THESIS

INFRARED BACKGROUND AND TARGET MEASUREMENT

by

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The corresponding values for buildings were $3.587 \times 10^{-4} \text{ W/cm}^2\text{sr}$ and $4.552 \times 10^{-4} \text{ W/cm}^2\text{sr}$ respectively.
Infrared Background and Target Measurement

by

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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 \( \text{W/cm}^2\text{sr} \). The emissivity of the different objects was also computed for the 8-14 \( \mu \text{m} \) window assuming that their emissivity in the 3-5.6 \( \mu \text{m} \) band is close to that of a blackbody. The average radiance of clouds was found to be \( 3.302 \times 10^{-4} \text{ W/cm}^2\text{sr} \) in the 3-5.6 \( \mu \text{m} \) window and \( 3.544 \times 10^{-3} \text{ W/cm}^2\text{sr} \) in the 8-14 \( \mu \text{m} \) window. The corresponding values for buildings were \( 3.587 \times 10^{-4} \text{ W/cm}^2\text{sr} \) and \( 4.552 \times 10^{-3} \text{ W/cm}^2\text{sr} \) respectively.
TABLE OF CONTENTS

I. INTRODUCTION .................................................... 10
II. BACKGROUND TO PROBLEM ........................................... 13
   A. GENERAL .......................................................... 13
   B. EFFECTS OF BACKGROUND CLUTTER IN IMAGING .............. 14
   C. BACKGROUND SUPPRESSION SCHEMES ............................ 15
   D. CLUTTER SUPPRESSION SCHEMES ................................ 17
   E. CONCLUSION .................................................... 21
III. CLOUDS, BACKGROUNDS AND THEIR SIGNATURES .............. 22
   A. CLOUDS ......................................................... 22
      1. Reflection of IR Radiation by Clouds .................. 25
      2. Scattering of IR Radiation by Clouds ................. 25
      3. Emission of IR Radiation by Clouds .................... 32
   B. BACKGROUNDS ................................................ 34
      1. Marine Backgrounds ....................................... 34
      2. Terrestrial Backgrounds .................................. 36
IV. LOWTRAN PROPAGATION / RADIANCE CODE ....................... 40
   A. MODELS FOR PROPAGATION OF IR RADIATION THROUGH
      THE ATMOSPHERE ............................................. 40
   B. LOWTRAN CODE ................................................. 40
   C. INPUTS TO LOWTRAN 6 CODE ................................ 41
   D. INPUT DATA USED ............................................. 42
   E. RESULTS OBTAINED ............................................. 42
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.</td>
<td>EQUIPMENT</td>
<td>43</td>
</tr>
<tr>
<td>A.</td>
<td>THE AGA THERMOVISION SYSTEM</td>
<td>43</td>
</tr>
<tr>
<td>B.</td>
<td>GENERAL DESCRIPTION OF THE &quot;AGA THERMOVISION 780&quot;</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>1. Optics and Scan Mechanism</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>2. Detectors and Cooling</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>3. Display</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>4. Technical Data</td>
<td>45</td>
</tr>
<tr>
<td>C.</td>
<td>MEASUREMENT TECHNIQUES</td>
<td>45</td>
</tr>
<tr>
<td>D.</td>
<td>DIRECT MEASUREMENT PROCEDURE</td>
<td>56</td>
</tr>
<tr>
<td>E.</td>
<td>CORRECTION OF MEASUREMENTS FOR NON-IDEAL SITUATION</td>
<td>59</td>
</tr>
<tr>
<td>VI.</td>
<td>EMPIRICAL CALIBRATION OF THE AGA</td>
<td>61</td>
</tr>
<tr>
<td>A.</td>
<td>GENERAL</td>
<td>61</td>
</tr>
<tr>
<td>B.</td>
<td>NEAR FIELD EXPERIMENT</td>
<td>61</td>
</tr>
<tr>
<td>C.</td>
<td>FAR FIELD EXPERIMENT</td>
<td>63</td>
</tr>
<tr>
<td>D.</td>
<td>CONCLUSIONS FROM THE EMPIRICAL CALIBRATION</td>
<td>67</td>
</tr>
<tr>
<td>VII.</td>
<td>SIGNATURE MEASUREMENTS</td>
<td>70</td>
</tr>
<tr>
<td>A.</td>
<td>MEASURED OBJECTS</td>
<td>70</td>
</tr>
<tr>
<td>B.</td>
<td>FORMULATION OF MEASUREMENTS</td>
<td>71</td>
</tr>
<tr>
<td>C.</td>
<td>APPLICATION OF THE FORMULATION TO THE EXPERIMENTAL DATA</td>
<td>78</td>
</tr>
<tr>
<td>D.</td>
<td>SAMPLE CALCULATION</td>
<td>79</td>
</tr>
<tr>
<td>VIII.</td>
<td>DATA ANALYSIS , PRESENTATION OF RESULTS</td>
<td>82</td>
</tr>
</tbody>
</table>
A. DATA ANALYSIS 
1. Emissivity
2. Calculation of the Emissivity in the LW
3. Comments
B. PRESENTATION OF RESULTS

IX. CONCLUSIONS, RECOMMENDATIONS
A. CONCLUSIONS
B. RECOMMENDATIONS

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

LIST OF REFERENCES
INITIAL DISTRIBUTION LIST
LIST OF TABLES

1. AGA SENSOR TECHNICAL INFORMATION ....... 46
2. NEAR FIELD MEASUREMENTS ................. 66
3. FAR FIELD MEASUREMENTS ................... 68
4. DATA COLLECTED ............................. 87
5. LOWTRAN OUTPUT ............................. 89
6. RADIANCE OF MEASURED OBJECTS ............. 89
7. AVERAGE RADIANCE VALUES ................... 90
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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 (e.g., birds) as well as from large objects (e.g., clouds) [Ref. 1].

Targets and clutter will be sensed by an imaging system as having a small temperature difference from the background, \( \Delta T \). 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\(^2\))
\[ W_B = \text{background radiant emittance (W/m}^2\text{)} \]

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

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

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

or, \( \Delta W(T) = 4 \sigma T^4 \Delta T \) \hspace{1cm} \text{(II-4)}

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

For \( W_B = W(T) = \sigma T^4 \) \hspace{1cm} \text{(II-5)}

and \( W_T = W(T+\Delta T) = W(T) + \frac{\partial W(T)}{\partial T} \Delta T \) \hspace{1cm} \text{(II-6)}

\[ \frac{\Delta W(T)}{\Delta T} = \frac{4 \sigma T^3 \Delta T}{2 \sigma T^4 + 4 \sigma T^3 \Delta T} \]

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

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

For typical scenes \( \Delta T \) is of order \( 1^\circ K \) so this approximation may be justified.

\[ \text{C. BACKGROUND SUPPRESSION SCHEMES} \]

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 $\Delta T$ 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 (e.g., 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 SIGNATURES

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].

![Graph showing frequencies of various kinds of weather along the 20°W meridian.](image)

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.

<table>
<thead>
<tr>
<th>Cloud level</th>
<th>Type of Clouds</th>
<th>Altitude at which they occur at Midlatitude.</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Cirrus</td>
<td>5 - 13 km</td>
</tr>
<tr>
<td></td>
<td>High Cirrocumulus</td>
<td>5 - 13 km</td>
</tr>
<tr>
<td></td>
<td>Cirrostratus</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>Altocumulus</td>
<td>2 - 7 km</td>
</tr>
<tr>
<td>Low</td>
<td>Stratocumulus</td>
<td>Earth's surface</td>
</tr>
<tr>
<td></td>
<td>Stratus</td>
<td>to 2 km</td>
</tr>
</tbody>
</table>

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.

[Refs. 10]
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 $hL$ 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 \( \mu m \) to about 10 \( \mu m \) and concentrations of 300-10 per \( cm^3 \). (For comparison purposes the corresponding values for raindrops are \( 10^2 \) - \( 10^4 \mu m \) 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 \( \mu m \). 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 \( \mu m \) and land radiation has a peak at about 10 \( \mu m \). 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 \( \mu m \) (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) nimbocumulus base
F) nimbocumulus 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 > 100 m) 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

Δz > 60 m τ → 0 , and
Δz > 100 m ε → 1
Figure 3.10: Spectral emissivity of cloud layers of thickness Δx. [Ref. 5]

Figure 3.11: Integral emittance (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 μm 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. BACKGROUND

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 Celcius
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 μm 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 SITRAN High Resolution models such as LASER and FASCOJE are direct computation models which provide very high resolution (i.e., 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

40
spectral fluctuations of atmospheric transmittance will vanish.

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

LOWTRAN6, 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 (23 km visibility) model was used most of the time.

For Card 4 the wavelength bands were the 3 to 5.6 \( \mu \text{m} \) (3340 to 1780 cm\(^{-1}\)) and the 8 to 14 \( \mu \text{m} \) (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°C 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

- **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

- **Effective Aperture Area (cm²):** 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 (ε = 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.8: 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
INDIVIDUAL CALIBRATION OF 780 DUAL BBAR

SERIAL NUMBERS

SCANNER: SWDB 4011
DETECTOR: G 1739
FILTER: HOF
LENSE: 7 3029

CALIBRATION CONDITIONS:

AMBIENT TEMPERATURE: 23 C
RELATIVE HUMIDITY: 50 %
OBJECTIVE DISTANCE: 1.0 M
CALIBRATION DATE: 02-09-17
OPERATOR: D.A

CALIBRATION CURVE CONSTANTS

<table>
<thead>
<tr>
<th>APERTURE</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
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<td>3117.74</td>
<td>1.00</td>
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<td>449342</td>
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<td>1.00</td>
</tr>
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<td>3.6</td>
<td>267514</td>
<td>3141.13</td>
<td>1.00</td>
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<td>5.1</td>
<td>141956</td>
<td>3182.06</td>
<td>1.00</td>
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<td>7.2</td>
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<td>1.00</td>
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<td>65232</td>
<td>3242.19</td>
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<td>38173</td>
<td>3253.91</td>
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<td>20</td>
<td>32088</td>
<td>3405.76</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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

The curves that follow are of the form

\[ \frac{A}{I} = \frac{B}{C e^{\frac{B}{T}} - 1} \]

A, B, C are the empirical constants above.
Figure 5.3: SW calibration curves for the AGA 780. Temperature range from -20°C to 50°C. [Ref. 7]
Figure 5.4: SW calibration curves for the AGA 730. Temperature range from -20°C to 150°C.
[Ref. 7]
Figure 6.6: SW calibration curves for the AGA 780. Temperature range from 0°C to 1000°C. [Ref. 7]
AGA Infrared Systems AB

INDIVIDUAL CALIBRATION OF 780 DUAL BBAR

SERIAL NUMBERS

SCANNER : LWDR 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

<table>
<thead>
<tr>
<th>APERTURE</th>
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<th>B</th>
<th>C</th>
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</thead>
<tbody>
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<td>1610.70</td>
<td>2.796</td>
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<td>7.2</td>
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<td>584</td>
<td>1604.29</td>
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<td>306</td>
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</tr>
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<td>20</td>
<td>195</td>
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<td>0.747</td>
</tr>
</tbody>
</table>

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.
Figure 5.7: LW calibration curves for the AGA 780. Temperature range from -20°C to 50°C. [Ref. 7]
Figure 5.8: Lrate calibration curves for the AGA 780.
Temperature range from -20°C to 150°C.
[Ref. 7]
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", i.e. 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,
\[ e_o = 1 \]
\[ \tau_a = 1 \]

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]
NOTE:
THermal LEVEL = L
RELATIVE THERMAL VALUE = I
MEASURED THERMAL VALUE = I_0 = L + I

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 ($\varepsilon < 1$), often non-uniform over the spectral range ($\varepsilon = \varepsilon(\lambda) < 1$). Typically the emissivity of a cloud ranges from 0.2 to 0.8 but for clouds of thickness greater than 100 $\text{m}$ 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

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

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.
Atmospheric absorption

Water vapor or ice (H₂O), Carbon dioxide (CO₂) 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, \( r_a \), 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 5302) in order to have emissivity close to unity, and was placed at a distance of 4m 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 (1m×1m) 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**

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>SW (IU) 1st exp.</th>
<th>SW (IU) 2nd exp.</th>
<th>LW (IU) 1st exp.</th>
<th>LW (IU) 2nd exp.</th>
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</thead>
<tbody>
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<td>96</td>
<td>-</td>
<td>183</td>
<td>-</td>
<td>138</td>
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</table>

**Note:** Ambient temperature : 23°C
SW CALIBRATION CURVES

LEGEND

MANUFACTURER CALIBRATION

EMPIRICAL CALIBRATION 1

EMPIRICAL CALIBRATION 2

TEMPERATURE IN DEGREES CELCIUS

ISOTHERM UNITS

Figure 6.2: SW calibration curves.
Figure 6.3: LW calibration curves.
### TABLE 3

**FAR FIELD MEASUREMENTS**

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>SW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>SW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
<th>LW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>LW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
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</thead>
<tbody>
<tr>
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**Mean**

<table>
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<tr>
<th>SW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>SW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
<th>LW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>LW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
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</thead>
<tbody>
<tr>
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<td>43.3</td>
<td>73.5</td>
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</tbody>
</table>

**Standard deviation**

<table>
<thead>
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<th>SW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>SW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
<th>LW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>LW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
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<td>2.1</td>
<td>2.3</td>
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</table>

**Corresponding temperature (°C)**

<table>
<thead>
<tr>
<th>SW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>SW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
<th>LW (IU) 1&lt;sup&gt;st&lt;/sup&gt; exp.</th>
<th>LW (IU) 2&lt;sup&gt;nd&lt;/sup&gt; exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.5</td>
<td>42</td>
<td>47</td>
<td>47</td>
</tr>
</tbody>
</table>

**Notes:**

* The actual temperature of the plate was
  - in the 1<sup>st</sup> exp.: 42°C at the center, 37°C at the corners.
  - in the 2<sup>nd</sup> 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 $\sigma = 1.5$ IU) and 73.5 IU in LW (with $\sigma = 2.1$ 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 ($\sigma = 3.7$ IU) and 74 IU in LW ($\sigma = 2.3$ IU) corresponding to 42°C and 47°C, respectively.

D. CONCLUSIONS FROM EMPIRICAL CALIBRATION

The conditions of the experiment (Estimated accuracies: IU reading ±5%, thermocouple reading ±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 9\textsuperscript{th} 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 9\textsuperscript{th} St. and figure 7.2 is a map of the city of Monterey showing the location of the Monterey Sheraton Hotel.
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 (i.e. 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 $S_{\text{atm}}$ 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, i.e. 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.
$S_{\text{atm}}$ 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 $\varepsilon_o S_o$, which attenuated via the atmosphere becomes

object radiation = $\varepsilon_o \tau_a S_o$

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

$\rho_o = 1 - \varepsilon_o$

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

reflected radiation = $\tau_a(1-\varepsilon_o)S_a$

Finally the radiation emitted from the atmosphere will be,

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

Then we can write the radiation received by the AGA in the form of the following summation
\[ S'_o = \tau_ao_o S_o + \tau_a (1-e_o) S_a + (1-\tau_a) S_{atm} \]  \hspace{1cm} (VII-1)

= object radiation

+ reflected radiation

+ atmospheric radiation

where,

\[ S'_o \] is the radiation received via the atmosphere from the object surface (photons/sec).

\[ e_o \] is the emissivity of the object.

\[ \tau_a \] 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 (i.e. \( C \) is an instrument response factor).

This yields,

\[ I'_o = \tau_ao_o I_o + \tau_a (1-e_o) I_a + (1-\tau_a) I_{atm} \] \hspace{1cm} (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,
\[
I_o = \frac{I'_o}{\varepsilon_o \tau_a} - \left( \frac{1}{\varepsilon_o} - 1 \right) I_a - \frac{1}{\varepsilon_o \tau_a} \left( \frac{1}{\varepsilon_o} - 1 \right) I_{atm} \quad (VII-3)
\]

\(I_o\) 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,

\[
I_o = \frac{I'_o}{\varepsilon_o \tau_a} - \left( \frac{1}{\varepsilon_o} - 1 \right) I_a \quad (VII-4)
\]

or,

\[
I_o = \frac{I'_o}{\varepsilon_o \tau_a} + I_a \quad (VII-5)
\]

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 \((W/cm^2sr)\) 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 $I_o$' (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, $\tau_a$.

(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.
If the observed object is a flat lamberian surface then the radiance, \( L_0 \), from that object will be,

\[
L_{OL} = \frac{\varepsilon M_0}{n} \text{ (W/cm}^2\text{sr)} \quad (\text{VII-6})
\]

The lamberian 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,

\[
L_{OS} = \frac{\varepsilon M_0}{4\pi} \text{ (W/cm}^2\text{sr)} \quad (\text{VII-7})
\]

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.

\[
\begin{align*}
I_{OSW}' &= 20 \text{ IU} \\
I_{OLW}' &= 49 \text{ IU}
\end{align*}
\]

79
(2) Entering the calibration curves with the ambient temperature \( t_a = 20^\circ C \) 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).

\[ \varepsilon_{SW} = 0.9 \]
\[ \varepsilon_{LW} = 0.733 \]

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

\[
I_{0SW} = \frac{20-19.5}{0.9 \times 0.1167} + 19.5 \text{ IU}
\]

or, \( I_{0SW} = 24.3 \text{ IU} \)

(6) From the calibration curves we found the temperature of the cloud as 26\(^\circ\)C using the SW \( I_o \) value and 23\(^\circ\)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.

\[ M_{\text{OSW}} = 0.001178 \text{ W/cm}^2 \]
\[ M_{\text{OLW}} = 0.01699 \text{ W/cm}^2 \]

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

\[
L_{\text{OSW}} = \frac{e M_{\text{OSW}}}{\pi}
\]

or,

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

and,

\[
L_{\text{OLW}} = \frac{e M_{\text{OLW}}}{\pi}
\]

or,

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

Here the LW radiance is computed using the "long wave" emissivity \( e_o \) 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 ≥ 15°) the cloud spectrum approaches the blackbody curves in the 3-5.6 µm range but is far different (less) in the
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 LW has been calculated.

The procedure used is described below.

2. Calculation of the emissivity in the LW

Equation (VII-5) solved for \( \varepsilon_o \) yields

\[
\varepsilon_o = \frac{I_o' - I_a}{\tau_a(I_o - I_a)}
\]  

(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 $\tau_a$ 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,

$$\varepsilon_{\text{LW}} = 0.733$$

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 ($0 < \varepsilon < 1$).
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 0.9 should be correct with an estimated error of ±0.1. 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 $I_o'$ of $\pm 3$ IU (which is about $\pm 6\%$) could yield an emissivity error of about $\pm 0.9$ which will cause the calculated emissivity to exceed the accepted range, $(0 < \omega < 1)$.

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 (Fort 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**

<table>
<thead>
<tr>
<th>Number of measurement</th>
<th>Object</th>
<th>Meas. (IU)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SW</td>
<td>LW</td>
</tr>
<tr>
<td>1.</td>
<td>SHERATON</td>
<td>25</td>
<td>52</td>
</tr>
<tr>
<td>2.</td>
<td>HALLIGAN</td>
<td>26</td>
<td>54</td>
</tr>
<tr>
<td>3.</td>
<td>WAREHOUSE</td>
<td>27</td>
<td>54</td>
</tr>
<tr>
<td>4.</td>
<td>CLOUD</td>
<td>20</td>
<td>49</td>
</tr>
<tr>
<td>5.</td>
<td>SHERATON</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>6.</td>
<td>CLOUD</td>
<td>16</td>
<td>44</td>
</tr>
<tr>
<td>7.</td>
<td>CLOUD</td>
<td>15</td>
<td>42</td>
</tr>
<tr>
<td>8.</td>
<td>CLOUD</td>
<td>16</td>
<td>43</td>
</tr>
<tr>
<td>9.</td>
<td>CLOUD</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>10.</td>
<td>HALLIGAN</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>11.</td>
<td>WAREHOUSE</td>
<td>23</td>
<td>50</td>
</tr>
<tr>
<td>12.</td>
<td>CLOUD</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>13.</td>
<td>CLOUD</td>
<td>16</td>
<td>43</td>
</tr>
<tr>
<td>14.</td>
<td>CLOUD</td>
<td>17</td>
<td>42</td>
</tr>
<tr>
<td>15.</td>
<td>CLOUD</td>
<td>18</td>
<td>44</td>
</tr>
<tr>
<td>16.</td>
<td>CLOUD</td>
<td>15</td>
<td>42</td>
</tr>
<tr>
<td>17.</td>
<td>LOW CLOUD</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>18.</td>
<td>LOW CLOUD</td>
<td>21</td>
<td>45</td>
</tr>
<tr>
<td>19.</td>
<td>CLOUD</td>
<td>16</td>
<td>44</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Number of meas.</th>
<th>Transmittance</th>
<th>Radiance (W/cm²sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW</td>
<td>LW</td>
</tr>
<tr>
<td>1</td>
<td>0.4296</td>
<td>0.7574</td>
</tr>
<tr>
<td>2</td>
<td>0.7954</td>
<td>0.9618</td>
</tr>
<tr>
<td>3</td>
<td>0.7954</td>
<td>0.9618</td>
</tr>
<tr>
<td>4</td>
<td>0.1167</td>
<td>0.3721</td>
</tr>
<tr>
<td>5</td>
<td>0.4296</td>
<td>0.7574</td>
</tr>
<tr>
<td>6</td>
<td>0.1067</td>
<td>0.4972</td>
</tr>
<tr>
<td>7</td>
<td>0.2065</td>
<td>0.6157</td>
</tr>
<tr>
<td>8</td>
<td>0.1247</td>
<td>0.3872</td>
</tr>
<tr>
<td>9</td>
<td>0.1247</td>
<td>0.3872</td>
</tr>
<tr>
<td>10</td>
<td>0.7954</td>
<td>0.9618</td>
</tr>
<tr>
<td>11</td>
<td>0.7954</td>
<td>0.9618</td>
</tr>
<tr>
<td>12</td>
<td>0.1067</td>
<td>0.4972</td>
</tr>
<tr>
<td>13</td>
<td>0.1247</td>
<td>0.3872</td>
</tr>
<tr>
<td>14</td>
<td>0.1247</td>
<td>0.3872</td>
</tr>
<tr>
<td>15</td>
<td>0.1935</td>
<td>0.4972</td>
</tr>
<tr>
<td>16</td>
<td>0.1935</td>
<td>0.4972</td>
</tr>
<tr>
<td>17</td>
<td>0.2243</td>
<td>0.5403</td>
</tr>
<tr>
<td>18</td>
<td>0.2243</td>
<td>0.5403</td>
</tr>
<tr>
<td>19</td>
<td>0.1935</td>
<td>0.4972</td>
</tr>
</tbody>
</table>

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

**COMPUTED RADIANCE**

<table>
<thead>
<tr>
<th>Number of meas.</th>
<th>SW emiss.</th>
<th>SW Radiance ( \times 10^3 )</th>
<th>LW emiss.</th>
<th>LW Radiance ( \times 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.8</td>
<td>3.280</td>
<td>0.938</td>
<td>5.108</td>
</tr>
<tr>
<td>2.</td>
<td>0.8</td>
<td>3.5345</td>
<td>0.778</td>
<td>4.539</td>
</tr>
<tr>
<td>3.</td>
<td>0.8</td>
<td>3.649</td>
<td>0.711</td>
<td>4.210</td>
</tr>
<tr>
<td>4.</td>
<td>0.9</td>
<td>3.375</td>
<td>0.733</td>
<td>3.964</td>
</tr>
<tr>
<td>5.</td>
<td>0.8</td>
<td>3.476</td>
<td>0.985</td>
<td>5.703</td>
</tr>
<tr>
<td>6.</td>
<td>0.9</td>
<td>2.961</td>
<td>0.7 **</td>
<td>3.558</td>
</tr>
<tr>
<td>7.</td>
<td>0.9</td>
<td>1.928</td>
<td>0.7 ***</td>
<td>2.923</td>
</tr>
<tr>
<td>8.</td>
<td>0.9</td>
<td>2.851</td>
<td>0.32</td>
<td>1.601</td>
</tr>
<tr>
<td>9.</td>
<td>0.9</td>
<td>1.791</td>
<td>0.7 **</td>
<td>2.825</td>
</tr>
<tr>
<td>10.</td>
<td>0.8</td>
<td>3.769</td>
<td>0.601</td>
<td>3.612</td>
</tr>
<tr>
<td>11.</td>
<td>0.8</td>
<td>3.206</td>
<td>0.742</td>
<td>4.138</td>
</tr>
<tr>
<td>12.</td>
<td>0.9</td>
<td>2.961</td>
<td>0.7 **</td>
<td>3.558</td>
</tr>
<tr>
<td>13.</td>
<td>0.9</td>
<td>2.851</td>
<td>1</td>
<td>5.004</td>
</tr>
<tr>
<td>14.</td>
<td>0.9</td>
<td>3.879</td>
<td>0.49</td>
<td>2.823</td>
</tr>
<tr>
<td>15.</td>
<td>0.9</td>
<td>4.105</td>
<td>0.7 **</td>
<td>4.144</td>
</tr>
<tr>
<td>16.</td>
<td>0.9</td>
<td>1.859</td>
<td>1</td>
<td>4.107</td>
</tr>
<tr>
<td>17.</td>
<td>0.9</td>
<td>5.767</td>
<td>0.22</td>
<td>1.525</td>
</tr>
<tr>
<td>18.</td>
<td>0.9</td>
<td>5.767</td>
<td>0.516</td>
<td>3.576</td>
</tr>
<tr>
<td>19.</td>
<td>0.9</td>
<td>2.851</td>
<td>1</td>
<td>5.004</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Location</th>
<th>SW Radiance $\text{W/cm}^2\text{sr} \times 10^{-4}$</th>
<th>LW Radiance $\text{W/cm}^2\text{sr} \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOUD FORMATIONS</td>
<td>3.302</td>
<td>3.544</td>
</tr>
<tr>
<td>MONTEREY SHERATON</td>
<td>3.682</td>
<td>5.406</td>
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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 i.e. 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/m²sr) 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:

\[ Q = \int_{\lambda_1}^{\lambda_2} c_0 \frac{q}{\lambda} d\lambda \]  

photons/cm² sec

or,

\[ W = \int_{\lambda_1}^{\lambda_2} c_1 \frac{q}{\lambda} d\lambda \]  

Watts/cm²
where \( q = \frac{1}{\lambda^n (e^x - 1)} \), \( x = \frac{c_2}{\lambda T} \)

and \( c_0 = 1.833651556 \times 10^{23} \)
\( c_1 = 37418.42875 \)
\( c_2 = 14388.32334 \)

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 \( \lambda_1 \) in microns, then press R/S.

(4) Enter \( \lambda_2 \) 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:

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Program statistics:
- **Memory Usage**: 240 bytes
- **Program Data**: 50 bytes
- **Program Access**: 21 bytes
- **Program Code**: 72 bytes

95
LIST OF REFERENCES


12. PH 3952 - PH 4952 class notes, Cooper, A.W. and Crittenden, Naval Postgraduate School.


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