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ANALYSIS OF SIX BROADBAND OPTICAL FILTERS FOR MEASURING CHLOROPHYLL a AND SUSPENDED SOLIDS IN THE PATUXENT RIVER

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Kodak Wratten broadband optical filters numbered 47B (400 to 500 nm), 57 (500 to 600 nm), 58 (500 to 600 nm), 12 (500 to 700 nm), 25 (600 to 700 nm), and 89B (690 to 900 nm) were tested on October 17, 1972, to see whether each spectral band by itself could be used to quantify chlorophyll a and suspended sediment in the Patuxent River. Band 690 to 900 nm showed promise in being able to detect gross changes in chlorophyll a above 28 $\mu g/l$. None of the broad spectral bands seem capable of measuring chlorophyll a concentrations less than 28 $\mu g/l$ in turbid estuarine water. Except for the 47B spectral band, the bands do show promise for measuring suspended solids.

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SUMMARY

Six broadband optical filters were flown over the Patuxent River on October 17, 1972, to evaluate their use in remotely measuring total chlorophyll a and suspended solids concentrations. The spectral range of the Kodak Wratten 89B filter (690 to 900 nm) shows promise for detecting gross changes in total chlorophyll a levels in estuarine waters. The filter-film system detected concentrations greater than 67 μg/l but did not detect concentrations lower than 28 μg/l. There is some indication that the 690 to 900 nm band can be used to measure suspended solids concentrations in the 20 to 70 mg/l range.

The broad spectral bands of 500 to 600 nm (Wratten filters 57 and 58), 600 to 700 nm (Wratten filter 25), and 500 to 700 nm (Wratten filter 12) do not by themselves seem capable of measuring total chlorophyll a levels below 28 μg/l in turbid water bodies. These spectral bands ranges do show some promise in being used to measure the concentration of total suspended solids in the range of 20 to 70 mg/l.

The spectral band of 400 to 500 nm (Wratten filter 47B) shows no indication of being able to measure either total chlorophyll a (less than 28 μg/l) or total suspended solids (20 to 70 mg/l range) in turbid estuarine waters.

INTRODUCTION

It takes considerable time and money to collect and analyze water samples to determine the water quality of most lakes and rivers. Development of instruments that could remotely determine water quality would be of great benefit to the effort of monitoring this nation's rivers, lakes, and coastal waters. It is hoped that such instruments will be able to analyze large areas in shorter times than conventional methods and in the long run become more economical.

The NASA Langley Research Center, in conjunction with other federal agencies, has been involved in a program to determine the spectral bandwidths that are needed to measure remotely various water quality indicators. The idea behind these programs is that it is thought to be possible to relate spectral signatures or parts of spectral signatures coming from a water body with certain parameters in the water.

One of the systems being used consists of wide-angle lens aerial cameras with spectral filters attached. After photographing and subsequent development, film densities are measured by using a microdensitometer. The densities are then studied to determine the correlation, if any, that there is between the film density, that is, radiant intensity of the spectral bands, and the water quality indicators measured. It has been shown in reference 1, for example, that the film density difference between a point on a photograph and the unexposed film border taken through a Kodak Wratten 89B filter (690 to 900 nm) can be correlated to chlorophyll a concentrations.

An opportunity arose in October 1972 for a follow-up to the Potomac experiment, discussed in reference 1, when it was learned that the Chesapeake Biological Laboratory, under contract to the Corps of Engineers, planned to collect ground truth data at seven locations in the Patuxent River. The purpose of this Patuxent River remote-sensing experiment was to continue the evaluation of specific broadband spectral filters for measuring and monitoring total chlorophyll a concentrations and total suspended solids. This paper describes the Patuxent River flight experiment and reports the results of the analysis of the broadband spectral filters used on 40-mm focal length Hasselblad cameras containing black and white film.

EXPERIMENT

On October 17, 1972, a remote-sensing experiment was conducted over the Patuxent River in Maryland. Three missions were flown. A C-54 aircraft out of NASA Wallops Flight Center (WFC) flew a morning and a late afternoon mission while a C-130 from NASA Johnson Space Center flew a noon mission. The times of each mission, the solar elevation angles, and flight altitudes are shown in table I. Each mission included the two flight lines shown in figure 1. The two flight lines were flown at different altitudes in order to have land features in all the photographs. This information was needed for location purposes.

The C-54 carried a T-11 camera and a bank of four 40-mm Hasselblad cameras. The 40 mm represents the focal length of the lens system. The C-130 had two RC-8 cameras, a Recon IV, four 40-mm Hasselblad cameras, two 80-mm Hasselblad cameras, and a 24-channel multispectral scanner. This report deals only with the spectral film data collected from the 40-mm Hasselblad cameras that contained black and white film.

The Zeiss 40-mm Distagon f/4 lenses used on the Hasselblad cameras have a field of view of approximately 88°. The film format was 70 mm. Kodak film type 2402 was used with all filters except the Wratten 89B filter where film type 2424 was used. The film was processed in a Kodak Versamat Film Processor, Model 11, with type 641 chemicals. Contact positive transparencies were made by using a Colorado Printer. Kodak film type 2420 was used to make the transparencies and they were developed in the same Versamat processor by using type B chemicals. The relative film densities presented in this paper were obtained from the positive transparencies, since the original negatives were not available for analysis. The camera setting and filters used for each mission are shown in table II. The transmission curves of the Kodak Wratten filters are shown in figure 2 (from ref. 2).

The filters used on the two C-54 missions were selected on the basis of the reflection and absorption curves of the various pigments known to be in phytoplankton. Figure 3 (from ref. 3) shows the reflectance of higher chlorophyll-containing plants. Notice the very high reflectance peak starting at about 690 nm and the smaller peak in the 500 to 600 nm region. The Wratten 89B filter (690 to 900 nm) was picked to measure the highest reflectance peak. The Wratten 58 filter (500 to 600 nm) was selected to measure the smaller first reflectance peak. It was also thought that the Wratten 58 filter might be able to detect total suspended solid concentration changes. Figure 4 (from ref. 4) shows absorption spectra for other phytoplankton photosynthetic pigments. The filter system flown on the C-54 was originally used over the Potomac River where blue-green algae dominate in the bloom season. Blue-green algae are known to have a group of pigments called phycobilins. Phycoerythrin and phycocyanin shown in figure 4 are in this group. The combination of those two pigments shows a strong absorption in the 500 to 600 nm wavelength range. Wratten filter 12 (500 to 700 nm) was picked to detect this absorption. Chlorophyll a is found in all types of phytoplankton but phycobilins are not. Even though blue-green algae were known not to be the dominating species in the Patuxent River, it was still decided to fly the Wratten 12 filter along with the Wratten 89B and 58 filters for this experiment. It was hoped that the intensity of both the reflectance and absorption peaks, recorded as increases or decreases in film density, respectively, could then be related to the quantity of the pigments in the water to give an indication of water quality.

The four filters on the C-130 mission were chosen to separate the visible spectrum into the three primary colors plus use of the 89B filter to measure the near-infrared spectrum.

Ground truth data were collected at seven stations along the Patuxent River by the Chesapeake Biological Laboratory under contract to Corps of Engineers (Contract DACW31-17-C-0077). The boat location of station 7-01, Jug Bay, was not covered by flight line 2; therefore, the number of ground truth sites filmed was reduced to six. The station names, identification numbers, and frame numbers of the photos taken over each station are given in table III. Ground data were collected hourly during the overflight with the result that all photographic data were taken within 25 minutes of the water sampling time except for two of the total suspended solids measurements. The ground truth data are shown in table IV. The suspended solid measurements were done by the Smithsonian Institute, Division of Sedimentology.

The Sun elevation at the start of the late afternoon mission was 11°. Figure 5 (from ref. 5) shows a plot of solar irradiance against wavelength for various Sun elevations. It can be seen that the intensity of energy reaching the Earth surface is reduced as the Sun elevation decreases. The proportion of incident light entering the water is also reduced because the reflectivity of the water surface increases as the solar elevation decreases. As can be seen in figure 6, the reflectivity dramatically increases as the Sun elevation falls below 30°. The net result is to reduce the amount of light available to be backscattered by the constituents within the water body. On the cameras, f stops would also have to be opened up more to compensate for the lower intensity which would induce greater exposure falloff. For these reasons it was felt that the 11° Sun elevation was too low to get meaningful remotely sensing data and thus the film data obtained in the late afternoon were not analyzed.

A summary of the mission data is presented in table V. Because of cloud cover and incomplete ground truth data, the analysis of total chlorophyll a with relative film density was reduced to five data points. The analysis of total suspended solids with relative film density was lowered to only four points.

ANALYSIS TECHNIQUE

A Joyce-Loebl and Co., Ltd., microdensitometer model Mark III C was used to measure the film density from the positive transparencies. A description of its operation is given in reference 6. The instantaneous spot size on the film surface was 37.5 μm by 250 μm. The spot size was small enough to provide a microdensitometer spatial resolution equal to or better than the film resolution, but big enough to average out variations due to film graininess. The reason for wanting the instrument resolution better was to cut down the ground area averaging as much as possible. A neutral density filter (density of 1.0) was added to the microdensitometer when the film exposed through the Wratten 89B filter of the C-54 morning mission was analyzed. This filter kept the internal density wedge of the microdensitometer in its middensity range.

If a picture is taken of a uniformly reflecting surface, the exposure over the whole photograph should be constant. It turns out that the exposure is not constant when wide-angle lenses are used. The spot on the film that is exposed by rays traveling along the principal axis (assumed here to be the center point of the photograph) will have the correct exposure but as the distance away from the center point increases, the exposure decreases.

This problem is usually referred to as vignetting and the falloff has been theoretically shown to be a $\cos^4$ function of the angle ϕ formed between the light ray going through the lens with one traveling along the principal axis (ref. 7). (See fig. 7.) Use of the wide-angle lens has thus made it necessary to a make offnadir (off principal axis) angle film exposure corrections. The $\cos^4\phi$ could not be directly applied to this set of data, however, because two other factors also influenced the exposure pattern on the film. One factor was the filter adapter used on the C-54 mounted Hasselblad cameras. It was undersize and did not permit exposure of the corners of the film. This condition possibly affected the exposure on other areas of the film as well. The second factor is atmospheric backscattering. As the offnadir angle ϕ increases, the atmospheric influence increases because a light ray traveling along the principal axis has traveled through less atmosphere than a light ray coming in at any other angle. This atmospheric effect reduces the magnitude of the exposure falloff.

The technique used to make this exposure correction was as follows: A photograph that had uniform water spectral intensity throughout was selected by visual inspection. A densitometer trace was then taken. It started at one border, passed horizontally through the center of the photograph, and continued to the opposite border. Likewise, a trace was taken across the bottom border, as illustrated in figure 8. A straight line was then faired through the border trace to be used as a reference base. The vertical pen distance between the center line pen trace and that of the border trace was then empirically corrected to equal the vertical pen distance between the center point and the border trace. This procedure was followed since the center needed no correction. The vertical pen distance is directly proportional to exposure. This correction results in a straight line which would be the result if the falloff problem did not exist. The correction was then applied to all the other photographs. More than one picture was used to determine the correction factor since it was known that the water spectral intensity was not uniform as desired. A falloff correction factor was calculated for each camera filter combination and the results are given in table VI.

Two assumptions were made when applying this correction. One was that the original film exposure and the newly calculated exposure were all within the linear portion of the H and D characteristic curve of the film. If this were not the case, then the conversion to density units would be wrong. The second assumption made was that constant atmospheric conditions existed over the complete Patuxent River.

The film density values reported herein are not the absolute film densities, but represent the density difference between any point on a photograph and the unexposed film border. Therefore, in this report, the larger the relative density value, the greater was the exposure; thus, a higher radiant intensity was measured. All the relative film densities reported in this paper except those called "weighted average film densities" were calculated from a single-line microdensitometer pen trace over the ground truth location. An example of the single-line microdensitometer pen traces used to obtain the data station relative film densities is shown in figure 9. Station 6-01 data are shown for both the morning flight and the noon flight. The vertical pen distance used for the ground truth location was taken next to the peak marked boat. All stations had the boat in the picture. All pen traces started from the left border and moved horizontally through the sampling boat to the right border. The border traces used as the zero were taken in the same direction from the bottom of the film. The relative film density was obtained by measuring the vertical distance between the point of interest on the densitometer pen plot of the line trace and that of the faired line drawn through the film border trace. After correcting the measured distance for instrumentation related intensity falloff, the distance was multiplied by a constant to put the film density difference into density units.

During the analysis it was decided that average relative film densities over the full water surface of some frames were needed. Getting the average relative density by using the single pen traces would have taken too long; thus the microdensitometer was put in the automatic mode and the microdensitometer measurements were recorded on tape. CONVERT, a computer program (ref. 8), was then used to convert each data point on tape to its corresponding corrected relative film density. Having all of these relative film densities made it possible to compute the average relative film density. The average density was given the name "weighted average film density (WAFD)." The method used to calculate the WAFD is given in the appendix.

The Broome Island station (identification no. 3-01) film data were taken at a higher altitude than were the rest of the stations. It was felt that the difference, 640 meters (2100 ft), for the C-54 morning mission and 609 meters (2000 ft) for the C-130 noon mission might be significant in terms of atmosphere effects. To find out, frames 14 and 17 of the morning mission containing the same water area but taken at the different altitudes were compared. The ratio of altitudes for the C-54 morning mission was 1.48. This same ratio was then applied to the microdensitometer film spot size setting so that the ground area covered by the spot would be the same for both altitudes. Since the falloff calibration factor would have to be applied, it was decided to take the center point of the lower altitude picture and the corresponding area on the higher altitude picture. This procedure would require only one correction since the center point needs no correction. Single scan pen traces were taken and then the relative film densities over the duplicated area were compared.

The test for the effect of the two altitudes resulted in a difference being found in the relative film densities between the overlapping test area. A 0.091 relative film density difference was found for the Wratten 12 and 58 filters whereas a 0.036 density difference was found for the 89B filter. The higher altitude picture had the higher relative density.

These density differences were then used as an altitude correction to station 3-01 relative film densities only. To make the correction, these calculated density differences were subtracted from the previous corrected relative film density computed for station 3-01. The altitude correction factors calculated from the morning mission pictures were also applied to the noon mission. It was felt that the atmospheric effect of the 31-meter difference in flight line 2 altitudes between the two missions would not be detected. The 0.091 factor was applied to data from Wratten filters 25, 47B, and 57 whereas the 0.036 factor was applied to the data from the Wratten 89B filter.

RESULTS AND DISCUSSION

The photographs taken during the morning mission are shown in figures 10(a) to 10(e). The six photographs covering the six data stations from the noon mission are shown in figure 10(f). The pictures used to obtain the offnadir correction factor for the morning mission (frame numbers 20, 19, 18, 12, 11, and 10) are shown in figures 10(d) and 10(e) whereas the ones used for the noon mission are shown in figure 11.

The corrected relative film densities calculated for each filter at each station are shown in table VII.

In table V, the C-54 morning flight shows a blank in the film density column at station 4-02. Even though there was no noticeable cloud shadow over the boat, the film density obtained from the microdensitometer was unusually low. Figure 12 shows a plot of film density against distance downriver obtained on the C-54 morning flight. At station 4-02 the density decreases appreciably in all three filters. The actual reason for the decrease is unknown. The Chalk Point power plant is in the vicinity and a water vapor cloud from the cooling towers might have formed and may have been over the area at flight time. A cloud shadow, even though not visibly detected, is thus thought to be responsible for these low station 4-02 film densities. Since those densities seem to be in error, they were deleted from the analysis.

In the following discussion, a mention of increasing relative film density is equivalent to an increase in radiant intensity in a specific spectral band.

Morning Mission

<u>690 to 900 nm broad spectral band (Wratten 89B filter)</u>.- The corrected relative film densities are plotted as a function of total chlorophyll $\underline{a}$ and suspended solids in figure 13. Chlorophyll $\underline{a}$ concentrations greater than 67 $\mu g/l$ were detected in the 690 to 900 nm range, but this spectral band seems to be insensitive to concentrations less than 26 $\mu g/l$. This insensitivity must be due in part to the high absorption of water at the near-infrared (NIR) wavelengths. The detection at higher concentration thus suggests

that the amount of increase in NIR reflected radiation by chlorophyll a is enough to overcome the water absorption.

Insufficient data points at intermediate chlorophyll a levels made it impossible to determine the lowest level detectable by the Wratten 89B filter in this mission. It must be emphasized that the lower detection limit of chlorophyll a by this spectral band will be a function of detector spectral sensitivity and possibly phytoplankton species. Instruments that are more sensitive than film might detect lower concentrations. Phytoplankton size, shape, pigment makeup, and chemical makeup may all play a part in determining the level of detection of each species through their absorption and scattering properties.

Initial analysis of the film exposed through the Wratten 89B filter showed a marked change in film density between the lower parts of the Patuxent (near mouth) and upriver around Nottingham. The change in density was examined to determine whether it was a gradual phenomena or an abrupt one and where it occurred. To do this, the microdensitometer was placed in an automatic mode and the relative densities over the complete water area for 16 pictures were obtained. The ground truth data were also analyzed to determine the cause of the change. Table VIII shows the weighted average film densities (WAFD) calculated from the relative density data. An abrupt WAFD change occurred between frame 26, just below Holland Cliff, (WAFD = 0.060) and frame 25, Cedarhaven, (WAFD = 0.125).

Figure 14 shows a plot of phytoplankton cell count against distance down the river. There is a big dropoff between stations 6-01 (frame 33) and 5-01 (frame 24). Total chlorophyll a, total suspended solids, and salinity are plotted against distance downriver in figure 15. As would be expected from the cell counts, there is a continuing drop in total chlorophyll a between stations 6-01 and 5-01. The suspended solids concentration plot does not follow that trend. The highest concentration of suspended solids is at station 5-01. The salinity shows a large increase (approximately 6 ppt) between station 5-02 (frame 30) and station 5-01. The high suspended solids concentration at station 5-01 seems to stem from the great amount of mixing between fresh and salt water that is occurring there. The increased mixing would tend to bring the suspended solids to the top. It is the decrease in total chlorophyll a concentration brought about by the increase in salinity that seems to cause this decrease in weighted average film density between frames 26 and 25. Above frame 25 the concentration of chlorophyll a seems to have increased enough to exceed the lower threshold camera detection level. The high weighted average film density extends from frame 26 up past station 6-01 (approximately 20 km) and then starts to decrease again. The 690 to 900 nm spectral band thus seems to have a use for measuring at least gross changes in phytoplankton levels with a side effect of possible measuring the salt water wedge intrusion in tidal rivers.

No trend was evident between the 690 to 900 nm spectral range densities and total suspended solids (15 to 58 mg/l range) when they were plotted against each other.

500 to 700 nm spectral band (Wratten 12 filter).- Figure 16 shows the corrected relative film densities plotted as a function of total chlorophyll a and suspended solids. At this spectral range relative film densities fluctuate at low chlorophyll a concentration. This fluctuation seems to indicate that the emission from the water is not being dictated solely by the level of chlorophyll a. However, this spectral range does show higher relative film densities at the higher chlorophyll a (greater than 67 μg/l) stations. This result seems to signify that when the phytoplankton concentration increases to some level (somewhere between 25 and 65 μg/l), that above the level the chlorophyll a within the phytoplankton becomes a significant factor in determining the spectral range of the upwelling light coming from the water. Whether this concentration is the same concentration as that of the lower limit needed to be detected by the 89B spectral range cannot be determined from these data.

The corrected relative film densities from this spectral range show a general increasing trend with increasing total suspended solids but the highest corrected relative film density is not recorded at the station of highest total suspended solids concentration; thus, no definite conclusion can be drawn.

500 to 600 nm spectral band (Wratten 58 filter).- The corrected relative film densities from this spectral range (see fig. 17) show no trends with total chlorophyll a at either the low or high concentration level nor with total suspended solids.

Noon Mission

690 to 900 nm spectral band (Wratten 89B filter).- As shown in figure 18, four out of the five total chlorophyll a concentrations usable were less than 28 μg/l. From the results of the morning mission, no response would be expected for this chlorophyll a range and, as expected, no definite trends appeared when the corrected relative film density was plotted against chlorophyll a. The lowest concentration had the highest corrected relative density. No apparent reason for this occurrence is known.

When the corrected relative film densities for this spectral band are plotted against total suspended solids (15 to 65 mg/l), an increasing trend in corrected relative film density is seen with increasing concentration of suspended solids. For this increase in film density to occur, the suspended solids must be very close to the surface because the water absorbs strongly over this spectral bandwidth. This increasing trend was not evident in the morning flight. No firm conclusion about the use of this spectral band to measure total suspended solids can thus be made.

400 to 500 nm spectral band (Wratten 47B filter).- Figure 19 shows the corrected relative film densities plotted as a function of total chlorophyll a and suspended solids. Again, four out of five total chlorophyll a concentrations are less than 28 $\mu g/l$. The corrected relative film density when plotted against chlorophyll a show no trends at this low concentration level. The pigments of the dominating phytoplankton when this experiment was conducted (mostly brown algae types) absorb strongly in the 400 to 500 nm range. This absorption should bring about a drop in relative film density. It is thought the scatter in the plotted data is caused by the combination of atmospheric backscatter and suspended material scattering dominating the absorption by the pigments. The plot of corrected relative film density against total suspended solids shows no trend. This condition again seems to indicate that atmospheric scattered radiation masks out the reflectance from the suspended material in the water.

500 to 600 nm spectral band and 600 to 700 nm spectral band (Wratten 57 and 25 filters, respectively).- Figures 20 and 21 show the corrected relative film densities plotted as a function of total chlorophyll a and suspended solids for filters 57 and 25, respectively.

Just like the 400 to 500 nm spectral range, the relative film density is randomly scattered when plotted against total chlorophyll a. This randomness is probably due to the fact that the chlorophyll a at low concentrations is not the overriding factor dictating the emission of 500 to 700 nm wavelengths.

The corrected relative film densities of both filters show a general increasing trend with increases in total suspended solids. This result tends to agree with the 500 to 700 nm spectral band recorded in the morning mission, but disagrees with the data from the 500 to 600 nm spectral range of the morning mission.

CONCLUDING REMARKS

The broad spectral range of the Kodak Wratten 89B filter (690 to 900 nm) shows promise for detecting gross changes in total chlorophyll a levels in estuarine waters. The filter detected concentrations greater than 67 $\mu g/l$ but did not detect concentrations lower than 28 $\mu g/l$. Insufficient data points at intermediate total chlorophyll a levels made it impossible to determine the lowest level detectable. There is also some indication that the 690 to 900 nm spectral range can be used to measure suspended solids concentrations in the 20 to 70 mg/l range.

The data from the broad spectral bands of Wratten filters 57 (500 to 600 nm), 58 (500 to 600 nm), 12 (500 to 700 nm) and 25 (600 to 700 nm) indicate that the bands do not by themselves seem capable of measuring total chlorophyll a levels below 28 $\mu g/l$ in turbid water bodies. These broad spectral bands do show some promise in being able to measure total suspended solid concentrations in the range of 20 to 70 mg/l.

The broadband of 400 to 500 nm (Wratten filter 47B) shows no indication of being able to measure either total chlorophyll a (less than 28 μg/l) or total suspended solids (20 to 70 mg/l range) in turbid estuarine waters.

To insure meaningful results, flight mission parameters such as number of ground truth stations, timing of data collection, Sun elevation, and instrument setting must be thoroughly planned before a test mission is flown.

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APPENDIX

CALCULATION OF WEIGHTED AVERAGE FILM DENSITY

Calculation of the weighted average film density by using the program CONVERT may be made as follows:

(1) Break up the density range into intervals.

(2) Place each density point into its corresponding interval.

(3) Subtract out unwanted density intervals. This step allows land areas, sunglint areas, and noise to be subtracted out if there is a distinct density difference between the water and these areas.

(4) Multiply the percentage of points in each interval by the median density of the interval.

(5) Add up the products generated by step 4.

Example:

Density range: 0.00 to 1.000

Intervals: 0.00 to 0.10, 0.10 to 0.20, 0.20 to 0.30, 0.30 to 0.50, 0.50 to 0.70, and 0.70 to 1.00

A data point density of 0.35 would be placed in the 0.30 to 0.50 density interval.
Total number of points digitalized, 20 000

Interval	Number of points
0.00 to 0.10	400
0.10 to 0.20	2300
0.20 to 0.30	1650
0.30 to 0.50	8700
0.50 to 0.70	6200
0.70 to 1.00	750

It is known that 0.00 to 0.10 is noise and 0.70 to 1.00 covers land densities so these two intervals are subtracted out. This results in 20 000 - (400 + 750) = 18 850 points.

Interval	Median of interval	Percentage of points in interval	Interval weighted Average = Median × percentage
0.10 to 0.20	0.15	2300/18 850 = 0.122	(0.15) (0.122) = 0.018
0.20 to 0.30	0.25	1650/18 850 = 0.088	(.25) (.088) = 0.022
0.30 to 0.50	0.40	8700/18 850 = 0.461	(.40) (.461) = 0.184
0.50 to 0.70	0.60	6200/18 850 = 0.329	(.60) (.329) = 0.197
Total weighted average			0.421

The sum of the interval weighted averages is the weighted average film density and in this example equals 0.421.

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TABLE I.- OCTOBER 17, 1972 PATUXENT RIVER EXPERIMENT

FLIGHT LINE SUMMARY

Aircraft	Mission flight line	Flight time, EST	Solar elevation[a] angle, deg	Flight altitude, m
Morning mission				
C-54 from NASA Wallops Flight Center	1 2	10:46 to 10:53 10:57 to 11:04	39	1981 1341
Noon mission				
C-130 from Johnson Space Flight Center	1 2	12:00 to 12:02 12:10 to 12:17	41	1981 1372
Late afternoon mission				
C-54 from NASA Wallops Flight Center	1 2	16:29 to 16:37 16:40 to 16:48	9	1981 1341

[a]Solar elevation angles were calculated by using the starting times of flight line 2.

TABLE II.- CAMERA/FILTER COMBINATION AND CAMERA SETTING FOR PATUXENT RIVER EXPERIMENT

Camera	Focal length, mm	Kodak Wratten filter	Film format, mm	Kodak film type	Aerial exposure index rating	Shutter speed, sec	Lens f number
				Morning mission			
1 Hasselblad	40	58	70	2402 black and white	6	1/250	11
2 Hasselblad	40	12	70	2402 black and white	40	1/250	5.6
3 Hasselblad	40	89B	70	2424 near infrared black and white	28	1/250	11
				Noon mission			
1 Hasselblad	40	57	70	2402	40	1/250	8
2 Hasselblad	40	25	70	2402	40	1/250	8
3 Hasselblad	40	89B	70	2424	28	1/250	16
4 Hasselblad	40	47B	70	2402	40	1/250	5.6
				Late afternoon mission			
1 Hasselblad	40	58	70	2402	6	1/250	4
2 Hasselblad	40	12	70	2402	40	1/250	8
3 Hasselblad	40	89B	70	2424	28	1/250	5.6

TABLE III.- DATA STATION LOCATION AND CORRESPONDING FRAME NUMBERS SHOWING EACH LOCATION

Name	Data station		Frame number for –		
	Identification number	Location,[a] longitude and latitude	C-54 morning flight	C-130 noon flight	C-54 late afternoon flight
Broome Island[b]	3-01	76°35'07" W 38°24'42" N	10	21	52
Long Point	4-01	76°39'55" W 38°29'38" N	19	50	60
Chalk Point	4-02	76°40'32" W 38°32'30" N	22	57	63
Truman Point	5-01	76°40'44" W 38°34'46" N	24	62	65
Lower Marlboro	5-02	76°41'03" W 38°39'23" N	30	74	71
Nottingham	6-01	76°42'02" W 38°42'33" N	33	82	74

[a]Coast and Geodetic Survey Map 553.

[b]The Broome Island station film data were collected on flight line 1 whereas the other stations were on flight line 2.

TABLE IV.- GROUND DATA FOR PATUXENT RIVER EXPERIMENT

Station	3-01	4-01	4-02	5-01	5-02	6-01	7-01
Morning mission							
Time of picture, EST	10:50	10:57	10:59	11:00	11:01	11:02	11:04
Data collection time, EST	11:11	11:14	11:13	11:04	11:00	11:07	11:00
Active chlorophyll[a] a, $\mu g/l$	9.1	7.3	16.5	22.4	46.4	61.4	11.2
Total chlorophyll[b] a, $\mu g/l$	11.4	8.9	18.5	26.5	67.7	75.9	15.4
Dissolved oxygen, mg/l	10.6	10.0	8.7	8.4	11.8	11.3	7.2
Salinity, ppt	----	10.7	8.7	7.6	1.9	.4	.4
Velocity,[c] cm/sec	-25.3	-20.1	-20.7	19.8	17.7	7.6	11.3
Suspended solids,[d] mg/l	[e]15.2	----	30.0	[f]58.0	36.0	37.0	34.0
Secchi disk, m	----	.9	.8	.7	.5	.4	.6
Depth of sampling, m	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Noon mission							
Time of picture, EST	12:07	12:10	12:11	12:12	12:14	12:15	12:17
Data collection time, EST	12:17	12:17	12:07	12:04	12:00	12:05	12:00
Active chlorophyll a, $\mu g/l$	6.8	6.3	18.0	22.4	61.4	76.3	14.3
Total chlorophyll a, $\mu g/l$	10.3	7.8	21.2	27.4	84.0	93.0	18.3
Dissolved oxygen, mg/l	10.5	9.2	9.6	9.1	11.7	12.2	7.5
Salinity, ppt	----	10.7	8.3	7.6	2.0	.5	.4
Velocity, cm/sec	-30.5	-17.1	-36.6	7.9	-20.1	-5.9	-5.2
Suspended solids, mg/l	14.4	----	44.0	64.0	36.0	28.0	32.0
Secchi disk, m	----	----	----	----	----	----	----
Depth of sampling, m	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Late afternoon mission							
Time of picture, EST	16:33	16:41	16:42	16:43	16:45	16:46	16:48
Data collection time, EST	16:08	16:33	17:05	17:03	17:00	17:05	17:00
Active chlorophyll a, $\mu g/l$	16.9	15.7	13.1	24.7	22.1	76.3	5.4
Total chlorophyll a, $\mu g/l$	20.3	18.7	17.2	35.7	28.5	94.2	7.7
Dissolved oxygen, mg/l	11.0	10.0	9.6	8.9	12.5	12.8	7.5
Salinity, ppt	11.5	9.5	6.4	4.7	.8	.2	.3
Velocity, cm/sec	-21.9	-29.0	19.1	-27.7	-28.3	-20.1	-16.8
Suspended solids, mg/l	18.4	----	59.0	60.0	51.0	45.7	20.0
Secchi disk, m	----	----	----	.5	.2	.3	----
Depth of sampling, m	1.2	1.2	1.2	1.2	1.2	1.2	1.2

[a]Represents the chlorophyll a that was alive; $\mu g/l$ equals microgram/liter, 10^{-6} gram/liter, also equal ppb.

[b]Sum total of both alive and dead chlorophyll a.

[c]Minus means ebb tide; plus means flood tide.

[d]Suspended solids are defined to be the total particulate weight of material per unit volume that was filtered out when the sample was passed through a 47-mm Millipore filter; mg/l equals milligram/liter, 10^{-3} gram/liter.

[e]These data were collected at 9:09 EST.

[f]These data were collected at 12:00 EST.

TABLE V.- SUMMARY DATA STATUS

[X means have data]

Station	Data for morning mission			Data for noon mission		
	Film density	Total chlorophyll a	Suspended solids	Film density	Total chlorophyll a	Suspended solids
3-01	X	X	X	X	X	X
4-01	X	X		X	X	
4-02		X	X	X	X	X
5-01	X	X	X	X	X	X
5-02	X	X	X	Cloud cover	X	X
6-01	X	X	X	X	X	X
7-01	Did not fly over boat	X	X	Did not fly over boat	X	X

TABLE VI.- INTENSITY FALLOFF CORRECTION FACTORS FOR CAMERA FILTER COMBINATIONS

[Theta is the angle formed between the light ray going through the lens with one traveling along the principal axis]

Filtered camera	Falloff correction factor for –	
	Morning flight	Noon flight
12 filter	$\cos^{2}\theta$	
58 filter	$\cos^{2.75}\theta$	
89B filter	$\cos^{2.75}\theta$	$\cos^{3}\theta$
57 filter		$\cos^{2.75}\theta$
47B filter		$\cos^{2}\theta$
25 filter		$\cos^{3}\theta$

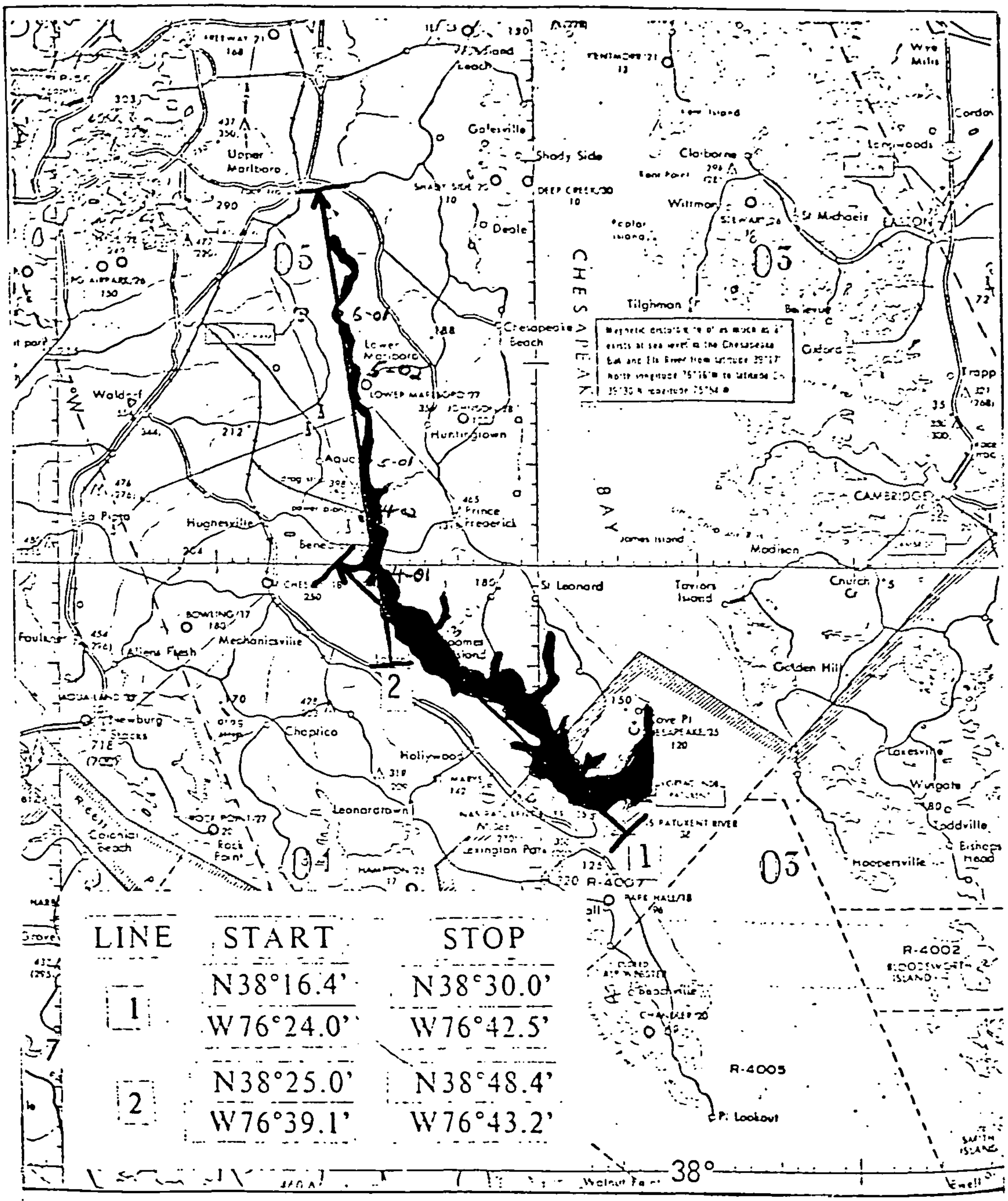
TABLE VII.- DATA POINT RELATIVE FILM DENSITIES[a]

Station	Relative film densities obtained on *morning flight*			Relative film densities obtained on *noon flight*			
	89B filter (690 to 900 nm)	58 filter (500 to 600 nm)	12 filter (500 to 700 nm)	89B filter (690 to 900 nm)	57 filter (500 to 600 nm)	47B filter (400 to 500 nm)	25 filter (600 to 700 nm)
3-01	0.028	0.629	0.907	0.080	0.829	0.531	0.630
4-01	.059	.876	1.352	.392	1.185	.431	1.219
4-02				.115	.867	.372	.906
5-01	.056	.767	1.335	.168	1.138	.553	1.172
5-02	.158	1.009	1.582	Cloud cover data point			
6-01	.131	.772	1.489	.091	.916	.358	1.074

[a]The relative film density is the density difference between data point and film border with falloff and altitude corrections made.

TABLE VIII.- WEIGHTED AVERAGE FILM DENSITY FOR WRATTEN 89B FILTER FROM MORNING FLIGHT

Frame	Data station identification number	Weighted average film density
41		0.049
37		.096
35		.123
34		.109
33	6-01	.117
32		.093
31		.138
30	5-02	.132
29		.161
28		.115
26		.125
25		.060
24	5-01	.072
22	4-02	.067
19	4-01	.069
10	3-01	.027



LINE	START	STOP
1	N38°16.4' W76°24.0'	N38°30.0' W76°42.5'
2	N38°25.0' W76°39.1'	N38°48.4' W76°43.2'

Figure 1.- Flight lines flown over Patuxent River.

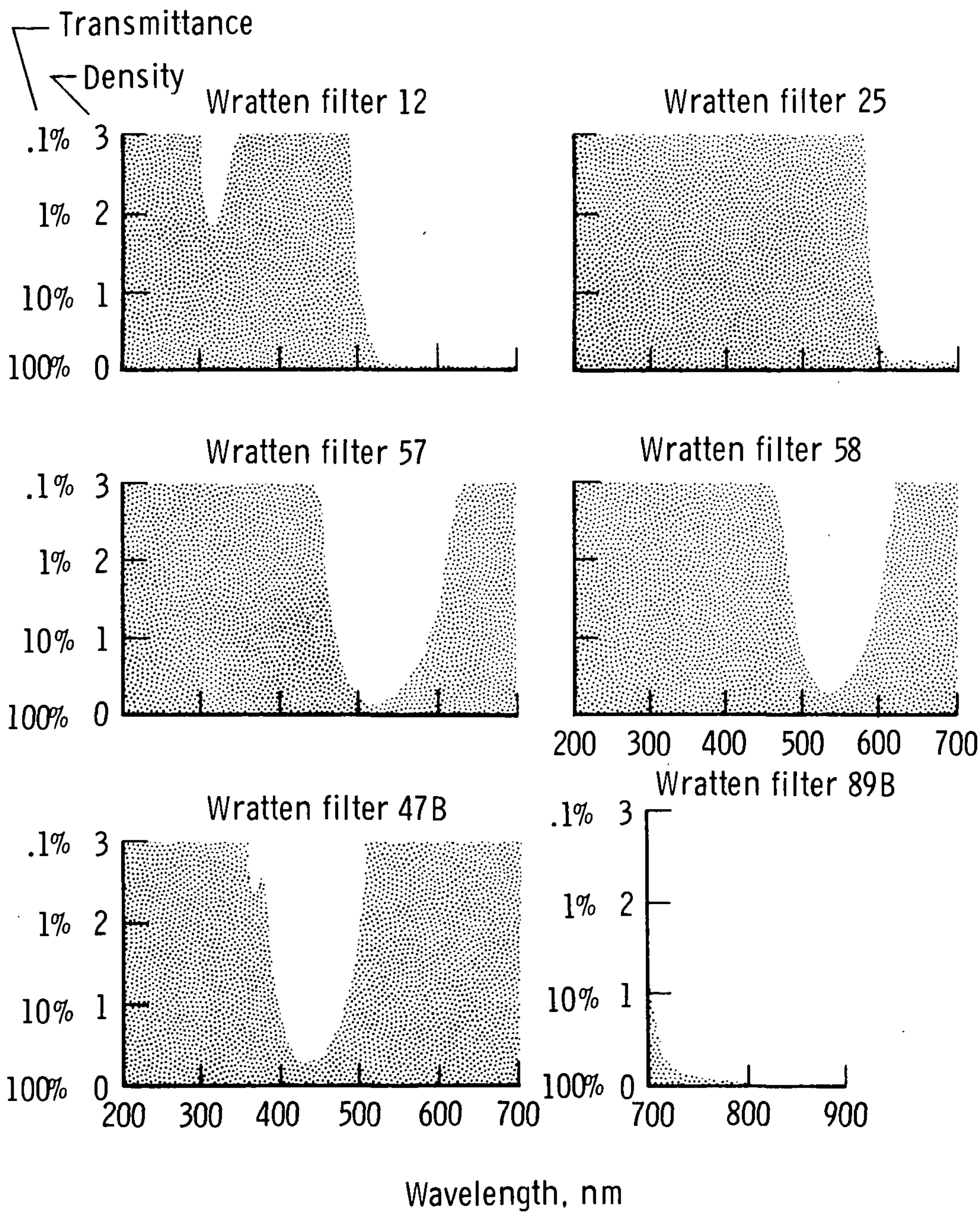


Figure 2.- Transmission curves of Kodak Wratten filters used for mission. (From ref. 2.)

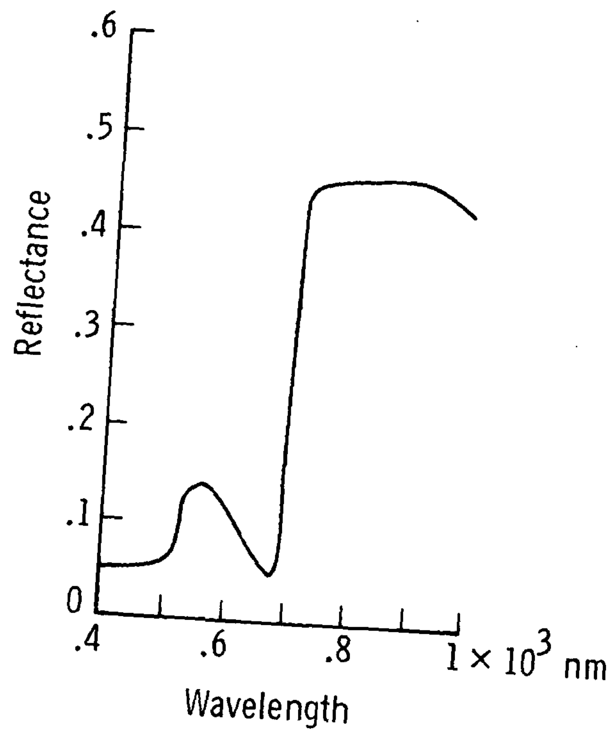


Figure 3.- Spectral reflectance of the higher chlorophyll-containing plants. (From ref. 3.)

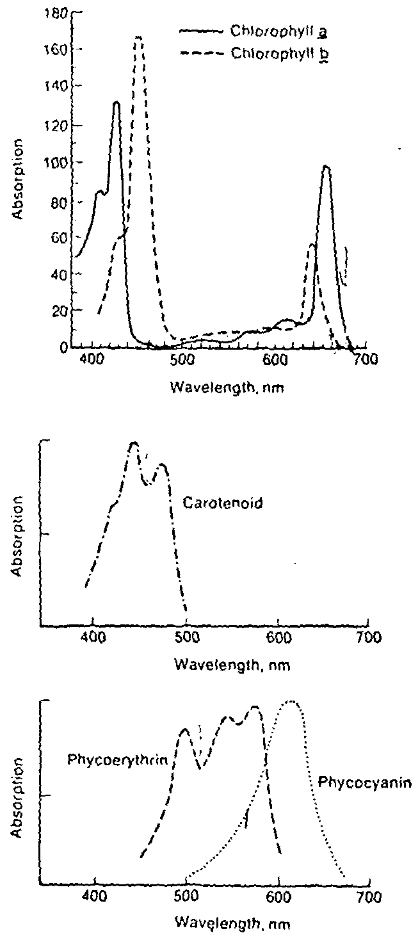


Figure 4.- Absorption spectra of several photosynthetic pigments. (From ref. 4.)

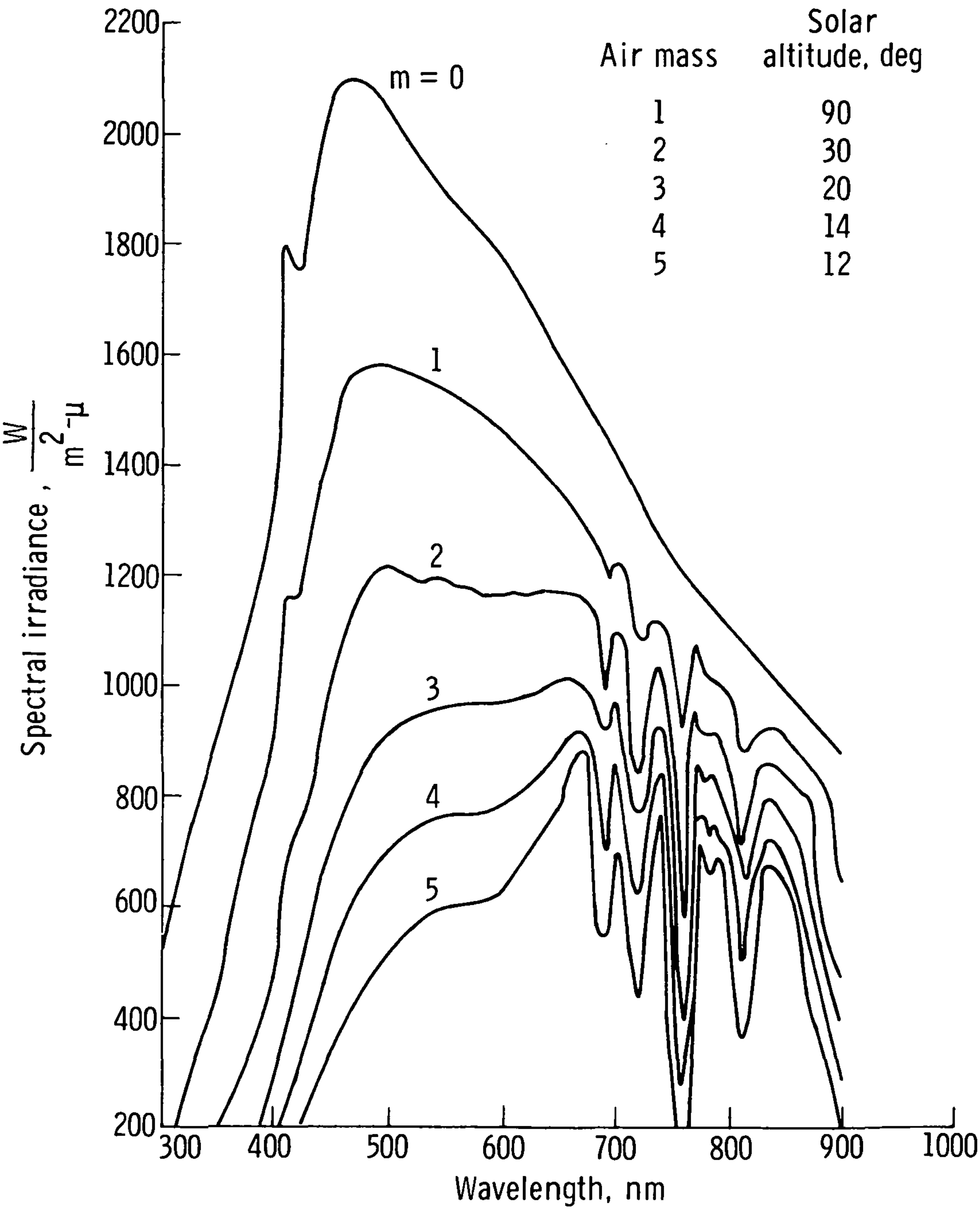


Figure 5.- Solar irradiance on Earth surface normal to Sun for standard atmosphere containing absorbing and scattering particles. Assumptions: 760 mm pressure; 2.0 Pr cm H_2O; 300/cm^3 dust particles; 0.28 atm-cm ozone from moon^3. (From ref. 5.)

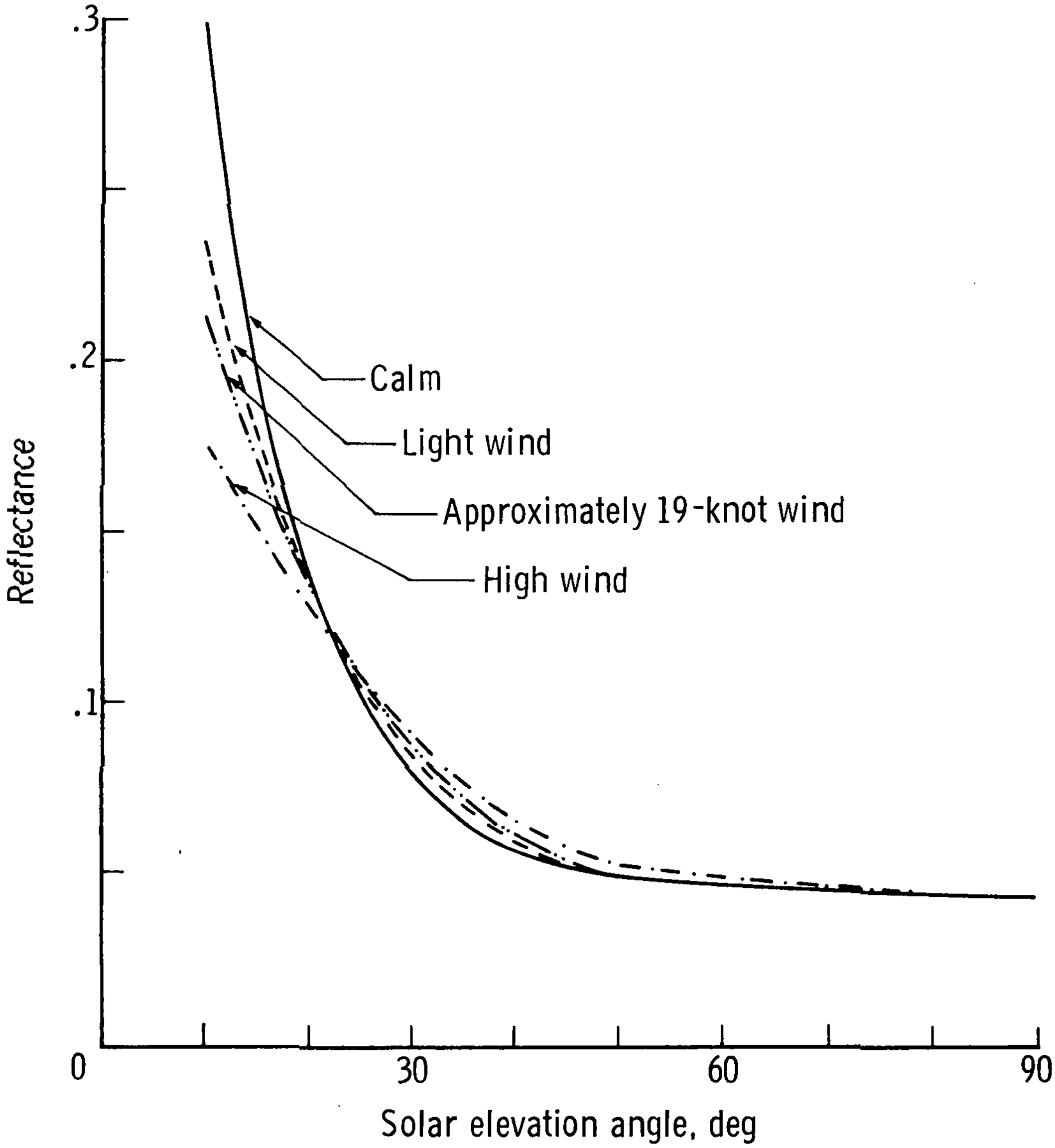


Figure 6.- Theoretical reflectance of smooth water and estimated reflectances (based on Gaussian distribution of surface slopes) of water, under high wind and under light wind, as functions of solar elevation angle. (From ref. 3.)

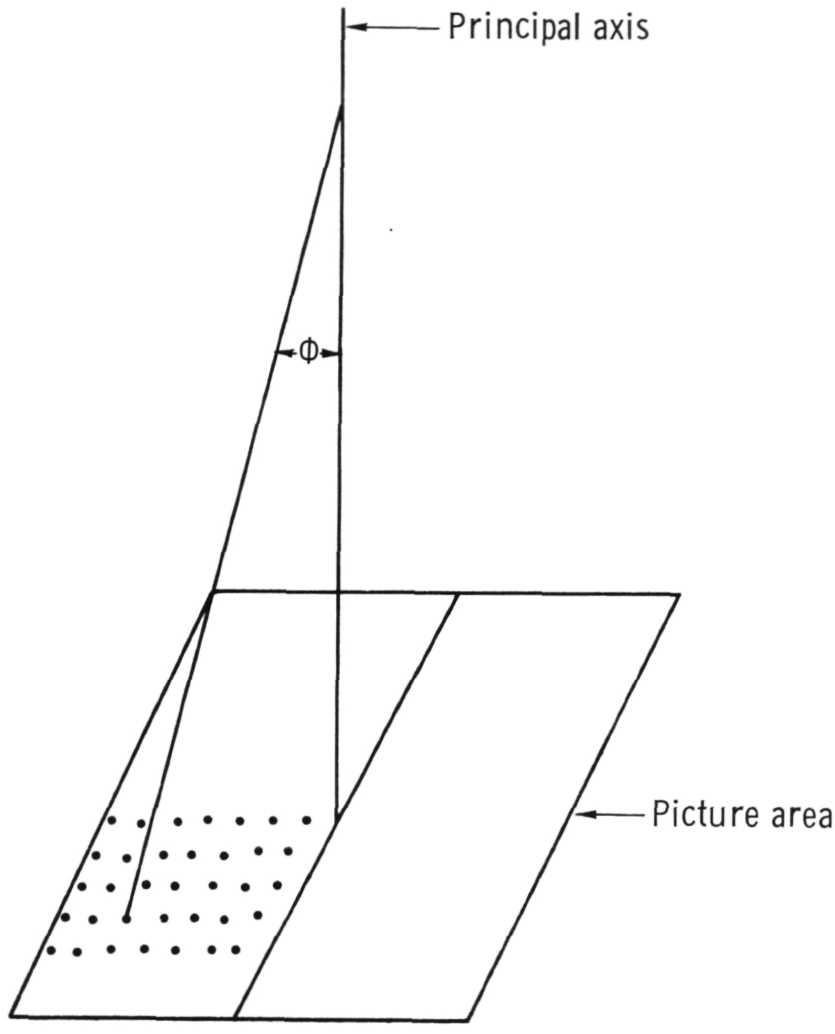


Figure 7.- Pictorial representation of camera system angle ϕ, where ϕ is the angle off the principal axis.

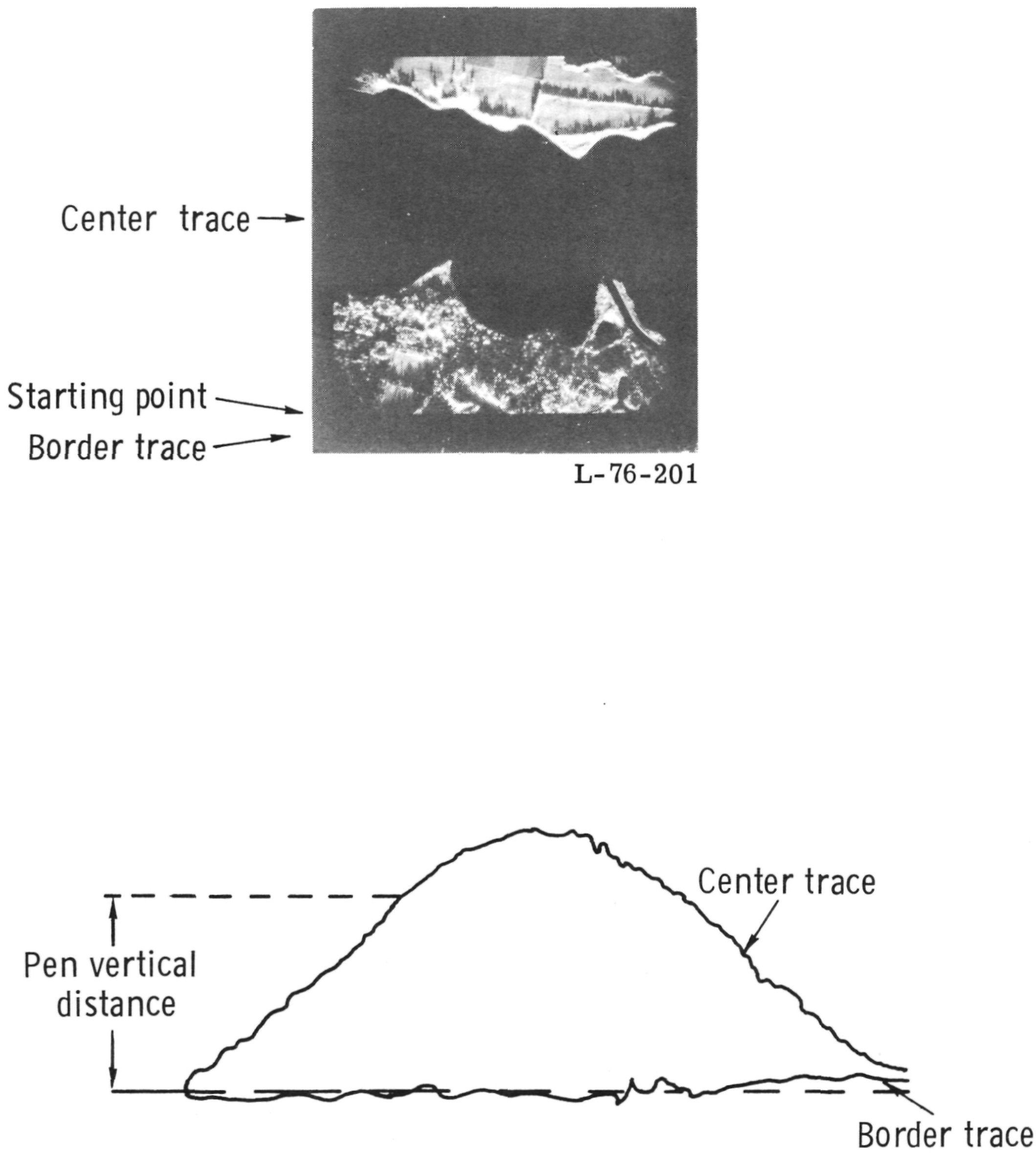
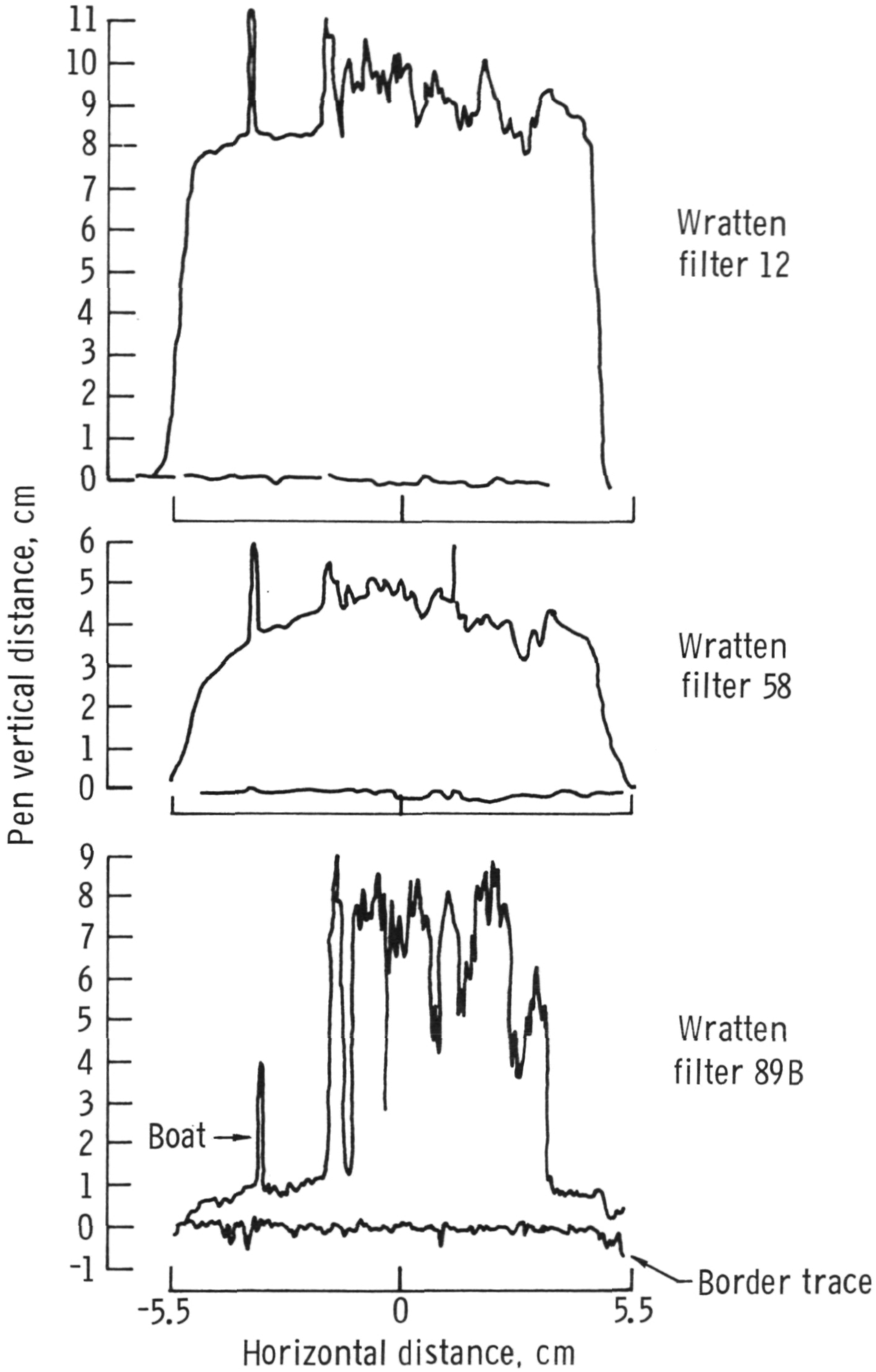
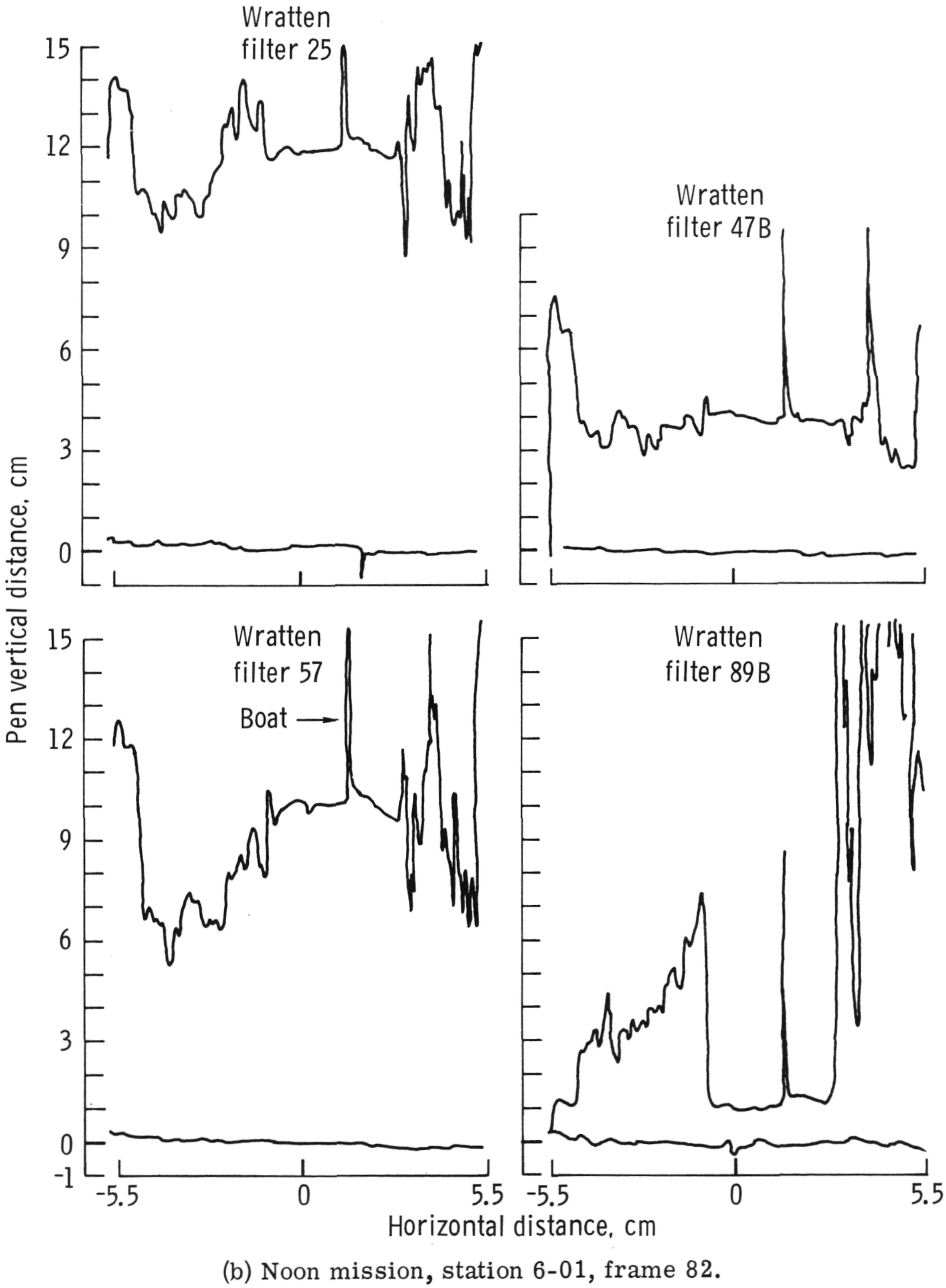


Figure 8.- Sample pen plots and photograph.



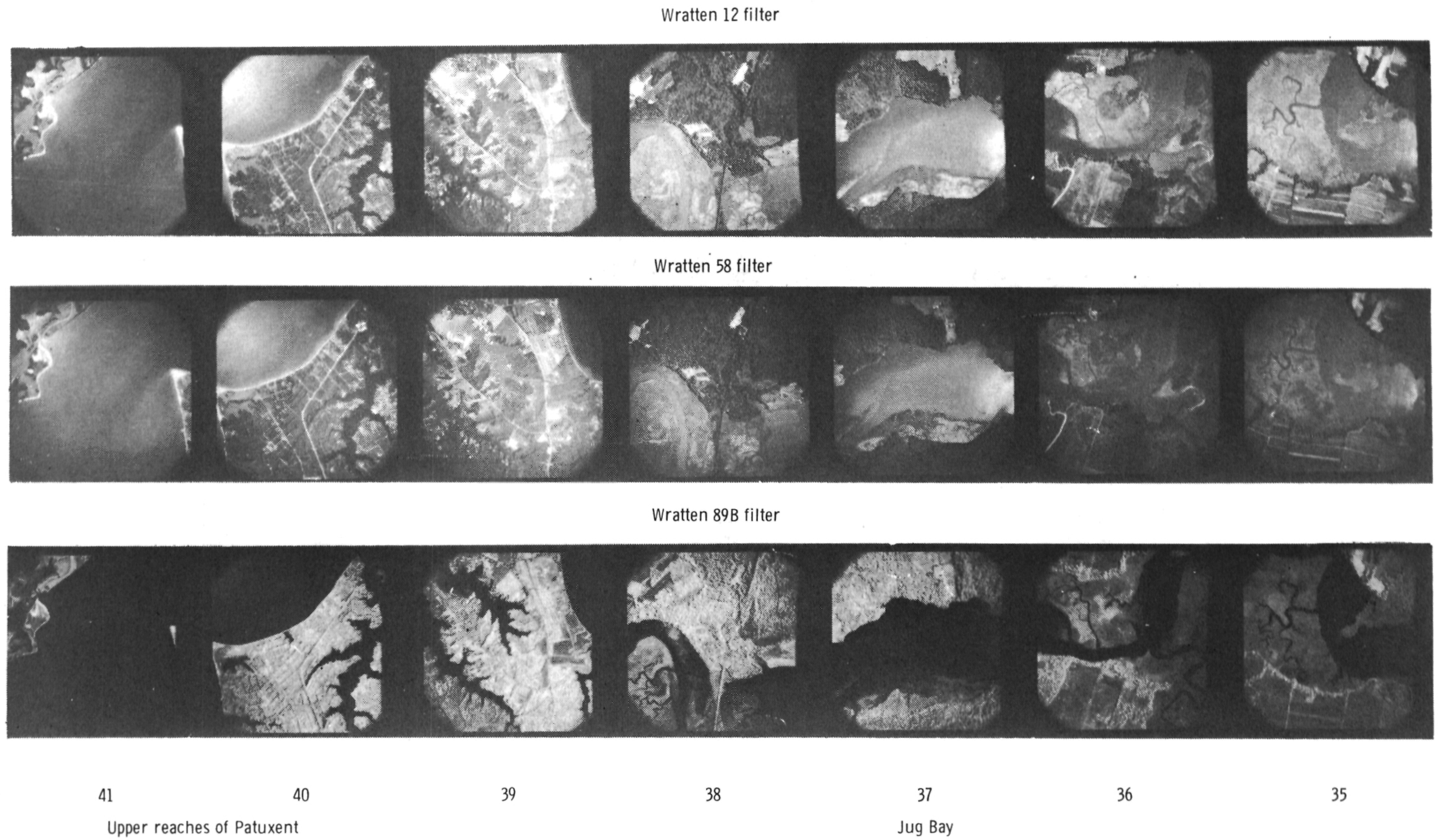
(a) Morning mission, station 6-01, frame 33.

Figure 9.- Microdensitometer single-scan pen traces through data point with corresponding border traces. The write-out arm ratio was set at two so that the horizontal pen distance is twice the actual photograph size.



(b) Noon mission, station 6-01, frame 82.

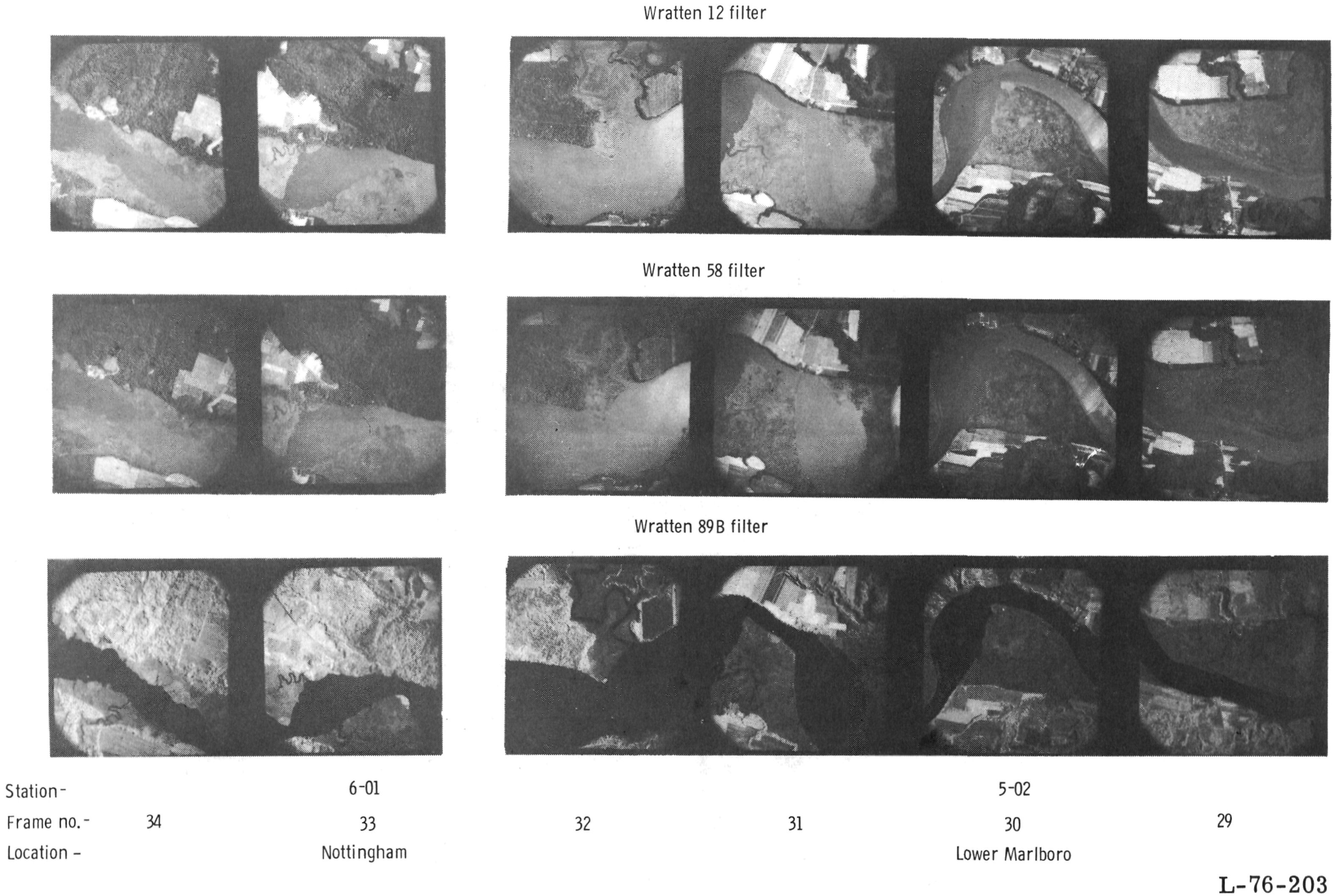
Figure 9.- Concluded.



L-76-202

(a) Morning mission photographs.

Figure 10.- Patuxent River experiment photographs taken on October 17, 1972.



(b) Morning mission photographs.

Figure 10.- Continued.

Wratten 12 filter

Wratten 58 filter

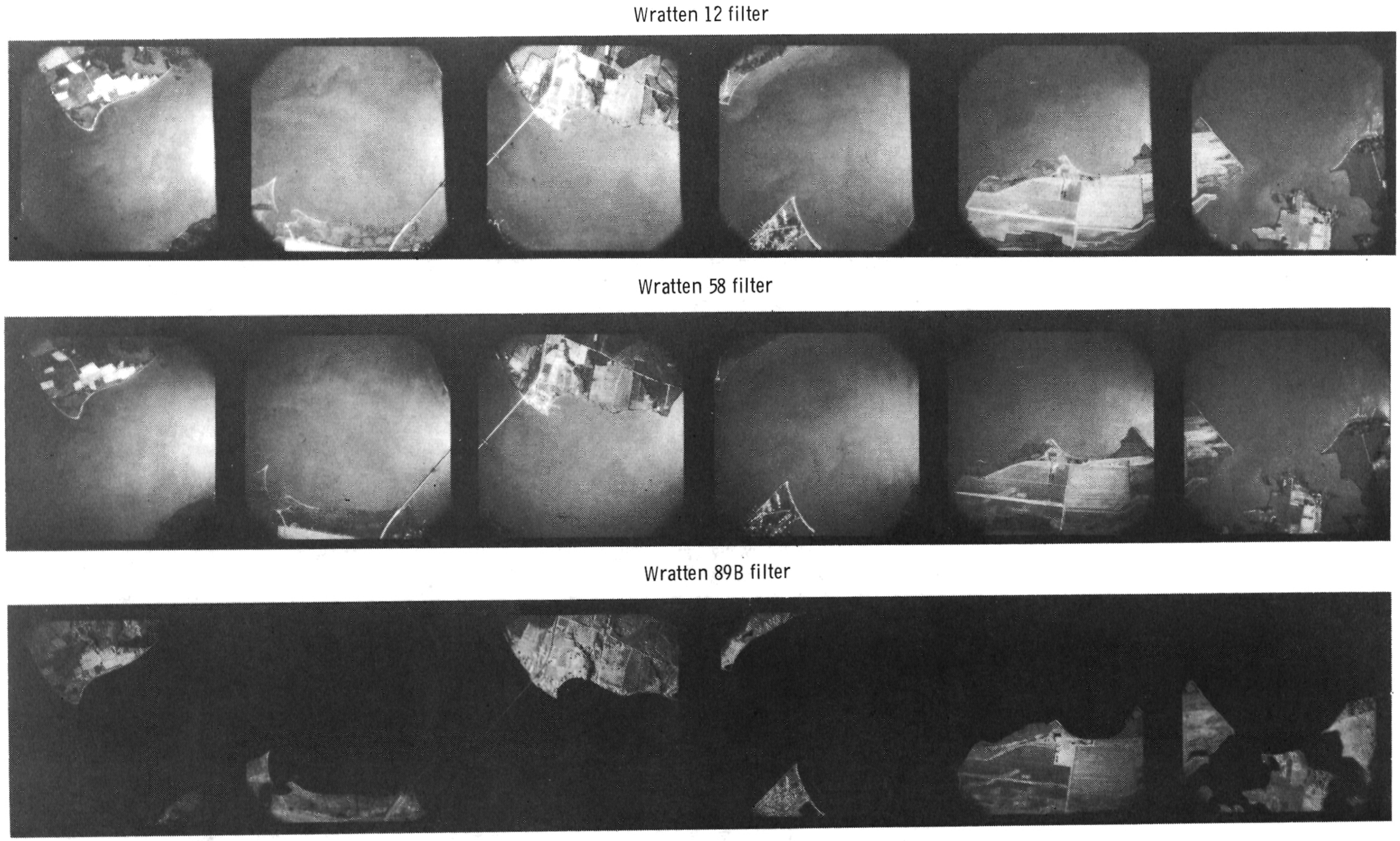
Wratten 89B filter

Station-					5-01	
Frame no.-	28	27	26	25	24	23
Location-	Milltown Landing				Truman Pt.	

L-76-204

(c) Morning mission photographs.

Figure 10.- Continued.

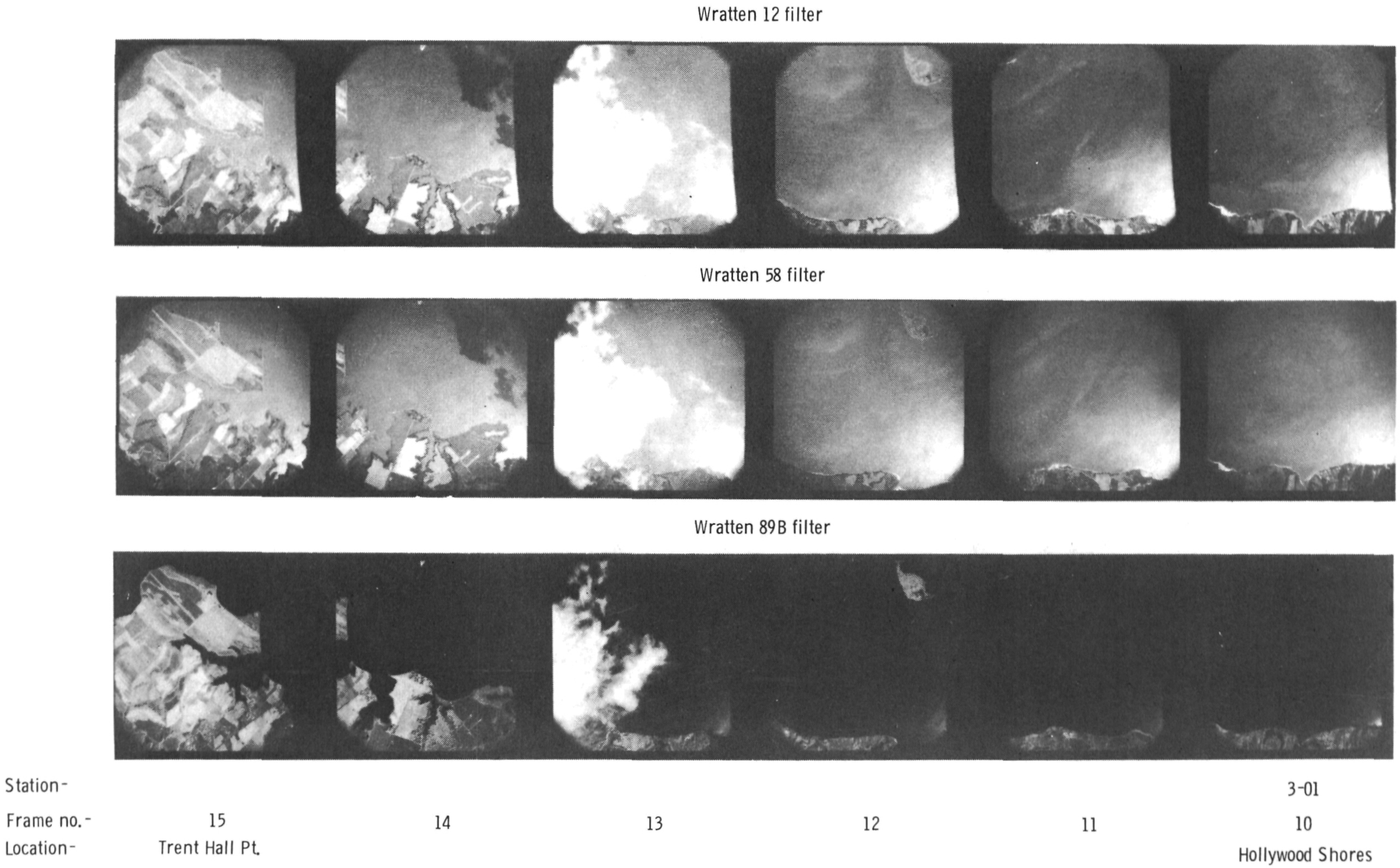


Station - 4-02 4-01
Frame no. - 22 21 20 19 18 17
Location - Gods Grace Pt. Long Pt.

L-76-205

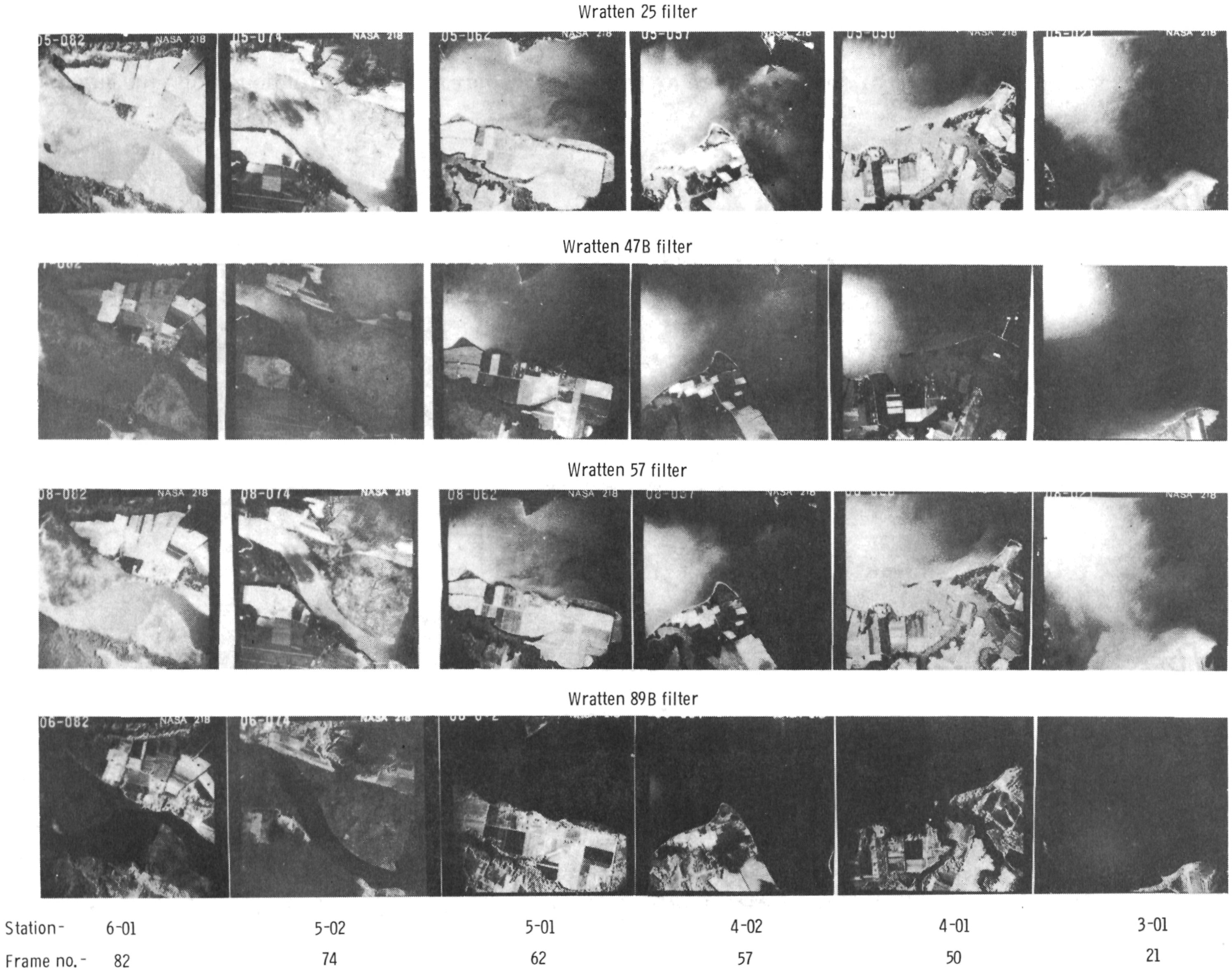
(d) Morning mission photographs with frames 20, 19, and 18 used to calculate the offnadir correction factors.

Figure 10.- Continued.



L-76-206

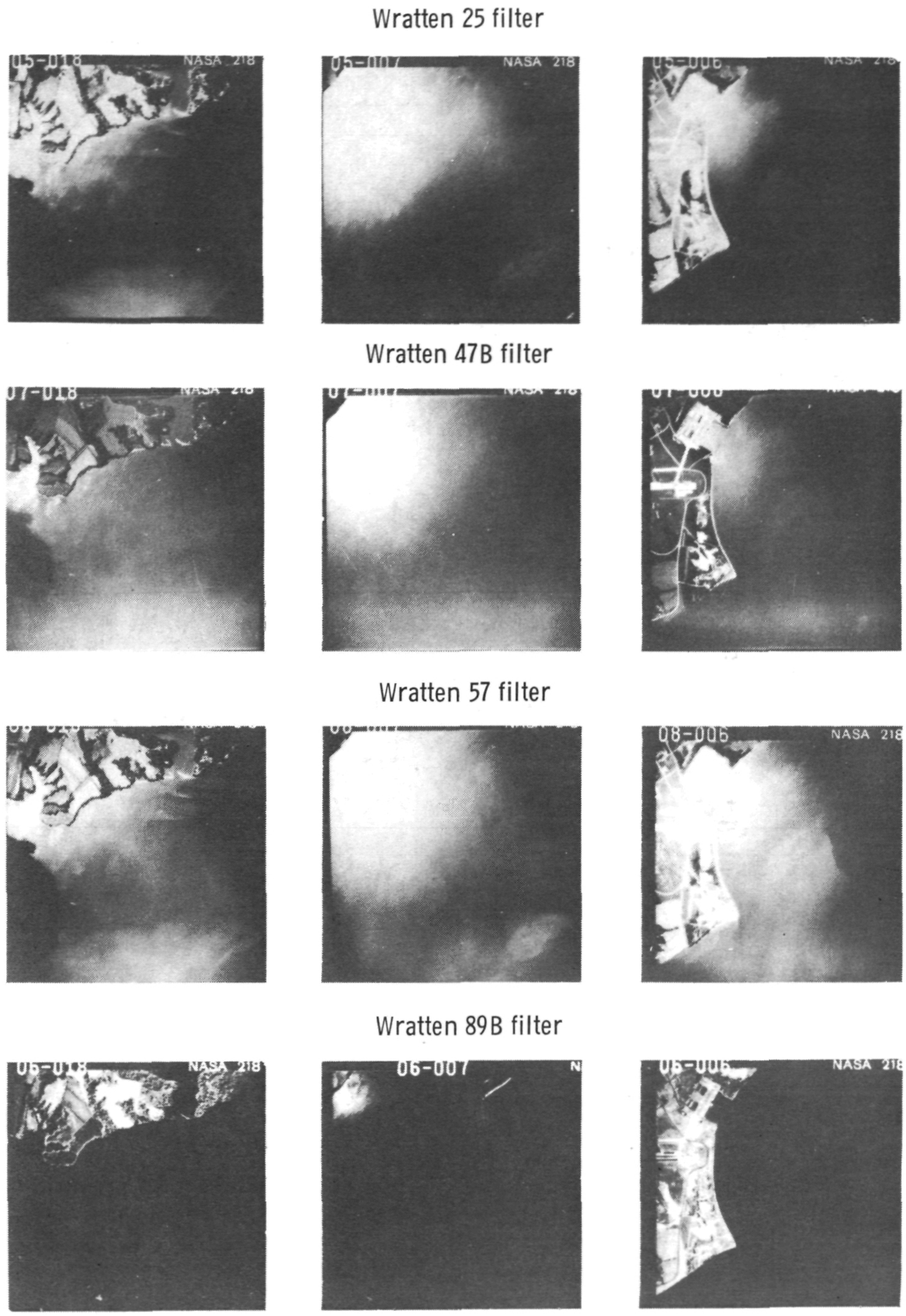
(e) Morning mission photographs with frames 12, 11, and 10 used to calculate the offnadir correction factors.



L-76-207

(f) Noon mission photographs taken over ground truth stations.

Figure 10.- Concluded.



Frame no.- 18 7 6

L-76-208

Figure 11.- Frames used to calculate the noon mission offnadir correction factors.

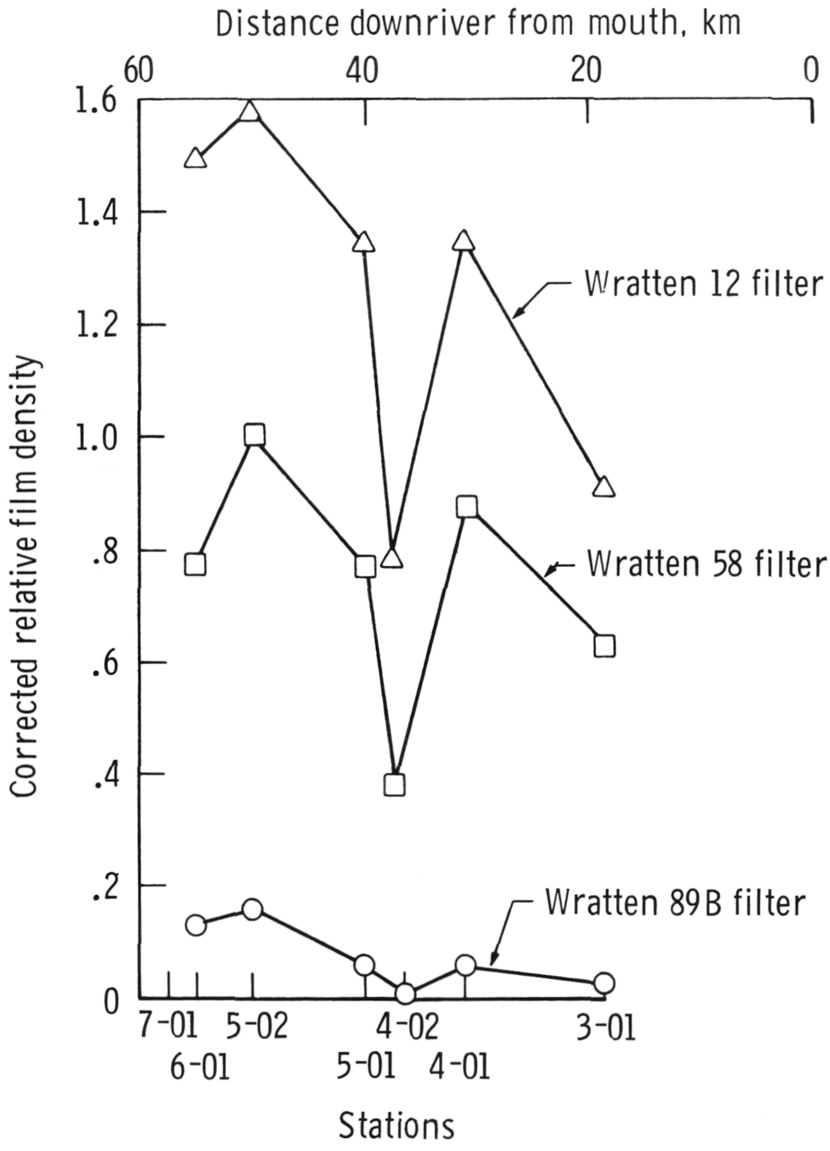


Figure 12.- Variation of data station corrected relative film density with distance downriver for morning mission.

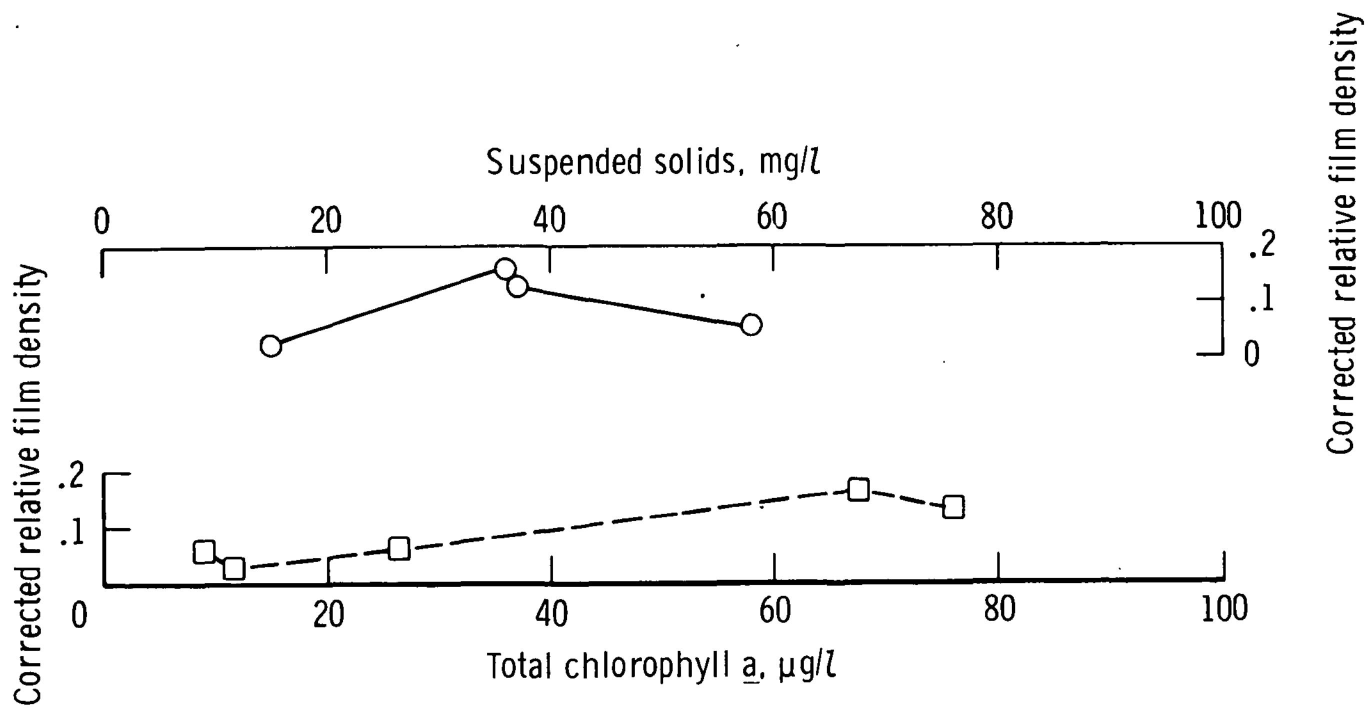


Figure 13.- Morning mission Wratten filter 89B (690 to 900 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

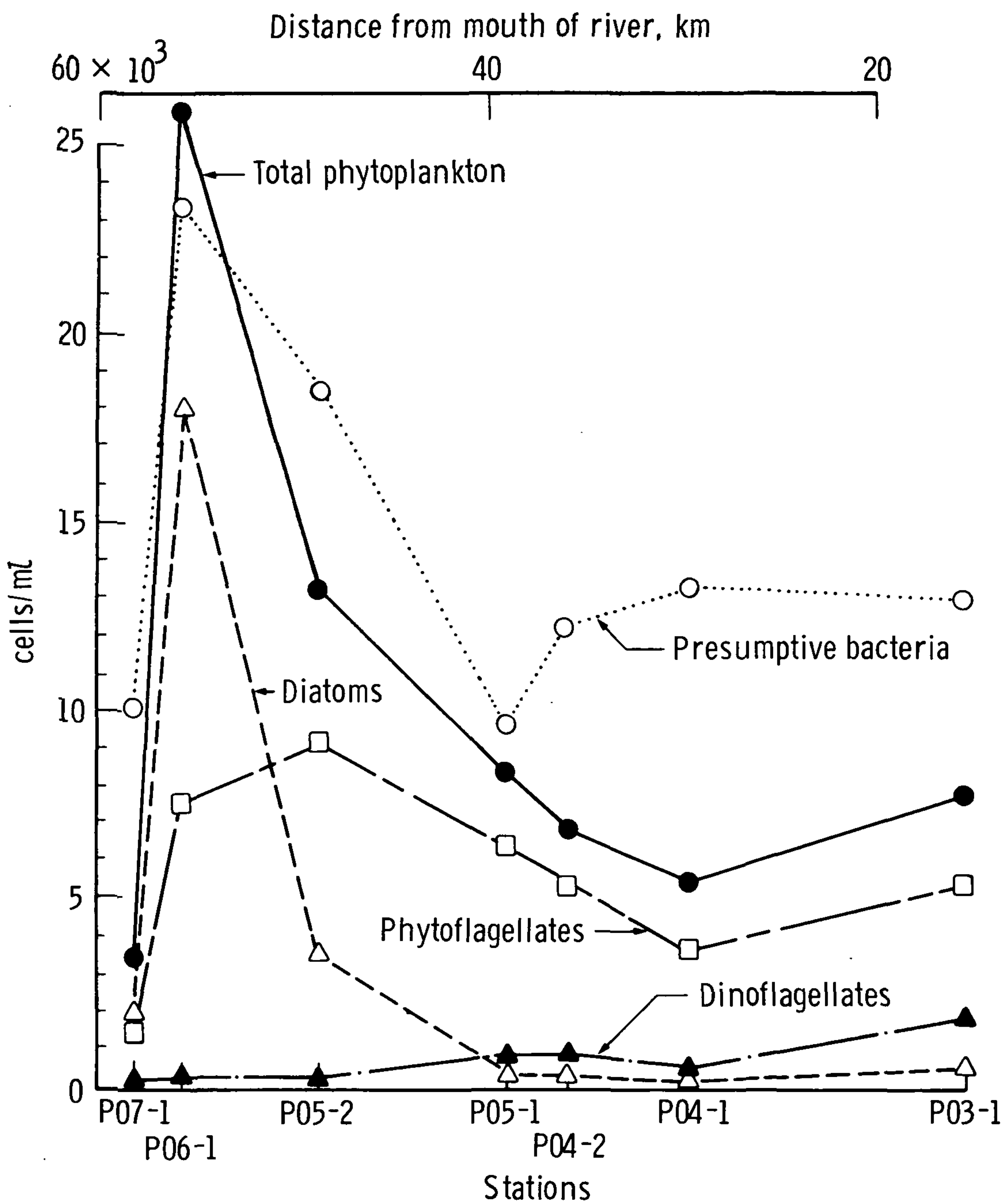


Figure 14.- Major categories of surface phytoplankton found in October 17, 1972 Patuxent River experiment. This figure is taken from data furnished by Dr. Kent Mountford of the Benedict Estuarine Laboratory.

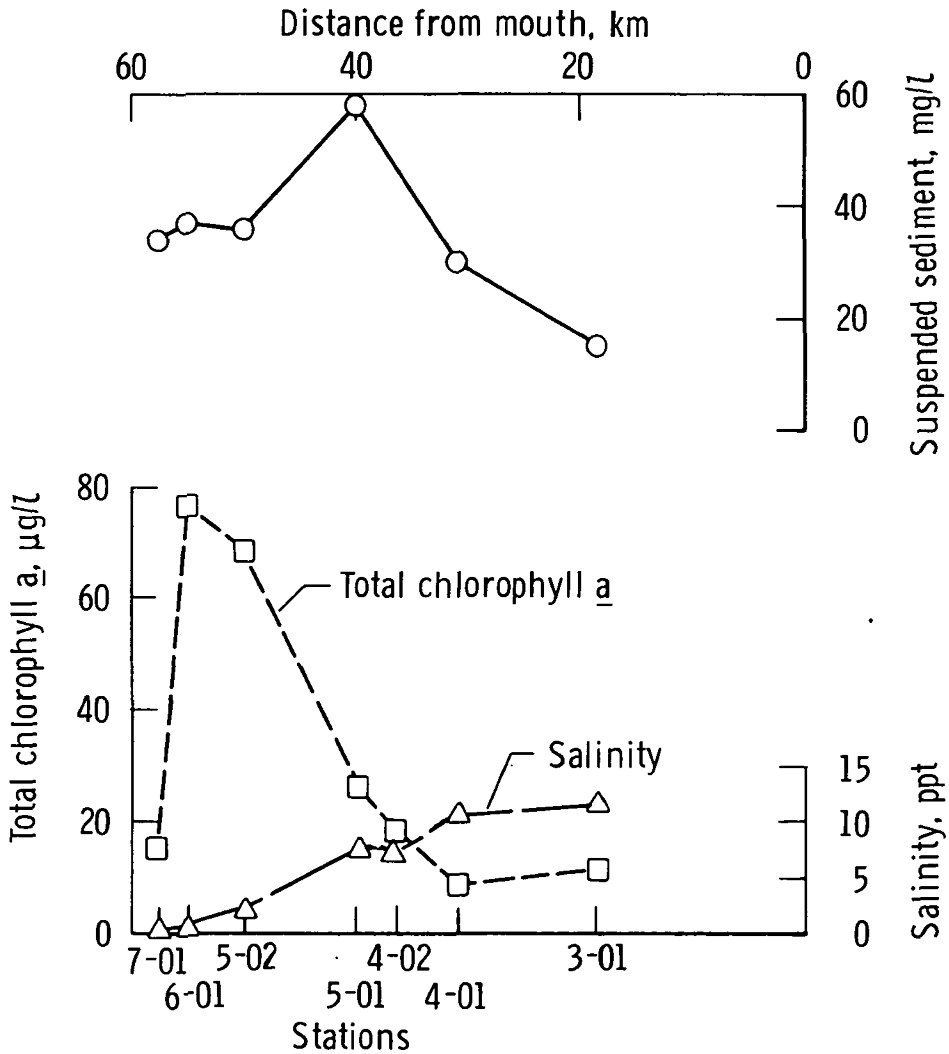


Figure 15.- Suspended solids, total chlorophyll a, and salinity against distance downriver for morning mission.

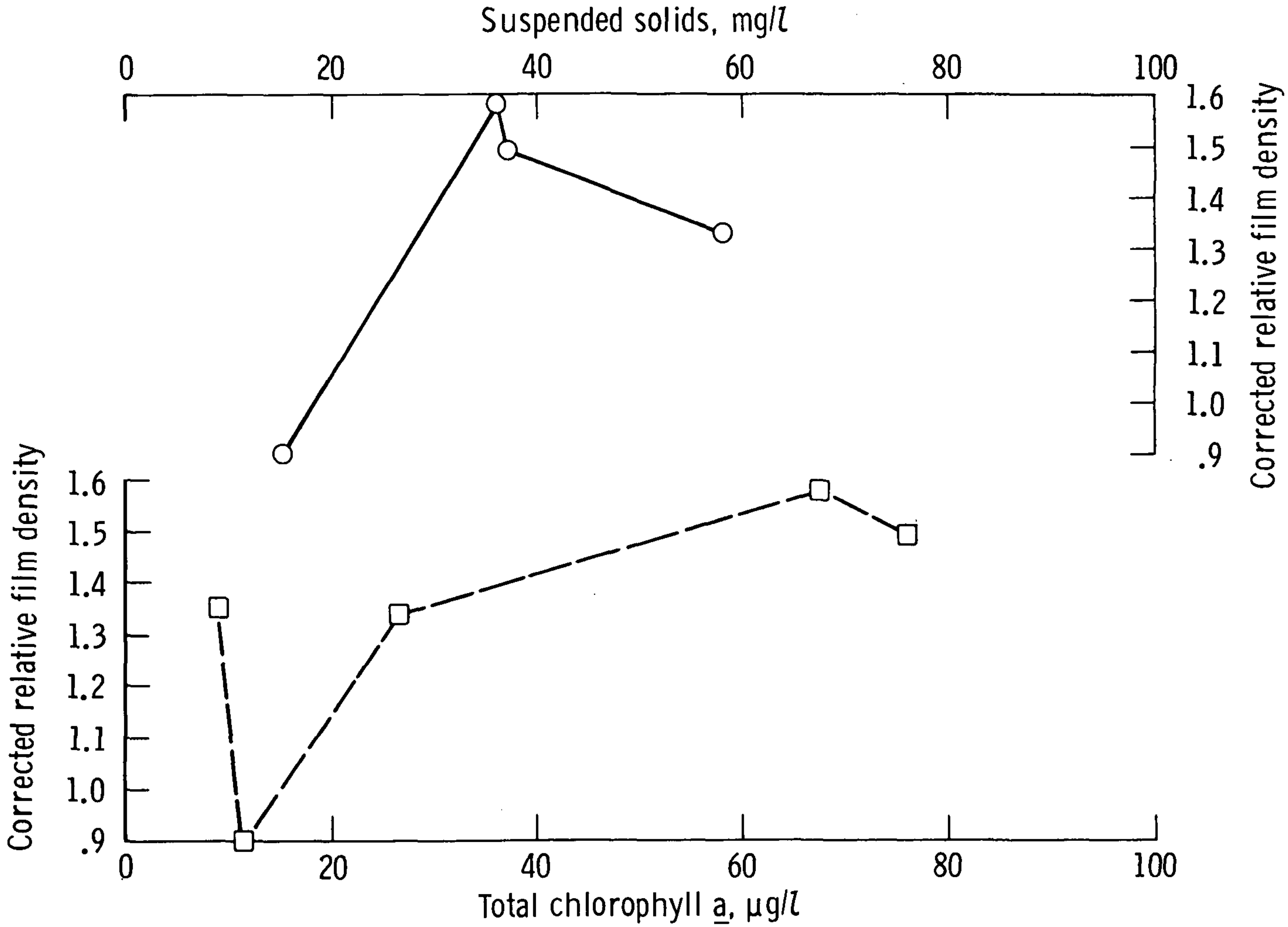


Figure 16.- Morning mission Wratten filter 12 (500 to 700 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

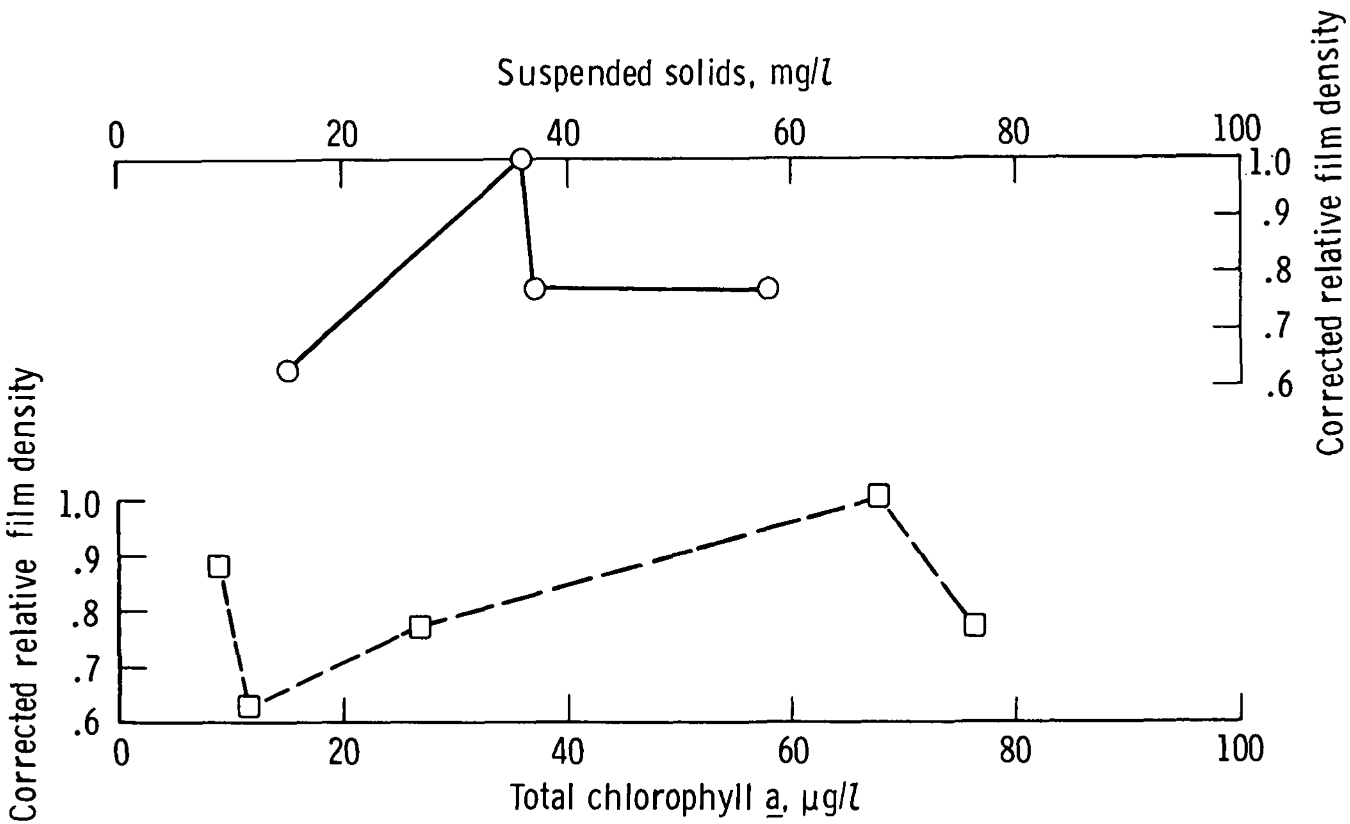


Figure 17.- Morning mission Wratten filter 58 (500 to 600 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

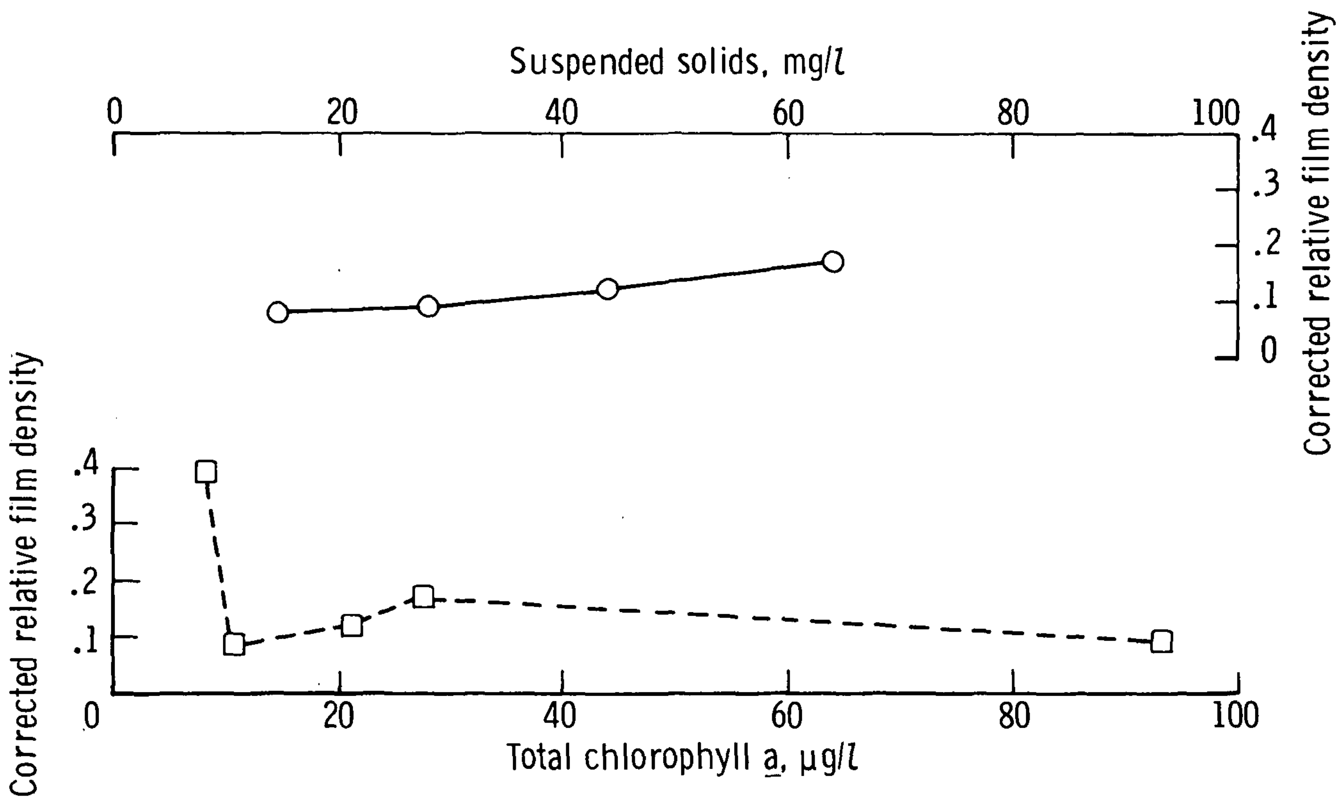


Figure 18.- Noon mission Wratten filter 89B (690 to 900 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

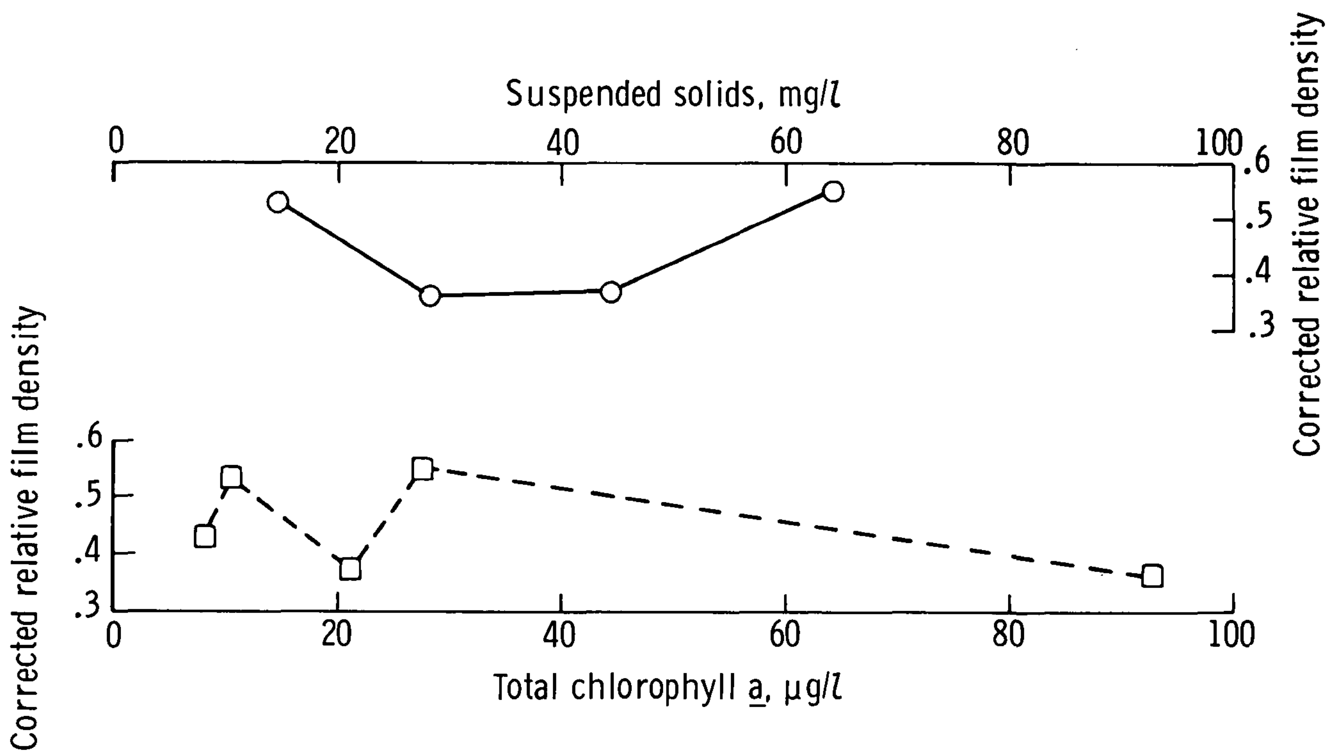


Figure 19.- Noon mission Wratten filter 47B (400 to 500 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

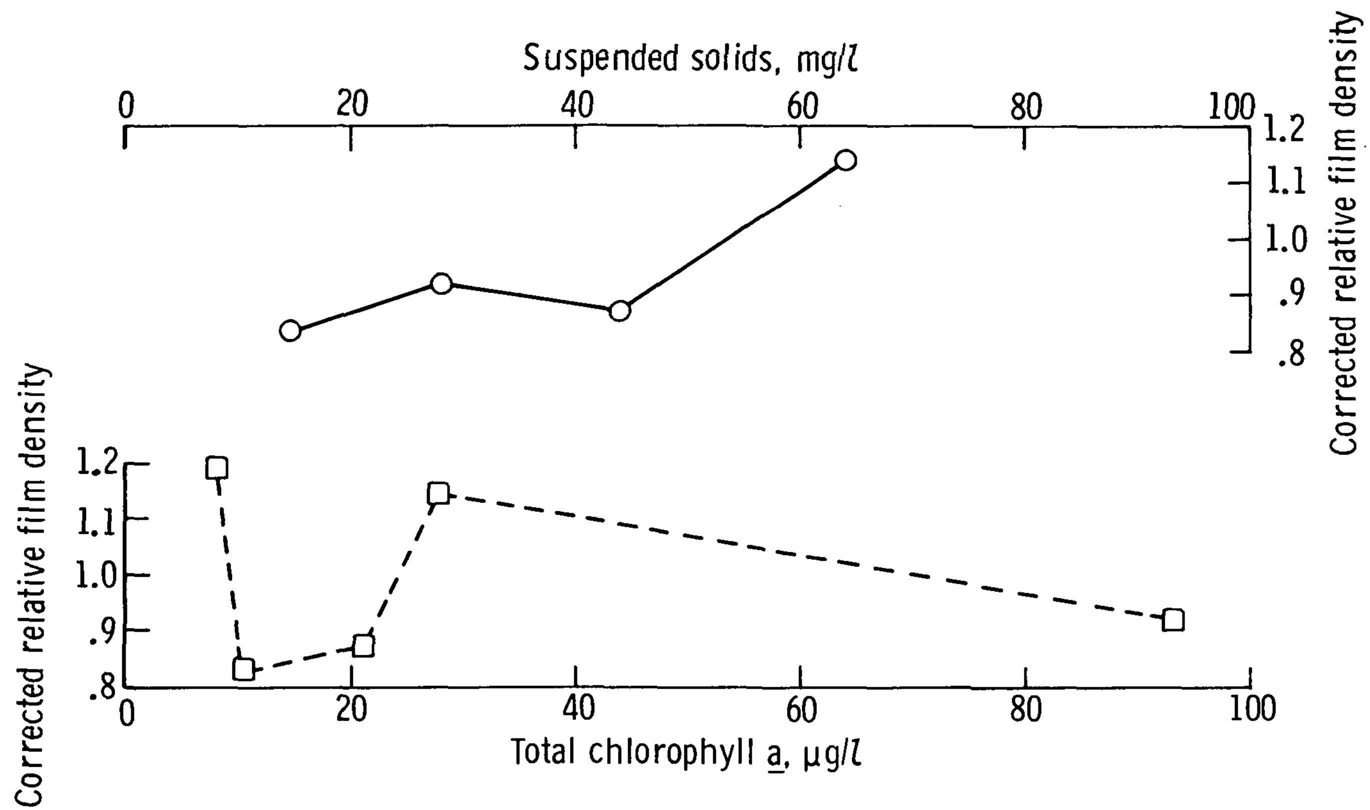


Figure 20.- Noon mission Wratten filter 57 (500 to 600 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

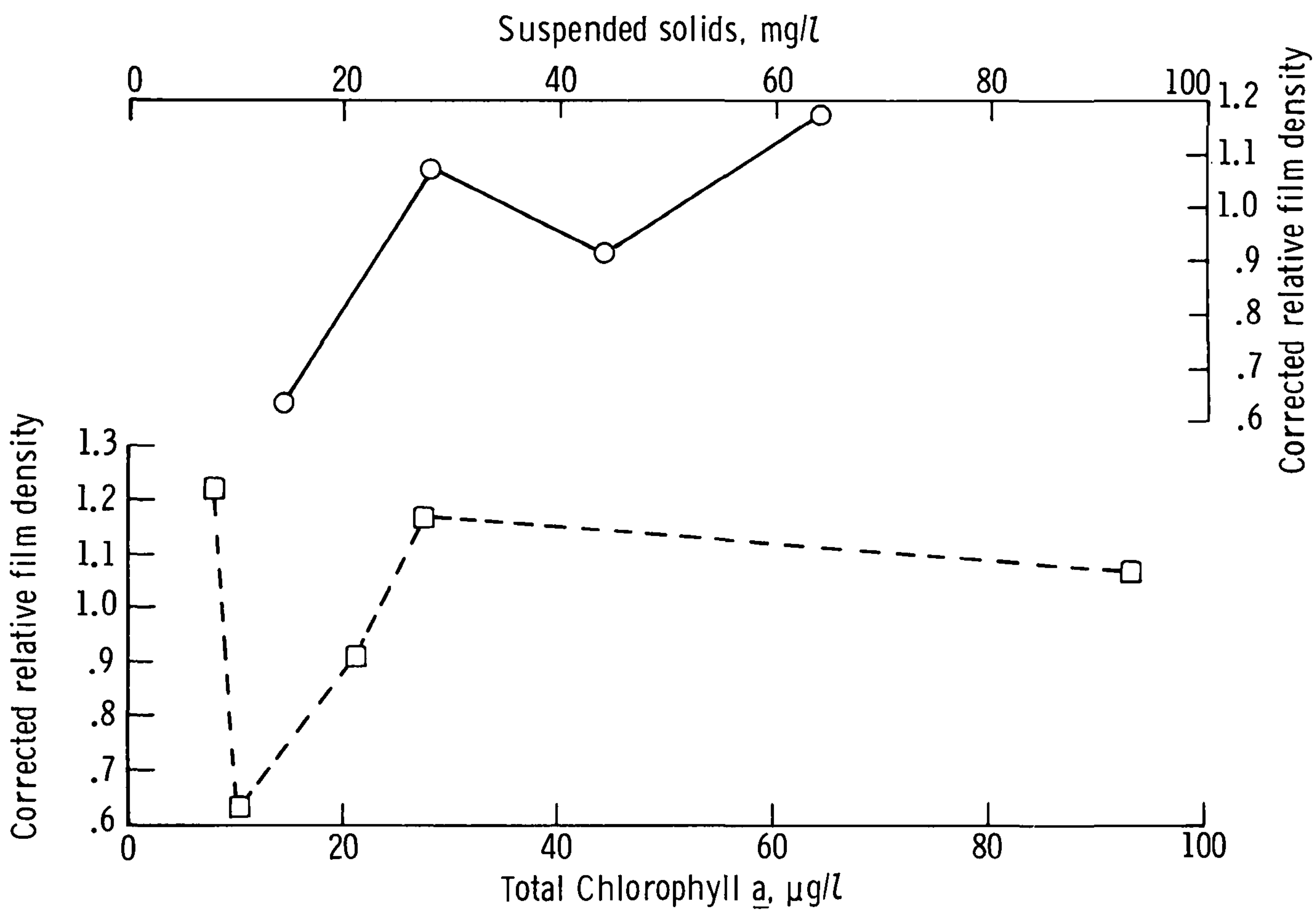


Figure 21.- Noon mission Wratten filter 25 (600 to 700 nm) data station corrected relative film density against suspended solids and total chlorophyll a.

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