REMOTE SENSING TECHNIQUES FOR MEASUREMENT OF WATER TEMPERATURES[1]

by

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INTRODUCTION

The increased concern in recent months about our natural resources has resulted in many interesting situations. The public is demanding stricter legislation concerning the manner in which we conserve, or manage, our resources, and the legislators are attempting to bring into being many pieces of legislation designed to prevent further deterioration of our environment. Yet, in this process, we are finding that our knowledge of the natural environment is woefully inadequate. For example, there seems to be relatively little detailed, factual information concerning the impact of hydroelectric plants on the adjacent rivers and lakes. One group of experts gives one set of facts and hypotheses, another group offers a rather different set of information and so on. This leaves the legislator in the rather precarious position of attempting to create legislation (which is almost certain to affect some people adversely) and not really knowing what set of "facts" really describes the situation involved.

The scientific community must therefore dedicate itself anew to develop better, more systematic and complete methods of studying our environment, so as to have a more reliable understanding of this ecosystem. Many recently developed instruments and techniques could and should be used in our efforts to better understand our ecosystem. One such tool is a thermal infrared optical-mechanical scanner or thermal IR scanner. This instrument can be mounted in an aircraft and flown over an area of interest, thereby allowing one to obtain a temperature map of the area below the aircraft. The U.S. Forest Service has found these instruments to be extremely useful in mapping perimeters of forest fires and for wild fire detection efforts. They are especially useful in these types of work because the instrument can be operated very effectively at night, and because it can "see" through smoke.

WATER TEMPERATURE MAPPING

Thermal IR scanners can also be utilized very effectively for water temperature mapping. They are most effective in the 8.0-13.5 micrometer (μm) portion of the spectrum, at much longer wavelengths than in the visible region (0.4-0.7μm). The output is in the form of either a magnetic tape or an image or both. The images produced (Figure 1) look quite similar to black and white photographs obtained in the visible wavelengths, but in this case the variations in gray tone on this image represent differences in temperature and/or emissivity of the objects, rather than differences in reflectance, as is the case with black and white photos.

A diagram showing the major components of optical-mechanical scanners, and the way in which they work is shown in Figure 2-a. In this case, the scanner shown is an

[1]*Presented at the Indiana Academy of Science, October, 1971. The work described in this paper was supported by the National Aeronautics and Space Administration, under Grant #NGR 15-005-112.*

airborne multispectral scanner, which allows energy to be measured and recorded from several portions of the visible and reflective infrared wavelengths, as well as from the thermal or emissive infrared wavelengths.

As the scanner sequentially sweeps individual strips of ground below the aircraft (similar to the scan-raster of a T.V. set), the amount of energy radiated from an instantaneous field-of-view of the scanner is recorded. This radiant energy is often referred to as the radiant temperature, or apparent temperature of the object sensed. The amplitude of such radiant temperature measurement is a function of both the true temperature of the object, and the emissivity of the object (which is largely a function of the surface characteristics of the object). The emissivity of water is nearly 1.0, (1) so the radiant temperature of a water body as measured by the scanner is very close to the true temperature of the water. Thus, the variations in gray tone on a thermal IR image of a water body correspond to the variations in true temperature of the water body.

Thus, the potential exists for mounting a thermal IR scanner in an aircraft, and flying over various water bodies, and accurately determining the location of warm or cold anomalies in the water below. Such systems could be utilized to accurately map the occurrance of thermal effluent being discharged into streams or lakes, as well as the p portions and extent of the water bodies affected. Such thermal IR scanning systems have been utilized very effectively off the coasts of Jamaica and Hawaii in locating sources of fresh water, which show up as relatively cool upwellings in the surrounding warmer salt water, just off the coasts of these islands. Needless to say, to be able to locate additional fresh water sources is very important to the people in these areas for many developmental purposes.

CALIBRATION TECHNIQUES

In order to make thermal IR scanner data meaningful, it is necessary to relate the relative radiance values (as measured by the scanner) to the true temperature of the area being sensed, or target area. Two quite different techniques have been utilized in remote sensing to date. These will be referred to as (a) the correlation method and (b) the internal calibration technique. (2)

The correlation method is relatively simple, but does have some serious drawbacks. As mentioned above, variations in tone on the thermal IR imagery correspond to differences in the radiant temperatures of the scene imaged. Therefore, if the actual temperature of the various objects on the earth's surface can be determined, it is possible to correlate these measurements with density values of the imagery to those points on the ground. In the case of water studies, temperature measurements are obtained for a number of locations on the river or lake at about the time the aircraft passes overhead. Later, these measurement points are located on the thermal IR imagery and the density of the film at that point is measured. In this way, instead of having the variations in gray tone on the imagery represent only relative differences in temperature, one can establish a correlation between actual temperature of the water at a few points and the film density at those same points, and interpolate for intermediate density values.

The major drawbacks to this technique are that (a) it takes only a few minutes to obtain the scanner data via airplane, but may take several hours to obtain surface temperature measurements during which time the water temperature may have changed significantly, and (b) development of the film on which the data are recorded is subject to many possible variations in chemical processing which can sometimes cause tonal differences to not have a linear relationship.

For several years, the correlation method was the only technique available, due to limitations in the thermal IR scanning equipment. Relatively recent developments in scanning equipment have allowed researchers to devise an internal calibration technique, with certain assumptions, whereby the actual water temperature can be determined directly from the scanner data. One of the assumptions made in the internal calibration technique is that the radiation characteristics of water in the thermal IR region approximate those of a blackbody radiator, defined as an object that will completely absorb all frequencies of radiation incident upon it. Water departs only 2-3% from being a perfect black-body radiator in these thermal IR wavelengths. A second major assumption is that atmospheric attenuation will have relatively little effect upon the amplitude of the signal received at the scanner. This assumption is based upon the fact that the 8.0-13.5μm region of the electromagnetic spectrum is in an atmospheric window (where absorption by the various components of the atmosphere is minimal), and also that most of the small amounts of energy absorbed by water vapor or other atmospheric constituents would be reradiated by the water vapor since water is a black body in this portion of the spectrum, thereby allowing only extremely small net losses of radiated energy between the water surface and the aircraft scanner. Some work last year indicated that these assumptions appear to be reasonable. (3)

EQUIPMENT AND METHODS USED WITH THE INTERNAL CALIBRATION TECHNIQUES

The scanner data used by LARS in this work was obtained by a multispectral scanner, owned and operated by the University of Michigan, and mounted in a C-47 aircraft. This system allows radiation to be measured simultaneously in as many as eighteen separate spectral bands, and then records this data in an analog signal format on a multiband magnetic tape recorder. (5)

Only two of the eighteen spectral bands are useful for remote measurements of temperature, the 4.5-5.5μm and 8.0-13.5μm bands (channels). The other channels detect and record energy in the ultraviolet, visible and near-infrared regions.

The University of Michigan scanner has been modified to accomodate two reference black bodies which are viewed by the scanning mirror during each revolution (Figure 2b). These reference sources are referred to as calibration plates, and are temperature controlled, one plate being cooler than the other, in approximately the same range of temperatures of the earth surface features over which the aircraft is flying.

Using the controlled temperature plates of the modified University of Michigan scanner system, it is possible to apply Planck's radiation theory (4) for the determination of water-surface temperatures. Karl Planck developed a law of radiation which described the radiation of a black body as a function of wavelength and temperature as given by the following expression:

$$E_{\lambda} = \frac{2\pi h\, c^{2} \lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \qquad \text{eq. (1)}$$

where,

> E_λ =Energy per unit time, per unit surface area at the wavelength (λ).
>
> T =Absolute Temperature, (°K)
>
> h =Planck's constant
>
> k =Boltzmann's constant
>
> c =velocity of light in vacuum.

Integrating Planck's equation over all wavelengths we obtain the Stephan-Boltzmann Law which describes the total amount in energy radiated by a black body as a function of temperature. In our case, the radiation measurements are limited to finite bandwidths of the electromagnetic spectrum, as determined by the characteristics of the thermal IR detector used in the scanner. Therefore, the integration of Planck's equation is carried out between a lower limit of 8.0μm and an upper limit of 13.5μm, assuming an emissivity of 1.00 and for a range of temperatures that would normally be encountered on the earth surface. Plotting the total energy emitted by a black body in this 8.0-13.5μm band, one obtains a curve which approximates a straight line (Figure 3).

This relationship between emitted energy and temperature may be expressed in the following form,

$$T = mE+b \qquad eq.\ (2)$$

which is a linear equation relating temperature to the energy recorded by the scanner system and where m and b are constants. In order to determine these constants, one must simply solve eq. (2) for the known temperatures and radiant energy of the target area over which the aircraft is flown can be fully determined from the radiant energy recorded by scanner system.

RESULTS

In this study, the objective was to determine the reliability of the temperature calibration procedures, using data collected over the Wabash River on June 30 and August 13, 1970. The earlier flight was at an altitude of 3000 feet at 10:45 am, with good, clear weather conditions, while the August flight was at an altitude of only 2000 feet with somewhat hazy weather, at 3:47 pm.

Using the data logs on the calibration plate temperatures, the data were calibrated for radiant temperature and gray scale maps were produced. The different temperature ranges were depicted by different computer symbols. Only those temperature ranges that corresponded to the river were displayed. A blank, or no symbol, was used for all other temperatures. Figure 4 shows an example of these results.

Figure 4 is a photo of the Wabash River with an island and a bridge being the dominant features. The temperature map printout in the center center (Figure 4b) shows the results for the June 30 flight. Measurements of the actual water temperature were made from a boat, in order to confirm the accuracy of the calibration techniques. The approximate location of these measurements is indicated by the circle, with the number indicating the actual temperature measurement obtained. This number can be compared with the symbols in that area on the map and the legend at the top of the printout describing the temperature range depicted by each symbol, according to the internal calibration procedure. As is indicated by Figure 4b, the calibration procedure appears to be highly accurate, allowing water temperatures to be measured to at least 0.5°C from a distance of 3000'. Note that the water on the west (left) side of the island is generally about 0.5°C cooler than the water on the east side of the island. This is thought to be caused by differences in water depths and upstream influxes of cool water on the western side of the Wabash which apparently have not become completely mixed. However, the August 13 data indicates that the water temperatures as measured by the scanner and internal calibration technique were about 0.8°C lower than actual water temperatures as measured from the boat. Since the August data were collected from an altitude of 2000 feet, rather than 3000 feet as was the June data, it does not seem that increasing altitude causes lower calibrated scanner temperatures. It is possible that the atmospheric conditions (more haze on August 13) may have caused more atmospheric attenuation on the latter set of data, but it would certainly appear that this problem will require additional research.

Figure 5 shows the junction of the Tippecanoe River (from left) with the Wabash River (from top). On June 30, the actual water temperatures, as measured from the boat, showed excellent correlation with the temperatures indicated by the calibrated scanner data. Note that the Tippecanoe River was approximately 1.2°C cooler than the Wabash, and that this temperature difference persisted for a considerable distance downstream. On August 13, the Tippecanoe was relatively warmer than the Wabash, but again the calibrated scanner data is indicating lower temperatures than were actually measured. Also note that on June 30, only the river areas are shown on the printouts, indicating that only the water occupied the temperature ranges indicated, but on August 13, considerable land areas were emitting the same amounts of energy as the water. This indicates that if we are to produce temperature maps showing only the water areas, we will need to develop a layered classification scheme whereby we first identify all water areas, and then map the temperature characteristics of the water only.

Figure 6 shows an area in West Lafayette, including some large ponds near an apartment house complex. The computer printout shows that these shallow ponds were about 2.0°C warmer than the adjacent Wabash River, and that the centers of the ponds were about 1.0°C cooler than the edges. Temperature measurements in these waters showed the same temperature differences, but the fact that the actual temperature were the same was fortuitous because the actual temperature measurement had been made 24 hours earlier than when the scanner data were collected. Such a time difference is significant in that at one point on the river actual changes in water temperature of 1.0°C were recorded between the time the aircraft flew over and two hours later. Thus, the time of day and time of year can have significant effect on actual and relative water temperatures.

SUMMARY AND CONCLUSIONS

1. Accurate water temperatures measurements from several thousand feet altitude appear feasible.

2. Additional research on a atmospheric attenuation phenomena, water boundary layer effects, and the accuracy of scanner calibration plate data will be required to determine the degree of accuracy that can be achieved.

3. Remote sensing offers a highly effective means for surveying and mapping thermal characteristics of water bodies over large geographical areas.

4. Periodic thermal mapping of our rivers and lakes could provide a wealth of information useful in our attempts at understanding the river ecosystems and in the management of the fish, wildlife, adjacent forest and farmland, and in the management of water bodies themselves.

Literature Cited

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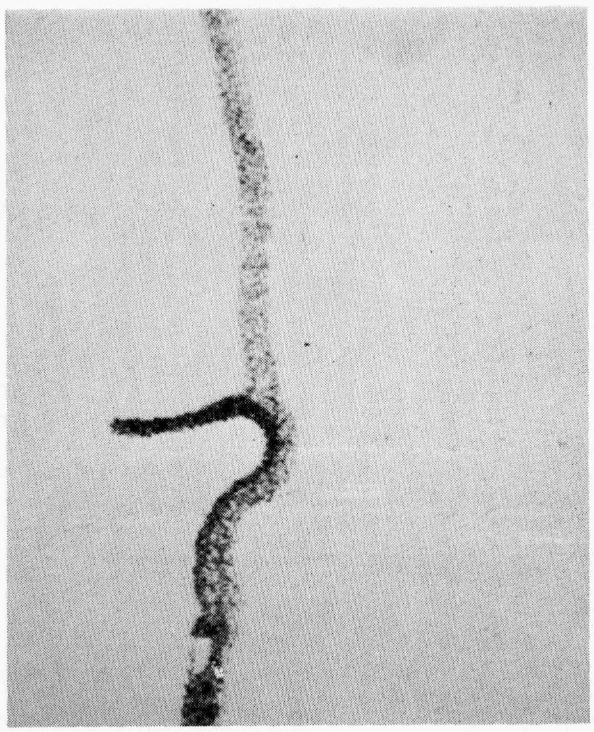
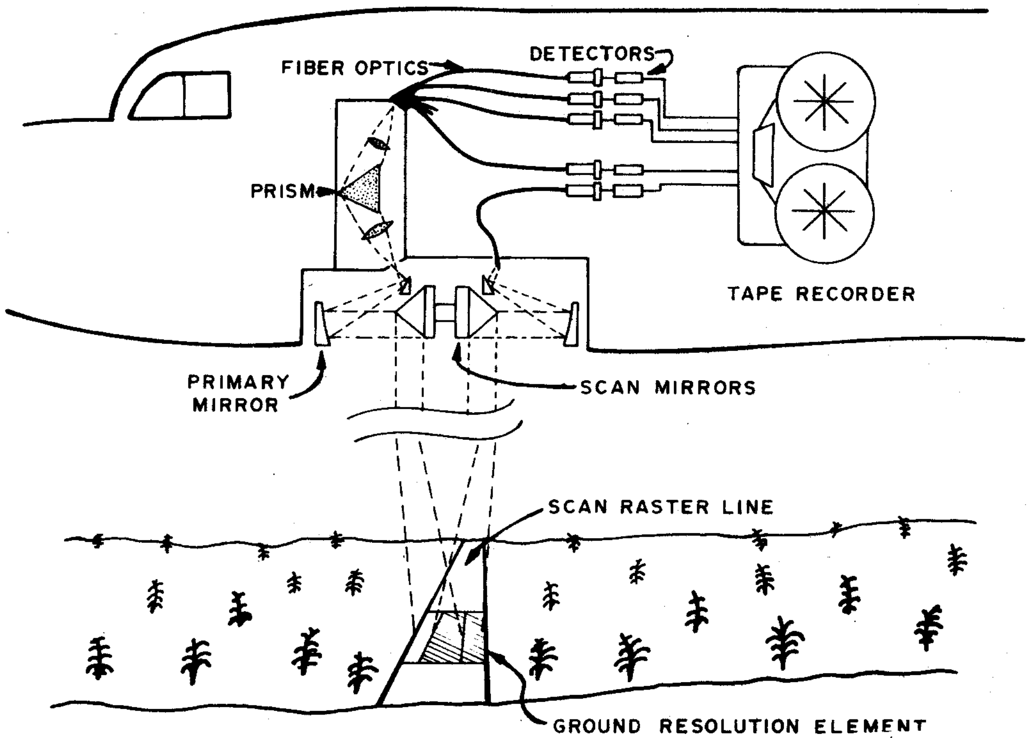
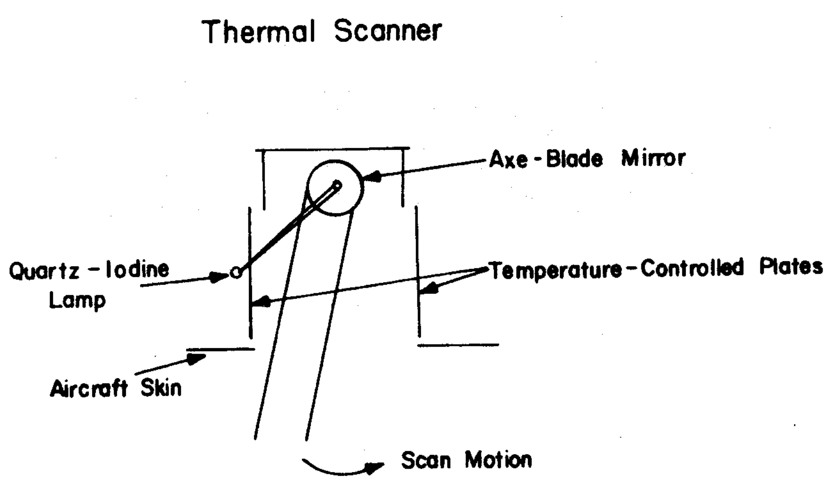


Figure 1. Thermal IR data, as projected onto a cathode ray tube. This is LARS' "digital display" unit, which allows the researcher to work with the data through the computer by selecting specific areas on the screen for analysis or training.



(a)



(b)

Figure 2. (a) The multispectral scanner configuration. (b) Schematic of thermal calibration plates used for calibrating 8.0-13.5μm scanner data.

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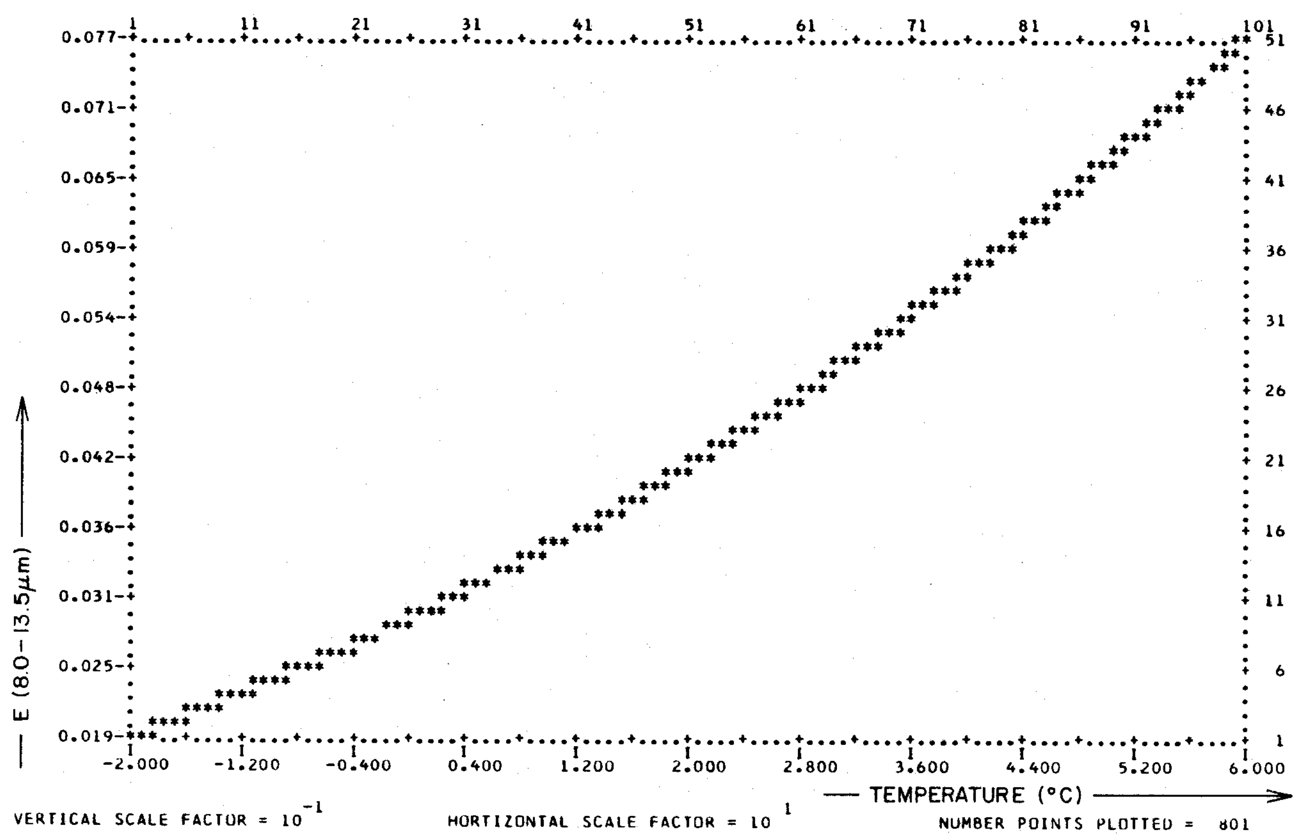

Figure 3. A plot of emitted energy in the 8.0-13.5μm wavelength region vs temperature of a black body.

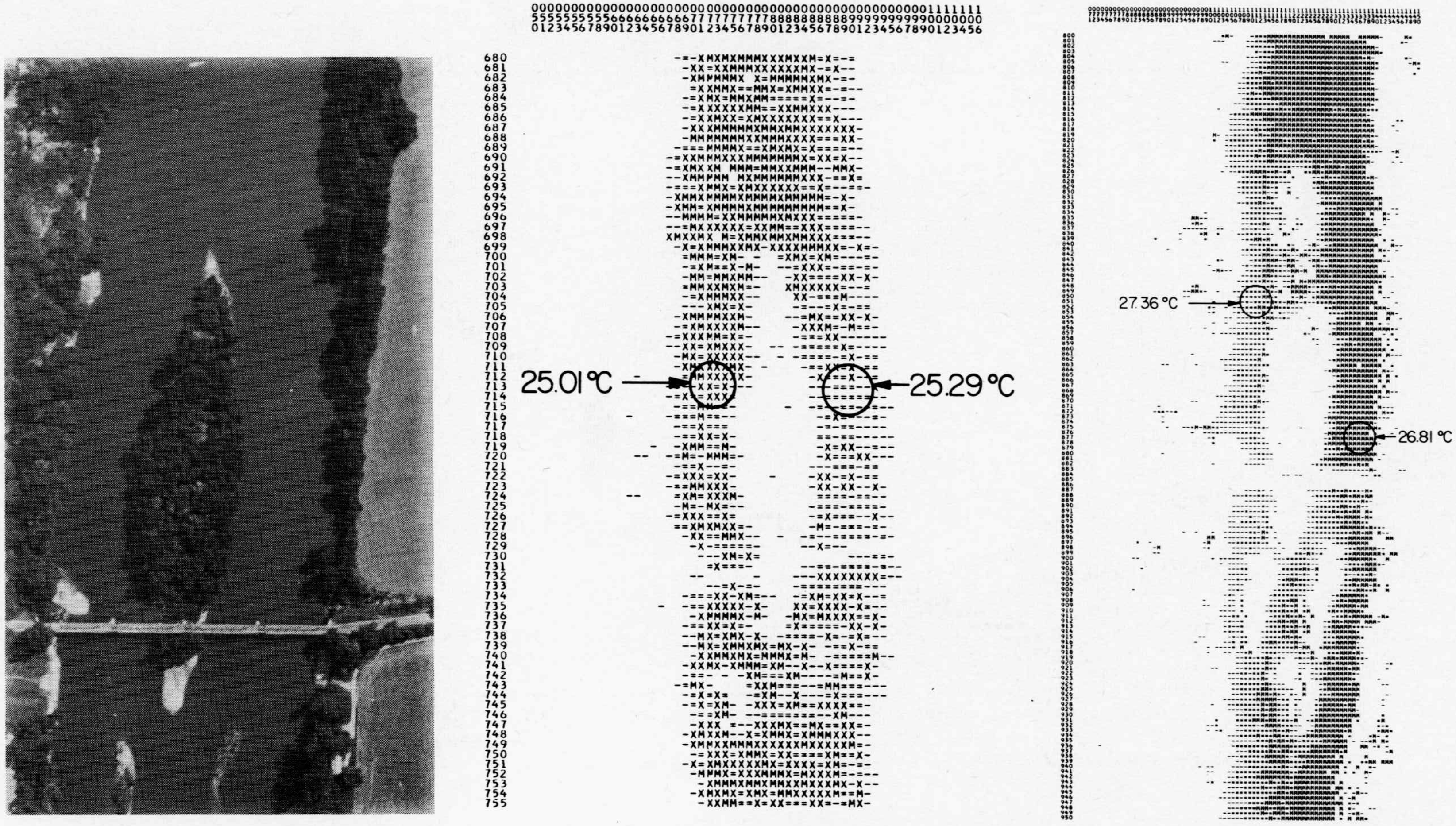

Figure 4. An aerial photograph and computer printouts illustrating the differences in water temperatures on opposite sides of this island in the Wabash River. The printouts represent calibrated thermal IR scanner data in the 8.0-13.5μm wavelength band. The center printout represents data obtained on June 30 from an altitude of 3000 feet. The data on the right was collected on August 13 from 2000 feet.

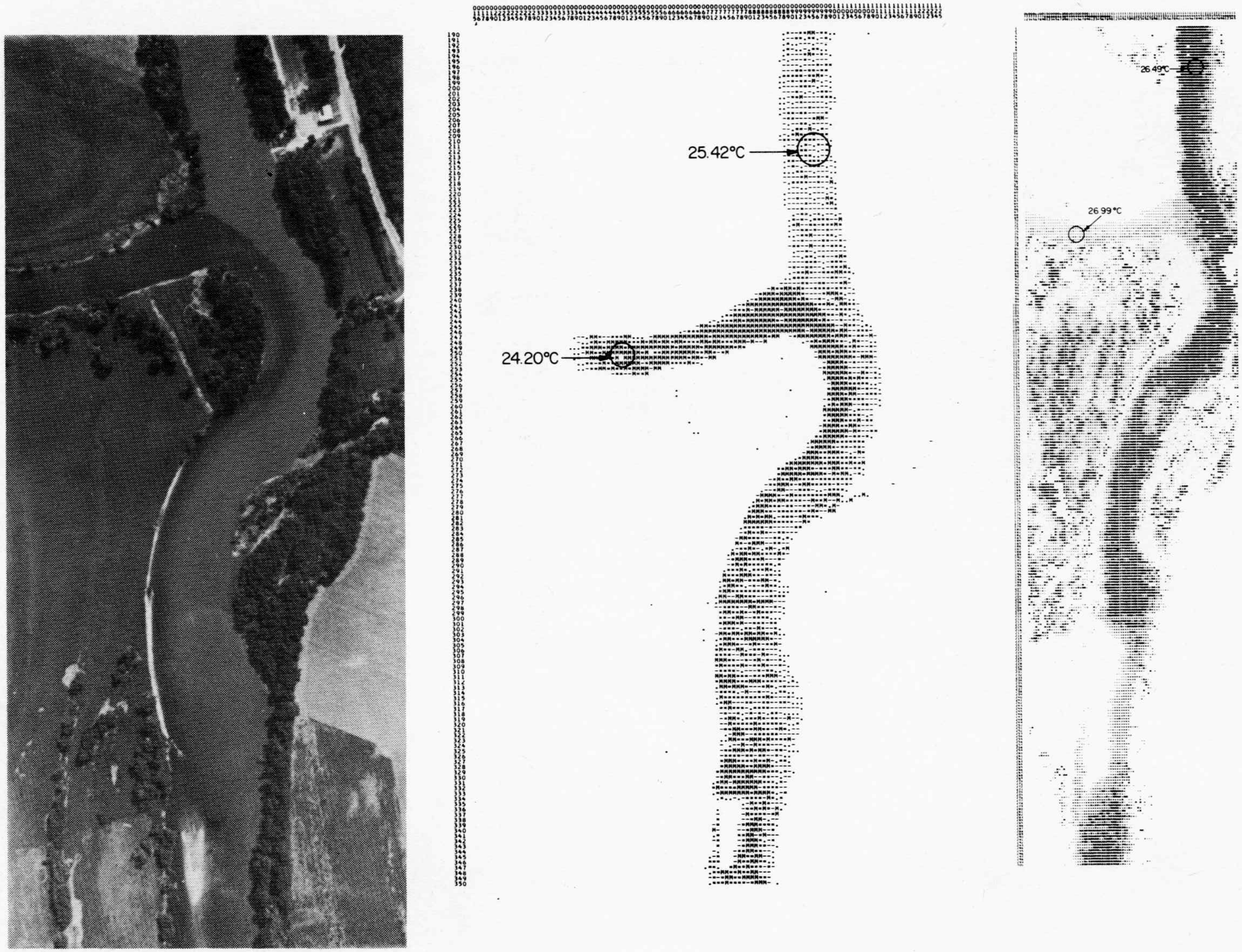

Figure 5. An aerial photograph and computer printouts of calibrated thermal IR scanner data, collected on the same flights as shown in Figure 3. The junction of the Tippecanoe River (from left) and Wabash River (from top) is shown. Note that the June 30 data shows that the water in the Tippecanoe is cooler than the Wabash, while the opposite is true for the August 13 data. The August data also shows much of the land area at the same temperature as the water.

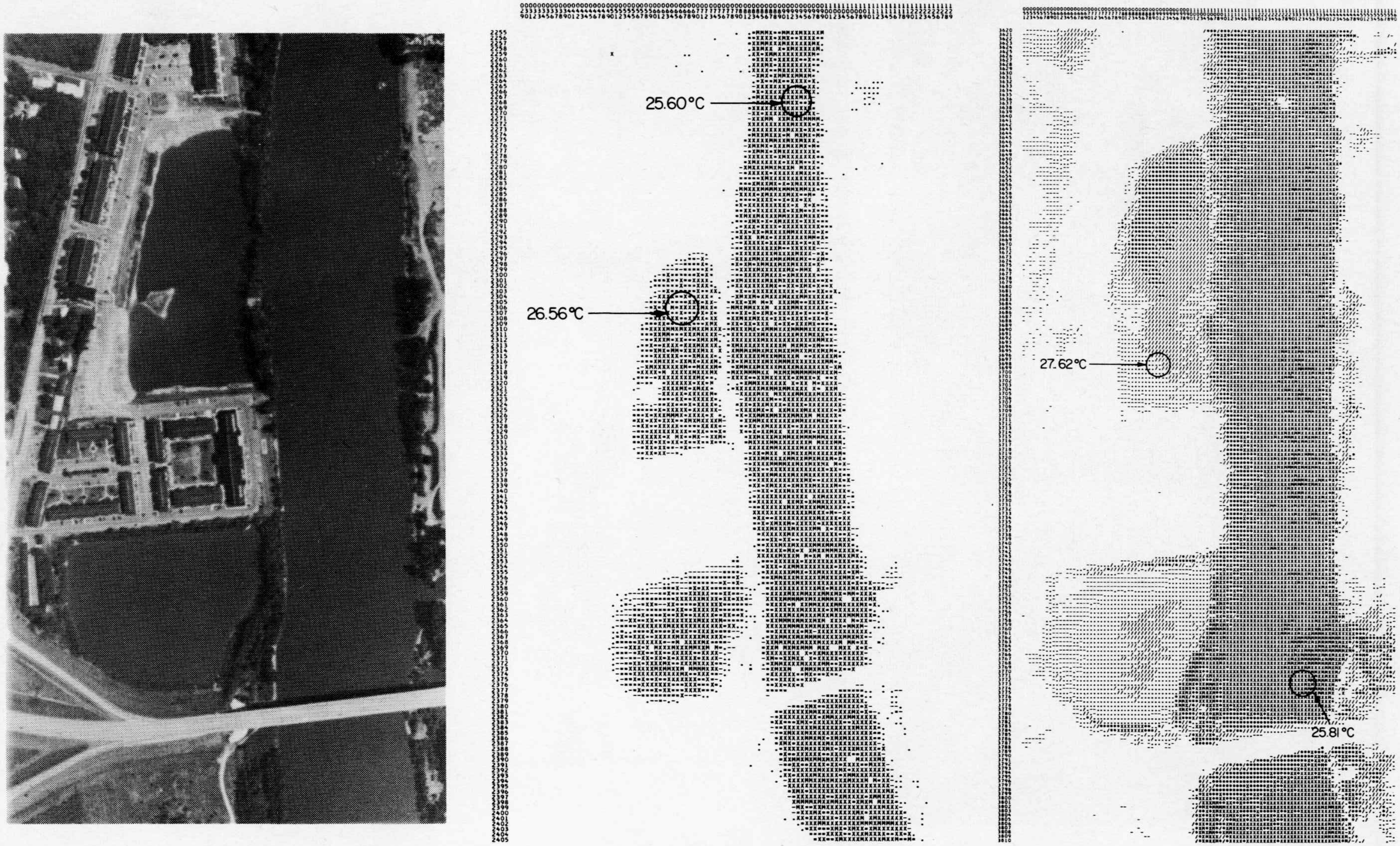

Figure 6. An example of calibrated thermal IR data, showing the distinct differences in water temperatures between the river and the ponds, and between the center and edges of the ponds. Note that some of the land areas are at the same radiant temperatures as the water.