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## THESIS

THERMISTOR VALIDATION AND PATH RADIANCE  
EFFECTS IN SHIP THERMAL IMAGE MEASUREMENTS

by

David S. Wood

September, 1991

Thesis Advisor:

Alfred W. Cooper

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| 19 ABSTRACT (Continue on reverse if necessary and identify by block number)<br>Thermal images in the 8 - 12 micrometer band were taken of the research vessel R/V POINT SUR in the Monterey Bay on 7 May 1991. The images were recorded using the AGA Thermovision 780 with an IBM AT computer using CATS 2.1 software. Corrections for computed transmittance, path length, and emissivity were made to the image files utilizing the locally developed computer program AGACATS. Temperature measurement distributions made with the AGA 780 compared to thermistor measurements of the ship temperatures were found to be extremely close (within one degree) at ranges of one half and one mile. PC-Tran in the radiance mode was than used to compute the path radiance to the ship and compared with the path radiance correction in the AGA 780 algorithm. The AGA measurements varied over the range from twenty-five to seventy-five percent while the LOWTRAN fraction ranges only from seventy-five to eighty-five percent with the biggest discrepancy occurring at the short paths. The predicted path radiance as |       |                                                  |                                                                                                            |                                                                  |                                  |
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EFFECTS IN SHIP THERMAL IMAGE MEASUREMENTS

by

David S. Wood  
Captain, United States Marine Corps  
B.S., University of Florida

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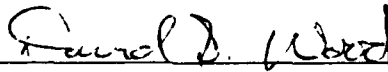
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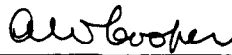
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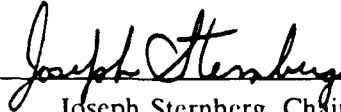
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Alfred W. Cooper, Thesis Advisor



Edmund A. Milne, Second Reader



Joseph Sternberg, Chairman  
Electronic Warfare Academic Group

## ABSTRACT

Thermal images in the 8 - 12  $\mu\text{m}$  band were taken of the research vessel R/V POINT SUR in the Monterey Bay on 7 May 1991. The images were recorded using the AGA Thermovision 780 with an IBM AT computer using CATS 2.1 software. Corrections for computed transmittance, path length, and emissivity were made to the image files utilizing the locally developed computer program AGACATS. Temperature measurement distributions made with the AGA 780 compared to thermistor measurements of the ship temperatures were found to be extremely close (within one degree) at ranges of one half mile and one mile. PC-TRAN in the radiance mode was then used to compute the path radiance to the ship and compared with the path radiance correction in the AGA 780 algorithm. The AGA measurements varied over the range from twenty-five to seventy-five percent while the LOWTRAN fraction ranges only from seventy-five to eighty-five percent with the biggest discrepancy occurring at the short paths. The predicted path radiance as computed using LOWTRAN 6 *did not fall off as much* with decreased slant range as the AGA path radiances. This difference may be attributed to problems with either the AGA algorithm or the LOWTRAN code, or with the accuracy of the inputs. A contributing factor may be the time delay of one to one and a half hours between the image data and the radiosonde balloon launch.

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## I. INTRODUCTION

Forward Looking Infrared (FLIR) technology is utilized on a daily basis by Navy/Marine tactical aircraft. FLIR systems are currently employed by military planners in the detection, identification and recognition of targets of tactical importance. A commander needs to know the standoff ranges at which an enemy can detect a ship using passive infrared (IR) sensors so that an estimate can be made of the time needed to perform countermeasures against weapons that are launched.

The performance of many military systems using FLIR technology is highly reliant on environmental conditions in the area of tactical operation (Figure 1.1).[Ref. 1]

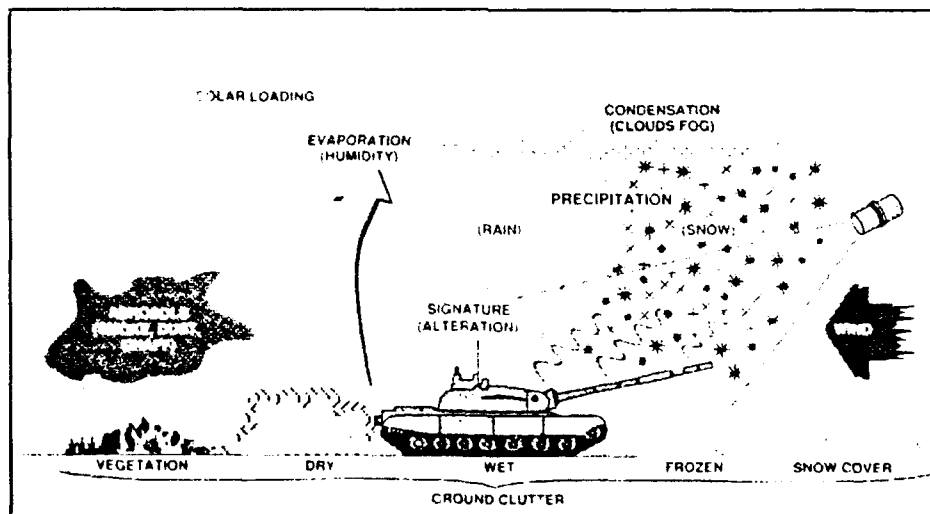


Figure 1.1 Environmental Effects on IR [Ref. 1]

These systems can have their effectiveness seriously degraded by atmospheric conditions such as precipitation, snow, clouds,

and aerosols due to absorption, scattering, refraction, and reflection of the infrared (IR) energy along the transmission path (Figure 1.2).

| WEATHER PARAMETERS | VISIBLE AND NEAR IR | SHORTWAVE IR       | MIDWAVE IR          | LONG WAVE IR        | MMW              |
|--------------------|---------------------|--------------------|---------------------|---------------------|------------------|
| LOW VISIBILITY     | SEVERE              | MODERATE           | LOW                 | LOW                 | NONE             |
| RAIN-<br>SNOW      | MODERATE            | MODERATE           | MODERATE            | MODERATE            | MODERATE-<br>LOW |
| HIGH HUMIDITY      | LOW                 | LOW                | MODERATE            | MODERATE            | LOW NONE         |
| FOG<br>CLOUD       | SEVERE              | SEVERE             | MODERATE-<br>SEVERE | MODERATE-<br>SEVERE | MODERATE<br>LOW  |
| PHOSPHORUS<br>DUST | SEVERE              | SEVERE<br>MODERATE | MODERATE            | MODERATE            | LOW<br>NONE      |
| FOG OIL<br>SMOKE   | SEVERE              | MODERATE           | LOW                 | LOW                 | NONE             |

Figure 1.2 Effects of Weather on IR at Different Wavelengths [Ref. 1]

In order to achieve the best possible performance for a FLIR system, Tactical Decision Aid (TDA) computer codes have been developed which are based on target and background characteristics and atmospheric conditions as well as FLIR parameters. Estimates of FLIR system performance against a target are frequently based on an assumed temperature difference between a target and its background. Computational algorithms are applied to determine the range at which the assumed temperature difference is lowered by the atmospheric IR transmittance to the minimum detectable temperature difference (MDTD) of the sensor system. This technique disregards the consequences of sky radiance reflections and

the atmospheric path emission contributions to the entire background scene which change with viewing angle and altitude of the sensor.

Mission planners and on-scene commanders use the Updated FLIR (UFLIR) prediction model which is a function of the Tactical Environmental Support System (TESS). UFLIR is an atmospheric computer program which provides expected ranges with a 50% probability to detect, categorize, and identify targets utilizing airborne FLIR sensors. The infrared sensors act as electronic cameras which image targets (ships, submarines, vehicles, etc.) by intercepting the excess IR radiation they emit as a result of being warmer than the surrounding environment. A sensor's capability of detecting or recognizing a target is dependent upon the image contrast. The image contrast is the difference between the target and background emittance. When a target is viewed against a uniform background of identical temperature, as in the case of a vehicle which has not moved in several days, it will be less easily detectable. The most advanced military IR sensors can detect temperature differences of less than one degree celsius and are extremely effective in detecting targets at night.

## II. THEORY AND BACKGROUND

The purpose of this chapter is to give the reader a fundamental understanding of IR radiation and its relationship to the electromagnetic spectrum. This chapter will also review the terminology and equations upon which the study of IR radiation is founded.

### A. THE INFRARED (IR) SPECTRUM

IR radiation is a small segment of the total electromagnetic spectrum which includes other forms of radiation (radio waves, X-rays, visible light, etc.) which are organized into bands or ranges according to wavelength or frequency as shown in Figure 2.1 [Ref. 2:p. 20].

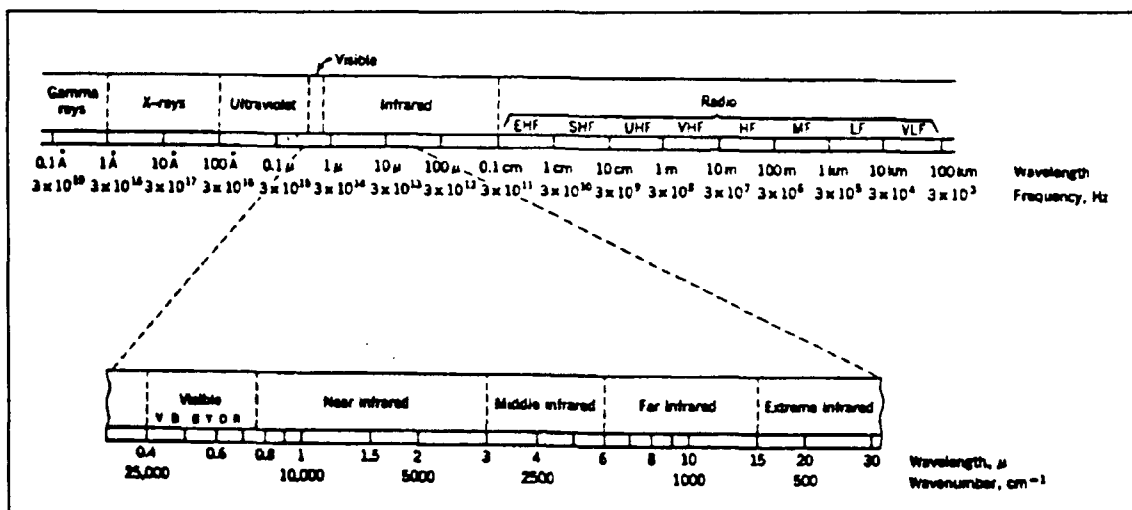


Figure 2.1 Electromagnetic Spectrum [Ref. 2]

The wavelength and frequency are related by the equation:

$$c=f\lambda \quad (1)$$

where  $c$  is the speed of light in meters per second,  $f$  is the frequency in Hertz, and  $\lambda$  is the wavelength in meters.

The IR band comprises the wavelength range from  $0.75 \times 10^{-6}$  [m] to  $1.00 \times 10^{-3}$  [m] or the frequency range from  $3.00 \times 10^{11}$  [Hz] to  $4 \times 10^{14}$  [Hz] and is divided into three regions - near, middle, and far infrared. Because IR radiation is a part of the electromagnetic spectrum, it will "obey the laws of reflection, refraction, diffraction, and polarization". [Ref. 2:p. 20]

## **B. THERMAL RADIATION**

In order to discuss the different quantities associated with IR radiation, an understanding of the vocabulary, terms, and laws must be conveyed. The equations and definitions for this section were primarily taken from Hudson [Ref. 2:p. 35-64], notes from Dr. Cooper [Ref. 3] and Lloyd [Ref. 4].

### **1. Blackbody Radiation and IR (Planck's Law)**

All objects that are at temperatures above absolute zero radiate IR energy into the electromagnetic spectrum. The amount of energy emitted is dependent upon the size and temperature of the object and the wavelength. The spectral radiant emittance is the radiant power emitted per unit area

of a source per unit wavelength interval ( $W_\lambda$  [ $\text{Wcm}^{-2}\mu\text{m}^{-1}$ ]). A benchmark used as the best radiator of IR energy is defined as a "blackbody". A blackbody theoretically emits and absorbs the greatest possible amount of thermal radiation at any given temperature, radiates at all wavelengths, and is perfectly diffuse. The spectral radiant emittance from a blackbody is given by Planck's Law:

$$W_\lambda = \left( \frac{2\pi hc^2}{\lambda^5} \right) \left( \frac{1}{e^{ch/\lambda kT} - 1} \right) \left[ \frac{\text{watts}}{\text{cm}^2 \mu\text{m}} \right] \quad (2)$$

where:

$\lambda$  = wavelength [m]

$k$  = Boltzmann's constant

=  $1.38054 \times 10^{-23}$  [W sec/ K]

$h$  = Planck's constant

=  $6.6256 \times 10^{-34}$  [W sec<sup>2</sup>]

$T$  = temperature (K)

Planck's Law is fundamental to all FLIR systems and is valid for the entire electromagnetic spectrum. This equation is graphically expressed for several temperatures in Figure 2.2.

## 2. Stefan-Boltzmann Law

Integrating Planck's Law yields the radiant emittance for a blackbody source over a spectral band as shown in the following equation:

$$W = \int_{\lambda_1}^{\lambda_2} W_\lambda d\lambda \quad (3)$$

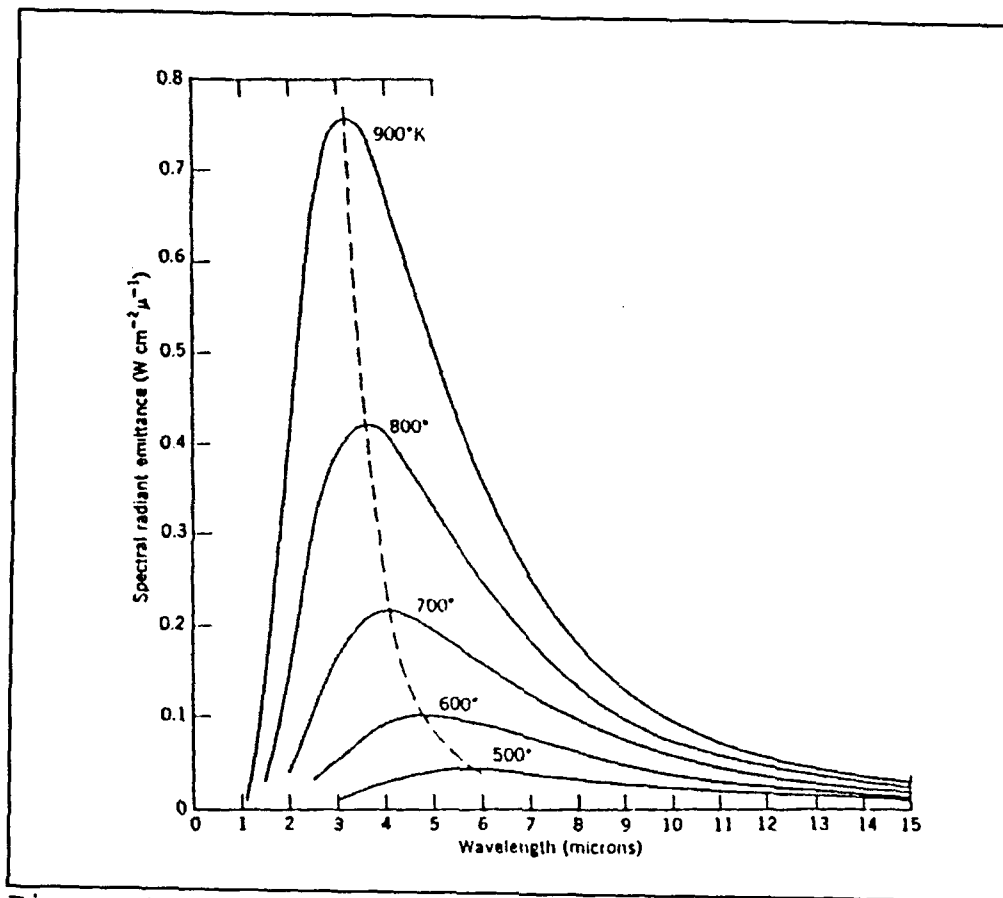


Figure 2.2 Spectral Radiant Emittance [Ref. 2]

where  $W_\lambda$  is the spectral radiant emittance while  $\lambda_1$  and  $\lambda_2$  are the spectral band boundaries. The Stefan-Boltzman Law is then derived by performing the above integration over the wavelength interval of zero to infinity resulting in:

$$W = \sigma T^4 \quad (4)$$

where:

$W$  = the radiant emittance in  $[W/cm^2]$

$\sigma$  = Stefan-Boltzman constant

=  $5.6697 \times 10^{-12} [W/cm^2 K]$

$T$  = temperature in Kelvin (K)

From the above expression the total radiant emittance of a blackbody source for all wavelengths can then be found.

### 3. Emissivity of an Object

The emissivity ( $\epsilon$ ) of an object is the ratio of the radiant emittance of the target or source to the radiant emittance of a blackbody at the same temperature. Most objects within our surroundings emit only a fraction, which is known as "emissivity", of blackbody radiant power. The values of emissivity are in the range of zero to one with one being a blackbody (Figure 2.3). Therefore the Stefan-Boltzmann law is written as follows:

$$W = \epsilon \sigma T^4 \quad (5)$$

In addition, a graybody has a constant emissivity less than unity and a selective radiator is one in which the emissivity varies with the wavelength [  $\epsilon(\lambda)$  ].

When radiant energy is incident on a surface, it will be reflected, absorbed or transmitted as shown by the following equation:

$$\alpha + \rho + \tau = 1 \quad (6)$$

where:

$\alpha$  = the fraction of energy absorbed,

$\rho$  = the fraction of energy reflected,

$\tau$  = the fraction of energy transmitted.

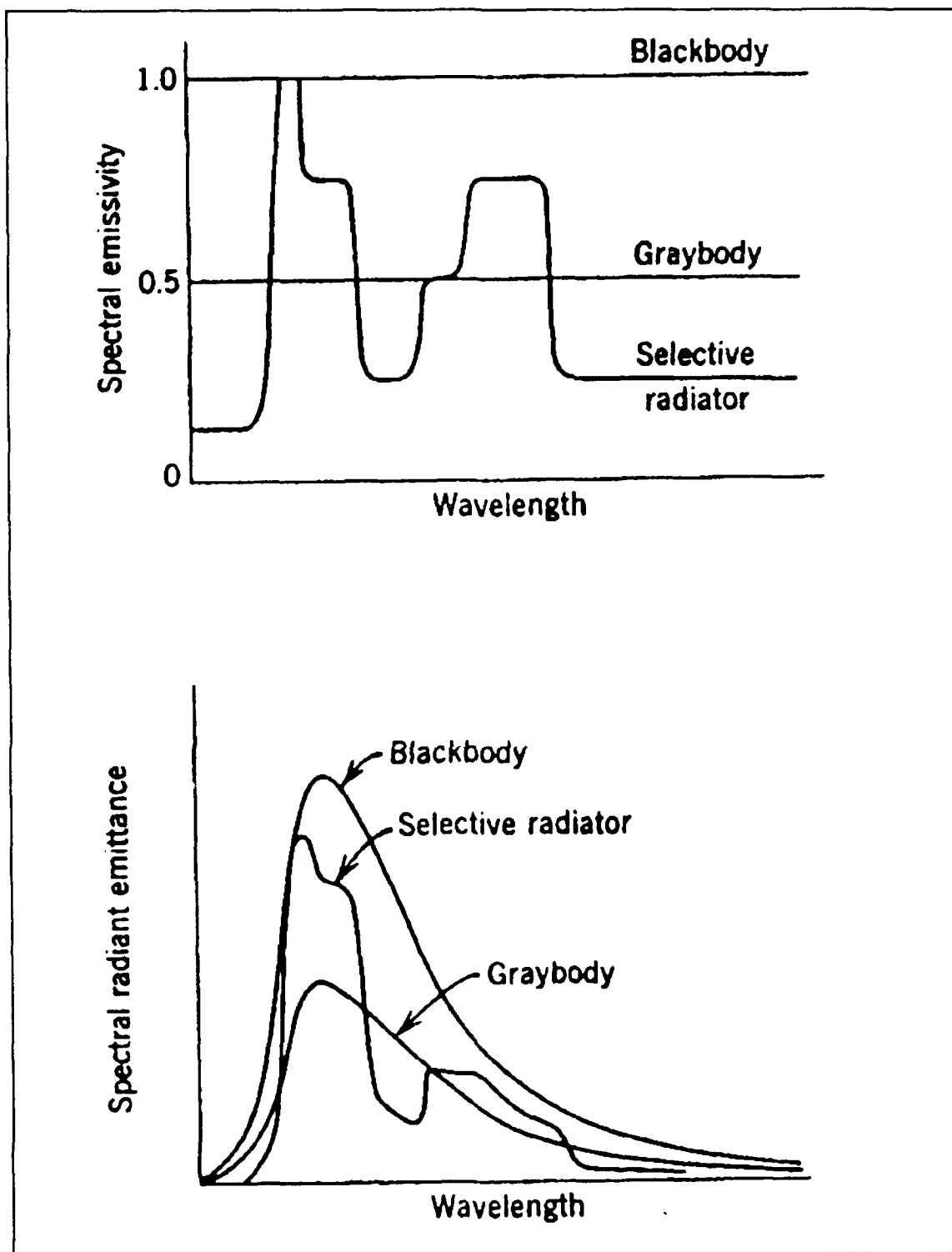


Figure 2.3 Spectral Emissivity and Spectral Radiant Emittance of Three Types of Radiator [Ref. 2]

By definition for an opaque object:

$$\epsilon = 1 - \rho \quad (7)$$

### C. ATMOSPHERIC EFFECTS

As shown in the Figure 2.4 , the majority of energy radiated by an object at atmospheric temperatures ( $\sim 300$  °K) will be in the  $3.0 - 14.0 \mu\text{m}$  region of the electromagnetic spectrum. The atmospheric transmittance is clearly a function of the wavelength which consequently produces windows in the  $3.5 - 5.0 \mu\text{m}$  and  $8.0 - 14.0 \mu\text{m}$  range. At other wavelengths the transmittance ( $\tau$ ) is diminished. The  $8.0 - 14.0 \mu\text{m}$  range is generally used because it has the advantage of performing better in haze, which is typical for long slant paths through humid environments.

#### 1. Lambert-Beer Law

The atmospheric transmittance [  $\tau_a(\lambda)$  ] at a specific wavelength for a specific set of atmospheric conditions is delineated by the Lambert-Beer Law:

$$\tau_a(\lambda) = \exp(-\mu(\lambda)R) \quad (8)$$

where:

$\lambda$  = the specific wavelength

$\mu$  = the extinction coefficient

$R$  = the range or path length.

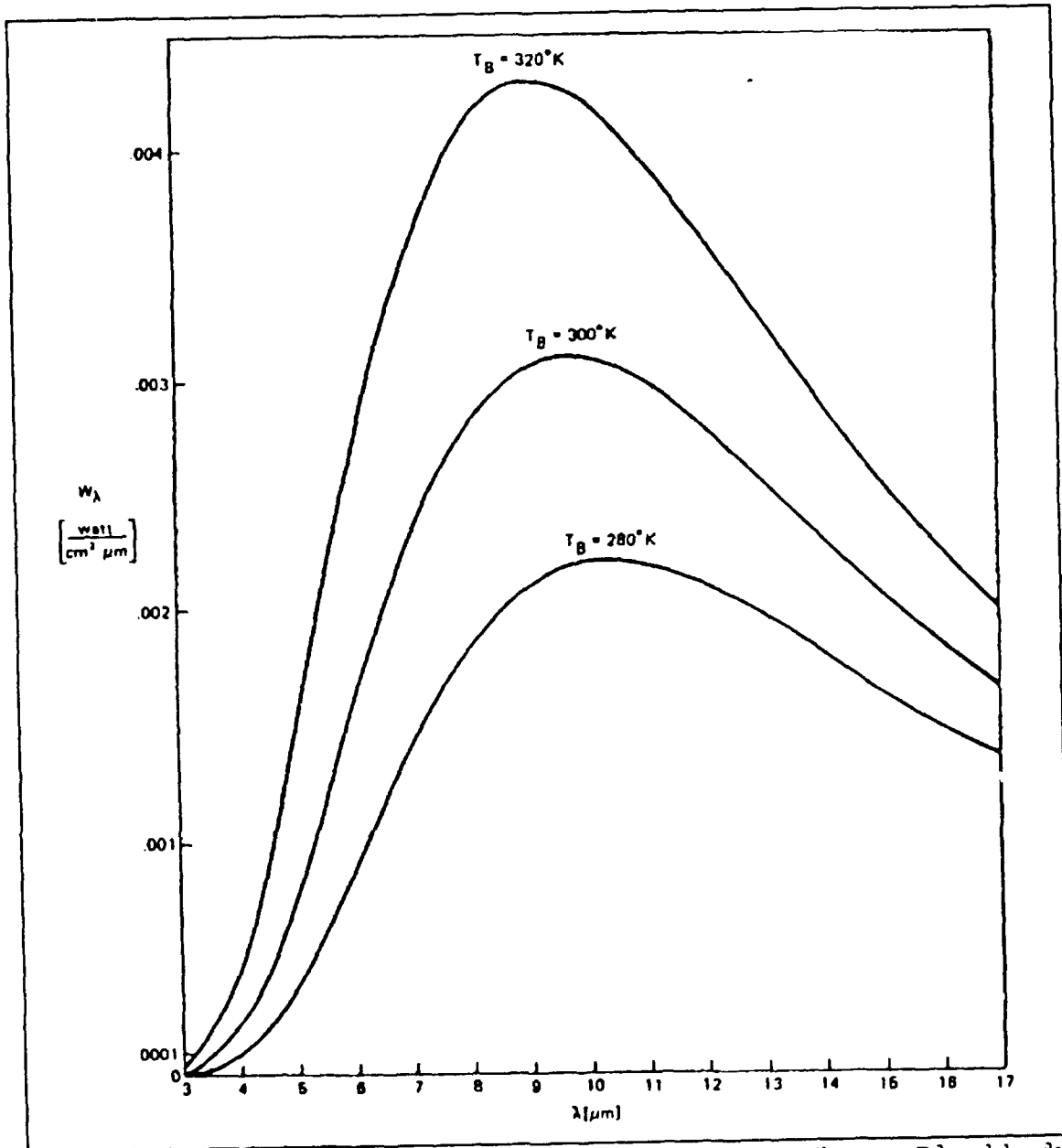


Figure 2.4 Spectral Radiant Emittance for Three Blackbody Temperatures [Ref. 4]

The average transmittance between two wavelengths is then written as:

$$\tau_a = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \exp[-\mu(\lambda)R] d\lambda \quad (9)$$

## 2. Absorption and Scattering

Absorption and scattering are two means by which IR attenuates as it propagates through the atmosphere. The attenuation is generally referred to as atmospheric extinction. Extinction is also a function of the wavelength of the IR signal. Figure 2.5 shows the spectral transmittance measured over a 6000 foot horizontal path at sea level.

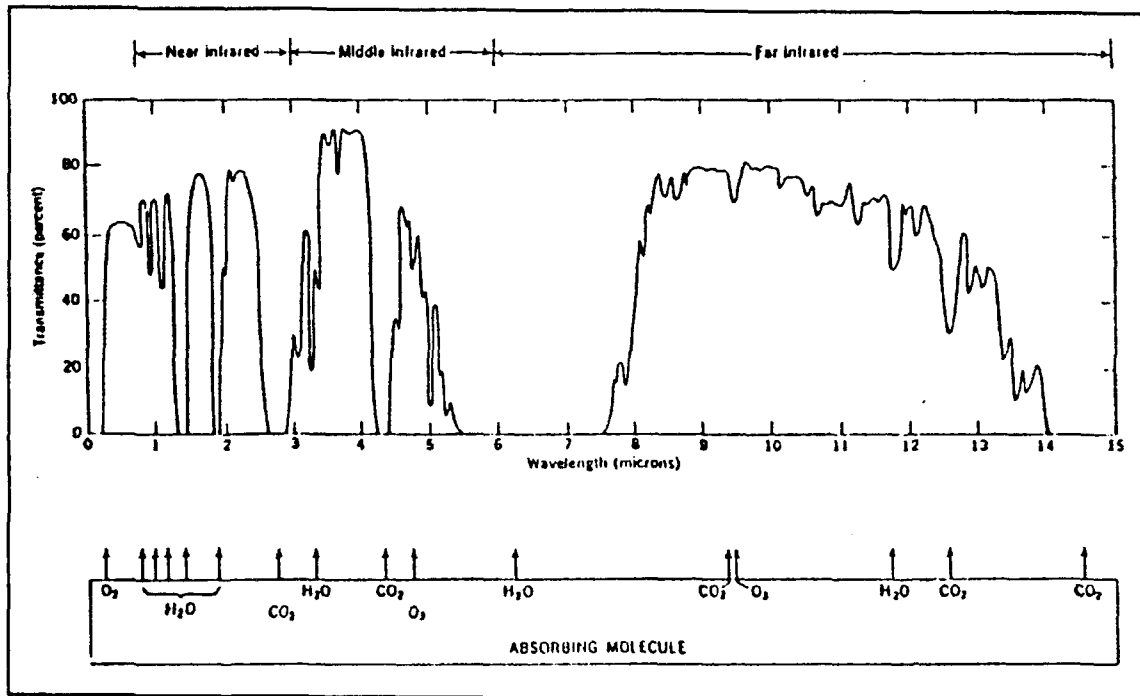


Figure 2.5 Infrared Windows [Ref. 2]

The total extinction coefficient is the sum of the coefficients for total absorption and total non-forward scattering as depicted in the following equation,

$$\mu = \mu_a + \mu_s \quad (10)$$

where:

$\mu$  = Total extinction coefficient

$\mu_a$  = Extinction coefficient for total absorption

$\mu_s$  = Extinction coefficient for non-forward scattering

Absorption and scattering can then be further divided into the sum of molecular absorption, aerosol absorption, molecular scattering and aerosol scattering coefficients:

$$\mu_a = k_m + k_a \quad (11)$$

$$\mu_s = \sigma_m + \sigma_a \quad (12)$$

where:

$k_m$  = Molecular absorption coefficient

$k_a$  = Aerosol absorption coefficient

$\sigma_m$  = Molecular scattering coefficient

$\sigma_a$  = Aerosol scattering coefficient

Scattering by both aerosols and molecules has the greatest effect in the visible region, and absorption in the IR region of the electromagnetic spectrum.

Water, carbon dioxide, ozone, nitrous oxide, carbon monoxide, and methane are the principal causes of molecular absorption. [Ref. 4:p. 30] Absorption affects atmospheric transmission by attenuating thermal radiation which consequently limits the spectral range to the two windows described above.

There are four standard types of aerosols - maritime, continental, urban, and stratospheric. Maritime aerosols primarily consist of salt water particles. Wind speed dictates

the concentration of the salt particles which are released from the ocean. Organic material, iron, sulphates, and silicon are the main contributors to continental aerosols. Urban aerosols are composed mainly from pollution resulting from industrial products and are typically found around cities. Stratospheric aerosols are predominantly sulphates and volcanic ash or dust.

### 3. LOWTRAN 6

LOWTRAN is a Fortran program, developed by the Air Force Geophysics Laboratory (AFGL), that calculates atmospheric transmittance and thermal radiance. The frequency range for LOWTRAN is from  $350\text{ cm}^{-1}$  to  $40000\text{ cm}^{-1}$ . The LOWTRAN code calculates transmittance at low spectral resolution, primarily  $20\text{ cm}^{-1}$  increments. The model contains code which calculates the refraction and earth curvature along the atmospheric slant paths. The atmosphere is handled as 33 layers from zero to a hundred kilometers.

The input to LOWTRAN consists of several "cards" or "input screens" which are used to define the atmospheric parameters for the model. If radiosonde data is used, the program will request data for the atmospheric layers. A maritime model is also included in the LOWTRAN code which includes the effects of wind and sea spray.

LOWTRAN 6 also provides the following four types of output  
[Ref. 5]:

1. path transmittance
2. path transmittance and path radiance
3. path transmittance and path radiance including single scattered contribution
4. directly transmitted solar irradiance

#### D. CONTRAST TRANSFER FUNCTION

How well a thermal imaging system is able to see a target against some background is highly dependent upon the radiation contrast. Radiation contrast is defined as:

$$C = \frac{(W_T - W_B)}{(W_T + W_B)} \quad (13)$$

where:

$W_T$  = the target radiant emittance

$W_B$  = the background radiant emittance

The contrast between target and background is frequently expressed as the temperature difference between them,  $\Delta T$ , which will provide this contrast. For image analysis the criterion for target detection is that  $\Delta T$  should exceed the minimum detectable temperature (MDT) for the sensor. The radiation contrast curves for four background temperatures are shown in Figure (A.5). [Ref. 4:p. 29]

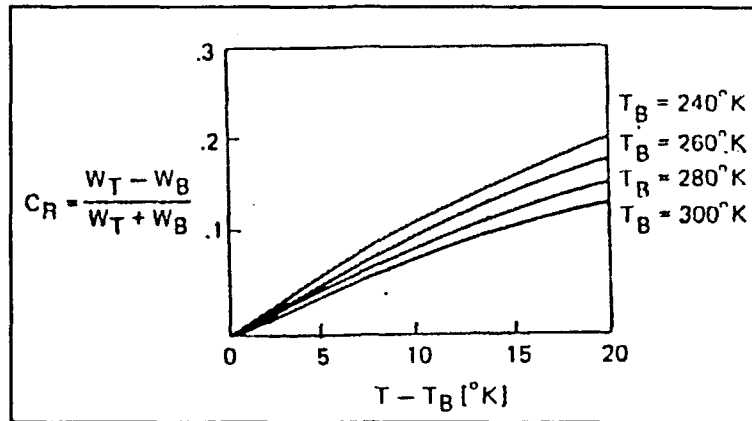


Figure 2.6 Radiation Contrast  
(8 - 14  $\mu\text{m}$  band)

### **III. DATA COLLECTION**

#### **A. GENERAL**

The research vessel R/V POINT SUR was used in gathering data during the period 7 May - 11 May 1991 in conjunction with the biannual NPS student meteorology cruise. The R/V POINT SUR carries a full suite of automatically recording meteorological and oceanographic instruments. The ship also provided hourly observations of ship position, air temperature, sea temperature, weather conditions, visibility, sea state, ship speed and heading, and surface wind speed and direction. The ship launched Rawinsondes to record the air temperature, pressure, and relative humidity profiles in the atmosphere up to 10,000 feet. Fourteen thermistor temperature sensors were mounted on the ship at various locations to measure the skin temperature of the hull and stack. The sensors were used to validate the temperature measurements made by the AGA on 7 May 1991. During the cruise radiance contrast measurements and FLIR range observations were collected.

#### **B. SHIP IMAGES RECORDING**

An AGA Thermovision 780 (Figure 3.1) with an IBM AT personal computer running CATS 2.1 software was used to collect images in the 8-14 micrometer band of the R/V POINT

SUR at the Navy beach off NPS.[Ref. 6] CATS 2.1 is a software package which allows the acquisition and storage of thermal images on an IBM AT computer hard disk.[Ref. 7] The images were recorded of the ship from different angles at one-half mile and one mile as shown in Figure (3.2). The AGA had to be initialized with the ambient air temperature around the ship, the ship distance, the ship emissivity, and the atmospheric transmittance.

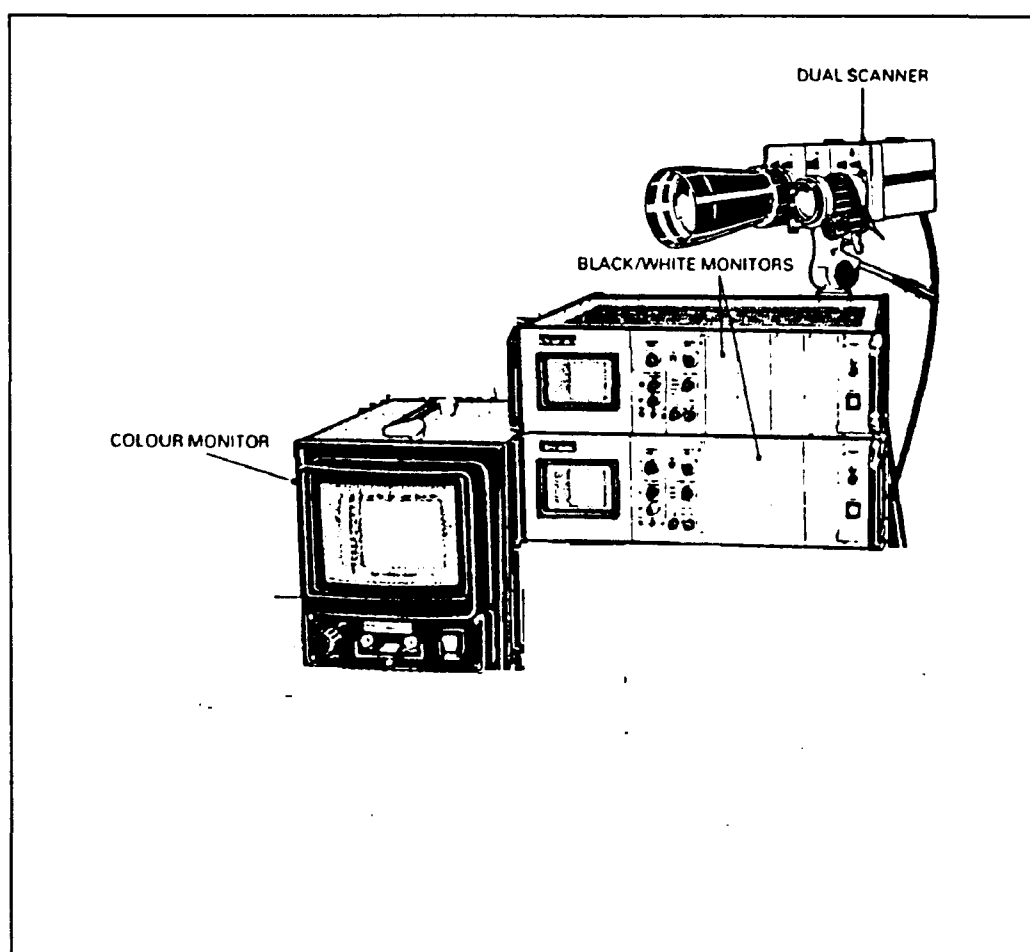


Figure 3.1 Dual Band AGA 780 Showing Scanner, Black and White Monitor and Color Monitor.

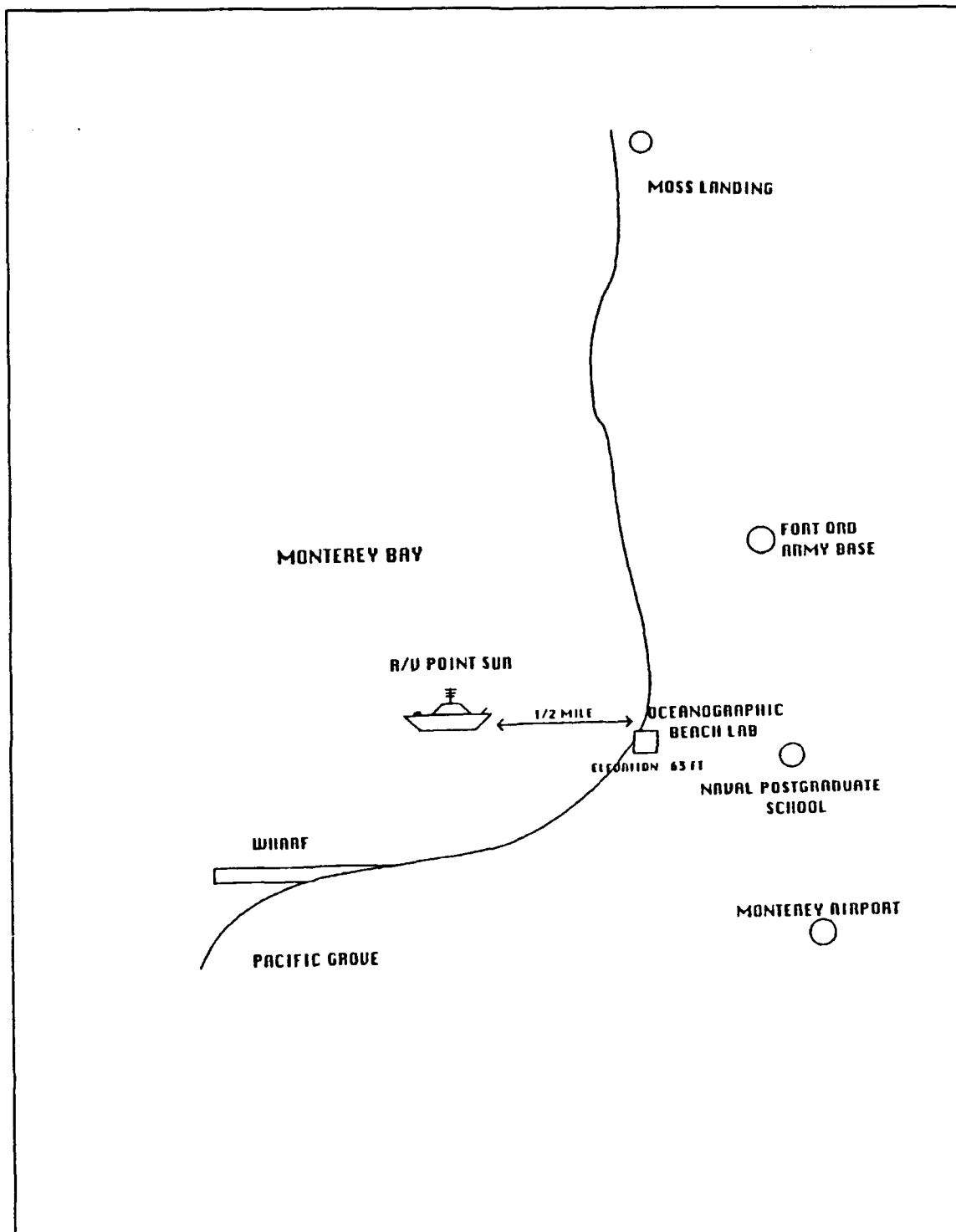


Figure 3.2 Site of Experiment

### C. THERMISTOR DATA

The skin temperature measurements of the R/V POINT SUR were recorded using fourteen thermistors distributed over the ship as shown in Table 3.1 and depicted in Figure (3.3). A portable computer aboard the ship was used to collect the temperature values for the duration of the cruise.

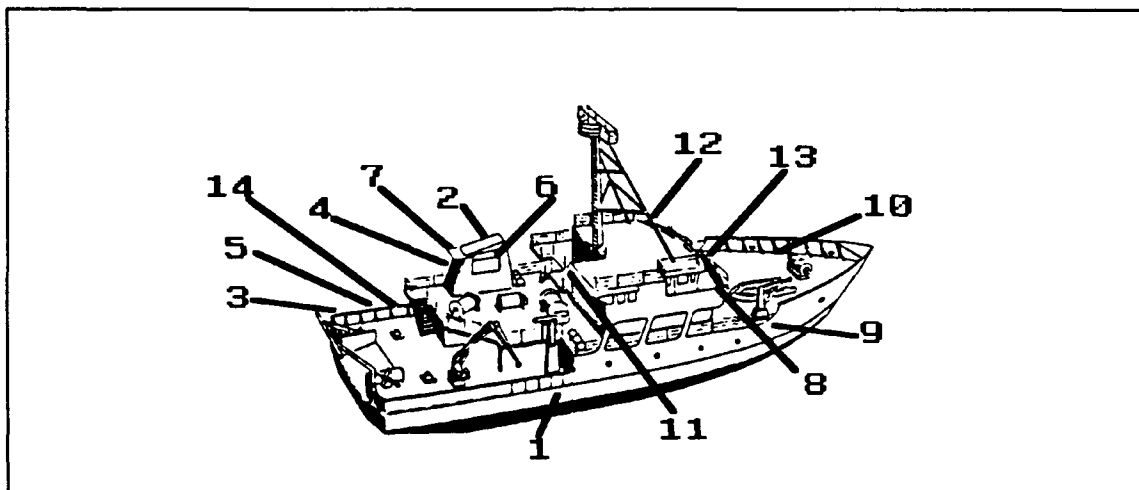


Figure 3.3 R/V Point Sur

TABLE 3.1 SENSOR LOCATIONS

| R/V POINT SUR SENSOR LOCATION | SENSOR NUMBER |
|-------------------------------|---------------|
| Starboard Aft                 | 1             |
| Port Top Stack                | 2             |
| Aft Port                      | 3             |
| Aft Stack Rear                | 4             |

| R/V POINT SUR SENSOR LOCATION | SENSOR NUMBER |
|-------------------------------|---------------|
| Water Probe                   | 5             |
| Starboard Stack               | 6             |
| Port Below Stack              | 7             |
| Bow Boathouse                 | 8             |
| Bow Starboard                 | 9             |
| Port Bow                      | 10            |
| Aft Boathouse                 | 11            |
| Boathouse Port                | 12            |
| Air Probe Bow                 | 13            |
| Deck Hoist                    | 14            |

#### **IV. DATA ANALYSIS**

The sensor temperatures were evaluated and specific time segments were taken from the thermistor temperatures which corresponded with the time when the thermal images were taken. The temperatures from the thermistors were then used as a comparison to the temperatures measured by the AGA camera. A listing of the image files with a brief description of what the thermal images consist of is included in Appendix B. A radiosonde was launched approximately 12:30 p.m. local time which was approximately an hour to an hour and a half after the measurements were taken. The recorded radiosonde data (Appendix A) was then input into LOWTRAN 6 to determine the atmospheric transmittance ( $\tau_a$ ).

The AGA images were processed to evaluate the temperature distributions of the ship. The biggest disparity between the actual (i.e. thermistor) and image temperatures was around the ship stack; this was a result of the temperatures being out of the range of the thermal settings.

##### **A. AGA SYSTEM THERMAL MEASUREMENTS**

###### **1. Thermal Measurement Techniques**

The AGA utilizing the CATS program reads out the distribution of source temperatures based on stored calibration constants and a software correction for radiance

reflected from the target, path losses, and path radiance, dependent on range and atmospheric transmittance. The correction for transmission loss requires use of the path transmittance  $\tau_a$ . This may be provided by LOWTRAN computations based on known meteorological parameters, or if this is not available using the empirical short path approximation of Equation 14 using the standard atmosphere value of extinction coefficient  $\alpha$ . [Ref. 8]

$$\tau_a = \exp[-\alpha(\sqrt{d}-1)] \quad (14)$$

where:

$\alpha$  = the atmospheric attenuation constant

$d$  = the distance to the object

The above equation is good only for short distances. The transmittance computed by LOWTRAN is more accurate and was used in this study for atmospheric correction of the AGA system output. The AGA uses the following equation in determining the thermal measurement [Ref. 7]:

$$P_i = \tau_a \epsilon_o P_o + \tau_a (1 - \epsilon_o) P_s + (1 - \tau_a) P_a \quad [\text{Watt}] \quad (15)$$

where:

$P_i$  = total radiant power received by the system

$\tau_a$  = the atmospheric transmittance

$\epsilon_o$  = the object's emissivity

$P_o$  = radiant power from the object as a blackbody

$P_s$  = the radiant power from the object's surroundings

$P_a$  = the radiant power received from the atmosphere  
along the path as a blackbody

Since the "thermal value", a quantity proportional to the detector output, of the system is also proportional to the received radiant power, the above equation can be rewritten as:

$$I_i = \tau_a \epsilon_o I_o + \tau_a (1 - \epsilon_o) I_s + (1 - \tau_a) I_a \quad [\text{Thermal Units}] \quad (16)$$

where:

$I$  = the thermal value of the corresponding radiation sources.

The received thermal value (Equation 17), was then substituted into Equation 16.

$$I_i = L + i \quad (17)$$

where:

$L$  = the thermal level setting on the monitor chassis

$i$  = a fractional portion of the thermal range

With the above substitution the object's thermal value could then be isolated as:

$$I_o = (L + i) / \tau_a \epsilon_o - (1 / \epsilon_o - 1) I_s - 1 / \epsilon_o (1 / \tau_a - 1) I_a \quad (18)$$

Equation 18 expresses the equivalent emission thermal value of the target in terms of the total measured thermal value ( $L + i$ ), the equivalent thermal value of the ambient flux reflected

from the target ( $I_s$ ), and the equivalent path radiance thermal value ( $I_a$ ).

The "thermal values"  $I$  are expressed in terms of equivalent source black body temperature through direct calibration using "black body" sources at known temperature (and emissivity) and are found to match the empirical relationship of Equation 19, where the calibration constants are determined by curve fitting. The equivalent source radiance is obtained from the radiation laws.

$$I = A / [C \exp(B/T) - 1] \quad (19)$$

where:

$A, B, C$  = predetermined calibration constants

The temperatures measured by the AGA are expressed in isotherm units which is an arbitrary unit of measurement proportional to received power.

## **2. Thermal Measurement Data**

The following four figures (Figures 4.1 - 4.4) are black and white representations of color scale computer displayed images of the R/V POINT SUR, starboard and port sides, at one half mile and one mile. Tables 4.1 - 4.4 following each figure give the variables used by the AGA system to compute the thermal images. These figures are generated using the AGACAT program developed at NPS [Ref. 9]. This program includes the capability of displaying a) the temperature profile along a vertical or

horizontal line through a selected pixel number, b) the spot temperature of a pixel defined by the pixel number coordinates (e.g. 91, 74) selected by cursor, c) the average temperature (TA) of the pixels included in a rectangular box selected using a "mouse", and d) the temperature difference (DT) between the interior of the box and the surrounding region limited by an additional box. The different shades represent the temperature range distributions corresponding to the scale on the left of the image. In the image the isotherm levels are arranged such that each shade represents an equal number of isotherm units. The isotherm units are then converted to a temperature using stored calibration constants. Additional information included on the screen image includes image number, field of view, aperture, wavelength, waveband, and filters.

Using these images the radiance temperature distributions were compared to the actual temperatures recorded by the temperature sensors located on the ship. There is error due to the pixel size of the image which corresponds to approximately 1 square meter on the ship, whereas the sensor is approximately 1 square centimeter. This error is also dependent upon the range of the ship. A ship much further away would result in the pixel size of the image covering a larger area of the ship. The ship's range from the AGA 780's location is computed using the following geometrical relationship:

$$R = (S_o / \tan \theta) (S_i / w)^{-1} = (w S_o / \tan \theta) (1 / S_i) \quad [m] \quad (20)$$

where:

R = ship's range

S<sub>o</sub> = ship's length (41.2m)

S<sub>i</sub> = image length in cm

w = display screen width (13cm)

θ = system field of view (7 degrees)

The variables used in computing the images were corrected to reflect the transmittance that LOWTRAN 6 predicted at 825 meters (one half mile) and 1650 meters (one mile). The variable for the emissivity of the ship was also corrected to .97 from 1.0. For the images produced at 1650 meters the thermal level was set at 4 so that the range of temperatures agreed with the sensors.

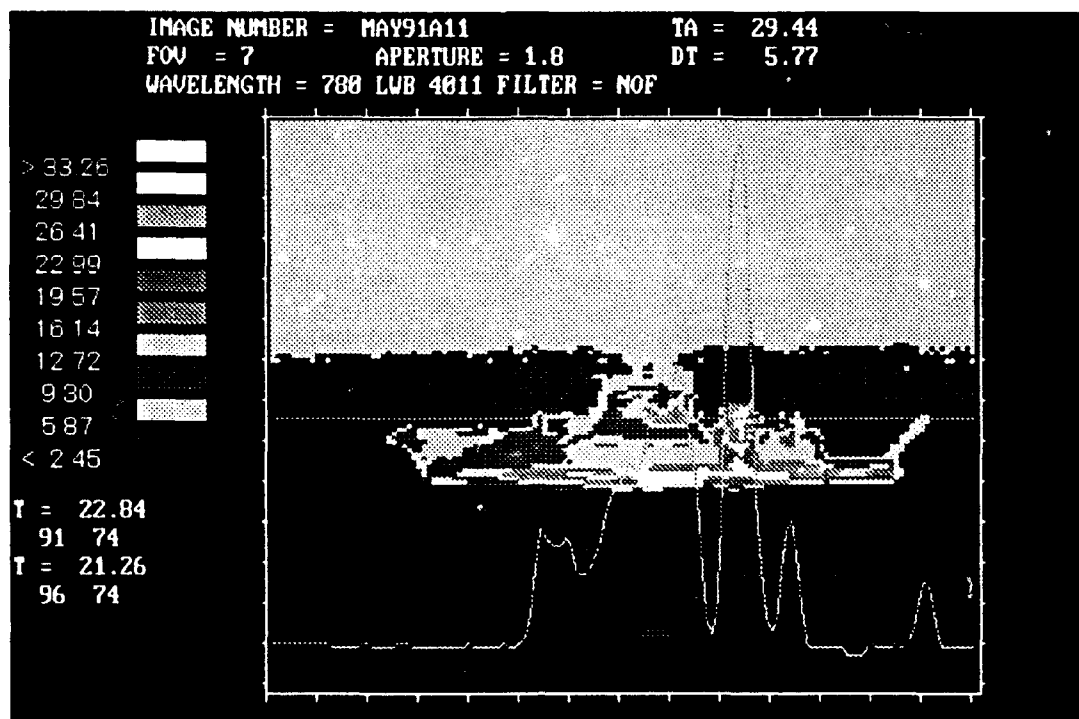


Figure 4.1 Portside of R/V POINT SUR at 825 Meters.  
Temperature Profile Shown for Pixel Row 74.

TABLE 4.1 AGA SYSTEM VARIABLES

| Variable                | Value   |
|-------------------------|---------|
| Object Distance         | 825 m   |
| Transmittance           | .7757   |
| Atmospheric Temperature | 294.7 K |
| Ambient Temperature     | 291.3 K |
| Emissivity              | .97     |

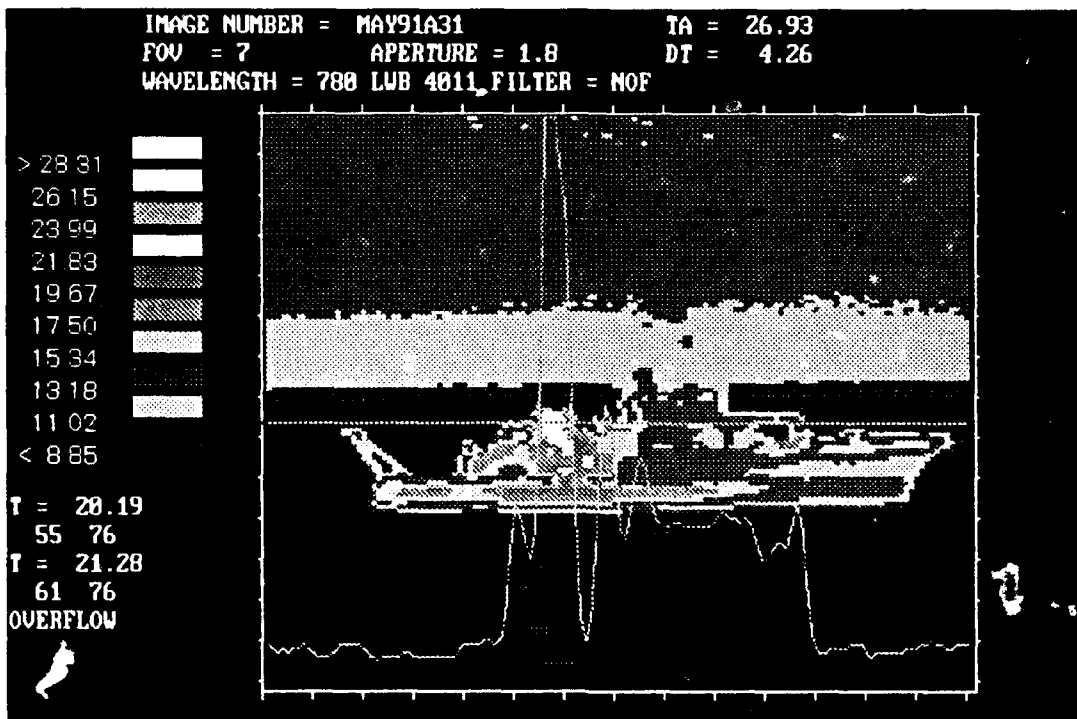


Figure 4.2 Starboard Side of R/V POINT SUR at 825 Meters.  
Temperature Profile Shown for Pixel Row 76.

TABLE 4.2 AGA SYSTEM VARIABLES

| Variable                | Value   |
|-------------------------|---------|
| Object Distance         | 825 m   |
| Transmittance           | .7757   |
| Atmospheric Temperature | 294.7 K |
| Ambient Temperature     | 291.3 K |
| Emissivity              | 97      |

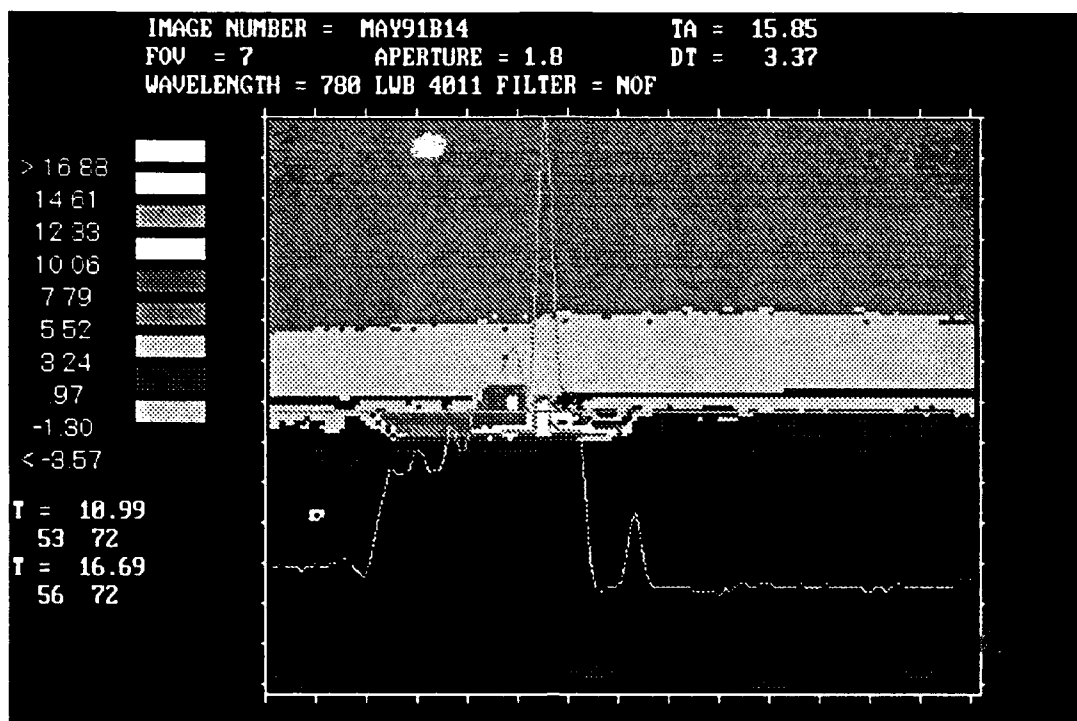


Figure 4.3 Portside of R/V POINT SUR at 1650 Meters.  
Temperature Profile Shown for Pixel Row 72.

TABLE 4.3 AGA SYSTEM VARIABLES

| Variable                | Value   |
|-------------------------|---------|
| Object Distance         | 1650 m  |
| Transmittance           | .6230   |
| Atmospheric Temperature | 294.7 K |
| Ambient Temperature     | 291.3 K |
| Emissivity              | .97     |

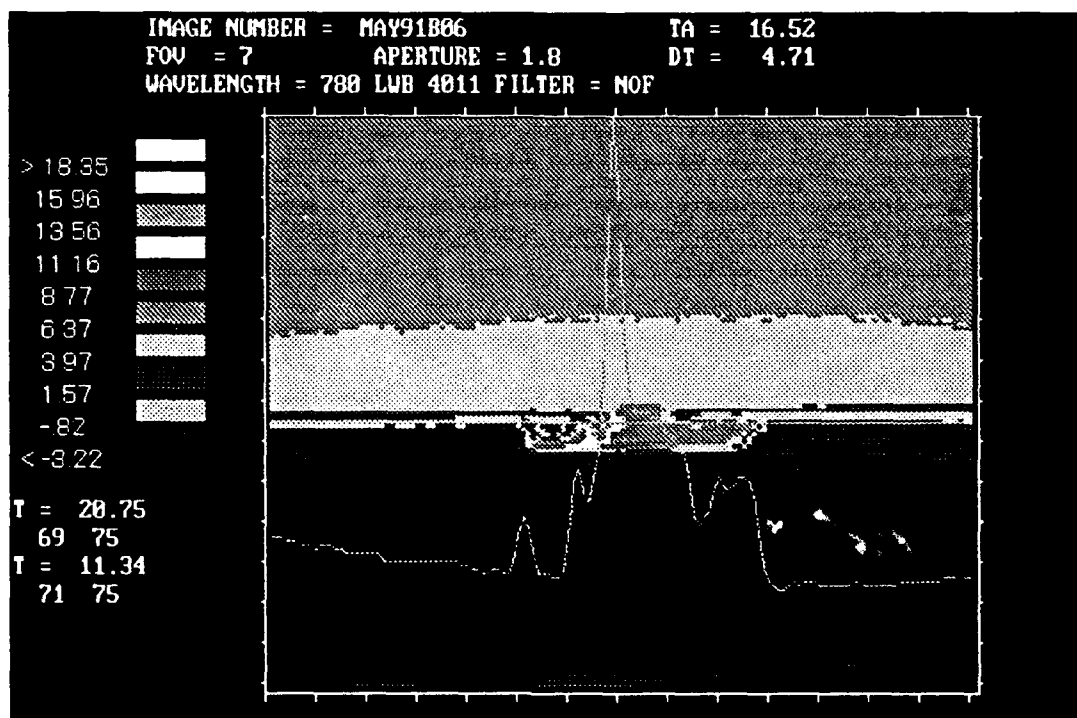


Figure 4.4 Starboard Side of R/V POINT SUR at 1650 Meters.  
Temperature Profile Shown for Pixel Row 75.

TABLE 4.4 AGA SYSTEM VARIABLES

| Variable                | Value   |
|-------------------------|---------|
| Object Distance         | 1650 m  |
| Transmittance           | .6230   |
| Atmospheric Temperature | 294.7 K |
| Ambient Temperature     | 291.3 K |
| Emissivity              | .97     |

Once all variables were changed in the images a comparison was made of the actual temperatures produced by the sensors to the temperatures derived by the AGA system. These comparisons are shown in Figures 4.5 and 4.6. The comparisons were produced for ranges of 825 and 1650 meters.

Figure 4.5 shows that the temperatures were very close at 825 meters. The mean for the temperature difference between the ship and AGA system was .132 with a standard deviation of .096 degrees celsius.

In Figure 4.6 there was a larger error in the temperature distributions at 1650 meters. At this range the mean temperature difference was .973 with a standard deviation of .453 degrees celsius. Pixel size was probably a factor in the temperature difference. At twice the distance, the pixel size corresponds to a larger area of the ship. The dominant temperature in the ship area corresponding to the pixel could obscure the variations in temperature. For this reason temperatures could not be found for sensors eight and eleven.

In most cases the temperatures were underestimated by the AGA system. The differences in temperatures were so small that they should be considered insignificant and could have been the result of several different factors such as ship range, transmittance, etc. This comparison between the thermistor sensors and the radiometric measurements gives confidence in prediction of the radiant signature of the target under "at-sea" conditions.

# Ship Temperatures (C) 7 May 1991

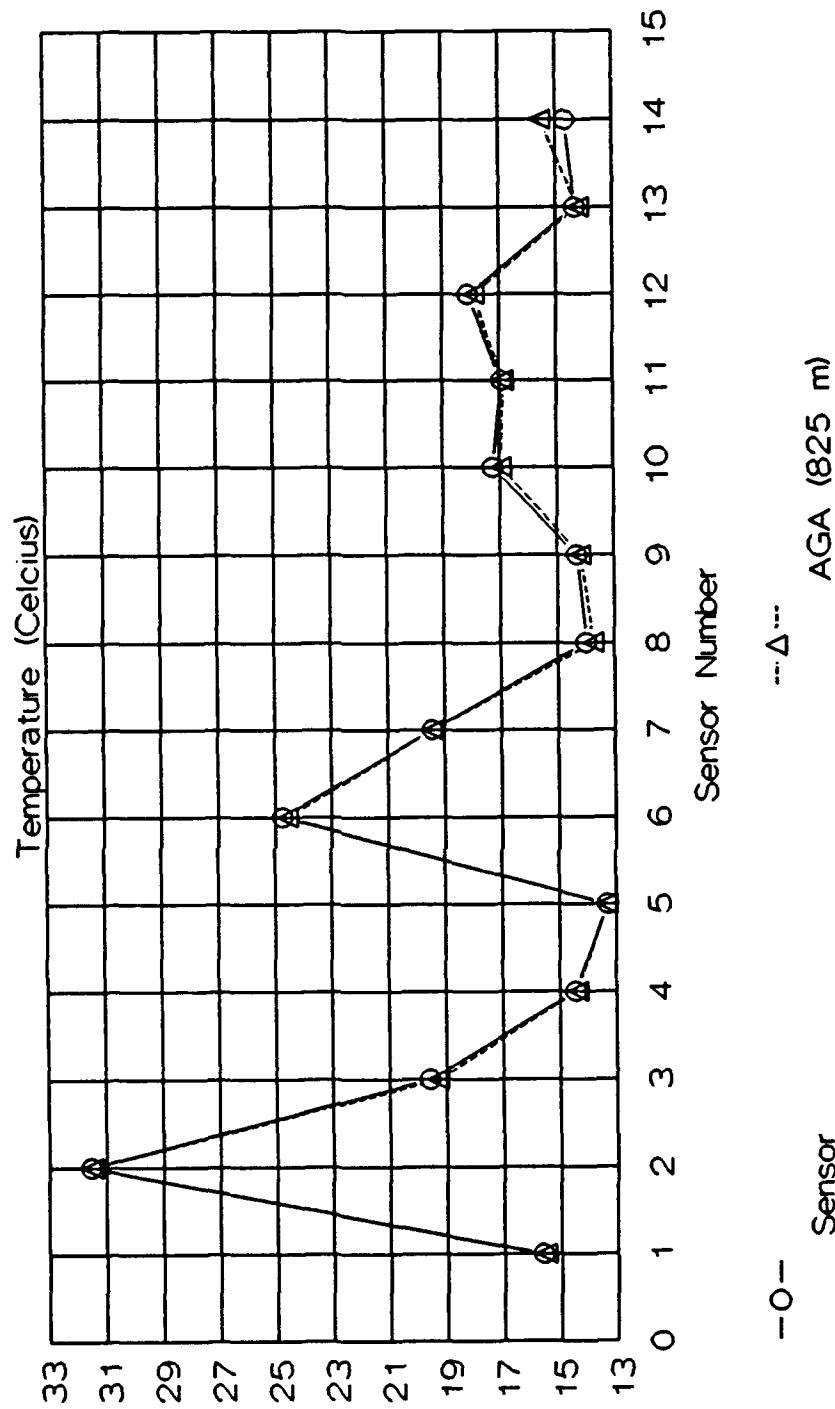


Figure 4.5 Ship Temperatures at 825 meters

# Ship Temperatures (C) 7 May 1991

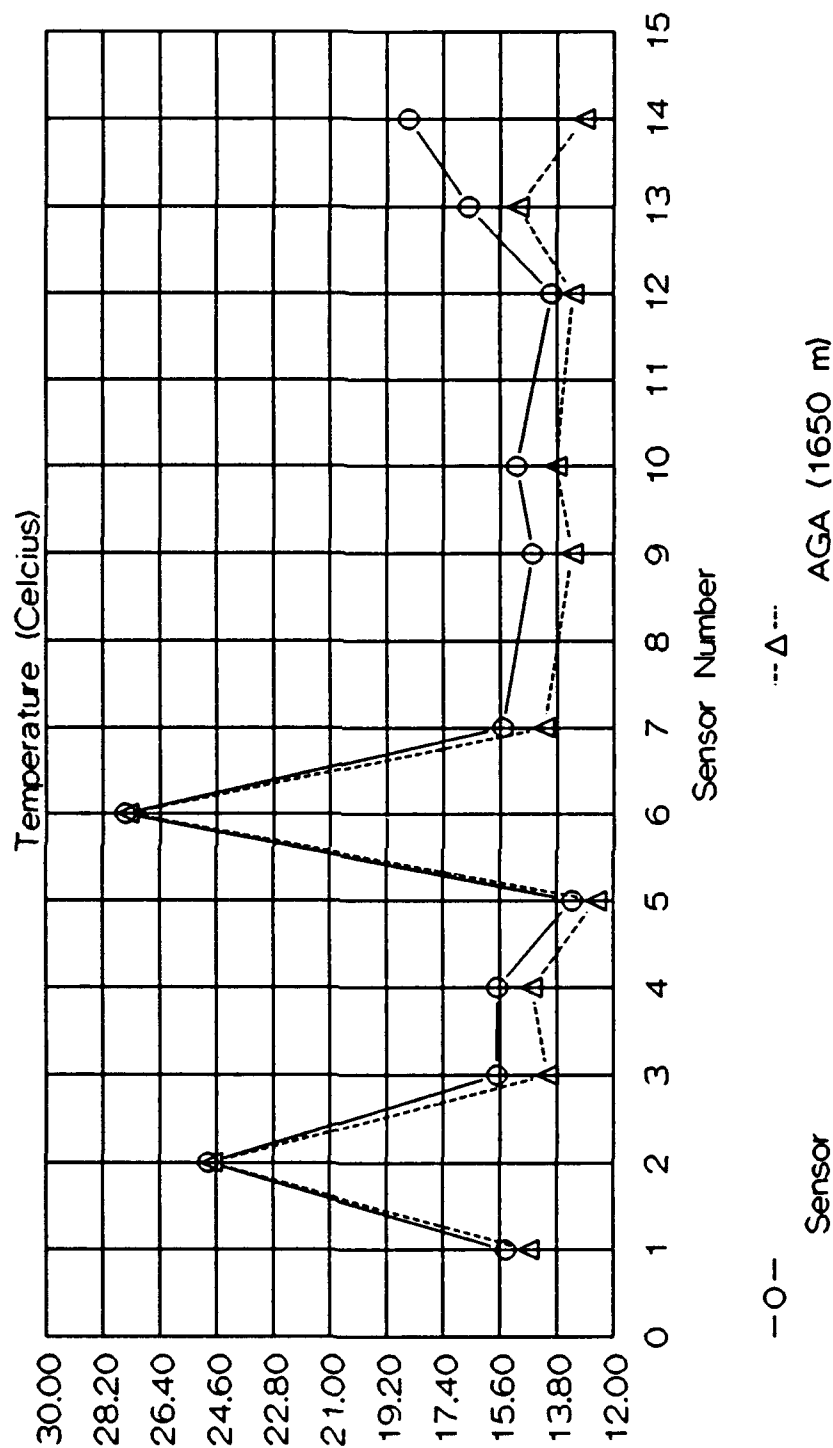


Figure 4.6 Ship Temperatures at 1650 meters

## B. PATH RADIANCE VALIDATION

As discussed in Chapter II, how well a thermal imaging system is able to see a target against a background is highly dependent upon the radiation contrast. It can be shown mathematically, that adding the path radiance ( $W_p$ ) to:

$$C = \frac{W_T - W_B}{W_T + W_B} \quad (21)$$

results in:

$$C = \frac{(W_T + W_p) - (W_B + W_p)}{(W_T + W_p) + (W_B + W_p)} \quad (22)$$

which then can be reduced to:

$$C = \frac{W_T - W_B}{2W_p + W_T + W_B} \quad (23)$$

Therefore, the above equation states that as the path radiance increases the contrast decreases: this was evident when the images were made of the R/V POINT SUR.

The path radiance for different viewing angles was computed using LOWTRAN 6 and a computer program (AGARADIA) by Professor Milne to compute radiances of the image files produced by the AGA system. Figure 4.7 shows an image of the R/V POINT SUR at a range of 825 meters with values associated with IA, I1, I2, and I3. The values corresponding to the variables IA, I1, I2, and I3 are the radiated, detected,

reflected, and path thermal values of the image (target radiance) as shown in following equations:

$$I_D = I_T \epsilon_T \tau_a + I_R (1 - \epsilon_T) \tau_a + I_P (1 - \tau_a) \quad (24)$$

$$I_1 = I_A + I_2 + I_3$$

where:

$I_T$  = target radiated thermal value

$I_D$  = detected thermal value

$\epsilon_T$  = emissivity of the target

$\tau_a$  = atmospheric transmittance

$I_R$  = target reflected thermal value

$I_P$  = path radiated thermal value

The AGA path radiated thermal value computed by the computer program was then compared to the path radiance calculated using LOWTRAN 6.

LOWTRAN 6 calculates the path radiance by doing a numerical integration over wavelength, and for each atmospheric layer, of the sum of the atmospheric absorption times the scattering times the blackbody radiation from the atmospheric layer, and the blackbody radiation from the boundary times the average total transmittance. The model can also compute the scattering of radiation into the atmospheric path. [Ref. 5]

The values associated with  $I_A$ ,  $I_1$ ,  $I_2$ , and  $I_3$  are computed as thermal values of the total received power of the image, therefore, the values in the following graphs are represented

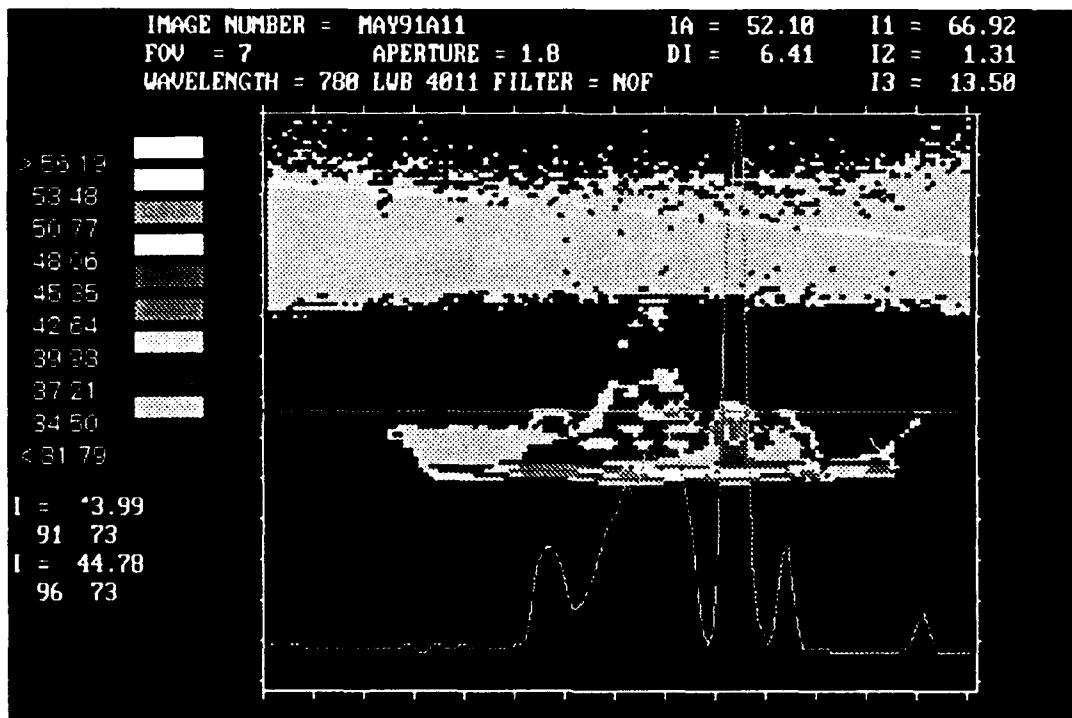


Figure 4.7 R/V Point Sur at 825 meters

as percentages of the total radiance so that comparisons can be made with the LOWTRAN 6 calculations. Figure 4.8 shows the contribution that path, reflected, and radiated radiances measured by the AGA system make toward the total radiance of the target as a function of zenith angle. The zenith angle of 90.585, shown in Figure 4.8, corresponds with 2000 meters and 91.699 degrees corresponds with 825 meters. Varying zenith angle varies the slant path for both the target and background. Therefore, radiated power received from the target will decrease as the zenith angle decreases, and reflected power received from the target will decrease as the zenith angle decreases, and power received from path radiance will increase as the zenith angle decreases. As the zenith angle

approaches ninety degrees, the path radiance is the major contributor to the total received radiant power. The rapid drop in the path radiant power with the increasing zenith angle is due to the shorter slant paths to the earth. The AGA system measured minuscule changes in the target reflected radiant power which shows in Figure 4.8 as a straight line. The target radiant received power increases as the zenith angle increases from ninety degrees, due to the decrease in path length. The graph in Figure 4.9, using data produced with AGACATS software and LOWTRAN 6, is consistent with similar research conducted by Naval Ocean Systems Center (NOSC), San Diego. [Ref. 10]

The AGA measured path radiance was then compared to the fractional path radiance component of received power computed by LOWTRAN 6 (Figure 4.9) using the Navy Maritime Aerosol Model and an air mass factor of three. The AGA measurements varied over the range from twenty-five to seventy-five percent, while the LOWTRAN fraction ranges only from seventy-five to eight-five percent, with the biggest discrepancy occurring at the short paths. This discrepancy suggests a deficiency in calculations with either the AGA path radiance algorithm or the LOWTRAN 6 calculations. Questions have been raised previously with respect to the accuracy of LOWTRAN in the region close to the horizon: however here the discrepancy is greatest at the shorter path lengths. LOWTRAN calculated the zenith angle for the infrared horizon to be at 90.18

# Calculations of Radiated, Reflected and Path Radiance

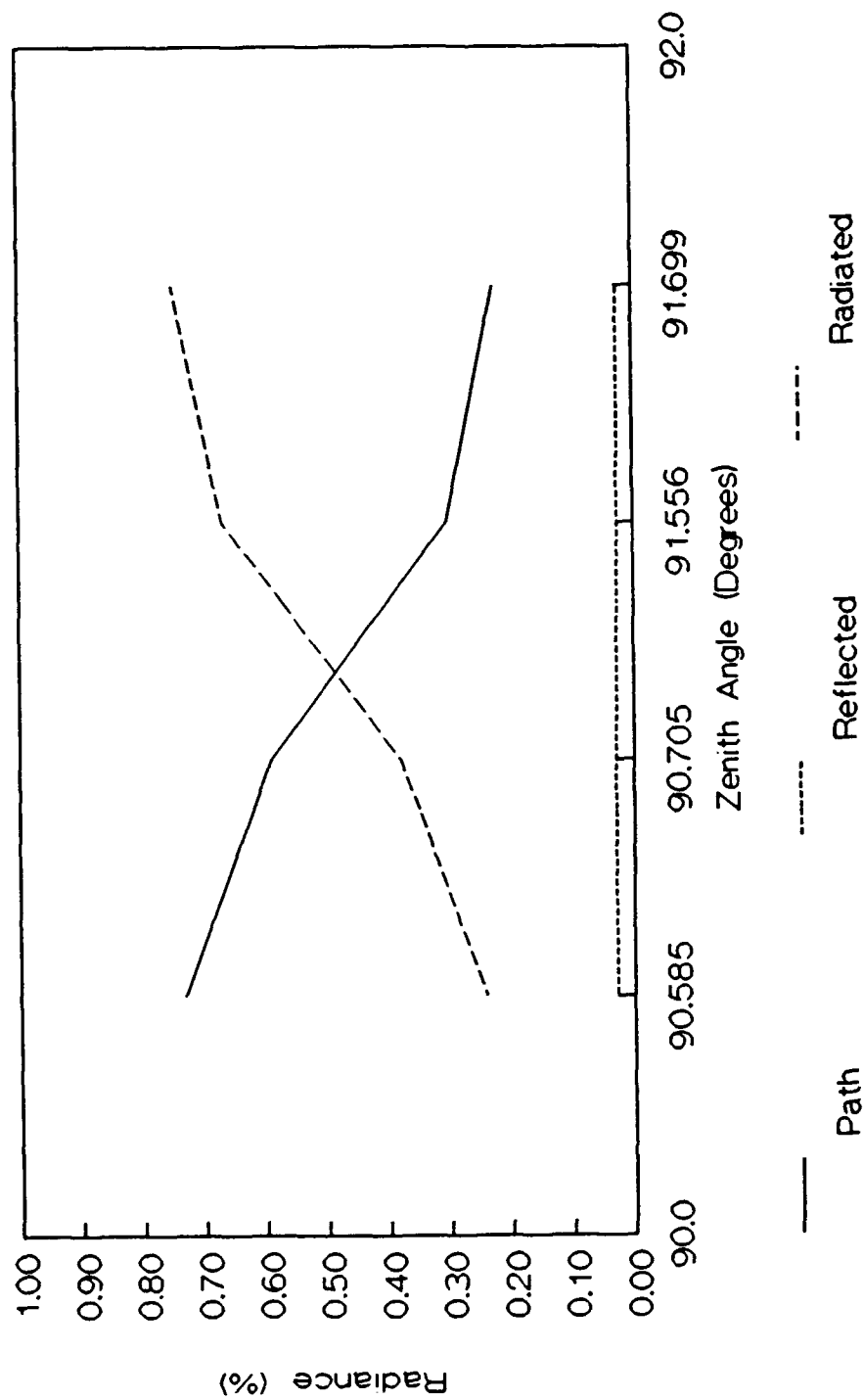


Figure 4.8 Calculated Path, Reflected, and Radiated Radiances Percentages

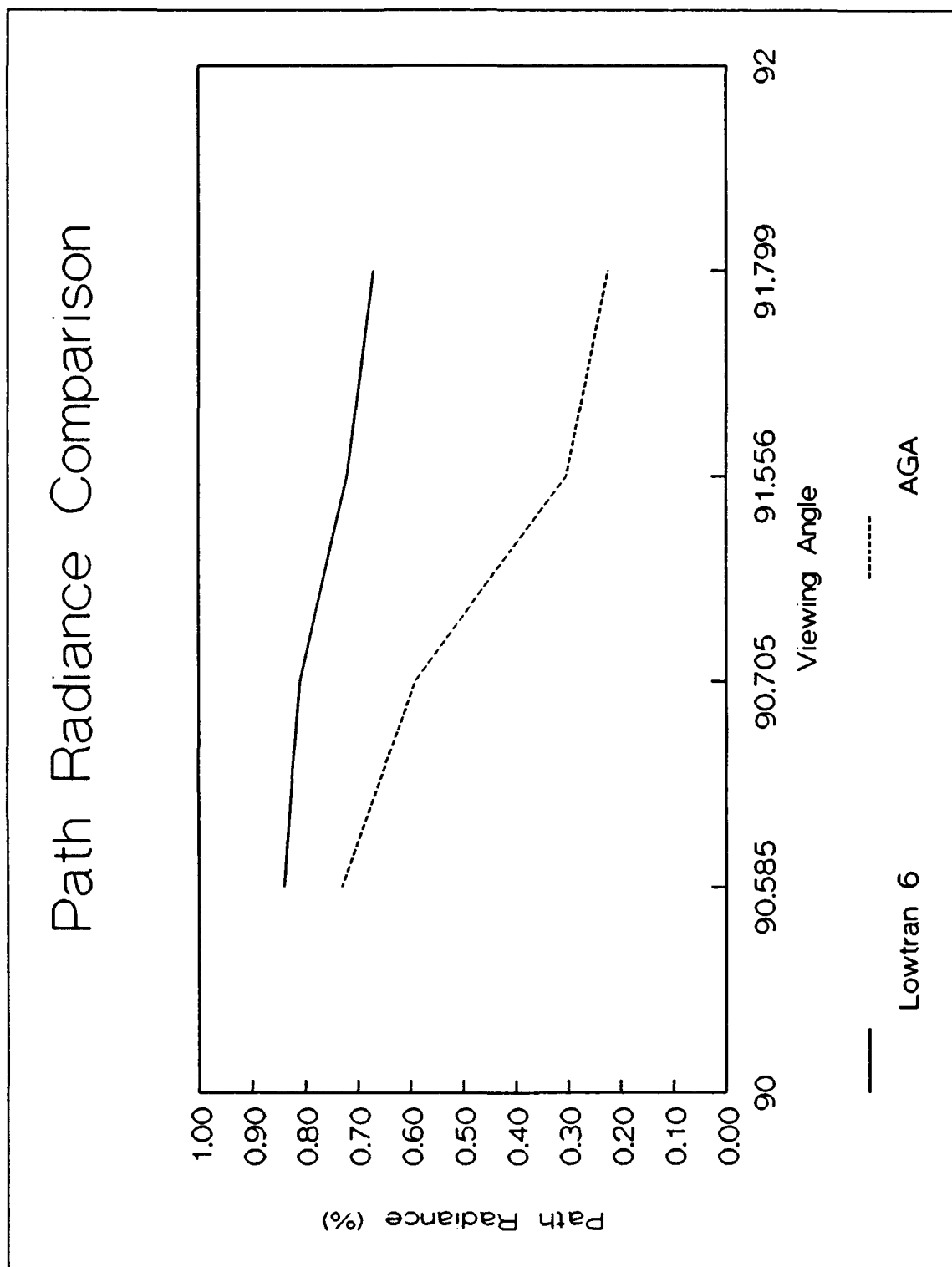


Figure 4.9 Calculated Lowtran 6 and AGA Path Radiance Percentages.

degrees which was the point at which the refracted ray path first hit the earth. A large difference in these percentages appears as the zenith angle increases. The measured radiances fall off sharply with increasing zenith angles. A contributing factor for the differences may be due to the radiosonde input to LOWTRAN 6. The radiosonde balloon was launched approximately one and a half hours after the AGA measurements were taken. If the radiosonde data was outside the 'window', it could be an additional reason for the difference between the measured and calculate radiances.

## **V. CONCLUSIONS AND RECOMMENDATIONS**

### **A. SUMMARY**

Thermal images of the R/V Point Sur were taken on 7 May 1991 off the Naval Postgraduate School Beach. The image file variables were then updated to reflect the actual transmittance computed from LOWTRAN 6. The range and emissivity variables were also updated to reflect the actual distances and true emissivity of the ship. The changes in the variables allowed the AGA measured temperatures to agree with the actual ship temperatures to within one degree celsius.

The temperatures of the ship were then compared between the AGA system and the fourteen thermistors which were attached to the ship. The mean and standard deviation of the ship temperature differences were then computed.

The path radiance was then computed using LOWTRAN 6 for different ranges. The path radiances from the thermal images were also measured utilizing the AGACATS software. The measured radiances were then compared to the LOWTRAN 6 predicted path radiances.

### **B. CONCLUSIONS**

In comparing the temperature distributions produced by the sensors and the AGA system with corrections, it was shown that

the AGA system slightly underestimated the temperatures. It was concluded the temperature differences were insignificant since they were less than one degree celsius. Some of the images had an overflow for the temperatures, but that was due to the thermal range settings which did not allow some of the higher temperatures to be measured.

The influence of path radiant power as measured by the AGA system was consistent with similar studies completed at NOSC. The power received from path radiance became more dominant as the slant path ranges increased due to absorption by the atmosphere. The AGA measurements of power received from path radiance varied over the range from twenty-five to seventy-five percent while the LOWTRAN fraction of path radiance ranged from seventy-five to eighty-five percent. The largest difference between the calculations occurred at the shorter path lengths. This disparity suggests that either the AGA or LOWTRAN algorithms has an erroneous algorithm. The differences in the calculated path radiances and measured radiances could also have been caused by the accuracy of the inputs. A contributing factor may have been the delay of an hour to an hour and a half between the image data and the radiosonde data input to LOWTRAN 6.

### C. RECOMMENDATIONS

Since the path radiance provides a significant contribution to the total radiance observed from a target at

long slant paths an effort should be made to incorporate or model the path radiance into UFLIR. UFLIR is based on the LOWTRAN 3 model which did not take into account path radiance.

There is a limited database with which to work with since in almost all of the experiments problems occurred in the data collection, for example, radiosonde balloons being released later than required due to equipment malfunction. Therefore, continued work in collecting measurement data should be done to provide more precise data for analysis. More measurements should also be made under a variety of weather conditions.

# APPENDIX A RADIOSONDE DATA

## RADIOSONDE LAUNCHES STUDENT CRUISE MAY 1991

| #  | FILE     | DATE     | TIME      | TIME        | EVENT           |
|----|----------|----------|-----------|-------------|-----------------|
| 0  | PS060523 | 05-06-91 | 21:03 GMT | 14:03 local | test            |
| 1  | PS070519 | 05-07-91 | 19:38 GMT | 12:30 local | 18z/FLIR (late) |
| 2  | PS070524 | 05-07-91 | 23:51 GMT | 16:51 local | 24z             |
| 3  | PS080506 | 05-08-91 | 05:35 GMT | 22:30 local | 6z              |
| 4  | PS080513 | 05-08-91 | 13:33 GMT | 06:33 local | 12z (late)      |
| 5  | PS080518 | 05-08-91 | 17:37 GMT | 10:37 local | 18z             |
| 6  | PS080521 | 05-08-91 | 21:26 GMT | 14:30 local | U2              |
| 7  | PS090500 | 05-09-91 | 23:33 GMT | 16:33 local | 24z             |
| 8  | PS090506 | 05-09-91 | 05:40 GMT | 22:40 local | 6z              |
| 9  | PS090512 | 05-09-91 | 11:36 GMT | 04:36 local | 12z             |
| 10 | PS090518 | 05-09-91 | 17:39 GMT | 10:39 local | 18z             |
| 11 | PS090521 | 05-09-91 | 21:22 GMT | 14:22 local | U2 / FLIR P3    |
| 12 | PS100500 | 05-10-91 | 23:35 GMT | 16:35 local | 24z             |
| 13 | PS100506 | 05-10-91 | 05:36 GMT | 22:36 local | 6z              |
| 14 | PS100512 | 05-10-91 | 11:37 GMT | 04:37 local | 12z             |

Radiosonde PS070519

| I  | Z<br>(KM) | P<br>(MB) | T<br>(K) |
|----|-----------|-----------|----------|
| 1  | .02       | 1017.900  | 285.4    |
| 2  | .22       | 993.900   | 284.4    |
| 3  | .42       | 970.100   | 288.4    |
| 4  | .62       | 947.900   | 290.9    |
| 5  | .76       | 932.500   | 290.5    |
| 6  | .94       | 912.700   | 289.1    |
| 7  | 1.10      | 896.400   | 288.4    |
| 8  | 1.29      | 876.000   | 287.8    |
| 9  | 1.47      | 857.800   | 288.4    |
| 10 | 1.61      | 843.300   | 287.9    |
| 11 | 1.76      | 828.400   | 287.1    |
| 12 | 1.91      | 813.600   | 286.4    |
| 13 | 2.07      | 798.200   | 284.9    |
| 14 | 2.33      | 774.200   | 283.3    |
| 15 | 2.47      | 760.900   | 282.1    |
| 16 | 2.62      | 747.100   | 281.5    |
| 17 | 2.74      | 736.600   | 280.6    |
| 18 | 2.87      | 725.500   | 279.6    |
| 19 | 2.99      | 714.800   | 278.6    |
| 20 | 3.14      | 701.300   | 278.4    |
| 21 | 3.22      | 694.500   | 277.9    |
| 22 | 3.37      | 681.900   | 277.0    |
| 23 | 3.56      | 666.400   | 276.1    |
| 24 | 3.81      | 646.300   | 275.3    |
| 25 | 4.01      | 630.400   | 274.4    |
| 26 | 4.17      | 617.600   | 273.5    |
| 27 | 4.33      | 605.600   | 272.3    |
| 28 | 4.55      | 589.300   | 271.1    |
| 29 | 4.74      | 574.800   | 270.8    |
| 30 | 4.97      | 558.200   | 269.5    |
| 31 | 5.13      | 547.700   | 268.4    |
| 32 | 5.32      | 534.100   | 267.0    |
| 33 | 5.67      | 510.700   | 264.5    |

# APPENDIX B AGA DATA TAKEN MAY 7 1991

| <u>FILE NAME</u> | <u>SUBJECT</u> | <u>COMMENTS</u>                       |
|------------------|----------------|---------------------------------------|
| MAY91A01.IMG     | BLACK BODY     | CALIBRATION OF SYSTEM IN LABORATORY   |
| MAY91A02.IMG     | BLACK BODY     | CALIBRATION OF SYSTEM IN LABORATORY   |
| MAY91A03.IMG     | BLACK BODY     | CALIBRATION OF SYSTEM IN LABORATORY   |
| MAY91A04.IMG     | BLACK BODY     | CALIBRATION OF SYSTEM IN LABORATORY   |
| MAY91A05.IMG     | BARGE          | TARGET FOR TESTING AND FOCUSING       |
| MAY91A06.IMG     | BARGE          | AGA CAMERA AND EQUIPMENT              |
| MAY91A07.IMG     | POINT SUR      | APPROACHING THE HORIZON               |
| MAY91A08.IMG     | POINT SUR      | STILL APPROACHING                     |
| MAY91A09.IMG     | POINT SUR      | APPROX ONE MILE AWAY                  |
| MAY91A10.IMG     | POINT SUR      | PORT SIDE ONE HALF MILE AWAY          |
| MAY91A11.IMG     | POINT SUR      | PORT SIDE SHIP'S HEADING 270 DEGREES  |
| MAY91A12.IMG     | POINT SUR      | PORT SIDE (UNDERFLOW)                 |
| MAY91A13.IMG     | POINT SUR      | PORT SIDE                             |
| MAY91A14.IMG     | POINT SUR      | PORT SIDE                             |
| MAY91A15.IMG     | POINT SUR      | PORT SIDE                             |
| MAY91A16.IMG     | POINT SUR      | PORT SIDE                             |
| MAY91A17.IMG     | POINT SUR      | PORT SIDE                             |
| MAY91A18.IMG     | POINT SUR      | PORT STERN SHIP'S HEADING 315 DEGREES |
| MAY91A19.IMG     | POINT SUR      | PORT STERN SHIP'S HEADING 325 DEGREES |
| MAY91A20.IMG     | P`INT SUR      | PORT STERN SHIP'S HEADING 315 DEGREES |
| MAY91A21.IMG     | POINT SUR      | PORT STERN                            |
| MAY91A22.IMG     | POINT SUR      | PORT STERN - WITH FISHING BOAT        |
|                  | FISHING BOAT   | STARBOARD SIDE WITH WAKE FOLLOWING    |
| MAY91A23.IMG     | POINT SUR      | STERN - WITH ANOTHER FISHING BOAT     |
|                  | FISHING BOAT   | PORT SIDE WITH WAKE FOLLOWING         |
| MAY91A24.IMG     | POINT SUR      | STERN                                 |
| MAY91A25.IMG     | POINT SUR      | STERN                                 |
| MAY91A26.IMG     | POINT SUR      | STARBOARD STERN                       |
| MAY91A27.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A28.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A29.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A30.IMG     | POINT SUR      | STARBOARD STERN                       |
| MAY91A31.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A32.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A33.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A34.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A35.IMG     | POINT SUR      | PORT BOW WITH WAKE                    |
| MAY91A36.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A37.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A38.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A39.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A40.IMG     | POINT SUR      | STARBOARD AND BOUY                    |
| MAY91A41.IMG     | POINT SUR      | STARBOARD                             |
| MAY91A42.IMG     | POINT SUR      | STARBOARD AND SMALL BOAT              |

|              |           |                     |
|--------------|-----------|---------------------|
| MAY91A43.IMG | POINT SUR | STARBOARD PLUS WAKE |
| MAY91A44.IMG | POINT SUR | STARBOARD PLUS WAKE |
| MAY91A45.IMG | POINT SUR | PORT PLUS WAKE      |
| MAY91A46.IMG | POINT SUR | PORT PLUS WAKE      |
| MAY91A47.IMG | POINT SUR | PORT PLUS WAKE      |
| MAY91A48.IMG | POINT SUR | PORT PLUS WAKE      |
| MAY91A49.IMG | POINT SUR | PORT PLUS WAKE      |
| MAY91A50.IMG | POINT SUR | PORT PLUS WAKE      |

|              |           |                               |
|--------------|-----------|-------------------------------|
| MAY91B01.IMG | POINT SUR | PORT WITH WAKE                |
| MAY91B02.IMG | POINT SUR | PORT WITH WAKE AND BOUY       |
| MAY91B03.IMG | POINT SUR | PORT WITH WAKE AND BOUY       |
| MAY91B04.IMG | POINT SUR | STERN                         |
| MAY91B05.IMG | POINT SUR | STARBOARD WITH BOUY           |
| MAY91B06.IMG | POINT SUR | STARBOARD WITH BOUY           |
| MAY91B07.IMG | POINT SUR | STARBOARD WITH BOUY           |
| MAY91B08.IMG | POINT SUR | STARBOARD WITH BOUY           |
| MAY91B09.IMG | POINT SUR | STARBOARD WITH BOUY           |
| MAY91B10.IMG | POINT SUR | STERN WITH BOUY               |
| MAY91B11.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B12.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B13.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B14.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B15.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B16.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B17.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B18.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B19.IMG | POINT SUR | PORT WITH BOUY                |
| MAY91B20.IMG | POINT SUR | PORT WITH SMALL BOAT IN FRONT |
| MAY91B21.IMG | POINT SUR | PORT WITH SMALL BOAT IN FRONT |
| MAY91B22.IMG | POINT SUR | PORT                          |
| MAY91B23.IMG | POINT SUR | PORT WITH SMALL BOAT IN FRONT |
| MAY91B24.IMG | POINT SUR | PORT WITH SMALL BOAT IN FRONT |

## APPENDIX C THERMISTOR TEMPERATURES

### Hull Temperatures of R/V Point Sur

10:30 a.m. - 12:00 noon 7 May 1991

The time in the following data is computed as the number of seconds from the beginning of the month local time.

| <u>Time</u> | <u>Sensor Number</u> | * - denotes calibration sensor |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|-------------|----------------------|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|             | *                    | 1                              | 2      | 3      | 4      | 5      | 6      | 7      | *      | 8      | 9      | 10     | 11     | 12     | 13     | 14     |
| 556474      | 25.001               | 14.204                         | 31.041 | 19.611 | 14.161 | 12.951 | 23.851 | 19.404 | 25.001 | 13.591 | 12.663 | 17.414 | 16.462 | 17.962 | 15.437 | 14.317 |
| 556494      | 25.001               | 14.214                         | 31.175 | 19.651 | 14.165 | 12.981 | 23.965 | 19.435 | 25.001 | 13.590 | 12.666 | 17.409 | 16.520 | 17.971 | 15.335 | 14.325 |
| 556514      | 25.001               | 14.221                         | 31.133 | 19.642 | 14.169 | 12.994 | 24.223 | 19.477 | 25.001 | 13.599 | 12.673 | 17.388 | 16.537 | 17.982 | 15.295 | 14.341 |
| 556534      | 25.001               | 14.228                         | 31.153 | 19.683 | 14.203 | 12.997 | 24.256 | 19.507 | 25.001 | 13.599 | 12.679 | 17.377 | 16.555 | 17.993 | 15.394 | 14.357 |
| 556554      | 25.001               | 14.224                         | 31.118 | 19.687 | 14.225 | 13.018 | 24.248 | 19.508 | 25.001 | 13.603 | 12.680 | 17.359 | 16.564 | 17.982 | 15.366 | 14.374 |
| 556574      | 25.001               | 14.230                         | 30.997 | 19.670 | 14.205 | 13.030 | 24.551 | 19.474 | 25.001 | 13.608 | 12.683 | 17.336 | 16.555 | 17.967 | 15.375 | 14.388 |
| 556594      | 25.001               | 14.226                         | 30.861 | 19.693 | 14.209 | 13.069 | 24.586 | 19.434 | 25.001 | 13.616 | 12.686 | 17.347 | 16.567 | 17.968 | 15.452 | 14.386 |
| 556614      | 25.001               | 14.231                         | 30.865 | 19.725 | 14.168 | 13.044 | 24.516 | 19.407 | 25.001 | 13.624 | 12.686 | 17.336 | 16.603 | 17.992 | 15.355 | 14.400 |
| 556634      | 25.001               | 14.235                         | 30.903 | 19.756 | 14.170 | 13.057 | 24.462 | 19.401 | 25.001 | 13.629 | 12.688 | 17.306 | 16.651 | 18.005 | 15.381 | 14.419 |
| 556654      | 25.001               | 14.236                         | 30.973 | 19.764 | 14.173 | 13.095 | 24.481 | 19.403 | 25.001 | 13.637 | 12.689 | 17.301 | 16.687 | 18.009 | 15.432 | 14.434 |
| 556674      | 25.001               | 14.243                         | 31.042 | 19.772 | 14.159 | 13.142 | 24.524 | 19.384 | 25.001 | 13.638 | 12.693 | 17.307 | 16.715 | 18.019 | 15.305 | 14.462 |
| 556694      | 25.001               | 14.241                         | 31.127 | 19.793 | 14.160 | 13.180 | 24.667 | 19.422 | 25.001 | 13.644 | 12.688 | 17.296 | 16.719 | 18.021 | 15.360 | 14.485 |
| 556714      | 25.001               | 14.236                         | 31.238 | 19.793 | 14.197 | 13.213 | 24.822 | 19.465 | 25.001 | 13.651 | 12.697 | 17.291 | 16.717 | 18.038 | 15.404 | 14.491 |
| 556734      | 25.001               | 14.238                         | 31.346 | 19.788 | 14.214 | 13.214 | 24.882 | 19.476 | 25.001 | 13.665 | 12.702 | 17.300 | 16.729 | 18.012 | 15.313 | 14.510 |
| 556754      | 25.001               | 14.246                         | 31.518 | 19.798 | 14.199 | 13.204 | 24.892 | 19.518 | 25.001 | 13.684 | 12.710 | 17.319 | 16.747 | 18.011 | 15.390 | 14.525 |
| 556774      | 25.001               | 14.252                         | 31.603 | 19.814 | 14.162 | 13.189 | 24.770 | 19.535 | 25.001 | 13.697 | 12.713 | 17.325 | 16.760 | 18.037 | 15.415 | 14.550 |
| 556794      | 25.001               | 14.258                         | 31.680 | 19.825 | 14.265 | 13.202 | 24.842 | 19.545 | 25.001 | 13.717 | 12.723 | 17.345 | 16.757 | 18.076 | 15.393 | 14.553 |
| 556814      | 25.001               | 14.271                         | 31.694 | 19.875 | 14.386 | 13.208 | 24.708 | 19.490 | 25.001 | 13.750 | 12.733 | 17.378 | 16.715 | 18.087 | 15.456 | 14.537 |
| 556834      | 25.001               | 14.275                         | 31.714 | 19.914 | 14.440 | 13.225 | 24.520 | 19.502 | 25.001 | 13.779 | 12.730 | 17.417 | 16.648 | 18.119 | 15.418 | 14.518 |
| 556854      | 25.001               | 14.281                         | 31.824 | 19.961 | 14.456 | 13.229 | 24.472 | 19.564 | 25.001 | 13.813 | 12.739 | 17.441 | 16.619 | 18.195 | 15.542 | 14.527 |
| 556874      | 25.001               | 14.306                         | 31.906 | 19.992 | 14.456 | 13.277 | 24.622 | 19.586 | 25.001 | 13.831 | 12.753 | 17.464 | 16.623 | 18.213 | 15.682 | 14.536 |
| 556894      | 25.001               | 14.326                         | 31.884 | 19.992 | 14.495 | 13.289 | 24.716 | 19.653 | 25.001 | 13.852 | 12.756 | 17.471 | 16.636 | 18.236 | 15.632 | 14.552 |
| 556914      | 25.001               | 14.352                         | 31.898 | 19.984 | 14.529 | 13.255 | 24.669 | 19.694 | 25.001 | 13.871 | 12.767 | 17.479 | 16.630 | 18.274 | 15.830 | 14.557 |
| 556934      | 25.001               | 14.367                         | 32.000 | 20.012 | 14.502 | 13.218 | 24.706 | 19.725 | 25.001 | 13.884 | 12.767 | 17.508 | 16.657 | 18.286 | 15.720 | 14.574 |
| 556954      | 25.001               | 14.377                         | 32.088 | 19.985 | 14.529 |        |        |        |        |        |        |        |        |        |        |        |

|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 557314 | 25.001 | 14.280 | 31.032 | 19.719 | 15.147 | 13.280 | 24.731 | 19.485 | 25.001 | 13.842 | 12.753 | 17.132 | 16.938 | 17.743 | 14.683 | 14.647 |
| 557334 | 25.001 | 14.290 | 31.151 | 19.749 | 15.192 | 13.268 | 24.553 | 19.526 | 25.001 | 13.860 | 12.757 | 17.117 | 16.888 | 17.715 | 14.656 | 14.648 |
| 557354 | 25.001 | 14.307 | 31.286 | 19.773 | 15.239 | 13.262 | 24.425 | 19.544 | 25.001 | 13.893 | 12.755 | 17.104 | 16.853 | 17.698 | 14.695 | 14.694 |
| 557374 | 25.001 | 14.328 | 31.392 | 19.773 | 15.307 | 13.273 | 24.457 | 19.559 | 25.001 | 13.933 | 12.772 | 17.122 | 16.849 | 17.697 | 14.627 | 14.749 |
| 557394 | 25.001 | 14.356 | 31.605 | 19.848 | 15.329 | 13.280 | 24.569 | 19.601 | 25.001 | 13.945 | 12.774 | 17.118 | 16.868 | 17.756 | 14.782 | 14.762 |
| 557414 | 25.001 | 14.379 | 31.721 | 19.886 | 15.325 | 13.274 | 24.724 | 19.631 | 25.001 | 13.946 | 12.774 | 17.164 | 16.900 | 17.798 | 14.849 | 14.780 |
| 557434 | 25.001 | 14.397 | 31.693 | 19.858 | 15.340 | 13.285 | 24.888 | 19.655 | 25.001 | 13.934 | 12.780 | 17.176 | 16.951 | 17.812 | 14.942 | 14.794 |
| 557454 | 25.001 | 14.407 | 31.572 | 19.778 | 15.398 | 13.279 | 25.106 | 19.653 | 25.001 | 13.929 | 12.785 | 17.196 | 16.987 | 17.821 | 14.975 | 14.797 |
| 557474 | 25.001 | 14.416 | 31.508 | 19.729 | 15.473 | 13.250 | 25.202 | 19.661 | 25.001 | 13.925 | 12.779 | 17.198 | 17.030 | 17.822 | 14.981 | 14.807 |
| 557494 | 25.001 | 14.424 | 31.526 | 19.692 | 15.433 | 13.232 | 25.240 | 19.676 | 25.001 | 13.918 | 12.782 | 17.183 | 17.063 | 17.828 | 14.976 | 14.840 |
| 557514 | 25.001 | 14.418 | 31.502 | 19.619 | 15.345 | 13.218 | 25.219 | 19.689 | 25.001 | 13.909 | 12.780 | 17.117 | 17.099 | 17.809 | 14.913 | 14.874 |
| 557534 | 25.001 | 14.392 | 31.443 | 19.577 | 15.283 | 13.223 | 25.256 | 19.634 | 25.001 | 13.894 | 12.783 | 17.033 | 17.153 | 17.721 | 14.980 | 14.918 |
| 557554 | 25.001 | 14.382 | 31.428 | 19.563 | 15.241 | 13.234 | 25.311 | 19.529 | 25.001 | 13.878 | 12.783 | 16.944 | 17.198 | 17.642 | 14.943 | 14.953 |
| 557574 | 25.001 | 14.375 | 31.305 | 19.520 | 15.246 | 13.233 | 25.419 | 19.395 | 25.001 | 13.872 | 12.792 | 16.865 | 17.264 | 17.578 | 14.877 | 14.990 |
| 557594 | 25.001 | 14.359 | 31.141 | 19.496 | 15.241 | 13.253 | 25.538 | 19.278 | 25.001 | 13.878 | 12.798 | 16.805 | 17.311 | 17.509 | 14.885 | 15.021 |
| 557614 | 25.001 | 14.350 | 30.915 | 19.413 | 15.253 | 13.258 | 25.580 | 19.199 | 25.001 | 13.878 | 12.810 | 16.767 | 17.338 | 17.445 | 14.823 | 15.046 |
| 557634 | 25.001 | 14.354 | 30.736 | 19.325 | 15.317 | 13.250 | 25.652 | 19.123 | 25.001 | 13.876 | 12.820 | 16.659 | 17.362 | 17.333 | 14.533 | 15.074 |
| 557654 | 25.001 | 14.379 | 30.477 | 19.207 | 15.576 | 13.256 | 25.760 | 19.024 | 25.001 | 13.899 | 12.848 | 16.482 | 17.402 | 17.133 | 14.410 | 15.110 |
| 557674 | 25.001 | 14.472 | 30.057 | 19.051 | 15.783 | 13.263 | 26.026 | 18.866 | 25.001 | 13.911 | 12.961 | 16.357 | 17.423 | 16.889 | 14.532 | 15.151 |
| 557694 | 25.001 | 14.579 | 29.553 | 18.911 | 16.002 | 13.273 | 26.460 | 18.717 | 25.001 | 13.929 | 13.114 | 16.265 | 17.416 | 16.685 | 14.363 | 15.185 |
| 557714 | 25.001 | 14.658 | 29.101 | 18.780 | 16.227 | 13.251 | 26.677 | 18.606 | 25.001 | 13.937 | 13.215 | 16.182 | 17.399 | 16.526 | 14.258 | 15.216 |
| 557734 | 25.001 | 14.714 | 28.741 | 18.673 | 16.439 | 13.263 | 26.916 | 18.493 | 25.001 | 13.952 | 13.291 | 16.114 | 17.406 | 16.380 | 14.420 | 15.254 |
| 557754 | 25.001 | 14.748 | 28.426 | 18.562 | 16.640 | 13.221 | 27.027 | 18.370 | 25.001 | 13.959 | 13.365 | 16.047 | 17.395 | 16.245 | 14.405 | 15.298 |
| 557774 | 25.001 | 14.769 | 28.179 | 18.451 | 16.746 | 13.144 | 27.169 | 18.250 | 25.001 | 13.957 | 13.454 | 15.986 | 17.406 | 16.103 | 14.480 | 15.385 |
| 557794 | 25.001 | 14.779 | 27.981 | 18.367 | 16.818 | 13.108 | 27.335 | 18.142 | 25.001 | 13.945 | 13.511 | 15.938 | 17.422 | 15.977 | 14.498 | 15.476 |
| 557814 | 25.001 | 14.782 | 27.793 | 18.294 | 16.846 | 13.082 | 27.584 | 18.058 | 25.001 | 13.949 | 13.537 | 15.893 | 17.444 | 15.872 | 14.526 | 15.524 |
| 557834 | 25.001 | 14.793 | 27.624 | 18.222 | 16.990 | 13.044 | 27.635 | 17.996 | 25.001 | 13.973 | 13.563 | 15.849 | 17.451 | 15.789 | 14.530 | 15.546 |

|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 558534 | 25.001 | 15.632 | 24.709 | 16.116 | 16.825 | 13.069 | 29.077 | 16.091 | 25.001 | 14.021 | 14.369 | 14.712 | 17.850 | 13.825 | 14.378 | 16.473 |
| 558554 | 25.001 | 15.667 | 24.663 | 16.079 | 16.842 | 13.102 | 29.080 | 16.062 | 25.001 | 14.036 | 14.379 | 14.693 | 17.853 | 13.799 | 14.260 | 16.508 |
| 558574 | 25.001 | 15.707 | 24.718 | 15.992 | 16.524 | 13.156 | 29.194 | 16.016 | 25.001 | 13.995 | 14.355 | 14.663 | 17.845 | 13.754 | 14.559 | 16.535 |
| 558594 | 25.001 | 15.730 | 24.814 | 15.907 | 16.236 | 13.216 | 29.364 | 15.985 | 25.001 | 14.004 | 14.362 | 14.643 | 17.866 | 13.718 | 14.745 | 16.545 |
| 558614 | 25.001 | 15.730 | 24.833 | 15.856 | 16.005 | 13.216 | 29.378 | 15.974 | 25.001 | 14.043 | 14.407 | 14.615 | 17.856 | 13.697 | 15.118 | 16.591 |
| 558634 | 25.001 | 15.745 | 24.769 | 15.806 | 15.825 | 13.186 | 29.311 | 15.952 | 25.001 | 14.101 | 14.459 | 14.590 | 17.785 | 13.681 | 15.440 | 16.677 |
| 558654 | 25.001 | 15.762 | 24.761 | 15.753 | 15.667 | 13.029 | 29.264 | 15.922 | 25.001 | 14.161 | 14.500 | 14.558 | 17.693 | 13.662 | 15.451 | 16.746 |
| 558674 | 25.001 | 15.789 | 24.752 | 15.724 | 15.481 | 12.949 | 29.305 | 15.879 | 25.001 | 14.186 | 14.534 | 14.535 | 17.694 | 13.639 | 15.577 | 16.782 |
| 558694 | 25.001 | 15.825 | 24.765 | 15.663 | 15.326 | 12.722 | 29.358 | 15.837 | 25.001 | 14.202 | 14.570 | 14.509 | 17.705 | 13.614 | 15.253 | 16.835 |
| 558714 | 25.001 | 15.879 | 24.817 | 15.592 | 15.201 | 12.680 | 29.446 | 15.792 | 25.001 | 14.206 | 14.590 | 14.484 | 17.721 | 13.586 | 15.267 | 16.894 |
| 558734 | 25.001 | 15.927 | 24.817 | 15.552 | 15.093 | 12.728 | 29.563 | 15.769 | 25.001 | 14.216 | 14.613 | 14.462 | 17.724 | 13.564 | 15.003 | 16.963 |
| 558754 | 25.001 | 15.944 | 24.733 | 15.521 | 14.981 | 12.859 | 29.583 | 15.751 | 25.001 | 14.225 | 14.659 | 14.449 | 17.728 | 13.543 | 15.232 | 17.025 |
| 558774 | 25.001 | 15.967 | 24.700 | 15.484 | 14.870 | 12.871 | 29.575 | 15.709 | 25.001 | 14.234 | 14.697 | 14.437 | 17.711 | 13.525 | 15.402 | 17.081 |
| 558794 | 25.001 | 15.967 | 24.747 | 15.441 | 14.773 | 12.949 | 29.646 | 15.684 | 25.001 | 14.247 | 14.709 | 14.426 | 17.724 | 13.515 | 15.283 | 17.150 |
| 558814 | 25.001 | 15.967 | 24.779 | 15.399 | 14.693 | 12.936 | 29.718 | 15.648 | 25.001 | 14.250 | 14.745 | 14.416 | 17.707 | 13.489 | 15.229 | 17.191 |
| 558834 | 25.001 | 15.976 | 24.851 | 15.357 | 14.633 | 13.124 | 29.748 | 15.618 | 25.001 | 14.246 | 14.753 | 14.405 | 17.667 | 13.469 | 15.215 | 17.230 |
| 558854 | 25.001 | 15.972 | 24.888 | 15.320 | 14.567 | 13.132 | 29.719 | 15.586 | 25.001 | 14.206 | 14.780 | 14.393 | 17.618 | 13.449 | 15.254 | 17.273 |
| 558874 | 25.001 | 15.968 | 24.937 | 15.290 | 14.500 | 13.150 | 29.764 | 15.558 | 25.001 | 14.199 | 14.806 | 14.381 | 17.608 | 13.421 | 15.240 | 17.327 |
| 558894 | 25.001 | 15.952 | 24.984 | 15.264 | 14.446 | 13.170 | 29.769 | 15.537 | 25.001 | 14.201 | 14.840 | 14.372 | 17.607 | 13.402 | 15.256 | 17.418 |
| 558914 | 25.001 | 15.954 | 24.933 | 15.253 | 14.446 | 13.223 | 29.723 | 15.516 | 25.001 | 14.183 | 14.883 | 14.360 | 17.628 | 13.391 | 14.759 | 17.493 |
| 558934 | 25.001 | 15.938 | 24.735 | 15.260 | 14.780 | 13.237 | 29.121 | 15.479 | 25.001 | 14.190 | 14.895 | 14.360 | 17.671 | 13.362 | 14.806 | 17.535 |
| 558954 | 25.001 | 15.838 | 24.671 | 15.286 | 14.859 | 13.252 | 28.894 | 15.465 | 25.001 | 14.218 | 14.796 | 14.398 | 17.719 | 13.349 | 14.607 | 17.517 |
| 558974 | 25.001 | 15.657 | 24.719 | 15.397 | 14.843 | 13.303 | 28.618 | 15.524 | 25.001 | 14.231 | 14.632 | 14.459 | 17.763 | 13.419 | 14.745 | 17.377 |
| 558994 | 25.001 | 15.496 | 24.754 | 15.454 | 14.853 | 13.254 | 28.516 | 15.568 | 25.001 | 14.230 | 14.501 | 14.515 | 17.827 | 13.515 | 14.539 | 17.229 |
| 559014 | 25.001 | 15.341 | 24.741 | 15.461 | 14.835 | 13.277 | 28.483 | 15.579 | 25.001 | 14.214 | 14.419 | 14.468 | 17.897 | 13.551 | 14.200 | 17.182 |
| 559034 | 25.001 | 15.251 | 24.668 | 15.431 | 14.911 | 13.269 | 28.407 | 15.570 | 25.001 | 14.220 | 14.375 | 14.417 | 17.955 | 13.480 | 14.120 | 17.209 |
| 559054 | 25.001 | 15.257 | 24.370 | 15.345 | 15.190 | 13.269 | 28.404 | 15.475 | 25.001 | 14.211 | 14.388 | 14.433 | 17.960 | 13     |        |        |

|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 559754 | 25.001 | 15.395 | 24.550 | 15.736 | 16.237 | 13.366 | 27.178 | 15.664 | 25.001 | 14.478 | 14.543 | 14.755 | 18.177 | 13.766 | 14.937 | 17.721 |
| 559774 | 25.001 | 15.449 | 24.245 | 15.650 | 16.448 | 13.346 | 27.381 | 15.552 | 25.001 | 14.469 | 14.595 | 14.724 | 18.206 | 13.670 | 14.897 | 17.785 |
| 559794 | 25.001 | 15.489 | 23.992 | 15.585 | 16.602 | 13.357 | 27.517 | 15.463 | 25.001 | 14.458 | 14.637 | 14.711 | 18.223 | 13.582 | 14.829 | 17.839 |
| 559814 | 25.001 | 15.502 | 23.815 | 15.529 | 16.639 | 13.354 | 27.564 | 15.396 | 25.001 | 14.459 | 14.652 | 14.698 | 18.231 | 13.524 | 14.753 | 17.892 |
| 559834 | 25.001 | 15.512 | 23.661 | 15.484 | 16.877 | 13.334 | 27.568 | 15.336 | 25.001 | 14.462 | 14.666 | 14.677 | 18.238 | 13.475 | 14.776 | 17.923 |
| 559854 | 25.001 | 15.512 | 23.552 | 15.440 | 17.081 | 13.332 | 27.614 | 15.285 | 25.001 | 14.470 | 14.674 | 14.657 | 18.271 | 13.427 | 14.701 | 17.965 |
| 559874 | 25.001 | 15.501 | 23.468 | 15.404 | 17.195 | 13.319 | 27.734 | 15.233 | 25.001 | 14.467 | 14.682 | 14.629 | 18.278 | 13.378 | 14.686 | 17.990 |
| 559894 | 25.001 | 15.491 | 23.370 | 15.367 | 17.298 | 13.326 | 27.882 | 15.179 | 25.001 | 14.470 | 14.683 | 14.610 | 18.298 | 13.334 | 14.689 | 18.028 |
| 559914 | 25.001 | 15.476 | 23.242 | 15.331 | 17.316 | 13.288 | 27.991 | 15.128 | 25.001 | 14.460 | 14.687 | 14.596 | 18.320 | 13.289 | 14.641 | 18.055 |
| 559934 | 25.001 | 15.463 | 23.116 | 15.293 | 17.444 | 13.274 | 27.996 | 15.075 | 25.001 | 14.451 | 14.687 | 14.600 | 18.353 | 13.254 | 14.610 | 18.097 |
| 559954 | 25.001 | 15.453 | 23.010 | 15.275 | 17.573 | 13.254 | 28.038 | 15.040 | 25.001 | 14.448 | 14.690 | 14.616 | 18.388 | 13.230 | 14.600 | 18.140 |
| 559974 | 25.001 | 15.446 | 22.956 | 15.243 | 17.649 | 13.258 | 27.975 | 14.997 | 25.001 | 14.442 | 14.697 | 14.613 | 18.407 | 13.198 | 14.620 | 18.159 |
| 559994 | 25.001 | 15.457 | 22.916 | 15.207 | 17.778 | 13.193 | 27.882 | 14.967 | 25.001 | 14.450 | 14.713 | 14.615 | 18.433 | 13.174 | 14.803 | 18.170 |
| 560014 | 25.001 | 15.512 | 22.880 | 15.192 | 17.665 | 13.182 | 27.989 | 14.959 | 25.001 | 14.466 | 14.754 | 14.587 | 18.435 | 13.165 | 14.993 | 18.141 |
| 560034 | 25.001 | 15.570 | 23.006 | 15.168 | 17.318 | 13.160 | 28.106 | 14.960 | 25.001 | 14.463 | 14.764 | 14.559 | 18.428 | 13.155 | 15.539 | 18.118 |
| 560054 | 25.001 | 15.609 | 23.204 | 15.150 | 17.028 | 13.153 | 28.275 | 14.979 | 25.001 | 14.483 | 14.775 | 14.538 | 18.439 | 13.159 | 15.746 | 18.133 |
| 560074 | 25.001 | 15.630 | 23.314 | 15.129 | 16.761 | 13.141 | 28.438 | 14.970 | 25.001 | 14.509 | 14.826 | 14.515 | 18.438 | 13.161 | 15.833 | 18.142 |
| 560094 | 25.001 | 15.647 | 23.422 | 15.104 | 16.561 | 13.125 | 28.528 | 14.951 | 25.001 | 14.544 | 14.874 | 14.488 | 18.435 | 13.162 | 15.937 | 18.187 |
| 560114 | 25.001 | 15.653 | 23.515 | 15.074 | 16.393 | 13.172 | 28.636 | 14.928 | 25.001 | 14.569 | 14.913 | 14.470 | 18.443 | 13.160 | 16.137 | 18.254 |
| 560134 | 25.001 | 15.660 | 23.621 | 15.054 | 16.231 | 13.161 | 28.804 | 14.906 | 25.001 | 14.550 | 14.953 | 14.453 | 18.416 | 13.168 | 16.139 | 18.366 |
| 560154 | 25.001 | 15.677 | 23.661 | 15.038 | 16.121 | 13.180 | 28.802 | 14.882 | 25.001 | 14.546 | 15.002 | 14.448 | 18.395 | 13.165 | 16.190 | 18.478 |
| 560174 | 25.001 | 15.720 | 23.623 | 15.019 | 16.028 | 13.197 | 28.755 | 14.858 | 25.001 | 14.548 | 15.048 | 14.446 | 18.416 | 13.168 | 16.182 | 18.559 |
| 560194 | 25.001 | 15.774 | 23.557 | 15.003 | 15.928 | 13.198 | 28.782 | 14.837 | 25.001 | 14.544 | 15.062 | 14.439 | 18.433 | 13.165 | 16.068 | 18.609 |
| 560214 | 25.001 | 15.828 | 23.474 | 14.976 | 15.825 | 13.204 | 28.775 | 14.810 | 25.001 | 14.536 | 15.065 | 14.432 | 18.441 | 13.164 | 15.931 | 18.613 |
| 560234 | 25.001 | 15.861 | 23.406 | 14.956 | 15.740 | 13.215 | 28.667 | 14.784 | 25.001 | 14.532 | 15.050 | 14.429 | 18.456 | 13.151 | 15.897 | 18.592 |
| 560254 | 25.001 | 15.878 | 23.415 | 14.933 | 15.671 | 13.213 | 28.624 | 14.767 | 25.001 | 14.560 | 15.046 | 14.433 | 18.475 | 13.158 | 15.864 | 18.574 |
| 560274 | 25.001 | 15.902 | 23.385 | 14.904 | 15.540 | 13.224 | 28.682 | 14.750 | 25.001 | 14.553 | 15.039 | 14.423 | 18.485 | 13.153 |        |        |

## APPENDIX D PC-TRAN INPUTS

\* Indicates input used in analysis

1. ATMOSPHERIC MODEL
  - A. Specify meteorological data
  - B. Tropical model atmosphere
  - C. Midlatitude summer
  - D. Midlatitude winter
  - E. Subartic summer
  - F. Subartic winter
  - G. 1962 U.S. standard
  - \*H. Radiosonde data
2. TYPES OF ATMOSPHERIC PATH
  - A. Horizontal
  - \*B. Vertical or slant path between two altitudes
  - C. Vertical or slant path to space
3. MODES OF EXECUTION
  - A. Transmittance mode
  - \*B. Radiance mode
4. SPECIFY TEMPERATURE/PRESSURE ALTITUDE PROFILES TO BE USED
  - \*A. Normal
5. SPECIFY WATER VAPOR ALTITUDE PROFILE USED
  - \*A. Normal
6. OZONE PROFILE
  - \*A. Normal
  - B. Tropical
  - C. Midlatitude summer
  - D. Midlatitude winter
  - E. Subartic summer
  - F. Subartic winter
  - G. 1962 U.S. standard atmosphere
7. SPECIFY NORMAL OPERATIONS OR RADIOSONDE DATA WILL BE USED EITHER INITIALLY OR ON SUBSEQUENT RUNS
  - A. Normal
  - \*B. Radiosonde
8. SPECIFY NOKMAL OPERATIONS OR SUPPRESS PRINTING
  - \*A. Normal
  - B. Suppress printing

9. TEMPERATURE OF THE EARTH AT THE LOCATION AT WHICH  
CALCULATION IS TO BE PERFORMED
  - \*A. (from data)
10. SPECIFY THE SURFACE ALBEDO OF THE EARTH
  - \*A. Assume blackbody default
11. EXTINCTION TYPE
  - A. No aerosol attenuation
  - B. Rural extinction, 23 km VIS
  - C. Rural extinction, 5 km VIS
  - \*D. Navy maritime
  - E. Maritime, 23 km VIS
  - F. Urban, 5 km VIS
  - G. Troposphere, 50 km VIS
  - H. User defined
  - I. Fog 1, 0.2 km VIS
  - J. Fog 2, 0.5 km VIS
12. SEASONAL DEPENDENCE OF PROFILES
  - \*A. Default to season of model
  - B. Spring/summer
  - C. Fall/winter
13. PROFILE AND EXTINCTION FOR STRATOSPHERIC AEROSOLS
  - \*A. Default to stratospheric background
  - B. Stratospheric background
  - C. Aged volcanic type/moderate volcanic profile
  - D. Fresh volcanic type/high volcanic profile
  - E. Aged volcanic type/high volcanic profile
14. SPECIFY AIR MASS CHARACTER
  - A. Open ocean
  - \*B. 3
  - .
  - .
  - .
  - J. Strong continental influence
15. DETERMINE THE INCLUSION OF CIRRUS ATTENUATION
  - \*A. No cirrus
  - B. Use cirrus profile
16. U.S. ARMY VERTICAL STRUCTURE ALGORITHM (not used)
17. SPECIFY METEOROLOGICAL RANGE (km) (default)
18. CURRENT WIND SPEED (from data)
19. 24 HOUR AVERAGE WIND SPEED (from data)

- 20. PRECIPITATION RATE (0 from data)
- 21. ATMOSPHERIC LEVELS
  - \*A. Initial altitude (0 at target)
  - \*B. Final altitude (0 at target)
  - C. Initial zenith angle as measured from the initial altitude
  - D. Path length
- 22. RADIUS OF THE EARTH
  - A. Specify radius
  - \*B. Default (6371.23 km)
- 23. PROGRAM OPERATION
  - \*A. Normal program operation
  - B. Select downward type two long path
- 24. SPECTRAL RANGE (corresponds to 8-12  $\mu\text{m}$  band)
  - \*A. Initial frequency ( $833.0\text{ cm}^{-1}$ )
  - \*B. Final frequency ( $1250\text{ cm}^{-1}$ )
  - \*C. Frequency increment ( $5\text{ cm}^{-1}$ )

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- |     |                              |   |
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|     | Naval Postgraduate School    |   |
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