REMOTE SENSING OF POWER STATION THERMAL DISCHARGES

I.R. Rodgers

Central Electricity Research Laboratories
Kelvin Avenue
Leatherhead
Surrey KT22 7SE

ABSTRACT

When considering the potential of a coastal or estuarine area for the siting of a power station, the CEGB requires to predict the effect on the receiving waterbody of the cooling water thermal discharge. The observation of the tidal motion and mixing of existing discharges enables more accurate predictions to be made in the future. Traditionally, measuring instruments are deployed in the sea at fixed locations or operated from a survey vessel. Since the mid 1960's the CEGB has also been making use of remotely sensed measurements in the thermal infra-red waveband from aircraft, helicopters and, more recently, satellites. These remote sensing techniques complement the more traditional hydrographic survey methods. This paper describes the use of remote sensing in thermal infra-red wavelengths in power station research, planning and design studies and looks to future developments in satellite remote sensing. The advantages and disadvantages of aircraft, helicopters and satellites as platforms for imaging devices are discussed with particular emphasis on the application to marine temperature field detection. The accuracy of measurement, cost of use, frequency and duration of data collection, flexibility of display and ease of interpretation are considered. The particular problems which arise when using infra-red imaging systems to measure sea surface temperature are highlighted.

INTRODUCTION

A modern direct-cooled power station has a requirement for large quantities of condenser cooling water. A station generating 1000 MW of electricity might typically draw 50 m^3 s^{-1} of water from the sea and return it warmed by some 10°C. When considering the potential of a marine or estuarine area for the siting of a power station the Central Electricity Generating Board (CEGB) requires to predict the effect on the receiving waterbody of such large thermal discharges for both ecological and operational reasons. To this end mathematical, computational and hydraulic scale models are all used to predict heat fields. An important part of the testing of these models is comparison of model predictions with data on existing discharges. Remote sensing techniques are playing an increasingly significant rôle in the collection of data about power station thermal discharges.

The marine temperature field around a power station may be divided into three components: the natural, solar-driven, heat field that exists in the absence of artificial heat sources; the plume phase of dispersion of power station cooling water in which the discharge forms a distinct, buoyant, vertically-stratified layer which moves with the tidal current and is diluted by turbulent mixing; and the vertically well-mixed background heat field which results from the tidal dispersion of the power station discharge over a period of days and from which the heat is ultimately lost to the atmosphere. Any measurement of the temperature distribution about a power station will contain contributions from all three fields. It is the combined effect of all three heat fields which must be assessed by the CEGB.

The natural, plume and background heat fields each have typical length, time and temperature scales which are an important determining factor when deciding on the technique to be used in their measurement. These scales are indicated in table 1.

Temperature field	Time scale (days)	Temperature Scale	Spatial dimension (km)	Stratification
natural	5-15	≤4	10 × 100	?
plume	0.25	≤8	.25 × 1.5	yes
background	5-15	≤2	2 × 15	assumed no

Table 1: Scales Associated with Marine Heat Fields

In this table the timescale is a measure of how rapidly changes occur in the temperature field, the temperature field indicates the size of tidal variations rather than absolute values, and the dimensions are in plan. Obviously all these scales depend in practice on meteorology, tidal conditions, bathymetry and power station discharge design. The natural field parameters are somewhat arbitary but are taken to correspond to coastal waters. An additional column has been added to the table to indicate whether or not the heat field is vertically stratified. Solar heat fields in near-shore regions tend to be vertically well-mixed but in deeper water stratification occurs. The question of the value of remotely sensed temperatures in the case of stratified temperature fields will be returned to later.

In the following a review will be given of the CEGB's experience in using remote sensing methods for the detection of power station discharges. This is necessarily brief but wherever possible references are given to more detailed studies.

DATA COLLECTION METHODS

Traditional Methods

Traditionally, natural and artificial heat fields at sea are measured using a combination of boat-borne or boat-towed equipment and fixed instruments moored at selected locations with some method for on-board recording or transmission of data. In the plume phase with its relatively short timescales and small lengthscales a boat-mounted system is most suitable: this can build up a 3-D picture of temperature variations within a plume within ½ hour (Pickles and Rodgers, 1985). For the slower variations and larger areas of interest in the natural and background fields a more practical technique is the long-term deployment of equipment to measure temperatures, salinities and currents at fixed measurement stations.

Two problems may be mentioned with the boat measurements: firstly, variations in plume shape can be rapid at the turn of the tide and a boat may well gather insufficient data at this practically important stage and secondly it is expensive to have a survey vessel at sea for long periods. The use of moored equipment also has difficulties: firstly because the large area of interest means that it is not feasible to measure data over the whole area - a small number of locations are chosen as being of particular interest and areal coverage is sacrificed. This presumes an a priori knowledge of which areas are important. A second problem, common to all oceanographic fieldwork, is the loss or malfunction of equipment caused by the harsh marine environment.

In addition to these traditional data-gathering methods the CEGB has also been using a variety of remote sensing devices and platforms for the measurement of radiometric sea surface temperature (SST) at both thermal infra-red (10-12 μm) and near infra-red (2-3 μm) wavelengths. Table 2 compares and contrasts the major strengths and weaknesses of ground-based and remotely-sensed temperature data.

From this table it is clear that the two sources of data are complementary. It is particularly noteworthy that for a stratified temperature field the aircraft or spacecraft data needs to be supplemented by measurements below the water surface. The problems of accounting for atmospheric and sea surface effects can also most readily be overcome by use of sea-truth data, a topic which will be discussed further later. An alternative way of contrasting satellite and aircraft imaging systems is to plot the performance of each device on a graph of repeat-overpass time against spatial resolution (see figure 1). It can be seen that aircraft and helicopters lie in a different region of this plot than satellites, which tend to lie in a broad band. For this reason the discussion of the use of aircraft and spacecraft by the CEGB will be separated.

	Ground based	Remotely sensed
1.	Data measured at exact location.	Data averaged over one pixel.
2.	Sub surface temperatures may be measured.	Only microsurfaces temperatures measured.
3.	Measurements obtained in all weather.	Data available only for cloud-free days (satellites) or days of good visibility/ moderate winds (aircraft).
4.	Accurate absolute temperatures ($\sim$0.1°C).	Accurate relative temperatures, but accuracy of absolute temperatures uncertain.
5.	Data gathered at a few locations.	Data gathered over a large area.
6.	Harsh environment and cost determine equipment lifetime.	Environment minimal (spacecraft) or controlled (aircraft)

Table 2: Comparison of Remote Sensing and Ground Measurements

Experience with Helicopters and Aircraft

During the last 20 years the CEGB has employed a variety of aircraft/equipment combinations for thermal imaging. Recent experience with two devices will be compared: helicopter-borne equipment recording onto videotape and multi-channel linescan imagers on board aircraft.

Thermal imagers flown in helicopters are used routinely by the CEGB for inspection of transmission lines for insulator faults. Recent improvements in the equipment which allow recording of video output within the helicopter have made the system also useful for studying plume dispersion. The equipment flown by the CEGB has an overall field of view of 60° × 40° with a minimum resolution of $\sim\frac{1}{2}$° and a relative temperature resolution to ≤0.1°C. Advantages of this technique include (a) no need for an airfield: recent plume surveys have used the power station itself as a take-off and landing area with consequent savings in time and improved communication between helicopter and ground-based scientists. (b) The use of video for data recording permits 'instant' playback which may be used to alter the flight programme very flexibly to re-examine areas of particular interest. (c) Dynamic effects may be observed unlike any other technique which only present 'snapshots'. Disadvantages of the method include those inherent in a less sophisticated imaging system: geometrical distortion and angle-of-view effects can become significant (and are impossible to remove) and quantitative information is difficult to extract. In addition the nature of the imager means that only part of the area of interest is visible at one time.

Aircraft-borne linescan devices have been used by the CEGB for some time. Early equipment was essentially qualitative in its output, often using a variable gain to optimise the sensitivity of the imager and thus losing information about temperatures. Despite this lack of quantitative data these devices gave much guidance and physical insight into the mechanisms at work in plume dispersion and mixing. More recently multi-channel linescan devices have been used which feature on-board recording onto magnetic tape and black-body reference sources to prevent channel drift and to allow data collected in thermal IR bands to be reduced to apparent SST's (Schweitzer, 1982). The imagers have a typical pixel size of 1 m × 1 m and relative temperature resolutions of ≈0.1°C. The advantages of such devices include (a) the ability to cover large areas quickly including the whole alongshore extent of a thermal plume, (b) the relative ease by which contours of temperature may be plotted automatically, (c) the high image quality, (d) the fact that information is available, from multi-spectral devices, in several wavebands means that not only can false-colour images be obtained to give a 'picture' of the site, but the data may be analysed to derive information about sediments, water depths and plankton densities, for example.

Against this must be set the high cost of such equipment and the restriction of the useful area to one swath width from the shore (which might typically be ∿500 m). Aircraft and helicopter-borne imaging systems are thus suitable for the detection of thermal plumes and can follow short-timescale variations through a single tide with high resolution. They are not ideal for the coverage of larger areas and become expensive if required over periods of months.

Use of Satellites

Thermal imagery of the earth's surface from space has been available for several years now from a variety of satellites. The most readily accessible and long term of these are METEOSAT, TIROS/NOAA and LANDSAT. The first of these is in geostationary orbit, the other two are earth-orbiting. The performance of the imaging sensors on board thse satellites, in terms of space and time resolution, is shown in figure 1.

METEOSAT has a sub-satellite pixel size of 5 km or 2.5 km square but is positioned above the equator and so angle-of-view effects increase this at UK locations. Images are transmitted to the ground at 30 minute intervals. The spatial resolution is rather coarse for the detection of artificial heating effects and no real use has been made of METEOSAT data for this purpose by the CEGB.

Recent satellites in the NOAA series have carried the Advanced Very High Resolution Radiometer (AVHRR) which, depending on the satellite, images in 4 or 5 bands including one in the near infra-red and one or two in the thermal infra-red. The AVHRR images over a swath of width 3000 km with a sub-orbital pixel size of 1 km square and a relative temperature resolution of $\approx 0.1°C$. Repeat overpasses of a given location are made at 12 hour intervals, but there are usually 2 operational satellites orbiting in tandem which give 4 images per day of any location. It is seen that the resolution is too coarse for plume studies, could be useful for background field detection and is useful for inshore natural field measurement. The availability of four images through a day allows observation of the solar effects on heat fields.

A number of NOAA images of coastal power station sites have been analysed by use of the GEMS facility at the National Remote Sensing Centre at RAE Farnborough. The results show clearly and in some detail the natural variations and at sites with larger discharges evidence of the artificial background has been observed. This imagery has been used at CERL to try to derive information about dispersion rates and surface heat exchange coefficients in estuaries. It also usefully places an upper limit on the size of artificial heating effects.

Advantages of the NOAA data include (a) relatively frequent repeat coverage of a given area over long periods, (b) the availability of 3 infra-red channels, each of which gives an apparent SST. Differences in the three temperature values can be used to parameterise atmospheric effects, (c) good temperature resolution, (d) the availability of night-time images. Disadvantages include (a) shoreline effects: imaging with a pixel size of 1 km means that data within this distance from the shore is corrupted by incorporation of land areas within the pixel. (b) The large angle of view of the AVHRR leads to geometrical distortions as the swath edge is approached. (c) The similarity between the 12 hour repeat overpass and 12.4 hour tidal periods means that tidal variations are difficult to detect, relying as they do on long cloud-free periods.

The LANDSAT series of satellites has carried a number of imaging instruments but the most valuable from the thermal imaging viewpoint is the Thematic Mapper (TM) on board LANDSAT 5. This device images in 7 bands, including one in the thermal infra-red. Pixel size is 30 m × 30 m in the visible and near IR and 120 m square in the thermal IR channel, with a swath width of 185 km (implying a narrower field of view than NOAA and hence less geometrical distortion). The repeat overpass period is 16 days. Temperature resolution is quoted to be $\sim 0.5°C$. The small pixel size of TM data means that for the first time plumes may usefully be imaged. Against this great advance in resolution must be set the repeat overpass period of 16 days which, together with the launch date of 1/3/84, means that only a small number of cloud-free images of a particular site are currently available.

The potential use of TM data for monitoring plume and background fields is considerable. For this reason a collaborative project is underway between the National Remote Sensing Centre and CERL to determine the quantitative information that may be derived about thermal fields in coastal waters by use of TM data. Early results show promise that this will develop into a valuable tool for the power station design engineer and scientists involved in predictions of thermal fields.

EXTRACTION OF QUANTITATIVE INFORMTION

Having obtained remotely sensed data on apparent SST's from whatever source the question then must be addressed as to how bulk water temperatures (as measured for example by a thermistor probe a few cm below the water surface) may be derived. This topic has been the subject of considerable research. Two sources of error may be identified; the sea surface skin effect and atmospheric effects.

Radiation at thermal IR wavelengths is strongly absorbed by water, with an absorption length scale dependent on wave-length but typically 0.1 mm. The question arises how much the temperature in this 'skin' depth can vary from that a few centimetres below the surface. Air/water heat transfer mechanisms tend to produce a negative temperature gradient near the free surface in which the skin temperature is $\sim$0.5°C lower than the bulk temperature. This difference depends in detail on both atmospheric and sea state conditions and the subject has been reviewed recently by Robinson et al. (1984). It is clearly important to know not only the magnitude of this correction but also its spatial variability over a typical satellite image.

In addition to this skin effect the atmosphere, in particular atmospheric water vapour, can modify the radiation received at a sensor at infra-red wavelengths. Attempts have been made to calculate in some detail the transmission of infra-red radiation through a realistic atmosphere (Sidran, 1980) but in general the atmospheric data required for such a calculation is not available. As a general rule such atmospheric effects generally lead to an apparent blackbody temperature lower than the actual SST.

There are a number of ways in which ground-based measurements may be used to relate apparent blackbody temperatures directly to bulk water temperatures. Many authors (see, for example, Kelly and Davis, 1986) have used an empirical approach in which a linear regression is made of bulk temperature against the apparent SST's seen in the various IR channels. The range of validity of such correlations both in space and time, is questionable but by using such a method r.m.s. errors in bulk temperature predictions may be reduced to $\approx$0.7°C. Interestingly this now makes satellites a more reliable source of oceanic temperatures than routine ship reports.

If the sensing equipment is flown in an aircraft atmospheric effects are less significant than when using satellite data but may still be important, especially if angle of view effects are great. In this case an alternative technique might be to use a boat to measure bulk and ground-level radiative temperatures simultaneously and to fly the aircraft over the boat location at several different heights to determine atmospheric effects.

Another problem when using thermal imagers over the sea is the effect of rainfall. Rain water forms a buoyant layer at the surface and could affect SST's. The question of how long to wait after rainfall before the results of thermal imagery may be trusted is important: a rule of thumb of 1-2 hours is used by some operators. A better estimate might be obtained by looking at turbulent mixing rates in the near-surface region of the sea.

A further difficulty when interpreting satellite imagery is the presence of sub-pixel sized clouds. This phenomenon is often difficult for the engineer to identify and can lead to incorrect conclusions about SST variations.

SOME APPLICATIONS WITHIN THE CEGB

The techniques described above are used primarily as an aid to the mathematical modeller and the power station design engineer, in particular when assessing the potential of a site for a given size of cooling water discharge. In the course of this work a number of physically interesting or unexpected phenomena have been noted which would probably have remained undetected by conventional hydrographic techniques.

It is not always necessary to have quantitative information about temperatures for value to be gained: in many cases it is only necessary to understand the patterns of relative temperature. An example of this is the movement of a power station thermal plume at the turn of the tide. This is a particularly difficult period for the boat-based survey as water currents and hence temperature fields are changing rapidly. At the same time plumes often attain their maximum offshore extent at this period, which must therefore be measured. Continuous overflights of the outfall area by an aircraft or helicopter lead to detailed imagery of slack-water plume movement. For similar reasons it is often valuable to obtain thermal imagery of a site before planning a large-scale hydrographic survey.

The level of detail that may be seen in a remotely-sensed image is at once a challenge and a source of dismay to the mathematician charged with the job of reproducing the observed phenomena. One area which has proved fruitful, however, is that of internal gravity waves which are often detected through their influence on SST's by thermal imagers. These wave systems have been analysed theoretically and in the laboratory (see, for example, the review by Simpson, 1982).

Quantitative information on SST may be used both to derive information about oceanographic parameters and to provide data against which computational models may be tested. A recent research project at CERL, for example, has looked at the use of NOAA 7 and 8 SST data for the determination of dispersion rates in the Severn Estuary. Satellite imagery here comes into its own: synoptic views of SST over an area of thousands of square kilometres may be obtained to a resolution of 120 m in the case of LANDSAT TM. This could not reasonably be achieved by using moored or boat-borne equipment.

DISCUSSION

In this paper an overview has been given of the CEGB's experience in using remote sensing methods to detect thermal discharges from power stations. Attention has been restricted to the application of data collected in thermal infra-red bands and the attendant problems in interpretation.

Remote sensing methods play a valuable complementary role to hydrographic surveys: they provide information about large areas rapidly and to good resolution. However, no information is obtained about depth variations of temperature and these are known to be significant in determining the motion and turbulent mixing of plumes.

The ideal thermal imager for studies of tidal phenomena would have the following features: (a) the ability to produce repeat images at intervals considerably shorter than a tidal period, (b) have temperature and spatial resolutions commensurate with the scales given in table 1, (c) produce its output onto computer-compatible magnetic tape to allow the power of modern image analysis systems to be used, (d) image in several infra-red bands to allow useful atmospheric correction algorithms to be deduced, (e) image simultaneously in visible bands for definition of land masses.

For plume studies the system which most closely matches the above is a multispectral linescan device flown in an aircraft. Helicopters with video imagers are valuable for detailed study of part of a plume, and for dynamic studies. Neither of these methods is ideally suited to the measurement of large areas or for use over long periods, however, and for these purposes satellite imagery is becoming increasingly of value; NOAA for its frequent coverage and LANDSAT TM for its resolution. Future improvements in performance can be anticipated and provided the cost of satellite data does not become prohibitive an increasingly significant rôle may be expected of this data in guiding everyday engineering decisions.

ACKNOWLEDGMENTS

The author would like to thank Mike Boswell of Space Department and Jan van Smirren of National Remote Sensing Centre at RAE Farnborough for invaluable assistance in using the GEMS image analysis facility. The work was carried out at the Central Electricity Research Laboratories of the Technology Planning and Research Division and the paper is published with permission of the Central Electricity Generating Board.

REFERENCES

Kelly, K.A. and Davis, R.E., 1986, An analysis of errors in sea surface temperature in a series of infrared images from NOAA 6: Journal of Geophysical Research, Vol. 91, No. C2, pp 2633-2644

Pickles, J.H. and Rodgers, I.R., 1985, Vertical heat transport in a cooling water plume: Turbulence and diffusion in stable environments, Clarendon Press, Oxford

Robinson, I.S., Wells, N.C. and Charnock, H., 1984, The sea surface thermal boundary layer and its relevance to the measurement of sea surface temperature by airborne and spaceborne radiometers: Int. J. Remote Sensing, Vol. 5, No. 1, pp 19-45

Schweitzer, G.E., 1982, Airborne Remote Sensing: Environmental Science and Technology, Vol. 16, No. 6, pp 338A-346A

Sidran, M., 1980, Infrared sensing of sea surface temperature from space: Remote Sensing of Environment, Vol. 10, pp 101-114

Simpson, J.E. 1982, Gravity currents in the laboratory, atmosphere and ocean: Annual Reviews of Fluid Mechanics, Vol. 14, pp 213-234

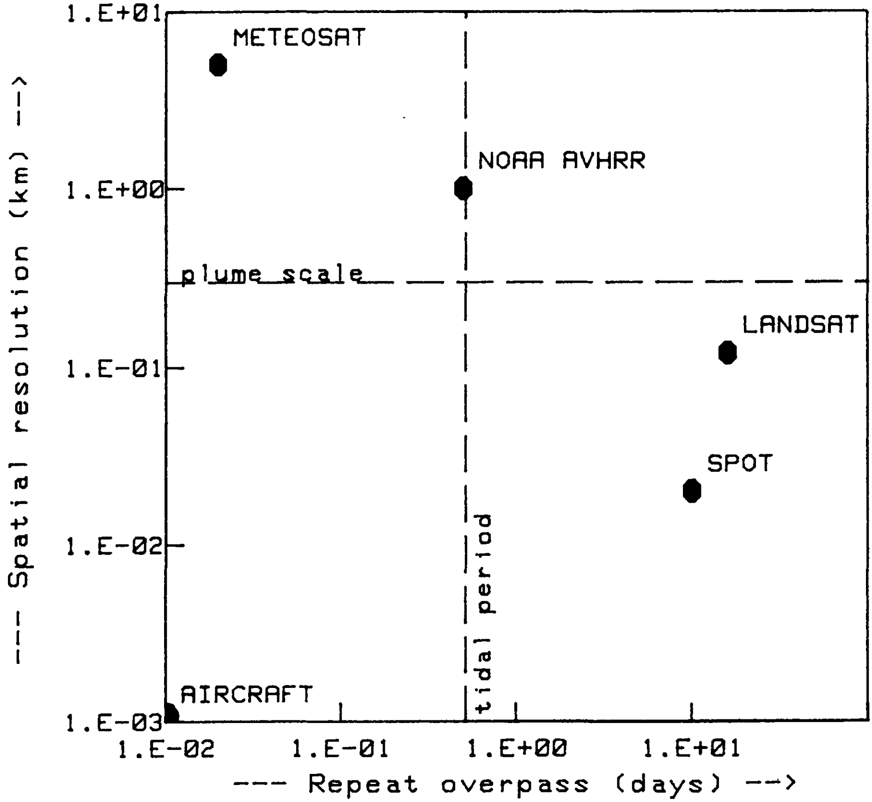

Figure 1: Comparison of Spatial and Temporal Resolutions