AERIAL REMOTE SENSING OF THERMAL PLUMES

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ABSTRACT

A twin Beechcraft airplane, operated by the NASA Kennedy Space Center, was used to provide thermal remote sensing data to assist in the development and initial application of a three-dimensional thermal plume mathematical model. The NASA aircraft was equipped with a Daedalus thermal scanner operating in the 8 - 14 μ region. Data from the scanner was recorded on analog magnetic tape which was converted to a color film product with specified temperature regimes identified by a unique color. A data collection mission usually consisted of two flights during the same day. Surface temperature contour maps were drawn from an early morning thermal scanner flight over a power plant discharge area; and this data, in conjunction with surface truth measurements, was used as the initial condition for a model test run. Approximately six hours later, another flight was made; and the resulting data was compared with the math model temperature contour predictions.

Thermal plume data from the two development sites in Florida selected for this model, Biscayne Bay and Hutchinson Island, is described in this paper. The rigid lid and free surface versions of this model are described in these conference proceedings under the numerical modeling section. Also, thermal plume data for the model's first application site, Lake Belews, North Carolina, is described. The thermal plume math model application at Lake Belews is also described in these conference proceedings under the case studies section.

1. INTRODUCTION AND BACKGROUND

Aerial remote sensing was used extensively to provide input data and verification of math model predictions during a three year effort to develop a universally applicable three-dimensional thermal plume math model. Remote sensing data was collected four times (on a seasonal basis) at three power plant discharge sites. These included two sites in Florida where versions of the model were developed. These were Biscayne Bay and Hutchinson Island, Florida. Biscayne Bay is a shallow estuary, and both the rigid lid and free surface models were developed at this site. The relatively small FPL power plant at Cutler Ridge provided classical thermal plume pictures in a very large receiving body of water. In contrast, the FPL St. Lucie Nuclear Power Plant discharges off shore Hutchinson Island some twelve hundred feet into the sea. Here, of course, only the free surface version of the model is

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applicable. The third site, an initial application of the model, was at Lake Belews, North Carolina. This represented still a different geographical site. It is a small, deep cooling pond for the Duke Power Company Belews Power Station.

The math model development was greatly aided by this aerial remote sensing. Its primary value was the synoptic view provided of the thermal plumes. Various shapes of the plumes and naturally occurring temperature changes in the far field could readily be detected under diverse operation and environmental changes. In some data collection missions, two or even three successive days of data were collected. This enables one to run the model for twenty-four hours or longer and then compare the results with the infrared and ground truth data. Whenever possible, a ground truth boat was positioned under each flight line. The ground truth boat was used, not only to collect subsurface parameters, but also to correct the infrared data for changes brought about by atmospheric phenomena.

In these development and initial application activities for this state-of-the-art thermal plume math model, aircraft provided the basic remote sensing platform. Existing satellites, such as the NOAA-4 and DMSP satellites, played only a minor role as a thermal data source because of their resolution. However, the thermal sensors in the next generation of satellites will have much finer spatial resolution. Landsat "C," schedule to be launched by NASA the latter part of this year, or early 1978, will have a resolution of approximately 237 meters in its thermal band, [1]. Landsat "D," which is in the planning stages for the 1980's, probably will have a resolution of 90 to 120 meters in its thermal IR band [2]. Ultimately, satellites will be used, not only for global ocean surface temperature mapping, but also to provide the accurate, high resolution water temperature data needed for monitoring thermal plumes from power plant discharges.

2. THERMAL SCANNER SYSTEM

A variety of excellent airborne infrared systems are now available commercially. The Kennedy Space Center utilizes a Daedalus DS-1250 series line scanner. Remote sensing of 8-14 μm radiation is achieved by a Hg: Cd: Te detector. This detector has a 0.015-inch square sensitive area which is optimum for the resolution and temperature sensitivity required. This detector is mounted in an end-looking, metal-cased vacuum dewar which has sufficient liquid nitrogen coolant capacity for approximately six hours of operation before refilling. This system projects through the floor of the twin Beechcraft airplane, NASA-6, and has a scan angle of 120° centered about the vertical. The scanner contains a horizontally mounted telescope with its axis aligned along the direction of flight of the airplane. A mirror rotating at 3,600 RPM is mounted at 45° to the telescope and directs heat radiation from the earth into the system. A one-third rotation of the mirror covers a complete step perpendicular to the scanner axis. Optical resolution is approximately 1.7 milliradians, so the ground areas from which the detected signal is averaged becomes a function of height. The aircraft was normally flown at an altitude of 2,000 ft. which results in an accuracy of the infrared data being within the model's predicted accuracy of 0.5°C in the far field.

The video signal from the infrared detector is amplified and recorded on magnetic tape in the aircraft. An aircraft mounted drift sight and Doppler navigation system can monitor actual draft angle and spread. These data enable the operator to eliminate drift angle distortions and along track versus across track scale errors. An 18° F dynamic range between black bodies has been used primarily, but a 24° F and a 36° F range have been found more useful in some thermal plume imagery.

3. COLOR CODING OF ANALOG THERMAL SCANNER SIGNALS

Daedalus has developed a method, termed Digicolor, which converts the original analog signal information directly into color-coded strip map imagery. The basic Digicolor system limits the number of output colors to eight for any input condition. The sequential thermal relationship commencing at the "hottest" level for a given range is white, red, yellow, green, cyan, blue, magenta and black. White indicates temperatures in excess of the upper limit of the set of interest and black is the base level indicating temperatures below the lower limit of the set of interest. The six colors between white and black are the six calibrated levels of the set of interest. The reason for using only eight colors is to produce maximum color distribution between levels for ease of interpretation.

The six basic colors are directly related to a six-step digital level selector. The digital level selector is critically controlled to accept the incoming analog signal and divide any portion of the dynamic range selected into six linear increments. The first set is called the "master" and includes the entire peak-to-peak range between the two reference levels. The master set is carefully adjusted to sense the "hottest" and "coldest" peaks of the total signal since these are the two reference levels with which all additional slices will be compared.

The digital level selector employs a precision voltage divider network which assures precision subdivision. Once the master set is generated, numerous other subdivided sets may be generated accurately by switching to the desired range on the selector. Referring to the chart in Diagram 1, each color range contained in the master set may be subdivided into six more subsets. Note that level 6 (red) for the master set produces subset 6 which repeats the color range. Thus, when viewing the master set imagery, all of the data shown in red will be further divided into all six colors for set 6. Each film run representing a set is identified to avoid any confusion about set relationships.

Diagram 1 illustrates an example of how a magnetic tape signal from the Daedalus quantitative scanner of water thermal data would be converted into Digicolor. Note that the scanner's thermal reference sources (BB1 and BB2) were preset in flight to 66° F and 84° F, respectively. The two blackbody references are always tape recorded on the same track with the detector video to insure accurate voltage relationships irrespective of all amplifier gain adjustments. The calibrated range selected divides the detector video signal into 3° F increments for each master color range, i.e., the blue range of 69° F to 72° F. By analyzing the resulting Digicolor master film, an interpreter can, for example, rapidly determine the thermal distribution of a power plant thermal discharge. The master film has encompassed the entire dynamic range of information between the reference sources which in the example is 18° F. If additional thermal sensitivity is required, any (or all) of the six subsets may be reproduced by replaying the tape and switching to the subset(s) of interest. The subset colors are the same as the master colors, but they represent 1/6th the temperature range which in the example will now be 0.5° F per color. The chart shows that all of the information which produced red on the master film (81° F to 84° F) would be produced in the basic six colors if subset 6 were reproduced. The temperature distribution of subset 6 is illustrated in Diagram 2.

All other subsets can be reproduced in the same manner, or subsets may be "bridged." One example of bridging subsets would be to combine subsets 1 and 2 (66° to 72° F), which when printed out, would provide six colors, each representing 1° F increments. This could then be applied to subsets 3 and 4 (72° to 78° F), resulting in 1° F increments for that portion of the master range, etc. By combining subsets 1 through 4 inclusive, a 12° range is bridged, thus producing 2° F increments for each of the six colors. Variations of these examples may be employed as long as there is continuity between the subsets which are bridged.

4. SELECTED COLOR-CODED THERMAL PLUMES

Figures 1 and 2 are false color thermal infrared images of the discharge from the fossil-fueled Cutler Ridge power plant into Biscayne Bay at Miami. North is to the left in these illustrations. They were taken with the thermal scanner system aboard the aircraft.

Figure 1 was taken at approximately 0912 EDT on 15 April 1975. The sensor-indicated temperatures represented by colors are as follows: white >80° F, red 79-80, yellow 78-79, green 77-78, cyan 76-77, blue 75-76, magenta 74-75, and black <74° F. These temperatures are not corrected for attenuation by water vapor between the surface and the aircraft flight level which was 2000 ft. Boat measurements of surface water temperatures indicated that a +4° F (2.3°C) correction should be added to the remote sensed temperatures. The Cutler Ridge plant had a discharge volume of 43,200 m^3/hr at a temperature of 35.9° C (96.6°F). The surface wind was from the southwest at about 9.76 m/sec (19 knots). The bay is shallow in the area where the plume is discharged, slightly more than one meter in depth.

Figure 2 was taken at approximately 1345 EDT on 4 September 1975 from a 2000 ft. altitude. The colors depict the following uncorrected temperatures: white >90° F, red 88.5-90, yellow 87-88.5, green 85.5-87, cyan 84-85.5, blue 82.5-84, magenta 81-82.5, black <81° F. Boat measurements indicated that a +7° F (3.8° C) correction should be added to the remote sensed temperatures.

The plant discharge volume was 34,560 m^3/hr at a temperature of 40.6° C (105° F). The surface wind was from the southeast at 3.44 m/sec (6.5 knots). The differences in the shapes of the plumes in Figs. 1 and 2 are largely due to different tide conditions. In Figure 1, there was a flow or incoming tide counter to the plume; while in Fig. 2, the tide was ebbing and aided in stretching the plume.

Figures 3 and 4 are thermal infrared images of the mixing pond and main lake, respectively, at the Lake Belews, N.C., fossil-fuel plant of the Duke Power Company. These thermal scans were made between 0900 and 0955 EDT on 19 May 1976 with the aircraft flying at 2000 ft. above the surface. In these figures the uncorrected temperatures are: > white 86° F, red 83-86, yellow 80-83, green 77-80, cyan 74-77, blue 71-74, magenta 68-71 and black <68° F. On the right side of Fig. 3, the plant discharge into the mixing pond exceeded 86° F. The discharge from the mixing pond into the main lake at the top center of Fig. 4 was 83-86° F.

Lake Belews is a man-made lake with an area of 3,863 acres. It was created by building a dam on Belews Creek in 1970. There are two power units each with a capacity of 1143 megawatts. Cool water at an average rate of 238,000 m^3/hr is taken from the main lake. At full load, the temperature of the water is raised by 10° C (18° F), and the hot water is discharged into the mixing pond. The hot discharge is cooled slightly in the mixing pond because of the initial mixing with cooler water. The mixing pond is connected to the main lake through a narrow canal. The maximum depth of the mixing pond is 13.72 meters (45 ft). The maximum depth of the main lake is 38.2 meters (125.3 ft).

Figures 5 and 6 show the plume from the Hutchinson Island nuclear plant extending northward along the Atlantic coast during the time it was scanned, 1048-1059 EDT, on 2 June 1976. North is toward the bottom of the page in these two illustrations, and Fig. 6 is a continuation of Fig. 5. The aircraft flight altitude was 2000 ft., and the color-coded uncorrected temperatures are as follows: >White 88° F, red 85-88, yellow 82-85, green 79-82, cyan 76-79, blue 73-76, magenta 70-73, and black < 70° F. In this image all temperatures were greater than73° F. Boat measurements indicated that a +4° F (2.1° C) correction should be added to the remote sensed water surface temperatures.

The Florida Power and Light Company's Hutchinson Island Nuclear Power Plant is located about midway between the cities of Fort Pierce and Stuart on the Atlantic coast of Florida. The rating of the plant is to be 850 megawatts electrical. The 3.66 meters diameter submerged discharge pipeline is buried in the ocean bed and terminates at a point about 366 meters offshore and 5.48 meters below mean water level. At its termination, a two port Y-type discharge is added with each arm being 2.29 meters in diameter. A short sloping concrete pan is located at the outlet to prevent scouring of the ocean floor. On 2 June 1976, at 50 percent rated load, the heated discharge had a flow rate of about 363,000 GPM (82,437 m^3/hr) with an exit velocity of 280 cm/sec at each end of the Y-type discharging pipe. The discharge water temperature was 35° C (95° F). The ambient water temperature was about 25.5° C (78° F) and air temperature was 29° C (84° F). The wind speed was 10 mph (4.5 m/sec) and air temperature was 29° C (84° F). The wind speed was 10 mph (4.5 m/sec) from the southeast. The ocean current was about 25 cm/sec predominantly toward the north.

5. CORRECTION OF AIRCRAFT INFRARED MEASUREMENTS

Aerial measurements of surface thermal plumes which are made in the 8 to 14 micron region of the spectrum are subject to errors. The primary source of error is atmospheric water vapor absorption. Non-blackness of the water body can be another source of error. There is a strong ozone absorption band between 9 and 10 microns, but the maximum ozone concentration is at high altitudes so that it can be ignored for low altitude aircraft measurements. There is also some absorption by CO_2, mainly in the 13 to 14 micron region.

A literature search was made into the methods and models used by other researchers to correct aerial infrared data [3], [4], [5], [6], [7]. It was concluded that these models fail to give true absolute temperatures in the low latitudes and south and central Florida where there is a large concentration of moisture at low altitudes. Consequently, we chose to use the numerous ground truth water temperature measurements made with a Barnes PRT 5 instrument and various thermistors to directly correct the aircraft infrared data rather than apply a theoretical method. At least one data collecting boat was scheduled to be on several NASA-6 flight lines to determine if the delta temperature correction changed during the data collection mission.

Most corrections for the aircraft thermal IR data were of the order of plus 2 to 3 degrees C. The uncorrected infrared isotherms give excellent relative thermal patterns, and after ground truth corrections are applied, they provide high quality quantitative results for modelling applications.

6. REFERENCES

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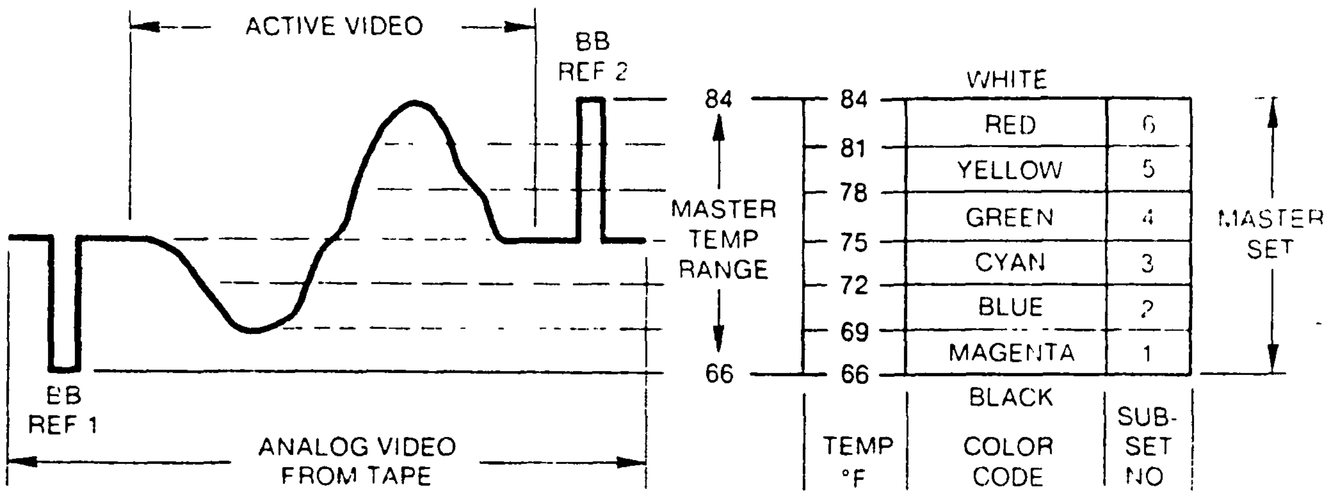

Diagram 1.

Conversion from Magnetic Tape Data to Color Film

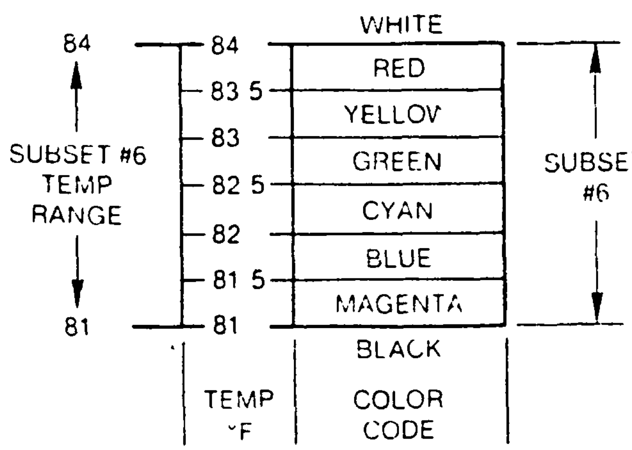

Diagram 2

AERIAL REMOTE SENSING OF THERMAL PLUMES

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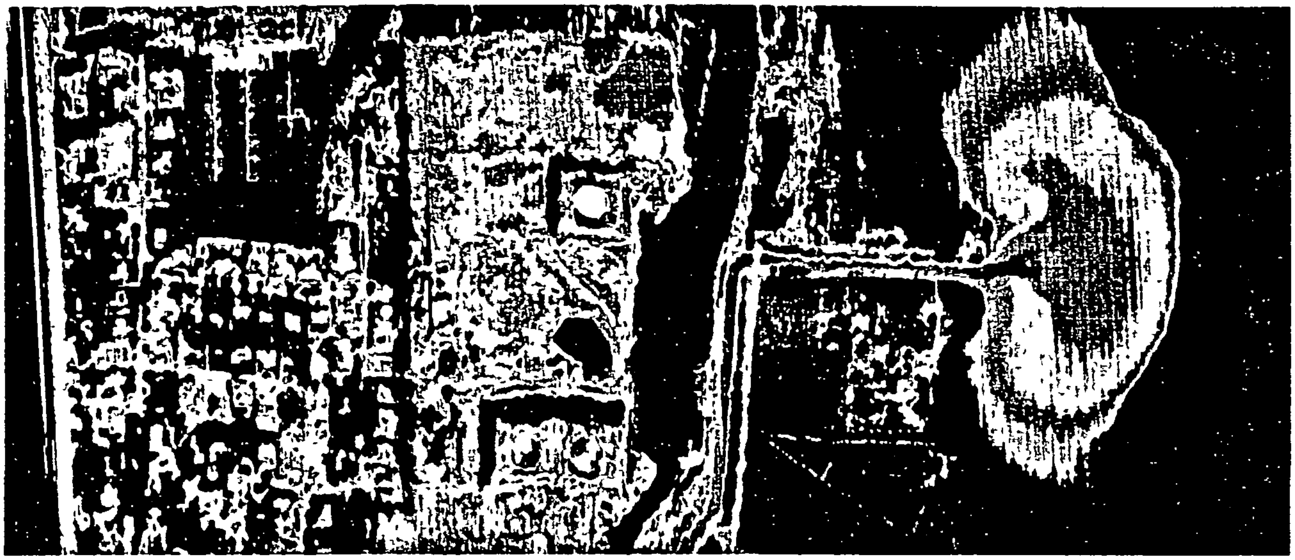

Figure 1

Figure 2

Figure 3

Figure 4

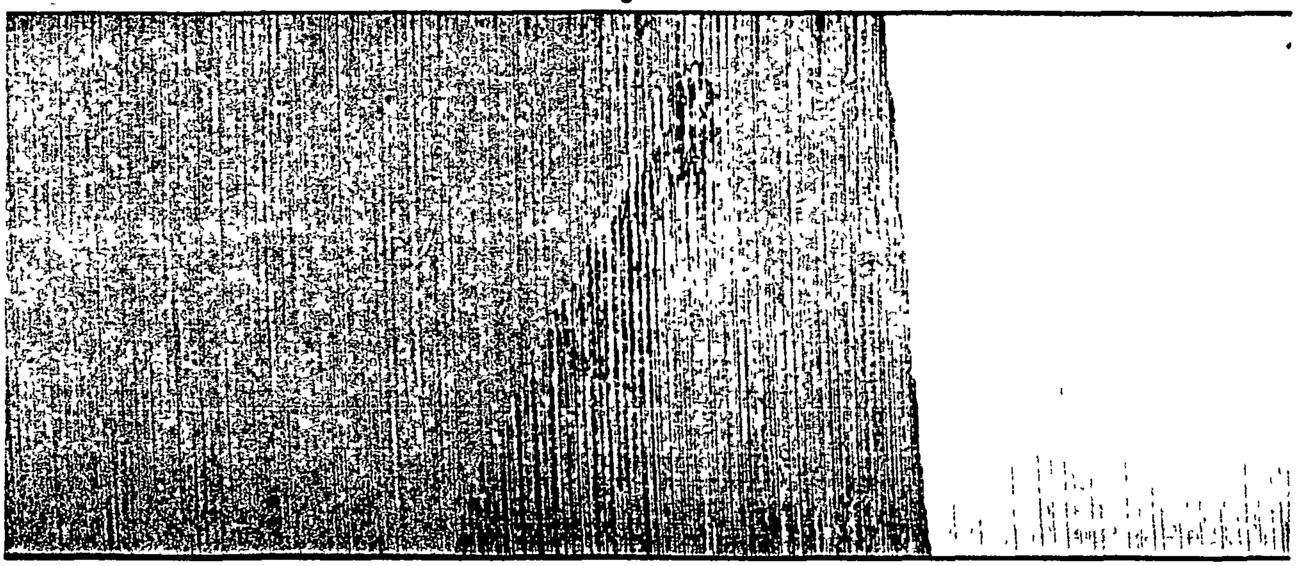

Figure 5

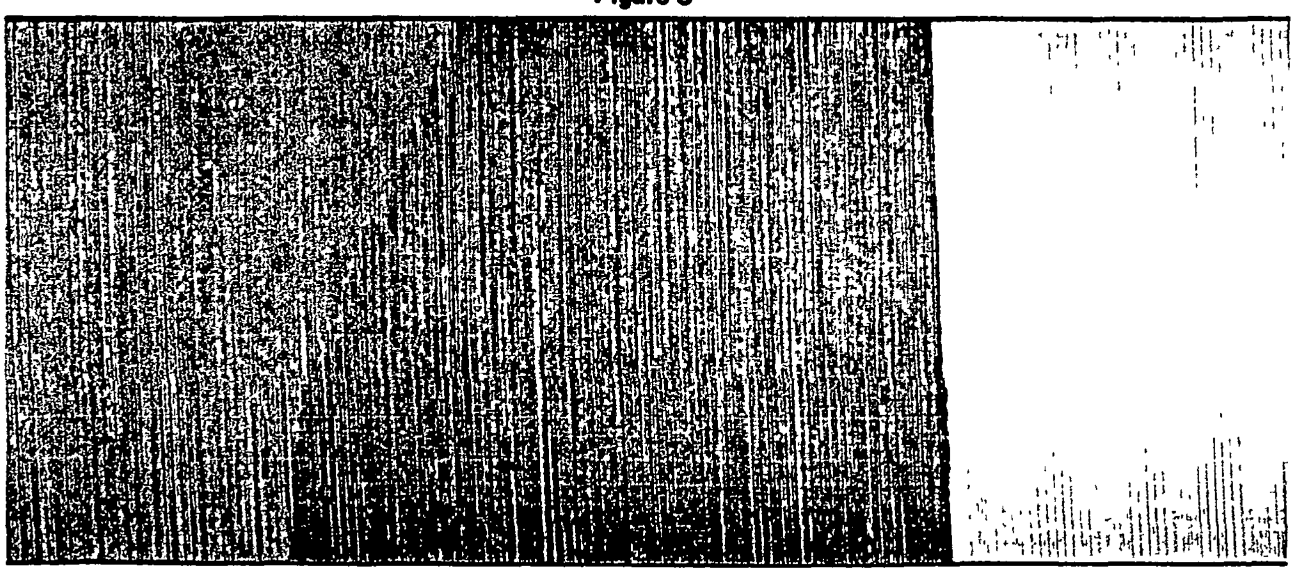

Figure 6