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# EFFECTS OF ALTITUDE AND WAVELENGTH BAND SELECTION ON REMOTE MEASUREMENTS OF WATER TEMPERATURE

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ABSTRACT

Various remote sensing instrumentation and analysis techniques are being developed to allow thermal mapping of water bodies over large geographical areas. In pursuing our objectives of further developing computer processing techniques for obtaining accurate radiometric temperature measurements from remote platforms, we found that aircraft altitude and atmospheric window selection had significant effects on the results. However, as demonstrated in this study involving the influence of the Cayuga power plant effluent on the Wabash River, proper selection of atmospheric window and detector bandwidth, coupled with adequate calibration procedures, allows temperature measurements to be obtained with an accuracy of about 0.2°C at altitudes of at least 1500 meters. This figure is based upon the correspondence between the remotely measured temperatures and temperature measurements obtained on the river at the time of the overflight.

The results of this study offer a great deal of insight into the potentials and limitations of automatically calibrating and processing thermal infrared scanner data. Such techniques could be applied on an operational basis, not only to situations involving thermal pollution, but also to situations in which indications of potential fresh water supplies are being sought.

## Introduction

There is a great deal of controversy concerning the Federal and state guidelines for the establishment of water quality standards, largely because legislative bodies and industry are both lacking accurate and comprehensive factual information concerning our streams and water bodies. This is particularly true in situations involving the setting of safe temperature standards for streams affected by the discharge of large quantities of waste heat from power plants. The discharge of heat into receiving waters and the resulting thermal alteration is one aspect of power generation which is especially amenable to study by thermal infrared scanner systems. Scanner measurements are particularly suitable for flowing water systems where no thermal stratification exists and where distinct thermal inputs may occur at numerous points along the length of a river.

In order to evaluate the sometimes subtle effects exerted by these heat additions on resident biota, it is necessary to describe the areal and temporal pattern of dispersion of the thermal plume under a variety of conditions. Conventional means of measuring temperatures in such a complex system are usually inadequate, requiring too much time and effort to provide a thermal portrait of comparable worth. It is only through a thorough knowledge of the thermal characteristics that ecological data can hope to be properly interpreted and heat dissipation models may be refined. The current use of heat dissipation models by Federal and State regulatory agencies in setting discharge requirements for power plants makes it particularly necessary to obtain accurate and comprehensive factual information.

## Background

Although thermal infrared scanner systems are becoming more common and the data from them can be utilized in a wide variety of situations, many of these instruments are capable of obtaining only relative temperature differences. Therefore the difference in gray tones observed on the resultant imagery indicates only relative difference in temperature levels. In order to define the meaning of the gray tones, one must correlate the imagery with surface observations obtained at the time of the overflight--a process that is very time consuming and difficult at best.

In the last few years, experimental thermal infrared scanner systems have been developed which contain internal calibration sources. These instruments allow one to calibrate the amplitude of the measured signal and achieve an indication of the actual or kinetic temperature of the water body. Under these circumstances, surface observations would be necessary only to verify the accuracy of the internal calibration capability.

One such experimental system with internal calibration plates is being flown by the Environmental Research Institute of Michigan.[1] Early analysis of calibrated data from this system indicated a good potential for accurate measurement of surface temperatures. However as additional data analysis proceeded, we found the data collected under a variety of atmospheric conditions and altitudes yielded rather variable results. These results led to the current study to investigate the accuracy of remote measurements of water temperatures as influenced by wavelength band selection of the scanner and altitude at which the data is collected. Of specific interest was the application of these findings to data collected over a fossil fuel power plant located on the Wabash River in Indiana.

We believe that this study, which involves automatic data processing (ADP) techniques applied to thermal infrared scanner data, moves remote sensing technology one step closer to an operational system capable of accurately and economically obtaining needed information about our aquatic ecosystems, a type of information which would be difficult if not impossible to obtain through any other technique.

Although it is sometimes not obvious, many difficult and involved steps are frequently required to move between (1) the point of showing feasibility for a system and (2) demonstrating a reliable, operational capability. Such has been the case in this research, in which several data calibration techniques have been investigated, data handling operations (including various weighting procedures for scan line averaging), and a new layered classification approach (to allow display of the thermal characteristics of water bodies only) have been developed. The current study of wavelength band selection and determination of atmospheric effects represents another phase in our overall program of developing automatic data processing techniques which will allow accurate remote measurements of the actual (or kinetic) temperature of water surfaces while eliminating other earth surface materials which may have the same apparent (or radiometric) temperature as the water body.

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[1]Previously the Institute of Science and Technology, University of Michigan.

## Objectives

As indicated above, the overall objective of this research has been to develop automatic (computer-aided) data processing techniques which can be used on an operational basis for accurate and reliable determination of surface water temperatures, using emissive infrared scanner data obtained from remote locations. The research reported upon in this paper involves the following specific objectives:

1. To compare the accuracy of calibrated remote sensed measurements of water temperatures using scanner systems operating in different portions of the thermal region of the spectrum.

2. To compare the effect of altitude on the accuracy of calibrated remotely sensed measurements of water body temperatures.

3. To test the current capabilities for measuring surface water temperatures using remotely sensed scanner data obtained over a fossil fuel power plant discharge in the Wabash River, as a preliminary step in assessing the effectiveness of such procedures for studying the effects of such thermal discharges on fish populations.

## Instrumentation and Data Collection

Near Cayuga, Indiana, the Wabash River has a series of sharp bends, which create an ideal natural site for a fossil fuel power plant location. The Cayuga Power Plant was constructed at this site and began operation in August 1970. An aerial photograph of the Cayuga Power Plant test site, as it appeared at this time is shown in Figure 1. Prior to the time when the power plant went into operation, thermal infrared scanner data were obtained over this portion of the Wabash River. A second set of data of particular value for use in this study were obtained in 1972, at which time the scanner configuration was such that data could be collected in the 9.3-11.7μm rather than 8.0-13.5μm portion of the spectrum. This change in the design of the scanner system represents a significant change in the potential for accurate calibration of the thermal data.

In 1970, data were collected in the 4.5-5.5μm and 8.0-13.5μm spectral bands, at both 3,000 meters (≈10,000 ft.), and 600 meters (≈2,000 ft.) altitude.[1]

In order to check the accuracy and reliability of the internal calibration techniques, and to determine the effects of altitude on remotely measured temperatures, measurements of water surface temperatures were obtained by a crew in a boat using a conventional contact thermometer. These temperatures were obtained at approximately the same time the aircraft passed overhead.

The internal calibration technique and the LARS automatic data processing (ADP) procedures employed in this study have been previously described (Atwell et al, 1971; Hoffer and Bartolucci, 1971; Bartolucci and Hoffer, 1973), so will not be described in this paper. Likewise the descriptions of the instrument and its performance have been reported elsewhere (Hasell and Larsen, 1968; Bartolucci and Hoffer, 1973). It should be noted, however, that the scanner accommodates two internal temperature reference sources for calibration purposes. One of the temperature plates is maintained at a higher and one at a lower temperature than the range of ambient temperatures being observed. Knowledge of the emissive properties of these calibration plates allows accurate calibration of the thermal scanner data to be made, but one does not know how much atmospheric attenuation has taken place between the scanner location and the water surface or ground, and what effect this attenuation has had on the accuracy of the radiometric measurements obtained by the scanner.

[1]Data at the 3,000 meter and 600 meter altitudes were collected at 9:44 and 9:56 EST respectively, and it is believed that no appreciable change in the thermal regime of the river would have occurred during this short interval of time.

Wavelength band and altitude effects upon radiometric temperature measurements.

For both the 1970 and 1972 data, normal calibration procedures were followed, using the two temperature plates contained in the scanner system. In order to compare the radiometric measurements obtained by the scanner to the kinetic measurements obtained from the boat, a number of scanner resolution elements in the data were averaged. These data were obtained from locations in the scanner output which correspond to the approximate locations on the river where kinetic temperature measurements were made. The areas used for averaging the radiant temperatures are outlined by rectangles on the computer-generated pictorial printouts shown in Figure 2. The data shown in Figure 2 represents the calibrated airborne scanner data collected in the 8.0-13.5μm spectral band at 3,000 and 600 meters respectively.

Table I shows the means of the radiant temperatures obtained for the scanner data at both altitudes and also for the two wavelength bands available, along with the kinetic temperatures measured at the surface. From these data, it is quite evident that the aircraft altitude, or more correctly, the atmospheric path length between the target and the sensor, plays an extremely important role on the degree of accuracy with which radiant temperatures can be determined from airborne scanner data. Note that for an altitude of 600 meters, water surface temperatures may be determined in the 8.0-13.5μm band to an accuracy of approximately 0.2°C. However, at 3000 meters altitude the radiant temperatures in this wavelength band appear to be approximately 2°C lower than they should be. For the 4.5-5.5μm band, the altitude effects are so pronounced that for the 3,000 meter data, the radiant temperatures are approximately 7°C lower than the actual surface (kinetic temperatures) and even at 600 meters altitude the radiant temperatures are approximately 0.5°C lower than the kinetic temperatures.

As has been pointed out by Ewing and McAlister (1960), water surface radiant temperatures usually are lower than the kinetic temperatures, regardless of spectral band or flight altitude, because of evaporative effects. In addition, we believe that radiant temperatures, as determined from measurements of emitted infrared energy in the 4.5-5.5μm band, are lower than the ones obtained through measurements on the 8.0-13.5μm band because: (1) the 4.5-5.5μm atmospheric window is by far less transparent than the 8.0-14.0μm window as shown in (Figure 3); (2) the "non-linearity effect" introduces larger errors on the remotely measured temperatures in the 4.5-5.5μm than in the 8.0-13.5μm band;[1] (3) the emissivity of natural materials is in general lower in the 4.5-5.5μm band than in the 8.0-13.5μm spectral region; and (4) the amount of energy available for measurements of temperatures from remote platforms (at typical terrestrial temperatures) in the 4.5-5.5μm band is only 3% as compared to 62% for the 8.0-13.5μm wavelength band, as illustrated in (Figure 4).

Since these results, as well as those of previous investigators, indicate that atmospheric attenuation in the 8.0-13.5μm region is significant, recent developments in detector sensitivity offer promise for alleviating some of these effects. In 1971 a Mercury Cadmium Telluride (Hg, Cd, Te) detector was incorporated into the scanner system being utilized in these studies and the 8.0-13.5μm wavelength band for data collection was narrowed to a band extending from 9.3-11.7μm. As can be seen from Figure 3, this narrower wavelength band window has very good atmospheric transmission characteristics, but as seen from Figure 4 only 23% of the total radiant energy available for a 20°C blackbody could be sensed in this narrower wavelength band. The question was therefore raised as to the relationship between calibrated radiometric temperature measurements of water bodies in this narrower wavelength band and those previously obtained in the 8.0-13.5μm band. Table II shows data collected at 1,500 m. altitude using the 9.3-11.7μm band and the kinetic temperatures measured at the water surface for a number of locations. These data indicate that use of the 9.3-11.7μm band at 1,500 m. altitude will produce results comparable to those

[1]Errors in radiant temperature measurements are brought about by assuming a linear relationship between the amount of energy emitted by a blackbody and its temperature when in fact that is not the case. (Bartolucci and Hoffer, 1973)

obtained with the 8.0-13.5μm band at 600μm. altitude. Thus, even though one is dealing with a narrower spectral band and therefore a smaller amount of radiant energy is available, the atmospheric attenuation is much less severe and the detector is sensitive enough to produce rather accurate results.

It can thus be concluded that the 9.3-11.7μm band is the best, and the 4.5-5μm band is the worst, among the three wavelength bands compared. Calibrated thermal infrared scanner data allows radiometric temperature measurements to be obtained with an accuracy of approximately 0.2°C, as compared to the kinetic temperature measurements obtained at the water surface itself, for altitudes of up to approximately 600 meters using the 8.0-13.5μm band or up to at least 1,500 meters using the 9.3-11.7μm wavelength band. Accuracies for higher altitudes using this narrow 9.3-11.7μm wavelength band have not yet been determined.

The next section of this paper shows the utilization of this narrower wavelength band at an altitude of about 1,500 meters for measurement of the location and extent of the thermal effluent of the Cayuga Power Plant. The effects that this power plant have had on the fish populations of the Wabash River during the two years in which the plant has been in operation are also discussed.

Remotely Sensed Temperatures of the Cayuga Power Plant Thermal Effluent

The 1970 scanner data utilized in this investigation was collected at the time when the Cayuga Power Plant was still under construction. In 1972, two 500 Mw (megawatts) electric power generating units were completed at the Cayuga test site. This fossil fuel power plant utilizes water from the Wabash river for cooling purposes at an approximate rate of 2,200 $m^3$/minute. The temperature of the cooling water is increased by approximately 8°C as it passes through the power generating units, and it is discharged back into the Wabash River.



On August 9, 1972 thermal infrared scanner data was gathered in the 9.3-11.7μm wavelength spectral band, at an altitude of 1,500 meters over the Cayuga Power Plant test site. A computer generated thermal map of the Wabash River and cinder ponds at the Cayuga Power Plant test site is shown in Figure 5. Although the calibration system was capable of producing a map showing 0.2°C temperature intervals, this map depicts only 0.5°C temperature intervals, since that level of accuracy appeared to produce the most meaningful map for the biologists working on this project. The numbers beside the rectangles indicate the locations at which the temperatures shown in Table III were determined. As can be seen from Figure 5 and Table III the water temperatures in the river above the outlet from the power plant and along the east side of the river below the outlet are approximately 20.6 to 21.1°C, but in the canal just below the power plant temperatures are 24.9 to 25.8°C. Below the outlet, a distinct thermal plume can be seen along the west bank of the river, with the temperatures slowly cooling as one moves farther down-stream from the power plant. However, it is significant that even for distances up to 6 km. from the power plant, temperature levels can be measured which are higher than those found anywhere above the power plant.

Does this type of thermal impact upon temperatures in a river appreciably influence the characteristics of the fish population? A study by fisheries biologists during the past seven years for this portion of the Wabash River would indicate that there are significant effects. In essence, the distribution and abundance of fish and macrobenthic populations in a 6.5 km. segment of the Wabash River was studied for three years prior to start-up of the Cayuga generating system and for two years after.[1]

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[1]The complete results of this study are described elsewhere (Gammon, 1973a).

Although post-operation summers were unusually cool, definite shifts in distribution occurred for some species as the result of the changed thermal conditions. These shifts were generally consistent with thermal preferences which had been determined earlier in another segment of the Wabash River (Gammon, 1973b).

The most striking response noted was the increase in density of young flathead catfish (Pilodictis olivaris) in the heated regions only, the result of increased reproductive success of this relatively sedentary species. Several other species, notably sauger (Stizostedion canadense) and redhorse (Moxostoma erythrurum and M. breviceps) moved out of the heated reaches. It remains to be determined whether the changed thermal conditions will adversely affect fish populations as a whole.

## Summary and Conclusions

From the studies described, it is apparent that remote sensing of thermal infrared radiation and automatic (computer-aided) data processing techniques can be utilized for accurate determination of surface water temperatures, provided the altitude of data collection and the wavelength band of the sensor system are properly selected. It would also appear that these techniques can be utilized to effectively study the impact of thermal discharges on aquatic ecosystems, and that such discharges do have a significant effect upon the fish populations present. This study indicates that the present capabilities of thermal infrared data processing can be satisfactorily utilized to determine radiant temperatures of water bodies on an operational mode. Such a capability is important where comprehensive, fast, and accurate knowledge of the thermal characteristics of waste heat effluents are mandatory for the establishment of safe temperature standards in the affected water bodies, and for the study and determination of the effects of such effluents on the distribution and abundance of fish populations. The following generalized conclusions could be drawn:

1. Atmospheric attenuation is much more apparent in the 4.5-5.5μm than in the 8.0-13.5μm wavelength band, and is least apparent in the 9.3-11.7μm band. These results agree well with existing knowledge of atmospheric attenuation in the various wavelength bands.

2. Data collected at higher altitudes will provide less accurate radiometric temperatures, because of the longer atmospheric path-lengths and resultant atmospheric attenuation. However, accuracies of approximately 0.2°C can be achieved for altitudes of up to 1,500 meters when using a scanner system operating in the 9.3-11.7μm wavelength band. Similar accuracies can be obtained in the 8.0-13.5μm band for altitudes of up to 600 meters.

3. Remote sensing techniques, including application of automatic (computer-aided) data calibration and analysis procedures, allow an effective method for determining the extent and magnitude of the effect of thermal effluents from electric power plants on a river ecosystem. Such effluent has been shown to significantly influence fish populations in the river.

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TABLE I. Altitude Effects on Radiant Temperatures.

| Measurement Site | Radiant Temperatures[1] (°C) 10,000 Ft. Alt. 4.5-5.5μm | 10,000 Ft. Alt. 8.0-13.5μm | 2,000 Ft. Alt. 4.5-5.5μm | 2,000 Ft. Alt. 8.0-13.5μm | Kinetic Temp.[2] (°C) (Contact Thermometer) |
|---|---|---|---|---|---|
| 1st River Bend | 19.3 | 24.6 | 25.8 | 26.2 | 26.5 |
| Above Intake | 19.2 | 24.4 | 25.9 | 26.2 | 26.5 |
| Intake | 19.3 | 24.6 | 25.9 | 26.1 | 26.2 |
| Outlet | 19.2 | 24.4 | 25.8 | 26.1 | 26.0 |
| 1/2 Mile Below | 19.3 | 24.4 | 25.6 | 26.1 | 26.2 |

[1]The standard deviation for the radiant temperatures is ± 0.2°C.

[2]All the surface measurements of temperatures listed above were conducted within half an hour from the time the aircraft passed overhead.

TABLE II. Comparison of Kinetic and Radiant Temperatures.

| Site | Date | Kinetic Temp. (°C) | Radiant Temp.[1] (°C) |
|---|---|---|---|
| | | 22.1 | 21.9 |
| Cayuga | 8/9/72 | 22.5 | 22.4 |
| | | 25.7 | 25.6 |
| | | 19.8 | 19.8 |
| Junction | 8/10/72 | 21.5 | 21.3 |
| | | 20.4 | 20.3 |

[1]From an altitude of 1,500 meters using the 9.3-11.7μm band.

TABLE III. Radiant Temperatures Corresponding to Measurement Sites in Fig. 5

| Test Site # | | Mean Radiant Temp.[1] (°C) | |
|---|---|---|---|
| Above Intake | (1) | 20.6 | |
| | (2) | 20.9 | |
| | (3) | 20.9 | |
| Canal | (4) | 25.6 | |
| Outlet | (5) | 24.9 | |
| | (6) | 24.1 | West Bank |
| | (7) | 21.1 | East Bank |
| | (8) | 24.2 | West Bank |
| | (9) | 21.1 | East Bank |
| | (10) | 23.6 | West Bank |
| | (11) | 20.6 | East Bank |
| | (12) | 22.7 | West Bank |
| | (13) | 21.3 | East Bank |
| | (14) | 22.5 | |
| | (15) | 21.3 | |
| | (16) | 20.8 | |
| Cinder Pond | (17) | 22.5 | |
| | (18) | 20.8 | |
| | (19) | 22.5 | |
| | (20) | 22.7 | |

[1]Data collected on August 9, 1972 in the 9.3-11.7μm spectral band. The flight altitude was approximately 1,500 meters.

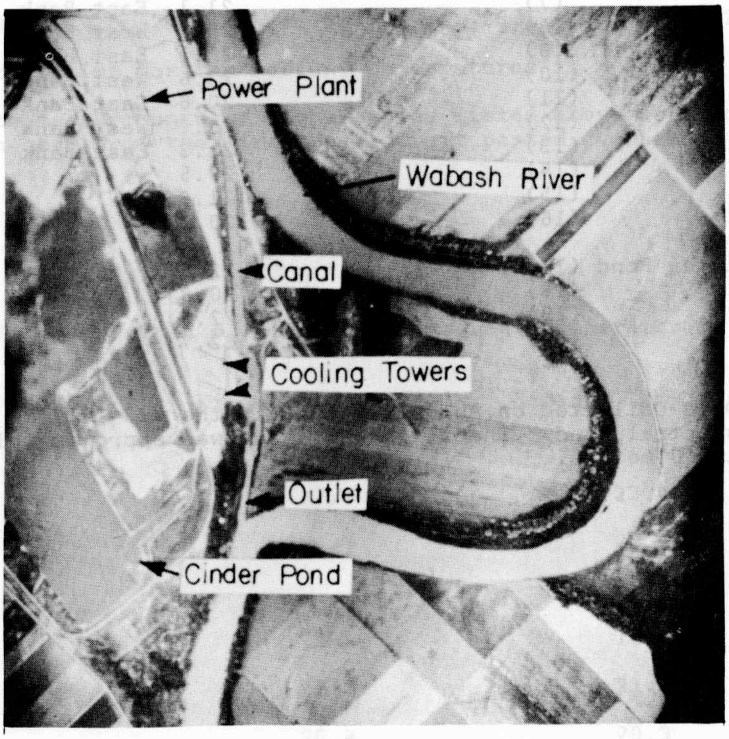


FIGURE 1. Aerial photograph of the Cayuga power plant and Wabash River in Vermillion County, Indiana.

8.0-13.5μm

1,500 m. 600 m.

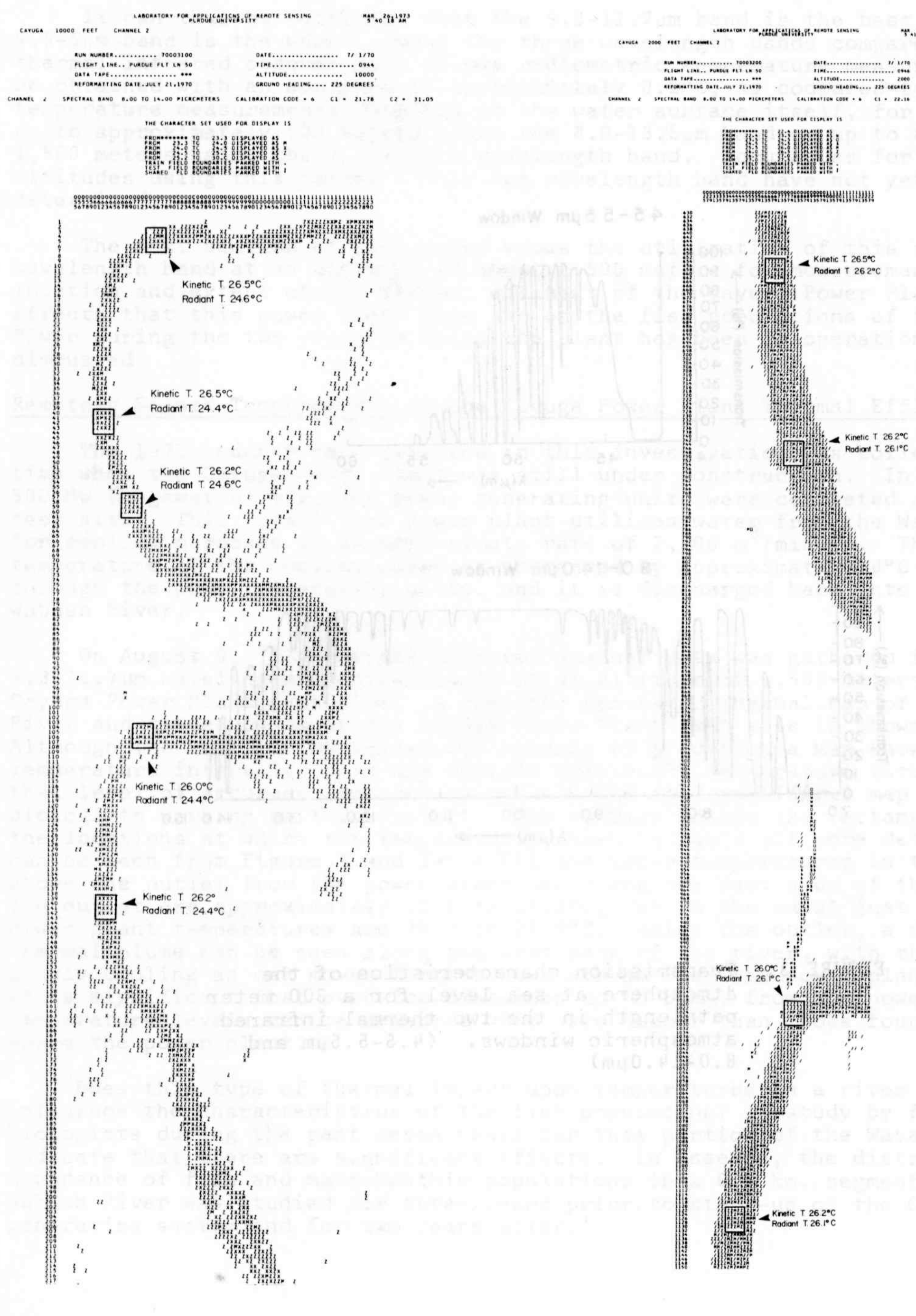


FIGURE 2. Computer-generated thermal maps for the Cayuga test site, using data in the 8.0-13.5μm wavelength band collected from 3,000 meters (left) and 600 meters (right) altitude.

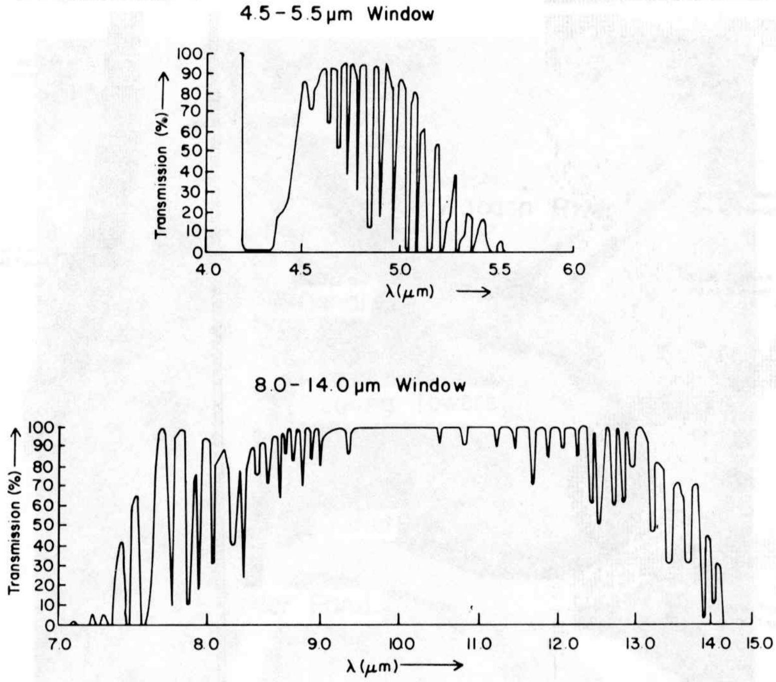


FIGURE 3. Transmission characteristics of the atmosphere at sea level for a 300 meter pathlength in the two thermal infrared atmospheric windows. (4.5-5.5µm and 8.0-14.0µm)

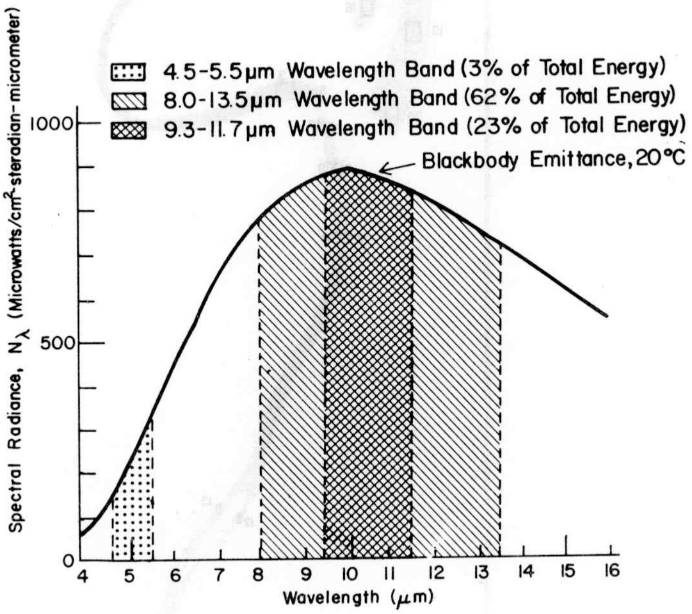


FIGURE 4. Planck's blackbody emittance curve for 20°C, and the amount of emitted energy available for remote sensing in the thermal infrared windows considered.

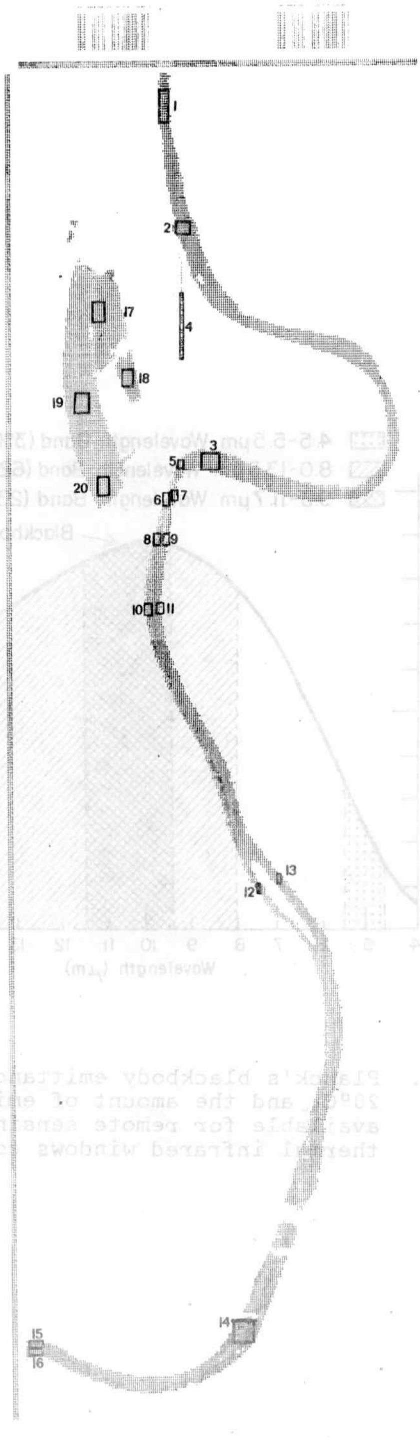


FIGURE 5. Computer-generated map of water in the Cayuga Power Plant Test Site area, showing temperature levels at selected test site locations. See Table III for radiant temperature levels at each of these locations.