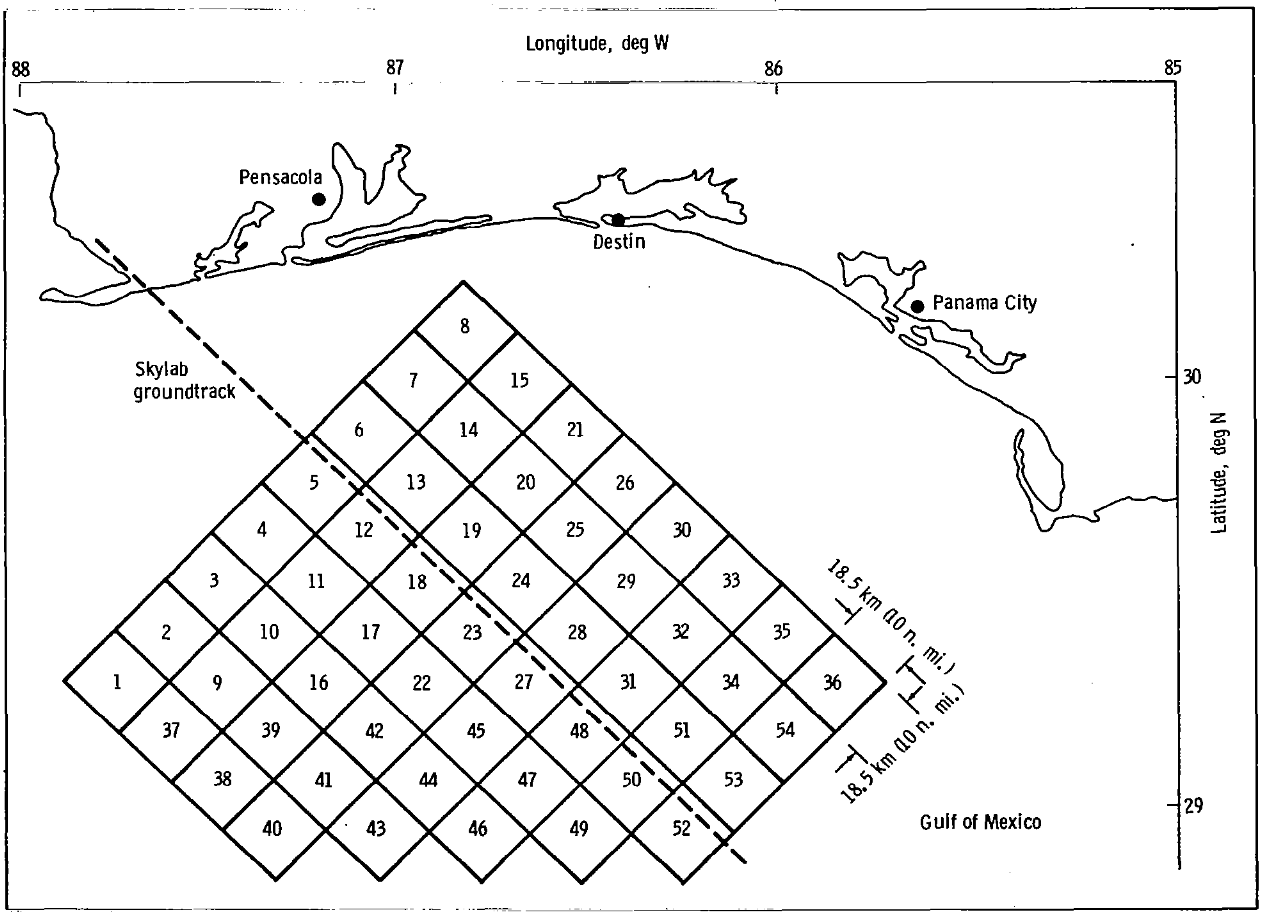


Figure 2.- Test area with fishing squares.

The three specific objectives of the work being reported were as follows.

1. To produce a composite thermal map from data acquired at two different altitudes at different times with three different instruments

2. To produce a contour map of chlorophyll-a concentration from spectral radiometer data taken at an intermediate altitude

3. To produce a contour map of turbidity from spectral radiometer data taken at an intermediate altitude

Tasks leading to the realization of these objectives included selection of optimum techniques for the measurement of chlorophyll and turbidity from water color data and evaluation of such techniques. The oceanic parameter maps produced in meeting the specific objectives were designed for the use of NMFS in its efforts to relate the resource data with information that could be remotely acquired.

## DATA ACQUISITION

Fulfillment of the NMFS objective required a large-scale acquisition effort that included satellites, aircraft, oceanographic vessels, and fishing boats. Woods and Cook (ref. 11) have documented the surface operations.

Figure 2 is a map of the test area showing the sampling squares to which all fisheries data were referenced. Also shown in the figure is the groundtrack of the Skylab satellite. The location of surface observation stations at which oceanographic and meteorological data were obtained by the oceanographic vessels and the location of flight lines scheduled for the two aircraft are shown in figure 3. Oceanographic vessels were equipped with long-range navigation (loran) systems, which enabled location of the ships at their stations with an accuracy estimated to be approximately 900 meters (0.5 nautical mile). By monitoring a radio beacon on the NASA vessel, The ERL, located at the intersection of the flight lines, the aircraft crews were able to closely fly the planned lines. Because the only orientation points were The ERL and the intersection of two of three flight lines with the coast, positioning of the light aircraft data along the flight line is subject to error, estimated to be on the order of as much as 4 kilometers (2.2 nautical miles). Inertial navigation equipment on the NC130B enabled much greater accuracy ($\leq$900 meters ($\leq$0.5 nautical mile)) in positioning of data acquired from that platform.

The first day of scheduled aircraft operations coincided with bad weather conditions that prevented acquisition of aerial and satellite data. On August 5, 1973, the second day of remote operations, which included the Skylab Earth resources experiment package (EREP) pass, conditions were partly cloudy but acceptable for aerial operations. Because cloud cover was expected to increase during the late morning and extensive thundershower activity was anticipated for the afternoon, aircraft operations were accelerated to begin data collection at approximately 9 a.m. central daylight

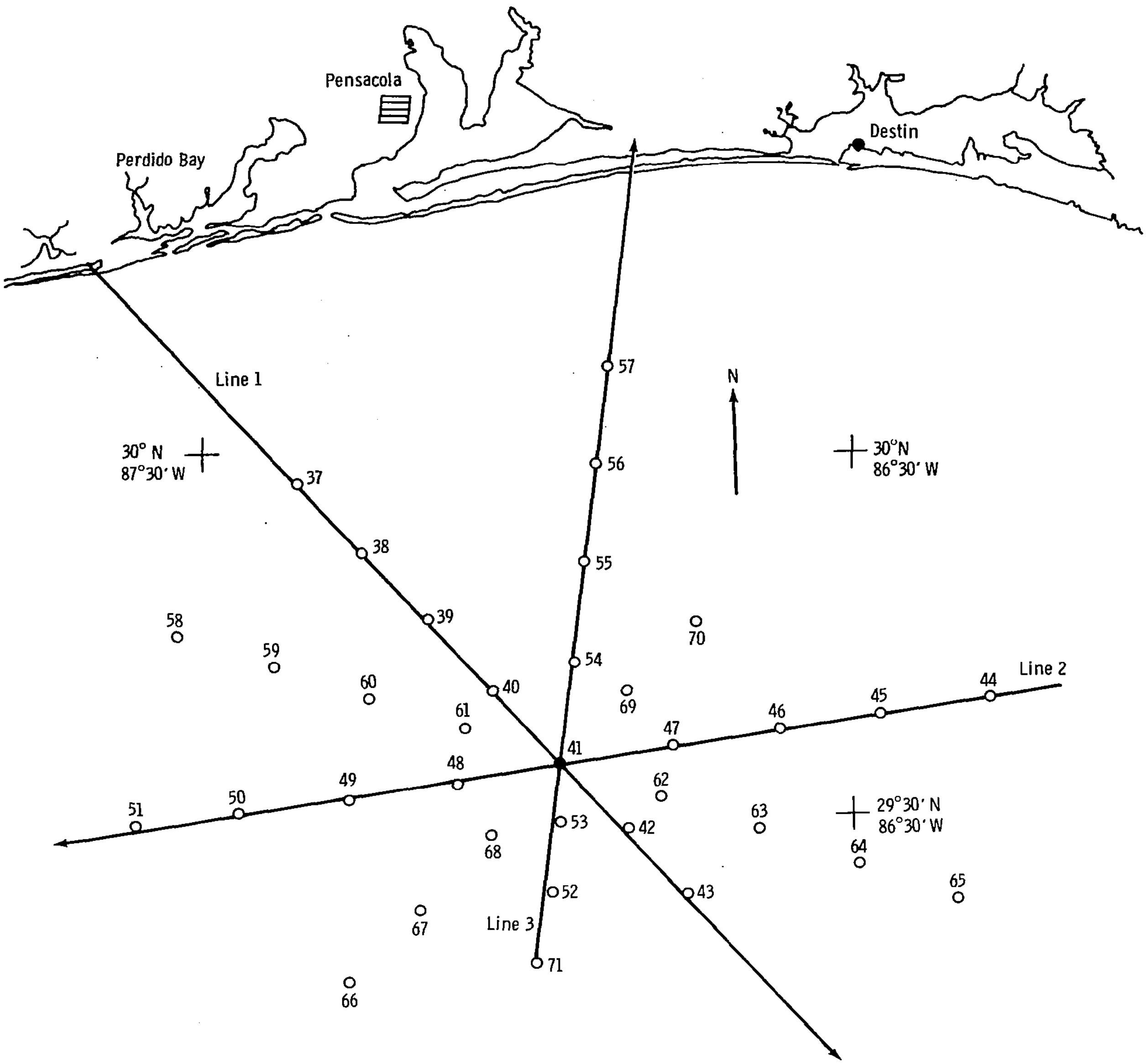


Figure 3.- Planned flight line and boat station map.

time. Increasing cloud cover during the morning resulted in the acquisition of data of questionable applicability on portions of the last flight line flown by the light aircraft.

While oceanographic and meteorological data were being collected and aircraft and satellites surveyed the test area, local fishermen were collecting the abundance of data on the gamefish. On August 4, 82 fishing boats were in the area; on August 5, 69.

## Surface Data

Scientific personnel onboard nine oceanographic vessels made and recorded the following observations: local time, water temperature, salinity, air temperature, wet- and dry-bulb thermometer readings, windspeed, wind direction, Secchi transparency, depth, and Forel-Ule color. Water samples were acquired for laboratory analysis; one sample from each station was prepared for chlorophyll extraction and refrigerated. Relative irradiance was measured at some stations, whereas spectroradiometer data were collected by two other vessels at different stations. Atmospheric pressure, visibility, and cloud cover were also recorded. The filter and suspended material that had been filtered from the water samples for chlorophyll analysis were frozen on the vessels and returned to the laboratory for analysis according to a slightly modified version[2] of the technique proposed by SCOR-UNESCO Group 17 in reference 12.

## Aircraft Data

Two aircraft were flown in the primary data acquisition effort, the light aircraft contracted by the ERL and the NC130B Earth survey aircraft operated by the NASA Lyndon B. Johnson Space Center. The light aircraft contained four data systems: three cameras, a spectral radiometer, a thermal scanner, and a boresighted radiation thermometer. The NC130B was equipped with several camera systems, a 24-channel multispectral scanner, a boresighted radiation thermometer, environmental sensors, and an inertial navigation system. The light aircraft operated at an altitude of 3000 meters, whereas the NC130B flew at 6100 meters.

A Texas Instruments RS-18 thermal scanner was operated with a trimetal detector sensitive in the 8- to 14-micrometer region of the spectrum. An Exotech 20-D spectroradiometer with a silicon detector element provided the spectral analysis of upwelling radiance in the visible and near-infrared regions. The data stream from these two radiometers and from the Barnes precision radiation thermometer (PRT-5) was recorded on analog tape for subsequent processing.

The camera systems on both aircraft provided good imagery, but, because of recording problems, the 24-channel scanner data were not usable. The PRT-5 onboard the NC130B provided good data that were used in the analysis described subsequently.

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[2]Jones, J. B.: Personal communication, 1973.

## Satellite Data

The NOAA-2 satellite and a U.S. Air Force satellite supplied data used in the direction of the surface operations. From the satellite imagery, it was determined that "blue water," thought to be good for fishing, had moved close enough to shore to enable concentration of the fisheries data acquisition effort in the area designated as the principal remote data acquisition area. Skylab data were collected shortly before 12 m., central daylight time, with the S190 camera systems, the S191 spectral radiometer, the S192 multispectral scanner, and the S194 L-band microwave radiometer. The Skylab data collection took place on track 62, orbit 15. The EREP sensors were operated on August 5, 1973, from 16:37:28 to 16:41:26 Greenwich mean time; coverage extended on both sides of the test area. Cloud cover rendered the S191 data unusable and sunglint contamination precluded use of the S192 scanner data for the water color analysis.

# MEASUREMENT OF WATER SURFACE TEMPERATURES

## Technical Approach

The RS-18 scanner data composed the principal data set for the surface temperature analysis. The calibration was performed according to verified algorithms (ref. 13) by which the data are corrected for atmospheric effects and displayed in a gray-level and digital form. In one technique, which requires an area of isothermal water, a corrective factor is constructed by forcing the remotely sensed temperature to agree with surface measurements in that area. Alternatively, radiosonde data can be used to construct an atmospheric correction term that can then be combined with a correction for known instrument errors. The RS-18 data were processed according to the first technique because of the atmospheric heterogeneity. The PRT-5 measurements for 50 points selected randomly were plotted as a function of the corresponding RS-18 temperature, which had been corrected for atmospheric effects. The slope and intercept of the best fit lines drawn through the two sets of data gave the corrections for the PRT-5 measurements of surface temperature for both the 6100- and 3000-meter altitudes. The high-altitude PRT-5 data are plotted as a function of corrected RS-18 data for one of the flight lines in figure 4. Thermal data from the 24-channel scanner were not available.

The thermal map of the study area was constructed from the three data sets. The RS-18 temperature was noted along each flight line at 40-second intervals, which correspond to distances of approximately 3.7 kilometers (2 nautical miles) on the surface. Where there appeared to be a momentary system malfunction, data from the light-aircraft-mounted PRT-5 were used; when clouds obscured the surface or when it appeared that atmospheric nonhomogeneities were distorting the measurement, the PRT-5 temperature acquired by the NC130B was examined to determine whether the same effects were present. If they were not, the temperature measured at the higher altitude at a slightly different time was used in constructing the surface temperature map. If the same anomalies were present and no clouds were visible in either set of coincident photography, it was assumed that the water temperature was varying in an unusual manner and the remote data

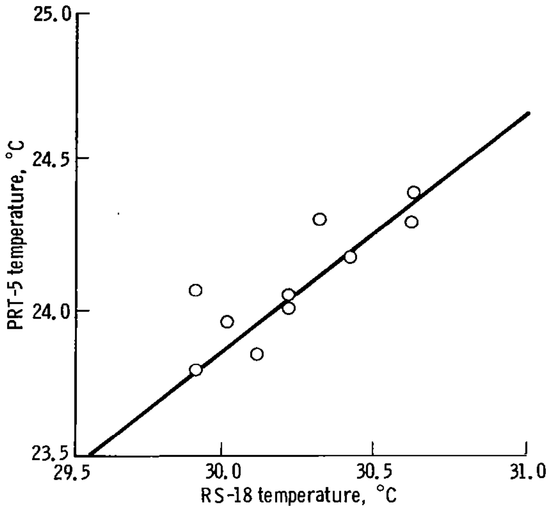
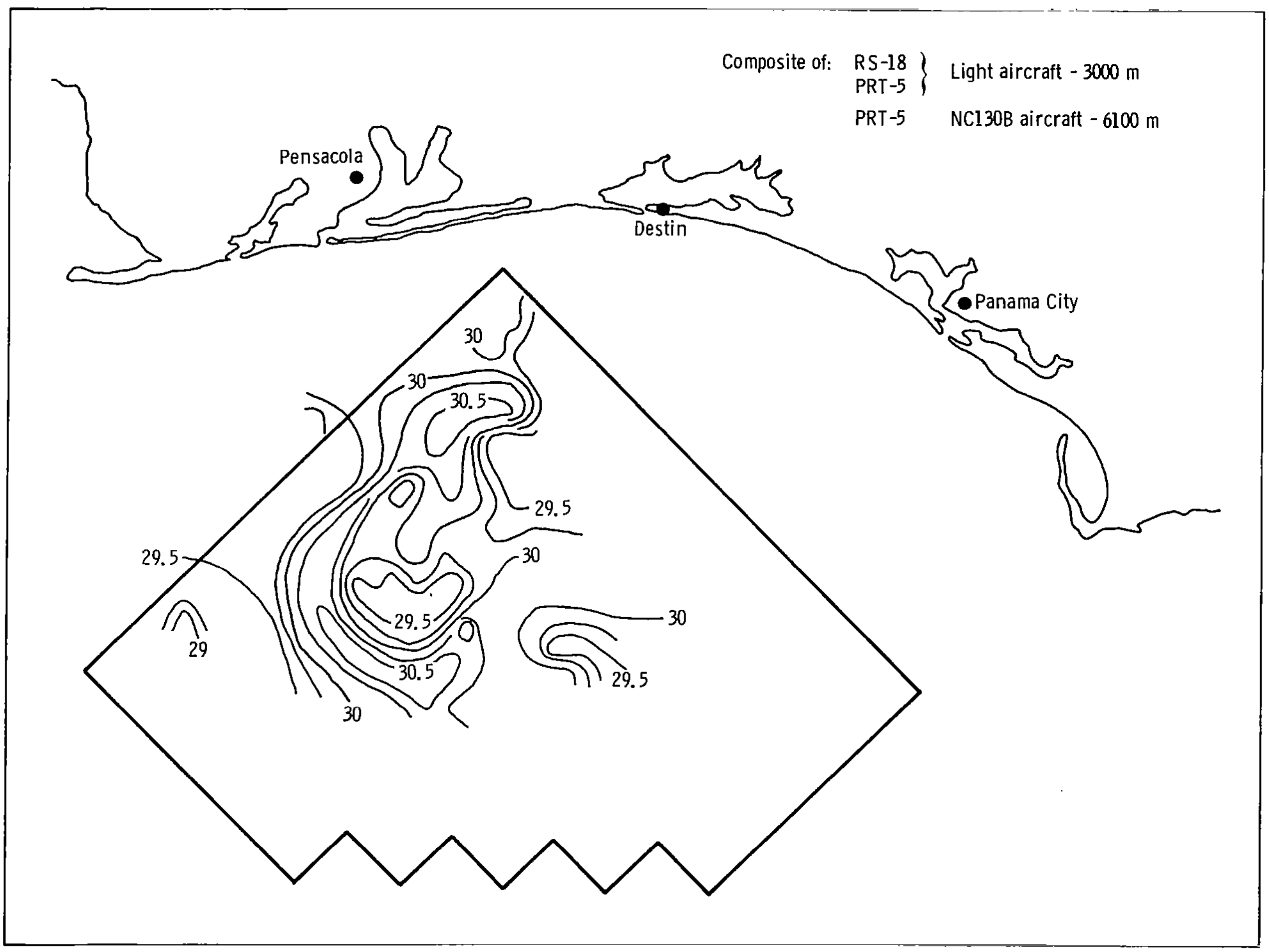
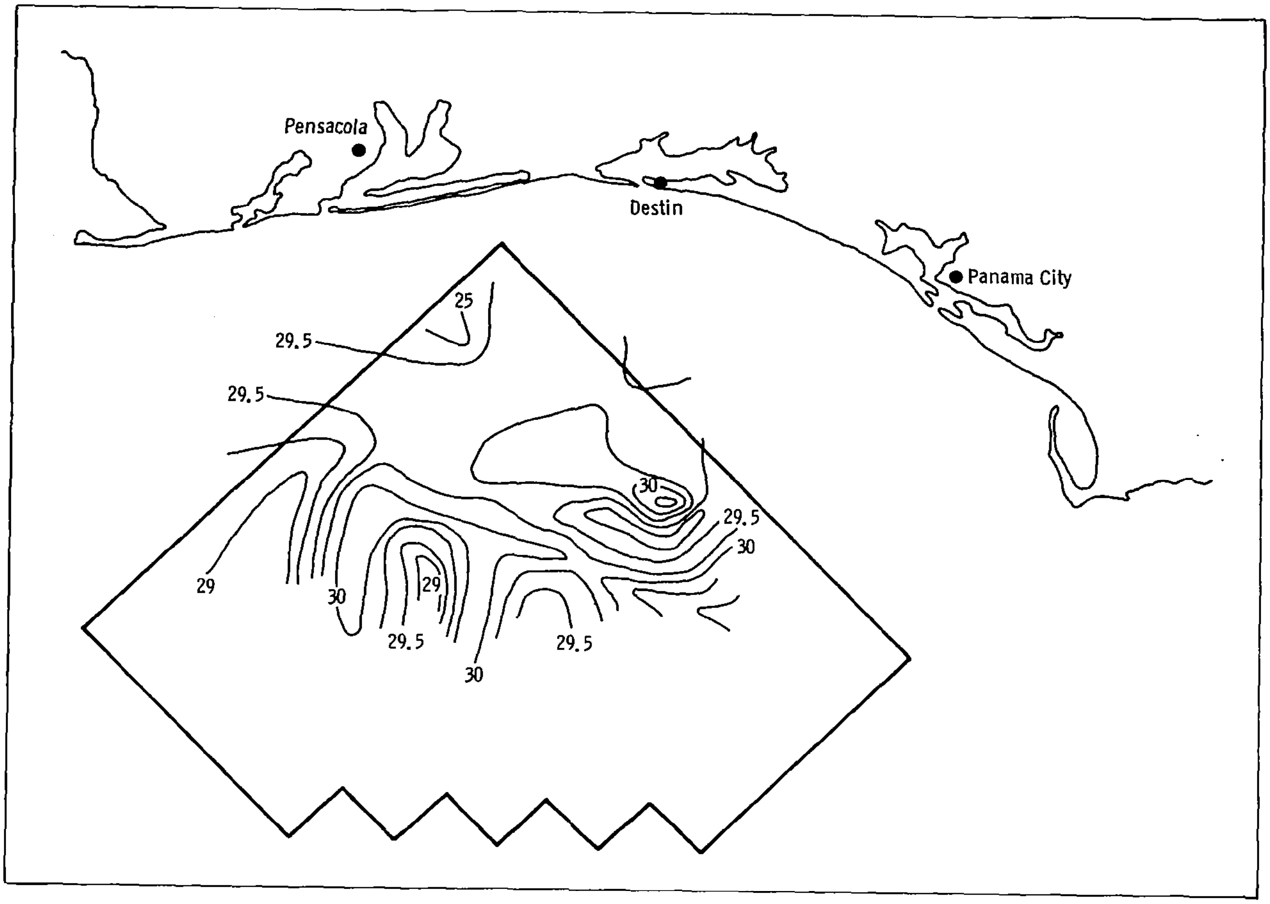



Figure 4.- Comparison of remotely sensed temperature as measured by the PRT-5 from an altitude of 6100 meters and derived from 3000-meter RS-18 measurements.




(a) Remote measurements.

Figure 5.- Analysis of water temperature data. Values are in degrees Celsius; contour interval: 0.25° C.




(b) Surface measurements.

Figure 5.- Concluded.

were accepted; if clouds were present in either set of coincident photography, neither temperature measurement was accepted because perturbations by clouds or atmospheric variations were assumed. From the compilation of temperatures along the flight lines, isotherms were hand-drawn in an attempt to interpolate between flight lines.

Because surface data were collected throughout the day and the temperature measurement at a given point was often made at a time different by several hours from the aerial survey, a normalizing procedure to account for surface warming due to insolation was developed. All the temperatures measured at each hour were averaged for the entire test area, and the deviation of this average from the average at a time midway through the aircraft mission was computed. These deviations were then used as corrective terms to normalize the surface measurements to the central time.

## Analysis Results and Evaluation

The remote and in situ surface temperature measurements have been used to construct thermal contour maps of the test area. Figure 5(a) is the contour map drawn from these data, figure 5(b) shows the isotherms derived from the surface measurements, which have been normalized for warming due to insolation to a time midway through the aerial data acquisition exercise.

Comparison of figures 5(a) and 5(b) does not reveal a high degree of similarity. The surface data were taken along two other transects in addition to the three that coincide with the flight lines, but the distance between sample stations along the transects was considerably more than the 4-kilometer (2.2 nautical mile) sampling distance used in processing the remote data. The differences in sampling locations may be the source of some of the discrepancy, but the poor matching of even general trends could not be attributable to such differences. Another source of error in the geographic presentation of the data is error in defining the location of the aircraft along the flight lines. For example, expansion of the remote data along flight line 2 (the east-west line), which would correct for possible underestimation of aircraft velocity, would improve the correspondence of the two data sets. Because of discrepancies observed in the overlap of photographic frames, the hypothesis that the actual groundspeed of the aircraft was greater than the speed used in the data reduction is tenable for the light aircraft, which had no inertial navigation equipment and which was the principal source of data for the remote measurement.

The major problems in interpreting the two sets of temperature measurements are the very small temperature gradients found in the test area and the variation of the moisture content of the atmosphere. The corrected in situ measurements varied by only $1.25^{\circ}$ C, whereas a variation of $1.7^{\circ}$ C was found in the remote data set. Because of atmospheric heterogeneity, which was indicated by surface measurements and the forming cumulus clouds, it would be unreasonable to expect the $0.1^{\circ}$ C relative accuracy theoretically possible with the remote thermal techniques to be achieved in this experiment. Only a single correction factor can be used for each flight line, but variations of the required correction factor of as much as $0.23^{\circ}$ C can be expected over a single line. The magnitude of this variation was determined using

Boudreau's model (ref. 2) with meteorological data acquired at the surface sampling stations and from a radiosonde launched at Eglin Air Force Base. This larger error would introduce rather large discrepancies into the remote thermal contour map. Another fact that must be considered is the precision of the in situ measurements, the error of which can normally be as large as 0.2° C. An error of this magnitude would distort the contours of either the surface or remote map considerably because of the small actual gradients involved.

The extent to which it was necessary to combine the data from the two PRT-5 sensors and the RS-18 scanner within the constraints of cloud cover and apparent severe atmospheric variation was not as great as had initially been anticipated. There were two areas along flight line 1 (the northwest-southeast line) where banding was present in the RS-18 data; data from the PRT-5 borne by the same aircraft as the RS-18 were used in these areas. The cause of the banding has not been determined conclusively. In most regions affected by clouds, it was possible to find cloud-free areas in the scanner imagery away from the center of the flight line. In several areas that were clouded across the entire scanner coverage, data from the PRT-5 flown at a different time were used. Even though the aircraft were flown at different times, some of the areas that were obscured by clouds in one data set were also at least partly under clouds when the other aircraft passed over the areas; thus, the extent to which the data from the two flights could be used as supplements was decreased.

## MEASUREMENT OF CHLOROPHYLL-a

### Technical Approach

As discussed previously, no algorithm based on elementary principles exists for the calculation of chlorophyll concentration or turbidity from spectral radiance measurements, even though variation of these parameters obviously does influence, if not determine, water color. An example of the change is seen in figure 6, in which the spectra from approximately 11 kilometers (6 nautical miles) of flight line 2 reflect a rapid change of 0.6 $mg/m^3$ in chlorophyll content and a change of 7 meters in the Secchi extinction depth. Weldon (ref. 7) and Holyer[1] have developed empirical models that were successfully applied to data acquired over the Mississippi Sound. Weldon's techniques and their variations were applied to the data acquired with the Exotech 20-D spectrometer in the open Gulf of Mexico during this experiment and were evaluated comparatively. The variations consisted primarily of optimizing the information contained in the set of radiance data used in the models by statistical analysis.

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[1]Holyer, Ronald J. (unpublished report): A Statistical Method for Determination of Chlorophyll Concentration From the Remotely Sensed Ocean Surface Albedo. Lockheed Electronics Co., Inc., Bay St. Louis, Miss., Contract NAS 9-11584, 1973.

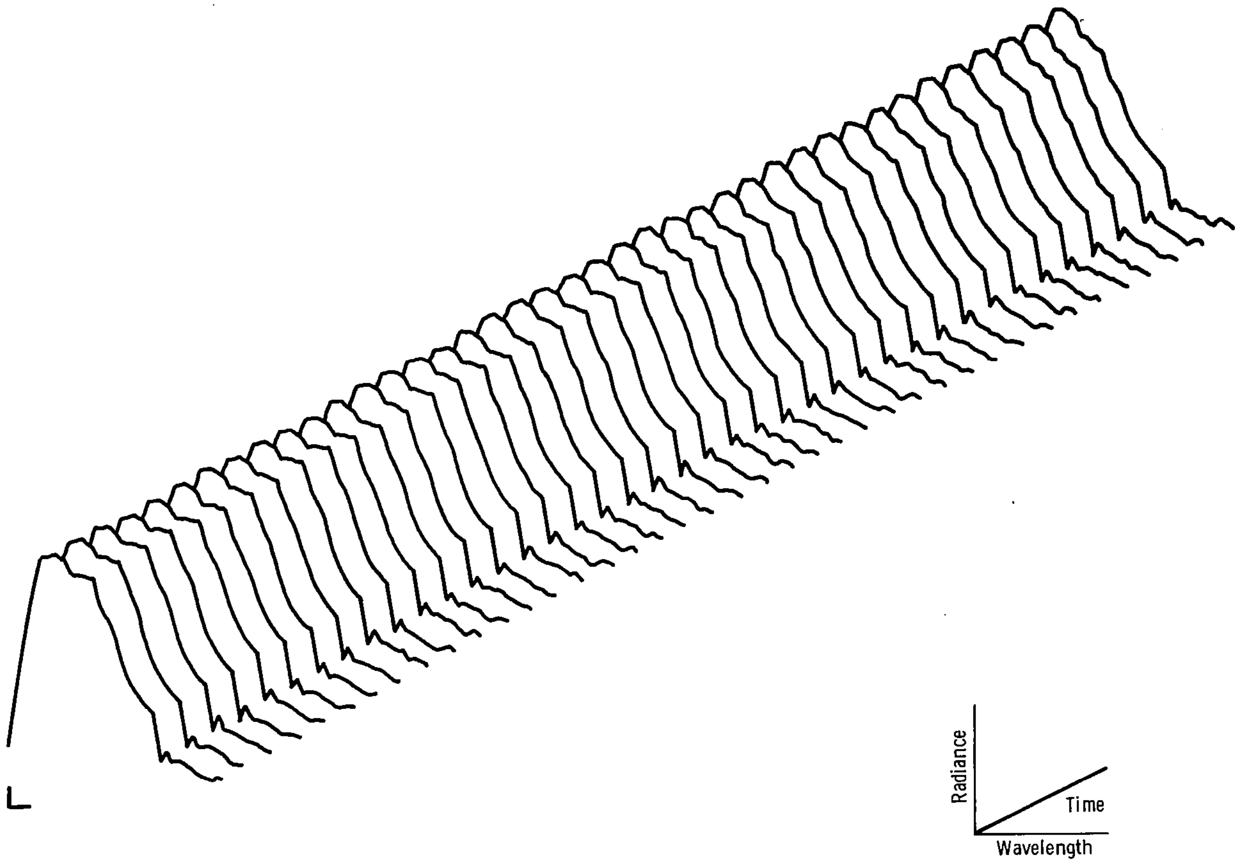



Figure 6.- Isometric plot of radiance spectra for approximately 11 kilometers (6 nautical miles) along flight line 2.

It was evident that the Weldon techniques were not adequate, and the number of surface measurements was insufficient to apply Holyer's technique. New procedures for determining these parameters from the spectra were therefore developed.

The selection of surface measurements to serve as calibrations for the models was primarily based on providing the best models for the remote measurement of the oceanographic parameters. All stations that were sampled within 3 hours of the aircraft flyover and that were not under clouds were selected as calibration points. Several calibrations were dropped because data from the spectrometer were erratic in the area of the station. This deletion left 9 of the available 18 calibration points to use for the chlorophyll models.

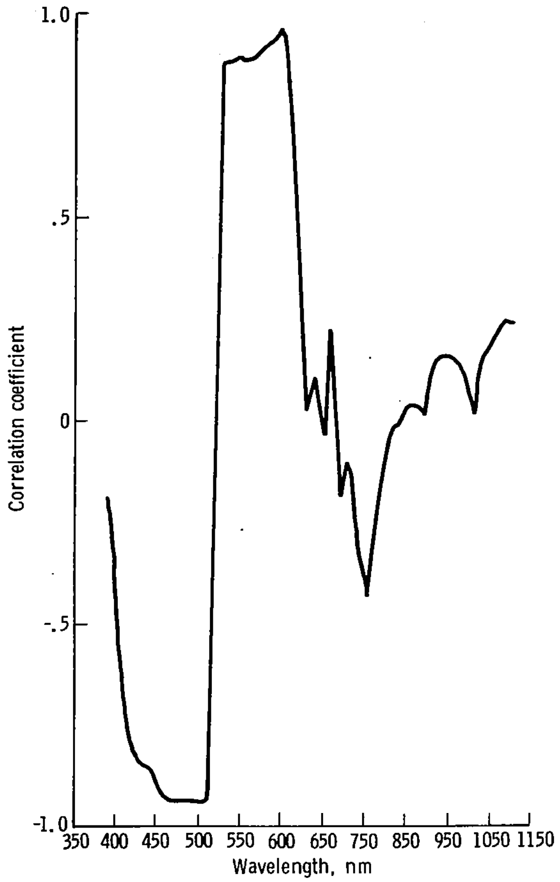
Using the selected surface control points, Weldon's technique (ref. 7) was first applied in the chlorophyll study. The coefficients $a_1$ and $a_2$ of the equation

$$C_W = a_1(R_{620} - R_{470})/R_{520} + a_2 \qquad (1)$$

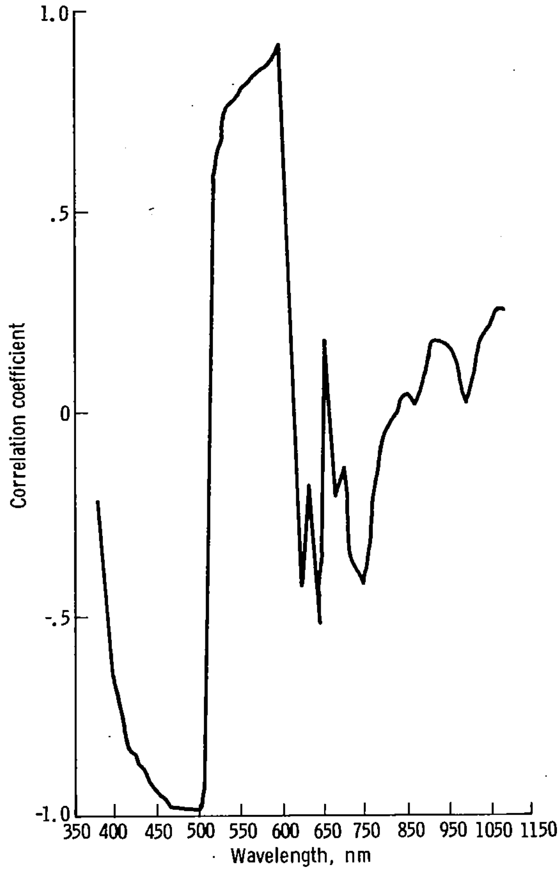
were determined by plotting the normalized difference of radiance values $(R_{620} - R_{470})/R_{520}$ against chlorophyll-a concentration and by measuring the slope and intercept of the straight line that best fitted the data. In equation (1), $R\lambda$ represents radiance at wavelength $\lambda$ in nanometers.

Because Holyer's technique showed improved accuracy over Weldon's for the Mississippi Sound data, it appeared that perhaps information important to the chlorophyll content determination was being lost by using only the three wavelengths. A technique known as principal-factor analysis was then applied to the 520-nanometer normalized radiance data in an effort to obtain maximum information content and minimum redundancy. Using a variation of this analysis, a set of six wavelengths was selected such that the normalized radiance at these wavelengths contained 99.9 percent of the total information contained in the entire normalized visible spectrum. The wavelengths selected by means of this analysis were 480, 560, 630, 769, 911, and 1073 nanometers. A least-squares technique was used to construct a linear function of these normalized radiance values for calculating the chlorophyll-a concentration $C_p$.

The principal-factor approach maximized the information content of the set of radiance measurements being used in the chlorophyll calculation, even though some of the information included was not relevant to the chlorophyll content. An effort was then made to optimize rather than maximize the information content by examining the linear correlation coefficient of the 520-nanometer normalized radiance with chlorophyll-a content on a wavelength-by-wavelength basis. Figure 7(a) is a graph of the correlation coefficient as a function of wavelength. This graph indicates that the radiance at 600 and 470 nanometers (normalized by the radiance at 520 nanometers) is highly correlated with the chlorophyll-a concentration. After considering the lower correlation between these wavelengths compared with several other pairs (which indicated relatively less redundancy between the two), they were selected as the optimum wavelengths for this study. Correlation coefficients were -0.941 for 470 nanometers, 0.974 for 600 nanometers, and 0.949 for the correlation




(a) Normalized by radiance at 520 nanometers.




(b) Normalized by radiance at 620 nanometers.

Figure 7.- Linear correlation of chlorophyll-a with radiance.

between the radiance measurement at the two wavelengths. Because Holyer used a fourth-power relationship between chlorophyll content and the weighted sum of normalized radiance values, a function of the form

$$C_c = \left[a_1(R_{600} - R_{470})/R_{520} + a_2\right]^{a^3} \qquad (2)$$

was analyzed using a least-squares error technique to determine values for $a_1$, $a_2$, and $a_3$ to compute the chlorophyll content $C_c$. The symbol $R_\lambda$ represents the radiance measurements at wavelength $\lambda$. Because the value of $a_3$ was found to be very close to 0.5, this parameter was set to 0.5 and the coefficients $a_1$ and $a_2$ were again computed.

The values of $C_c$ followed the surface measurements well at low chlorophyll levels, whereas $C_p$ matched better at higher values. Because the $C_c$ function flattened out at just above 2.2 mg/m$^3$, a composite function was developed that used $C_c$ until it exceeded 2.0 mg/m$^3$, then used $C_p$. Equation (3) represents the composite function.

$$C_{comp} = \begin{cases} (1) \sqrt{a_1(R_{600} - R_{470})/R_{520} + a_2} & \text{if } (1) < 2.0 \\ (2) \displaystyle\sum_{n=1}^{6} a_n R_{\lambda_n} \Big/ R_{520} & \text{if } (1) \geq 2.0 \end{cases} \qquad (3)$$

where $\lambda_n$ = 480, 560, 630, 769, 911, and 1073 nanometers and $n$ = 1,6.

The 520-nanometer radiance was used for normalization because of the relative constancy of this radiance with respect to chlorophyll content. The 520-nanometer radiance appears to be the point in the spectrum at which absorption by chlorophyll-a is offset by scattering by the chlorophyll-bearing phytoplankton. Toward the shorter wavelength end of the spectrum, the absorption by chlorophyll is the dominant effect; toward the longer wavelengths, the scattering by the phytoplankton increases the upwelling light to more than compensate for the chlorophyll absorption. The chlorophyll molecule has an absorption minimum in the 550- to 625-nanometer region of the spectrum (ref. 5); therefore, if it were not for scattering effects, this would obviously be the best spectral region for normalization. However, the fact that other scatterers besides phytoplankton (e.g., inorganics) are present in the water suggests that the contribution of the chlorophyll-bearing organisms to the total backscattering function may not be dominant and, hence, that the 600-nanometer region of the spectrum might provide a normalization because of increased independence of absorption by chlorophyll. Consequently, the correlation analysis was repeated using the radiance at 620 nanometers for normalization. A graph of the correlation coefficient for this data set is shown in figure 7(b).

This analysis demonstrated that the blue region of the spectrum was again negatively correlated, with a maximum correlation at 490 nanometers; a second maximum in the plot of correlation coefficient as a function of wavelength is found at 610 nanometers, only 10 nanometers away from the normalization wavelength. Predictors were developed that use the ratio of radiance at 490 nanometers to that at 620 nanometers, the ratio of radiance at 610 nanometers to that at 620 nanometers, and the difference of radiances at 490 and 610 nanometers divided by the radiance at 620 nanometers.

## Analysis Results and Evaluation

The chlorophyll models based on the 520-nanometer normalization were stable and were subjected to detailed evaluation. The normalization by the radiance at 620 nanometers yielded results that matched the calibration points very well, as would be expected from the high linear correlation, but the functions developed with this data set were very erratic and frequently yielded large negative values. The cause for the unusual behavior of the function was not determined, and the models based on 620-nanometer normalization were not subjected to detailed evaluation because of the obvious failure to provide a physically acceptable prediction.

Table I contains the surface measurements ($C_s$) with the remote measurement ($C_w$,$C_p$,$C_c$) given by each of three techniques (with 520-nanometer normalization) and the respective deviations ($\Delta_w$,$\Delta_p$,$\Delta_c$). It is evident that the first set of values given by the Weldon function $C_w$ is more accurate than the other two sets. Further analysis demonstrates that the function for $C_c$ (eq. (2)) flattens out above 2.2 mg/m$^3$ but gives accurate results when the predicted chlorophyll concentration is less than 2 mg/m$^3$. The function for $C_p$ is the most accurate of the three above 2 mg/m$^3$ as the function continues to track the surface measurements. The remotely acquired chlorophyll-a measurements that were used in the contour map were computed using the composite technique (eq. (3)). Table II contains the surface measurements with the corresponding remote measurement as determined by this composite technique, which gave a root-mean-square (rms) error of 0.4 mg/m$^3$ over a range of 0.0 to 5.0 mg/m$^3$ for 18 points, 9 of which were used for calibration. The rms error for the nine points not used for calibration was also 0.4 mg/m$^3$.

Using the composite technique, plots of chlorophyll-a content along flight lines 2 (east-west) and 3 (north-south) were developed (figs. 8(a) and 8(b)). They indicate that, when geographical errors are considered, the remote measurement may be more accurate than 0.4 mg/m$^3$ as indicated by the error analysis. The remote measurement of chlorophyll-a content based on the composite technique was used to develop the contour map of the test area (fig. 9(a)). This map may be compared with a similar map generated from surface measurements (fig. 9(b)).

One very interesting point in the comparison is the small patch of high chlorophyll concentration seen at the center of the study area in the remote chlorophyll map but not found in the map based on surface measurements. No surface measurements were taken in this area; thus, the sharp gradient could not appear in those interpolated data. The crew of the oceanographic vessel that was stationed immediately south of this area reported passing through an area of very green water shortly before arriving on station, where the water was considerably more blue. Although the description of the water

## TABLE I.- EVALUATION OF REMOTE CHLOROPHYLL MEASUREMENTS

(Values in milligrams per cubic meter)

| Surface measurement | $^{a}C_w$ | $^{b}\Delta_w$ | $^{c}C_p$ | $^{b}\Delta_p$ | $^{d}C_c$ | $^{b}\Delta_c$ |
|---|---|---|---|---|---|---|
| $^{e}$1.3 | 0.9 | 0.4 | 1.0 | 0.3 | 1.2 | 0.1 |
| 1.6 | 1.1 | .5 | 2.0 | .4 | 1.2 | .4 |
| $^{e}$.8 | .8 | .0 | .7 | .1 | 1.1 | .3 |
| $^{e}$1.7 | 1.8 | .1 | 1.8 | .1 | 1.7 | .0 |
| $^{e}$.3 | .4 | .1 | .4 | .1 | .5 | .2 |
| $^{e}$.3 | .3 | .0 | .4 | .1 | .3 | .0 |
| $^{e}$.4 | .3 | .1 | .4 | .0 | .3 | .1 |
| $^{e}$1.5 | 1.5 | .0 | 2.5 | 1.0 | 1.6 | .1 |
| $^{e}$1.7 | 2.1 | .4 | 2.2 | .5 | 1.6 | .1 |
| $^{e}$1.6 | 1.4 | .2 | 1.8 | .2 | 1.5 | .1 |
| 2.3 | 2.5 | .2 | 3.4 | 1.1 | 1.8 | .5 |
| 3.5 | 2.2 | 1.3 | 3.6 | .1 | 2.1 | 1.4 |
| .4 | .4 | .0 | 1.3 | .9 | .3 | .1 |
| .3 | .6 | .3 | 1.2 | .9 | .4 | .1 |
| .4 | 1.3 | .9 | 1.8 | 1.4 | 1.3 | .9 |
| 1.5 | 1.9 | .4 | 1.8 | .3 | 1.8 | .3 |
| 1.7 | 1.8 | .1 | 1.8 | .1 | 1.9 | .2 |
| 4.7 | 3.5 | 1.2 | 5.0 | .3 | 2.5 | 2.2 |
| rms deviation | | 0.52 | | 0.62 | | 0.73 |

$^{a}C_w = a_1(R_{620} - R_{470})/R_{520} + a_2$.

$^{b}\Delta_m$ = magnitude of deviation of $C_m$ from surface measurement.

$^{c}C_p = \Sigma a_n R_{\lambda n}/R_{520}$ where $\lambda_n$ = 480, 560, 630, 769, 911, and 1073 nanometers.

$^{d}C_c = \sqrt{a_1(R_{600} - R_{470})/R_{520} + a_2}$.

$^{e}$ Calibration point.

TABLE II.- EVALUATION OF REMOTE CHLOROPHYLL MEASUREMENTS USING COMPOSITE TECHNIQUE

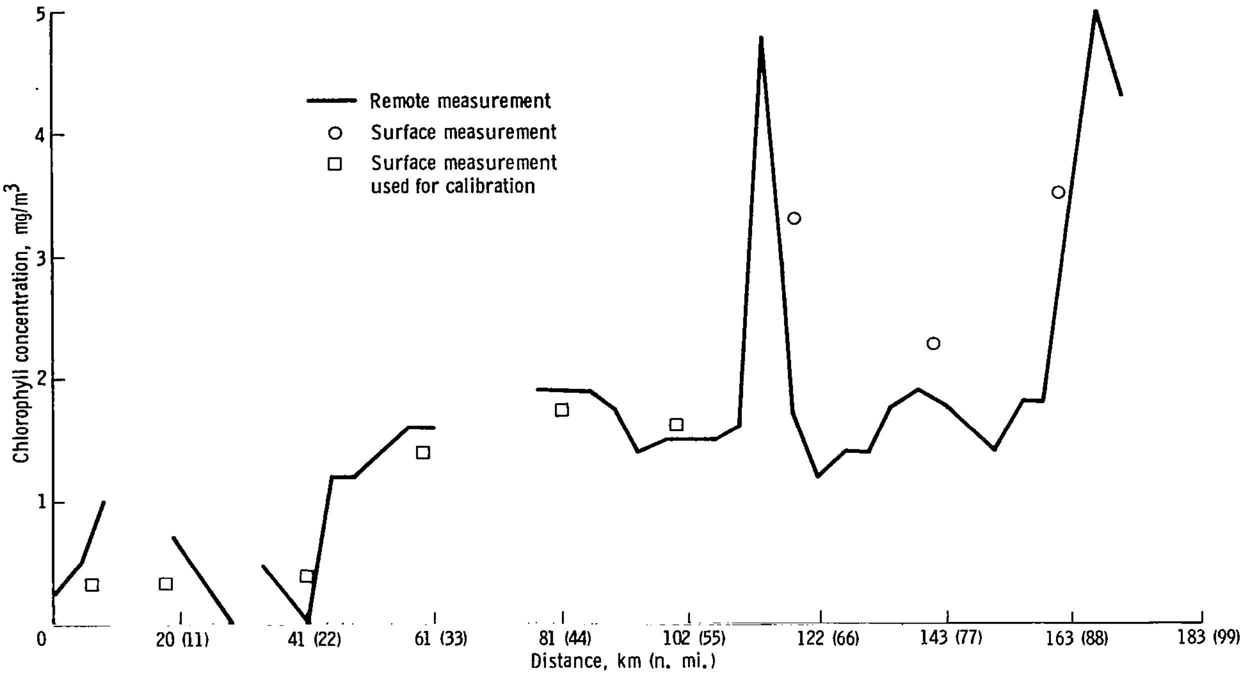
(Values in milligrams per cubic meter)

| Surface measurement | [a]$C_{comp}$ | [b]$\Delta_{comp}$ |
|---|---|---|
| [c]1.3 | 1.2 | 0.1 |
| 1.6 | 1.2 | .4 |
| [c].8 | 1.1 | .3 |
| [c]1.7 | 1.7 | .0 |
| [c].3 | .5 | .2 |
| [c].3 | .3 | .0 |
| [c].4 | .3 | .1 |
| [c]1.5 | 1.6 | .1 |
| [c]1.7 | 1.9 | .2 |
| [c]1.6 | 1.5 | .1 |
| 2.3 | 1.8 | .5 |
| 3.5 | 3.6 | .1 |
| .4 | .3 | .1 |
| .3 | .4 | .1 |
| .4 | 1.3 | .9 |
| 1.5 | 1.8 | .3 |
| 1.7 | 1.9 | .2 |
| 4.7 | 5.0 | .3 |
| | | .2 |
| rms deviation | | 0.38 |

[a]See equation (3).

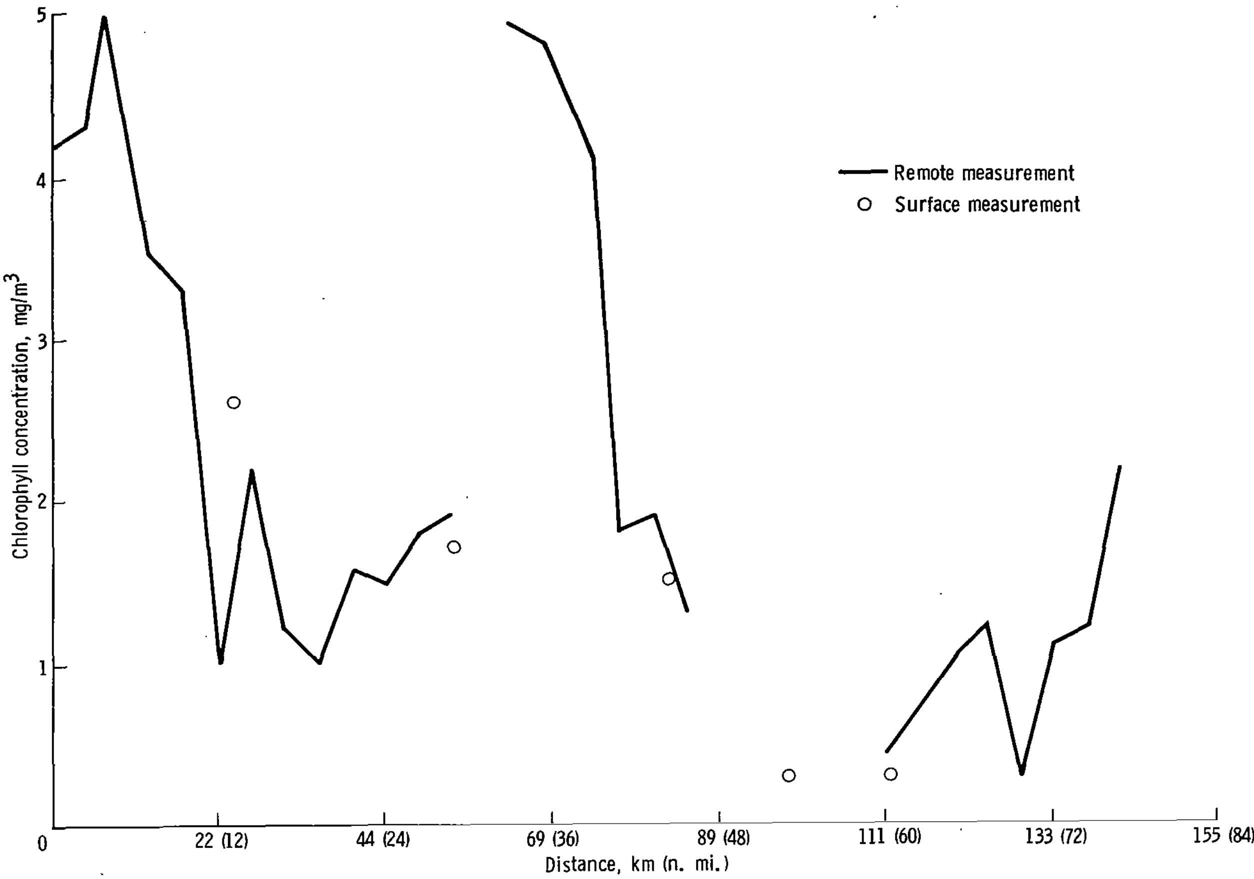
[b]$\Delta_{comp}$ = magnitude of deviation of $C_{comp}$ from surface measurement.

[c]Calibration point.



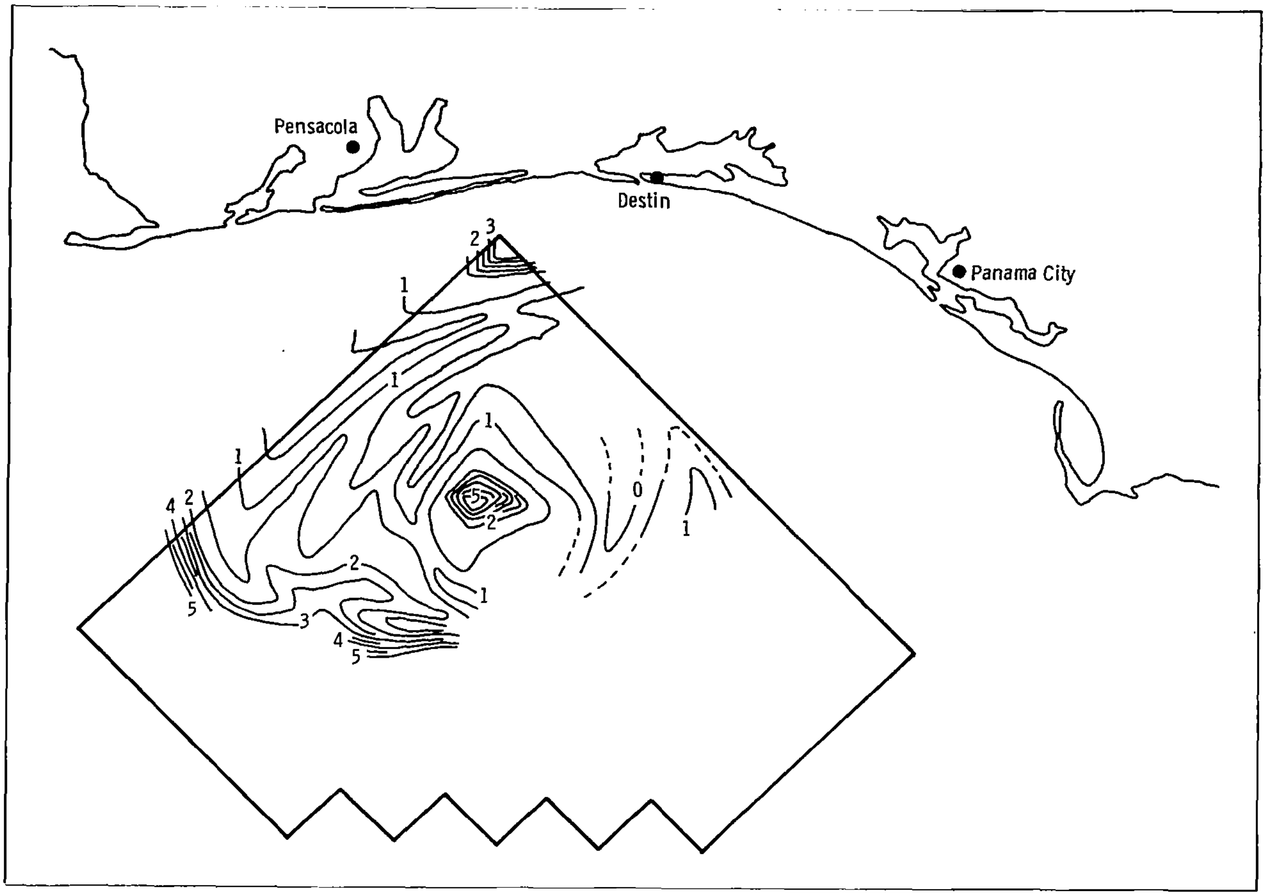

(a) Along flight line 2.

Figure 8.- Chlorophyll-a measurements.



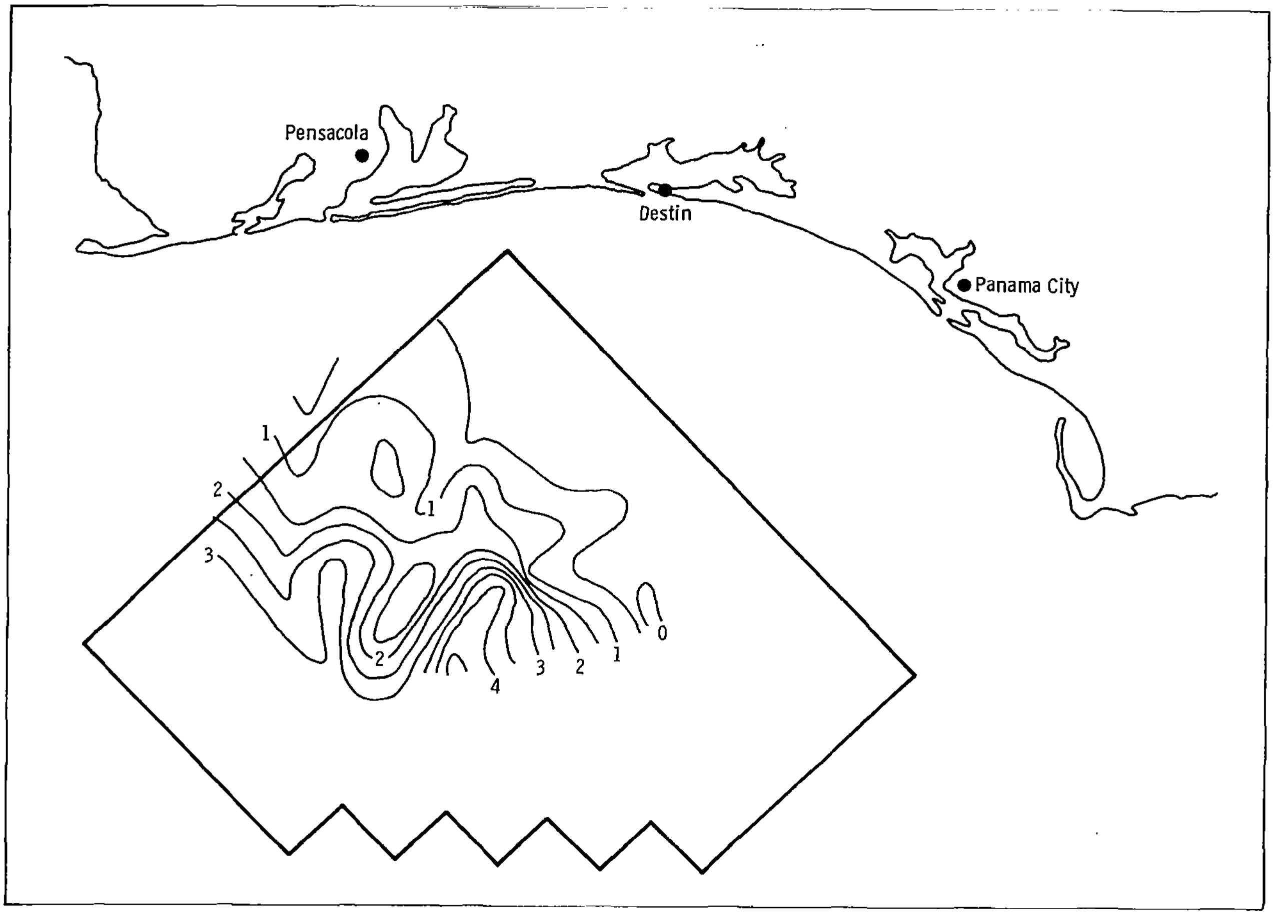

(b) Along flight line 3 (no calibration points on this flight line).

Figure 8.- Concluded.




(a) Remote measurements.

Figure 9.- Analysis of chlorophyll-a data. Values are in milligrams per cubic meter. Contour interval: 0.5 mg/m$^3$.




(b) Surface measurements.

Figure 9.- Concluded.

color does not verify the high chlorophyll concentration measured remotely, it does lend credibility to the measurements.

The accuracy of the chlorophyll-a measurements that were used to evaluate and calibrate the remote measurements must also be considered. The laboratory analysis of the sample is the most readily evaluated phase of the surface measurement of chlorophyll and has been found to be repeatable with an error of 5 percent. Another factor that affects the error analysis is variation of pigment in a given sample with time. The average error estimated for the entire process, from sample acquisition through spectroscopic analysis, is 10 to 15 percent.

In evaluating the success of this attempt to remotely measure chlorophyll-a content, one must consider a very important qualification on the analysis. The experiment was conducted in an area that appeared to be homogeneously free of large concentrations of dissolved organic pigments. Although no direct measurements of such pigments were made, such a conclusion may be drawn from the fact that the waters were generally described as very blue. The presence of dissolved organic pigments, known as Gelbstoffe, would have caused the water to be green. Had there been a high Gelbstoffe concentration or if it had varied significantly over the test area, the accuracy of the remote measurement would have been degraded. It is possible that the area indicated in the remote data set to have a high chlorophyll content, in fact, had a high concentration of Gelbstoffe rather than chlorophyll.

## MEASUREMENT OF TURBIDITY

### Technical Approach

The approach used for calculating Secchi transparency measurements of turbidity was similar to the one used for determining chlorophyll concentration. Weldon's technique was attempted first, followed by principal-factor analysis and linear correlation analysis to select wavelengths at which the radiance would be used in a linear model. Several normalization procedures were used. The criteria for selecting the calibration points were the same as those used in the chlorophyll study and eliminated 11 of 19 possible surface measurements.

Weldon (ref. 7) found that the ratio of radiance at 550 nanometers to that at 600 nanometers provided an accurate calculation of the Secchi extinction depth in the Mississippi Sound. Analysis showed that this algorithm was not applicable to the data obtained over the Gulf of Mexico, because it was impossible to define the necessary coefficients because of the scatter of the points. The ratio of radiance at 420 nanometers to that at 570 nanometers correlated well with the turbidity measurements; therefore, a model using this simple ratio method was constructed according to the following equation.

$$S_R = a_1 R_{420}/R_{570} + a_2 \qquad (4)$$

The fact that Holyer's calculation of turbidity was more accurate than Weldon's calculation again led to the hypothesis that not all relevant information contained in the spectral radiance data was being used in the simple two-wavelength ratio technique. Principal-factor analysis was again used to maximize the information content of a selected set of wavelengths. For this analysis, the radiance was normalized using the average radiance over the entire visible spectrum, the same normalization procedure used by Holyer. Six wavelengths that contained 99.95 percent of the information of the entire normalized visible spectrum were selected. A linear combination of the radiance at these wavelengths was then fitted to the surface measurements by the least-squares technique to give the model for $S_D$. The wavelengths selected for this analysis were 440, 490, 560, 630, 748, and 867 nanometers.

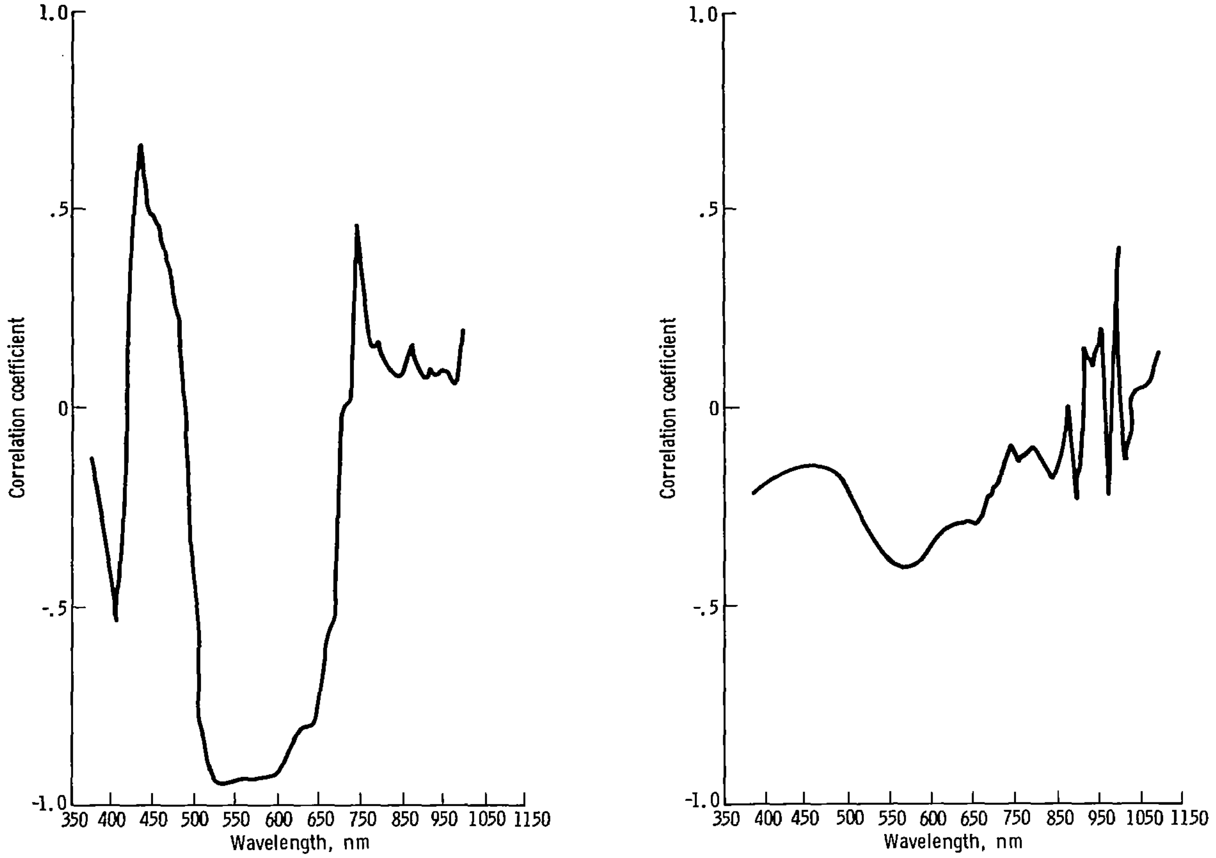
A third algorithm was applied to optimize, rather than maximize, the information content relative to the Secchi transparency measurement. Using a procedure analogous to that used with chlorophyll, this optimization was performed selecting wavelengths that showed high correlation between radiance and turbidity and relatively low correlation between the respective radiance measurements. Unnormalized radiance data, radiance normalized by a wide band in the blue (390 to 430 nanometer) region of the spectrum, and radiance normalized by a wide band in the infrared (911 to 1073 nanometer) region were examined in the correlation analysis. Figures 10(a) and 10(b) are graphs of the linear correlation coefficients from the last two analyses plotted as a function of wavelength. With correlation coefficients of -0.554, 0.622, and -0.942, wavelengths of 410, 440, and 550 nanometers were selected from the blue normalized data to construct a linear function to calculate the remote turbidity measurements. Correlation of 410 to 440 nanometers was only -0.172, whereas the 410- to 570-nanometer correlation was 0.817 and the 440- to 570-nanometer correlation was 0.902. The unnormalized and infrared normalized analyses indicated very little correlation.

## Analysis Results and Evaluations

As had been anticipated, the remote measurement of turbidity corresponding to the Secchi transparency proved to be more difficult than the chlorophyll-a measurement, and the results were less satisfactory. The three different turbidity calculations with their widely divergent coefficients yielded very similar results. All followed the surface measurements well except in areas where Secchi extinction depths of 25 to 30 meters were reported.

Of the three sets of calculations, the linear function of the simple ratio of radiance (eq. (4)) gave the best results, with an rms error of 4.5 meters over the range of 3.2 to 28 meters for 19 points, of which 8 served as calibrations for the function. For the 11 points not used in calibration, the rms error was 5.6 meters. This value should be used with caution because of nonrandom selection of points for calibration and for evaluation. Table III contains the surface measurements, the three sets of remote measurements, and the respective deviations.

Figure 11 is a plot of the Secchi extinction depth along flight line 2 (east-west) and includes the surface measurements. The turbidity was computed using the simple ratio technique described by equation (4). The




(a) Normalized by mean blue radiance (390 to 430 nanometers).

(b) Normalized by mean infrared radiance (911 to 1073 nanometers).

Figure 10.- Linear correlation of Secchi transparency with radiance.

TABLE III.- EVALUATION OF SECCHI TRANSPARENCY MEASUREMENTS

(Values in meters)

| Surface measurement | [a]$S_R$ | [b]$\Delta_R$ | [c]$S_p$ | [b]$\Delta_p$ | [d]$S_c$ | [b]$\Delta_c$ |
|---|---|---|---|---|---|---|
| 20 | 18 | 1.8 | 22 | 2.4 | 20 | 0.3 |
| [e]13 | 13 | .3 | 12 | .3 | 15 | 2.1 |
| 9 | 16 | 3.7 | 14 | 5.5 | 18 | 9.1 |
| [e]4 | 8 | 3.4 | 5 | .6 | 5 | .9 |
| [e]18 | 15 | 2.7 | 27 | 8.8 | 17 | .9 |
| [e]17 | 16 | 1.2 | 15 | 1.5 | 16 | 1.2 |
| [e]12 | 16 | 3.0 | 16 | 3.0 | 16 | 3.0 |
| 28 | 20 | 7.6 | 19 | 9.4 | 19 | 8.8 |
| [e]8 | 7 | .6 | 5 | 2.1 | 6 | 1.5 |
| [e]4 | 3 | 1.5 | 2.1 | 2.1 | 2 | 1.8 |
| [e]99 | 6.1 | 3.4 | 9 | .9 | 8 | 1.2 |
| 6 | 4.6 | 1.5 | 12 | 6.1 | 6 | 0 |
| 5 | 5 | .6 | 8 | 2.7 | 8 | 3.4 |
| 27 | 12 | 15 | 10 | 16.8 | 12 | 14.3 |
| 21 | 16 | 4.9 | 15 | 5.8 | 16 | 4.9 |
| 8 | 8 | 0 | 11 | 3.0 | 7 | .6 |
| 5 | 3 | 1.5 | 5 | 0 | 5 | .3 |
| 17 | 14 | 2.7 | 18 | 1.2 | 14 | 2.7 |
| 16 | 12 | 3.0 | 19 | 3.0 | 12 | 3.0 |
| rms error | 4.5 | | 5.6 | | 4.8 | |

[a]$S_R = a_1 R_{420}/R_{570} + a_2$.

[b]$\Delta_m$ = magnitude of deviation of $S_m$ from surface measurements.

[c]$S_p = \sum^{6} a_n R_{\lambda n}/\langle R\rangle$ ($\lambda_n$ determined by principal-factor analysis).

[d]$S_c = \sum^{3} a_n R_{\lambda n}/\langle R_{390-430}\rangle$ ($\lambda_n$ determined by examination of linear correlation coefficients).

[e]Calibration point.

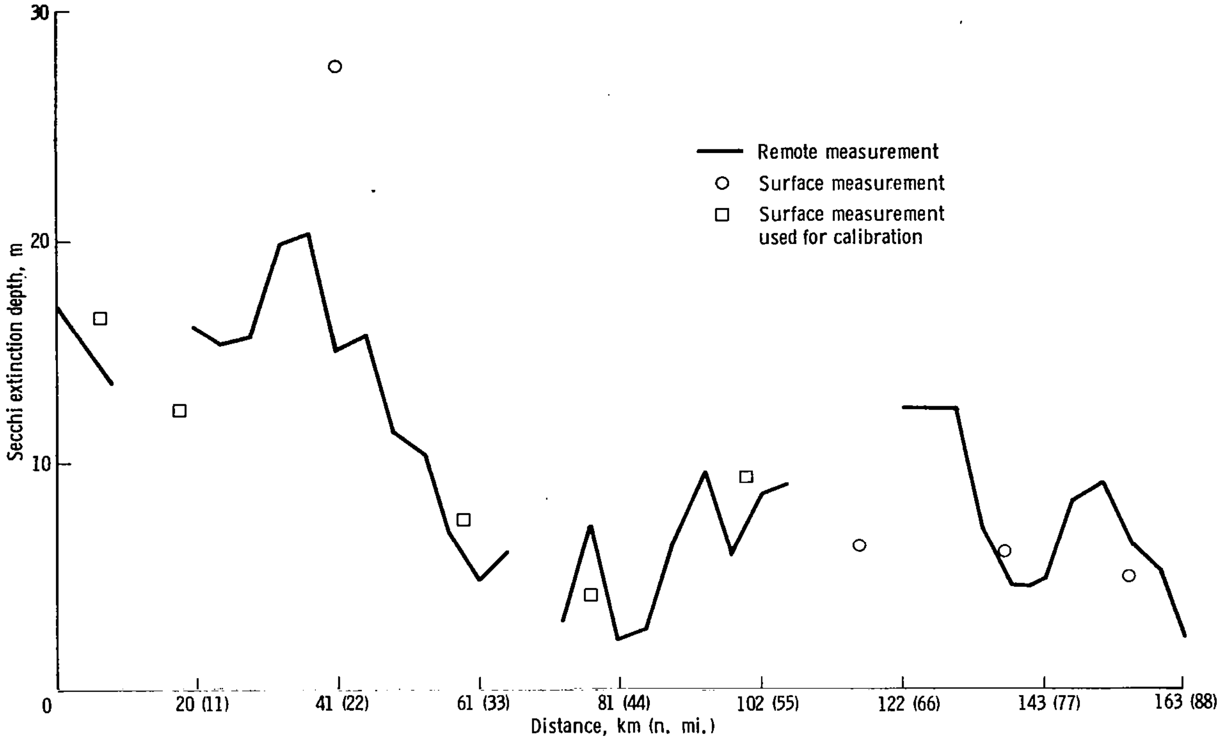



Figure 11.- Secchi transparency along flight line 2.

values computed using this function were then applied to generate a turbidity contour map of the test area (fig. 12(a)). A contour map based on surface measurements of the same parameter (fig. 12(b)) is included for comparison. Although basic similarities exist, the absence of the very low turbidity values (high Secchi transparencies) in the remote data has drastically distorted the appearance of the remote map.

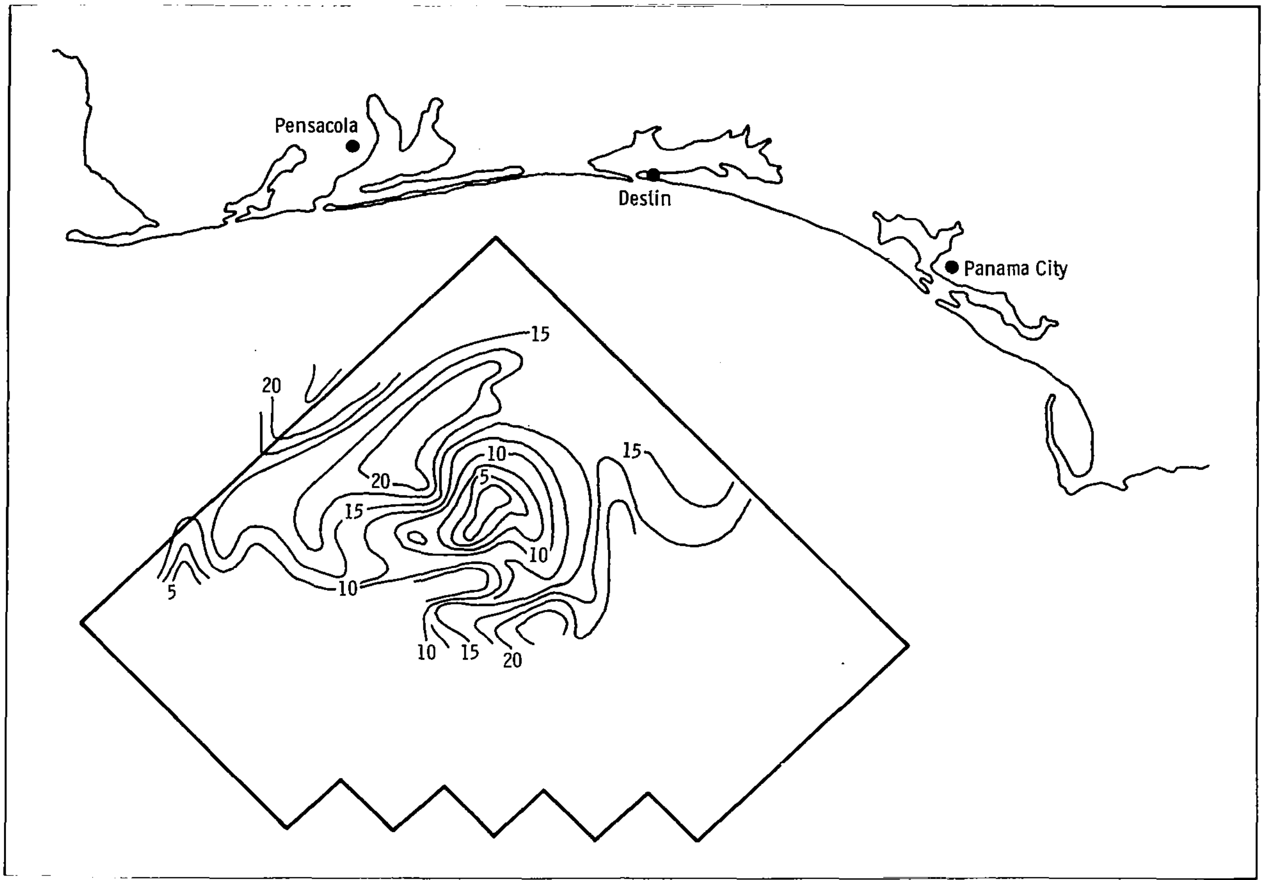
There are two likely explanations for discrepancies, apart from the most basic problem of the complexity of the phenomena reflected in inaccuracy of the model. Because of the criteria used in selecting calibration points for the remote measurements, which included a maximum time difference of 3 hours between surface and remote sampling, no calibration points had Secchi depths greater than 17 meters. This fact introduces an uncertainty of unknown magnitude into measurements outside the calibrated range. The rms error for all points having Secchi depths less than or equal to 20 meters is 2.3 meters. Also, reports from the surface observers indicated that water conditions were changing over the test area. It is thus possible that the sea conditions changed during the time between surface and remote sampling.

The Secchi measurement is a subjective parameter that is influenced by factors external to the water turbidity. These factors include cloud cover, Sun elevation, surface roughness, shading of the water surface or Secchi disk, and the eyes of the observer. In an analysis of Secchi measurements made during two scientific cruises, Tyler (ref. 14) observed that field conditions may exert "an undue influence on the Secchi disk experiement." The use of Secchi extinction depths as a measure of turbidity therefore necessitates the tolerance of undetermined external influences on the turbidity measurement.

A factor that must be considered in examining the surface measurements is the basic measurement procedure. The instructions for making the Secchi measurement specified that it be made on the shady side of the boat. Although there is some controversy over this question, Tyler (ref. 14) points out that measurements made on the shady side of the boat are influenced by the shadow of the boat below the surface. Discontinuities in the measurement occur at the point at which the extinction depth drops below the shadow of the vessel. Obviously, elevation of the Sun, orientation of the surface vessel with respect to the Sun, and size of the vessel all introduce perturbations into the measurements of turbidity when the reading is made on the shady side of the boat. Furthermore, discussion with some of those making the measurements during the experiment reveals that the detailed procedure for taking the reading was not strictly followed - that some measurements were made on the sunny side of the boat and some on the shady side.

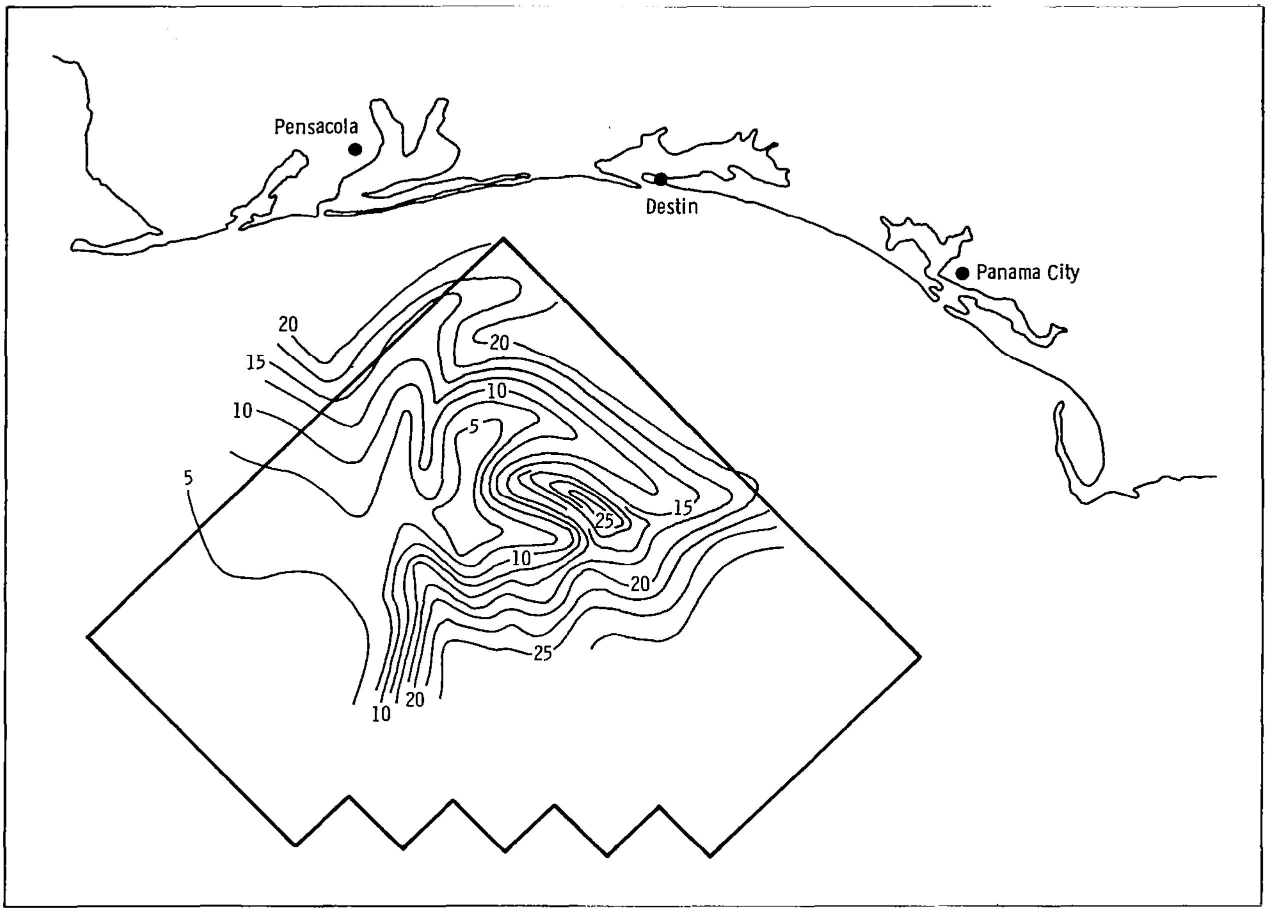
## ANALYSIS APPLICATION

The motivation for this work was principally to support the National Marine Fisheries Service in their Skylab/Gamefish Experiment. The chlorophyll-a concentration measurements, the turbidity estimation, and the surface temperature measurements made from aircraft were therefore promptly transmitted to the Principal Investigator for the experiment. The data were used by him in a white marlin distribution model that had been developed




(a) Remote measurements.

Figure 12.- Analysis of turbidity data. Values are in meters; contour interval: 2.5 meters.




(b) Surface measurements (Secchi extinction).

Figure 12.- Concluded.

from surface data taken the day before the remote data acquisition mission. The prediction of the model for white marlin distribution the day of the mission, using these remote data in addition to other parameters that were not remotely sensed, was much less successful than the predictions made using only the surface measurements. Reasons for this include decreased precision of the measurements, more extensive interpolation between flight lines, and the "instantaneous" nature of the remote measurements as opposed to the full day of fishing and surface sampling. The most important reason may be that the number of samples which could be used in the model with the remote data was very small for performance of a statistical analysis yielding significant results.

That some of the parameters of the white marlin distribution model can be sensed remotely from aircraft flying at 3000 meters is significant to the fisheries investigation. At this relatively low altitude, the usefulness of the data in monitoring applications would be restricted by limited coverage, but if the techniques described here can be applied to synoptic data acquired by satellites, the utility of the remote measurement of these parameters will be greatly enhanced.

Savastano (ref. 1) found that a model based directly on the water color as measured with the S192 multispectral scanner was very successful in predicting the locations of the white marlin. If the modeling performed by the National Marine Fisheries Service for white marlin distribution proves to be valid and if similar models can be developed for other gamefish, satellite-acquired oceanographic data may be used in living marine resource-management applications.

## CONCLUSIONS AND PROGRAM EVALUATION

The following capabilities have been demonstrated by the work reported.

1. Thermal radiance data acquired with different types of sensors on platforms at different altitudes can be combined to generate a composite surface temperature map.

2. Chlorophyll-a concentration can be calculated from spectral radiance measurements with an accuracy of 0.4 $mg/m^3$ over a range of 0 to 5 $mg/m^3$.

3. Secchi extinction depth can be derived from spectral radiance measurements. An accuracy of better than 5 meters over a range of 2 to 30 meters was achieved with this data set.

The results of the remote thermal mapping and turbidity measurement are not as good as had been desired, whereas the remote chlorophyll-a measurement surpassed the accuracies achieved in previous experiments. The success of the statistical approach to the remote measurement of chlorophyll indicates that, if an ocean system to be studied is sufficiently free from interfering factors such as Gelbstoffe or greatly varying concentrations of sediment or plant fragments, such an approach should be considered because of its simplicity.

The thermal measurement suffered from atmospheric variation over the study area, and the results of this analysis show that the accuracy of this technique is limited by this variation. The turbidity measurement indicates that a more thorough analysis of the optics of the water system is in order before pursuing the problem further. A statistical model would probably be appropriate if it could be formulated in terms of the physical phenomena, as opposed to the approach taken here. The Secchi extinction depth measurement itself is probably not the best measurement of the turbidity of the sea. It would probably be better to use measurements of the beam attenuation coefficient and the diffuse attenuation coefficient. Although requiring much more complex measurements, the volume scattering coefficient has good potential for application in remote measurement studies.

Factors such as the distribution of indices of refraction of suspended particles, particle size distribution, concentration of particles, and pigmentation of particles should be studied with respect to remote water color analysis. Such detailed experimental work will bring a better understanding of the influence of basic physical phenomena on water color and facilitate the measurement of some form of the turbidity parameter by remote techniques.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, August 23, 1977
640-03-00-00-72

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16. Abstract

Efforts to demonstrate the feasibility of using remotely acquired information to assess and monitor the distribution of oceanic gamefish are described. Data supplied by Skylab and two aircraft flying at different altitudes surveying an area in the Gulf of Mexico with thermal and optical radiometers and cameras were used in conjunction with oceanographic data provided by surface vessels to explore a relationship between oceanographic parameters and remotely acquired data. Thermal scanner imagery and precision radiometric thermometer data obtained by the two aircraft are combined to provide a composite surface temperature map of the test area. Spectral radiometer data were studied in conjunction with surface measurements of chlorophyll-a and turbidity, and several models were developed which predicted these two oceanic parameters from the radiance data. Results compare favorably with those obtained with similar models and data collected over the Mississippi Sound. Contour maps of the chlorophyll-a content and turbidity were developed from the best chlorophyll and turbidity models and from surface measurements. Basic problems concerning the remote measurement of the Secchi extinction depth are discussed, and suggestions are made for improving the remote measurement turbidity.

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