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Ocean Color Algorithm for Remote Sensing of Chlorophyll

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Information Branch

INTRODUCTION

For many years investigators have been searching for an algorithm which uses remote data of ocean color to map areas of primary productivity efficiently. Most of this research was restricted to procedures that consisted of first determining the absolute radiance impinging on the remote sensor, and then, through theoretical considerations, separating the component of backscattered light from phytoplankton from all extraneous factors, such as solar elevation, sea state, aerosols, air and water molecules, sediments, and the ocean floor. The task of stripping away these extraneous factors is the most formidable challenge of remotely sensing chlorophyll a.

In 1973 a remote sensing program to collect visible ocean spectra with a very stable multispectral scanner known as the Multichannel Ocean Color Sensor (MOCS) was begun. MOCS was developed by TRW, Inc., under the Advanced Applications Flight Experiments (AAFE) program conducted at NASA Langley Research Center (LaRC). After analyzing several data sets collected on aircraft flight tests of the new scanner, the search began for a new type of algorithm; perhaps one existed for monitoring primary productivity which was independent of absolute radiance measurements and which did not require constant recalibration. (MOCS does not have an internal calibration system.) Confidence in this possibility grew from analyses of unique cluster patterns that seemed to reappear for different data sets when blue-band data were plotted versus green-band data (ref. 1). Later analysis, however, demonstrated that these unique patterns occurred only under special conditions, specifically when the only variable along the flight path was phytoplankton concentration. Normalization of the blue- and green-band data provided sporadic improvement in the cluster patterns. The conclusion was reached that single-band data and simple ratios of spectral bands were too sensitive to extraneous factors to be useful for monitoring phytoplankton remotely, except under ideal conditions.

A signature extraction technique which uses regression analysis was worked out to study the variations in backscattered light from phytoplankton (ref. 2). This led to a more general extraction technique which uses characteristic vector analysis (principal components) (refs. 3 and 4). It became clear from studying the eigenvectors derived from these techniques that an algorithm was needed which monitored only the variations in several spectral features that could be associated with phytoplankton concentration. Algorithms involving first and second derivatives which could serve this purpose were investigated, but they too varied with the environment. This led to the discovery of an algorithm which, although similar to a second derivative, is much less sensitive to environmental variations.

The algorithm was tested with MOCS data collected during a 6-year period in nearshore regions over plumes consisting of complex mixtures of suspended solids. Although these data sets were good enough to demonstrate the consistency of this algorithm over a long time period compared with all others investigated, the complexity of the plumes and the difficulty in obtaining coincident sea truth has prevented the establishment of a clear relationship between the algorithm and the chlorophyll a concentration. To verify the potential of the algorithm, data were needed from offshore regions away from the high-turbidity waters in the coastal zone. In particular, data were needed over ocean water where chlorophyll a concentrations vary between 0.1 to 10.0 µg/L. In past years, concentrations in this range have been measured during the spring and summer months by oceanographic ships both on Nantucket Shoals and in deep water off the shoals. Thus, the Nantucket Shoals experiment proposed in 1980 presented an excellent opportunity for obtaining the vitally needed data to verify the new algorithm.

The Nantucket Shoals experiment was designed in May 1981 at LaRC to investigate the distribution of phytoplankton biomass on the shoals in relation to rates of nutrient supply, growth, vertical mixing, and advective processes. One objective of the experiment was to use real-time remote sensing techniques to determine spatial distributions of temperature, chlorophyll, phytoplankton diversity, suspended solids, and salinity at subtidal frequencies over the entire region. Investigators included scientists from the Northeast Fisheries Center, Brookhaven National Laboratory, Woods Hole Oceanographic Institution, Marine Sciences Research Center (State University of New York), and Bigelow Laboratory for Ocean Science. The experiment involved two NASA aircraft and six oceanographic research vessels.

This paper presents MOCS data from the Nantucket Shoals as a demonstration of the value of the new algorithm rather than as a discussion of the details of the Nantucket Shoals experiment. Reports on the ship data have been published in references 5 and 6. This report contains brief descriptions of the MOCS system, the algorithm, and the flight data, calibration of the algorithm, and verification of the algorithm using MOCS data collected over the 8-day experiment.

INSTRUMENT DESCRIPTION

The MOCS system flown on the NASA P-3 during the experiment consisted of two basic parts, the MOCS itself and the data processing subsystem. MOCS is a visible-imaging spectroradiometer which performs multispectral scanning electronically by means of an image dissector (ref. 7). It covers the visible region of the spectrum (from about 400 to 700 nm) in 20 adjacent bands (tables 1 and 2). As shown in figure 1, the output from MOCS is fed into an analog-to-digital (A/D) converter; all the data are stored serially on an analog tape recorder.

By means of the data selector in the real-time subsystem, samples of the data (usually center-of-track data) are processed and stored in a microprocessor; these data can be stored in and recalled from a digital tape recorder. During flight or in the laboratory, a thumb-wheel algorithm selector is used to display on an x-y oscilloscope the algorithm in various formats during flight.

In a much improved version of the real-time system flown in a more recent experiment, loran C data are fed into a minicomputer along with MOCS data. With this system, latitude and longitude positions of special oceanic features are determined rapidly and accurately.

ALGORITHM

The general form of the new algorithm is given by

$$G_{j,m,n} = \frac{S_j^2}{S_{j-m} S_{j+n}} \tag{1}$$

where S_j is the MOCS signal for band j and m and n are constants. This algorithm, which amplifies and monitors changes in the spectral features, has been labeled the "inflection ratio algorithm."

As a first step toward simplifying the analyses, all forms of the $G_{j,m,n}$ algorithm in which m equals n, or

$$G_{j,m} = \frac{S_j^2}{S_{j-m}S_{j+m}} \tag{2}$$

were investigated. Subsequently, as a further simplification, all possible values of this algorithm for $m = 2$, or

$$G_{j,2} = \frac{S_j^2}{S_{j-2}S_{j+2}} \qquad (j = 3 \text{ to } 18) \tag{3}$$

were investigated because the smaller the value of m the less the influence of the environment on the algorithm and the spectral features are about 60 nm wide (four MOCS channels at 15 nm bandwidth per channel).

In figure 2 an example of the consistency of the algorithm shows the ranges of values for the inflection ratio spectra from equation (3) for MOCS data collected over relatively clear water on various missions during a 6-year period. The atmospheric conditions, sea state, and solar elevation, as indicated in the figure, varied from mission to mission. Further discussion of the algorithm can be found in references 8 and 9. In the remainder of this paper, the discussion is confined to the algorithm for $j = 7$, that is,

$$G_{7,2} = \frac{S_7^2}{S_5S_9} = \frac{(S_{490\ nm})^2}{(S_{460\ nm})(S_{521\ nm})} \tag{4}$$

Analyses of data collected prior to the Nantucket Shoals experiment indicated that $G_{7,2}$ was very sensitive to phytoplankton concentration (chlorophyll a).

MOCS FLIGHT DATA

Seven flights were made between May 7 and May 13, 1981, over the shoals. A typical flight path of the NASA P-3 aircraft is shown in figure 3. The missions were conducted during various phases of the tidal cycle. Points on the map occurred at 9-sec intervals as recorded from a loran C system aboard the aircraft. Isobath values are indicated in meters (M). The basic flight pattern consisted of 10 east-west (E-W) lines (numbered from north (N) to south (S)) 5' apart between latitudes 41°35' N and 40°50' N and longitudes 69°12' W and 70°05' W. Deviations from this pattern were made occasionally for special purposes. An eighth mission, the Warm

Core Ring flight flown from Nantucket but not as part of the Nantucket Shoals experiment, is discussed in a separate paragraph.

Most of the lines during the seven missions were flown at an altitude of 150 m to accommodate the prime remote sensor on the P-3, the Airborne Oceanographic Lidar (AOL). The AOL is an active system which senses fluorescence induced by laser pulses (ref. 10). The limited power of the laser restricts its operation to low altitude.

To avoid instrument saturation resulting from specular reflection of sunlight, MOCS is usually flown at an altitude at which the instantaneous field of view covers an ocean surface area with dimensions several times greater than the wavelengths of the ocean waves. At an altitude of 150 m MOCS, with a spatial resolution of less than 0.2 m^2, could view a portion of an ocean wave where sunlight is reflected vertically upward. (Sea foam is another problem.) These data spikes result in instrument saturation and loss of usable data. Good MOCS data at a 150-m altitude depend on both sea state and solar elevation. At this altitude, data collected with solar elevations above 50° are generally not usable. During the experiment a total of eight lines were flown at a 2300-m altitude specifically for MOCS; all yielded good data.

Table 3 shows dates, times, and environmental conditions when MOCS data were collected during the seven flights. The wind speeds and wave heights are based on the hourly log of the R/V Albatross, a National Oceanic and Atmospheric Administration (NOAA) ship; the measurements do not necessarily represent conditions at all points on the shoals but serve as a guide. The last three columns in the table list the lines along which good data were collected and the solar elevations during those overflights. This data set, which consists of 24 lines at 150-m altitude and 8 lines at 2300 m representing about 40 percent of the total collected, is discussed in the following paragraphs.

CALIBRATION

The Nantucket Shoals experiment was the first in which extensive MOCS data were collected at a 150-m altitude. Previous data analyses have shown that, although the conversion of the MOCS data to chlorophyll a concentration remains relatively constant for a given altitude, small corrections are required for different altitudes. Light backscattered from the atmosphere changes the shape of the inflection ratio spectrum. The change with altitude is greatest at low altitude, where the atmosphere is denser. Thus, the 150-m data needed to be calibrated.

During the experiment the P-3 aircraft flew directly over or near a number of sea truth stations. Of 21 such events analyzed, all except 3 did not yield precise enough calibration points because of at least 1 of the following reasons: (1) solar elevation was too high; (2) time lapse between the overflight and sea truth collection was too long; and (3) distance between station and aircraft was too great. The three acceptable events occurred on different days. Thus, another means of converting the $G_{7,2}$ algorithm to chlorophyll units was needed.

Even before the above analysis was completed, it was noticed that contour maps of the MOCS $G_{7,2}$ algorithm and the AOL chlorophyll data for flight 5 on May 9, 1981, were similar. For this particular flight the AOL data correlated highly (0.98) with sea truth. It was decided to use these AOL data to convert the $G_{7,2}$ algorithm to chlorophyll units. Figure 4 is a plot of coincident AOL and MOCS data for line 9 of flight 5. The solar elevation during this pass was 37°. Regression analysis of the data set resulted in a correlation coefficient of 0.985 and the linear regression equation (for an altitude of 150 m)

$$\ln C = 10.19 - 7.33G_{7,2}(h{=}150\ \text{m}) \tag{5}$$

where C is the chlorophyll a concentration in μg/L and h is the altitude.

For the eight lines flown at the 2300-m altitude, another equation was needed to convert to chlorophyll a concentration; the component of atmosphere scattering added to the upwelling light, as viewed by MOCS, changes slightly the conversion of $G_{7,2}$ to chlorophyll a concentration. On May 13, line 9 was flown at 2300 m and almost immediately afterward at 150 m in the opposite direction. The solar elevation during these passes varied between 30° and 36°. The flight lines were nearly coincident, especially on the western half. Comparison of coincident points for both altitudes is shown in figure 5. This data set yielded a correlation coefficient of 0.949 and the linear regression equation

$$G_{7,2}(h{=}2300\ \text{m}) = 0.799 + 0.369G_{7,2}(h{=}150\ \text{m}) \tag{6}$$

Substituting equation (6) into equation (5) we have

$$\ln C = 26.06 - 19.86G_{7,2}(h{=}2300\ \text{m}) \tag{7}$$

for an altitude of 2300 m.

With equations (5) and (7) a comparison can be made in figure 6 between the chlorophyll a concentrations for the passes over line 9 at different altitudes. As expected from the data in figure 5, the same features appear in the two passes. Depending on flight altitude, all MOCS data discussed in the following paragraphs have been converted to chlorophyll a concentrations through either equation (5) or equation (7).

VERIFICATION

Contour maps of chlorophyll a concentration based on MOCS data are shown in figures 7 to 9 for May 8, 9, and 13. Flights 4 and 5 on May 9 have been plotted on one map (fig. 8). Data from all four flights present a consistent, general distribution - strong chlorophyll a concentrations (2.0 to 3.0 μg/L) in the northern and southern regions of the study area and lower concentrations in the central region.

The same trend is apparent in figure 10 for line data for flight 3 on May 8. The lines were too far apart on this flight for contouring. The general distribution is indicated quite nicely by the south-to-north (S-N) track along longitude 69.23° W, where the concentrations are higher at each end of the track than in the middle.

The persistence of a patch of higher chlorophyll a concentration in the southern region of the study area is demonstrated in figure 11. Data for line 10 along latitude 40.83° N are plotted for five of the seven flights. All show chlorophyll a concentrations of 1.0 μg/L or less on the western end of the track and a patch of higher chlorophyll a concentrations to the east. The shape of the patch changed from flight to flight, perhaps a tidal effect.

An interesting feature in figure 10 is the chlorophyll a depression at longitude 69.04° W on line 6. Its boundaries correspond closely with the 100-m isobath as shown in figure 12. This region is of special interest to marine biologists; large numbers of whales and other sea mammals congregate there during the spring and summer months (ref. 11). Many were spotted in the area during the overflights.

In all cases where coincident data were available, sea truth and MOCS data agreed. Measurements made by the R/V Albatross (ref. 6), which zigzagged over the Nantucket Shoals during the period May 6 to 15, 1981, confirm the persistence of the same general chlorophyll a distribution. Concentrations in the 2.8 to 6.8-μg/L range were measured by the Albatross on May 6 on and to the north of line 1. Concentrations in the central region on May 8 and 9 were less than 2.0 μg/L . Passes through the patch in the south between May 7 and 14 consistently showed high chlorophyll a concentrations, as indicated in table 4 for crossings of line 10. On May 12 the Albatross surveyed the southwestern region of the study area, where concentrations ranged between 0.6 and 1.3 μg/L.

The cruise tracks of the other ships were for the most part in the northern half of the shoals study area, where concentrations were generally lower the farther south they cruised. Data collected in this region by the R/V Onrust (ref. 5) and by MOCS are compared in figure 13. The tracks for the ship and for the aircraft were along line 2 (lat 41°30' N). The aircraft flew between 0° and 1° north of the line, whereas the ship's position varied between 1° south and 2° north of the line. Onrust collected data on both eastbound and westbound legs between 0630 and 1341 EDT, whereas MOCS on the P-3 made a westbound pass between 1120 and 1128 EDT. The Onrust consistently measured higher chlorophyll a concentrations on its eastbound leg than on its return leg. The chlorophyll a concentrations measured with MOCS fell on or between these values. The "hot spot" observed by the Onrust at 0830 EDT was not observed by either MOCS at 1124 EDT or by Onrust on its return at 1232 EDT. These types of variations are common, making it often difficult to obtain truly coincident remote and sea truth data. However, it can be stated with confidence that all three curves have the same general shape and concentration ranges.

Another comparison is made by examining the data in figure 14, a blowup of the contour lines in figure 8 for flight 4 including the positions and measured chlorophyll a concentrations of three ships in the region on the same day. Agreement is good despite lapses in time between overflights and sea truth of about 0.5 hour for the three higher concentrations and about 8 hours for the two lower concentrations.

In summary, the chlorophyll a concentrations for the data collected at an altitude of 150 m for five separate flights between May 7 and 13, 1981, were calculated with equation (5). The same equation was used despite the variations of solar elevation, atmospheric conditions, and sea state (table 3). The contours of chlorophyll a concentration are smooth and in general agreement from day to day. The ranges and distributions of chlorophyll a concentration are in agreement with sea truth to within 1.0 μg/L. The persistence and magnitude of a high-concentration patch of chlorophyll a in the southern region of the shoals was verified after examining sea truth data from the R/V Albatross. It appears there is no other remote sensor or algorithm that can be applied over an extended period without frequent calibration for environmental corrections.

On May 14, after completion of the Nantucket Shoals flights, a flight from Nantucket was conducted to investigate a warm core ring centered at latitude 38°40' N and longitude 72°40' W (ref. 12). En route to the ring the P-3 aircraft flew along a cruise track of the R/V Albatross. MOCS and AOL data in figure 15 were collected along a southerly track from latitude 40°8' N and longitude 69°31' W to latitude 39°11' N and longitude 69°44' W between 0725 and 0758 EDT. The Albatross began collecting data along the same track at 0930 EDT. After 2000 EDT, the tracks of the ship and aircraft no longer coincided sufficiently for data comparison.

The MOCS data clearly show lower chlorophyll a concentrations on the shoals and the higher levels of the southern patch, as observed on the previous flights. Again, considering the time differences, the three plots in the figure are remarkably similar, particularly for the southern half of the track from the high chlorophyll a concentrations on the shelf to the low concentrations beyond the shelf break. Thus, equation (5), used to convert the MOCS algorithm to chlorophyll a concentrations based on data collected 5 days before, was still applicable to different regions of the ocean. The AOL data are plotted in relative units because the AOL must be calibrated for each flight.

CONCLUDING REMARKS

The Nantucket Shoals experiment provided an excellent opportunity to test the Multichannel Ocean Color Sensor (MOCS) algorithm. The chlorophyll a concentrations determined from MOCS data collected at an altitude of 150 m for five separate flights were based on calibration data from only one flight line at one particular solar elevation. A limited amount of data were also collected at a 2300-m altitude. In the cases presented, where comparisons between the remote data and sea truth were possible, the algorithm determined chlorophyll a concentrations to an accuracy better than 1.0 μg/L. This accuracy was maintained despite the fact that the solar elevation varied between 20° and 56° during the flights, which occurred over an 8-day period. As the data collected on May 14, 1981, demonstrated, there was no apparent change in the calibration between the water over the Nantucket Shoals and the deep water regions of the Continental Shelf.

Valuable data pertinent to the scientific objectives of the Nantucket Shoals experiment were obtained through the MOCS data. In particular, no other investigator demonstrated the persistence of the chlorophyll a patch in the southeastern region of the study area. The several crossings of the patch by the R/V Albatross support this finding. The region of higher chlorophyll a concentration in the north, particularly in the northeast, and the lower concentrations over the middle region are also important results. The existence of a chlorophyll a depression where large numbers of sea mammals graze may prove to be significant. As a consequence of preliminary analyses of the total Nantucket Shoals experiment, marine scientists are questioning current theories on the dynamics of the shoals.

As for remote sensing technology, it is very significant that the same equation was successfully used throughout the experiment to convert the MOCS algorithm to chlorophyll a concentration. This is consistent with the data in figure 2, which show that the inflection ratio algorithm remained relatively constant over a 6-year period. Thus, this algorithm holds promise of becoming a valuable remote sensing tool in aircraft and satellites, inasmuch as it seems to be fairly independent of the environment.

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TABLE 1.- MOCS SPECIFICATIONS

Sensor	Image dissector
Scan rate, scans/sec	3.51
No. of spectra per scan	150
Spectral range, nm	400 to 700
Spectral resolution, nm	15
Field of view, deg	17.1
Spatial resolution, mrad	4 × 2

TABLE 2.- MOCS SPECTRAL BANDS

Band	Center wavelength, nm
1	400
2	415
3	430
4	445
5	460
6	475
7	490
8	506
9	521
10	537
11	552
12	568
13	584
14	601
15	616
16	631
17	647
18	663
19	678
20	694

TABLE 3.- ENVIRONMENTAL CONDITIONS DURING MOCS DATA COLLECTION

Flight	Date	MOCS data time frame, EDT	Solar elevation, deg	Wind speed, m/sec	Sea wave height, m	Good MOCS data for - Line at - 150-m altitude	Good MOCS data for - Line at - 2300-m altitude	Good MOCS data for - Solar elevation, deg
1	May 7, 1981	1159-1512	50-66	8-10	1-1.5	9-10		50-53
2	May 8, 1981	0820-1130	32-62	1-4	0	1-10	2	32-56
3	May 8, 1981	1518-1741	20-46	0-2	0	6,A[a]	(a)	20-46
4	May 9, 1981	0845-1138	35-63	4-5	0-0.3	1-3		35-44
5	May 9, 1981	1408-1731	24-60	5-6	0.3	7-12		24-43
6	May 11, 1981	1108-1432	56-67	4-5	0.3			
7	May 13, 1981	1312-1714	24-67	8	1	9	9,10	28-38

[a]See figure 10.

TABLE 4.- CHLOROPHYLL *a* CONCENTRATIONS DURING CROSSINGS OF R/V ALBATROSS

[Crossings at lat 45°50' N, line 10]

Date	Time, EDT	Longitude	Chlorophyll *a* concentration, µg/L, at - Crossing	Chlorophyll *a* concentration, µg/L, at - Peak in vicinity
May 7, 1981	2300	69°31' W	4.3	5.1
May 8, 1981	0400	69°37' W	2.7	6.1
May 10, 1981	1615	69°15' W	3.1	4.1
May 11, 1991	0400	69°39' W	3.2	3.2
May 14, 1981	2230	69°17' W	3.2	3.7

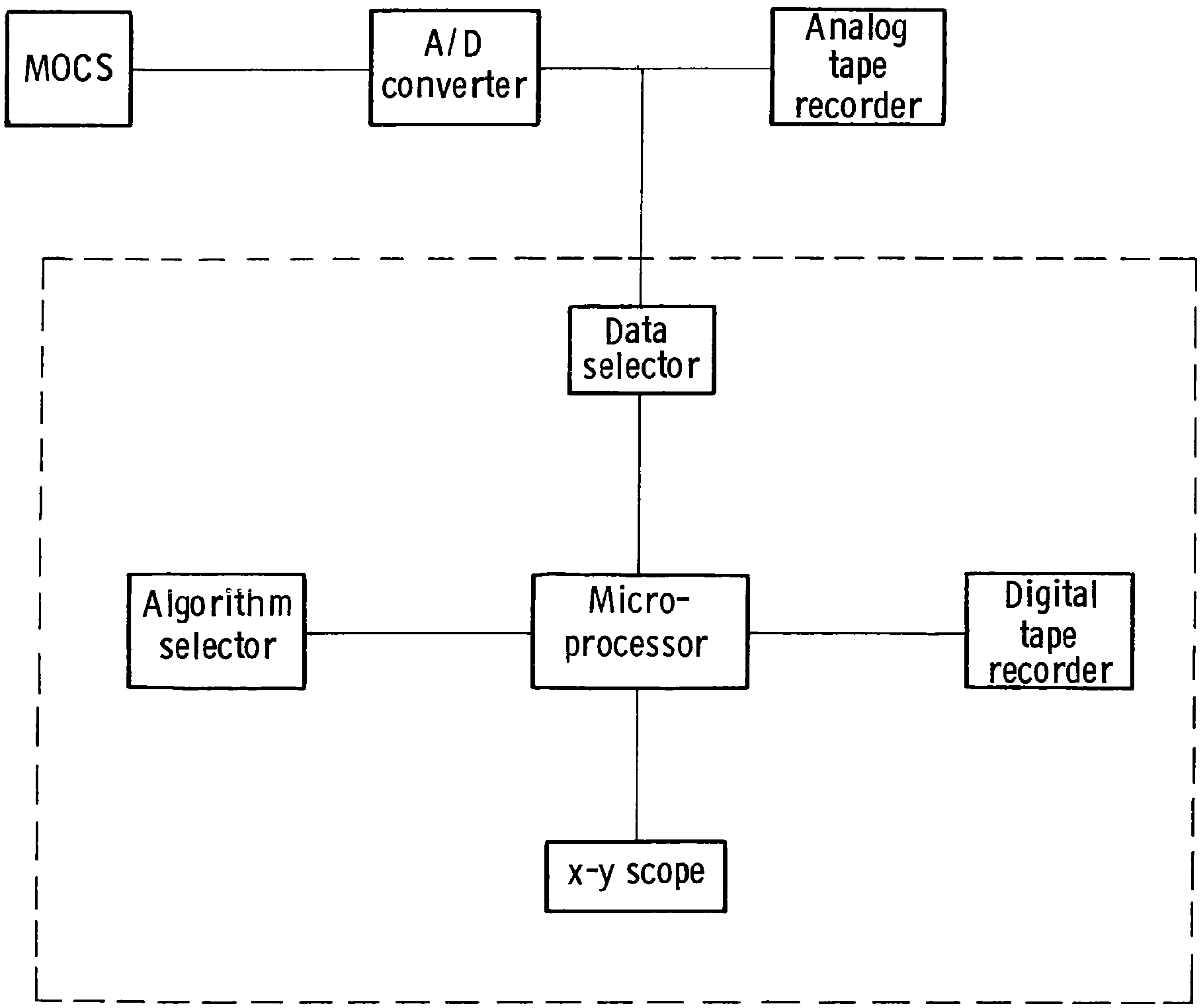
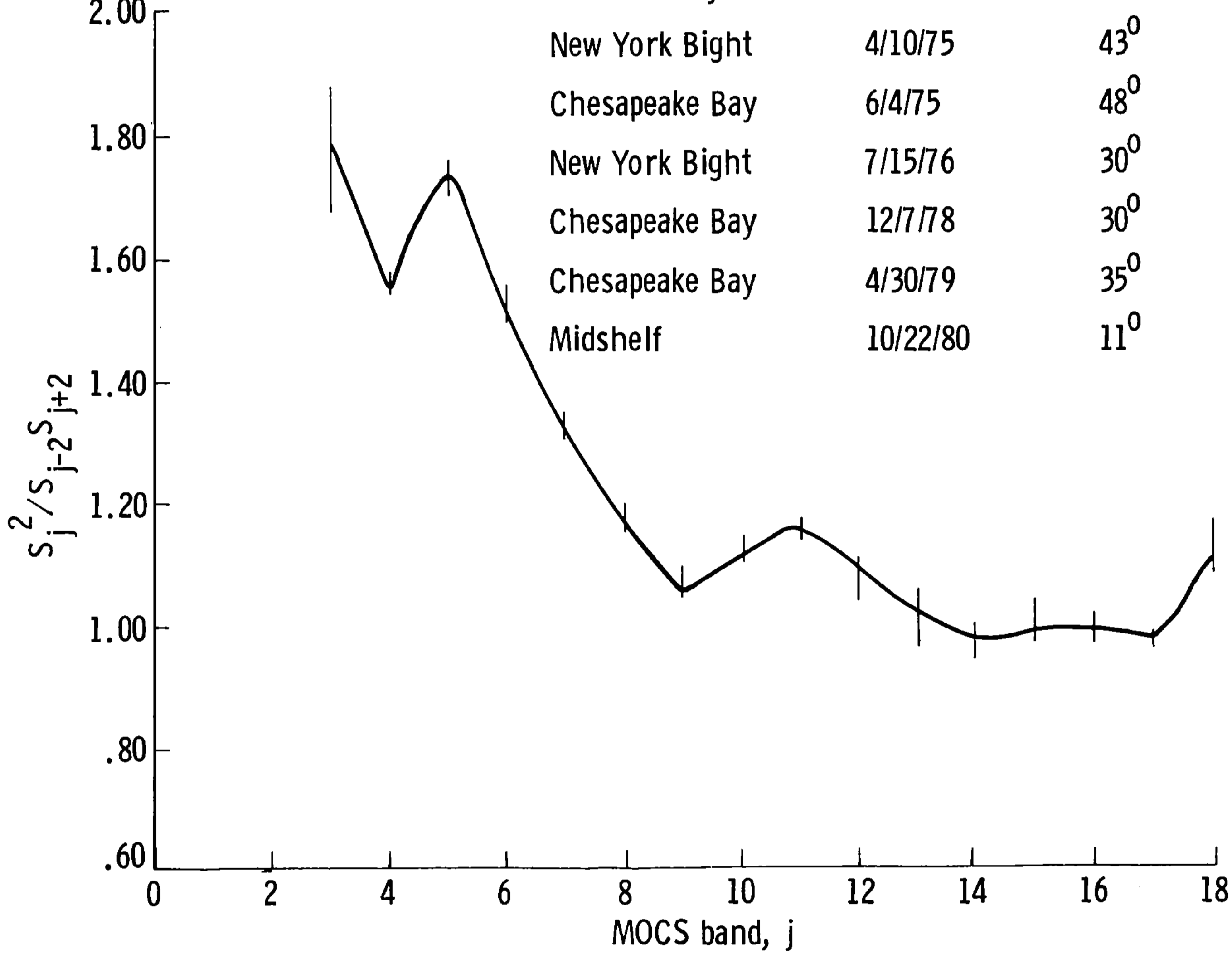


Figure 1.- MOCS aircraft real-time ocean color analyzer.



Region	Date	Solar elevation	Aircraft altitude, km
Norfolk Canyon	1/29/74	35°	5.3
New York Bight	4/10/75	43°	5.3
Chesapeake Bay	6/4/75	48°	5.3
New York Bight	7/15/76	30°	5.3
Chesapeake Bay	12/7/78	30°	5.3
Chesapeake Bay	4/30/79	35°	3.2
Midshelf	10/22/80	11°	2.3

Figure 2.- MOCS inflection ratio spectra for clear water. Vertical lines indicate range for samples from listed missions.

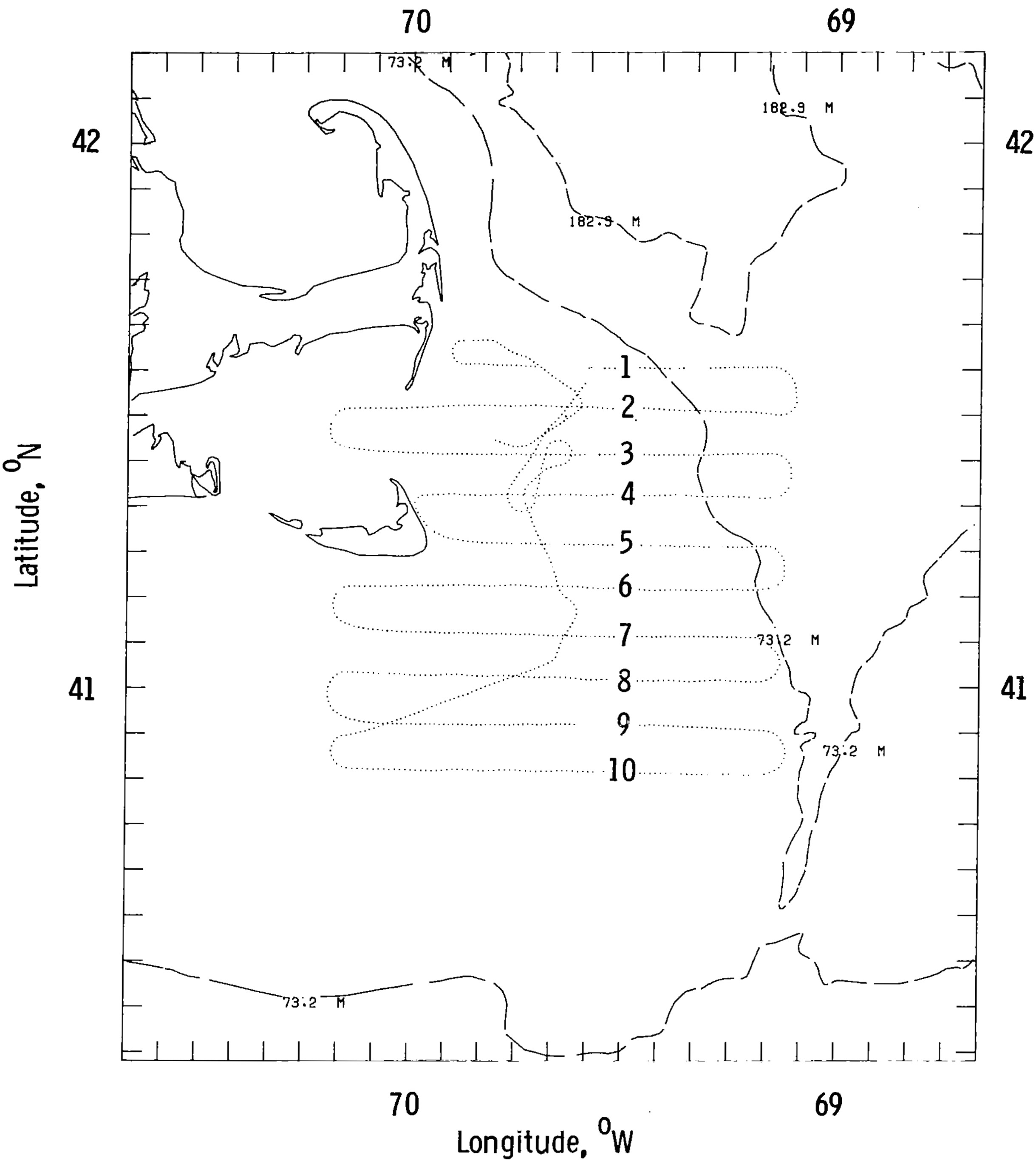


Figure 3.- Flight path of NASA P-3 on May 8, 1981, based on loran C data.

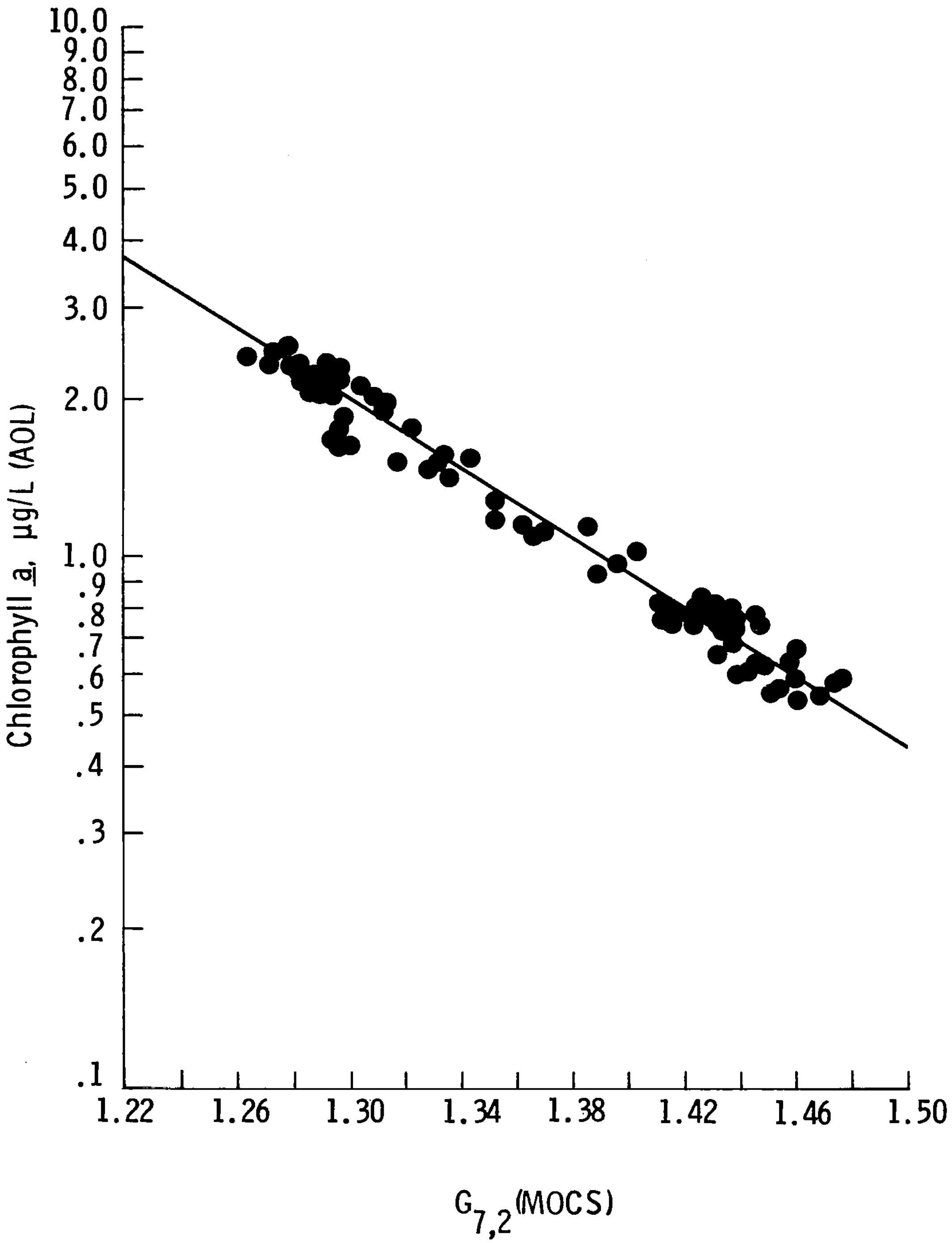


Figure 4.- Calibrated AOL chlorophyll a versus MOCS algorithm for data collected along line 9 at 150-m altitude on May 9, 1981. Solar elevation = 37°.

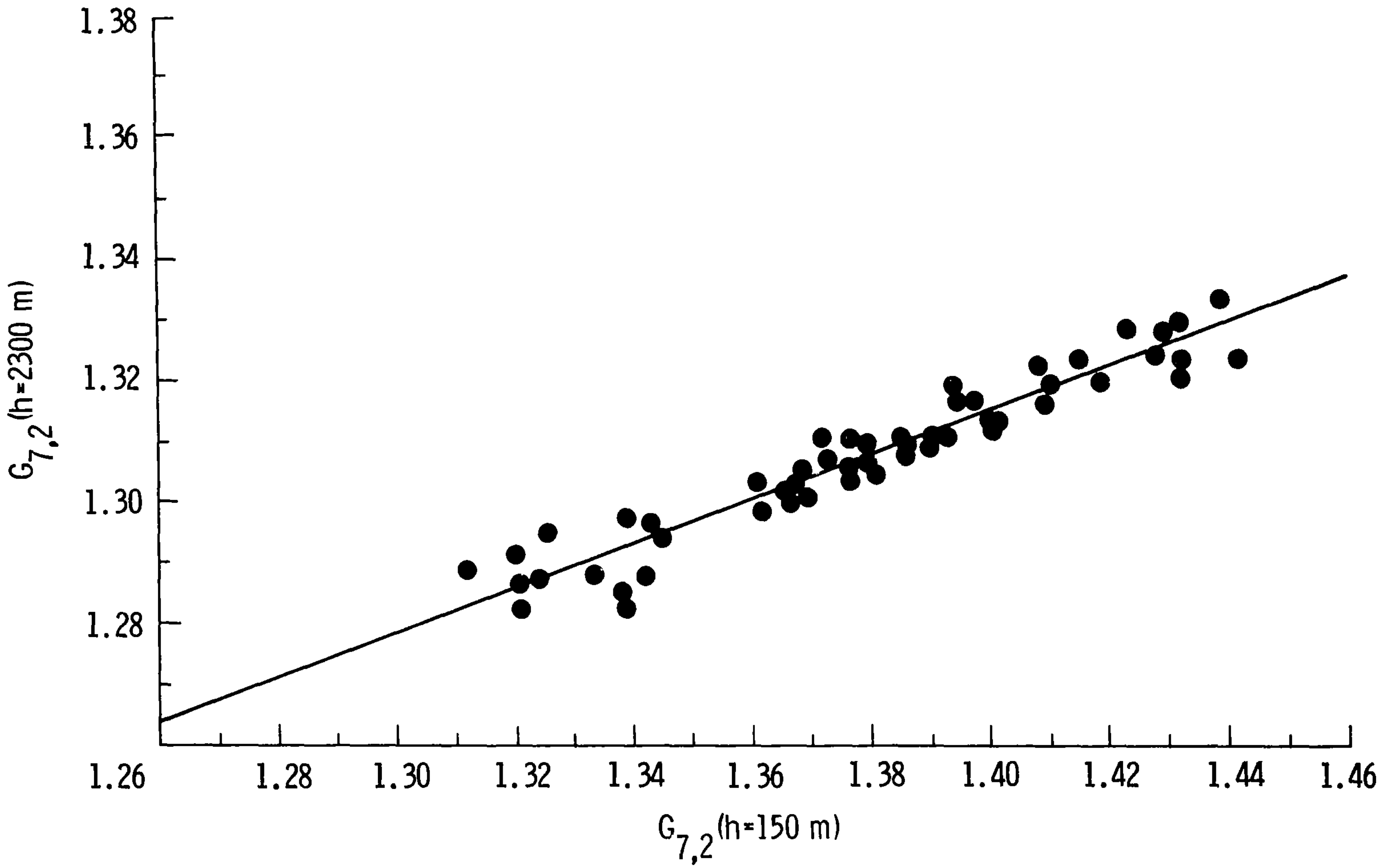


Figure 5.- High-altitude (2300 m) versus low-altitude (150 m) MOCS data collected along line 9 on May 13, 1981. Solar elevation = 30° to 36°.

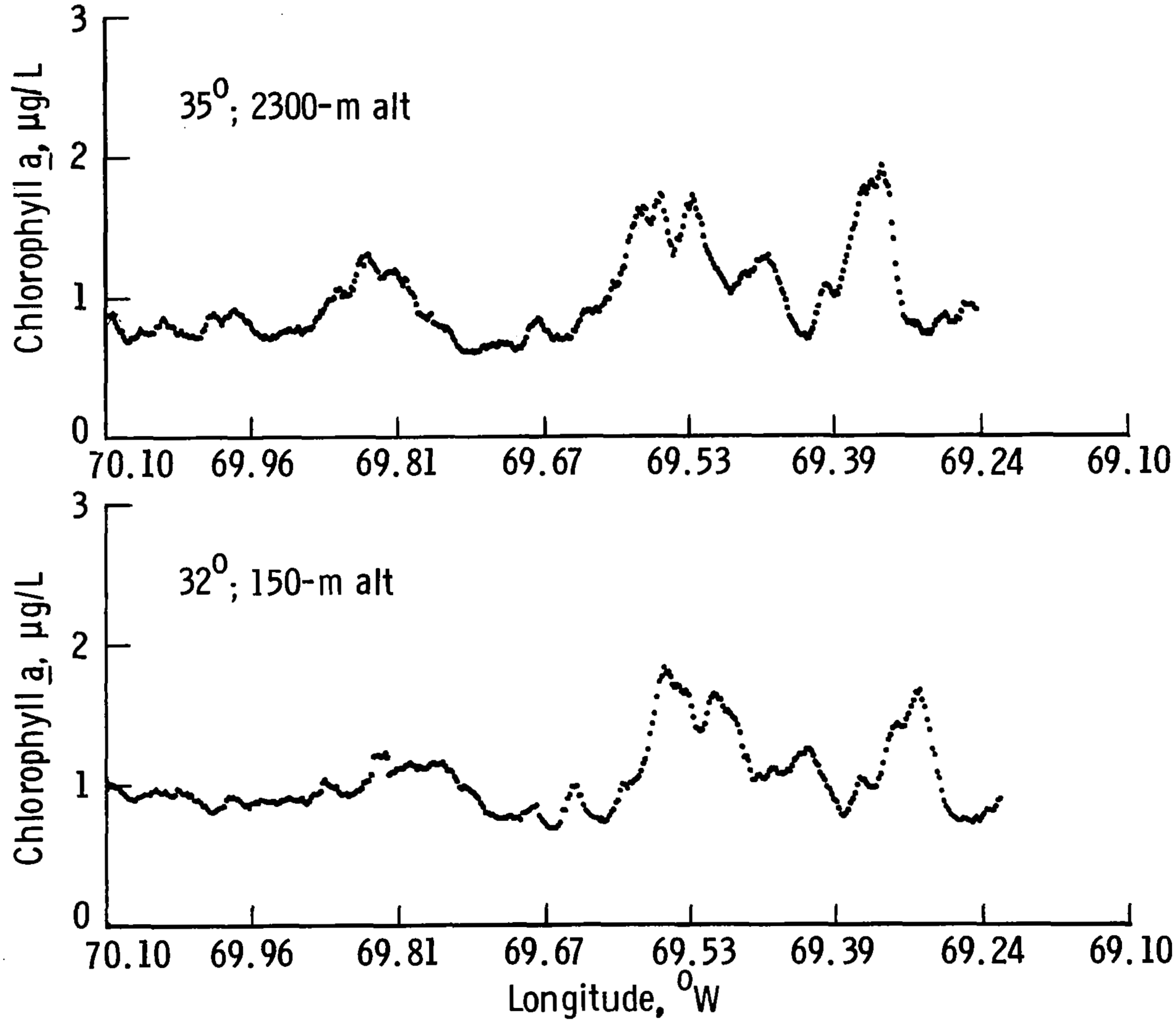


Figure 6.- Altitude comparison of calculated chlorophyll a concentrations using MOCS data collected along line 9 on May 13, 1981. Solar elevations and flight altitudes are indicated on plots.

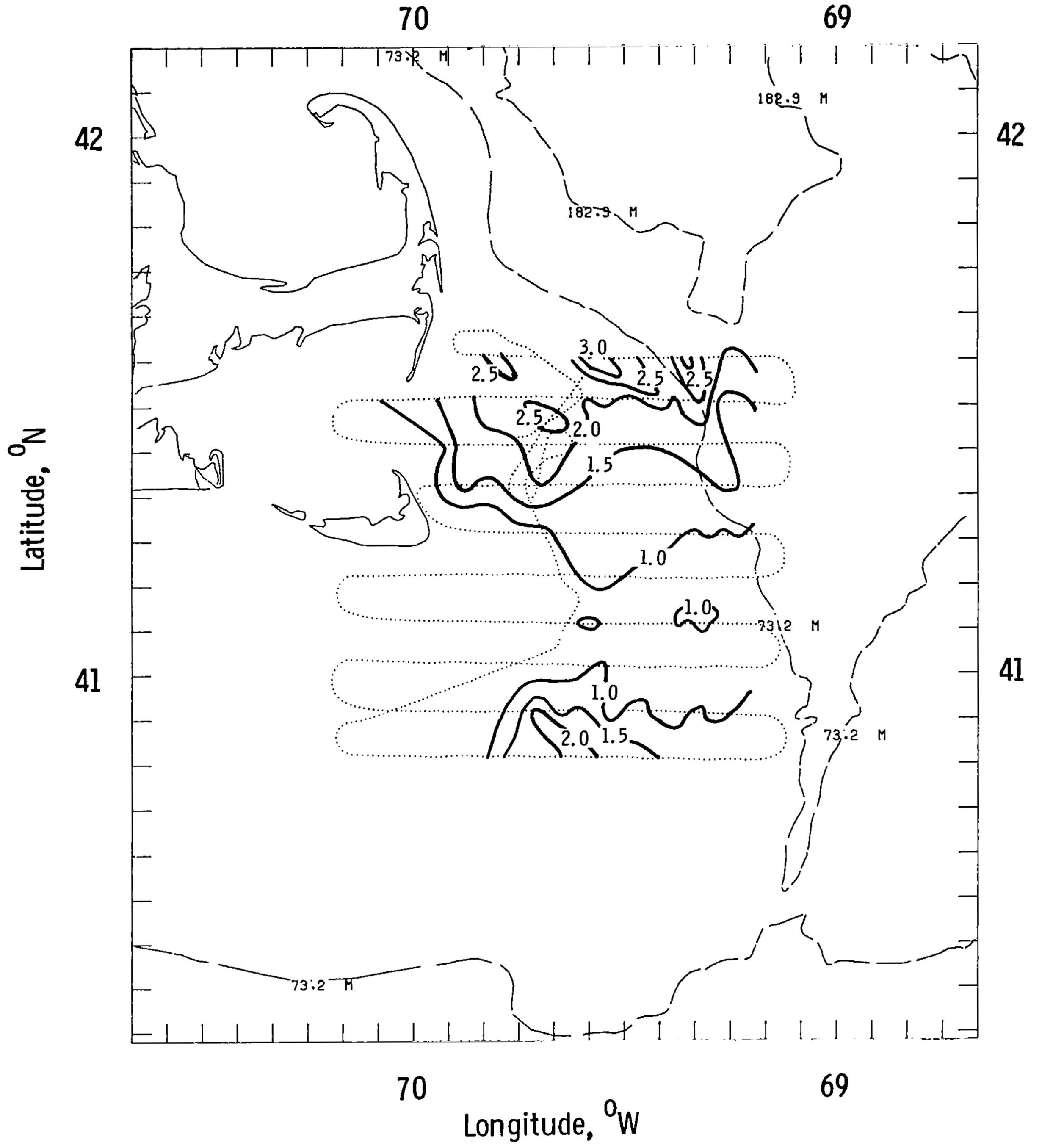


Figure 7.- Chlorophyll a distribution (µg/L) based on MOCS data collected at 150-m altitude on May 8, 1981 (flight 2). Solar elevation varied from 32° for line 1 to 56° for line 10.

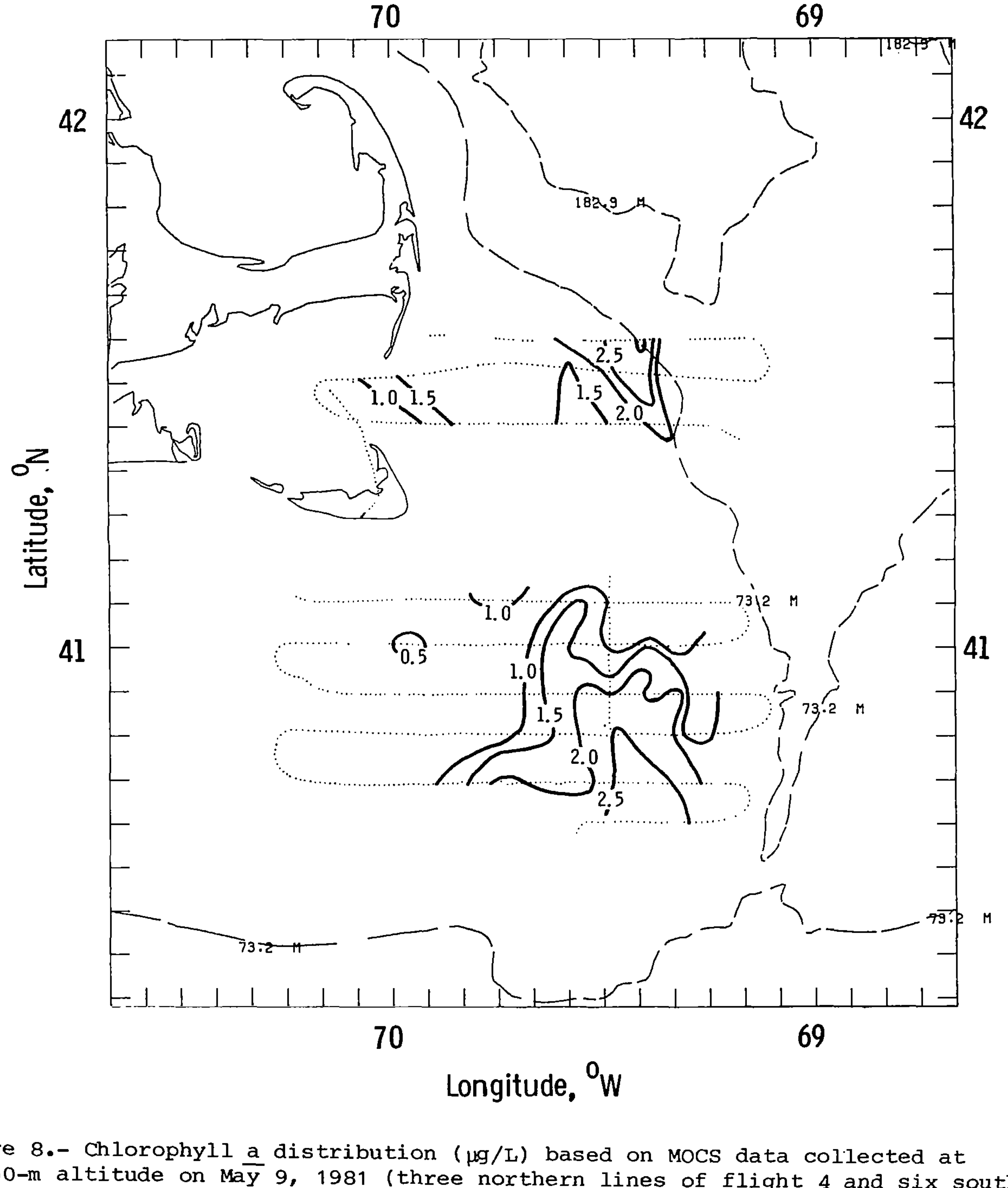


Figure 8.- Chlorophyll a distribution (μg/L) based on MOCS data collected at 150-m altitude on May 9, 1981 (three northern lines of flight 4 and six southern lines of flight 5). Solar elevations varied from 35° to 44° for northern lines and from 24° to 43° for southern lines.

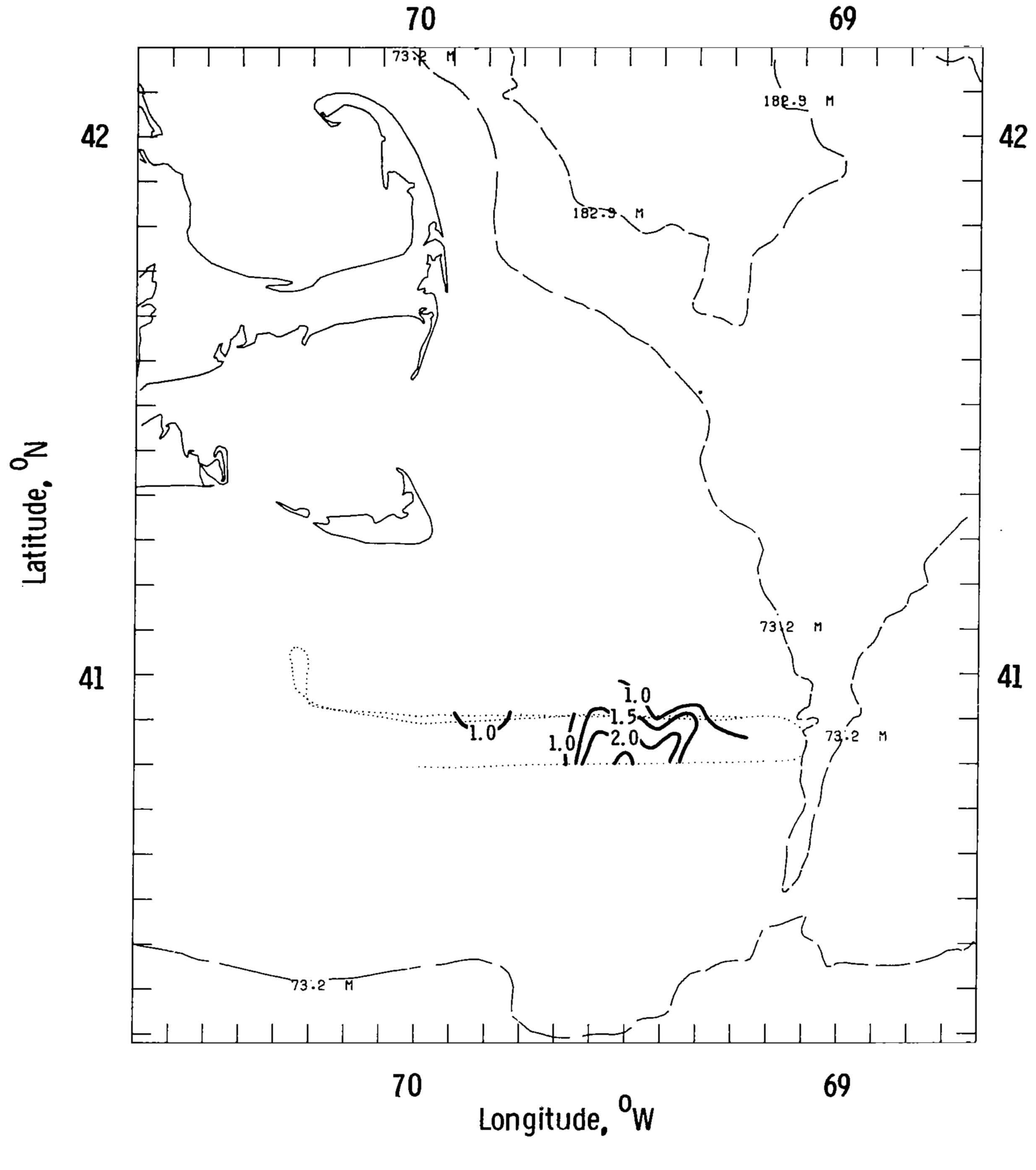


Figure 9.- Chlorophyll a distribution (μg/L) based on MOCS data collected at 2300-m altitude on May 13, 1981 (flight 7). Solar elevations varied from 33° to 38°.

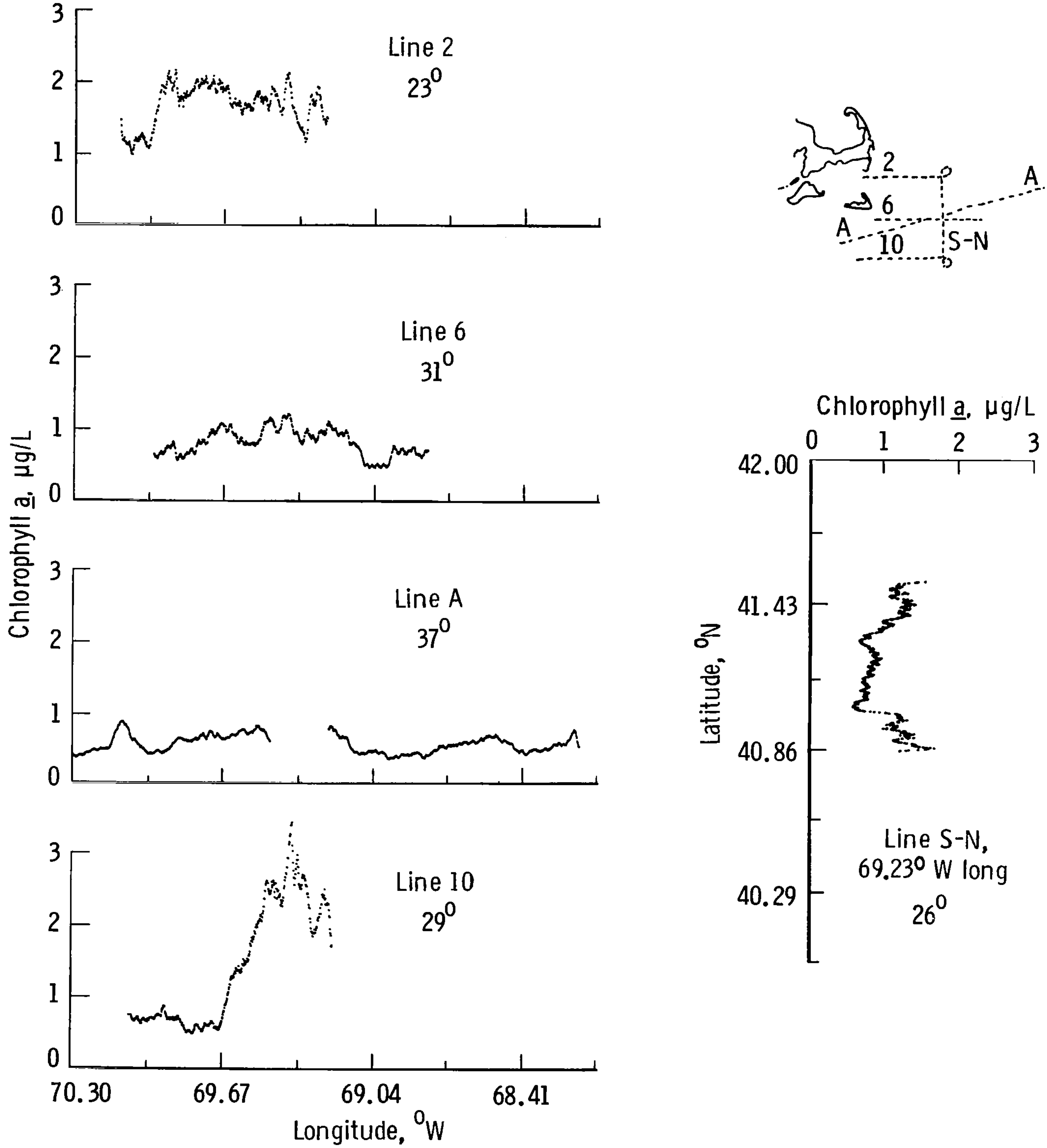


Figure 10.- Chlorophyll a concentrations from MOCS data collected at 2300-m altitude on flight 3 on May 8, 1981. Solar elevations are indicated on each plot.

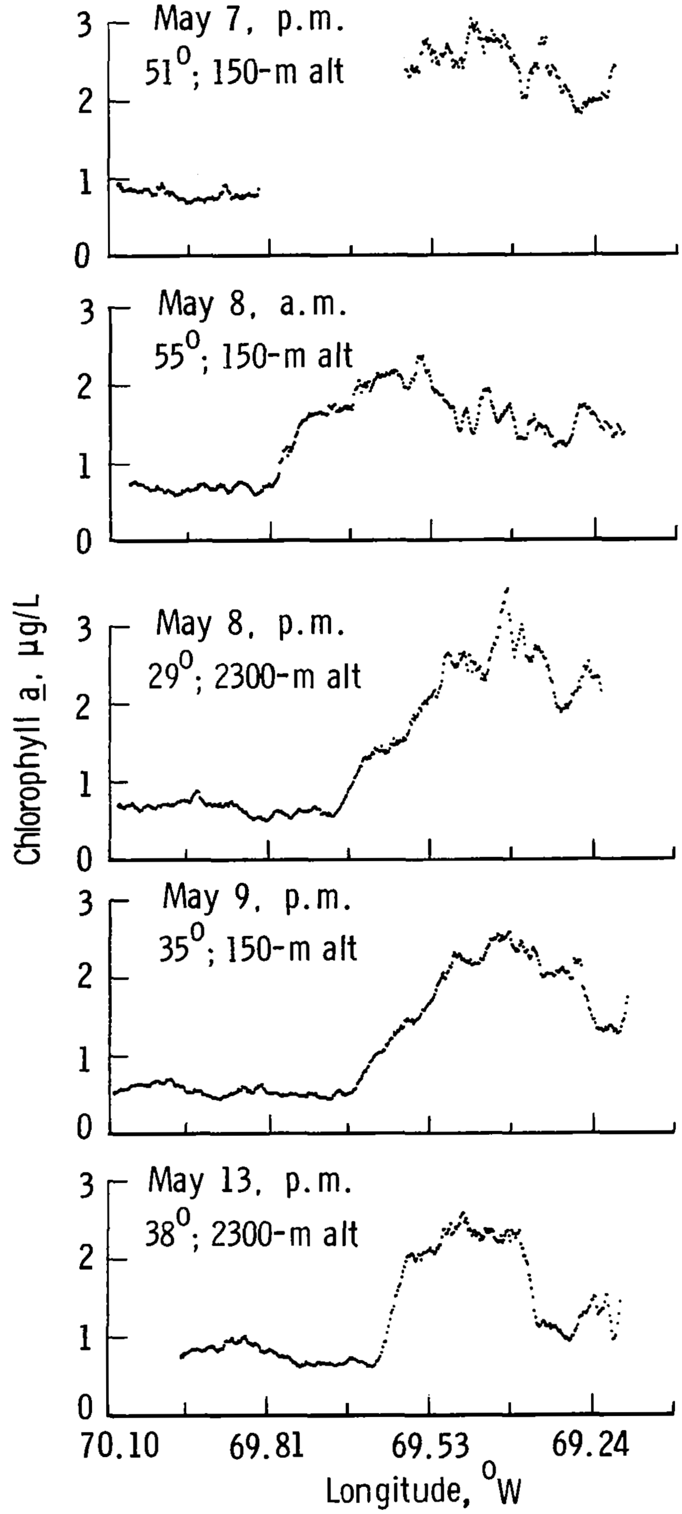


Figure 11.- Chlorophyll a concentrations along line 10 (lat 40.83° N) based on MOCS data. Solar elevations and flight altitudes are indicated on each plot.

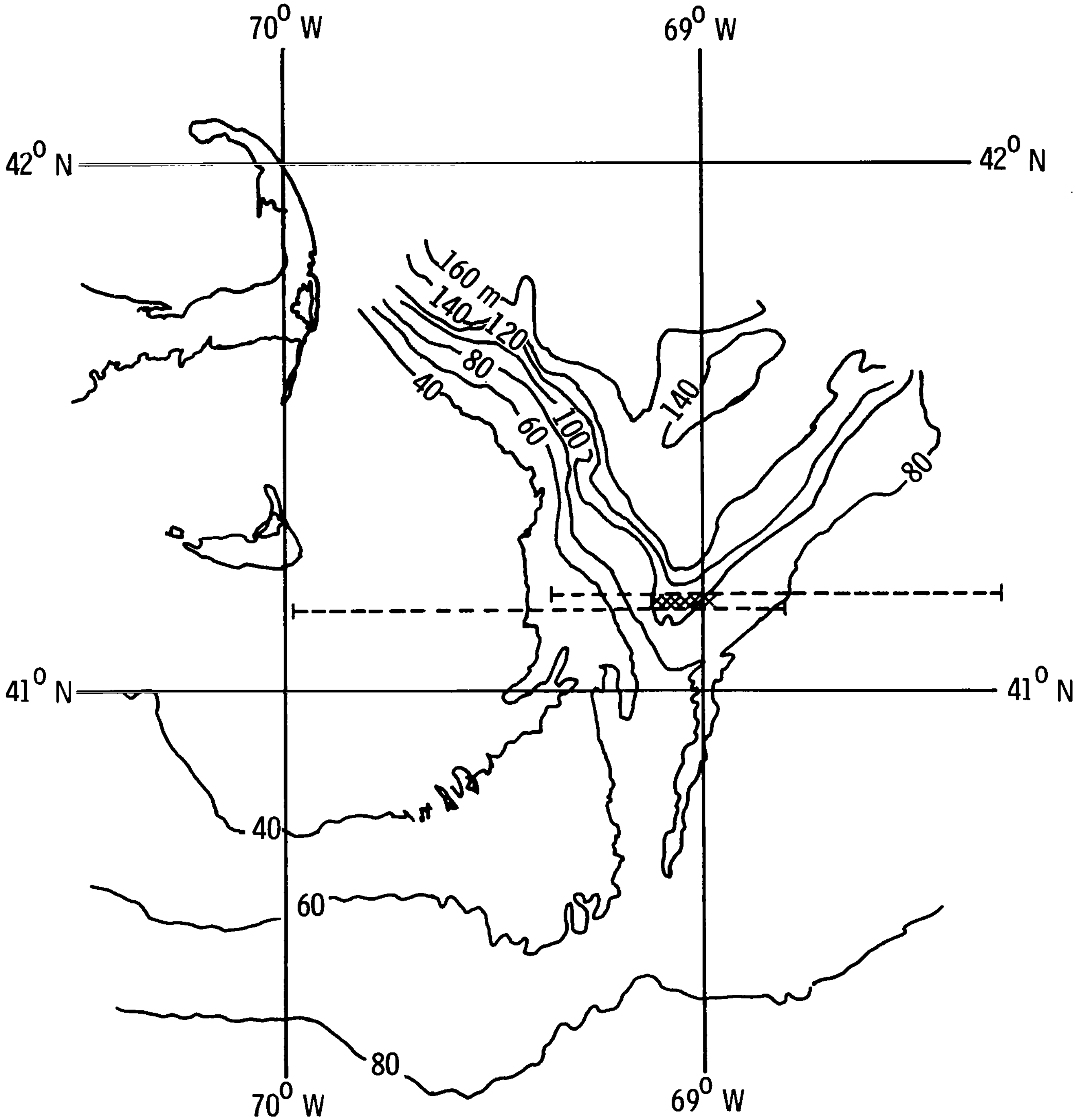


Figure 12.- Two flight tracks of the P-3 on May 8, 1981, are indicated by dotted lines. Hatched area at the 100-m isobath was a region of depressed chlorophyll a concentration (fig. 10, line 6) and a region where a large number of sea mammals were observed.

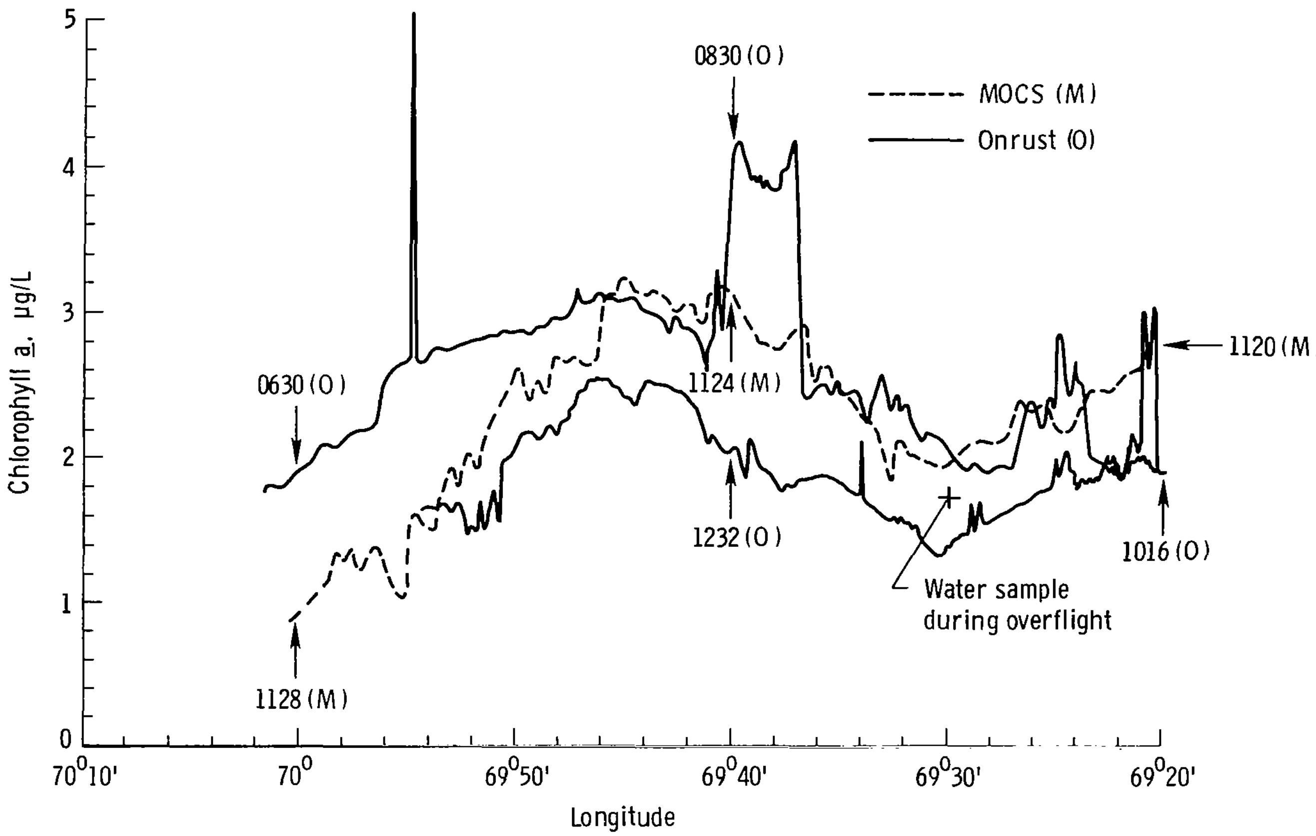


Figure 13.- Comparison of chlorophyll a measurements for May 8, 1981, along line 2 (lat 41°30' N) made by MOCS and by R/V Onrust on both eastbound and westbound legs. Numbers indicate times measurements were made. Solar elevation during MOCS flight was 60°.

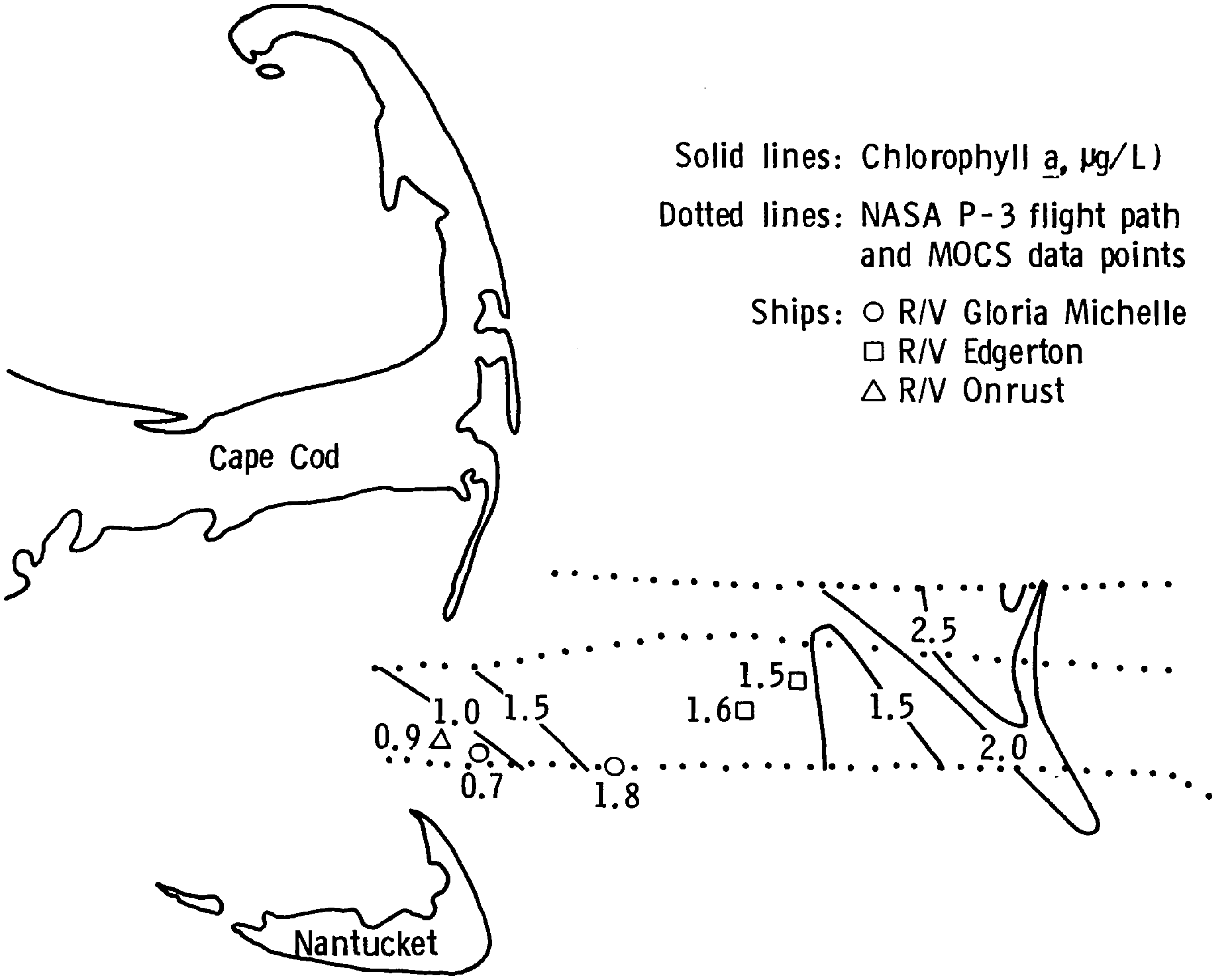


Figure 14.- Enlargement of flight 4 data region in figure 8 with the addition of chlorophyll a concentrations from water samples.

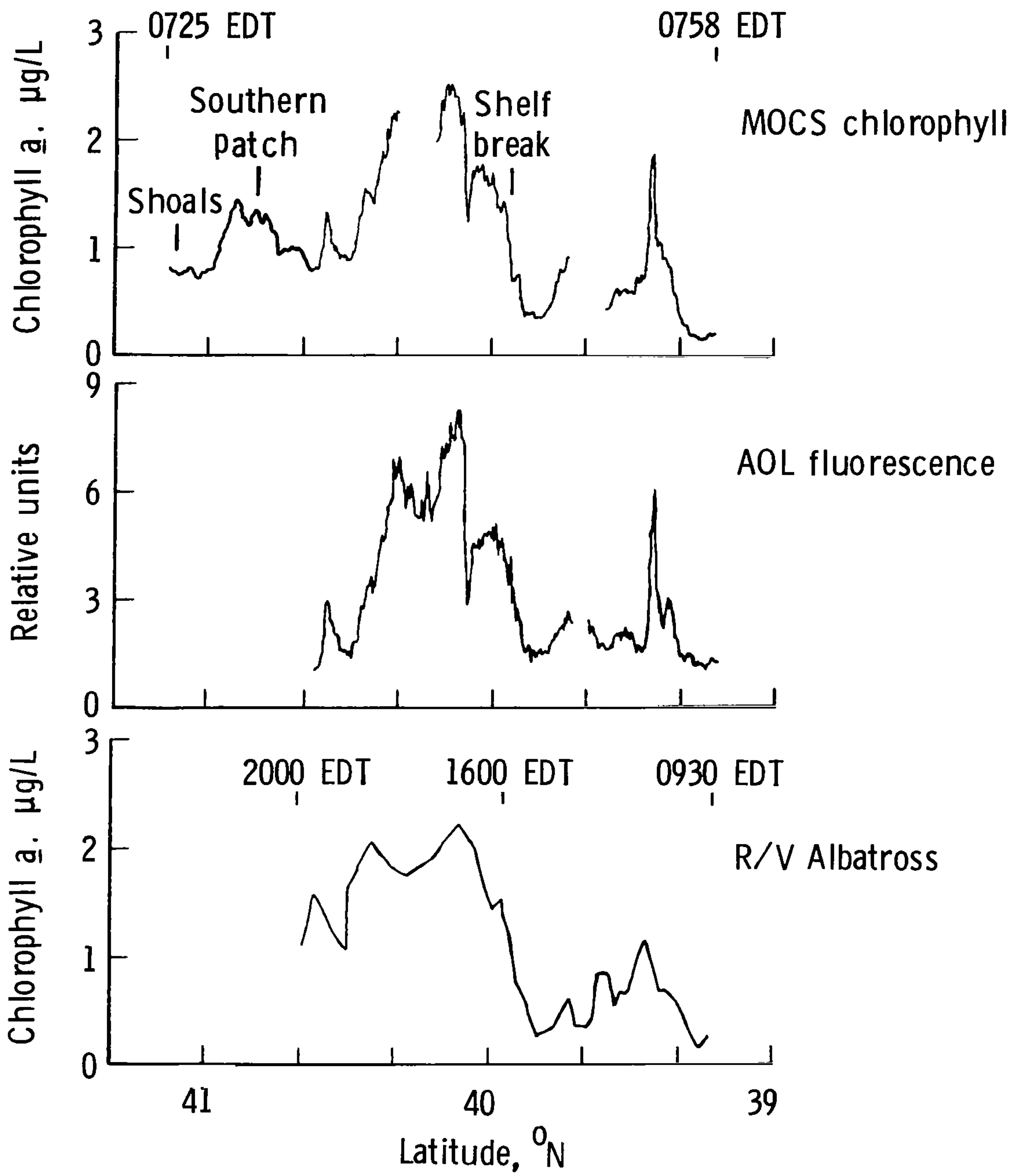


Figure 15.- Comparison of chlorophyll a concentration measurements made by MOCS and AOL aboard NASA P-3 and by R/V Albatross along longitude 69°40' W.

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16. Abstract

An algorithm for the remote detection of chlorophyll a in the ocean was tested during a Nantucket Shoals experiment conducted by NASA. A set of Multichannel Ocean Color Sensor (MOCS) data selected from one flight for each of the two altitudes flown was used to calibrate the algorithm for chlorophyll a concentration. The equations were then applied to all unsaturated MOCS data collected during the 8-day experiment to generate contour maps of chlorophyll a concentration over the shoals. One additional flight was conducted away from the shoals both on and off the Continental Shelf. Although no solar elevation or environmental corrections were made to the original conversions, the equations in these tests determined chlorophyll a concentrations to an accuracy better than 1.0 μg/L despite the fact that the solar elevation varied between 20° and 56° during the data collection periods of the experiment.

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