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# Shipboard Measurements of Air-Sea Temperature in the Evaporation Duct

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## INTRODUCTION

Surface-based evaporation ducts often exist at the boundary between the atmosphere and the ocean surface. The environmental conditions at this boundary can significantly affect electromagnetic radiation propagating through the medium and consequently can significantly influence radio and radar transmissions. The refractive properties of the surface evaporation duct are dependent upon the air temperature and moisture profiles immediately above the ocean surface. Models have been developed<sup>1</sup> for calculating ducting conditions and have been used by the U.S. Navy in the Integrated Refractive Effects Prediction System (IREPS) since 1978. The evaporation duct height may be calculated by measuring wind speed, sea surface temperature, air temperature, and relative humidity.

Problems with measuring the required parameters, especially temperature, from ships at sea are well known.<sup>2-6</sup> Air temperature has typically been measured on ships with hand-held sensors or by instruments remotely mounted on the masts. Measurements using these methods have often been contaminated by the thermal influence of the ship and are highly dependent on the selected location. Water temperatures have typically been determined by measuring the seawater intake for engine cooling with readings taken from analogue gauges located in the power plant spaces by engine-room personnel. Calibration and reading errors are common. These water inlets do not measure surface temperature because they are located well below the surface and are also subject to thermal contamination.

Even more important than absolute accuracy in air and sea temperature measurement is relative accuracy. Differences between air and sea temperature are generally small, and under certain conditions large errors result in the calculation of duct height. The relative accuracy of the air-sea temperature difference is most important for these cases since the difference has the greatest effect on the calculated duct height. The use of two independent instruments read by two observers at two locations is definitely the wrong instrumentation approach. Large relative errors (of several degrees centigrade) would be expected and have been observed under these conditions. Clearly, a better approach is needed.

## SELECTION OF MEASURING INSTRUMENTS

Desirable features in a shipboard instrument for improving IREPS air-sea temperature measurements would include the following:

1. Small; present a minimal storage and procurement problem (and therefore, be nonexpendable).
2. Easy and quick to use; important in the difficult operational shipboard environment, especially aircraft carrier use.
3. Portable; capable of being readily moved to the optimum shipboard location.
4. Battery powered; long life, non-lithium.
5. Inexpensive.
6. Susceptible to minimal external environmental influence from, for example, ship thermal effects, solar radiation, wind, rain, fog, wave height, salt spray, and electromagnetic interference (EMI).
7. Fast thermal response.

8. Capable of measuring both air and sea temperature.
9. Absolute accuracy:  $\pm 1^{\circ}\text{C}$ .
10. Relative accuracy:  $\pm 0.1^{\circ}\text{C}$ .
11. Resolution/read-out:  $0.1^{\circ}\text{C}$  minimum.
12. Inherently capable of achieving high relative accuracy; capable of being easily field-checked and adjusted if necessary.
13. Easy to calibrate; capable of being calibrated in the field or at pierside, thus, minimizing laboratory calibrations with long downtimes.
14. Capable of measuring sea temperature at the surface, not at some depth.

Several instruments were considered and empirically evaluated in order to improve the quality of the shipboard temperature measurements. Generally these fall into two categories: resistance temperature devices (RTD) and noncontact sensors such as infrared (IR) sensors. In order to properly compare different sensors, experimental work was conducted in the laboratory, at various piers, on ships pierside, and finally onboard an underway ship. Wind tunnel tests determined sensor time constants in air, while tank tests determined air-water time constants. In addition, self-heating, radiation errors, noise levels, and the long-term stability of sensors were estimated.

From the beginning it was felt that a portable system was better than a fixed installation. Modern electronic components allow a unit to be not only portable but small and lightweight. Portability allows measurements to be taken in the best shipboard location available at the time and thereby minimizes undesirable influences. Portability also allows the sensor system to be stored in a clean, dry location and to be checked, cleaned, or adjusted if needed.

Whether sensors should be expendable or retrievable was considered next. If RTD sensors were to be used, it was felt that retrievable types would not be practical. The potential damage to small fast-response sensors during deployment or cleaning, the effect of wind on the cables to which they are attached, and the problems of hand-coiling these cables, all detracted from the reusable sensor.

If a portable, expendable RTD sensor was used, the launching method would have to be safe, easy to approve, and the kind that does not use explosives or other restrictive devices. This led to the approach of hand-throwing a sensor away from the ship. For this, the sensor would have to have enough weight to be easily handled and thrown, even under high wind conditions. Keeping the sensor simple, rugged, and easy to use was of great importance. Launching methods using multiple sensors, parachutes, and surface floats were intriguing, but were rejected for practical reasons.

An expendable RTD sensor would have to be fast, low cost, interchangeable, and easy to assemble. Thermistors were considered and tested at first, but were later rejected because they failed to meet all of these objectives. Sensors with a sufficiently fast time response, especially in air, are less than 0.25 mm (0.01 in.) in diameter, cost more than \$10 each, have poor interchangeability (typically 20%), and require highly skilled labor during assembly.

Thermocouples with small time constants are readily available at reasonable costs. Lower outputs, marginal interchangeability, and some added electronic complexity, however, reduce their attractiveness somewhat. For these reasons, the use of thermocouples was shelved for this application. But they may be useful as sensors for research purposes and should not be rejected completely.

The chosen method of data transmission from the RTD sensors back to the ship was hard wire, specifically a standard XBT wire, using a 4-20 mA current loop or frequency-modulated signal. These wires are readily available, low cost, small, and lightweight. RF links were considered and rejected because of potential interference problems in an operational shipboard environment. Also rejected was the use of fiber optic cables because of the expense and the narrow bandwidth actually required for the intended use. Both of the methods should be reconsidered for research versions at a later time.

Taking all these considerations into account, it was decided to evaluate two measurement systems—a commercially available combination IR/RTD system and a NOSC-developed RTD profiling system.

Although remote IR sensors were initially rejected because of the technical problems usually associated with them, a new hand-held combination IR/RTD instrument with many desirable features is now available commercially. This instrument was included in a sea test aboard the aircraft carrier U.S.S. *Ranger*. The results of that test and an evaluation of the instrument will be described in the following section.

Profiling RTD expendable sensors made from small insulated wires were eventually constructed and satisfied most of the requirements. The large surface-to-mass ratio of the wires, along with reasonable costs and assembly methods, made this sensor the first choice. Tests and descriptions of this device are included later in this report.

## IR/RTD SYSTEM

### DESCRIPTION

The IR/RTD device used was an Everest Interscience Inc. model 110C hand-held thermometer originally developed for agricultural use. The instrument was loaned by the manufacturer for evaluation at no cost. It is a self-contained, microprocessor-based, portable, battery-operated device with digital display. Pertinent specifications from the manufacturer follow:

Overall Configuration. . . . .	Small (25 cm long × 75 mm in diameter) Light (1 kgm)
Scale Range . . . . .	-30°C to 100°C
Optical Configuration . . . . .	Precision 50-mm refractive optics; completely corrected for spherical aberrations
Field of View . . . . .	3 degrees, includes solid angle between half-intensity rays
Spectral Pass-Band . . . . .	8-14 microns
Display . . . . .	13-mm liquid crystal, 3 1/2 digits
Operating Distance . . . . .	2 cm to infinity
Response Time . . . . .	Less than 0.5 second
Accuracy . . . . .	±0.5°C
Linearity . . . . .	±0.1°C
Resolution . . . . .	±0.1°C
Noise Effective Temperature . . . . .	Less than 0.05°C
Operating Environment . . . . .	0°C to 65°C, up to 90% relative humidity
Nonoperating Environment . . . . .	-20°C to 65°C
Power Source . . . . .	Rechargeable nickel-cadmium batteries

Two options were also supplied. First, air temperature was measured with a small gold-foil-covered thermistor located at the end of a short rod which is pulled from the housing. When a button is pushed, the difference between the ambient air temperature and the absolute surface temperature of the water is displayed on the digital display. The second and most important option furnished was an upward-looking sensor which automatically senses and continuously applies a correction factor for sky radiation.

The following instructions and tips for proper use were given:

1. Keep the sun at the operator's back.
2. Don't get salt deposits or finger prints on windows. Clean windows with alcohol and cotton swabs.
3. Keep sighting depression angles between 45 and 90 degrees.
4. Allow air temperature thermistor 1 minute to equilibrate.

The proper operation of the instrument was verified before and after the sea tests with the aid of a NOSC calibration facility, a well-stirred temperature-controlled water bath. Bulk bath temperature is measured by a platinum resistance thermometer, with calibration traceable to the National Institute of Standards and Technology (formerly the National Bureau of Standards), with resultant absolute errors less than 0.005°C. Readings were taken while aiming the IR sensor at the bath a few inches above the surface and with the air temperature thermistor (RTD) submerged 5 cm. Results of this calibration were encouraging and are shown in Table 1.

**Table 1.** Calibration of Everest Interscience Model 110C IR Sensor, S/N 1363.

Bulk Water Bath Temp. (°C)	Pretrip		Posttrip	
	Water Temp. <sup>a</sup> (°C)	Delta T <sup>b</sup> (°C)	Water Temp. <sup>a</sup> (°C)	Delta T <sup>b</sup> (°C)
15.00	15.2	-- <sup>c</sup>	15.1	+0.1
17.00	17.1	--	17.0	0.0
19.00	19.0	--	19.0	0.0
21.00	20.9	--	20.9	-0.1

<sup>a</sup>Measured by IR sensor.

<sup>b</sup>Difference between air temperature measured by RTD thermistor and water temperature measured by IR sensor.

<sup>c</sup>Data not taken.

## SEA TEST

The recommended procedure written for use of the IR/RTD device during the sea test was as follows:

1. Operate in a location with minimum airflow disturbance.
2. Stand in the shade if possible.
3. Remove instrument from carrying case.
4. Aim at sea surface, away from sun, using a 45-degree depression angle, and record value in log book.

5. Measure and record air temperature value in log book.
6. Replace instrument in case.

Figure 1 shows the instrument in use from the quarter deck, starboard side, at an elevation of 11 meters above the water. Measurements were taken on a not-to-interfere basis and had to fit into a busy ship routine which included 12 hours of flight operations a day. As a result, best-made plans often went on hold and quick improvising was a necessity.



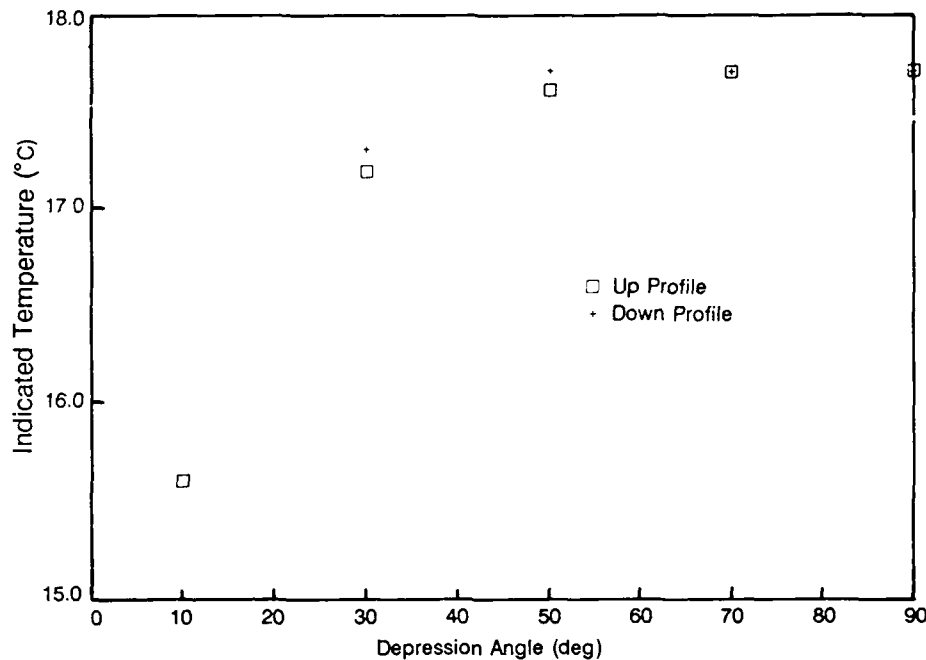
Figure 1. Weather Officer LCDR T. McPherson with infrared sensor.

In order to address the accuracy of measurements taken, a brief descriptive summary of pertinent tests and their results will now be given.

### **Water Temperature**

Effects on the surface water temperature by the ship's hull could not be seen except in the main wake. Indicated water temperature was remarkably constant, within 0.1-0.2°C, as profiles were taken perpendicular to the ship axis through turbulent boundary layer water to and beyond the bow waves and associated white-water patches. Ship speed ranged from 10 to 29 knots, with wind speed between 5 and 15 knots. An example of data taken from the "weather deck," located very far aft, with the depression angles measured by eye is shown in Fig. 2. Note the constant indicated temperatures, with good repeatability for the recommended range of depression angles of 45 to 90 degrees.





**Figure 2.** Sea surface temperature profile from weather deck; 6 Oct 1988, 1038; ship speed, 12 knots; wind speed, 15 knots; measurement elevation, 13 meters.

Note also how rapidly the indicated temperature drops for depression angles less than the recommended 45 degrees. Unfortunately, the platform geometry did not permit safe observation of sight angles back toward the hull. If profiling all the way back to the ship's hull could be done, eventually some rise in surface water temperature would be expected. Obviously, the carrier's large cantilevered hull and deck structure extending from bow to stern is a real advantage for hand-held IR sensor pointing. An angle of 60 to 80 degrees is recommended and easy to accomplish.

### Air Temperature

Radiation errors on the gold-foil-covered thermistor and conduction errors down the stainless steel mounting rod are unknown. Experiments to determine the magnitude of these effects were inconclusive; however, comparison with other independent RTD sensors during the sea test was generally good. It is felt that these problems are not serious and can be reduced to acceptable levels if required.

Power dissipation in the air temperature thermistor is not known. Such information can be obtained from the sensor manufacturer, and with a knowledge of the electronic circuit, the self-heating error could be estimated.

In order to minimize ship contamination, measurement location is critical, especially during flight operations. Measurements taken from different levels of the island showed large temperature variations, up to several degrees. Warm updrafts from aircraft on the flight deck and contamination from hot air vents were severe. Unfortunately, observers using hand-held instruments tend to migrate toward these warm locations, especially during long watches. Some ship's radar interference was noticed at elevations of the flight deck and above. Overall, therefore, it is felt that the best location for measuring air temperature with a hand-held sensor is from one of the forward

catwalks or platforms at the 03 level. Going to the "best" part of the ship is simply not practical on an operational ship of this size, because of the added safety restrictions of movement during flight operations. If the sensor is easy and quick to use (e.g., 1-2 minutes), acceptable locations could be determined and would be used. Locations forward are preferred, close to the weather office. Written guidelines and common sense from the observers will both be required.

Fixed mounted IR and RTD sensors were considered; however, because of the presence of salt spray and other particulates on the windows, the long-term reliability of fixed mounted sensors would be uncertain. Fixed mounting would have two other serious drawbacks. First, the temperature difference between the IR sensor and thermistor could not be field-checked easily and therefore would probably not be done even at pierside. This is an easy test to do with the hand-held sensor, simply by covering it with aluminum foil and waiting a few minutes for equilibrium. The delta temperature can be easily read from the display and adjusted for zero if needed. A second problem with a fixed sensor with a remote read-out, say in the weather office, would be the recognition of temporary heat source artifacts. During the sea trip, fixed RTD sensors showed large variations with time. One mounted for 24 hours at the bow recorded temperature variations of several degrees during flight operations. Effects of a plane warming up or taking off would never be noticed when it is time to take a reading ("arm chair oceanography").

The conclusion is that air temperature is not easy to measure accurately, especially during flight operations. However, as with the water temperature measurements, the cantilevered shape of the ship's hull provides acceptable locations for hand-held instruments.

## PROFILING SYSTEM

### DESCRIPTION

A fast-response expendable RTD sensor which could be thrown by hand from the ship's influence was developed for the NOSC-developed profiling system. The single sensor measures both air and water temperature profiles as it falls. The complete instrument is small, battery operated, and completely portable, allowing operation from the optimum part of a ship. Capable of being hand-thrown, it is also safe and easy to use.

The construction of the sensor, as shown in Fig. 3, consists of a small-diameter, coated resistance wire wound on an open frame in order to achieve fast time response.<sup>7-11</sup> Other reasons for choosing wire sensors are the low initial material cost, the ease of probe construction, and the good interchangeability from sensor to sensor. The AWG number 40 bifilar wound wire is aligned with the fluid flow to minimize errors from radiation emitted by and reflected from the surface as well as strain gage effects upon impact with the water. This sensor and signal-conditioning electronics are mounted inside a thin, white, painted plastic tube, externally weighted. Care was taken to minimize thermal conduction and radiation errors to the sensor while maintaining good fluid flow past the sensor. As shown in Fig. 4, the battery-operated signal-conditioning electronics provides an optically isolated frequency output proportional to temperature which is carried to the surface recorder by a standard two-conductor XBT wire. The completed probe fits into a lengthened XBT canister stored in a hand-held launcher.

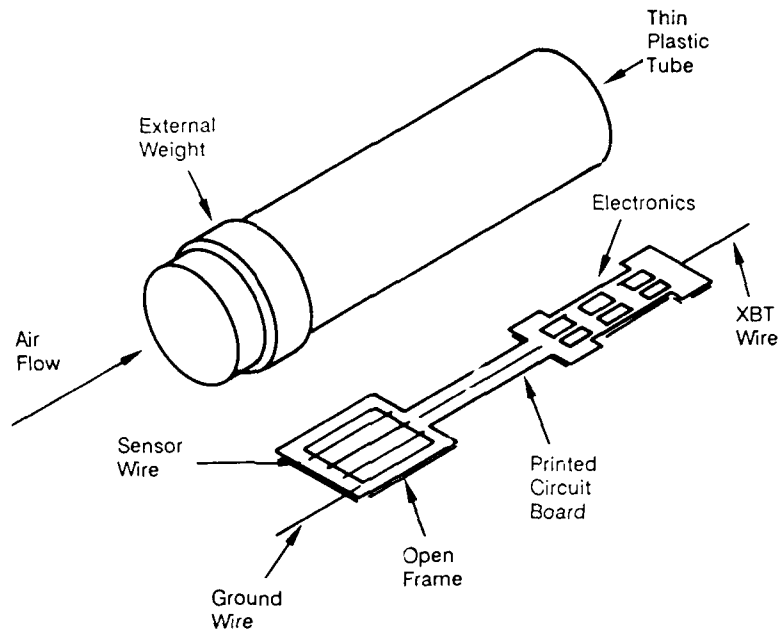


Figure 3. Sensor construction.

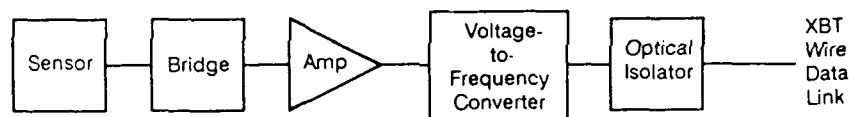


Figure 4. Block diagram of profiling system.

Temperatures recorded on the battery-operated recorder are processed and plotted at a later time on a desk-top computer. Later operational packaging could have microprocessor-based special-purpose computers to calculate and display the mean air temperature and the temperature of the near-surface water. Electronic and construction details down to the individual parts level have taken many various forms and thus will not be given here, but can be furnished by the author upon request.

Temperature calibrations were performed by sensor immersion in the same controlled water bath described earlier. During this development phase, all sensors were individually calibrated. This would not be necessary, however, for production-type work of large numbers of probes. The interchangeability of sensors was fair, generally within  $\pm 0.5^\circ\text{C}$ . Long-term sensor stability was good, with errors less than  $\pm 0.1^\circ\text{C}$ , and absolute system accuracy with individual calibrations was within  $\pm 0.5^\circ\text{C}$ .

The water bath calibration was used for the sensor during both air and water temperature profiles. An empirical proof of accuracy during the air portion of the profile was more difficult, due in part to larger sensor self-heating. In order to test this, the sensor dissipation constant was measured in a wind tunnel at  $400 \text{ mW}/^\circ\text{C}$ . With the current electronics, this corresponds to an acceptable  $0.005^\circ\text{C}$  error.

Figure 5 shows the probe being hand-thrown. The battery-operated data recorder is suspended from a neck strap, leaving both hands free to handle the launcher and

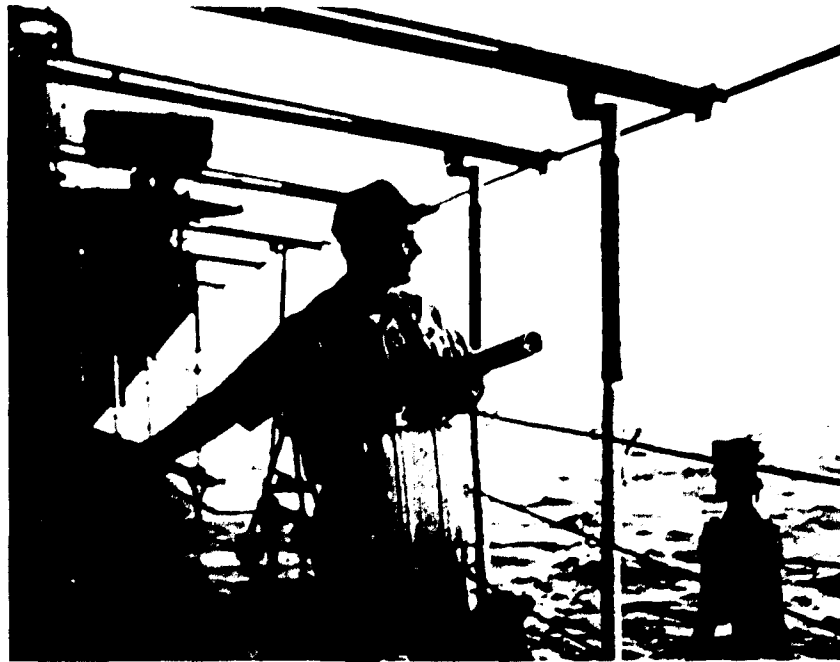


Figure 5. Crewman throwing profiling sensor from the deck of the U.S.S. Ranger.

probe. In order to maximize the distance from the ship, the probe is thrown up and out at an angle of 45 degrees to the horizontal. This also gives the sensor the maximum time to come into thermal equilibrium with the air medium. The simple trajectory in Fig. 6 is calculated for each throw and each temperature time series is converted to an elevation-vs.-temperature plot. The time of the splash point is determined by observation from the plotted data and then more accurately from the digitized data listing. Independent "splash sensors" were designed, but were not implemented for lack of time. As the sensor hits the water, an assumption is made that the speed reduces exponentially from the terminal air value to some new terminal water value. To determine the constants required, empirical average speeds are measured for the first 1 and 2 meters in the water by removing the insulation from the XBT wire at these locations and looking for the resulting large output change. It should be emphasized that for the operational requirements, a complete temperature profile is not required, only air and surface water values. Therefore, a precise determination of the trajectory is not required. Air temperatures are generally an average from 5 to 10 meters elevation, and water temperature is taken as soon as the sensor has equilibrated.

Throwing involves the first time constant of importance, namely, that from equilibrium of the sensor in air on the ship to the generally cooler air when thrown. To evaluate this response the time constant was measured for a step-function input in a small wind tunnel by quickly moving the probe in a transverse direction behind a splitter plate separating two air masses with different temperatures. Sensor time constants at 63% of the step input obtained with this method measured about 80 ms (Fig. 7). These sensors, therefore, are sufficiently fast to reach good equilibrium by the time they arrive at the trajectory apex.

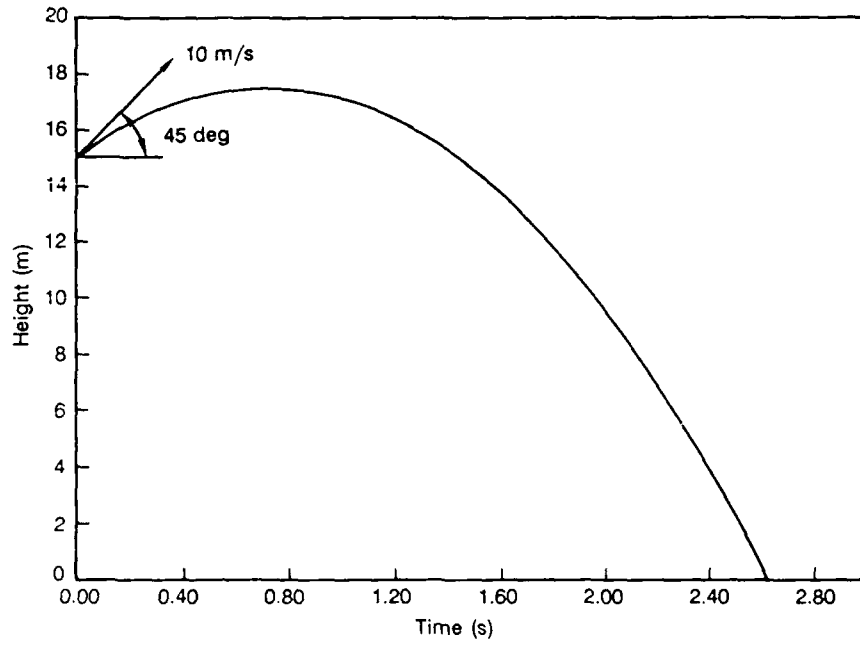


Figure 6. Typical trajectory of hand-thrown probe.

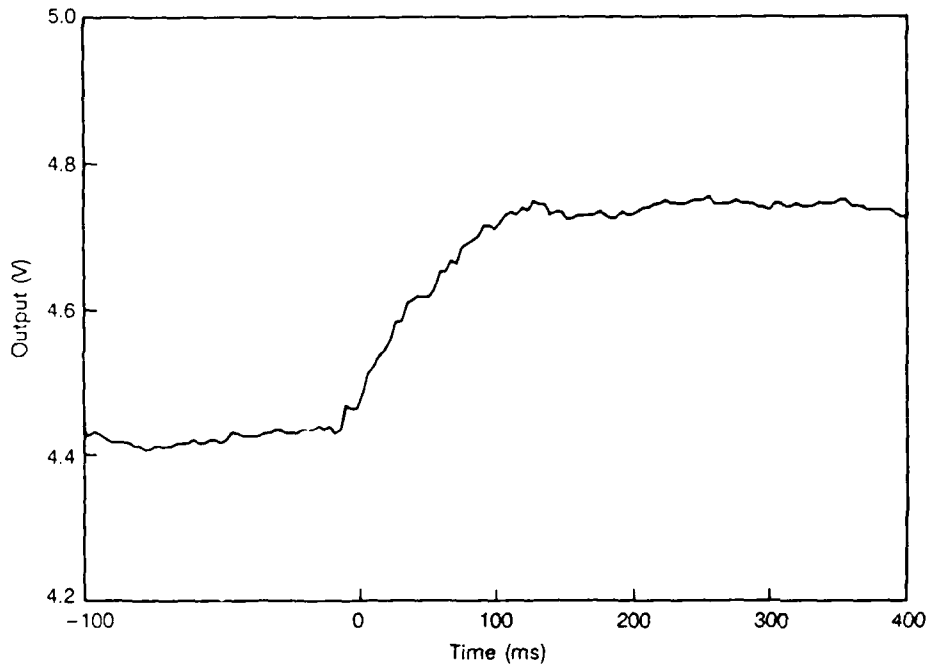


Figure 7. Response to air-to-air step temperature input.

The second time constant of interest is that from air to water. This is the more traditional measured quantity obtained by plunging the probe from air into a water bath. Results are subject to large experimental errors,<sup>12</sup> but are about 7 ms, as shown in Fig. 8.

Caution should be taken in using the equilibrium value after, say, 5 or 10 time constants for the surface temperature. During periods of low wind stress, sizable temperature gradients near the surface have been reported.<sup>13-20</sup>

The expendable sensor has an advantage when used near the air-sea boundary, namely that of a clean, dry sensor. Problems with contamination, especially for fast-response sensors, can be troublesome and have been documented.<sup>21-23</sup>

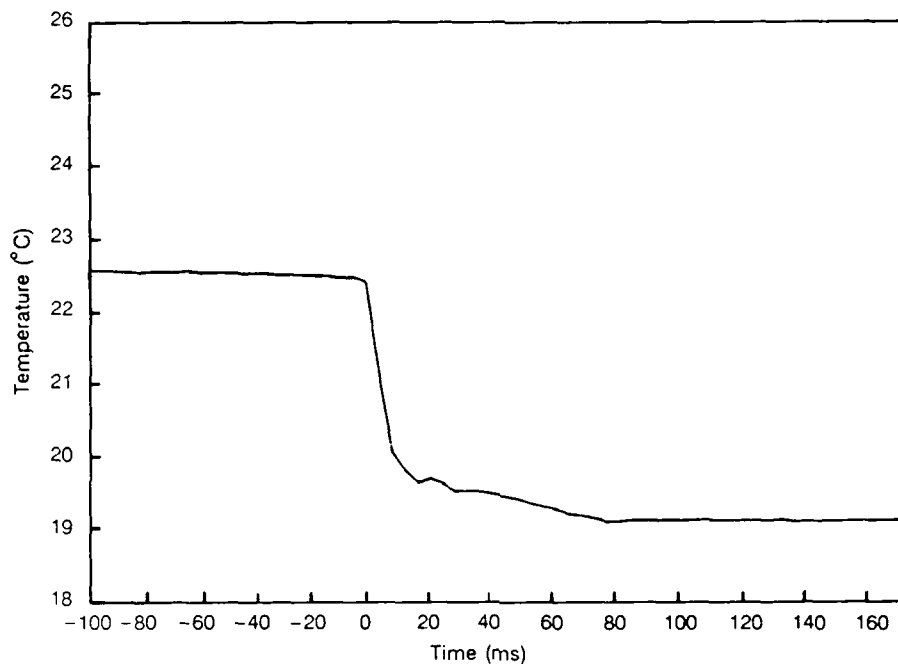


Figure 8. Air-water time response.

## SEA TEST

The profiling system was also tested during the sea trip aboard the U.S.S. *Ranger*. A total of 20 sensor probes were thrown or dropped under different conditions and in various locations. In spite of operational restrictions and some RFI, the use and results were generally satisfactory. When RFI was a problem, it was usually severe. Pickup through the XBT wire data link increased as the wire spooled out. Radio transmitting antennas extending horizontally from the flight deck in the aft portion of the ship gave the largest interference as they were located just above the throwing area. The effectiveness of various filters and shielding schemes on some of the probes was inconclusive. EMI is a serious problem that cannot be ignored for any sensor system on ships of this type.

Figure 9 shows an example of a throw without RFI from the quarter deck. The rapid cooling of the temperature sensor and the splash point can be seen. When this temperature time series is converted to an elevation-vs.-temperature plot, the result is shown in Fig.10. Again, the rapid cooling of the sensor is apparent as well as the splash point. Note the good agreement with the IR/RTD system and independent RTD truth sensors, but poor agreement with the ship values.

Another example of data is shown in Fig. 11. This throw from the weather deck shows increasing RFI as the probe falls to the water.

In summary, the profiling sensor has great potential for many applications but is not recommended for the present need. Instead, it is more suited for a research environment. Disadvantages for operational use when compared with the IR/RTD system are as follows: not as small and easy to use; has expendables which have to be purchased and stored; does not measure surface water temperature; is more susceptible to RFI problems; and gives more information than required, adding unnecessary complexity.

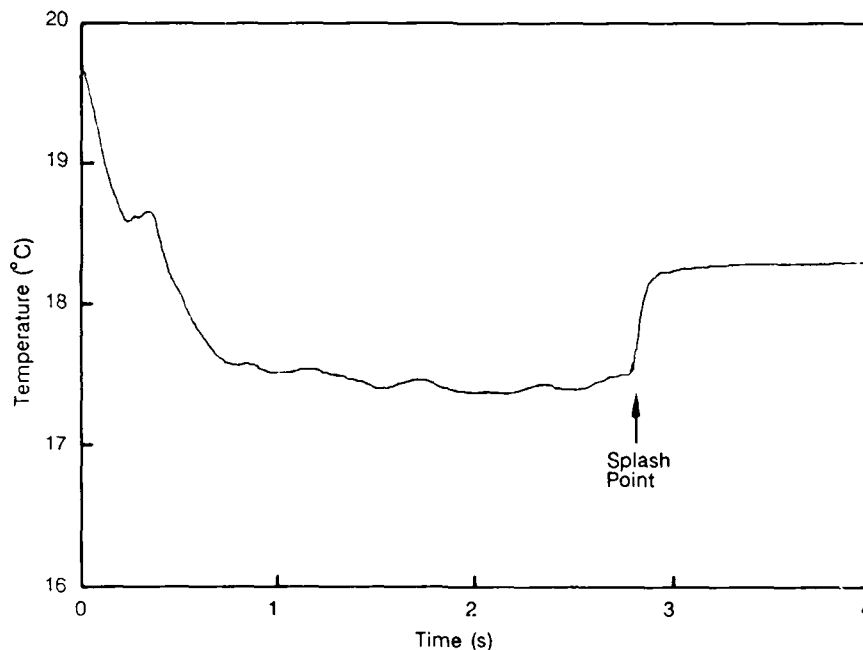


Figure 9. Time series of throw from quarter deck; 0850, 5 Oct 1988; ship speed, 10 knots; wind speed, 7 knots; RH, 78%.

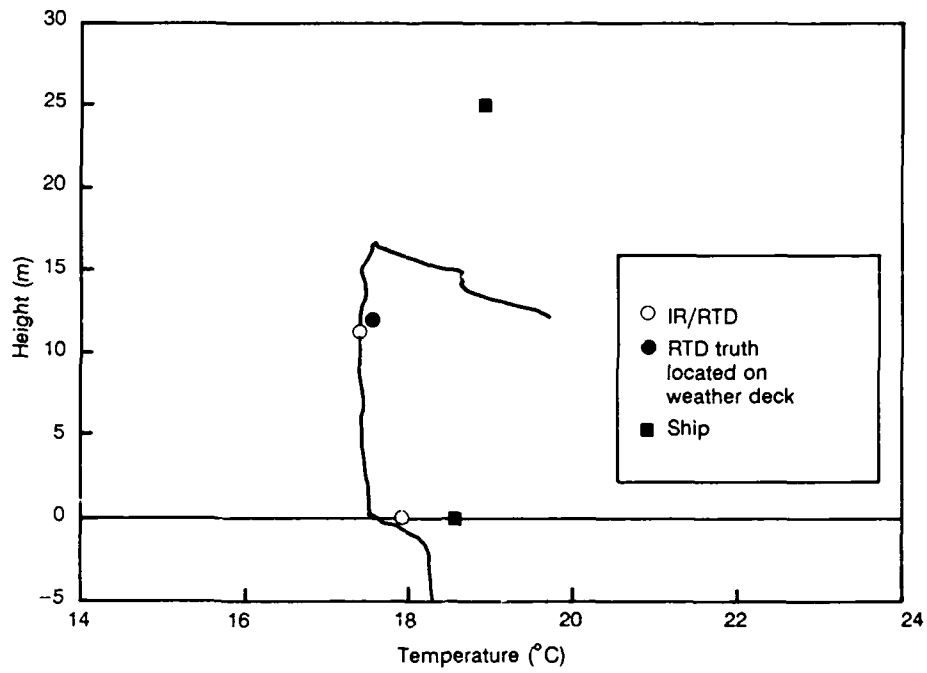


Figure 10. Height vs. temperature for Fig. 9 data.

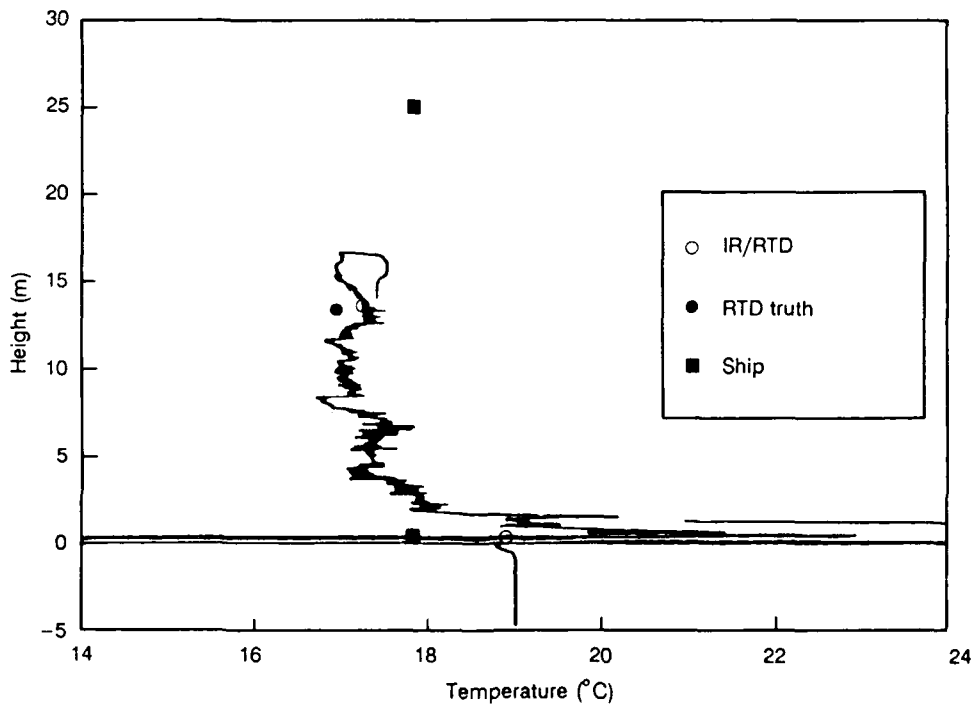


Figure 11. Height vs. temperature from the weather deck of the U.S.S. Ranger; 0902, 4 Oct 1988; ship speed, 8 knots; wind speed, 2 knots; RH, 78%.



## RESEARCH OPTIONS

The profiling sensor would be useful for air-sea interaction research studies. Lifting constraints placed by Navy operational use would permit many other options and deployment methods. Some possibilities will be briefly listed:

1. Larger profiling distances can be obtained by—
  - a. Launching the sensor from balloons, rockets,<sup>24</sup> and aircraft, and by employing slingshots and compressed air.
  - b. Lowering the sensor to greater ocean depths, say 100 meters.
2. Higher resolution profiles can be obtained by—
  - a. Adding parachutes to achieve a slow drop rate.
  - b. Achieving faster time constants with smaller wires.
  - c. Achieving faster time constants with small thermocouples.<sup>25-27</sup> Less expensive electronics are possible. Relative temperature profiles are easier to achieve.
3. Other methods of data links, such as RF links or fiber optics, can be used.
4. Other sensors can be used, such as relative humidity sensors or pressure transducers for the direct measurement of altitude or depth. (Inexpensive, small, low-power pressure sensors are now commercially available.)
5. The profiling sensor can be used in conjunction with the IR sensor, which can determine the real surface temperature.

## CONCLUSIONS

The IR/RTD system manufactured by Everest Interscience, Inc., is small, easy and quick to use, with no expendable components. The upward-looking sensor automatically correcting for sky radiation is an indispensable feature. When this system is used properly, air and sea surface temperature measurements of sufficient accuracy can be obtained for the intended application. Under operational Navy shipboard use, the ease of use is of utmost importance. If a measuring system is too hard to set up and use, it simply will not be used properly.

The profiling system in conjunction with the IR/RTD system would make a useful research tool for air-sea boundary studies.

## RECOMMENDATIONS

1. Buy two or more IR/RTD systems from Everest Interscience, Inc., with the following options:
  - a. Upward-looking sensor
  - b. Thermistor air temperature sensor
  - c. Rugged germanium windows
  - d. Air and sea temperature displays
  - e. Read and hold feature for displays
  - f. LCD illumination for night work
  - g. Relative humidity read-out
  - h. More rugged carrying case
2. Perform controlled laboratory tests on the received instruments.
3. Perform at-sea tests with two or three instruments operated simultaneously from different locations under operational conditions.
4. Determine and document a matrix of acceptable environmental operating conditions.
5. If above results are satisfactory, incorporate into the Fleet.

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