Aerial Thermography Studies of Power Plant Heated Lakes

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ABSTRACT

Remote sensing temperature measurements of water bodies is complicated by the temperature differences between the true surface or "skin" water and the bulk water below. Weather conditions control the reduction of the skin temperature relative to the bulk water temperature. Typical skin temperature depressions range from a few tenths of a degree Celsius to more than one degree. In this research project, the Savannah River Technology Center (SRTC) used aerial thermography and surface-based meteorological and water temperature measurements to study a power plant cooling lake in South Carolina. Skin and bulk water temperatures were measured simultaneously for imagery calibration and to produce a database for modeling of skin temperature depressions as a function of weather and bulk water temperatures. This paper will present imagery that illustrates how the skin temperature depression was affected by different conditions in several locations on the lake and will present skin temperature modeling results.

INTRODUCTION

On February 2000, the Multispectral Thermal Imager (MTI) satellite sponsored by the Department of Energy (DOE) will be launched to kick-off the beginning of a research & development project for accurate temperature retrieval. The MTI mission described by Weber et al.¹ is to demonstrate the efficacy of highly accurate multispectral and thermal imaging for passive characterization of industrial facilities and related environmental impacts from space. The MTI goal is to compare the remotely sensed information from the satellite instrument to information available directly at the cooperative sites being observed. In this role, MTI is a technology demonstration experiment, and is designed to observe a very limited number of selected sites per day, with modest spatial coverage and spatial resolution.

The MTI satellite has 15 spectral bands in the visible (VIS), near (NIR), shortwave (SWIR), midwave (MWIR) and the longwave (LWIR) infrared spectral regions. Figure 1 shows the location of the 15 spectral bands in the electromagnetic spectrum. The spatial resolution of the spectral bands is divided in two subsets. Spectral bands A-D have a 5-meter spatial resolution. Bands E through O are 20-meter spatial resolution. Garrett et al.² summarized the combination of the spectral bands and the 14 selected ground truth targets to validate and verify the 16 MTI science algorithms. Top of the atmosphere (TOA) radiances from five thermal spectral bands in the MWIR and LWIR spectral regions (bands J [3.50-4.10 μ m], K [4.87-5.07 μ m], L [8.00-8.40 μ m], M [8.40-8.85 μ m], N [10.15-11.50 μ m]) in conjunction with two algorithms will be used to retrieve ground temperatures. The two algorithms for satellite temperature data processing are Physics-

based Water and Land Temperature Retrieval and Robust Water Temperature. The validation and verification ground truth targets for the temperature algorithms are unheated natural lakes such as Crater Lake, the tropical western Pacific near Nauru, the Savannah River Site's "L" Lake and several power plant cooling lakes and cooling towers. Power plant heated lakes provide a field laboratory to study an extensive range of water temperatures within a satellite image.

A difficulty in assessing true bulk water temperatures with satellites is the skin temperature effect. The skin temperature measured by a satellite is within the upper 1 mm layer. Although the skin temperature effect is typically 0.5 – 1.0 C below the bulk water temperature (uppermost 10 cm), deviations larger than 1C are not uncommon. Theoretically, the skin temperature can be calculated from knowledge in the exchange of IR radiation between water surface and the atmosphere, heat transfer from the surface to the atmosphere via latent and sensible heat flux, and mixing to the water surface.

In order to develop validation and verification methods for the temperature retrieval algorithms, experiments were conducted at Lake Robinson near Columbia, SC. Lake Robinson is a power plant cooling lake with a temperature gradient along a 5-mile tract between the outlet canal and the inlet of the power plant. A ground truth team was deployed at the lake with a "skin temperature rig" to record weather, radiances, and water temperatures. A helicopter equipped with a radiometric infrared camera was flown over the lake to acquire imagery similar to future satellite collections. A calibrated infrared mosaic of Lake Robinson was prepared and the image was compared to simulations from a 3-D hydrodynamic model (Garrett and Hayes³).

EXPERIMENTAL

Thermal imaging over the lake was collected with an infrared camera model 760 manufactured by Inframetrics. The 8-12 μm spectral bandpass was selected in the infrared camera to eliminate the sun's interference present in the 3-5 μm . Frame averaging, emissivity, and ambient temperature were set at 1, 1.0 and 25C respectively in the camera's menu. An 80° nominal wide-angle lens (74.4° in the horizontal FOV) was attached to the infrared camera. The camera's calibration was corroborated in the laboratory at better than 0.1°C within 0-40C even though the manufacturer's worst case temperature accuracy is stated at $\pm 2^\circ\text{C}$ or $\pm 2\%$. Further calibrations were conducted with temperature data obtained at ground level in order to correct for atmospheric effects.

Visible imagery was collected with a camcorder. The camcorder was also equipped with a wide-angle lens. The infrared camera and the JVC camcorder had similar FOV. The infrared and visible cameras were assembled side by side into a specially built aluminum frame. The camera's frame was built with a cushioned bracket for snug fit onto the stripe of the helicopter. The camera handler maintained the aluminum frame with the attached cameras steady at normal incidence to the water's surface. During the overpass, the helicopter speed was maintained between 45 and 55 miles per hour. The position and direction of the helicopter was recorded with a GPS unit. The analog signals from the 760 infrared camera and the JVC camcorder were fed into two 8mm video Walkman

(GV-A500) manufactured by Sony Corporation. The videotapes were analyzed in the laboratory with Thermagram Pro (manufactured by Inframetrics) for temperature retrieval. A mosaic of Lake Robinson was built from several images at different locations along the lake.

Several flights were conducted at different elevations over Lake Robinson. Temperature range on the camera was selected near the power plant by observing the temperature extremes at the cold water inlet and the hot water outlet canal. Flight at elevations of 2300 and 5000ft were used to assemble thermal mosaics.

A "Skin Temperature Rig" was constructed to study the skin temperature effect and to provide data for the calibration of the helicopter imagery. The rig was anchored at the exit of the outlet canal to the lake (~5 miles from the power plant) and at the middle of the lake to measure water and air temperatures, humidity, wind speed, broadband IR, solar radiation. Figure 2 shows the temperature rig under development. Water temperatures were measured using thermocouples calibrated to 0.1C and the data downloaded to a data logger (Campbell CR23). Broadband IR and solar radiation were obtained with radiometers manufactured by Eppley (models PIR and PSP respectively). The water skin temperature was measured with an 8-14 micron radiometer manufactured by Heimann and calibrated in the laboratory to within 0.2C. The radiometer was positioned approximately 0.5 meters above the water. Temperature and humidity were measured with a Vaisala50Y sensor and wind speeds with a Met One cup anemometer.

The skin depression was determined by comparing the temperature measured with the radiometer (skin temperature) and a thermocouple at 10 cm below the surface (bulk temperature). Because of the inherent difficulties of this approach, the skin temperature depression was also determined by comparing radiometer measurements of the natural water surface and the 'stirred' surface. The 'stirred' surface temperature was obtained by pumping a jet of water from 10cm below the surface into the radiometer's field of view. Because the skin depression takes ~10 sec to form, the stirred temperature will be equivalent to the bulk temperature.

RESULTS AND DISCUSSION

In the past decade, the increased accuracy of satellite measurements focussed attention on the difference between the temperature of bulk water (uppermost 10 centimeters of water) and the temperature of the 'skin' (the upper 1mm). This is because the skin temperature, which is measured by satellite, is typically 0.5 – 1.0°C less than the bulk temperature, the quantity usually measured from ship or buoy. The skin effect is more significant over bodies of fresh water because of the greater variability of water temperature, air temperature, wind and humidity. The skin temperature depression often exceeds 1C over heated bodies of water, or may even be positive, as is the case of warm air over cold water. Understanding the skin temperature effect is of practical importance for ground truth programs because the bulk temperature is much easier to measure accurately than the skin temperature. Although the skin temperature effect was studied in the past (Schluessel et al.⁴), a reliable method to estimate its size and variability for a range of

conditions is not available. The most important factors which govern the skin temperature effect are the exchange of IR radiation between the water surface and the atmosphere, heat transfer from the surface to the atmosphere via latent and sensible heat flux, and mixing of the sea surface. Typically, the skin temperature depression is increased by radiative loss and evaporation and decreased by turbulent transport of heat upward through the bulk water layer.

Figure 3 shows results obtained from an unheated lake in a two day period. The figure shows the bulk water temperature at 10 cm deep (thermocouple), the radiometer temperature of the natural water surface, and the radiometer temperature of the pumped water (the vertical bars at 10 minute intervals). The pump was operated every 10 minutes for 10 seconds. The radiometer "pump temperature" is the average of the radiometer measurements at 4, 6, 8 and 10 seconds after the pump was turned on. Ideally, the bulk water temperature will equal the temperature of the pumped water as measured by the radiometer. Figure 3 shows, however, that the radiometer pumped water temperature is $\sim 0.2^{\circ}\text{C}$ cooler than the bulk temperature. This is due to a bias of the radiometer of 0.1°C compared to the thermocouple and to the contribution to the radiometer temperature from reflected (cooler) sky radiation. This effect is estimated to be between -0.2 to 0.5°C .

An interesting feature in Figure 3 is the greater variability of the temperature of the natural water surface compared with the pumped water temperature; both obtained with the radiometer. This difference is surprising since the former is an average of 30 values while the latter is an average of 4 values. However, this difference is believed to reflect the large variability of the skin temperature in very light winds (less than 1 m/s), when large skin temperature depressions can form in the absence of mixing in the bulk water layer. The results also suggest that the skin temperature effect may be most difficult to account for over small inland bodies of water on clear nights, when the winds will be near calm. Conversely, the most reliable estimates of the skin temperature may be possible during windy days, when the water surface and atmospheric boundary layer are well mixed.

The aerial thermal overview in Figure 4 is a mosaic of seven frames taken from a helicopter flying at an elevation of 5000-ft. The camera was set with a 20°C range from 14.7 - 34.7°C . Although most frames in the video contained clouds, the wide-angle lens (74.4° deg FOV) gave us the opportunity to selectively choose appropriate frames for the mosaic. Some frames were cropped to eliminate cloud contribution. The composite image was built using Adobe Photoshop software. The 5000-ft flight over the lake lasted approximately 6 minutes. During the lake's image composition, apparent temperatures in some of the frames looking at the same scenery were off by as much as 0.8°C . These off values corresponded to pixels at wide angles from zenith. Frames were cropped to eliminate wide-angle bias. With our corrections, worst-case temperature ranges did not exceed 0.4°C .

The thermal aerial view (500ft elevation) of the discharge canal into the lake opening is shown in Figure 5. The apparent water surface temperature is cooler in the canal prior to the water break at the property fence line. The bulk water temperature is the same across

the fence line in the canal. The apparent water surface temperature discrepancy is the result of turbulent mixing affecting and increasing the skin temperature. This effect is also shown in Figure 5 with temperature profiles along the Lines 1 and 2.

The apparent water temperature after the fence line crossing is 26.1C. Prior to the fence line crossing, the apparent water temperature of the canal is variable with a maximum in the center of the canal and a minimum along the canal sides. The largest and smallest temperature gradients ΔT (after-before fence line) correspond to Line 2 and Line 1 at 0.6 and 0.3C respectively. The smaller ΔT (after-before fence line) along the center of the canal is the resultant of stronger turbulent water mixing. Bulk-skin ΔT values measured by personnel at the boat corresponds to about 1.0C (27.6C bulk, 26.7C skin). Figure 5 shows the skin temperature discontinuity caused by the water turbulence at the discharge canal-lake interface. Since the aerial discontinuity $\Delta T = 0.6C$ and the bulk-skin ΔT measured by ground personnel is 1.0C it is safe to assume that the skin temperature was not completely destroyed by the water turbulence at this point.

The surface temperature along the canal was investigated during our low elevation overpass. The minimum, mean and maximum temperatures near the discharge canal outlet to the lake were 25.4, 25.6 and 27.7C respectively. These temperatures slowly increased along the discharge canal in the direction of the reactor. Within 100 meters from the reactor outfall, the minimum, mean and maximum temperatures increased to 26.5, 27.5 and 27.9C respectively. At the reactor outfall, the temperatures exceeded the saturation value. The temperature profile of the water surface seen by the infrared camera was adjusted for skin temperature effect using bulk water temperature measurements obtained by personnel in a boat at the canal outlet and at the middle of the lake.

Power plants and many other industrial facilities frequently use surface water systems to dissipate large quantities of waste heat. The temperature and amount of the water being discharged determine whether it has any adverse environmental effects. The thermal plumes created by the discharge of waste heat to the environment are well suited to analysis by thermal imaging. Garrett et al.² developed an algorithm that combines calibrated thermal imagery, 3-D hydrodynamic modeling, local meteorological data and the physical characteristics of the surface water system to find the heat dissipation rate. Figure 6 compares observed surface temperatures from the calibrated helicopter overpass imagery of Lake Robinson to simulated temperatures for the same time. The 3-D hydrodynamic model (Garrett and Hayes³) predicted heat dissipation rates in Lake Robinson within 10% of the data provided by the power plant.

SUMMARY

A thermal mosaic of Lake Robinson surface temperatures was created from imagery recorded during a helicopter overpass at Lake Robinson. Temperatures measured by ground personnel were used to adjust the thermal imagery for skin temperature effect. A 3-D hydrodynamic code was used to model the temperatures in the lake. Discharge heat rates were computed and compared with measured data from the power plant. A

comparison of the experimental and modeled data suggests heat dissipation prediction accuracy within 10%. Once the MTI satellite has been launched, surface-based bulk water and skin temperature measurements in conjunction with helicopter-based thermal imagery will be used to validate satellite temperature retrievals.

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Figure 1: Calculated radiance at the MTI satellite and the 15 spectral bands.

Figure 2: Skin temperature experimental apparatus.

Figure 3: Typical comparison of measured skin and bulk water temperatures in a cooling lake.

Figure 4. Thermal image mosaic of Lake Robinson with its respective grayscale temperature profile.