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THESIS

INFRARED BACKGROUND AND TARGET
MEASUREMENT

by

Alexander Manolopoulos

December 1985

Thesis advisor:

A. W. Cooper

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Window. The corresponding values for buildings were 3.587×10^{-4} W/cm²sr and 4.552×10^{-3} W/cm²sr respectively.

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Infrared Background and Target Measurement

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The present work describes measurements of IR background radiance. To provide background radiance values for the development of the AN / SAR - 8 (IRSTD) system, the radiance of clouds and buildings was measured using the AGA Thermovision 780. The measurement values given in Isotherm Units (photon flux equivalent) were translated into radiance values ($\text{W}/\text{cm}^2\text{sr}$). The emissivity of the different objects was also computed for the 8-14 μm window assuming that their emissivity in the 3-5.6 μm band is close to that of a blackbody. The average radiance of clouds was found to be $3.302 \times 10^{-4} \text{ W}/\text{cm}^2\text{sr}$ in the 3-5.6 μm window and $3.544 \times 10^{-3} \text{ W}/\text{cm}^2\text{sr}$ in the 8-14 μm window. The corresponding values for buildings were $3.587 \times 10^{-4} \text{ W}/\text{cm}^2\text{sr}$ and $4.552 \times 10^{-3} \text{ W}/\text{cm}^2\text{sr}$ respectively.

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I. INTRODUCTION

An important element in Naval Warfare Defence is the development of a surveillance system capable of monitoring the appearance and progress of any potential threat. The infrared (IR) spectral region shows good promise for passive detection systems able to detect a variety of targets at different altitudes. Such a system is the Infrared Search and Target Designation (IRSTD) System (AN/ SAR-8) currently in engineering development.

In support of the development of such a system, it is necessary to fully specify and understand the IR radiance from the earth - atmosphere scene within a given field-of-view (FOV). Detecting a target by its radiation requires that not only the target intensity but also the spectral and spatial structure of the background be fully understood.

Important inputs to the design of successful detection systems are recorded magnitudes and variations in the radiance from various scenes. This information will help in developing data processing algorithms to distinguish radiation signatures of clouds and other surfaces from those of the target.

In the context of this THESIS, data on cloud and background radiance were collected and analyzed for the

purpose of later development of algorithms that will aid the AN/SAR-8 to ignore false targets generated by background, atmospheric or non atmospheric, IR radiation.

These data were collected using the "AGA 780 Thermovision", a liquid nitrogen cooled thermographic device able to detect IR radiation in the Middle IR, called hereafter Short Wave - SW (3-5.6 micrometers), and in the Far IR, called hereafter Long Wave - LW (8-14 micrometers).

The present work consists of eight chapters following the introduction. The first chapter describes the problem and the expected output of the work. In the second chapter a theoretical overview is presented, along with data from the literature, of clouds and different backgrounds. The third chapter describes how the LOWTRAN propagation / radiance code was used to give transmittance of the atmosphere under the various circumstances of the measurements. The fourth chapter lists the capabilities of the AGA equipment and the mode of operation used. The fifth chapter describes how the AGA was calibrated empirically. In the sixth chapter the method which was actually used is presented both mathematically and analytically. In the seventh chapter measured cloud and background signatures are listed, analyzed and presented as final results. The last chapter consists of the

conclusions that the results lead to and suggestions for possible improvements and future work in the area.

The results obtained are not expected to have significant quantitative importance, due to the wide variety of possible background radiators and meteorological conditions, but it is hoped that they will provide a starting point for further work on the subject.

II. BACKGROUND TO PROBLEM

A. GENERAL

All objects in our environment, either cold or hot, radiate IR energy detectable by the IRSTD system.

The IRSTD, as mentioned before, should be capable of determining whether an observed IR source is (1) an airplane/missile, or (2) an unwanted source such as clouds, birds, or shore features.

There are several atmospheric and terrain conditions affecting the translation of emitted radiation into meaningful signal. Two of the most important factors are the atmospheric background and the atmospheric absorption.

Atmospheric background consists mainly of clouds, rain, snow, clear sky etc. Terrestrial background consists of land, mountains, hills, cities, buildings etc.

Here we will deal with cloud and building signatures. The radiance of a selection of such sources was measured using the "AGA 780" system.

The equipment used is designed to provide the temperature of an object if its emissivity is known or vice versa. An empirical calibration of the "AGA 780" along with the application of some simple mathematical formulae was needed in order to obtain radiance measurements.

The second factor mentioned above, the atmospheric absorption, has been dealt with by using the LOWTRAN code for propagation of IR radiation. Specifically the LOWTRAN 6 computer program was used to provide attenuation factors under different atmospheric conditions.

B. EFFECTS OF BACKGROUND CLUTTER IN IMAGING

Background clutter is an important factor limiting the performance of thermal imaging equipment. Clutter emission from clouds, birds and terrestrial objects generates a sensor response which may either mask the signal from a target or appear as a false target.

It is impossible to predict how large spatially or how intense a clutter signal from background would be. Background clutter may consist of either emission or scattering from small objects (eg. birds) as well as from large objects (eg. clouds) [Ref. 1].

Targets and clutter will be sensed by an imaging system as having a small temperature difference from the background, ΔT . This temperature difference can be expressed as radiation contrast C_R , as described by Lloyd [Ref. 2].

$$C_R = \frac{W_T - W_B}{W_T + W_B} \quad (\text{II-1})$$

W_T = target radiant emittance (W/m^2)

W_B = background radiant emittance (W/m^2)

If the total radiant emittance $W(T)$ is

$$W(T) = \sigma T^4 \quad (\text{Stefan's law}) \quad (\text{II-2}), \text{ then}$$

$$\frac{\partial W(T)}{\partial T} = 4 \sigma T^3 \quad (\text{II-3})$$

$$\text{or, } \Delta W(T) = 4 \sigma T^3 \Delta T \quad (\text{II-4})$$

$$\text{Now } C_R = \frac{W_T - W_B}{W_T + W_B} \quad (\text{II-1})$$

$$\text{For } W_B = W(T) = \sigma T^4 \quad (\text{II-5})$$

$$\text{and } W_T = W(T + \Delta T) = W(T) + \frac{\partial W(T)}{\partial T} \Delta T \quad (\text{II-6})$$

$$C_R = \frac{\Delta W(T)}{2W(T) + \Delta W(T)} \quad (\text{II-7})$$

$$= \frac{4 \sigma T^3 \Delta T}{2 \sigma T^4 + 4 \sigma T^3 \Delta T}$$

$$= \frac{2 \Delta T}{T + 2 \Delta T} \quad \text{or,}$$

$$C_R = \frac{2 \Delta T}{T}, \text{ for small } \Delta T. \quad (\text{II-8})$$

For typical scenes ΔT is of order $1^\circ K$ so this approximation may be justified.

C. BACKGROUND SUPPRESSION SCHEMES

A filtering system (subtraction scheme) will be needed to suppress the background signal. This could

be an automatic background suppression system that will sense the average background signal and subtract it.

A problem could arise here when the temperature of the target and its background are nearly the same (zero contrast). This will happen twice each day .

Hudson [Ref. 3] gives a very good example showing that last point. A truck is parked in an open field so that an infrared system can view it . Observations are made over a period of 24 hours and variations are found in the contrast between the vehicle and its background . In the afternoon the truck has been heated enough by the sun to be warmer than the background ,giving a positive contrast. During the early evening hours the vehicle , because of its large thermal capacity , cools more slowly than the background and the contrast is even greater (more positive) . At night the truck cools more rapidly , passes the point of equal temperature to the background and the contrast passes through zero to become negative. As the sun rises again the background warms more rapidly than the truck and the contrast becomes more negative . Later in the morning the heating of the sun will be sufficient to cause a period of zero contrast and then a positive one. That

shows that " for many targets and background combinations , there are two intervals in any 24-hour period during which the target cannot be detected because there is insufficient radiation contrast between it and its background " .

There are no good methods of eliminating this effect ; the best thing to do would be to wait until the period of "washout" passes.

D. CLUTTER SUPPRESSION SCHEMES

Assuming that targets and clutter will have different temperature from the background and that the background suppression is successful , the problem of eliminating clutter still remains.

Several unwanted signals that will have small ΔT above the background will be present . These signals can be from birds , clouds , buildings etc. . They will all appear as threshold crossings exactly as a target could appear.

To avoid confusion caused by these signals several methods can be used . The use of each one will depend on the task that the system will perform (early warning, detection , tracking etc.) and on the kind of clutter expected (small or large , intense or not).

One method could be the use of a rotating reticle , in the equipment's image plane , to achieve space filtering . This method is described by Hudson [Ref. 3] and can be used for discrimination of small targets against large clutter like clouds in seeker or tracker systems.

Other methods will be dependent mainly on the size of the target to be detected .

For example for a small target we could divide the scan electronically into small windows (each one being equal in dimension to one Instantaneous field-of-view) and test if the target appears in more than two neighbouring windows. In figure 2.1 signals A and B will be classified as targets and signal C will be classified as clutter and discarded. This scheme will not be effective against small false targets such as birds .

For large targets (eg. ships) a useful logic method could be to check if the target appears in three out of four successive windows. In figure 2.2 signals A and B will be classified as targets but signal C will be classified as clutter. This system may perhaps not detect a small target (however , a missile may be detected since its booster is heating the air surrounding the exhaust gas , and will give a large target).

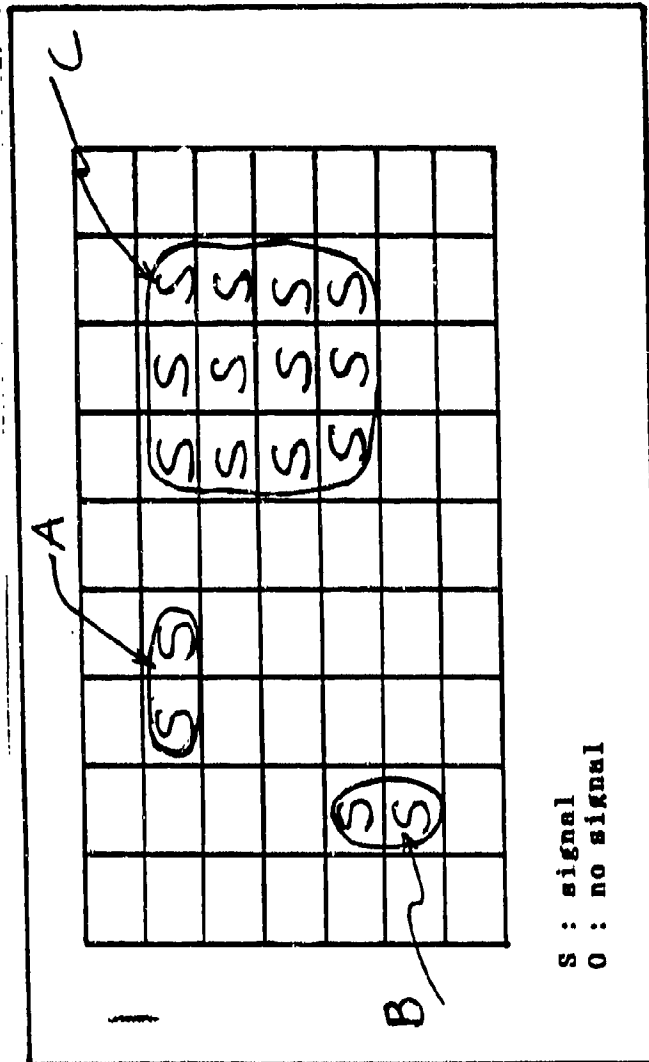


Fig. 2.1 Clutter suppression scheme for use in system that will detect small targets.

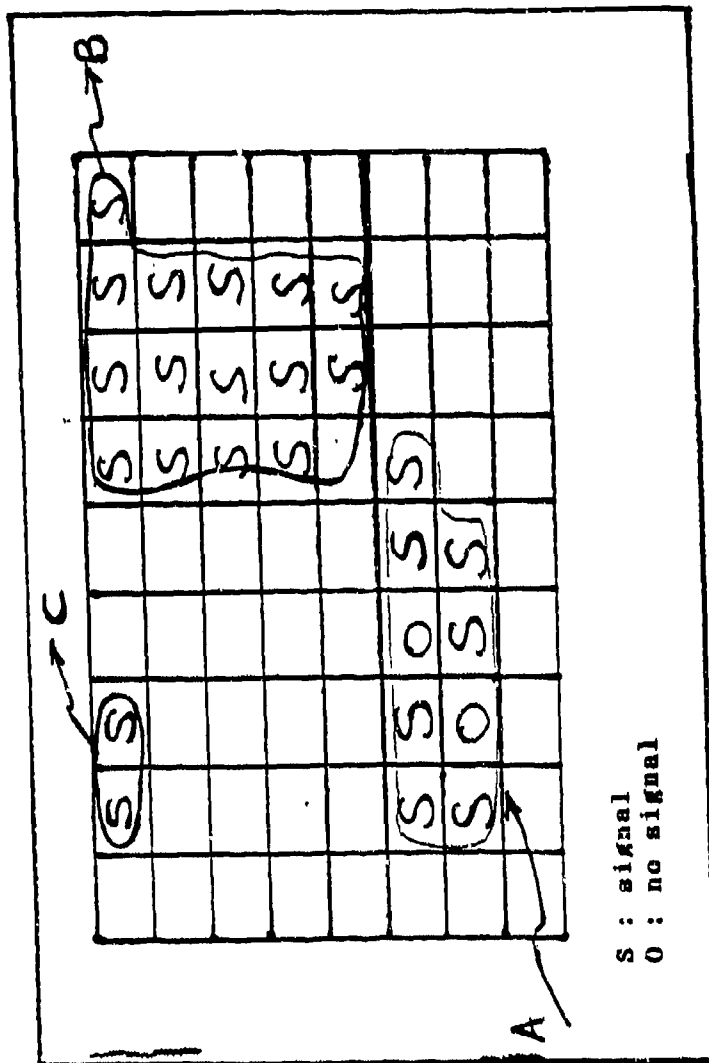


Fig. 2.2 Clutter suppression scheme for system that will detect large targets.

Other possible methods could be software analysis of the movement of the targets (eliminating for example all signals not showing any movement at the risk of discarding ships that will be stationary) , or analysis of signature patterns and statistical comparison with known signatures (although this might be very difficult due to the wide variety of clutter signatures).

E. CONCLUSION

What is obvious from the above is that it will be useful to know what amount of thermal radiation is emitted by different kinds of clutter like clouds, buildings etc. . The purpose of this THESIS is to provide and analyze thermal radiation values from such clutter.

III. CLOUDS , BACKGROUNDS AND THEIR SIGNIATURES

A. CLOUDS

Clouds are one of the main causes of undesirable IR radiation . Cloud cover in most of the regions of the world is a condition that exists about one half of the time. Figure 3.1 shows the frequency of overcast skies (curve 1) and the total frequency of overcast and partly cloudy skies (curve 2) along the 20° W Meridian, as a function of Latitude [Ref 5].

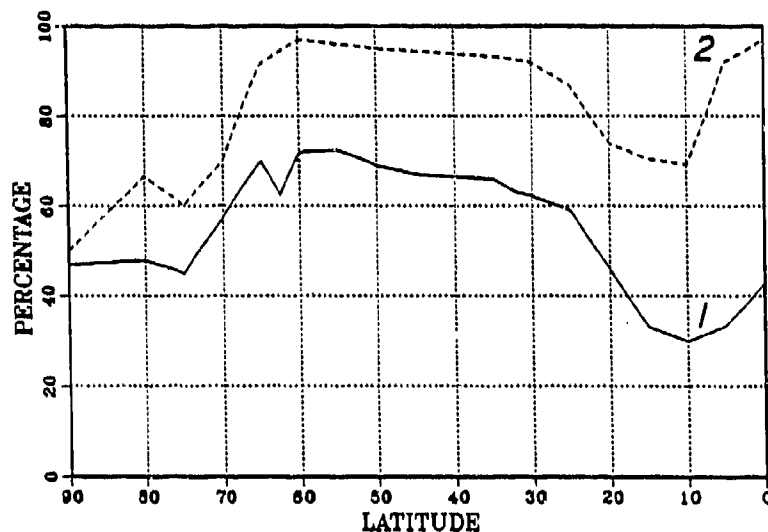


Fig. 3.1 : Latitude and dependence of frequencies of various kinds of weather along the 20° W meridian. (1) frequency of overcast skies (8-10 on a 10 fold scale for cloudiness) (2) frequency of overcast and partly cloudy (3-7) skies . Region above curve 2 characterizes frequency of clear skies. [Ref.5]

Clouds may be classified into three major categories according to the height at which they occur.

- (i) High level clouds.
- (ii) Middle level clouds.
- (iii) Low-level clouds.

The following table shows those categories, the type of clouds in each and typical heights at which they occur.

Cloud level	Type of Clouds	Altitude at which they occur at Midlatitude. (Avg. all seasons)
	Cirrus	
High	Cirrocumulus	5 - 13 km
	Cirrostratus	
Middle	Alto cumulus	2 - 7 km
Low	Stratocumulus	Earth's surface
	Stratus	to 2 km

Figures 3.2 and 3.3 both from [Ref. 6] show spectral radiance from two types of clouds, Cumulus and Cirrus respectively.

Discussion of the particular behavior of each category is beyond the task of this THESIS but in general we can state that the clouds perform three things of interest in the present context:

- (i) They reflect radiation originating from terrestrial objects.

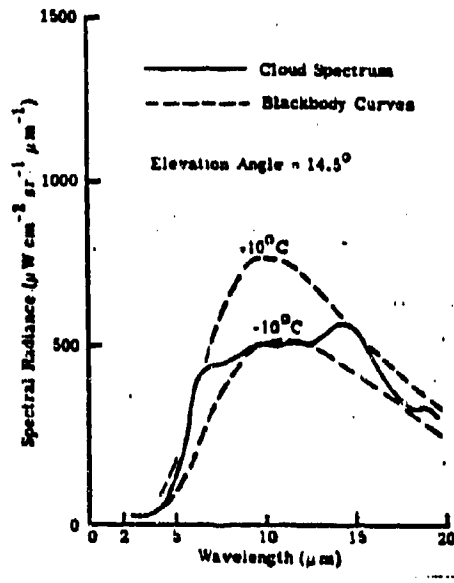


Figure 3.2 : The spectral radiance of the underside of a dark cumulus cloud . [Ref. 6]

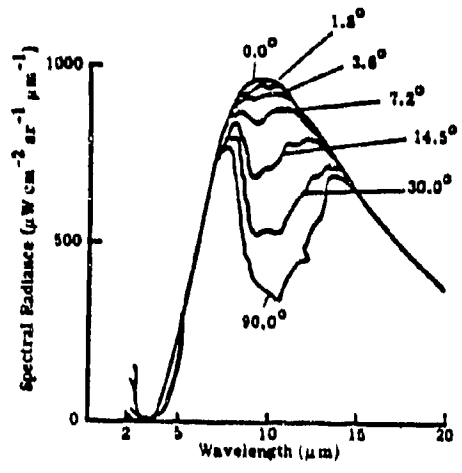


Figure 3.3 : The spectral radiance of sky covered with cirrus clouds at several angles of elevation. [Ref. 6]

- (ii) They scatter solar radiation strongly , and
- (iii) They emit IR radiation due to their own temperature.

Figure 3.4 [Ref. 10] shows how solar thermal radiation components reach the surface of the earth and then how they are reemitted back. There we see that of the incoming thermal radiation , 3% is absorbed by clouds and 20% is reflected by clouds back to space. On the other hand emission by clouds is responsible for 26% of the outgoing radiation to space.

1. Reflection of IR Radiation by Clouds

Clouds reflect IR radiation from terrestrial objects. Typically the reflectance of a middle layer cloud ranges from 0.75 to 0.1 in the spectral range 0.2 to 4 μm (fig. 3.5) [Ref. 6].

The reflectance of a cloud increases with the cloud thickness, and with decreasing mean free path of a light ray. It also varies with the solar zenith angle (fig. 3.6) [Ref. 6].

2. Scattering of IR Radiation by Clouds

The scattering process is the process by which particles absorb energy from an incident electromagnetic wave , from some direction , and reradiate that energy into the total solid angle centered at the particle. Scattering is a function of particle size, density and refractive index and also wavelength of incident light.

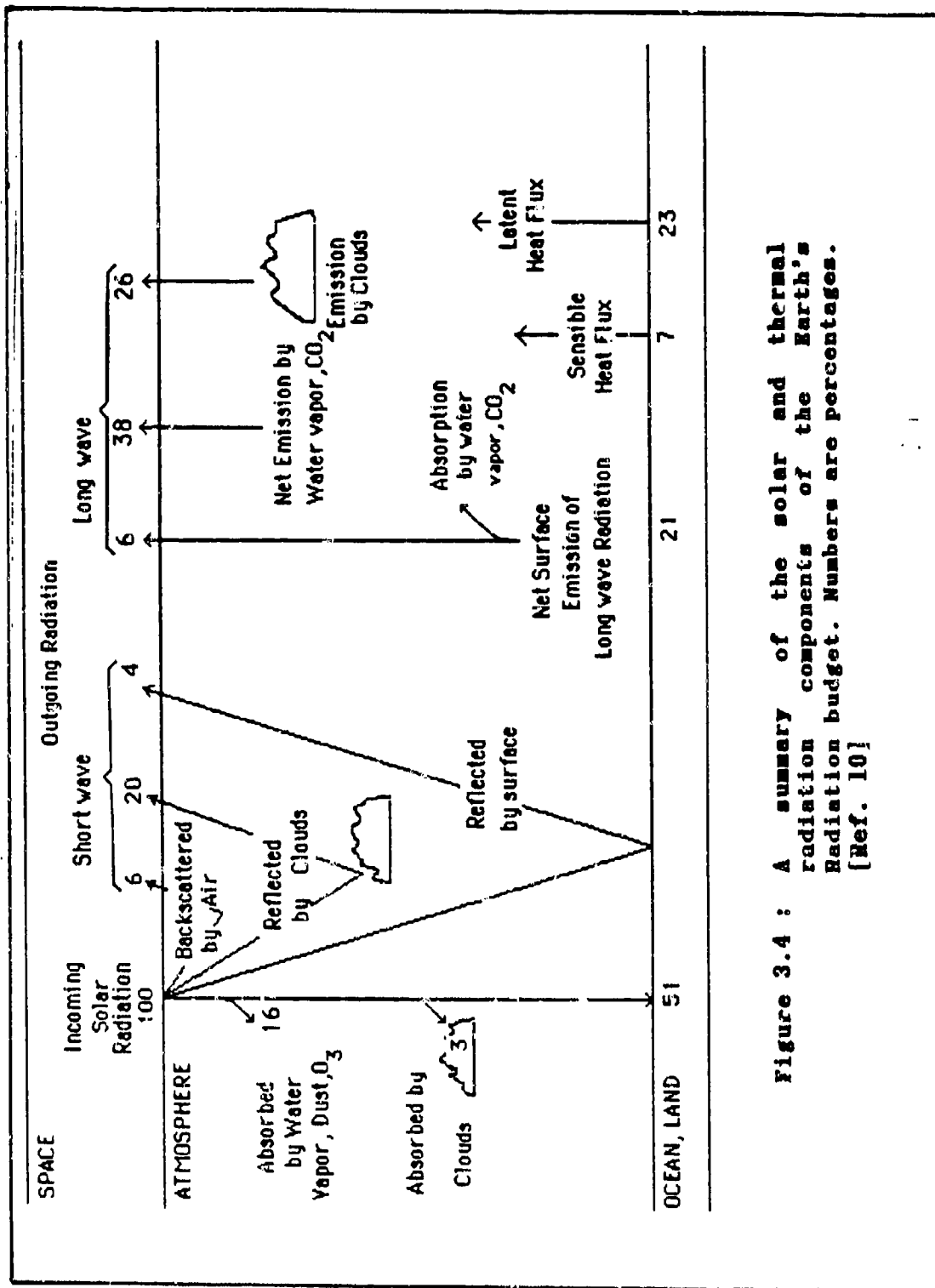
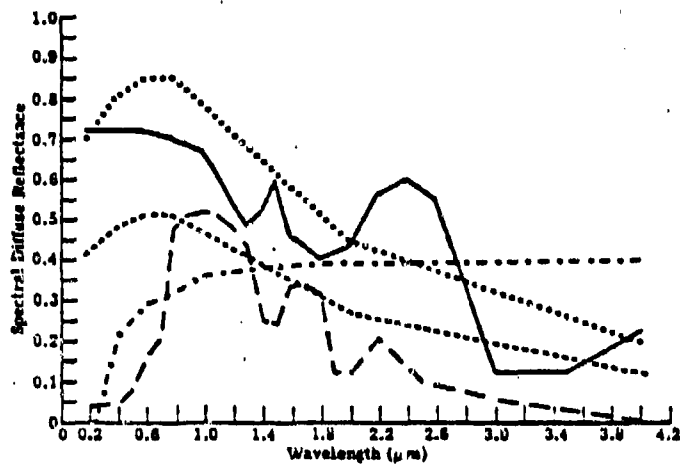


Figure 3.4 : A summary of the solar and thermal radiation components of the Earth's Radiation budget. Numbers are percentages. [Ref. 10]



- Clouds. Data are directional reflectance of a middle layer cloud.
- Winter Snow and Ice. Data are directional reflectance of dry snow.
- · - · - Summer Ice. Data are directional reflectance of summer Arctic ice.
- - - - Soil and Rocks. Data represent the average value of the bidirectional reflectance, $\rho_b(45^\circ, 0, 0, 0)$, of gravel, wet clay, dry clay, tuff bedrock, and sandy loam.
- - - - Vegetation. Data represent the average value of directional reflectance of many types of vegetation (from the ERIM Data File).

Figure 3.5 : Spectral diffuse reflectance of Earth-atmosphere constituents. [Ref. 6]

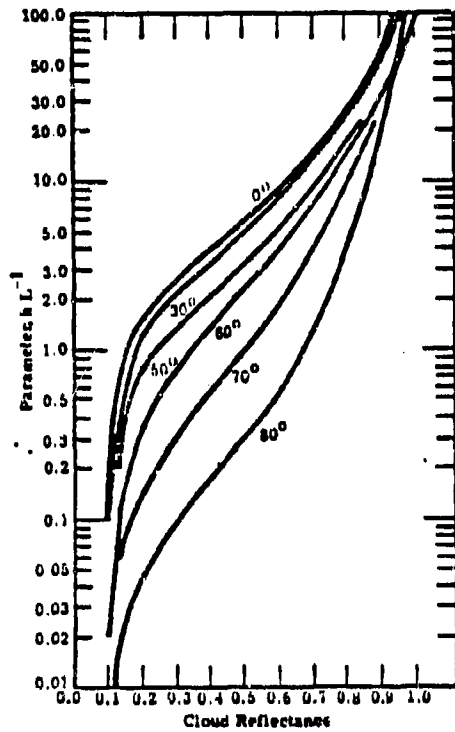


Figure 3.6 : The variation in reflectance as a function of cloud thickness parameter hL^{-1} for different solar zenith angles. The cloud thickness is h and the mean free path of a light ray is L . [Ref. 6]

Water clouds contain water-droplets and ice-crystals with radii from $1 \mu\text{m}$ to about $10 \mu\text{m}$ and concentrations of $300-10^3$ per cm^3 . (for comparison purposes the corresponding values for raindrops are $10^2 - 10^4 \mu\text{m}$ and $10^{-2} - 10^{-3}$ per cm^3). Figure 3.7 [Ref. 11] shows the water droplet size distribution as a function of drop radius for various cloud cases. The highest clouds are composed of large ice crystals of radii greater than $50 \mu\text{m}$. The lower clouds can be assumed to be at above freezing temperatures and therefore water droplet clouds. Figure 3.8 [Ref. 10] shows the composition of clouds vs. temperature.

Under those considerations, Mie scattering (particle size comparable to wavelength) is dominant assuming that incident solar radiation at the clouds has a peak at about $0.5-1 \mu\text{m}$ and land radiation has a peak at about $10 \mu\text{m}$. Rayleigh scattering (particle size much less than wavelength) is of less importance in connection with water clouds.

We can say that the solar scattering through clouds occurs at wavelengths shorter than $3 \mu\text{m}$ (Near IR). Middle IR is less affected by particle scattering and the Far IR is barely affected at all.

Near IR radiation exhibits strong forward scattering in clouds, but for a heavy overcast sky multiple scattering reduces this effect.

Finally, it is clear that the relative positions of sun, observer and cloud cover are of importance in

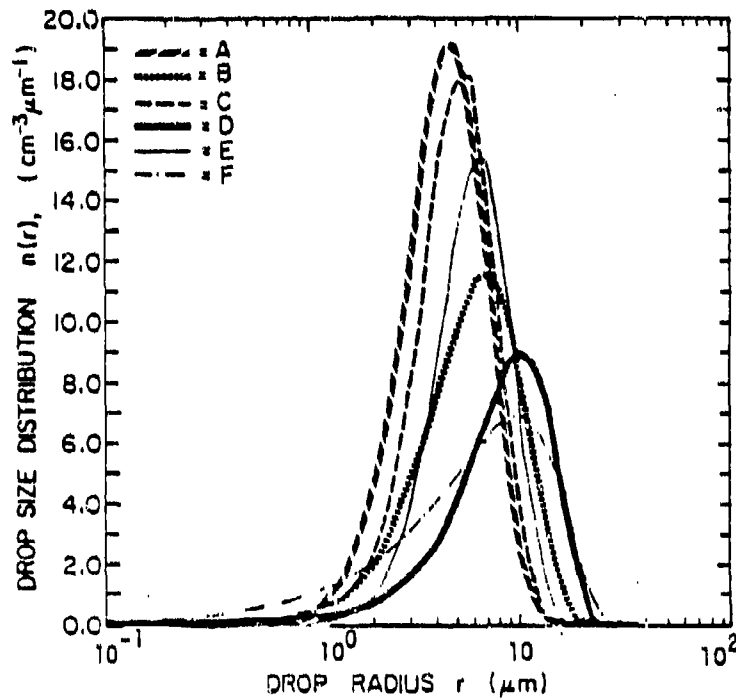


Figure 3.7 : Drop size distributions $n(r)$ for various cloud cases. [Ref. 11]

- A) stratus base
- B) stratus top
- C) stratocumulus base
- D) stratocumulus top
- E) nimbostratus base
- F) nimbostratus top

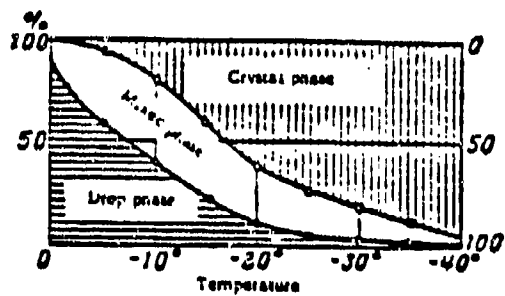


Figure 3.8 : Phase composition of clouds vs. temperature . [Ref. 10]

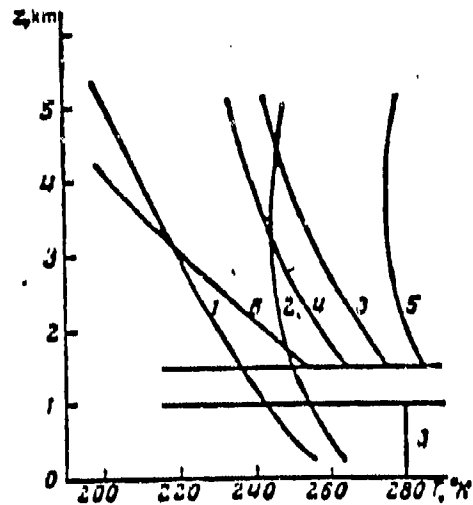


Figure 3.9 : Vertical temperature distribution for various models. [Ref. 10]
 1 and 2 Cloudless atmosphere night and day
 3 and 4 Cloud, night without and with scattering
 5 Cloud day
 6 Cloud night (selective absorber)
Note : In curves 3 and 4 the cloud is assumed to be graybody.

determining the amount of IR radiation (due to scattering) received through clouds.

3. Emission of IR Radiation by Clouds

Like all other bodies, clouds emit IR radiation due to their temperatures. Usually the temperature of a cloud differs from the surrounding air by not more than some tenths of a degree. This difference reaches a maximum of one degree for dense cumulus clouds [Ref. 10]. Under those considerations the temperature of a low cloud is about 10° C below ambient temperature at the sea surface. Also it is obvious that a cloud's temperature decreases with height. Figure 3.9 [Ref. 10] shows the vertical temperature distribution for various models of clouds.

Thick clouds (thickness > 100m) i.e. many free paths in thickness and clouds with content of water droplets (or ice crystals) greater than 0.5 g/cm³ are good blackbodies [Ref. 5]. Since their temperature is of the order of 300°K they emit mainly in the 8-13 μm band. Figure 3.10 [Ref. 5] shows the spectral emissivity of cloud layers of thickness Δz and figure 3.11 [Ref. 5] shows how the integral emissivity, transmittance and absorptance varies with Δz. It is clear from that last figure that for

$\Delta z > 60\text{m}$ $\tau \rightarrow 0$, and

$\Delta z > 100\text{m}$ $\epsilon \rightarrow 1$

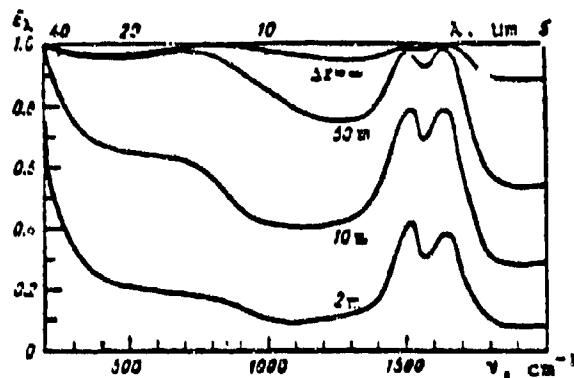


Figure 3.10 : Spectral emissivity of cloud layers of thickness Δz . [Ref. 5]

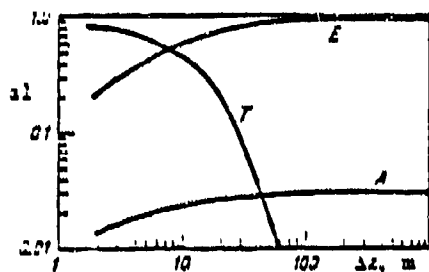


Figure 3.11 : Integral emissance (E), transmittance (T), and absorptance (A) curves. [Ref. 5]

Figure 3.12 [Ref. 6] shows the zenith sky spectral radiance from a cloud. In this figure we note two things:

(a) The large variation of the cloud spectral radiance for different ambient air temperature.

(b) That neglecting the absorption band centered at about $10 \mu\text{m}$ the cloud spectrum approaches very closely the blackbody curves of the ambient air temperature thus making the latter a very good estimate of the cloud's own temperature.

B. BACKGROUNDS

For our purpose we may consider two general categories of background (surface backgrounds).

1. Marine Backgrounds

The surface of the sea emits its own thermal radiation and also reflects incident IR radiation. The major factors that determine the amount of IR radiation due to a marine background are (1) the surface temperature of the water (2) the optical properties of the water (3) the amount of agitation of the water (4) the material properties of the bottom of the sea [Ref. 6] .

For our purpose, it has been assumed that marine backgrounds won't produce any effect by reflecting IR radiation since the reflectance of the water is less than 0.05 for angles of incidence of 50° or less as can be

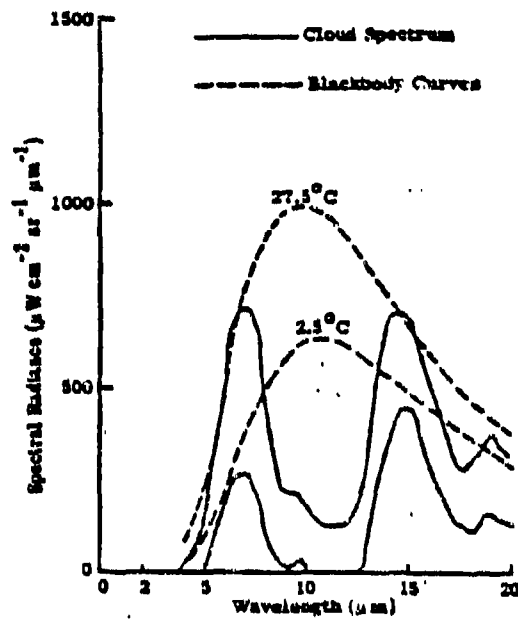


Figure 3.12 : Zenith sky spectral radiance showing the large variation with ambient air temperature. [Ref. 6]

seen in figure 3.13 [Ref. 6]. Rough sea may change that. For a Beaufort 4 wind roughened sea, for the sun at the horizon, the reflectance reaches a maximum of about 0.20. But for the sun at an elevation of 30° or more the reflectance will be less than 0.05. (Figure 3.14 [Ref. 6])

What remains is the emission of IR radiation by the sea. The emissivity of an average rough sea is about 0.8 but the amount of IR radiation actually emitted depends on the water temperature. This temperature is near 0°C (about 4°C) in the arctic regions and 29°C near the equator. Currents may produce anomalies of several degrees Celsius as warm water flows into cold water or vice versa.

2. Terrestrial Backgrounds

Terrestrial objects have a wide variety of emissivities and temperatures. Some of them also are not opaque. Obviously the radiance of a sun heated object falls during the night when heating from the sun is absent. Figure 3.15 [Ref. 6] shows the variation in the 10 μm radiance of selected backgrounds during a 24 hour time period.

Most terrestrial objects are not blackbodies. This can be seen in figure 3.16 taken from [Ref. 6], which represents the radiance of a city on a plain (Colorado Springs) as viewed from a mountain (Pikes Peak) at a

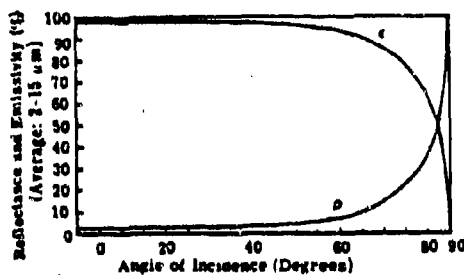


Figure 3.13 : Reflectance and emissivity of water (2 to 15 μm average) versus angle of incidence. [Ref. 6]

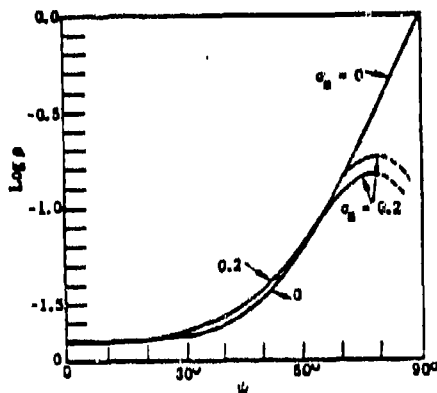


Figure 3.14 : Reflection of solar radiation from a flat surface ($\sigma_s=0$) and a surface roughened by a beaufort 4 wind ($\sigma_s=0.2$) The lower and upper branches of the curve marked $\sigma_s=0.2$ represent two assumptions regarding the effect of multiple reflection. True values are expected to lie between the indicated limits. [Ref. 6]

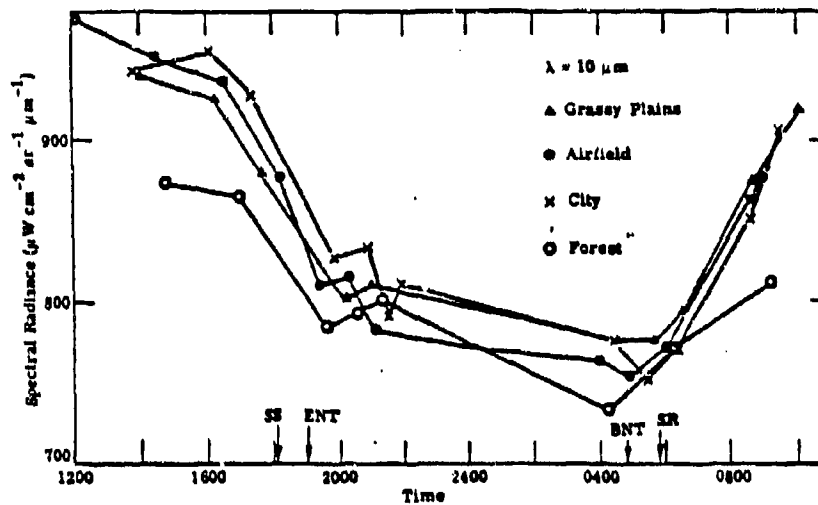


Figure 3.15 : Diurnal variation in the $10 \mu\text{m}$ Radiance of selected backgrounds .
 SS : sunset; ENT : end of nautical twilight;
 SR : sunrise; BNT : beginning of nautical twilight. [Ref. 6]

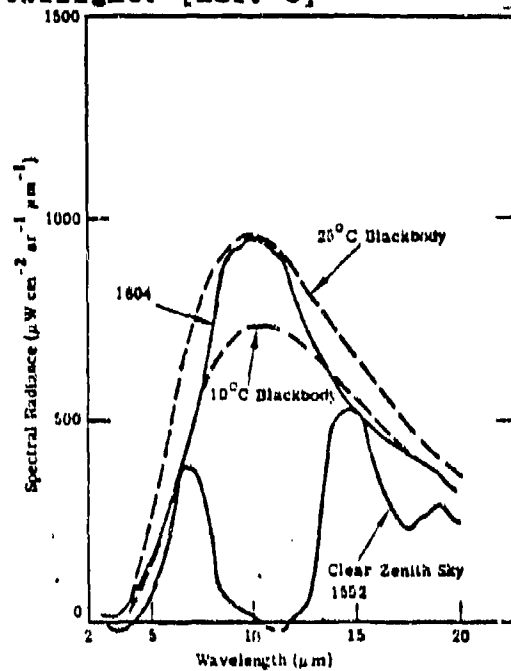


Figure 3.16 : Radiance of an urban area and clear zenith sky (Colorado Springs from Pikes Peak). [Ref. 6]

distance of about 24 km. On the other hand most of the terrestrial objects behave as graybodies .

IV. LOWTRAN PROPAGATION / RADIANCE CODE

A. MODELS FOR PROPAGATION OF IR RADIATION THROUGH THE ATMOSPHERE

For many applications, and specifically for the performance of military systems in imaging, a model which will provide accurate transmission and modification of IR radiation through an atmospheric path, and also the fluctuation in these effects is needed.

Two such models are available, the High resolution model developed by the AFCRL and the Low resolution model called LOWTRAN.

The HITRAN High Resolution models such as LASER and FASCODE are direct computation models which provide very high resolution (ie. single frequency) results. This is necessary to predict atmospheric behavior of laser radiation, but not for thermal (broad band) sources such as considered here.

B. LOWTRAN CODE

LOWTRAN has been developed as a curve-fitting program matching empirical or precomputed attenuation data. This empirical data is averaged over some specific spectral interval (20 cm^{-1}). As a consequence of the averaging over finite spectral interval, many of the rapid

spectral fluctuations of atmospheric transmittance will vanish.

Thus the LOWTRAN code can be considered as a fast but not very accurate computer program.

LOWTRAN 6, the latest version of LOWTRAN, is a program designed to calculate transmittance and/or radiance of the atmosphere for a specific set of geometrical and weather conditions, in the spectral range 0.25 to 28.57 micrometers (350 to 40,000 cm^{-1}) at 20 cm^{-1} intervals (ie. 20 cm^{-1} spectral resolution).

C. INPUTS TO LOWTRAN 6 CODE

To run LOWTRAN 6 one must specify four sets of input data (cards).

In Cards 1 & 2 one of the six available atmospheric models or a user defined set of meteorological conditions (model atmosphere) must be specified.

In Card 3 are specified the different geometrical path parameters of the problem.

In Card 4 finally are specified the spectral range over which data are required and the frequency increment at which the data are to be printed out.

D. INPUT DATA USED

This model has been used in this study to predict sky radiance and correct other radiance values for atmospheric effects.

For Card 1 the Midlatitude Winter model was used.

For Card 2 the Maritime extinction (23km visibility) model was used most of the time.

For Card 4 the wavelength bands were the 3 to 5.6 μm (3340 to 1780 cm^{-1}) and the 8 to 14 μm (1250 to 710 cm^{-1}) windows with 20 cm^{-1} spectral intervals.

Otherwise the rest of the data was dependent on the specific conditions of each measurement.

E. RESULTS OBTAINED

The program was used in its radiance mode . The average transmittance of the atmosphere and the radiance of the clear sky were recorded.

These results appear in the Table 5 of chapter eight along with the radiance values provided by the program.

V. EQUIPMENT

A. THE AGA THERMOVISION SYSTEM

"AGA Thermovision" was first introduced in 1965. The 780 System is a fourth generation development of a system which combines real time IR scanning with thermal measurement capability. By thermal measurement is meant measurement of the temperature of an object. Chapter 7 will analyze how the AGA was used to measure radiance.

The "AGA Thermovision" 780 owned by the Naval Postgraduate School (Electro-Optics Laboratory, Department of Physics) consists of a dual scanner: one channel for the 3 - 5.6 μm band (SW) and one for the 8-14 μm band (LW). It uses a two dimensional object-plane scan. Figure 5.1 shows the different components of the AGA system.

B. GENERAL DESCRIPTION OF THE "AGA THERMOVISION" 780

1. Optics and Scan Mechanism

In the AGA Thermovision 780, the scan is performed by two refractive prisms with eight sides. Horizontal scan lines are interlaced (with 4:1 interlace) to provide a complete frame of 400 lines. A mask at the display of the system allows 280 lines of the 400 to be viewed.

AGA Thermovision®

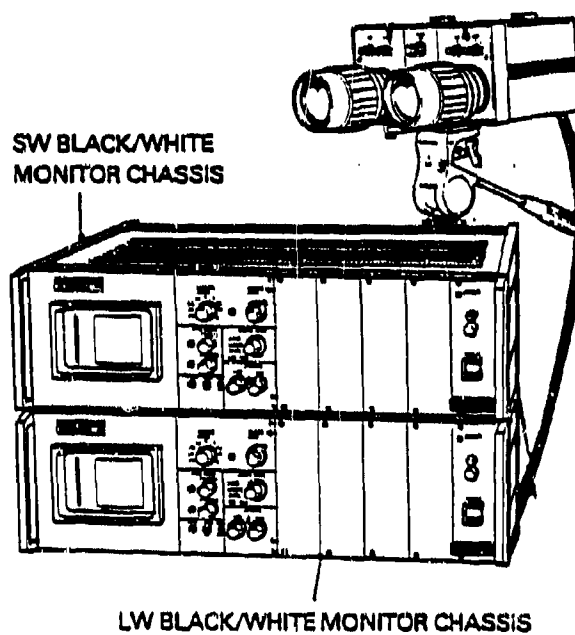


Figure 5.1 : Components of the AGA Thermovision 780.
[Ref. 7]

The lenses of the SW system are constructed from silicon, and those for the LW system are constructed from germanium.

From the front of the scan head the aperture stop and the bandpass filter can be selected. For our purpose the non-filter position and the f/1.8 aperture stop have been used.

2. Detectors and Cooling

There are two detectors, both cooled to 77°K using liquid nitrogen. For SW applications an Indium-Antimonide (InSb) and for LW applications a Mercury-Cadmium-Telluride (HgCdTe) detector is used.

3. Display

A black and white display for each band gives an image of the object viewed. The brighter the object appears on the display, the more IR radiation it emits.

4. Technical Data

Technical data for the "AGA 780" appear in Table 1.

C. MEASUREMENT TECHNIQUES

The "AGA Thermovision 780" measures, as mentioned before, IR radiation within two bands (windows) or spectral ranges, the 3-5.6 μm window and the 8-14 μm window. The radiation received by the equipment includes radiation reflected by terrestrial objects in the line of

TABLE 1

AGA SENSOR TECHNICAL INFORMATION [Ref. 13]

Performance characteristics

Spectral Region (μm) : 3 to 5.6 and/or 8 to 14 (1)
Frame rate (sec^{-1}) : 6.25
Field rate (sec^{-1}) : 25
Interlace : 4 : 1

Replaceable Fore-Optics FOV2 (2)

FOV (deg) , AZ : 7
 EL : 7
IFOV (mrad) , AZ : 1.1
 EL : 1.1
NEAT at 22°C (°C) : 0.12
MDT (°C) : <0.1
Dynamic Range (°C) : -20 to 900

Optical Data FOV2 (2)

Effective Aperture Area (cm^2) : 24
Diameter of Aperture (cm) : 5.5
Effective Focal Length (cm) : 9.9
f/ number : 1.8

Detector and Cooler Data

Type and Material : InSb or HgCdTe
Number of Elements : 1
Peak Wavelength (μm) : 5 or 10

- Notes: (1) According to [Ref. 13] the SW window is 2 to 5.6 μm but [Ref. 7] gives 3 to 5.6 μm .
(2) There are four other possible FOV's (3.5X3.5, 12X12, 20X20, 40X40) but data is presented only for the one used.

sight and also is affected by atmospheric absorption , thus making the relation to the temperature of the objects observed a non linear one.

The equipment measures the received IR radiation in " Isotherm Units (IU) " , an arbitrary unit of measurement. The value obtained has a linear relationship with received photon flux (photons/second).

If object temperature is desired , the non-linear relation of IU and Temperature (C) is given by calibration curves (SW figures 5.2 to 5.5 ,LW figures 5.6 to 5.9). In these curves the object surface emissivity has been assumed equal to one ($\epsilon = 1$, object:black body), and no atmospheric absorption has been considered. If the object is not a black body ,or atmospheric absorption has to be taken into account, corrections have to be applied (See section V.R : Corrections of measurements for non-ideal situation).

There are two basic methods of thermal measurement using the AGA 780 :

(i) The Direct measurement where the equipment is used to obtain directly the temperature of the object without any reference to any other source of radiation.

(ii) The Relative measurement where the equipment is used to obtain temperature by comparing the radiation received from the observed object and the radiation

AGA

AGA Infrared Systems AB

INDIVIDUAL CALIBRATION OF 780 DUAL 88AR

SERIAL NUMBERS

SCANNER : SWDB 4011
DETECTOR : G 1739
FILTER : NOF
LENS : 7 3009

CALIBRATION CONDITIONS:

AMBIENT TEMPERATURE : 23 C
RELATIVE HUMIDITY : 50 %
OBJECTIVE DISTANCE : 1.0 M
CALIBRATION DATE : 82-09-17
OPERATOR : B.A

CALIBRATION CURVE CONSTANTS

APERTURE	A	B	C
1.8	811203	3117.74	1.00
2.5	449342	3127.50	1.00
3.6	267514	3161.13	1.00
5.1	161958	3182.86	1.00
7.2	96669	3220.95	1.00
10	65832	3242.19	1.00
14	38173	3253.91	1.00
20	30288	3405.76	1.00

Figure 5.2 : SW calibration curves for the AGA 780. [Ref.7]

The curves that follow are of the form

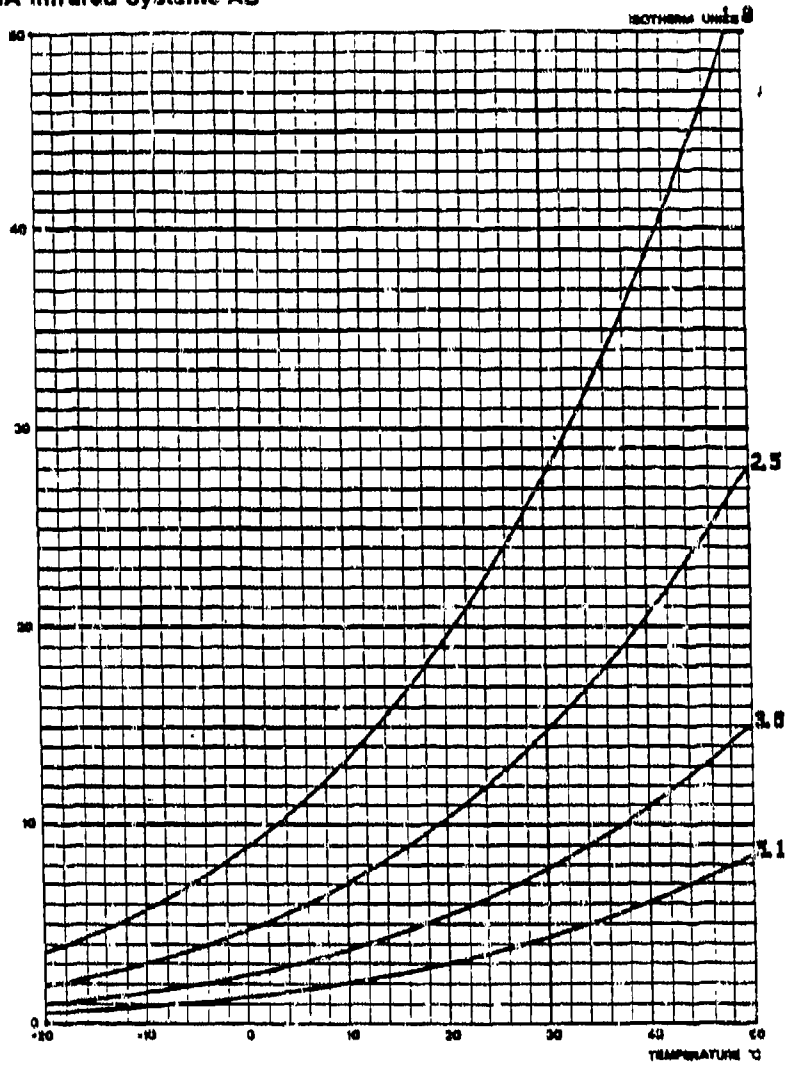
$$I = \frac{A}{C \cdot e^{B/T} - 1}$$

A, B, C are the empirical constants above.

AGA

Calibration curves

AGA Infrared Systems AB



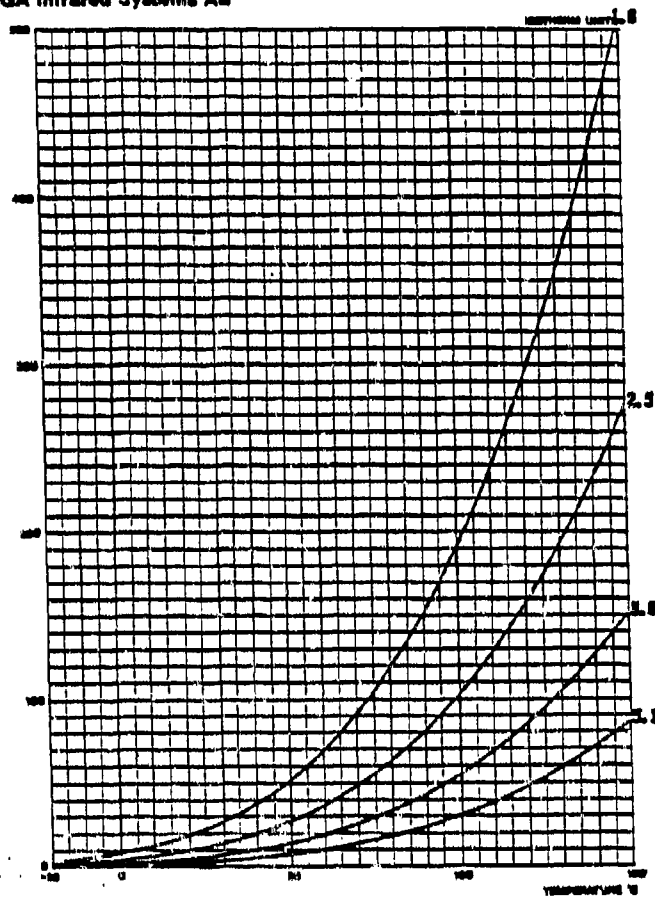
Scanner: SNOB 4811 Date: 82-09-17 Operator: B.A
 Detector: G 1739 Ambient temp: 23 °C
 Filter: NOF Rel. humidity: 58 %

Figure 5.3 : SW calibration curves for the AGA 780.
 Temperature range from -20°C to 60°C.
 [Ref. 7]

AGA

Calibration curves

AGA Infrared Systems AB



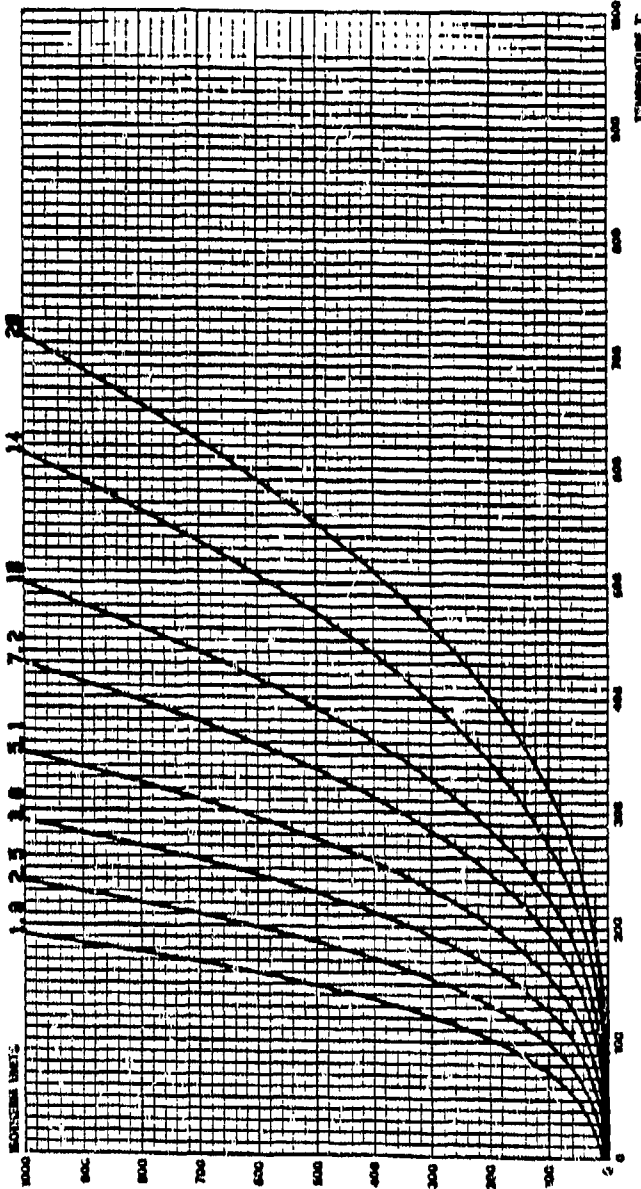
Scanner: SW 401 C 2002-08-17 Operator: B.A.
 Detector: G 1730 Ambient temp: 23 °C
 Filter: NDF Rel. humidity: 50 %

Figure 5.4 : SW calibration curves for the AGA 780.
 Temperature range from -20°C to 150°C.
 [Ref. 7]



AGA Infrared Systems AB

Calibration curves



Scanner: SIES 4811 Filter: MF Date: 82-80-17 Rel. Humidity: 58 % Operator: B.A.
Detector: G 1798 Lens: 7 3086 Ambient temp: 28 °C Object distance: 1.8 m

65811

Figure 6.6 : SW calibration curves for the AGA 780.
Temperature range from 0°C to 1000°C.
[Ref. 7]

AGA

AGA Infrared Systems AB

INDIVIDUAL CALIBRATION OF 780 DUAL BBAR

SERIAL NUMBERS

SCANNER : LWDB 4011
DETECTOR : G 1739
FILTER : NOF
LENS : 7 3105

CALIBRATION CONDITIONS:

AMBIENT TEMPERATURE : 24 C
RELATIVE HUMIDITY : 55 %
OBJECTIVE DISTANCE : 1.0 m
CALIBRATION DATE : 82-09-27
OPERATOR : B.A

CALIBRATION CURVE CONSTANTS

APERTURE	A	B	C
1.8	-3581	1506.49	-0.436
2.5	-4060	1569.30	-0.759
3.6	-6514	1629.70	-1.824
5.1	5420	1610.70	2.796
7.2	1123	1606.54	1.098
10	584	1604.29	0.885
14	306	1610.60	0.773
20	195	1650.51	0.767

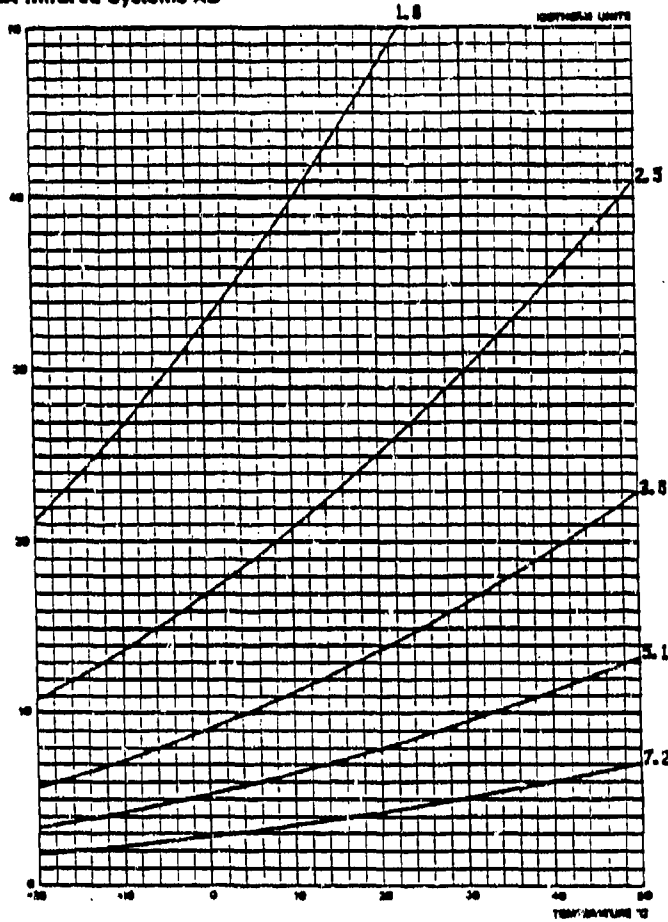
Figure 5.6 : LW calibration curves for the AGA 780. [Ref.7]

The curves that follow are of the form

$$I = \frac{A}{C e^{B/T} - 1}$$

A, B, C are the empirical constants above.

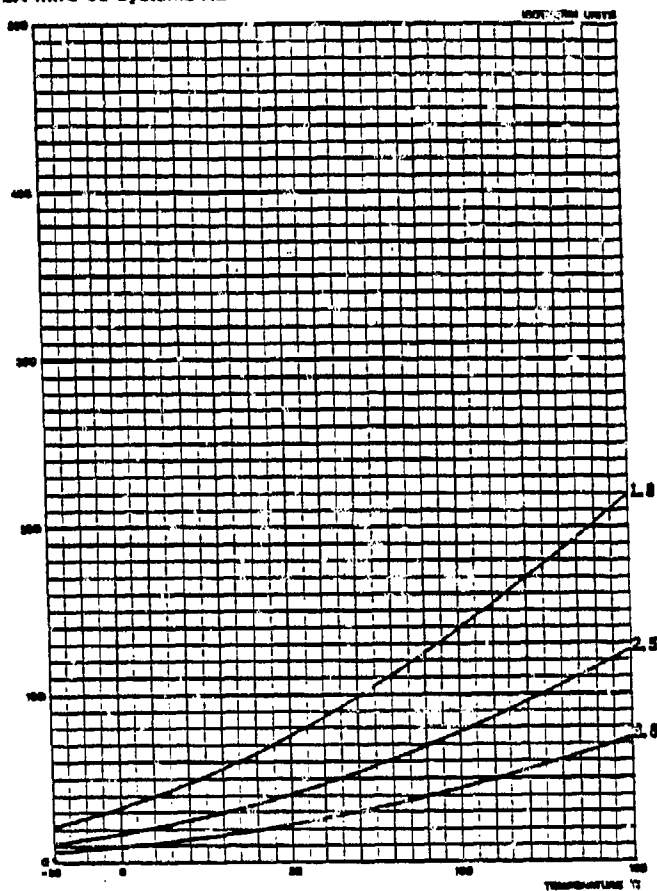
AGA Infrared Systems AB



Scanner: LW08 4811 Date: 82-08-27 Operator: R.A.
Detector: G 1739 Ambient temp: 24 °C
Filter: NOF Rel. humidity: 55 %

Figure 5.7 : LW calibration cuves for the AGA 780. Temperature range from -20°C to 50°C. [Ref. 7]

AGA Infrared Systems AB



Scanner: LMD 4811 Date: 02-08-77 Operator: B.A.

Detector: G 1738 Ambient temp: 24 °C

Filter: HOF Rel. humidity: 55 %

Figure 5.8 : LW calibration curves for the AGA 780.
 Temperature range from -20°C to 150°C .
 [Ref. 7]

AGA
AGA Infrared Systems AB

Calibration curves

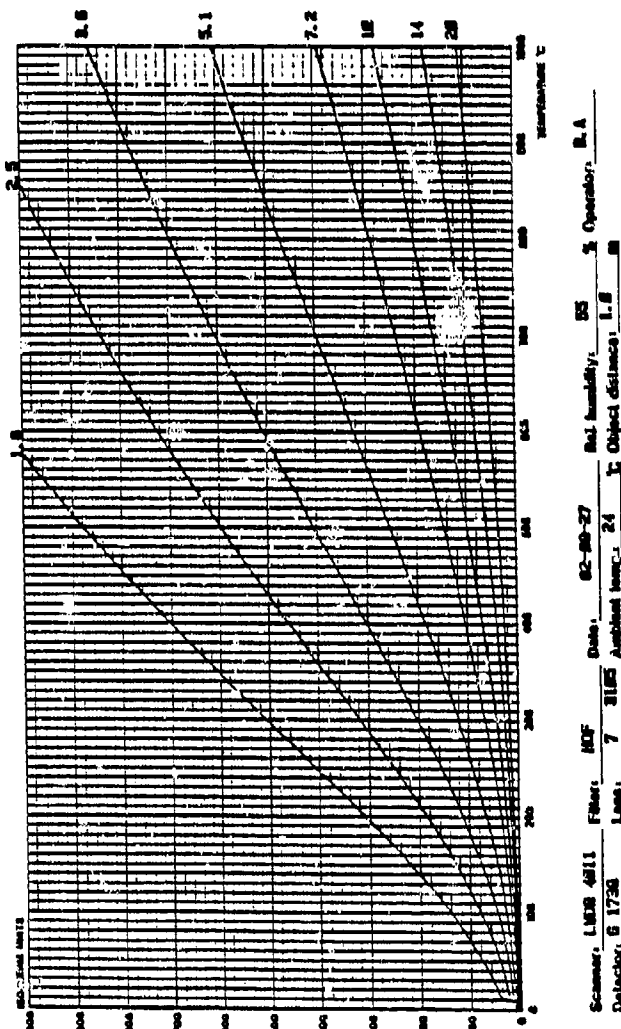


Figure 5.9 : LW calibration curves for the AGA 780.
 Temperature range from 0°C to 1000°C.
 [Ref. 7]

received from an external reference source of known temperature and emissivity.

For our purpose the Direct measurement method was used mainly because of the lack of an "ideal reference", ie. an object of known temperature, having the same emissivity and situated near the observed object. For example it was (almost) impossible to have an "ideal reference" near a cloud.

D. DIRECT MEASUREMENT PROCEDURE

Assuming that the emissivity of the object and the transmittance of the atmosphere are equal to one,

$$\begin{aligned} \epsilon_o &= 1 \\ \tau_a &= 1 \end{aligned} \quad (V-1)$$

the following procedure was used (figure 5.10 and 5.11 show the equipment and the procedure respectively):

(i) The "THERMAL LEVEL" control knob was set to some specific value "L" ,to obtain a satisfactory picture.

(ii) The "THERMAL RANGE" control knob was set to improve the picture obtained above.

(iii) The "ISOTHERM LEVEL 1" control knob was set at some value "i" in order to brighten up the object of interest.

(iiii) The values "L" and "i" were added to obtain the radiance I in Isotherm Units.

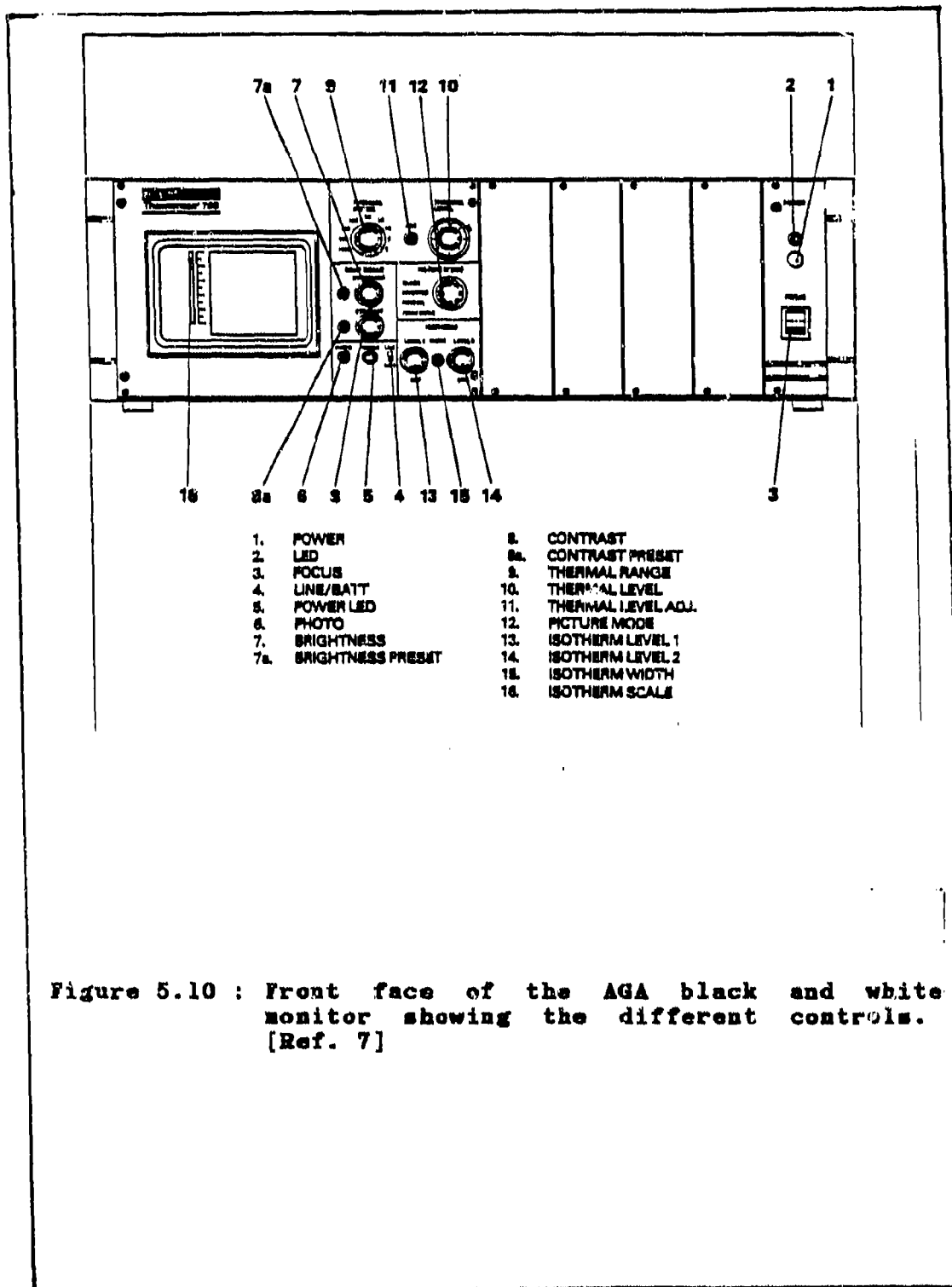


Figure 5.10 : Front face of the AGA black and white monitor showing the different controls.
[Ref. 7]

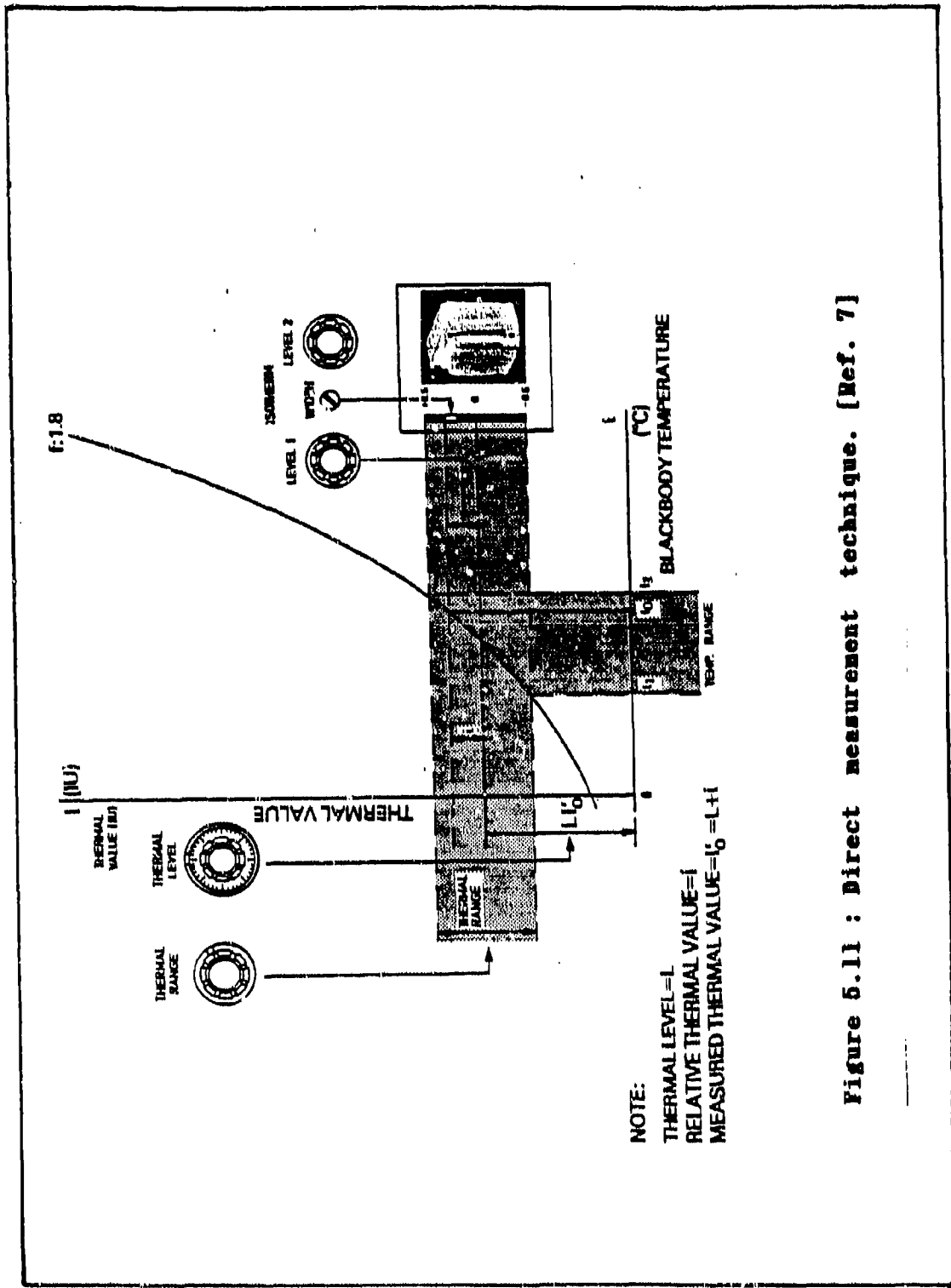


Figure 5.11 : Direct measurement technique. [Ref. 7]

E. CORRECTION OF MEASUREMENTS FOR NON-IDEAL SITUATION

Many factors affect the radiation received by the AGA 780 from an object. The most important ones and the actions taken, either to correct them or just to take them into account, are listed below.

(i) Emissivity.

Most of the objects have an emissivity less than one ($\epsilon < 1$), often non-uniform over the spectral range ($\epsilon = \epsilon(\lambda) < 1$). Typically the emissivity of a cloud ranges from 0.2 to 0.8 but for clouds of thickness greater than 100 m the emissivity can be assumed to be close to unity. (refer to III-B-3)

(ii) Object reflections

An object will emit not only its own radiation but also it will reflect radiation from other objects (surroundings). If the object to be measured does not transmit IR radiation its reflectivity will be

$$\rho = 1 - \epsilon \quad (V-2)$$

So, according to the assumption made in the above a cloud's reflectivity will be less than 0.1.

(iii) Object size

If the object does not cover the solid angle subtense of the detector then radiation will be received from the background. In most of the measurements made here an effort was made to have the object more or less covering the entire field-of-view.

(iiii) Atmospheric absorption

Water vapor or ice (H_2O), Carbon dioxide (CO_2) and also some other constituents of the atmosphere absorb the IR radiation. Thus IR radiation received by the system will be less than that emitted by the object observed. The ratio of these two is the transmittance of the atmosphere, τ_a , and is provided by the LOWTRAN code.

VI. EMPIRICAL CALIBRATION OF THE AGA

A. GENERAL

An empirical calibration of the "AGA Thermovision 780" was made in order to determine if the calibration curves provided by the manufacturer were accurate enough under the circumstances in which the equipment was used.

The calibration of the AGA consisted of a two scale experiment :

- (i) A near field experiment and,
- (ii) A far field experiment.

B. NEAR FIELD EXPERIMENT

The thermal radiance of an aluminium can filled with water was measured. The can was painted black (painting procedure :1. Aluminium plate polished, 2. first coating , zinc chromate TT-P-1757 , 3. second coating , flat black paint , Part no. 8010 582 5382) in order to have emissivity close to unity, and was placed at a distance of 4 m from the AGA (figure 6.1 shows the setup for the experiment). The water in the can was heated from ambient temperature up to its boiling point. The temperature of the can was measured with a

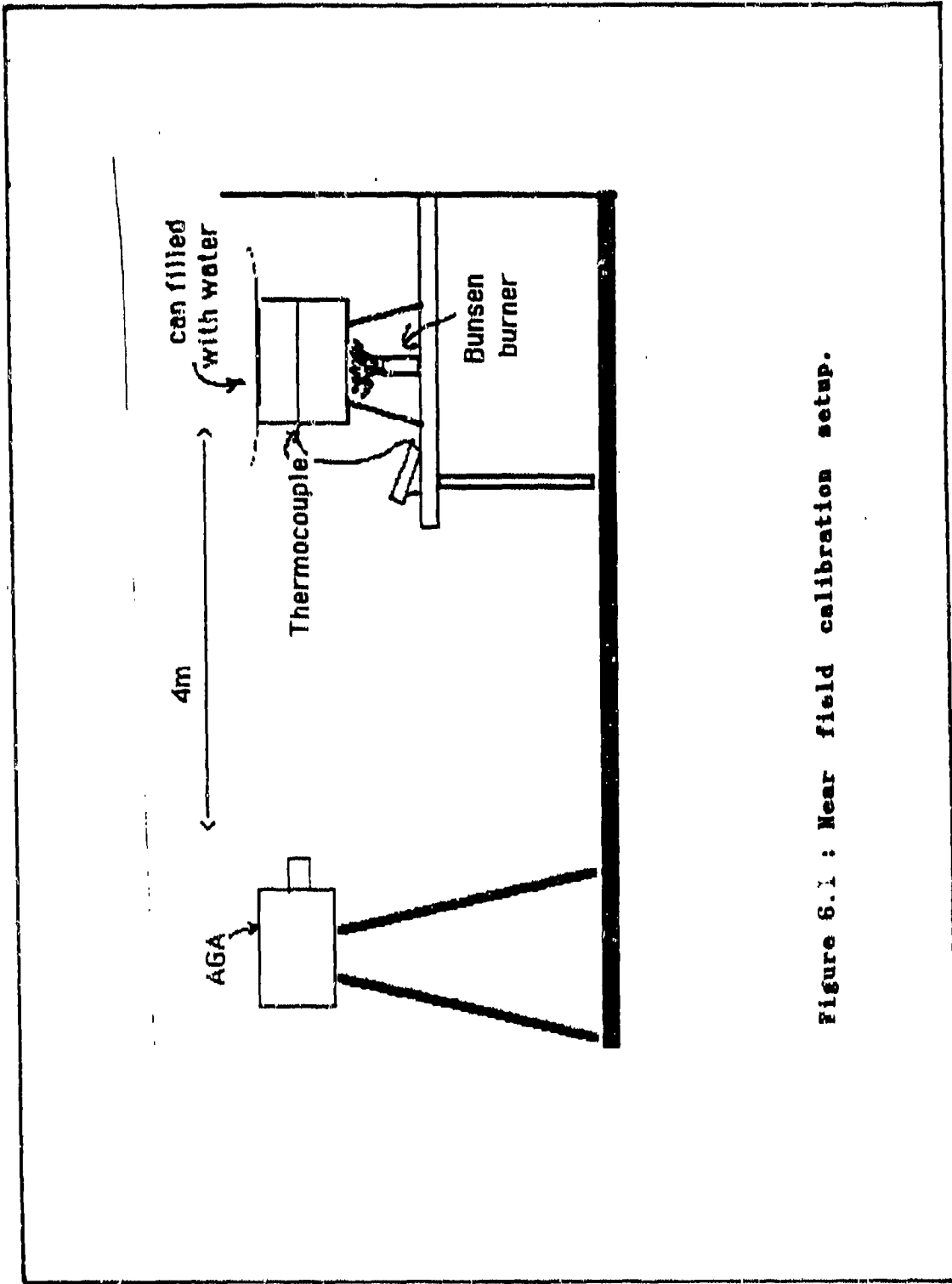


Figure 6.1 : Near field calibration setup.

thermocouple and every 2°C measurements of the thermal radiance were made using the AGA.

This experiment was carried out twice and the "Isotherm Units" reading of the AGA for each temperature appears in Table 2 . In figures 6.2 and 6.3 IU's are plotted versus temperature for SW and LW respectively. In these same figures the calibration curves given by the manufacturer were also plotted for comparison purposes . As can be seen the empirical calibration , data falls pretty well into the manufacturers curves. The data of the curves noted "empirical calibration 2" is a little offset , it is believed , mainly because of inaccuracies in the thermocouple readings of the temperature (offset of approximately 3 to 4°C).

C. FAR FIELD EXPERIMENT

The thermal radiance of an aluminium plate of 1 m² surface (1mX1m) was measured. The plate was painted black (Same painting procedure used as the one described for the Aluminium plate) in order to have emissivity close to unity. The experiment was carried out during two periods on the roof of Spanagel Hall (building 232 ,NPS). The plate heated by the sun can be assumed to have small fluctuations in its temperature throughout the experiment. Readings were taken with the plate at

TABLE 2
NEAR FIELD MEASUREMENTS

Temp. (°C)	SW (IU)		LW (IU)	
	1 st exp.	2 nd exp.	1 st exp.	2 nd exp.
48	51	-	77	-
50	53	-	79	-
52	57	-	81	-
54	61	-	83	-
56	63	-	85	-
58	66	-	87	-
60	71	77	90	94
62	76	83	92	97
64	80	86	93	99
66	84	90	96	101
68	89	95	98	103
70	96	99	101	105
72	99	104	103	107
74	104	109	106	109
76	106	113	107	110
78	112	122	109	114
80	116	127	111	117
82	121	134	114	120
84	130	139	116	121
86	133	148	119	124
88	142	155	121	126
90	147	165	124	132
92	155	171	127	134
94	-	177	-	136
96	-	183	-	138

Note: Ambient temperature : 23°C

SW CALIBRATION CURVES

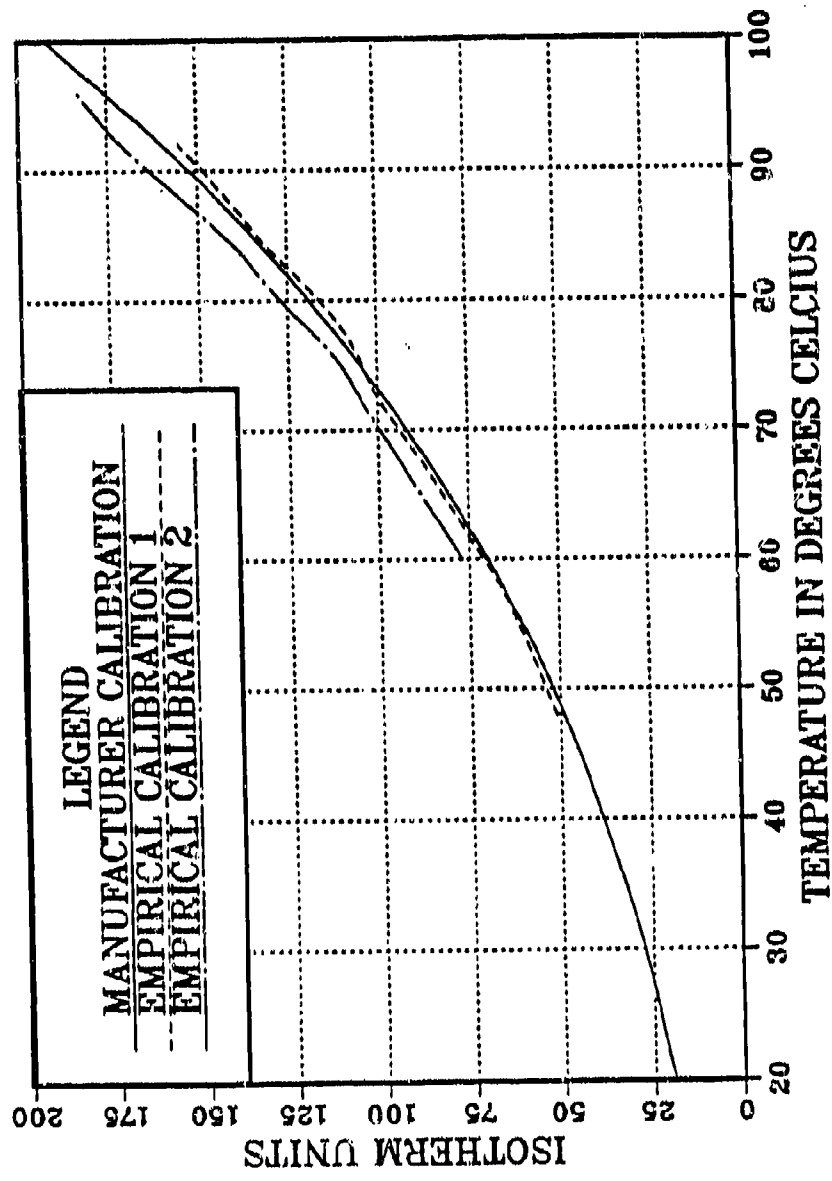


Figure 6.2 : SW calibration curves.

LW CALIBRATION CURVES

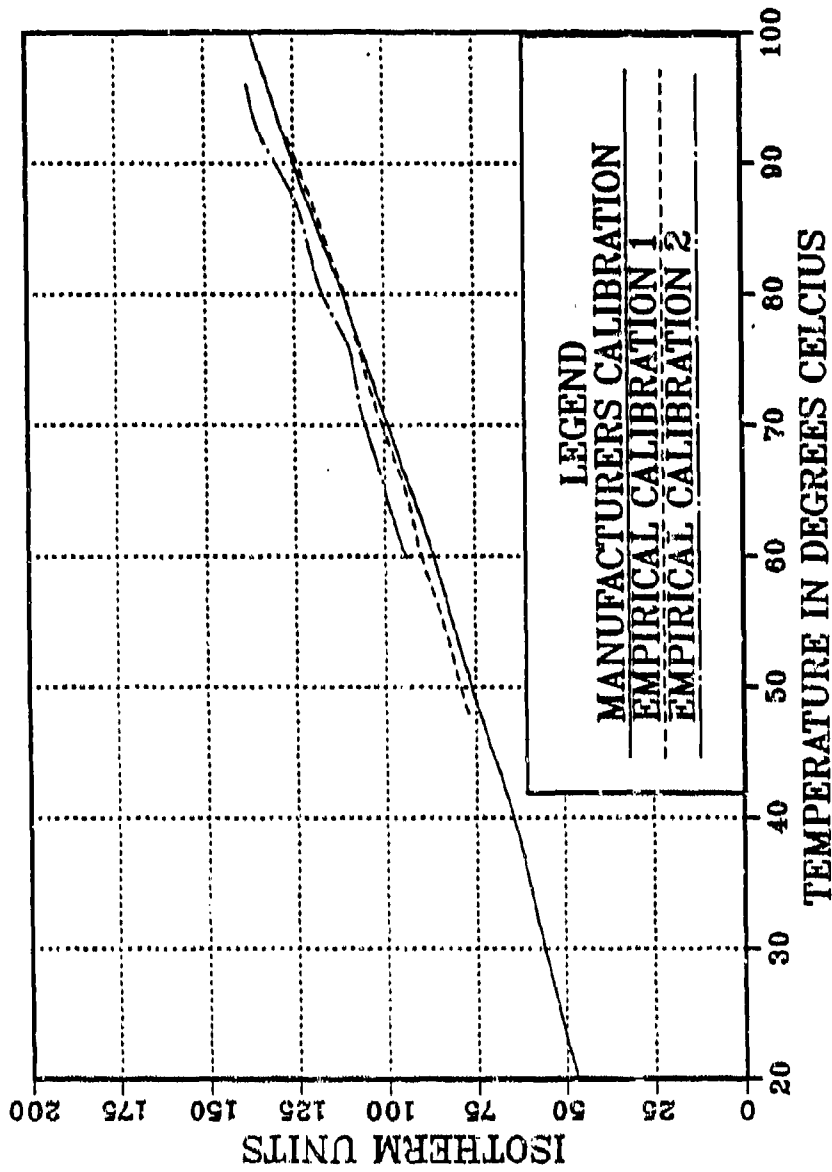


Figure 6.3 : LW calibration curves.

TABLE 3**FAR FIELD MEASUREMENTS**

Distance (ft)	SW (IU)		LW (IU)	
	1 st exp.	2 nd exp.	1 st exp.	2 nd exp.
30	48	48	76	78
60	48	48	72	78
90	46	47	68	78
120	48	44	75	75
150	47	44	74	75
180	46	44	74	75
210	44	41	74	74
240	**	41	75	73
270	**	39	74	71
300	**	37	74	71
330	**	**	75	72
360	**	**	73	74
390	**	**	71	**
Mean	46.7	43.3	73.5	74
Standard deviation	1.5	3.7	2.1	2.3
Corresponding temperature(°C)	43.5 *	42 *	47 *	47 *

Notes : * The actual temperature of the plate was
in the 1st exp. : 42°C at the center,
37°C at the corners.
in the 2nd exp. : 44°C at the center
38°C at the corners.

** Plate not detectable by the system.

different distance intervals (from the AGA) from 30ft up to 390ft away.

The values obtained appear in Table 3 . These values as it can be seen are more or less the same , independent of distance.

Specifically for the first far field set of measurements the plate temperature was 42° C at the center and 37° C at the corners and the average thermal values measured were 46.7 IU in SW (with standard deviation σ =1.5 IU) and 73.5 IU in LW (with σ =2.1 IU). These values correspond to 43.5 °C in SW and 47 °C in LW.

For the second set of measurements the temperature of the plate was 44° C at the center and 39° C at the corners. The average thermal values measured were 43.3 IU in SW (σ =3.7 IU) and 74 IU in LW (σ =2.3 IU) corresponding to 42° C and 47° C respectively.

D. CONCLUSIONS FROM EMPIRICAL CALIBRATION

The conditions of the experiment (Estimated accuracies : IU reading \pm 5% , thermocouple reading \pm 5%) were not good enough to give good empirical calibration curves.

The near field experiment showed that empirical calibration curves are not better than manufacturer's

curves and the far field experiment showed that absorption of the atmosphere is not a big factor at small distances (up to 130m).

What has been shown is that for the purpose of the present work one should better use the manufacturer's calibration curves and keep in mind that the results will have a tolerance of at least $\pm 5\%$ (IU reading accuracy).

VII. SIGNATURE MEASUREMENTS

A. MEASURED OBJECTS

All the measurements, using the AGA, were made from the roof of Building 232 (Spanagel Hall) of the Naval Postgraduate School (NPS), (observers height 30m).

The objects measured were in the vicinity of the NPS and specifically the following :

- (i) Different cloud formations at different ranges and altitudes.
- (ii) The following buildings:
 - (a) The Monterey Sheraton Hotel located at 401 Alvarado St., Monterey CA. 93940.
 - (b) Halligan Hall (building 234 of the NPS)
 - (c) A warehouse located at 1260 9th St., Monterey CA. 93940, viewed across the NPS.

Figure 7.1 is a map of the Naval Postgraduate School showing the location of Halligan Hall and the warehouse at 9th St. and figure 7.2 is a map of the city of Monterey showing the location of the Monterey Sheraton Hotel .

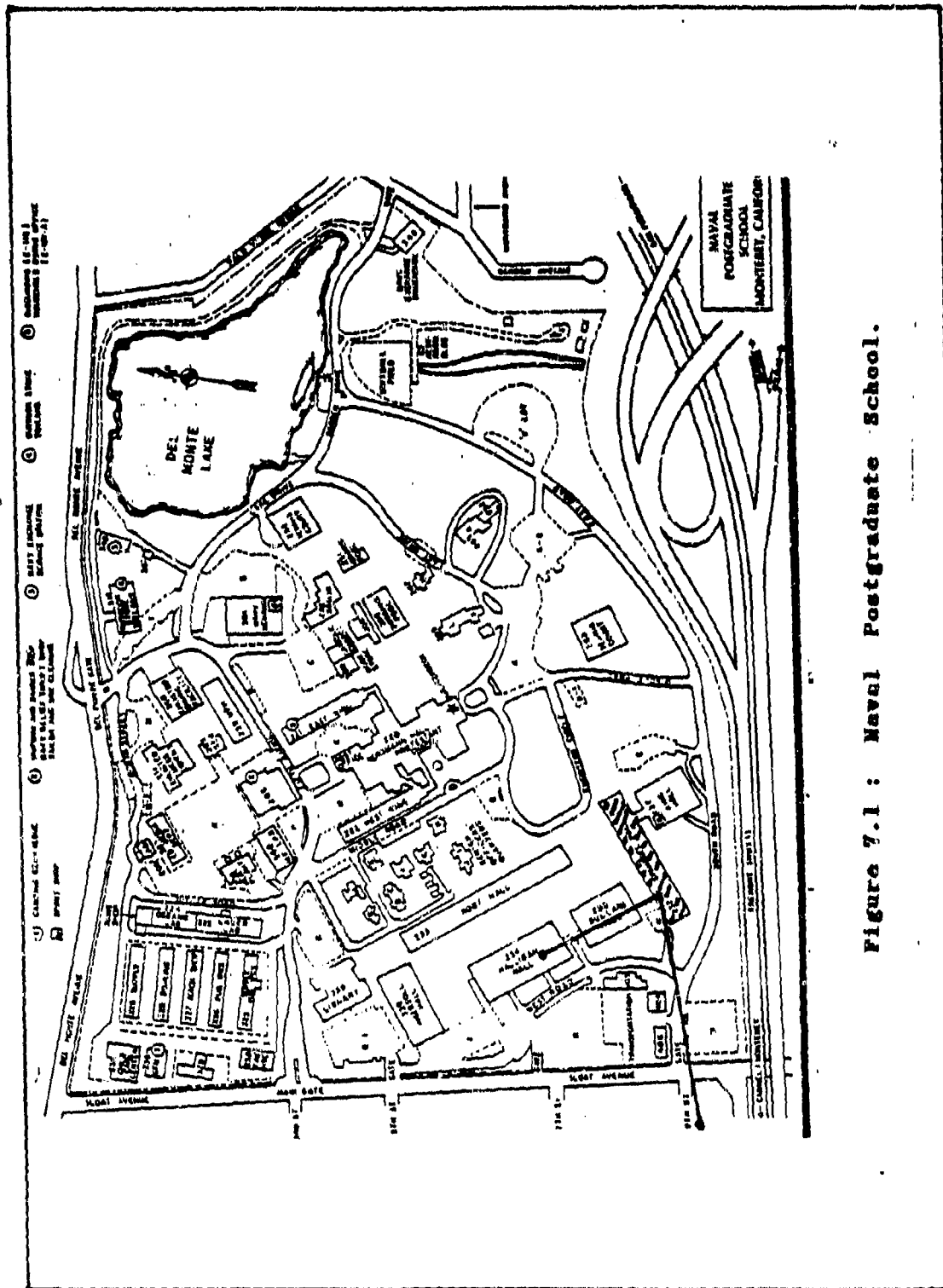


Figure 7.1: Naval Postgraduate School.

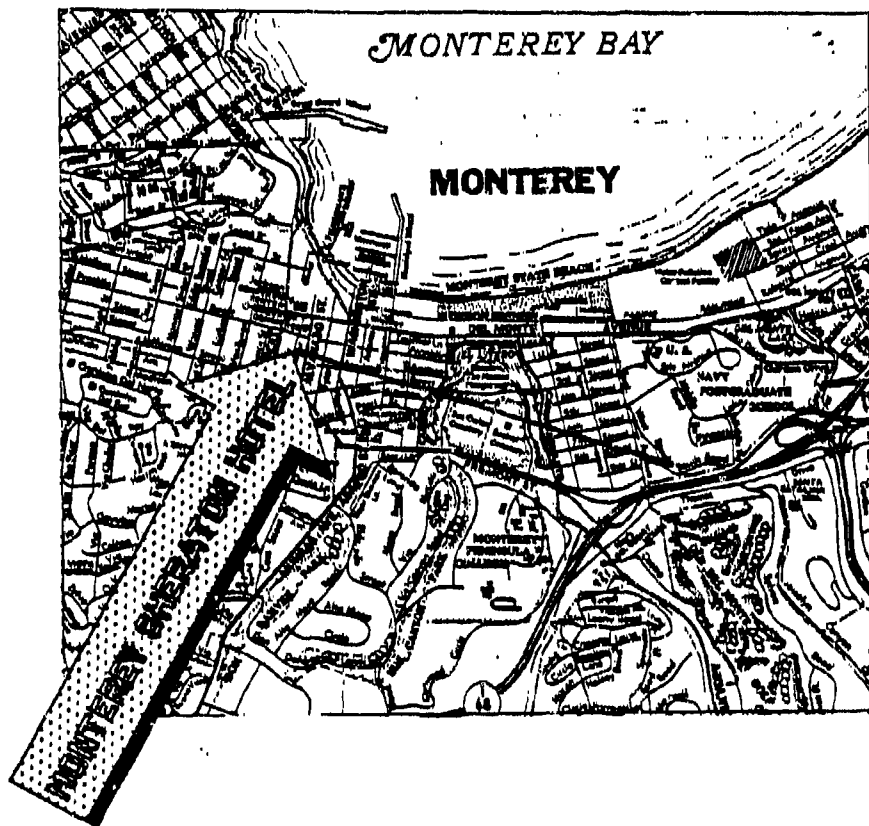


Figure 7.2 : Map of Monterey ,CA.

B. FORMULATION OF MEASUREMENTS

An object will emit thermal radiation due to its temperature. The objective of the present work is to find this thermal radiance.

The radiation received by the AGA is the sum of the object radiation, the radiation reflected by the object and the radiation emitted from the atmosphere (figure 7.3).

If we make two assumptions :

(i) That the observed object is opaque (ie. there is no transmission of IR radiation through the object), and,

(ii) That the ambient temperature is uniform for all surroundings :

we can assume that the three factors above are equivalent to three objects laid one on top of the other, with the same dimensions, that emit photon fluxes S_o , S_a and S_{atm} respectively.

S_o is the photon flux (photons/sec), into the FOV of the receiver, emitted from a blackbody of temperature t_o at short distance, ie. no atmospheric absorption present.

S_a is the photon flux (photons/sec), into the FOV of the receiver, due to reflection of ambient radiation from the object.

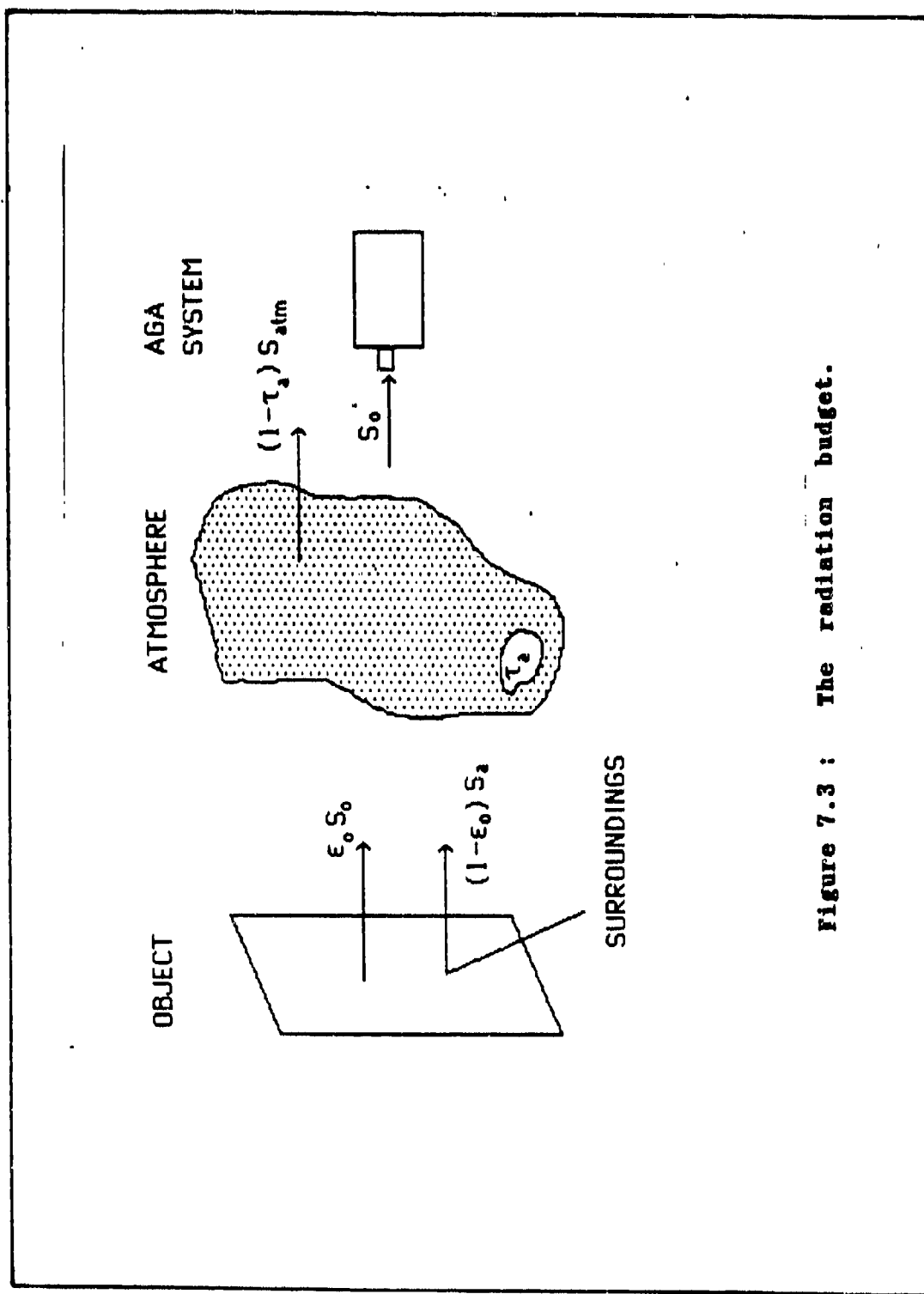


Figure 7.3 : The radiation budget.

S_{atm} is the photon flux (photons/sec) , into the FOV of the receiver , due to atmospheric emission and scattering.

t_o is the object temperature.

The first object , being the source itself , emits photon flux equal to $\epsilon_o S_o$, which attenuated via the atmosphere becomes

$$\text{object radiation} = \epsilon_o \tau_a S_o$$

The second object , corresponding to the radiation reflected by the object , will emit photon flux equal to $\rho_o S_a$, where ρ_o is the reflection coefficient of the source. From the assumption that the source is opaque we have that

$$\rho_o = 1 - \epsilon_o$$

then the reflected photon flux is equal to $(1-\epsilon_o)S_a$ which attenuated through the atmosphere becomes

$$\text{reflected radiation} = \tau_a (1-\epsilon_o) S_a$$

Finally the radiation emitted from the atmosphere will be,

$$\text{atmospheric radiation} = (1-\tau_a) S_{atm}$$

Then we can write the radiation received by the AGA in the form of the following summation

$$S_o' = \tau_a \epsilon_o S_o + \tau_a (1 - \epsilon_o) S_a + (1 - \tau_a) S_{atm} \quad (\text{VII-1})$$

= object radiation

+ reflected radiation

+ atmospheric radiation

where ,

S_o' : is the radiation received via the atmosphere from the object surface (photons/sec).

ϵ_o : is the emissivity of the object .

τ_a : is the atmospheric transmittance .

The "AGA 780" has a linear photon counting detector. Thus the relationship between S values (photons/sec) and thermal values I (IU) is a linear one .

$$I = C \times S$$

where C is a constant factor relating the signal in Isotherm Units to the received photon flux at the receiver (ie. C is an instrument response factor).

This yields ,

$$I_o' = \tau_a \epsilon_o I_o + \tau_a (1 - \epsilon_o) I_a + (1 - \tau_a) I_{atm} \quad (\text{VII-2})$$

where the I values are radiation detected by the AGA in IU and refer to the calibration curves of IU vs T °C provided by the manufacturer .

Equation (VII-2) solved for I_o gives ,

$$I_o = \frac{I_o'}{\epsilon_o \tau_a} - \left(\frac{1}{\epsilon_o} - 1 \right) I_a - \frac{1}{\epsilon_o} \left(\frac{1}{\tau_a} - 1 \right) I_{atm} \quad (\text{VII-3})$$

I_o' is the measured IU (thermal) value and I_o is the thermal value of the object at the position of the object. By thermal value is meant the radiance of the object converted into IU through the calibration curves.

If we assume that the ambient temperature (t_a) is the same as the atmospheric temperature (t_{atm}) then the equivalent source thermal values from the surroundings and the atmospheric path will be equal, and equation (VII-3) can be rewritten as follows,

$$I_o = \frac{I_o'}{\epsilon_o \tau_a} - \left(\frac{1}{\epsilon_o} - 1 \right) I_a \quad (\text{VII-4})$$

$$\text{or, } I_o = \frac{I_o' - I_a}{\epsilon_o \tau_a} + I_a \quad (\text{VII-5})$$

Equation (VII-5) will be used to give the source thermal value of the object in IU, and from that the radiance of the object ($\text{W/cm}^2\text{sr}$) will be computed.

The procedure that was followed appears in the next section.

C. APPLICATION OF THE FORMULATION TO THE
EXPERIMENTAL DATA

(1) A measurement with the AGA will provide a value I_0' (of irradiance equivalence) in IU.

(2) Entering the calibration curves of the AGA with the ambient temperature (t_a) we obtain the value I_a (IU) .

(3) From the LOWTRAN 6 code with the meteorological and geographical data of each case we obtain the transmittance of the atmosphere, τ_a .

(4) The emissivity will be assumed to be 0.90 for clouds (in the SW) and 0.80 for buildings in the SW). The LW emissivity is calculated assuming the emissivities in the SW are correct , as analyzed in the next chapter.

(5) Using equation (VII-5) we obtain the thermal value I_0 of the object .

(6) From the thermal value I_0 of the object we find , using the calibration curves again , its temperature . The temperature of the object calculated from the SW data has been assumed to be the correct one (see Chapter 8).

(7) Using a TI-59 program (listing and analysis of that program appears in Appendix A) we compute the in-band radiant flux density M_0 (W/cm^2) of the object.

(8) If the observed object is a flat lambertian surface then the radiance, L_0 , from that object will be ,

$$L_{0L} = \frac{\epsilon M_0}{\pi} \quad (\text{W/cm}^2 \text{ sr}) \quad (\text{VII-6})$$

The lambertian surface assumption was reasonable for most of the objects observed .

For clouds where the thickness is much less than the range of observation another approximation might be considered ; the spherical surface approximation where the radiance of that object will be ,

$$L_{0S} = \frac{\epsilon M_0}{4\pi} \quad (\text{W/cm}^2 \text{ sr}) \quad (\text{VII-7})$$

This last approximation was never used because in all the cases observed the extent of the clouds was greater than or about equal to the range of observation.

D. SAMPLE CALCULATION

(1) The radiance of a cloud in the SW and LW windows was measured . The values obtained were 20 and 49 IU respectively.

$$I_{OSW}' = 20 \text{ IU}$$

$$I_{OLW}' = 49 \text{ IU}$$

(2) Entering the calibration curves with the ambient temperature $t_a = 20^\circ\text{C}$ we obtained the value I_a ,

$$I_{aSW} = 19.5 \text{ IU}$$

$$I_{aLW} = 47.5 \text{ IU}$$

(3) From the LOWTRAN 6 code we obtained

$$\tau_a = 0.1167 \text{ in the SW, and}$$

$$\tau_a = 0.3721 \text{ in the LW}$$

(4) Since we dealt with a cloud, its emissivity in the SW was assumed to be 0.90 and the LW emissivity was calculated as 0.733 (this calculation appears in the next chapter).

$$\epsilon_{SW} = 0.9$$

$$\epsilon_{LW} = 0.733$$

(5) Using equation (VIJ-5) we obtained

$$I_{OSW} = \frac{20-19.5}{0.9 \times 0.1167} + 19.5 \text{ IU}$$

or, $I_{OSW} = 24.3 \text{ IU}$

(6) From the calibration curves we found the temperature of the cloud as 26°C using the SW I_o value and 23°C using the LW I_o value. This deviation is attributed to departure of the spectral radiance from the blackbody curve in the vicinity of the peak,

as found by E.E. Bell et al. [Ref. 14]. This "short wave" temperature is thus assumed to be appropriate.

(7) Using the TI-59 program the in-band radiant flux density was computed for the two wavebands.

$$M_{OSW} = 0.001178 \text{ W/cm}^2$$

$$M_{OLW} = 0.01699 \text{ W/cm}^2$$

(8) Finally dividing by π and multiplying by the corresponding emissivity we obtained the in-band radiance of the cloud in the SW and the LW windows.

$$L_{OSW} = \frac{\epsilon M_{OSW}}{\pi}$$

or,

$$L_{OSW} = \frac{0.9 \times 0.001178}{\pi} = 3.375 \times 10^{-4} \text{ W/cm}^2 \text{sr}$$

and,

$$L_{OLW} = \frac{\epsilon M_{OLW}}{\pi}$$

or,

$$L_{OLW} = \frac{0.733 \times 0.0165}{\pi} = 3.964 \times 10^{-3} \text{ W/cm}^2 \text{sr}$$

Here the LW radiance is computed using the "long wave" emissivity ϵ_0 as computed in Chapter eight.

VIII. DATA ANALYSIS, PRESENTATION OF RESULTS

A. DATA ANALYSIS

1. Emissivity

The major uncertainty in the determination of cloud radiance from direct radiometric measurements is the determination of the appropriate value of emissivity. In the absence of a reference source at or near the location of the cloud this can only be inferred indirectly.

The procedure adopted to determine source temperature was carried out using an assumed value (appropriate to literature values) of 0.9 for both long and short wavebands. In all cases the temperature of the object calculated from the SW data, assuming that the emissivity was 0.90 in both SW and LW (graybody approximation), was greater than the temperature calculated using the LW data.

An interpretation of this result is clear if we observe figures 3.2 and 3.3. There we can see that for about the same conditions of measurements as the ones we had (cirrus-cumulus clouds, elevation angle $\approx 15^\circ$) the cloud spectrum approaches the blackbody curves in the 3-5.6 μm range but is far different (less) in the

8-14 μm window . The same was also observed for a city scene in figure 3.16.

This phenomenon is not due to the atmospheric transmittance because as it can be seen in Table 5 the transmittance in the SW is less than that in the LW.

The reasonable interpretation of this is that the emissivity in the SW is close to one (according to figures 3.2 and 3.3) , but that this is not the case in the LW .

To account for this variation the emissivity in the SW has been assumed to be 0.9 for clouds and 0.8 for buildings . Using these values a temperature of the object is deduced . This temperature has been assumed to be correct , and from this tracking back a consistent emissivity for the the LW has been calculated.

The procedure used is described below.

2. Calculation of the emissivity in the LW

Equation (VII-5) solved for ϵ_o yields

$$\epsilon_o = \frac{I_o' - I_a}{\tau_a(I_o - I_a)} \quad (\text{VIII-1})$$

In this equation I_o' is the measured thermal value (IU) of the object , I_a is the atmosphere thermal value (IU) , I_o is the object thermal value

taken from the calibration curves where we enter with the temperature of the object as computed with the SW data, and τ_a is the transmittance calculated with the LOWTRAN 6 code.

The following is a sample calculation of the emissivity in the LW band.

In section VII.D the temperature of the cloud using the SW data was calculated to be 26°C.

With this value entering the calibration curves we get,

$$I_o = 53 \text{ IU}$$

The other variables on the right hand side of equation VIII-1 are the same as in section VII.D,

$$I_o' = 49 \text{ IU}$$

$$I_a = 47.5 \text{ IU}$$

$$\tau_a = 0.3721$$

Equation VIII-1 then gives an emissivity for the LW,

$$\epsilon_{oLW} = 0.733$$

This emissivity is then used in step VII.D.(8) to calculate the in-band radiance of the cloud in the LW.

3. Comments

In some cases the computed emissivity in the LW did not fall in the permissible range ($0 < \epsilon < 1$).

This may have been caused by a number of factors, of which the most likely are the following :

(a) Invalid assumption that the emissivity is 0.9 or 0.8 (clouds or buildings) in the SW.

(b) Different transmittance from the one computed by the LOWTRAN 6 code .

(c) Invalid assumption that the objects measured are opaque.

(d) Error in the measurement.

The analysis showed that the emissivity of the clouds in the SW is more or less close to unity; therefore the assumption of their emissivity being .9 should be correct with an estimated error of $\pm .1$. The same holds for the emissivity of the buildings .

The transmittance computed by the LOWTRAN 6 code might be in error , since the atmospheric model used (Midlatitude Winter) might not match with the actual atmospheric conditions. No local meteorological measurements were made during the experiments. The magnitude of the error inserted in the computation of the emissivity , due to a transmittance error of a factor of 0.3 , will be a factor of three .

The assumption of opacity of the objects is valid for the buildings and for clouds thicker than 60 m (fig. 3.11).

The main source of errors comes from the measurement itself. An accuracy in the measured thermal value I_0' of ± 3 IU (which is about $\pm 6\%$) could yield an emissivity error of about ± 0.9 which will cause the calculated emissivity to exceed the accepted range, ($0 \leq \epsilon < 1$).

For those cases in which the computed emissivity in the LW was outside the valid range it has been assumed to be 0.7 for computation of radiance.

B. PRESENTATION OF RESULTS

The data collected appear in Table 4 along with information about the range of the object. Data on clouds was obtained from Monterey Air Traffic Control Tower (MATCT) and from Fritzsche Field (ForC Ord).

Table 5 shows the LOWTRAN atmospheric transmittance for each case along with the clear sky radiance.

Table 6 shows the calculated radiance of the different objects along with their emissivity.

Finally the average radiance values obtained appear in Table 7.

TABLE 4**DATA COLLECTED**

Number of measurement	Object	Meas. (IU)		Range
		SW	LW	
1.	SHERATON	25	52	3.7km
2.	HALLIGAN	26	54	100m
3.	WAREHOUSE	27	54	150m
4.	CLOUD	20	49	10km
5.	SHERATON	20	45	3.7km
6.	CLOUD	16	44	10km
7.	CLOUD	15	42	10km
8.	CLOUD	16	43	15km
9.	CLOUD	15	40	15km
10.	HALLIGAN	25	50	100m
11.	WAREHOUSE	23	50	150m
12.	CLOUD	16	40	10km
13.	CLOUD	16	43	15km
14.	CLOUD	17	42	15km
15.	CLOUD	18	44	10km
16.	CLOUD	15	42	10km
17.	LOW CLOUD	21	44	7km
18.	LOW CLOUD	21	45	7km
19.	CLOUD	16	44	10km

Note: (1) The ambient temperature for measurements 1 through 4 was 20°C, and for measurements 5 through 19, 14°C.

(2) The range to the clouds was estimated from weather information provided by the Monterey Air Traffic Control Tower (MATCT) on the cloud coverage of the Monterey Bay area.

TABLE 5**LOWTRAN OUTPUT**

Number of meas.	Transmittance		Radiance ($W/cm^2 sr$)	
	SW	LW	SW ($\times 10^{-4}$)	LW ($\times 10^{-3}$)
1.	0.4296	0.7574	0.9966	0.8437
2.	0.7954	0.9618	0.4997	0.1593
3.	0.7954	0.9618	0.4997	0.1593
4.	0.1167	0.3721	0.944	1.866
5.	0.4296	0.7574	0.9966	0.8437
6.	0.1067	0.4972	1.231	1.547
7.	0.2065	0.5157	1.021	1.497
8.	0.1247	0.3872	0.9753	1.832
9.	0.1247	0.3872	0.9753	1.832
10.	0.7954	0.9618	0.4997	0.1593
11.	0.7954	0.9618	0.4997	0.1593
12.	0.1067	0.4972	1.231	1.547
13.	0.1247	0.3872	0.9753	1.832
14.	0.1247	0.3872	0.9753	1.832
15.	0.1935	0.4972	1.001	1.547
16.	0.1935	0.4972	1.001	1.547
17.	0.2243	0.5403	1.014	1.45
18.	0.2243	0.5403	1.014	1.45
19.	0.1935	0.4972	1.001	1.547

The above values are path average transmittance and path radiance computed using the LOWTRAN 6 code.

TABLE 6

COMPUTED RADIANCE

Number of meas.	SW emiss.	SW Radiance W/cm ² sr X10 ⁻⁴	LW emiss.	LW Radiance W/cm ² sr X10 ⁻³
1.	0.8	3.888	0.838	5.108
2.	0.8	3.5348	0.778	4.539
3.	0.8	3.649	0.711	4.210
4.	0.9	3.375	0.733	3.964
5.	0.8	3.476	0.985	5.703
6.	0.9	2.951	0.7 **	3.558
7.	0.9	1.928	0.7 ***	2.923
8.	0.9	2.851	0.32	1.601
9.	0.9	1.791	0.7 ***	2.825
10.	0.8	3.769	0.501	3.612
11.	0.8	3.206	0.742	4.138
12.	0.9	2.951	0.7 **	3.558
13.	0.9	2.851	1	5.004
14.	0.9	3.879	0.49	2.823
15.	0.9	4.105	0.7 **	4.144
16.	0.9	1.859	1	4.107
17.	0.9	5.767	0.22	1.525
18.	0.9	5.767	0.516	3.576
19.	0.9	2.851	1	5.004

The emissivity in the SW band is assumed as 0.9 for clouds and 0.8 for buildings .

The emissivities marked ** or *** are assumed 0.7 because the calculation yielded emissivity out of accepted limits (>1 and <0 respectively)

TABLE 7

AVERAGE RADIANCE VALUES

	SW RADIANCE $W/cm^2 sr \times 10^{-4}$	LW RADIANCE $W/cm^2 sr \times 10^{-3}$
CLOUD FORMATIONS	3.302	3.544
MONTEREY SHERATON	3.682	5.406
HALLIGAN HALL	3.652	4.076
WAREHOUSE AT 9th ST.	3.428	4.174

IX. CONCLUSIONS / RECOMMENDATIONS

A. CONCLUSIONS

The radiance measurements obtained appear analytically in chapter 8.

A comparison of radiance from a cloud, for example, and the radiance of the background sky, shows that the cloud would always have, in these cases, a positive contrast with respect to its background. This shows the necessity of the existence of more than a background suppression scheme ie. a system that, after the subtraction of the background radiance, will differentiate between real targets and clutter.

B. RECOMMENDATIONS

During the present work the main problem encountered was the translation of IU into meaningful radiance values. The problem was solved by using very general approximations ; the Lambertian surface approximation and the spherical surface approximation.

For better results a calibration curve of IU versus radiance units would be useful. The representative of the AGA Corporation (Mr. Jack M. Patterson , 108 Arena st. , El Segundo , CA. 90245 , tel. (213)- 3226257) has been contacted on that subject

and a telex has been sent to the manufacturing company in Sweden.

At the time of completion of this work no answer yet has been received on the matter.

It is recommended that this subject be pursued because, for any application, and specifically for radiance measurements like the ones made here, it will be very helpful to have on hand a calibration of IU measured versus radiance (W/m^2sr) emitted by an object.

An interesting experiment will be to measure simultaneously an object with both the AGA and the IRSTD and obtain IRSTD signal calibration versus radiance.

APPENDIX A

TI-59 PROGRAM FOR CALCULATION OF THE IN-BAND FLUX

A. GENERAL

The TI-59 program used to calculate in-band flux was originally written by Robert Pitlak (Appollo Lasers, 6357 Arizona Circle , Los Angeles CA 90045) for an HP-67 calculator.

The inputs of the program are:

- (1) The initial and final wavelengths that define the band .
- (2) The temperature of the object (in °K, or in °C, or in °F).
- (3) The number of intervals in the numerical integration (this no. must be even).

The result may be given either in Photons/cm² sec or in W/cm² .

B. THEORY

Plank's blackbody radiation law may be written in the form:

$$Q = \int_{\lambda_1}^{\lambda_2} c_0 q d\lambda \quad \text{photons/cm}^2 \text{ sec}$$

$$\text{or, } W = \int_{\lambda_1}^{\lambda_2} c_1 (q/\lambda) d\lambda \quad \text{Watts/cm}^2$$

where $q = \frac{1}{\lambda^4 (e^x - 1)}$, $x = \frac{c_2}{\lambda T}$

and $c_0 = 1.883651556 \times 10^{23}$
 $c_1 = 37418.42875$
 $c_2 = 14388.32334$

The above integrations are carried out by the TI-59 numerically in any (even) no. of intervals specified by the user.

C. PROCEDURE

To use the program

- (1) Load the card into the TI-59 (both faces to be read).
- (2) Press RST.
- (3) Enter λ_1 in microns , then press R/S.
- (4) Enter λ_2 in microns , then press R/S.
- (5) Enter T (temperature) then press
 - A if in °K
 - B if in °F
 - C if in °C
- (6) Enter n : number of intervals of the numerical integration.
 (n MUST be EVEN)
- (7) Press D for answer in W/cm^2 .
 or E for answer in Photons/sec cm^2 .

D. LISTING OF THE PROGRAM

A listing of the program follows :

000	42	STO	055	07	7	114	02	2	174	23	LNX
001	01	01	056	03	3	115	03	3	175	42	STO
002	99	PRT	057	95	=	116	03	3	176	06	06
003	91	R/S	058	42	STO	117	04	4	177	36	PGM
004	42	STO	059	00	00	118	55	+	178	09	09
005	02	02	060	91	R/S	119	43	RCL	179	14	D
006	99	PRT	061	76	LBL	120	07	07	180	22	INV
007	91	R/S	062	13	C	121	55	+	181	52	EE
008	76	LBL	063	42	STO	122	43	RCL	182	99	PRT
009	11	R	064	00	00	123	00	00	183	98	ADV
010	42	STO	065	01	1	124	54	)	184	91	R/S
011	00	00	066	05	5	125	54	)	185	76	LBL
012	02	2	067	00	0	126	75	-	186	15	E
013	06	6	068	00	0	127	01	1	187	98	ADV
014	00	0	069	00	0	128	54	)	188	42	STO
015	00	0	070	00	0	129	54	)	189	05	05
016	00	0	071	69	DP	130	35	1/X	190	99	PRT
017	00	0	072	04	04	131	65	X	191	98	ADV
018	69	DP	073	43	RCL	132	43	RCL	192	53	<
019	04	04	074	00	00	133	08	08	193	43	RCL
020	43	RCL	075	69	DP	134	54	)	194	02	02
021	00	00	076	06	06	135	92	RTN	195	75	-
022	69	DP	077	69	DP	136	76	LBL	196	43	RCL
023	06	06	078	00	00	137	14	D	197	01	01
024	69	DP	079	43	RCL	138	98	ADV	198	54)
025	00	00	080	00	00	139	42	STO	199	55	+
026	91	R/S	081	83	+	140	05	05	200	43	RCL
027	76	LBL	082	02	2	141	99	PRT	201	05	03
028	12	B	083	07	7	142	99	ADV	202	95	=
029	42	STO	084	03	3	143	53	<	203	42	STO
030	00	00	085	95	=	144	43	RCL	204	03	03
031	02	2	086	42	STO	145	02	02	205	01	1
032	01	1	087	00	00	146	75	-	206	93	.
033	00	0	088	91	R/S	147	43	RCL	207	08	9
034	00	0	089	76	LBL	148	01	01	208	08	9
035	00	0	090	16	R	149	54	)	209	03	3
036	00	0	091	42	STO	150	55	+	210	06	6
037	69	DP	092	07	07	151	43	RCL	211	05	5
038	04	04	093	53	<	152	05	05	212	01	1
039	43	RCL	094	53	<	153	95	=	213	06	6
040	00	00	095	43	RCL	154	42	STO	214	52	EE
041	69	DP	096	07	07	155	03	03	215	02	2
042	06	06	097	45	YX	156	03	3	216	03	3
043	69	DP	098	43	RCL	157	93	.	217	42	STO
044	00	00	099	09	09	158	07	7	218	08	08
045	75	-	100	65	X	159	04	4	219	04	4
046	03	3	101	53	<	160	01	1	220	42	STO
047	02	2	102	53	<	161	05	5	221	09	09
048	95	=	103	43	RCL	162	00	0	222	01	1
049	65	X	104	06	06	163	07	7	223	22	INV
050	05	5	105	45	YX	164	04	4	224	23	LNX
051	55	+	106	53	<	165	52	EE	225	42	STO
052	09	9	107	01	1	166	04	4	226	06	06
053	85	+	108	04	4	167	42	STO	227	36	PGM
054	02	2	109	03	3	168	06	08	228	09	09
			110	08	8	169	05	5	229	14	D
			111	08	8	170	42	STO	230	22	INV
			112	93	.	171	09	09	231	52	EE
			113	03	3	172	01	1	232	99	PRT
						173	22	INV	233	98	ADV
									234	91	R/S

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