Evaluation of the Utility of Landsat Imagery for Determination of Sediment Concentration: Prudhoe Bay, Alaska

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Introduction

This report describes the results of a pilot study to determine the utility of Landsat imagery to quantatively map suspended sediment load in Alaskan coastal waters. The chief reasons that this ability is desired have been detailed by Naidu (1982): among the proposed activities associated with the development of offshore petroleum leases are the construction of man-made islands and causeways. Not only will these facilities promote greater oceanic suspended particulate load through the resuspension of their constituent materials, but since dredging has been proposed as a construction technique, an increase in suspended particulate load will probably result from that activity as well.

Naidu, using Landsat imagery, has shown that much of the midsummer suspended particulate load along the Beaufort Sea coastal region is generated by the resuspension of unconsolidated river delta material by wave action during windy periods. During these periods, the rivers associated with these deltas can be seen to produce relatively clear water plumes within the sediment-laden waters overlying the shallow delta areas. Hence, the immediate source of the coastal suspended sediment is the river deltas rather than the riverbed.

Naidu has suggested that if development activities do not alter suspended sediment loads, no adverse environmental impact might be anticipated. On the other hand, if these activities result in significantly greater suspended particulate loads, then their environmental impact should be further evaluated.

The technique described in this report has been investigated in order to enhance procedures for monitoring sediment loads with respect to previous load conditions.

Background

Several researchers cited below have noted that sunlight of wavelengths in the 5 to 6 μ range (Landsat band 4) has the ability to penetrate water to some depth and reflect off the bottom. These authors have hypothesized that Landsat imagery might be used for the preparation of bathymetric charts and have viewed the sediment content of the water as a source of interference for which a correction coefficient must be found.

Warne (1978) studied the use of Landsat data for the preparation of hydrographic charts in Australian coastal waters. Warne related reflectance to water depth with the equation: $R = a + b^{-cz}$ where R = reflectance, z = depth and a,b, and c are constants related to optical properties of the sea and atmosphere. Warne concluded that in principle Landsat imagery was useful in the preparation of hydrographic charts and that Band 4 could be used under optimal conditions to depths of 20 meters at an accuracy of 10% Root Mean Square. However, the general lack of homogeneity in the optical constants a,b, and c required frequent measurement of these constants and hence, the method is less efficient than was originally assumed.

Whitlock, et al. (1978) studied the influence of different concentrations and mineral compositions of sediment on the depth penetration of light of wavelength 0.52 μ. They concluded from laboratory experiments that the apparent remote sensing depth is influenced by the mineral content and/or size of suspended sediments, and from field measurements that even when the suspended sediment concentration is nearly constant there is wide variation in apparent penetration depth. These authors postulate a penetration depth of from 3 to 7 meters at 2 mg/l concentration and from one to two meters at 10 mg/l concentration for light of wavelength 0.52 μ.

Gordon and McCluney (1975) defined Z_{90} as the depth above which 90% of the diffusely reflected irradiance originates in the penetration of light in the sea. They determined Z_{90} for band 4 and band 5 at Crater Lake to be 18.5m and 2.7m respectively, and at San Vicente Reservoir to be 1.9m and 1.5m respectively. Crater Lake has been designated as equivalent to distilled water and San Vicente Reservoir is considered to have very small penetration depths due to its extreme turbidity. Thus, this data may be used to define the limits for penetration depths for both band 4 and band 5. This data also illustrates the extreme sensitivity of band 4 penetration depth to sediment concentration and contrasts this sensitivity with the relative insensitivity of band 5. Band 5 penetration depth is apparently little more than 2 meters independent of sediment concentration.

Data

Ten sediment samples, ranging from 2 to 10 mg/l were taken by a field team working under the direction of Dr. A.S. Naidu off the West Dock in Prudhoe Bay on July 22, 1981. The sampling was timed to correspond with Landsat Pass E-22374-21130 on July 23, 1981 (see Figure 1 and Table I). Computer printouts were obtained for bands 4,5, and 6 of this Landsat image.

Figure 1, Map of suspended sediment concentration from a computer printout of Landsat image E-22374-21130, band 5 reflectance values.

Explanation of Features

❑ Sample site: a nine-pixel array (numbered 1 to 10)

- - - - 2 meter isobath

Miniranger sites:

A: a small lake

B: Heald Point Tower

├────┤ Track C-D

Classification of sediment concentration areas from band 5

I: an area in less than 2 meters depth where there is probably influence on the reflectance value by the bottom

II: reflectance values 7 to 8, patches of 9, lowest concentration

III: reflectance values 9 to 13, patches 7-8 and 14-15

IV: reflectance values 14 to 17, patches of 13, 18-19

V: reflectance values 18 to 21, patches of 16-17, and 22 (less than 2 meters)

VI: reflectance values $\geq$ 22 (less than 2 meters)

There is a small distortion factor in this map because it was taken directly from the computer printout. The characters used to produce the computer printout do not have the same relative proportions as the Landsat pixels. The result is a 7% stretch in the vertical which is most obvious in the shape of large features like Prudhoe Bay.

FIGURE 1

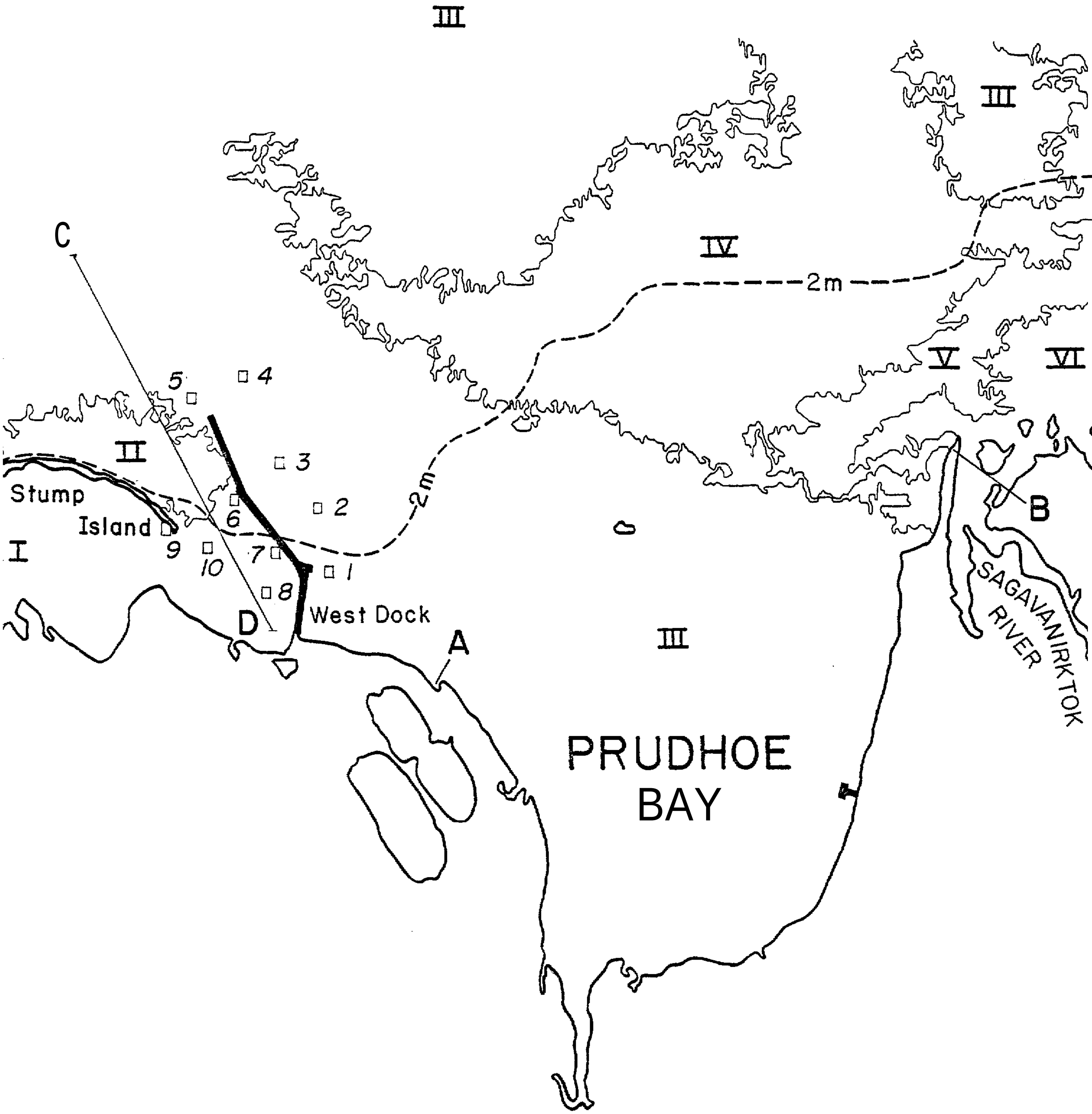

III
III
IV
2m
C
5
4
II
3
Stump
Island
2
6
9
10
7
1
I
8
West Dock
D
A
III
V
VI
B
SAGAVANIRKTOK
RIVER
PRUDHOE
BAY
0 1 2 3 4
KILOMETERS

Table I. Sediment Concentration and Reflectance Values

Site	Band 4 Average Reflect. (span)	Band 5 Average Reflect. (span)	Sample Content. mg/ 1	Band 4 Calculated Content,	Band 5 Calculated Content.
1	15.7 (4)	11.6 (2)	10.16	7.76	8.75
2	16.3 (2)	11.8 (2)	7.18	9.88	9.57
3	16.2 (4)	11.7 (3)	8.26	9.53	9.16
4	15.8 (2)	11.3 (3)	8.46	8.12	7.53
5	13.8 (4)	9.8 (3)	2.32	1.05	1.40
6	13.1 (4)	9.7 (7)	10.27		
7	13.6 (2)	11.3 (5)	4.81		
8	13.0 (3)	9.4 (2)	5.55		
9	13.2 (6)	10.9 (3)	6.28		
10	12.7 (5)	10.9 (3)*	7.45		

Mean	15,560	11.240	7.276
Standard Deviation	1.016	0.826	2.969
Slope	0.283	0.245	
Reflectance Intercept	13.503	9.456	
Regression Equation	R=0.283S + 13.503	R=0.245S + 9.456	(R = reflectance, S = sediment concentration)
Correlation Coefficient	.826	.881	

* 8 pixel array

Shaded figures were not used in the above calculations

Analysis

The locations of the sediment sampling sites were determined by transferring mini-ranger triangulation measurements made from a tower on Heald Point on the eastern side of Prudhoe Bay and from the shore of a small lake on the western shore of Prudhoe Bay to each site onto NOAA nautical chart 16061. The mini-ranger distances are usually good to + 4 meters for distances ranging from 2900 meters to 15,000 meters. However, difficulties in precisely locating the western mini-ranger station on the small lake on NOAA chart 16061 undoubtable increased this error. Measurements which were taken from NOAA chart 16061 and were converted to measurements for location of the sample sites on the Landsat print-outs were good to the nearest millimeter which is conveniently equivalent to the size of a pixel (the area represented by a character on the printouts). The NOAA chart was 1:50,000 scale and a millimeter error on the chart translates into 50 meters on the ground. Reflectance values (Table I) were calculated by averaging over a square array of 9 pixels where each pixel represents a 59x79 meter area. Thus, the total area averaged for reflectance was approximately 0.042 km^2. Thus, averaging the reflectance of 9 pixels should have been adequate to accommodate any error in locating sediment sample sites on the printouts.

Linear regression analyses were performed for reflectance versus sediment load for bands 4,5, and 6. These results are discussed in sequence.

Band 4 (0.5 to 0.6 μ): The band 4 printout shows some details of a sediment plume which originates from the Sagavanirktok River and is deflected by the West Dock on Prudhoe Bay. The linear regression analysis using all 10 sites had a slope of 0.2, an intercept of 13 and a correlation coefficient of 0.35 indicating a minimal relationship between reflectance and sediment load.

Band 5 (0.6 to 0.7 μ): The band 5 printout gives the most detailed picture of the sediment plume. The linear regression analysis of reflectance versus sediment load in mg/1 had a slope of 0.12 an intercept of 10 and a correlation coefficient of 0.33 indicating a minimal relationship between reflectance and sediment load,

Band 6 (0.7 to 0.8 μ): The band 6 printout shows very little variation of reflectance with location. A linear regression analysis of reflectance versus sediment load in mg/l had an essentially horizontal slope and a correlation coefficient of -0.035 indicating essentially no relationship existed between the measured reflectance and sediment loads on band 6. .

Examination of the bathymetry using NOAA chart 16061 for Prudhoe Bay reveals the maximum depth in the vicinity of the West Dock and of the sediment sample sites is no more than 6 meters. Using Whitlock et al.'s estimation of the penetration depth for 0.52 μ (band 4) as 3 to 7 meters at 2 mg/l sediment and 1 to 2 meters at 10 mg/l, it seems reasonable to exclude sampling sites 7,8,9, and 10 since these sites appear to be in a depth and concentration range where band 4 reflectance is likely to be influenced by the sea floor as well as the sediment concentration.

Using Gordon and McCluney's observation that the band 5 penetration depth is approximately 2 meters and independent of sediment load, one can also exclude sampling sites 7,8,9, and 10 from the band 5 analyses as they are in a region of 2 meters or less depth.

Sampling site 6 is anomalous. Sampling site 6 appears to be on a boundary between sediment laden water behind Stump Island and relatively clear water. It is unclear whether the bathymetric chart accurately gives the depth of a site so close to the West Dock though site 6 appears to be at greater than 2 meters. The 9 pixel array averaged to give the reflectance assigned to site 6 contained characters spanning 7 different intensities of reflectance in band 5 where the other deep water sampling sites contained a maximum of 3 different intensities. It seems likely that the single sediment sample taken at site 6 was not representative of what the satellite was capable of sensing.

Linear regression analyses for band 4 and band 5 were run for the remaining 5 sampling sites (Table I). The band 4 regression has a slope of 0.28, an intercept of 13.5, and a correlation coefficient of 0.826. The band 5 regression has a slope of 0.25, an intercept of 9.5 and a correlation coefficient of 0.881. Thus, for sediment sampling sites in deep, open water, there appears to be a significant relationship between reflectance and sediment concentration. Furthermore, the similarity of these slopes implies that band 4 and band 5 data might be-used interchangeably over the concentration range of the sampling sites.

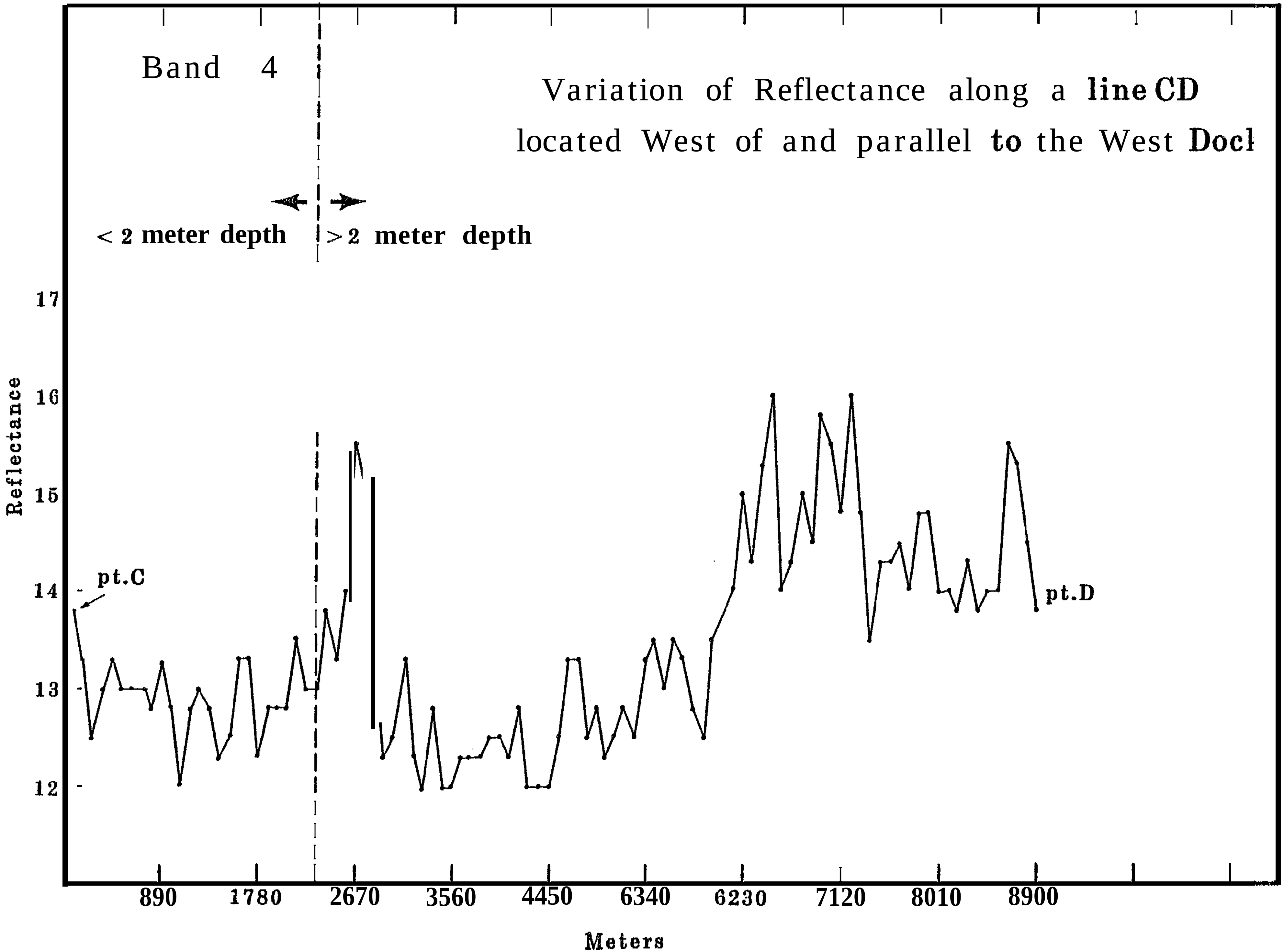
An attempt was made to evaluate the sensitivity of bands 4,5, and 6 to the three regions of distinct sediment load evident near the West Dock: a plume originating from the Sagavanirktok River just east of Prudhoe Bay and deflected by the West Dock (Figure 1, Zone III), a low sediment area between this plume and Stump Island (Zone II), and a confined region of low sediment load between Stump Island and the mainland (Zone I). Reflectance values were averaged for 100 linear arrays of 4 pixels each perpendicular to Track C-D (Figure 1) originating near the base of the West Clock extending 9 km into the Arctic Ocean. This was done for the bands 4,5, and 6 and plotted with position along Track C-D (Figures 2 and 3). Band 6 failed to show any significant or regular variation in reflectance.

Bands 4 and 5 showed a region of low reflectance and presumably low sediment load near Stump Island and the second bend of the West Dock and a region of maximum reflectance presumably originating from a plume of sediment from the Sagavanirktok which is deflected by the West Dock,

It is interesting to observe that when the plots are superimposed, the seaward two thirds of the plots have the same general shape and noise features, but the inshore third (that part of less than two meters depth) is different for each band. For band 4, the inshore reflectance are more like the low sediment area between Stump Island and the second bend of the West Dock; for band 5 the inshore reflectance are more like the sediment plume from the Sagavanirktok which is deflected by the West Dock. This is a further confirmation that band 4 and 5 reflectance respond in an equivalent manner to sediment concentrations of moderate range in water of greater than two meters depth, but respond differently in water of less than two meters depth. This difference in reflectance response may be due to differences in the way band 4 and band 5 sense the bottom in less that two meters of water, but it is also possible that the mineralogical and/or biological origin of the sediment present in the water between Stump Island and the shore is different from that in the deep water areas.

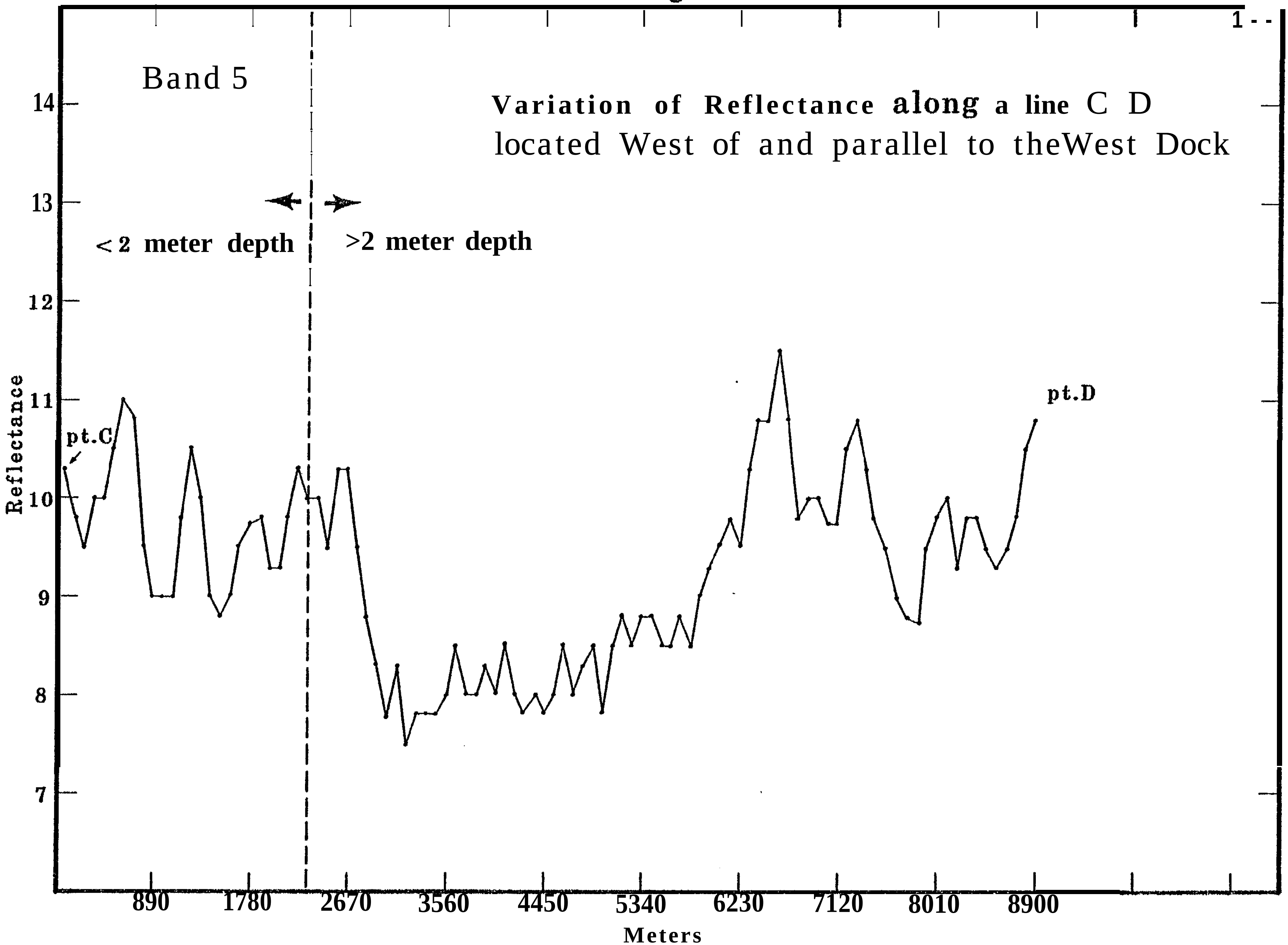
In order to determine the relative response of bands 4 and 5 to sediment and depth, a plot of band 4 versus band 5 reflectance averaged over square arrays of 9 pixels each was compiled from points chosen from

Figure 2


Band 4
Variation of Reflectance along a line CD
located West of and parallel to the West Docl
< 2 meter depth
> 2 meter depth
Reflectance
17
16
15
14
13
12
pt.C
pt.D
890
1780
2670
3560
4450
6340
6230
7120
8010
8900
Meters

10

Figure 3



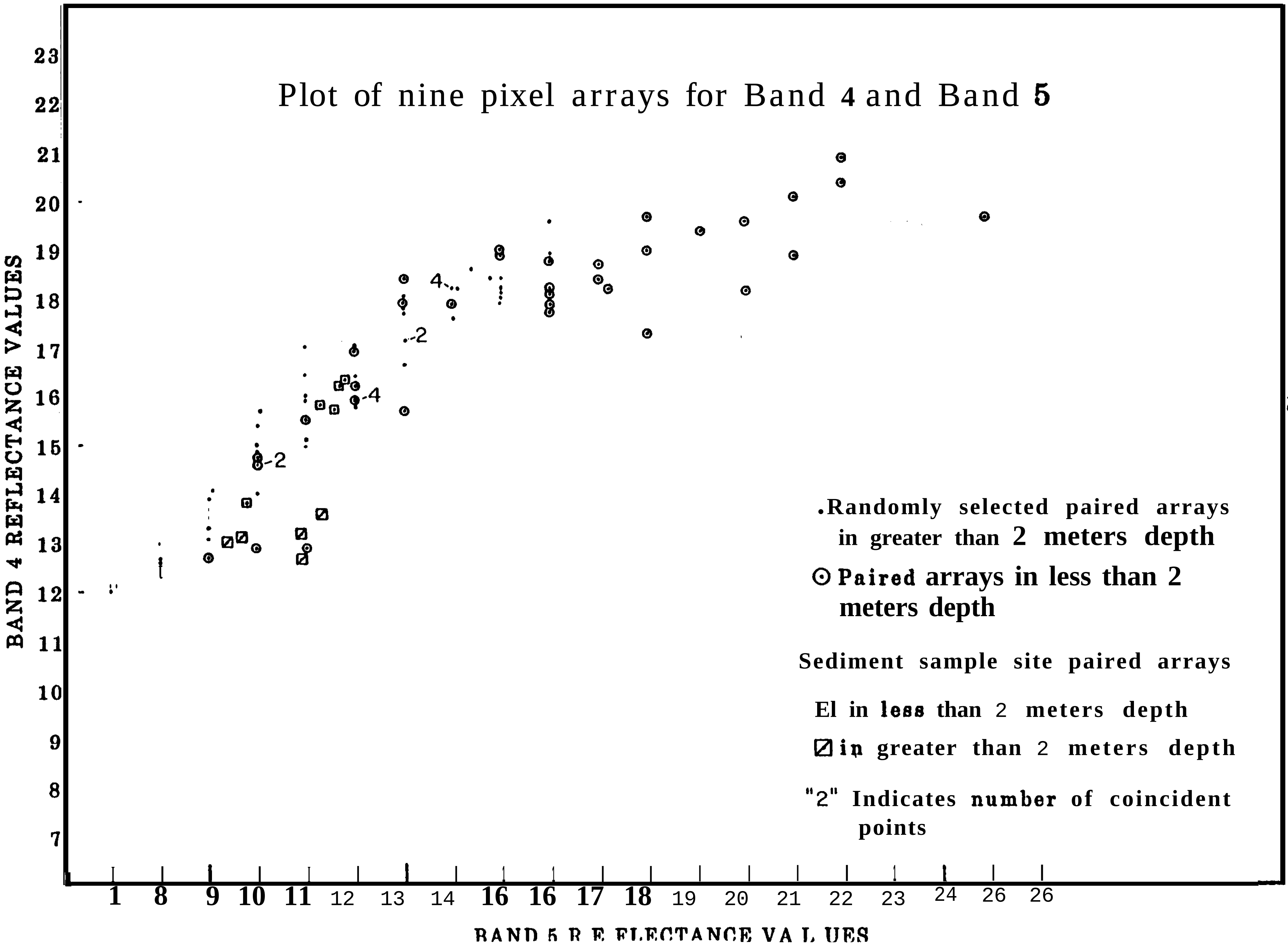
Band 5
Variation of Reflectance along a line C D
located West of and parallel to theWest Dock
< 2 meter depth
>2 meter depth
pt.C
pt.D
Reflectance
14
13
12
11
10
9
8
7
890
1780
2670
3560
4450
5340
6230
7120
8010
8900
Meters

throughout the Prudhoe Bay area covered by the computer printout (Figure 4). The result appears to be a two-step linear relationship: below reflectance of 15 for band 5 and 19 for band 4, the slope appears to be around 1; beyond this point the slope decreases, suggesting that the relationship between band 4 and band 5 changes at higher reflectance values which in this case correspond to higher levels of sediment concentration. However, as virtually all of these high sediment sites in the Sagavanirktok Delta are less than 2 meters in depth, the bands may be responding to the bottom in a different manner. Another possibility is that the mineral content and/or biological activity of sediment within the Sagavanirktok Delta is different from that of sediment in other regions of the study area.

The reflectance values in Figure 4 from depths of greater than two meters were separated out and an analysis was undertaken to establish the validity of the hypothesis that band 4 and band 5 could be used interchangeably in deep water and for concentrations of less than 25 mg/l sediment.

For convenience the band 5 nine-pixel arrays were chosen so that all nine pixels in each array had the same reflectance value 'in order that the averaged value for each nine-pixel array would be a whole number. The band 5 reflectance ranged from 7 to 16. The band 4 nine-pixel arrays which corresponded to the preselected band 5 arrays often were represented by as many as four different reflectance values instead of by nine identical reflectance values as might have been expected. Table II compares the preselected band 5 reflectance with the averages of the corresponding band 4 reflectance. The standard deviations of the band 4 averages ranged from 0.2 to 0.8 σ. Using the regression equations

Figure 4


Plot of nine pixel arrays for Band 4 and Band 5
BAND 4 REFLECTANCE VALUES
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
1 8 9 10 11 12 13 14 16 16 17 18 19 20 21 22 23 24 26 26
BAND 5 R E FLECTANCE VA L UES
4
2
4
2
•Randomly selected paired arrays in greater than 2 meters depth
⊙ Paired arrays in less than 2 meters depth
Sediment sample site paired arrays
El in less than 2 meters depth
▨ in greater than 2 meters depth
"2" Indicates number of coincident points

for band 4 and band 5, sediment concentrations were calculated.

As band 5 reflectance were chosen to be whole numbers, the only appropriate measure of variance was that of the 50% confidence limit provided by the regression analysis. Sediment concentration and variations from band 5 reflectance values are presented in Table II. Since the band 4 reflectance values corresponding to band 5 did have variation within the arrays, standard deviation as well as 50% confidence limits provided by the regression analysis are listed. Calculations of the sediment concentration using the band 4 regression equation and the variations predicted by the 50% confidence level and the standard deviation are given in Table II.

Table II suggests that band 5 reflectance value 10 is equivalent to an averaged band 4 reflectance value 14.7 + 0.5, Band 5 reflectance value 10 is equivalent to '2.2 + 2.5 mg/l sediment at the 50% confidence level, and band 4 reflectance value 14.7 is equivalent to 4.2 ± 2.6 mg/l sediment at the 50% confidence level. There is some overlap of these independent calculations, but it is not as good as might be expected.

The standard deviations recorded for the averaged band 4 reflectance corresponding to preselected band 5 reflectance are a measure of the smallest variation one can hope to achieve using the band 4 or 5 regression formulas to calculate sediment concentration. As seen in Table II, these range from ± 0.2 to ± 0.8 reflectance units. Assuming a standard deviation of ± 1.0 which is constant for the whole range of band 4 reflectance values, calculations of sediment concentrations from the band 4 regression equation should be at least good to ± 3.5 mg/l and in some cases better than this.

Table II. Statistical Limits of Reflectance Measurements

Band 5 Reflect-ante	Band 4 Reflect-ante average and σ	Calculated Band 5 Sediment Concentration		Calculated Band 4 Sediment Concentration		
		mg/l	50% Confidence limit (mg/l)	mg/l	50% Confidence (mg/l)	Variation from 1 σ of reflect. average (mg/l)
7	12	-				
8	12.6±0.3	-				
9	13.5±0.4	-		-		
10	1407*0.5	2.2	±2.5	4.2	±2.6	±3.5
11	15.9±0.8	6.3	±3.6	8.5	±5.3	±3.5
12	16.0±0.4	0.4	±4.6	9.5	±5.7	±3.5
13	17.5±0.5	14.5	±5.6	14.1	±7.2	±3.5
14	18.1±0.2	18.5	±6.6	16.2	±7.9	±3.5
15	18.3±0.4	22.6	±8.0	17.0	±8.2	±3.5
16	18.9±0.7	26.7	±9.0	19.1	±8.9	±3.5

Table 111. Miniranger Fixes

Sample Site	West Dock (meters)	Heald Pt. Tower (meters)
1	2894	12046
2	3664	12142
3	4625	2796
4	6123	3578
5	6539	4514
6	4994	3691
7	3927	2990
8	3730	3209
9	5090	4343
10	5879	4955

Table II reveals that the variation at the 50% confidence level for calculation of sediment concentration is much greater than ± 3.5 mg/l for most of the concentration range and for both band 4 and band 5 regression equations. This implies that with more, better-selected field data, one should be able to derive regression equations for both band 4 and 5 which will yield sediment concentrations good to at least ± 3.5 mg/l for a range of approximately 2 to 20 mg/l.

An attempt was made to discover if there was any difference in reflectance response for band 4 and band 5 within the Sagavanirktok plume and within the deep water of Prudhoe Bay such as occurred with these responses within the area between Stump Island and the mainland and the deep water near the West Dock. If such a difference existed, it would have perhaps been possible to reduce even further the variation in reflectance values for band 4 which correspond to a preselected band 5 value. No difference was found.

Conclusions

1. Landsat imagery for both bands 4 and 5 is unsuitable for normal quantitative sediment determination in less than 2 meters of water. Band 5 might be considered for high concentrations in shallow waters.
2. Linear regression equations for bands 4 and 5 were obtained that could be used interchangeably up to 20 mg/l sediment concentration at least to the nearest 10 mg/l. Refinement of these regression equations should be possible to enable the calculation of sediment concentrations to ± 3.5 mg/l or better.
3. Band 5 will most likely yield the best results for sediment concentrations above 20 mg/l.

Additional things to be studied to improve the accuracy of the linear regression equations:

1. The 9-pixel array averaged for reflectance tabulation seems essential to allow for errors in locating the sample site on the computer printout and to smooth out noise in the printout reflectance data. The 9-pixel array covers 0.042 km^2 and has the dimensions 180 x 240 meters. For calibration purposes, it would be desirable to take more than one sediment sample per sampling site to insure the sediment concentration assigned to this large area is truly representative of sediment levels over the area of the satellite measurement.
2. More sediment samples should be taken off the Sagavanirktok delta as this preliminary analysis implies that the relationship between sediment concentration and reflectance changes at sediment concentrations above 20 mg/l. One should pay special attention to the depth of these stations for the following reasons: First of all, it has been demonstrated that reflectance values are influenced by interference from the bottom at depths of less than 2 meters and most of the Sagavanirktok delta is no deeper than this. Secondly, there is no clear reference in the literature as to how important the influence of reflectance from the bottom is on reflectance in areas of very high sediment concentration. One should, therefore, record depth as well as site bearings in this region as an aid in insuring the sediment samples will be useful and also to gain some insight into whether reflectance from the bottom does influence reflectance at very high sediment levels.

3. Some attention should be made to the mineralogical and biological nature of the sediments as there are many references in the literature on the complicating effects of variations in sediment composition on reflectance values (Warne, 1978; Whitlock et al. ,1978) If the suspended sediment is not fairly homogeneous, it may not be possible to use Landsat imagery to quantitfy sediment load. It should be noted that the only evidence available of inhomogenous sediments in the Prudhoe Bay area is for the water between Stump Island and the shore, and reflectance data for other parts of the Bay and the Sagavanirktok Delta reveal no change in reflectance that can be associated with sediment source. It should be possible to use Sagavanirktok regression curves for any river delta on the north coast which has similar sediment composition.

4. It would appear that none of the 1981 sampling sites were inside the minimum sediment load area (Fig. 1, Zone II). An attempt should be made to adequately sample the low sediment concentration areas, again paying particular attention to the depth of the sample sites.

5. The ten sediment samples for this study were taken around midnight on July 22; the satellite pass was at noon the following day. Perhaps some effort should be made to do the sediment sampling in a time frame bracketing the satellite pass. In any event, the time period for sampling should be noted.

Acknowledgements

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Whitlock, C. H., W. G. Witte, J. W. Usry, and E. A. Gurganus, Penetration depth at green wavelengths in turbid waters, Photogrammetric Engineering and Remote Sensing, 44, (11), pp. 1405-1410, 1978.