Application of Landsat Thematic Mapper Data for Coastal Thermal Plume Analysis at Diablo Canyon

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ABSTRACT: The possibility of using Landsat Thematic Mapper (TM) thermal data to derive absolute temperature distributions in coastal waters that receive cooling effluent from a power plant is demonstrated. Landsat TM band 6 (thermal) data acquired on 18 June 1986 for the Diablo Canyon power plant in California were compared to ground truth temperatures measured at the same time. Higher-resolution band 5 (reflectance) data were used to locate power plant discharge and intake positions and identify locations of thermal pixels containing only water, no land. Local radiosonde measurements, used in LOWTRAN 6 adjustments for atmospheric effects, produced corrected ocean surface radiances that, when converted to temperatures, gave values within approximately 0.6°C of ground truth. A contour plot was produced that compared power plant plume temperatures with those of the ocean and coastal environment. It is concluded that Landsat can provide good estimates of absolute temperatures of the coastal power plant thermal plume. Moreover, quantitative information on ambient ocean surface temperature conditions (e.g., upwelling) may enhance interpretation of numerical model prediction.

INTRODUCTION

THE THEMATIC MAPPER (TM) flown on Landsat 4 and 5 provides the opportunity to perform qualitative and quantitative analyses in the visible, near-infrared, and thermal infrared portions of the spectrum. Incorporation of the thermal band capability allows the study of power plant thermal plumes. Although the spatial resolution of the thermal band (band 6) is only 120 m, it can provide some insight into the temperature and distribution of thermal discharges in large water bodies. The feasibility of using band 6 to detect thermal effluents in large, closed-lake systems developed specifically for nuclear reactor cooling has already been accomplished (Wukelic *et al.*, 1985; Sadowski and Covington, 1987). The usefulness of TM band 6 for studying more complex coastal thermal discharges is demonstrated here.

A cooperative study was initiated by the Pacific Gas and Electric Company (PG&E) of California and the U.S. Department of Energy's Pacific Northwest Laboratory (PNL) to investigate this possibility, using the Diablo Canyon power plant as the study case. The strategy was to apply PNL's procedure for converting TM band 6 radiance values to absolute temperature (developed under contract as a Landsat TM investigator to National Aeronautics and Space Administration/Goddard Space Flight Center) with the unique and extensive ground truth (GT) data being acquired by PG&E in the Diablo Canyon area in support of power plant environmental studies. This paper describes the results of the cooperative analysis of a Landsat TM day scene of the Diablo Canyon power plant thermal plume area acquired on 18 June 1986. At this time, Unit 1 was operating at 89 percent of full-power level, and Unit 2 was at full-power level.

BACKGROUND: DIABLO CANYON POWER PLANT

Figure 1 is an aerial photograph of the Diablo Canyon power plant showing the structure of Diablo Cove (the location of the reactor cooling outflow), the reactor buildings, and Diablo Rock, located at the edge of the cove. The Diablo Canyon power plant uses water from the Pacific Ocean for once-through cooling of the condensers. The cooling water discharges into shallow waters of a coastal embayment (Diablo Cove) that connects to deeper waters in the open ocean. From 1984 to 1986, PG&E conducted extensive field studies to characterize water temperatures and velocities to meet regulatory requirements. Near-field temperature patterns (i.e., within Diablo Cove) were also studied with a 1:75-scale hydraulic model (Tu *et al.*, 1986; Leighton *et al.*, 1986).

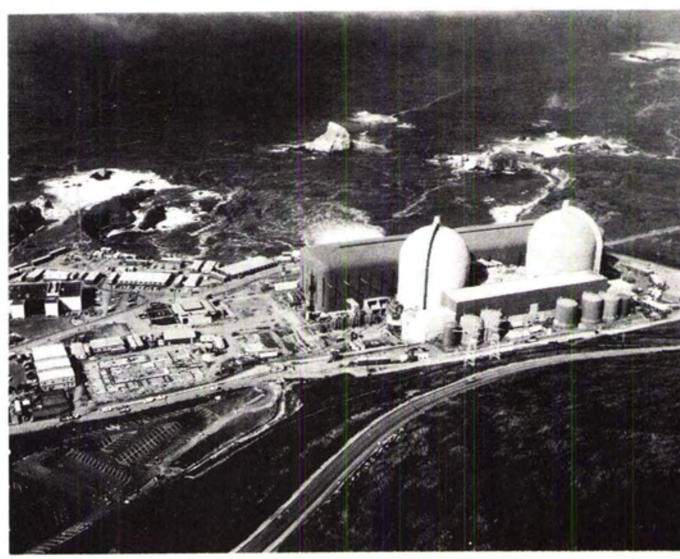

FIG. 1. Air photo of the Diablo Canyon power plant.

PG&E's operating permit requires bimonthly offshore (far-field) monitoring of surface temperatures. A numerical model is being verified to predict and describe offshore temperatures (Tu, 1988). A complex offshore environment exists where winds, tide, seasonal currents, and waves each play a part in determining the

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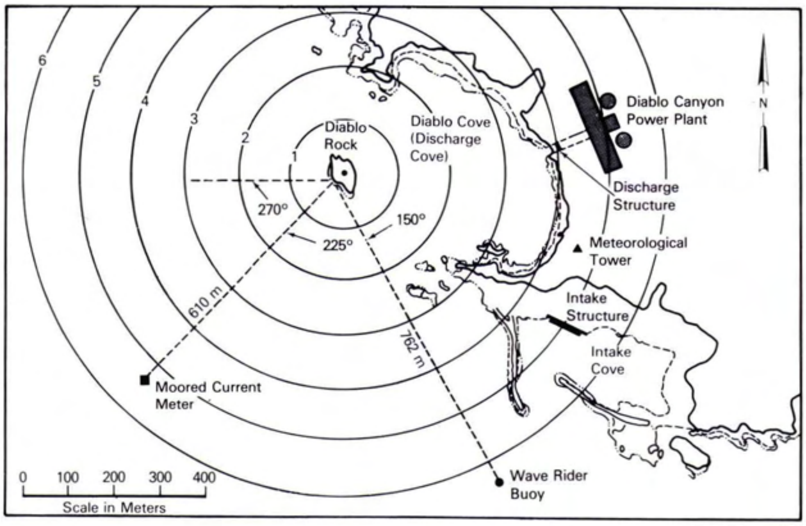

FIG. 2. A scaled map indicating major Diablo Canyon power plant features (Leighton *et al.*, 1986). Numbers on circles indicate distances from Diablo Rock in units of Landsat-5 TM band 6 pixels (120 m).

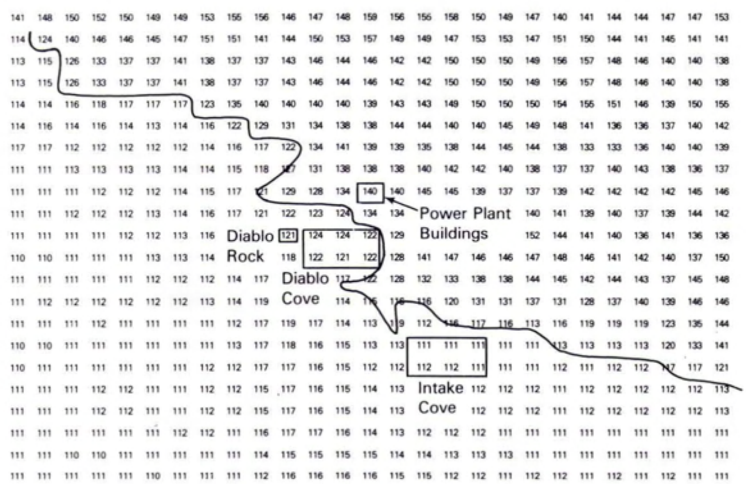

FIG. 3. Digital counts map for Diablo Canyon area for 18 June 1986, showing thermal pixels used for analysis.

size and orientation of the thermal plume. Seasonal temperature patterns and the presence of upwelling also influence the thermal plume.

LANDSAT TM CHARACTERISTICS AND TEMPERATURE DETERMINATION PROCEDURE

Landsat-5 TM is designed to obtain broad-band multispectral data of the Earth in six spectral bands ranging from the visible (0.45 to 0.69 μm) to near-infrared (IR) (0.76 to 2.35 μm) portions of the solar spectrum. A seventh band (designated as TM band 6) at 10.5 to 12.5 μm is located in the thermal IR region of the electromagnetic spectrum. Because the direct solar irradiance at this band location is negligible, thermal temperatures of surface features can be estimated during either day or night passes of the satellite by conversion of radiance to temperature values. Using appropriate atmospheric corrections for water vapor and ozone, quantitative estimates of the temperature of surface-water pixels can be determined using digital data acquired by TM band 6. TM band 6 radiances represent average values over spatial areas of 120 by 120 m, and temperatures derived are thus averages. A derived water temperature from the smallest digitized number, or digital count (DN), has been shown to be accurate to within 1° to 2°C (Lansing and Barker, 1984; Schott and Volchok, 1985), and more recently to 1°C or less for the Landsat-5 TM band 6 while in flight (Wukelic *et al.*, 1987). Thus, the possibility of mapping and estimating surface temperatures of large water bodies using Landsat has been clearly shown.

Because TM band 6 provides radiance calibration while on orbit by comparing scene radiance with an onboard calibrator, it is possible to convert the digital counts processed on computer-compatible tapes (CCT) that have been radiometrically and geometrically corrected (P-tape nearest-neighbor format) into absolute temperature determinations. Constants relating the DN to the effective at-satellite, in-band spectral radiance have been determined. The values for both spectral radiance (R_u) and temperature (T_u) derived from the radiances through a blackbody inversion algorithm are termed "uncorrected," because atmospheric adjustments are not included. These determinations are accomplished by use of Equations 1 and 2 for Landsat-5 TM band 6 (Markham and Barker, 1986).

$$R_u = \alpha\,(\mathrm{DN}) + \beta \qquad (1)$$

where R_u = uncorrected spectral radiance in mW cm^{-2} Sr^{-1} μm^{-1} and
α, β = 0.005632 mW cm^{-2} Sr^{-1} μm^{-1} DN^{-1}, 0.1238 mW cm^{-2} Sr^{-1} μm^{-1};

and $$T_u = \{K_2/\ln\{(K_1/R_u) + 1\}\} \qquad (2)$$

where T_u = uncorrected temperature in degrees K,
K_2 = 1260.56 K, and
K_1 = 60.776 mW cm^{-2} Sr^{-1} μm^{-1}.

Wukelic *et al.* (1987) have shown that, by comparing pure water pixel (containing no land) thermodynamic temperatures measured on the ground at the time of Landsat-5 overpass with the at-satellite Landsat derived values, the uncorrected temperature can deviate as much as 3°C from the GT value for large water bodies. By using meteorological data, however, atmospheric effects on remotely sensed data can be accounted for by calculating a corrected radiance, R_c, and using the blackbody inversion formula to determine a corrected temperature, T_c. The scattering/absorption of the atmosphere can be found by using atmospheric models or, by inputting local radiosonde data into the LOWTRAN 6 computer code developed by the U.S. Air Force (Kneizys *et al.*, 1983) and using modeled values of the atmospheric transmittance, τ, and the upward atmospheric radiance, R_a, the corrected radiance can be calculated from

$$R_c = \{(R_u - R_a)/\epsilon\tau\} - \{(1/\epsilon) - 1\}R_{\mathrm{sky}} \qquad (3)$$

where ϵ = emissivity of water 0.986, and R_{sky} is the sky radiance between 10.5 and 12.5 μm obtained from the empirical Idso-Jackson formula (Wukelic *et al.*, 1987; Suits, 1985), which is given by

$$R_{\mathrm{sky}} = f\sigma T_A^4 \{1 - 0.26\ \mathrm{EXP}\{-7.77 \times 10^{-4}(273 - T_A)^2\}\} \qquad (4)$$

where

T_A = ground-level absolute air temperature,
σ = Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and
f = fraction of thermal radiation between 10.44 and 12.42 μm, equals 0.3187 estimated as a ratio between the blackbody radiation at 8 to 14 μm and 10 to 12 μm.

When R_c is found, Equation 2 is used to find T_c by substituting the value R_c from Equation 3. The resulting inverted temperature is the corrected surface temperature.

ANALYTICAL RESULTS

Measurements made by PG&E at Diablo Canyon show that the structure and size of the thermal effluent depends on the total power output of the plant, the prevailing winds, and the tidal flow into and out of the cove. The time of Landsat overpass occurred at 18:04 GMT, or 10:04 AM PST on 18 June 1986. National Weather Service Meteorological data taken at nearby Vandenberg Air Force Base indicated that the sky was free of clouds and coastal fog at the time of satellite overpass.

Wukelic (1986) had developed and field tested a methodology for quantitatively extracting and analyzing Landsat-acquired digital data for both water and nonwater surface features to obtain thermodynamic temperatures. The steps in the procedure include

- Registration of the Landsat scene to ground control points to correlate GT measurements with the proper pixel value obtained by the satellite. UTM coordinates can be related directly to line and pixel number of the TM image.
- Extraction of raw digital counts from the CCT for analysis.
- Calculation for each DN of the corresponding uncorrected radiance and temperature values, using the inversion formulae given in Equations 1 and 2.
- Calculation of transmittance and path radiance by putting radiosonde data into LOWTRAN 6 to correct for atmospheric effects. Using Equation 3, corrected radiances and temperatures can be determined.
- Synergistic use of visible near-IR bands, if available, to adjust for mixed-pixel effects, where land and water are contained within a single thermal pixel.
- Comparison of at-satellite corrected temperature determinations with GT temperature measurement points for validation of atmospheric correction algorithm.
- Construction of a Landsat TM-derived estimated temperature map of the region of interest.

For a coastal Landsat scene such as Diablo Canyon, it is difficult to locate exact surface positions in the scene to extract the raw digital counts for analysis. Using a combination of an aerial photograph (Figure 1) and scaled map of the intake and discharge coves (Figure 2), it is possible to ascertain the location of the DN for both intake and discharge temperatures for comparison with PG&E GT data.

The variation of DNs over an assumed homogeneous, constant-temperature water area can be caused by such effects as poorly mixed or turbulent water, wave motion, and foam. It is assumed that, if pixel "noise" is small for water pixels, the calculation of a statistical average will provide an average temperature determination that can be compared to GT information. To determine the location in the DN map (Figure 3) for a thermal block to calculate an average temperature for Diablo Cove, Landsat-5 TM band 5 is used to establish the shore locations using Diablo Rock, which is clearly visible in the band 5 digital image, as a central reference point. The resolution of band 5 is 30 m, as compared with the 120-m resolution of band 6. Figure 4 shows the shoreline determination in band 5 digital data,

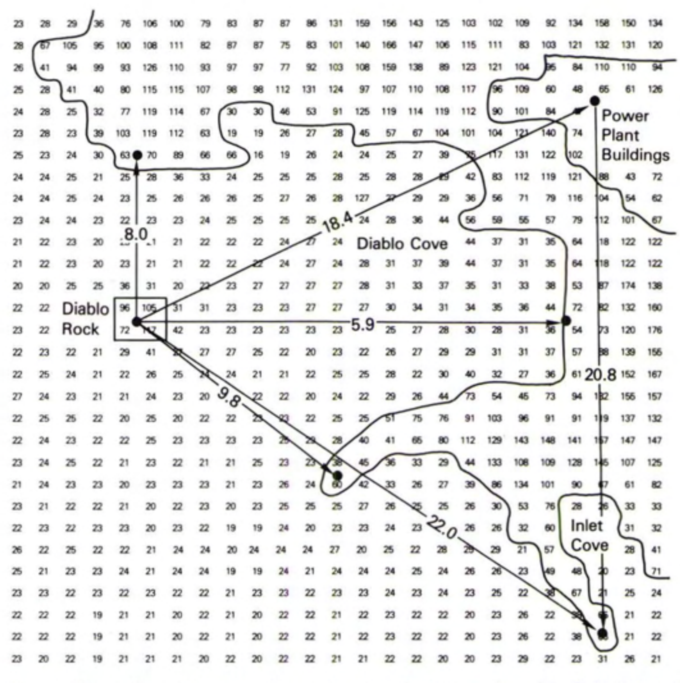

FIG. 4. Shoreline determination using Landsat-5 TM band 5 digital counts and distances to control points. Numbers indicate approximate 30-m pixel units to control points.

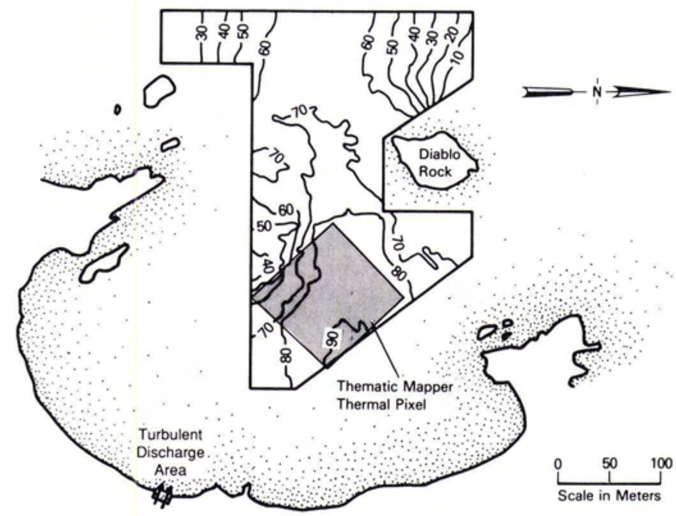

FIG. 5. Contour plot of percentage of discharge plant temperature rise for 18 June 1986 Landsat overpass based on groundtruth measurements.

using the PG&E map (Figure 2), which is scaled appropriately in distances on the surface.

An approximate position of key location points shown in Figure 4, such as the inlet cove, power plant buildings, and water-land interface, can be determined by locating the sudden increase or decrease of band 5 digital counts, because the reflectance of solar energy in the near-IR band from the water surface is much lower than from the land surface. Validation of this determination is provided by converting the number of band 5 (30-m) pixels between the control points, as indicated by the numbers in Figure 4, to distance and then comparing these distances with Figure 2. These compare quite well, leading to confidence in the determination of the position of the power plant discharge into Diablo Cove (depicted in Figure 1). Figure 3 also indicates the position of the thermal block chosen from the TM band 6 DN map for the inlet/discharge Landsat-5 TM temperature determination.

National Weather Service radiosonde data acquired at nearby Vandenberg Air Force Base were obtained for the overflight date. The vertical measurements of atmospheric pressure, temperature, and dew point, from sea level to 16.6 km, were used as input to LOWTRAN 6 to correct atmospheric scattering and absorption. For levels above the radiosonde data set, the U.S. Standard Atmosphere model (including an ozone profile) was used. Table 1 indicates the calculation of uncorrected and corrected radiances and temperatures from the DNs of interest for Diablo Canyon on 18 June 1986. The uncorrected values are scene independent, because they are determined from Equations 1 and 2. The LOWTRAN 6 U.S. Standard Atmosphere model-corrected temperatures are also scene independent and are shown in the last column. The corrected values of radiance and temperature, determined by means of local raidosonde data, however, are scene dependent, because they are calculated from Equations 1 and 2, but with R_c and T_c replacing R_u and T_u in Equation 2. For 110 counts, the uncorrected and corrected temperatures agree to within three significant figures; however, at higher temperatures or 124 counts, they differ by 2.3°C. The U.S. Standard Atmosphere model-corrected temperatures, however, agree closely with the local radiosonde at the higher temperatures, but differ by 1.6°C at the lower temperatures.

To validate the calibration procedures, it is necessary to compare the corrected temperatures with known GT measurements. Figure 5 is a contour plot of temperature measurements of Diablo Canyon's thermal plume, as determined by PG&E, in terms of percentage of the discharge excess temperature. The temperature at any point within the plume is the product of this percentage and the measured rise in temperature caused by the plant operations, added to the measured intake temperature. For the 18 June 1986 overflight date, the measured intake temperature (at −30 feet) was 11.6°C, and the plant temperature rise (ΔT) was 10.8°C. There was also a 1°C rise in temperature between the intake level and the surface of the intake cove, giving a GT value of 12.6°C.

Because a clear thermal pixel of 120 by 120 m spans several contour lines (Figure 5), it is necessary to integrate the energy radiated from the water surface within one Landsat-5 TM band 6 pixel. If A is the area of a thermal pixel with a radiance R, then the energy radiated to Landsat $E = AR$. Letting $E_i = A_i R_i$ be the energy from any portion of the pixel within the contour, where A_i = area of the portion and the total flux within the contour $E = \Sigma E_i$, then

$$R = R_o + \sum_{i=1}^{N} (A_i / A)\, R_i \tag{5}$$

where R_o is the radiance if the whole pixel were at the intake cove surface temperature. For the small temperature ranges observed by Landsat, $R = \alpha T$, where α is some constant of proportionality. Substituting into Equation 5 gives

$$T = T_o + \sum_{i=1}^{N} (A_i / A)\, f_i\, \Delta T \tag{6}$$

where ΔT is the measured plant temperature rise, T_o equals the intake temperature, and f_i is the fractional discharge temperature rise from Figure 5. For a continuous distribution of f_i, Equation 6 will become an integral over measured contours enclosed by the Landsat band 6 pixel size.

$$R = R_o \iint \{A(x,y)/A\}\, f(x,y)\, dxdy \tag{7}$$

where $R\,(x,y)$ is the radiance at the location (x,y) within the contours. The average temperature obtained for the Landsat thermal pixel size that covers several contours becomes

$$T = T_o + \Delta T \iint \{A(x,y)/A\}\, f(x,y)\, dxdy \tag{8}$$

where $f\,(x,y)$ is the fractional discharge plant temperature rise at any location (x,y).

Using ΔT = 10.8°C and the intake temperature = 11.6°C, the estimated GT temperature within the discharge cove would be 19.9°C. The value for the summation in Equation 6, or the integral in Equation 7, is 0.7667. Multiplying by the plant temperature rise of 10.8°C, the resulting temperature is 8.28°C; when this value is added to the intake temperature of 11.6°C, the result is 19.9°C for GT discharge temperature. The 6-pixel thermal blocks analyzed for the discharge and intake coves (Figure 3) have average DN values of 122.5 and 111.3 DN, respectively, which convert to 20.3°C for discharge temperature and 13.2°C for inlet surface temperature (Table 1). These values are in excellent agreement with the measured GT temperatures. Because the Landsat band 6 is linear at these nominal temperature ranges, with respect to onboard radiance values, these two calibration points allow accurate temperature estimations of pixels within the receiving waters, assuming the atmospheric profiles of temperature, pressure, and water vapor do not change significantly. The surface temperature of the receiving waters can be interpreted with confidence, and the values are probably accurate to within 0.5°C.

Plate 1 is a smoothed, color-coded map showing the distri-

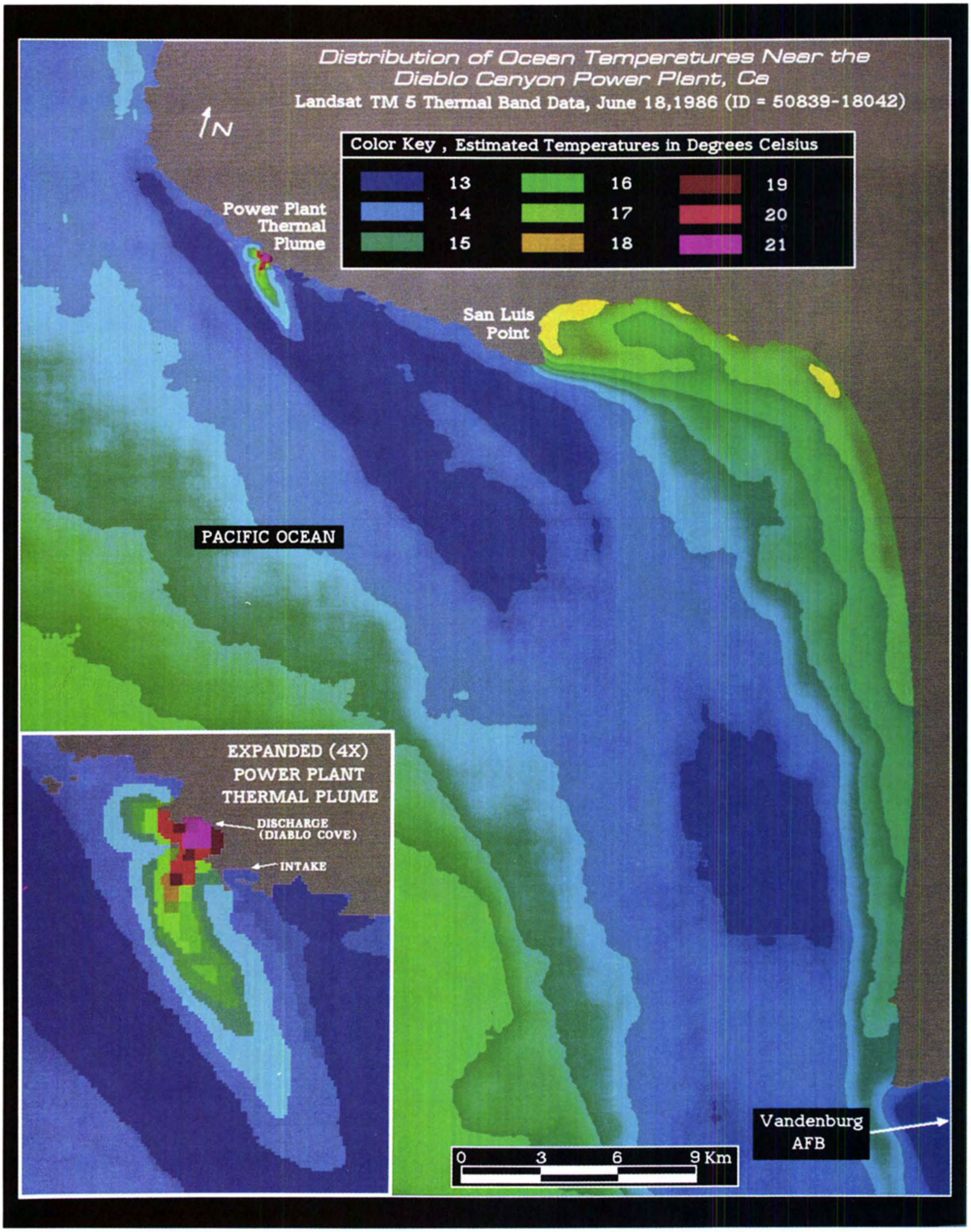

PLATE 1. Distribution of ocean temperatures near Diablo Canyon power plant derived from expanded Landsat-5 TM band 6 image of 18 June 1986 Diablo Canyon thermal plume, smoothed for clarity. (Reproduced by permission of Earth Observation Satellite Company, Lanham, Maryland, USA)

TABLE 1. DIGITAL COUNTS IN DIABLO CANYON SCENE CONVERTED TO UNCORRECTED AND CORRECTED SPECTRAL RADIANCES AND TEMPERATURES

Digital Counts (DN)	Uncorrected Radiance ($mWcm^{-2}\mu m^{-1}sr^{-1}$)	Uncorrected Temperature (°C)	LOWTRAN 6 (Radiosonde data) Corrected Radiance ($mWcm^{-2}\mu m^{-1}sr^{-1}$)	LOWTRAN 6 (Radiosonde data) Corrected Temperature (°C)	LOWTRAN 6 (US Std) Corrected Temperature (°C)
110	0.743	12.3	0.744	12.3	13.9
111	0.749	12.8	0.751	13.0	14.5
111.3(intake)	0.751	13.0	0.753	*13.2	14.7
112	0.755	13.3	0.759	13.6	15.1
113	0.760	13.7	0.767	14.3	15.6
114	0.766	14.2	0.774	15.0	16.2
115	0.771	14.7	0.782	15.6	16.8
116	0.777	15.2	0.790	16.2	17.4
117	0.783	15.6	0.797	16.9	17.9
118	0.788	16.1	0.805	17.5	18.5
119	0.794	16.6	0.813	18.1	19.0
120	0.800	17.0	0.820	18.7	19.6
121	0.805	17.5	0.828	19.4	20.1
122	0.811	18.0	0.836	20.0	20.6
122.5(discharge)	0.814	18.2	0.840	**20.3	20.9
123	0.816	18.4	0.843	20.6	21.2
124	0.822	18.9	0.851	21.2	21.7

*GT = 12.6°C (intake temperature)
**GT = 19.9°C (discharge temperature)

bution of estimated Landsat-derived ocean surface temperatures on 18 June 1986 near the Diablo Canyon power plant. The scene includes several kilometres of coastline as well as deep ocean features. The thermal plume is a small structure on the larger thermal environment. Some coastal areas (e.g., San Luis Point) and deep-ocean surface temperatures are on the order of, or slightly higher than, the outer portions of the Diablo Canyon thermal plume. The maximum digital counts in the scene of 122 to 124 occur at the discharge in Diablo Cove, near Diablo Rock. This corresponds to a Landsat-5 TM band 6 uncorrected temperature of 18.0 to 18.9°C. The lowest digital counts of 110 to 111 occur in the ocean upwelling (dark blue areas in Plate 1) near the coast, corresponding to an uncorrected temperature range of 12.3 to 12.9°C.

Landsat-5 TM band 6 data used to create the various relative temperature (contoured) regions in Plate 1 have been smoothed with a "box" filter to remove scene striping and variations in pixel counts caused by "sampling" noise. Because of the large spatial resolution of 120 m for a thermal pixel, the thermal plume cannot be mapped in detail, especially the near-field portion of the plume within the discharge cove. The temperatures of the various colors in the legend are approximate absolute temperature values that have been corrected for atmospheric effects. The inset image of Plate 1 is an expanded view of the discharge plume that has been smoothed, showing the various temperature regimes indicated by Landsat.

CONCLUSIONS

- This study has shown that the Landsat-5 TM band 6 can be used to provide good estimates of coastal zone thermal plume temperatures associated with power plant cooling effluents. The results indicate that, for atmospherically corrected temperatures using radiosonde data, the variation between PG&E GT and TM band 6 values is only 0.4 to 0.6°C. These findings indicate that, for the conditions studied here, the Landsat-5 TM band 6 is performing on orbit according to the design criteria of a noise equivalent temperature difference (NEΔT) of 0.5°C, and an absolute temperature accuracy of ±10 percent.
- The method chosen to obtain GT data from PG&E excess temperature contours is workable and gives excellent correlation with the Landsat-5 TM band 6 data.
- The synergistic use of visible/near-IR bands to locate land-water features and positions of pure thermal pixels has been demonstrated by the small variation between GT and TM data.
- Bands 5 and 7 can be used to identify or delineate the water-land interface along the coastal area, and inversion of data from thermal pixels gives good estimates of the temperatures over this region. It can be assumed that, for specific coastal locations, monitoring by the TM can be performed spatially to within ±15 m and thermally to within ±0.5°C, with confidence in the resulting values.
- Measuring the spatial and temporal extent of upwelling may assist in the evaluation of numerical model predictions.

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