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HYDROGRAPHIC CHARTING FROM LANDSAT SATELLITE: A COMPARISON WITH AIRCRAFT IMAGERY

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—— **GODDARD SPACE FLIGHT CENTER** ——
GREENBELT, MARYLAND

HYDROGRAPHIC CHARTING FROM LANDSAT SATELLITE:
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Elizabeth M. Middleton
Computer Sciences Corporation

and

John L. Barker
Earth Resources Branch
Goddard Space Flight Center

May 1976

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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HYDROGRAPHIC CHARTING FROM LANDSAT SATELLITE: A COMPARISON WITH AIRCRAFT IMAGERY

Elizabeth M. Middleton
Computer Sciences Corporation
8728 Colesville Rd.
Silver Spring, Md. 20910

John L. Barker
Goddard Space Flight Center
Greenbelt, Md. 20771

Abstract

The relative capabilities of two remote-sensing systems in measuring depth and, consequently, bottom contours in sandy-bottomed and sediment-laden coastal waters were determined quantitatively. The Multispectral Scanner (MSS), orbited on the Landsat-2 Satellite, and the Ocean Color Scanner (OCS), flown on U-2 aircraft, were used for this evaluation. Analysis of imagery taken simultaneously indicates a potential for hydrographic charting of marine coastal and shallow shelf areas, even when water turbidity is a factor.

Several of the eight optical channels examined on the OCS were found to be sensitive to depth or depth-related information. The greatest sensitivity was in OCS-4 (0.544 ±0.012 μm) from which contours corresponding to depths up to 12 m were determined. The sharpness of these contours and their spatial stability through time suggests that upwelling radiance is a measure of bottom reflectance and not of water turbidity. The two visible channels on Landsat's MSS were less sensitive in the discrimination of contours, with depths up to 8 m in the high-gain mode (3 X) determined in MSS-4 (0.5 to 0.6 μm).

1. Introduction

Intensive investigation of coastal waters in the eastern Gulf of Mexico along the west coast of Florida was initiated by the Florida Department of Natural Resources (FDNR) with the Hourglass Cruises (see reference 9). Ongoing research of water quality and color is currently in progress as the major thrust of the Red Tide Program, a cooperative effort between the National Aeronautics and Space Administration (NASA) and FDNR. These agencies provide, respectively, satellite/aircraft imagery of the study area and surface truth collection for evaluation of the potential use of satellites in the monitoring of phytoplankton blooms.

Analysis of these data revealed that depth-related information appears to represent the major contribution to the total recorded radiance in those satellite/aircraft sensor channels that are expected to be of most value for phytoplankton and sediment detection. This finding agrees with previous demonstrations by several investigators (1, 5, 6, 7, and 11) that a capacity exists for the discrimination of bottom features in lakes and clear oceanic water by remote sensors. Efforts have also been made to model expected theoretical spectral responses of sunlight penetration and upwelling radiance in Landsat MSS-4 and MSS-5 for clear and turbid water cases by McCluney (4), Gordon and McCluney (3), and Sherman (8). The drawback of the modeling approach is that it requires extensive field measurements of the optical parameters at the study site, an expensive and time-consuming operation.

The purpose of this paper is to demonstrate a functional relationship between absolute recorded radiance and depth, without knowledge of measured optical properties of the water investigated. The original objective was to identify and quantify depth information and isolate it from other factors to permit study of superimposed transient phenomena such as the red tide. In pursuit of this objective, an additional application of considerable merit—namely, hydrographic mapping of coastal areas—was recognized and is reported here.

2. Methods

In conjunction with the Red Tide Program, Landsat Multispectral Scanner imagery of the Gulf of Mexico and Tampa Bay was available in normal (1X) and high-gain (3X) modes. Six days were chosen for depth analysis: July 18, 1975 in 3X; August 5, 1975 in 3X; August 14, 1975 in 1X; September 19, 1975 in 3X; October 16, 1975 in 3X; and February 28, 1976 in 3X. On September 19, 1975, simultaneous coverage was provided by the Ocean Color Scanner flown at an altitude of 20 km on the U-2 aircraft. A subarea of both OCS and MSS imagery along the west coast of Florida from approximately 27° 35′N to 27°50′N and extending 20 km offshore into the Gulf of Mexico was chosen for intensive study.

It should be noted that the OCS is currently available for specific research programs only. Because it was designed for coastal-zone color analysis (W. Hovis, National Oceanic and Atmospheric Administration), its Landsat-sized pixels are primarily useful for evaluation of the MSS performance in coastal analysis. However, the OCS (renamed the Coastal Zone Color Scanner, CZCS) will be flown on the Nimbus-G satellite to be launched in 1978, when its unique qualities for water-color studies should be available at 800-m squared resolution to general users.

Table 1 shows the correspondence of the spectral ranges and maximum radiances for the MSS and OCS channels. The following imagery were used to compare these channels for relative bathymetric capacity: MSS imagery obtained September 19, 1975

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in 3X (Scene ID: 2240-15213) and August 14, 1975 in 1X (Scene ID: 2204-15215), and OCS imagery obtained September 19, 1975 (Flight 7525). The data stored on magnetic tapes were processed on the Image-100, a computer system with an interactive visual-display unit. Maximum resolution data comprised of every line and pixel of the subarea for both the OCS and MSS were stretched to 256 radiance intensity levels (gray levels), and were output as binary prints (Figures 1b and 2). Each mark on the binary print represents the spatial location of a pixel with a given radiance value or range of radiance values. In this manner, the spatial distribution patterns for single or grouped radiance values for the spectral bands examined on the OCS and MSS imagery were obtained. For comparison with the binary prints, depth contour lines (Figure 1a) were taken from 1974 U.S. Geological Survey (USGS) nautical charts and then drawn at the same scale as that of the binary prints using a zoom transfer scope.

To determine if the depth features observed in Landsat high-gain imagery were stationary through time and thus probably bottom-related, a temporal evaluation was made for 5 days spanning a 7-month period, for the dates with high-gain mode data given previously. The relative geographical location of the most prominent depth features on Landsat MSS-4 scene positive transparencies were compared to each other and to binary prints on the zoom transfer scope.

3. Results

In this investigation, data corresponding to shallow water depths between 0 and 13 m were examined. A variability in the exact geographic positioning of a radiance contour was introduced from at least two sources: the envelope of radiance values which together define a given depth contour, and the apparent shifts which have occurred in the location of depth contours shown on charts. This variability is the error associated with the accuracy of matching radiance contours with charted depth contours and the depth potential stated for each sensor channel is the maximum depth at which the given confidence estimate for matching contours was maintained. In most cases, depth information was present for greater depths. Where the confidence in matching depth and radiance contours was less in deeper water,
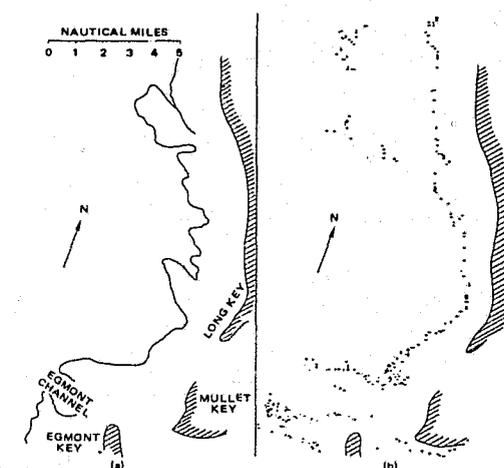

Figure 1. The charted depth contour (USGS 1974) for 18 ft in the study site along the Florida coast from Egmont Key to Sand Key is shown at left (a). The binary print of the OCS-4 radiance-value distribution pattern for a single gray level in this depth range is shown on the right (b) for September 19, 1975, data.

these data were not included in the depth potential. The radiance intensity range (number of gray levels) indicates the channel sensitivity to variations in water features in a given sensor channel over a standard distance from shore. All linear correlation coefficients, r^2, greater than 0.8 are reported, and these were found to be significantly different statistically from zero ($0.05 < p < 0.001$) for both slopes and intercepts by the proper t-test. Table 2 summarizes the results.

OCS data obtained September 19, 1975 were used to examine channels 2, 4, 5, and 7. These channels have approximate bandwidths of 0.023 μm and mid-band wavelengths of 0.47 μm, 0.54 μm, 0.58 μm, and 0.67 μm, respectively. OCS-4 and OCS-5 were

Table 1

A Comparison of the Spectral Locations and Maximum Radiance Expressed as
$(mW/cm^2$ per 0.1 micron per steradian) $\times 10^{-3}$ for Channels on the Multi-
spectral Scanner and Ocean Color Scanner. The Count (number of
gray levels) for MSS = 64; for OCS = 512.

Multispectral Scanner		Maximum Radiance per Count		Ocean Color Scanner*		
Channel	Spectral Range (µm)	Low Gain	High Gain	Channel	Average Spectral Range (µm)	Maximum Radiance per Count
				OCS-2	0.45-0.48	4.65
MSS-4	0.5-0.6	38.8	13.0	OCS-4	0.53-0.56	1.88
				OCS-5	0.57-0.59	1.43
MSS-5	0.6-0.7	31.3	10.5	OCS-7	0.66-0.68	0.87
MSS-6	0.7-0.8	27.5	—			
MSS-7	0.8-1.1	24.0	—			

*OCS spectral-band locations and gain factors are recalibrated at intervals to account for changing Sun angles, etc.
The numbers given here represent the operative values for the data collected here.
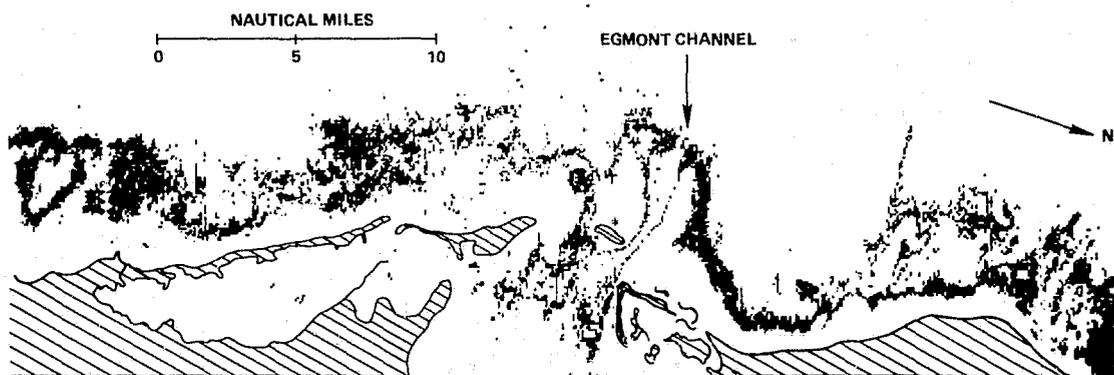
2

Figure 2. A Binary Print generated on the Image-100 computer off the west coast of Florida, from Clearwater south to Sarasota, is shown here as an example of large-scale contour mapping. The coast is on the bottom. Egmont Key can be located by the asterisk (*). The radiance-value distribution pattern for a specific depth interval is shown at the top for OCS-4 data obtained September 19, 1975. Note the outline of Egmont Channel.

found to be the most sensitive to depth or depth-related factors. The greatest sensitivity, as indicated by a radiance intensity range of 56 gray levels, was found in OCS-4, which measured depths to at least 12 m. An error of 5 percent was associated with the confidence in matching radiance contours with depth contours in the 3- to 13-m range. Depth contours up to at least 10 m were determined in OCS-5 over an intensity level range of 42, but the error associated with matching radiance contours and depths in the 3- to 13-m range was 10 percent. In both OCS-4 and OCS-5, an inverse linear relationship was demonstrated for the logarithm of radiance value as a function of depth. For OCS-4, $r^2 = 0.94$,

and for OCS-5, $r^2 = 0.88$ (Figure 3). OCS-2 exhibited poor discrimination (probably attributable to atmospheric attenuation) with 30-percent error. OCS-7 data were not useful for extraction of depth information.

The most sensitive channel on either sensor to depth or depth-related factors, OCS-4, was analyzed further with inclusion of shallow water to 0 depth. When level-sliced into large, equal intervals ($\geq$ 18 gray levels per interval), the range of radiance values for water was more accurate for producing shallow-water contours, whereas level-slicing into smaller, equal intervals (< 10 gray

Table 2
Analysis of Comparative Bathymetric Capabilities for the
Available Channels on OCS and MSS Imagery, Off the West Coast of Florida.

Channel	Depth Determination (m)	Radiance: Depth Matching Confidence (%)	Radiance Range (No. of gray levels)	Depth Range Examined (m)	Depth versus Radiance Correlation Coeff., r^2	Graph of Function
1) Aircraft: Ocean Color Scanner (OCS) (Flight # 7525)						
OCS-2	8*	70	4	3-13	—	——
OCS-4	12*	95	56	3-13	0.94	——
OCS-5	10*	90	42	3-13	0.88	Fig. 3
OCS-7	–	–	–	3-13	—	——
OCS-4	12*	95	56	0-13	0.99	Fig. 4
2) Landsat: Multispectral Scanner (MSS) a) High Gain (Sept. 19, 1975)						
MSS-4	8*	90	42	3-13	0.99	Fig. 3
MSS-5	5*	90	26	3-13	0.93	Fig. 3
MSS-6, 7	–	–	–	3-13	—	——
b) Low Gain (Aug. 14, 1975)						
MSS-4	8*	70	16	3-13	0.88	——
MSS-5, 6, 7	–	–	–	3-13	—	——

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levels per interval) produced more accurate deeper-water contours. The inverse linear relationship between depth and the logarithm of radiance value was improved, $r^2 = 0.99$ and $\log y = 2.35$ to $0.045X$ (Figure 4). This line can be approximated with three points chosen for reasonable confidence in spatial distribution: the land-water interface radiance value, a near-shore radiance value, and a deep-water radiance value. The lower bound to the radiance contour is used in the latter two cases for plotting purposes. This procedure is suggested for estimating the slope of the line with a minimum of sensor and depth information.

For Landsat imagery taken in the high-gain mode on the same day (September 19, 1975), all four MSS channels were considered. Depth was best discriminated with MSS-4 (0.5 to 0.6 μm). Depth contours to at least 8 m were recognized (10-percent error) over a radiance intensity range of 42 gray levels. A 26-level range in MSS-5 (0.6 to 0.7 μm) gave depth information to at least 5 m (10-percent error). Plotting the logarithm of radiance values as an inverse function of depth yields an $r^2 = 0.99$ for MSS-4 and an $r^2 = 0.93$ for MSS-5 (Figure 3). Both near-infrared channels, MSS-6 (0.7 to 0.8 μm) and MSS-7 (0.8 to 1.1 μm), did not contain useful depth information. In normal gain mode on August 14, 1975, depth detail was demonstrated to approximately 8 to 9 m (30-percent error) in MSS-4, and was not found to be useful in MSS-5.
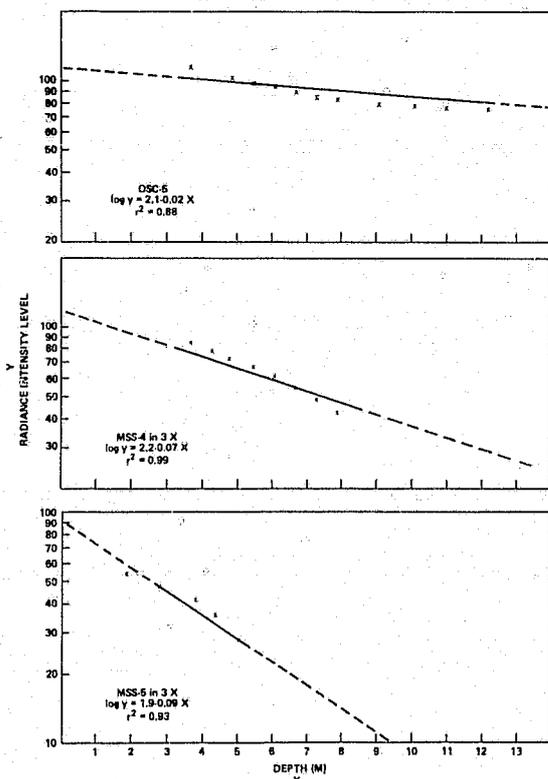

Figure 3. Comparison of OCS-5, MSS-4 in high-gain mode, and MSS-5 in high-gain mode for depth determination on September 19, 1975, off the west coast of Florida.
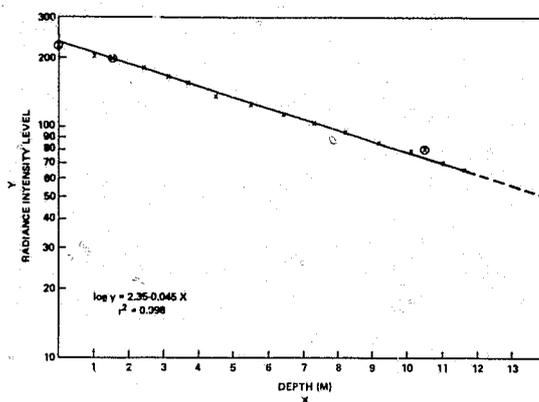

Figure 4. OCS-4 depth determination, 0 to 12 m, on September 19, 1975, off the west coast of Florida. The circled x's indicate three points which can be determined selectively from the radiance-distribution patterns and used to approximate this line.

From the foregoing results for depth estimation, a clear distinction was not made between depth and factors highly correlated with depth. One method of estimating whether upwelling radiance is bottom-related is to look at imagery on different days. A temporal comparison of MSS-4 images taken in high-gain mode and spanning a 7-month period, shows that: (1) the prominent depth features are geographically stationary from at least July to the following February, and (2) the hand-drawn contours from transparencies which delineate these depth features correspond better to computed radiance contours than to the most recent charted depth contours.

4. Discussion

For bodies of water where light penetrates below the surface, several vertical sources contribute to the observed upwelled radiance, recorded by remote sensors as radiance-intensity values. In relatively clear and shallow water, light is reflected from both the water surface and bottom surface, as well as from the water column. It is assumed that the magnitude of surface-reflected light is independent of depth, whereas the magnitude of bottom-reflected light is dependent primarily on the bottom reflectivity and on the distance light travels through the water column, where it is diminished exponentially by the same processes of absorption and scattering that act on downwelling light (12). Therefore, where water transparency and bottom reflectivity are horizontally homogeneous, variations in upwelled radiance are directly related to variations in bottom depth or depth-related factors.

Because concentrations of substances that contribute to water turbidity are frequently correlated with shore distance and thus with depth, seemingly bottom-related radiance patterns are likely to be partially caused by turbidity in the water column. Although a clear distinction between depth and depth-related factors therefore cannot presently be made, horizontal homogeneity for water quality and bottom reflectivity at the given

pixel resolution (approximately 80 m squared) was assumed to be a reasonable first approximation. To determine if variations in absolute radiance were associated spatially with depth, the comparison between radiance value and nautical chart contours was made.

From the results, the available sensor channels determined to have some bathymetric capabilities can be ranked from best to poorest as follows: OCS-4, similar performance by OCS-5 and MSS-4 in high-gain mode; MSS-5 in high-gain mode; and MSS-4 in normal mode. This ranking demonstrates that depth information in coastal waters with sandy bottoms can be extracted from a spectral range of 0.50 to 0.60 μm, with an average peak performance in the 0.50- to 0.55-μm range.

Because both the OCS and MSS fulfill the requirement of channels in the 0.50- to 0.60-μm range, the relative performance and level of acceptable depth discrimination, as well as the sensor availability, should be taken into account. The OCS has good spectral resolution and band location for coastal study, but is presently limited in general availability. However, where hydrographic mapping accurate to 1 m is required, as in mapping to a 1:24,000 scale, data comparable to OCS-4 are essential. Landsat MSS coverage is obtained over coastal areas, but its spectral resolution and usual normal gain setting limit its usefulness. (The channel deficiency in the 0.40- to 0.50-μm range is not a severe limitation to coastal depth studies.) However, in the high-gain mode, MSS-4 is adequate for large-scale (e.g., 1:80,000) hydrographic mapping. The usefulness of the high-gain option for monitoring water, low in irradiance relative to land, as recommended by Thomson (10) is supported.

Polcyn (5) has shown that, in clear oceanic water, the optimal spectral range for depth determination may be lower than 0.50 μm, but that the optimal spectral range shifts upward with an increase in water turbidity. For coastal waters, this means a shift from an optimal wavelength of 0.49 μm in "mean ocean" (waters oceanic in optical properties) with an attenuation coefficient of 0.08, to 0.54 μm in "mean coastal" waters (coastal in terms of optical properties) with an attenuation coefficient of 0.26 (5). This effect may be responsible, in part, for the greater radiance intensity range exhibited by shallow water when all depths are surveyed by the same sensor channel, probably because of an increase in the magnitude of those parameters making significant input to the radiance values. An example is the exponential decline in the concentration of suspended, small, inorganic particles with shore distance, which itself is highly correlated with average depth for this study area as discussed above.

Polcyn (5) and Barker (1) have both used the technique of plotting log depth as a function of radiance to determine a "deep-water value," the lower bound intensity level for depth discrimination in clear oceanic water. This value is subsequently subtracted from the absolute radiance to obtain relative radiance, which is then plotted in log scale as a function of depth. In the data presented here, a lower bound intensity level was not approached in turbid coastal waters by this method, and, consequently, absolute radiances were maintained throughout. This technique demonstrates that the limits were not reached for depth discrimination in any of the sensor channels which performed well.

Given the dynamic nature of coastal areas and the parameters which contribute to the total recorded radiance for coastal waters, it is satisfying that a log linear relationship as derived here on a simple set of assumptions is adequately descriptive. At present, the best description of this relationship between depth and absolute radiance (calculated from OCS-4 data over depths 0 to 12 m) is given by the equation:

$$\log y = 2.35 - 0.045X, \text{ where } y = \text{radiance (arbitrary units)}$$
$$x = \text{depth (m)}$$

The suggested procedure for estimating the slope of this line with three points offers a means of simplifying depth analysis in regions of homogeneous bottom cover. If this procedure is found to be of value, considerable savings in time and funds might be realized. But, it must also be demonstrated that the relationship holds for additional imagery because the regressions and correlations obtained refer to a particular point in time. Variances in radiance as a function of depth are not known, but are critical because they may be related to reflectance from those substances in the water column which are correlated with depth. That the data are truly depth information and not depth-related is supported by two sources: the sharpness of the radiance contours and the spatial stability through time of those features assumed here to be bottom topography over a 7-month period. To be conclusive, however, more data must be examined to determine that correlations between turbidity in the water column and depth are not also stable in time, although this possibility is unlikely.

Use of binary prints for depth analysis was especially advantageous in that anomalies were clearly exposed, and not averaged. This type of information is lacking in most standard nautical charts of greater scale than 1:24,000. The accuracy of the depth data on charts from 1974 (the most recent revisions) is uncertain for a coastal region subject to constantly changing physical conditions. Some of the errors associated with matching radiance and depth contours can probably be attributed to this. Because consistent contours were obtained over many months with satellite data, and anomalies that did not appear on standard charts were delineated, it may in fact be possible to chart sandy-bottomed depth contours from Landsat in high-gain mode at a greater accuracy than by the traditional method of depth soundings from ships.

In the future, it is hoped that the depth determination techniques developed on OCS-4 can be refined and applied to MSS-4 in the high-gain mode for hydrographic mapping of coastal areas, an application of considerable potential (2).

5. Summary and Conclusions

The available channels of two remote sensors were analyzed spatially and temporally for capacity to discern bathymetric information. OCS-4 provided the greatest depth penetration and discrimination with the smallest error estimate and is recommended for small-scale hydrographic mapping of sandy-bottomed coastal areas. Considering current availability of coverage, however, Landsat's MSS-4 in the high-gain mode is recommended to most interested users, especially when mapping at a scale of 1:80,000 is sufficient.

Bottom depth and log of radiance intensity were found to be related by a continuous functional relationship for depths up to 12 m, allowing the possibility for depth estimation in this range given several values, as demonstrated for one set of OCS-4 data. Although highly significant correlations for the inverse relationship were found in several sensor channels, an estimate of sample variance is not presently available. Duplication of these results on additional data sets and the feasibility of application to MSS-4 data in the high-gain mode comprise the suggested thrust of future research. In addition, it is hoped that quantification of depth information will allow identification of a radiance background against which the dynamic processes related to water color and quality, such as high concentrations of pollutants and phytoplankton, can be examined.

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