Imaging land/water demarcation lines for coastal mapping

Kirk Smedley
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by

Kirk G. Smedley

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A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology.

Kirk Smedley

Signature of the Author

Center for Imaging Science

John Schott

Certified by

Thesis Advisor

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ABSTRACT

The objective of this research has been to improve upon the imaging methods currently used by the Photogrammetry Branch of the National Oceanic and Atmospheric Administration, for locating coastal boundaries. In keeping with this objective, a near-infrared radiometer/exposure meter has been developed and constructed. This device gives f-number and shutter speed values for a given scene radiance in the near-infrared region, and the aerial camera may then be set at these values for proper exposure. As an addendum to the research, a simple image processing technique, color ratioing, has been applied to demarcation photography with extremely promising results. Using an array processor, false-color infrared images may be processed and analyzed so that water and non-water representations are dramatically different, and easily distinguishable.
Mr. Victor Weidner, Mr. Robert Saunders, and Mr. Bill Roberts of the National Bureau of Standards donated their time and the use of their technical facilities, and their contributions to this thesis are greatly appreciated.

A special word of recognition and thanks is due to Mr. Loren VanGorder and Mr. Dan Phillips of NOAA for their skillful contributions to the construction of the near-infrared radiometer/exposure meter.

Thanks is extended to Mr. Gary Guenther of NOAA who offered technical advice and insight at the beginning of the research, and possibly prevented unfruitful investigation.

A word of thanks also goes to Ms. Cathy Warsh of NOAA, who gathered some fifty samples of seawater during a NOAA research mission.

A word of thanks goes to the Delaware Seashore State Park for their gracious permission to conduct research on their beaches and piers.

A word of thanks goes to Dr. John Schott of RIT, the thesis advisor of this research, for his guidance in determining the system response functions at the latter part of this project.
Finally, a word of appreciation is extended to all of those NOAA employees who, in various capacities, supported this research on a day-to-day basis during the summer of 1985.
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INTRODUCTION

Since 1961, the National Oceanic and Atmospheric Administration (NOAA), Photogrammetry Branch, has been using black-and-white infrared (B/W IR) photography as a method for locating the demarcation line between land and water in coastal regions. These photography missions are flown at altitudes of approximately 25,000 feet, and each successive photo is taken with a 60 percent overlap to obtain stereoscopic coverage. The reason for this overlap is that it enables the cartographer to accurately determine the positions of objects in the image using aerotriangulation. Angular distortions, lens distortions, film deformations, and errors due to aircraft motion are corrected for each exposure. A more detailed description of photogrammetric procedures is available in Brewer and Heywood (1972).

An inherent property of water is that it is an excellent absorber of infrared (IR) radiation. This property is taken advantage of by the B/W IR imaging system by recording water on the final print as almost totally black. Since land and other non-water items generally reflect near infrared radiation (NIR) quite well, the images of these items are recorded very much like they naturally appear. This is the fundamental operating principle of NOAA's B/W IR imaging technique. This high contrast between water and non-water in the print demarcates the land from the water; the sharp edge around images of land masses guides the cartographer in locating the official shoreline to be recorded on the nautical chart.
In principle, this method is a sound one, but the critical assumption here is that water absorbs 100 percent of the NIR falling on it. This is simply not the case in the NIR region being photographed. Certain factors influence the exposure such that the apparent demarcation line may vary in location from one image to the next. Also, wide greyish areas are often recorded in the demarcation vicinity so that it is uncertain where the shoreline actually is.

Almost since this method was first adopted, it has been apparent that NIR penetrates the water to some extent. This statement is supported by observations of "bottom effects," current patterns found only on the bottoms of large water bodies, where there at first appears to be land.

If an image of land located only 1 or 2 feet below the water surface is registered on the film, the apparent shoreline could potentially vary in location by hundreds of feet.

Because of the variability inherent in this NIR photographic technique, as well as in the photographic process in general, there is a high degree of uncertainty as to where the shoreline is to be drawn on the nautical chart. If there is a discrepancy in apparent shoreline location between two adjacent images, and there often is, the cartographer often chooses to draw the line midway between the two.

Once the nautical chart is completed, the shoreline is final (until the next revision of course.) Any boundary disputes involving state controlled vs. federal waters, or even international waters, may be resolved according to an erroneous shoreline record. This has
happened in the past.

Since it is unlikely that a shoreline can be located with 100 percent accuracy, (because of varying weather conditions, tide, waves etc.) it is a goal of demarcation photography to minimize the variability in the imaging process so that images are as consistent as possible.

Most of the factors which influence the variability in this process are inherent to silver halide photography, and are strictly regulated. These factors include film exposure, film processing time, temperature and chemical concentration. All of the above apply to the print making process as well. These factors could potentially cause extreme demarcation variability, but with appropriate regulation and control, their effects can be minimized, and every precaution is taken to see that they are.

Because it has been obvious for some time that the NIR radiation does, indeed, penetrate the water, attempts have been made to quantify and compensate for this problem. Mr. Morton Keller, formerly of NOAA's Photogrammetry Branch, conducted a sub-float experiment in 1979 in which it was determined that "a water penetration of about one foot is indicated on the B/W IR film." (The underwater targets Mr. Keller used were made of sediment available in the area.)

In 1983, the Photographic Technical Representative of the Photogrammetry Branch, Mr. Edwin Hawbecker, called a meeting to discuss policy and procedures in this matter. One extremely controversial procedure was that of printing all waters to a specific density. This way, images on the print with this density are
considered to be water, and those with a lesser density are considered to be non-water. The cartographer is granted a certain amount of freedom to use his best judgement in this matter, of course. Another procedure was to burn-in the water until all detail was lost and the water was quite black.

"It was agreed" in this meeting that:

(A) present instructions to 'print for no water detail' or 'sharp cut-off between water and land' are subjective and should be avoided if photos are to be used to establish a waterline (B) guidelines be developed to give the laboratory technician specific measurable standards for printing photographs that are requested for a specific task.

Also, it was determined that some dodging and burning-in is necessary "to prevent loss of detail, but has to be prudently applied." The policy of printing waters to a certain density, as questionable as this is, is still part of the procedure today, with somewhat more relaxed density tolerences.

One of the conclusions of this meeting which most directly applies to this thesis, is that "the reliability of [the exposure meter] is questionable" in its ability "to give proper exposure values in the photographic infrared region." It was recommended that "use of infrared filters on exposure meters should be evaluated to determine" whether this improves exposure determination.

These incidents indicate that the influence of NIR photography on apparent shoreline variability was actively being investigated at this time. Since no beneficial alternatives were immediately available, however, the problem was not acted upon.
Over the years, it has been apparent that the exposure meter (Sekonic Model-S) gives incorrect exposure readings. Subsequently, a correction table, based purely on in-the-field experience and trial-and-error, has been devised and is still used. This exposure meter, as will be discussed in the "Experimental" section, proves to be quite inadequate, and an NIR exposure meter is designed to replace it.

The following is a list of the components of the imaging system presently used:

System Breakdown

**AIRCRAFT:** ROCKWELL Turbo Commander

**CAMERA:** WILD RC-8

**Wavelength band recorded:** 712 nm to 900 nm

**LENS:** f/5.6, 6 inch focal length, UAgII

**FILTRATION:** WILD visible cutoff filter

**FILM:** KODAK 2424 B/W IR, 9" X 9" aerial format

**EXPOSURE METER:** SEKONIC Model-S

* Processed according to manufacturers specifications.

The basic procedure for demarcation photography/chart making, as it is still practiced, is the following:
I. B/W IR film is stored in refrigeration until one day before use.

II. Sekonic is used to determine exposure settings, while in route to the flight line, and those settings are used throughout the pass.

III. Exposed film is sent to Precision Labs in Dayton, Ohio for processing and printing.
   A. Processed according to Kodak specifications
   B. Printed so that water has an optical density of approximately 1.61

IV. Photos are given to cartographer so that nautical charts may be drawn (using photogrammetry techniques.)

The problem as it has been identified, is the inability to decide where the shoreline should be drawn on the nautical chart based upon the image of the shoreline in the B/W IR photograph. This shoreline image, or apparent shoreline, often fails to be representative of the location of the actual shoreline because it varies as a function of water penetration. The NIR not only penetrates the water, but the depth to which it penetrates varies widely depending on several parameters.

The first objective of this thesis was to quantify the depth of water penetration recorded by the RC-8 camera and to identify the causes of this penetration. Since variability in apparent shoreline location is entirely attributable to variability in water penetration, the major cause of penetration variability needed to be identified and corrected. The order in which the investigation proceeds is the
following:

I. Quantification of scene characteristics.

II. Quantification of imaging system characteristics.

III. Determination of the suitability of the imaging system to the scene radiance and to the demarcation objective.

IV. Recommendation of ways to correct the discrepancies.
Alternative Imaging Systems

Alternative imaging technologies were investigated as to their suitability to this problem.

Infrared line scanning technology was investigated because of its compatibility with the fundamental operating principle* in NOAA's demarcation imagery. This technology appeared to be appropriate, and the absorption by water at much longer wavelengths could be taken advantage of. Upon investigation, however, it was discovered that, from NOAA's standpoint, the cost of implementing such technology would again be prohibitive. Another consideration was that the resolution of such a system would be questionable for this application. The self-emission for water would also need to be considered because in the spectral range of approximately 5-15 microns, objects act as sources of radiation. Obviously this would require far more research than was able to be performed in this thesis.

Laser hydrography was also investigated. The basic operating principle in this case would be exactly the opposite of the convention, namely, water penetration would be maximized. The potential for this technology was investigated, and was found to be quite intriguing in principle:

* The fundamental operating principle referred to is, of course, the exploitation of water's NIR absorption tendencies for the purpose of distinguishing water from non-water.
Pulsed laser technology offered a possibility. Very high frequency pulses would be emitted from the aircraft and then collected after reflection. For each pulse emitted, there would be two pulses returned, one from the water surface, and one from the bottom. In each sweep, the two return pulses would be closer and closer together until, at the land interface, the two pulses would again be one.

Continuous wave laser scanning devices would exploit the specular reflectance of water vs. the lambertian reflectance of land, and in this way differentiate between the two.

Both of the above technologies are interesting to consider, but in reality, there are extreme disadvantages from every standpoint. The pulsed laser, at present, only has a maximum pulse frequency capability of about 1 kHz, precluding acceptable resolution. Although there is a copper vapor laser under investigation by the Navy with a frequency potential of 15 kHz, there aren't information storage systems which can record and store information adequately at that rate. Many other drawbacks exist, but the main one, technically speaking, is the ability to locate the aircraft at all times relative to the ground.

These sophisticated technologies show some potential to locate objects at a distance, but the air station itself is so unstable that satellite location control would need to be performed. The effort involved, not to mention the expense, obviously makes the implementation of such technologies completely impractical.
I SECCHI DISK EXPERIMENT

To quantify the depth of penetration (ie. the maximum depth under the water surface that the camera is able to "see"), the following experiment was conducted. All conditions (ie. water clarity, atmospheric clarity, etc.) were optimized so that the water penetration indicated here would be the maximum possible. Unlike Mr. Keller's experiment, the results here would represent the worst possible situation. This secchi penetration experiment was carefully designed so that the distance into the water registered by the Hassleblad was the same as the distance registered by the RC-8 camera. This experiment took place at the Delaware Seashore State Park.

A

A secchi disk was attached to the end of a cord so that it would be suspended under water parallel to the water surface.

B

The cord was marked every three inches, beginning at the disk surface.

C

Size 120 Kodak 2424 film was obtained for a Hasselblad camera, and the camera was equipped with a Kodak 89B visible cutoff filter. In this way, the Hasselblad responded almost exactly like the Wild RC-8 aerial
The camera was positioned on a pier to "look" straight down at the water.

The secchi disk was lowered into the water in 3 inch increments. At every increment an exposure was made, bracketing by 1 stop (3 exposures for each increment.) The sun angle was between 40 and 50 degrees relative to the normal during the entire procedure. (This is the same sun angle used in actual missions.)

The 120 film was handled, stored, and processed exactly as the 9" X 9" film is.

No prints were made, rather, the film was analyzed directly. The water penetration indicated here was between 1.5 and 2 feet.

II ON-LOCATION SPECTORADIOMETER EXPERIMENT

An "Optical Spectrum Analyzer" (OSA) made by EG&G, Gamma Scientific, was purchased. This unit consists of a scanning monochrometer and a germanium detector; the output is displayed on an oscilloscope.
How it Works

The scanning monochromator layout is of the Ebert type. A blazed diffraction grating that is continuously rotated by a d.c. motor causes a spectrum to be "swept" across the exit slit of the monochromator. With a stabilized rotation rate of about one quarter the line frequency, a new spectrum is "swept" across the exit slit about every 67 milliseconds. From 250 nm to 1100 nm, it takes about 8 milliseconds for a spectrum sweep. Placed at the exit slit is a detector (silicon shown, several types available) whose output is coupled into an amplifier. Motor drive control circuits and amplifier as shown are contained within the scanning monochromator housing. An uncorrected spectrum is displayed on an oscilloscope by connecting the trigger output to the scope's external trigger input, and the spectrum output to the scope's vertical input.

Uncorrected spectrum of a warm white fluorescent tube showing mercury lines and the fluorescent continuum in the visible region. Displayed on an oscilloscope using a Model 6101 Scanning Monochromator and a Model 6111 Silicon Detector. With the slit plate provided, bandpasses of 2.5, 5, 10 and 20 nm can be achieved. When using an oscilloscope with delayed sweep, small portions or the display can be examined in finer detail.

Figure I, Optical Spectrum Analyzer
unit allows for a real-time display of relative intensity vs. wavelength of radiation incident on the entrance slit of the monochrometer. The germanium detector was chosen so that reflectance and transmittance spectra could be measured in the wavelength region of 600 to 2000 nm. Analysis in this broad range permitted the quantification of the scene's spectral characteristics at somewhat longer wavelengths, as well as in the 700 to 900 nm range.

Because the stability of oscilloscope adjustments was extremely precarious, calibration was to be performed on-location. The exact transmittance spectra of a didymium filter and of a tap water sample were measured on a Varian Cary 2300 spectrophotometer. These very same standardized items were then to be used for wavelength calibration in-situ before each measurement.

On-location (Delaware Seashore State Park) the OSA was powered by a small Honda gasoline generator. The OSA was mounted on a tripod, connected to the oscilloscope, and displays on the oscilloscope were recorded using an oscilloscope camera.

With the apparatus described above, reflectance spectra of sand, soil, and foliage samples were measured. Because the intensity of the sun was not adequate to register a reflectance signal in the OSA, an artificial source was used. This source (a sun lamp) was calibrated with respect to wavelength and then used to illuminate the objects of interest. The reflectance spectra of all 3 objects (soil, beach sand, and foliage), were quite constant across the entire 600 to 2000 nm
TABLE 1. Calibration wavelengths for prism instruments

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Wavelength (nm)</th>
<th>State</th>
<th>Thickness (mm)</th>
<th>Substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.946</td>
<td>0.992</td>
<td></td>
<td>Solid</td>
<td>Didymium glass</td>
</tr>
<tr>
<td>1.206</td>
<td>1.331</td>
<td>Solid</td>
<td>Solid</td>
<td>2,4-Dichlorobenzene</td>
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<tr>
<td>1.374</td>
<td>1.378</td>
<td>Solid</td>
<td>Solid</td>
<td>Triphenylaromamide</td>
</tr>
<tr>
<td>1.834</td>
<td>1.872</td>
<td>Solid</td>
<td>Solid</td>
<td>4-Chlorotoluene</td>
</tr>
<tr>
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<td>2.331</td>
<td>Solid</td>
<td>Solid</td>
<td>Chrysene</td>
</tr>
<tr>
<td>2.531</td>
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<td>Solid</td>
<td>Solid</td>
<td>1,2,3-Trimethylbenzene</td>
</tr>
<tr>
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<td>Solid</td>
<td>Anthracene</td>
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<tr>
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<td>2.993</td>
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<td>Solid</td>
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<td>Solid</td>
<td>Pyrene</td>
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<tr>
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<td>Solid</td>
<td>Solid</td>
<td>Benzo[z]pyrene</td>
</tr>
</tbody>
</table>

The maximum values for 0.740 and 0.748 μ are noted as a principal band observed with prism spectrometer.

Figure 2 is a trace of the record obtained for the two bands at 0.743 and 0.808 μ under high resolution. The emission lines are produced by a mercury arc. The wavelengths listed on the graph for these lines are given as twice the standard values since they are recorded in the second order. Figure 3 represents part of the spectrum of polystyrene and shows the regions used for calibration. The 1.681-μ band is composed of one component, but the 2.170-μ band has two side branches that are hardly noticeable on the prism instrument. Figure 4 represents the spectrum of 1,2,4-trichlorobenzene from 1.6606 to 2.543 μ. The wavelengths are marked on the bands which have been calibrated. In a previous publication (see footnote 2) the bands with wavelengths 2.404 and 2.543 μ were not labeled; two other bands were incorrectly labeled with these wavelengths. A glass prism was used in the spectrometer for the measurement of the emission spectrum of krypton, the results being represented by figure 5. The width of some of the observed lines indicated that several components might be present. Further measurements with the grating spectrometer proved that all the lines measured by the prism instrument had several components.

All of the calibrating wavelengths determined in the present study are listed in tables 1 and 2. The position of the maximum absorption of those bands, which are not symmetrical or which have two or more components, is usually changed when measured...
Figure III, Water Standard Calibration
A. Relative Intensity vs. wavelength for sun lamp of experiment II A.

(All oscilloscope photos represent the spectra from approximately 600 to 2000 nm.)

B. Sun lamp with Didymium

C. Sun lamp with water standard

Figure IV
spectrum. This was an indication that, in a system which is sensitive to these longer wavelengths, non-water would be recorded in much the same way as it is recorded in the B/W IR system. (This uniformity was to be important if the high absorptivity of water at these longer wavelengths was to be exploited.)

B

Atmospheric transmittance spectra were measured by simply aiming the OSA at the sun. By calibrating this spectrum with the didymium filter and the standard water cell, this was also a source spectrum for part C. By measuring the radiation from the sun directly, the attenuation of the atmosphere was automatically taken into consideration. This transmittance spectrum was also a radiance spectrum of sorts, because it described the only illumination in the seawater transmittance measurements.

C

Transmittance spectra of freshly gathered seawater samples were measured by aiming the OSA at the sun and placing a cell of seawate in front of the entrance slit. The transmittance spectra of the seawater samples were indistinguishable from eachother, further, they were indistinguishable from those of the standard water cell. The general shape of the sun spectrum from part B was very similar to that of the water transmittance spectrum. This similarity is very likely due to the attenuation by water in the atmosphere.
A. Sun spectrum of experiment II B

B. Didymium calibration of sun spectrum

C. Water standard calibration of sun spectrum

Figure VI
A. Relative reflectance of foliage sample

B. Reflectance spectrum of medium-white sand sample

C. Reflectance spectrum of dark soil/sand sample

Figure V
Figure VII, Transmittance spectra of seawater samples
III SEAWATER TRANSMITTANCE VS. LOCATION EXPERIMENT

From a NOAA research vessel, over 50 samples of ocean water were gathered from various off-shore locations throughout the east coast. These were surface samples taken within one mile of the coast. These samples were analyzed using the Cary spectrophotometer and a 1 cm cell. The purpose of gathering these samples was three-fold:

A

The first objective was to measure the transmittance spectrum of each sample to find differences in transmittance as a function of geographic location. There had been some concern that any measurements taken at one location may not be relevant to other locations. For each water sample measured, however, the transmittance spectrum was identical. There is no indication of a significant relationship between location and the optical properties of seawater. If any exist, they are negligible for this application. Not only were the spectra of the samples identical to each other, but they were almost identical to that of distilled water.

There appears to be no significant difference between the optical properties of stored, refrigerated seawater, and those of freshly analyzed samples. Upon comparison of the transmittance spectra of this experiment and those of experiment II C, no extreme differences were observed.

B

The second objective was to measure the exact percent-transmittance of
Figure VIII. Map showing locations of seawater samples of experiment III. Each indicator corresponds to a site where a sample was taken.
seawater in the 700 to 900 nm region.

The transmittance of each 1 cm cell of seawater is approximately 99% between 700 and 800 nm, and drops gradually to about 95% at 900 nm. (These values were calculated by removing the attenuation by air.) This does show a small degree of attenuation, and this attenuation seems to be characteristic of water. This, however, does not appear to be an appropriate fundamental principle upon which to base and operation of such magnitude and importance.

The third objective was to determine a wavelength band further in the infrared which is attenuated more strongly by water than the 700 to 900 nm band.

There is a region in the transmittance spectrum of water, just beyond the upper sensitivity of the film. At approximately 970 nm there is a sharp drop to about 65%. There is a second, far more drastic drop at about 1180 nm to about 34%. Beyond this wavelength, there is a small rise and then it goes practically to zero. These findings are very consistent with Jerlov (1976).

If the only optical characteristic of water to be exploited is its absorption in a certain spectral band, a band should be chosen which absorbs more strongly than 2% per cm. If the spectral sensitivity could be centered about the 970 nm mark, this operating principle of land/water contrast demarcation would be much more valid. The results of experiment II A support this conclusion.
Figure 6. Transmittance spectrum of distilled water from experiment III.
From experiment I, the indicated water penetration is approximately 18 inches. This means that for a photon incident on the water surface, that photon must travel 18 inches to reach the bottom, and another 18 inches to emerge again from the water. The total path length a photon may travel in water, therefore, and still register an image of the bottom on the film (excluding atmospheric attenuation) is a maximum of 36 inches, or 91.4 cm. The average transmittance of water in this wavelength region is approximately 98% per cm. Therefore, the transmittance along the above path length is:

\[
\frac{91.4}{0.98} = 0.158
\]

because, for each 1 cm the radiation travels, it is reduced by 2%.

\[
[0.98 \times 0.98 \times 0.98 \times \ldots \times 0.98, \text{ 91.4 times}]\]

This means that the minimum transmittance of the water along this path length enabling the camera to still "see" the bottom is 15.8%.

By the same reasoning, the maximum depth of penetration which would be observed on a film which is sensitive to the wavelength region about 970 nm, may be calculated. The transmittance of water in this region is 65% per cm. Therefore:

\[
\frac{pl}{0.65} = 0.158
\]

or

\[
pl = 4.28 \text{ cm}
\]

where \( pl \) is the maximum path length the radiation would be able to travel and still register an image of the bottom. The depth of penetration in one-half of this quantity, or:
dp = 2.14 cm = 0.84 inches

The maximum depth of penetration, if such a film were used, would be less than one inch. It seems obvious that a film with such a spectral sensitivity should be investigated. Upon investigating the availability of a silver halide film with the above spectral sensitivity criteria, it was immediately discovered that there were none on the market. The time and expense requirements for having such a film researched and produced were prohibitive for the time being. The upper sensitivity of the films that are available, including the Kodak 2424 film, is about 910 nm. Using appropriate filtration, this upper spectral sensitivity could be isolated, but just as the absorption of water increases in this region, the absolute sensitivity of the film dies rapidly. To do this would require exposure times that are much too long for aerial photography.

IV WILD CUTOFF FILTER TRANSMITTANCE MEASUREMENT

The transmittance spectrum of the Wild visible cutoff filter was measured. This was necessary since all records of the filter had long since been misplaced. Again, the Cary spectrophotometer was used. It was found that the filter is opaque to the visible and it transmits wavelengths above 712 nm. The peak transmittance varies from the center to the edge; this "antivignetting" feature is designed to compensate for radial lens falloff.

V SEKONIC RESPONSE MEASUREMENT
Figure XI, Transmittance spectrum of Wild cutoff filter
A

The spectral response of the Sekonic Model-S exposure meter was measured using a calibrated source/monochrometer and an ammeter. (The leads going from the sensor to the meter were severed and the sensor was attached to the ammeter.) It was determined, as it was suspected, that the Sekonic's sensitivity is primarily in the visible, and it is very insensitive in the NIR region.

B

The spectral sensitivity curve of the 2424 film was obtained from Kodak. The response of this film combined with the Wild filter was compared to the response of the exposure meter. It was immediately obvious that this exposure meter was ill-matched to the imaging system. The relationship between the exposure meter and the camera system is so fundamentally crucial, that such a discrepancy seemed to be the root of many problems.

VI NEAR INFRARED EXPOSURE METER DESIGN

It was decided that this discrepancy was of such importance that, because of the gross mismatch of the exposure meter to the imaging system, plans were made for the design and construction of an NIR exposure meter.

A

Selection of the components was then underway.
Figure XII, Spectral Response of Sekonic Exposure Meter
1. The first and most critical choice was that of a sensor. Considerations such as responsivity, spectral response, and physical size were the main criteria. The sensor chosen was an EG&G Electro Optics HUV-1100-BG silicon photodiode/amplifier. This sensor is extremely responsive and it has an inherent field of view of 80 degrees, roughly the same as the camera system.

2. Once the detector was chosen, proper filtration was investigated. Two filters were chosen in order that the sensor would only be exposed to the same wavelength region as the film is exposed to. The filters chosen were:
   a. Corion LS 900 R
   b. Corion LL 700 R

The LS 900 filter transmits radiation below 900 nm, cuts off (1/2 peak) at 900 nm, and is opaque to longer wavelength. The LL 700 filter transmits radiation above 700 nm, cuts off (1/2 peak) at 700 nm, and is opaque to shorter wavelengths.

A protective glass cover was chosen to be placed over the filters. (The transmittance curve of Fig. XII is that of all three items above superimposed.)

B

With the main operational components selected, the body of the detector was then designed. It was required that the unit be able to fit into a narrow space next to the camera in the floor of the aircraft. The aperture needed to allow the detector to be exposed to the same cone-angle of radiation as the camera is because, for a
Figure XIII, Transmittance Spectrum of Filtration
proper exposure meter/camera combination, the two should "see" the same information. The cylindrical design of the body allows for ease of handling and stability once the unit is placed in the floor-window of the aircraft. The screw-on filter hood allows for filter removal and replacement without disturbing the internal electrical components. For B/W IR photography, both filters are to be used, and for false-color IR the LL 700 filter may simply be removed, (the unit, of course, would need to be recalibrated in this situation.) The adjustable space capacity of the hood allows for filter combinations with a total thickness of up to 1.2 inches. (The total thickness of the LS 900, LL 700, and protective glass is only 0.7 inches.) Also, the hood has been designed so that even when it is fully extended, the view-angle of the detector is not affected.

VII NIR EXPOSURE METER CALIBRATION

After the radiometer was completely assembled, it needed to be calibrated. A source/monochromometer system was set up with a detector of known spectral responsivity at the exit slit. Over the wavelength region of 400 to 900 nm, in 10 nm increments, spectral output (in amps) of the calibrated detector was recorded.

\[ \text{Ost}(\lambda) \text{[Amps]} = \beta_{st}(\lambda) \text{[Amps/Watt]} \times \Phi(\lambda) \text{[Watts]} \]

Where Ost(\lambda) is the current output of the standard detector, \( \beta_{st}(\lambda) \) is its responsivity, and \( \Phi(\lambda) \) is the flux incident on the standard detector. The new NIR detector was then placed at the exit slit and the same procedure was followed.

\[ \text{Osmed}(\lambda) \text{[Volts]} = \beta_{med}(\lambda) \text{[Volts/Watt]} \times \Phi(\lambda) \text{[Watts]} \]
Figure X111, Drawing of Radiometer Body and Electrical Schematic of sensor circuit.
Figure XV, Finished NIR Radiometer
Where $O_{\text{smed}}(\lambda)$ is the voltage output of the new NIR detector and $\beta_{\text{smed}}(\lambda)$ is the responsivity of the new detector. (This is the quantity being solved for.) From the data generated in this experiment, a spectral responsivity curve for the new NIR detector was plotted.

VIII SCENE MODEL

A mathematical model was devised which describes the geometry and radiation/matter interactions of the scene. A curve was plotted which models the scene radiance reaching the air station.

For a transmittance, $\eta$, vertically through the atmosphere;

$$\eta = e^{-az}$$

where

$\eta$ = transmittance of the atmosphere measured on ground at point $p$, as a function of wavelength, $\lambda$

$a$ = extinction coefficient, function of $\lambda$

$z$ = depth of atmosphere

the transmittance along the slant path, $z'$, is:
RESPONSIVITY OF NIR RADIOMETER

VOLTS/WATT*nm

Figure XVI
\[ \eta' = e^{-az'} \]
\[ \eta' = e^{-az/cos\theta} \]
\[ \eta' = e^{-az\ sec\theta} \]
\[ \eta' = \eta^{\ sec\theta} \]
\[ \eta' = \eta \]

where
\[ \eta' \] = transmittance through slant-path as a function of \( \lambda \)
\[ \theta \] = angle between incoming radiation and normal
\[ z' \] = distance through slant path = \( z/cos\theta \)

The radiance reflected from the ground at point \( p \) is expressed as:

\[ L_r = E' \eta^{\ sec\theta} \frac{r \ cos\theta}{\pi} \]

where
\[ L_r \] = radiance reflected from ground at point \( p \), function of \( \lambda \)
\[ E' \] = exo-atmospheric irradiance of the sun
\[ r \] = reflectivity on ground, function of \( \lambda \)

and the quantity \( r \ cos\theta \) is the perpendicular component of the reflected energy, and the quantity \( \pi \ sr \) appears because of the assumption that the earth's surface is approximately lambertian. (See appendix A). The upwelled radiance due to atmospheric scatter is only about 3% to 7% of the total radiance reaching the air station. So an approximation to the fraction of the energy which never reaches the ground, but is scattered by the atmosphere into the imaging system is:

\[ L_u = E' \eta^{\ sec\theta} \frac{r' \ cos\theta}{\pi} \]
where
\[ \text{Lu} = \text{upwelled radiance due to atmospheric scatter, function of } \lambda \]

and \( r' = 3\% \) for a clear day, \( 5\% - 7\% \) for a hazy day.

The value of \( \text{Lr} \) is the amount of reflected radiance at point \( p \).
This radiance must then travel back upward through the atmosphere to reach the aircraft.

To account for the fraction of \( \text{Lr} \) which reaches the air station, \( \text{Lr} \) is multiplied by \( \eta^{1/2} \). The exponent \( 1/2 \) because the reflected radiance only effectively travels through \( 1/2 \) of \( z \). (This exponent may be manipulated for denser atmosphere, \( \eta^{2/3}, \eta^1 \), the exponent on \( \eta \) will be called \( \varphi \).) The final expression for the radiance reaching the air station is:

\[
\text{L}(h,0) = \text{Lr} \eta^\varphi + \text{Lu}
\]

or
\[
\text{L}(h,0) = \frac{E' \sec \theta}{\pi} \eta \frac{r \cos \theta}{\pi} \eta^\varphi + \frac{E' \sec \theta}{\pi} \eta \frac{r' \cos \theta}{\pi}
\]

which, when reduced, is:

\[
\text{L}(h,0) = \frac{E' \sec \theta}{\pi} \eta \cos \theta \frac{(r \eta^\varphi + r')}{\pi}
\]

where
\[ \text{L}(h,0) = \text{radiance reaching aircraft for height } h, \text{ and } \theta = 0, \text{ function of } \lambda \]
\[ h = \text{altitude of aircraft} \]

Using atmospheric transmittance values and exo-atmospheric irradiance values obtained from Theknekara (1972), a model curve of \( \text{L}(h,0) \) was
plotted.

IX  RESPONSE FUNCTIONS

A. Camera Response Function

A mathematical response function for the imaging system was derived.

\[ A = \frac{\pi d^2}{4} \]

where

- \( A \) = area of aperture [m²]
- \( d \) = diameter of aperture [m]

\[ E(\lambda) = \frac{L(h,0,\lambda) \eta_1 \eta_V A}{f^2} \]

where

- \( f \) = focal length of lens [m]

(note: there is no quantity representing lens falloff because the Wild filter was designed to correct for this.)

\[ D(\lambda) = E(\lambda) S(\lambda) t \]

where

- \( E(\lambda) \) = irradiance reaching film plane [W/m²]
- \( t \) = time [s]
- \( D(\lambda) \) = density produced on film
- \( S(\lambda) \) = sensitivity of film, given by the amount of energy required to produce a density of 1.0 on film [D/(ergs/cm²)] or [D/(W*s/m²)]

\[ D = \int_{\lambda_1}^{\lambda_2} E(\lambda) S(\lambda) t \, d\lambda \]
\[
D = \frac{\lambda^2}{\lambda 1} \int L(h,0,\lambda) \eta_1(\lambda) \eta_{vf}(\lambda) A S(\lambda) \Delta \lambda
\]

where

\[
\eta_1 = \text{transmittance of lens}
\]
\[
\eta_{vf} = \text{transmittance of Wild cutoff filter}
\]

or in the discrete case:

\[
D = \sum_{\lambda 1} \frac{\lambda^2}{\lambda 1} L(h,0,\lambda) \eta_1(\lambda) \eta_{vf}(\lambda) A S(\lambda) \Delta \lambda
\]

where D represents the average density produced throughout the film plane.

B. Detector Response Function

A separate response function representing the new radiometer was also derived.

\[
E_2(\lambda) = L(h,0,\lambda) \Omega \eta_{f1} \eta_{f2}
\]

where

\[
E_2(\lambda) = \text{irradiance incident on sensor [W/m}^2]\]
\[
\eta_{f1} = \text{transmittance of filter #1}
\]
\[
\eta_{f2} = \text{transmittance of filter #2}
\]
\[
\Omega = \text{solid angle of view [sr]}
\]
\[
\Phi(\lambda) = E_2 As
\]

where

\[
\Phi(\lambda) = \text{flux incident on the sensor [W]}
\]
\[
As = \text{surface area of sensor [m}^2]\]
\[ \text{Od}(\lambda) = \beta(\lambda) \phi(\lambda) \]

where

\[ \text{Od} = \text{voltage output of the detector [V]} \]
\[ \beta(\lambda) = \text{responsivity of detector [V/W]} \]

\[ \text{Od} = \int_{\lambda_1}^{\lambda_2} \beta(\lambda) \phi(\lambda) \, d\lambda \]

where \( \lambda_1 \) and \( \lambda_2 \) are in the visible and NIR region

\[ \text{Od} = \int_{\lambda_1}^{\lambda_2} L(h,0,\lambda) \Omega \phi(\lambda) \eta f1(\lambda) \eta f2(\lambda) \text{ As } \beta(\lambda) \, d\lambda \]

or in the discrete case:

\[ \text{Od} = \sum_{\lambda_1}^{\lambda_2} L(h,0,\lambda) \Omega \phi(\lambda) \eta f1(\lambda) \eta f2(\lambda) \text{ As } \beta(\lambda) \Delta \lambda \]

X EXPOSURE METER ALGORITHM

An algorithm was derived from the two response functions above which is capable of assigning f-number and shutter speed values to any given scene radiance. Because of this algorithm, a table may be generated to give choices of exposure values for any voltage output given by the radiometer. In order to derive a working algorithm, several approximations were made. All of the approximations are quite valid in the wavelength region of 700 to 900 nm. Without these assumptions, the mathematical expression could not be solved for \( L(h,0,\lambda) \). This is due to the fact that the radiometer gives a single voltage value. To try to solve for \( L(h,0,\lambda) \) is to try to solve one equation with 21
unknowns.

Constants:

\[ \Omega = 1.919933419 \text{ sr} \]
\[ \text{As} = \frac{\pi (0.00254 \text{ m})^2}{4} = 5.0670747 \times 10^{-6} \text{ m}^2 \]
\[ f = 0.153 \text{ m} \]

Approximations:

\[ \eta_{fl} \cdot \eta_{f2} = 55\% \text{ between 700 and 900 nm (see Fig. XIII)} \]
\[ \beta = \beta(\lambda = 800 \text{ nm}) = 2.315753 \text{ V/\text{W} (see Fig. XVI)} \]
\[ S(\lambda = 700 \text{ to 900 nm}) = 12.6 \left[ \frac{1}{(\text{ergs/cm}^2)} \right] = 12600 \left[ \frac{1}{(\text{W s/m}^2)} \right] \]
\[ \eta_{vf} = 40\% \text{ at center of filter (see Fig. XD)} \]
\[ d = \text{diameter of the entrance pupil of lens} \]

Consequently, the expression:

\[ \text{Od} = \sum_{\lambda_1} \lambda^2 L(h,0,\lambda) \Omega \eta_{fl}(\lambda) \eta_{f2}(\lambda) \text{ As} \beta(\lambda) \Delta \lambda \]
where \( \lambda_1 = 700 \text{ nm} \)
\( \lambda_2 = 900 \text{ nm} \)

becomes:

\[ \text{Od} = L(h,0)\Omega \eta_{fl} \eta_{f2} \text{ As} \beta \]

or

\[ L(h,0) = \frac{\text{Od}}{\eta_{fl} \eta_{f2} \text{ As} \Omega \beta} \]

and the expression:

\[ D = \sum_{\lambda_1} \lambda^2 \frac{L(h,0,\lambda) \eta_{vf}(\lambda) \eta_{1}(\lambda) A S(\lambda) \Delta \lambda}{f^*} \]
becomes:

\[ D = \frac{L(h, 0) \eta vf \eta_l A S t}{f^{*2}} \]

or

\[ D = \frac{L(h, 0) \eta vf \eta_l \left[ \pi d^{*2/4} \right] S t}{f^{*2}} \]

and since f-number is defined as

\[ f/# = \frac{f}{d} \]

then

\[ D = \frac{L(h, 0) \eta vf \eta_l \pi S t}{4 \left( f/# \right)^{**2}} \]

and since f/# and t are the quantities being solved for;

\[ \frac{(f/#)^{*2}}{t} = \frac{L(h, 0) \eta vf \eta_l \pi S}{4 D} \]

These f/# and t are the f-number and shutter speed, respectively, at which the camera is to be set to obtain an average density \( D = 1.0 \).

By substitution:

\[ \frac{(f/#)^{*2}}{t} = \frac{0d \eta vf \eta_l \pi S}{4 \eta f1 \eta f2 \ As \ \beta D \ Omega} \]

This is the final working algorithm from which values of f-number and shutter speed may be obtained directly from voltage values given by the detector.

The result of this algorithm will be a single numerical value. This number is to be most closely matched by possible f/# and t options available on the camera. These options are:

\[ f/# = 5.6, 8, 11, 16 \]
The aerial photographer will have at his disposal, a chart of voltage values corresponding to proper f/# and t settings so that these settings may be chosen directly from a voltage reading from the NIR exposure meter.

To test this algorithm, the radiometer was taken outdoors, and reflectance readings were taken from several objects. The voltage output of the radiometer has a range of 0 to 10.5 Volts. For each reading, the voltage value was fed to the algorithm and the resulting values were in the range of 3000 to 13000. These numbers are in extreme agreement with the options of \((F/#)^2/t\) available on the camera. Using the options F/# = 5.6 and 8 and t = 1/125, 1/160, and 1/200, all of these ratio values can be very closely matched. This is a strong indication that the algorithm/radiometer combination is a useful tool for determining exposure values and these values are very reasonable with respect to the radiance being measured.

To emphasise this point, \(((F/#)^2)/t\) for F/# = 5.6 and for t = 1/160, 
\[
(5.6)/(1/160) = 5017.6
\]
and this falls within the range of detectability of the radiometer.

To enable the radiometer to give values which cover all options, the offset control would need to be adjusted so that much higher intensity radiation would be required to flood the radiometer. The device would need to be recalibrated in this case.

XI IMAGE PROCESSING, COLOR RATIO

Most of the research thus far has been aimed at identifying and
Figure XVIII, Example of exposure chart for NIR radiometer
(Voltage values of Od would fill chart)
quantifying various radiometric parameters for the purpose of improving the consistency of on-location photography. This next experiment was designed for the purpose of determining the potential of an in-vitro image processing technique for enhancing the demarcation line. During a photography mission, photographs were taken of coastal regions on false-color infrared film instead of B/W IR film. False-color infrared film represents IR as red, red as green, and green as blue.

A

One of these photographs was digitized on a DeAnza array processor (model 64) using color separation. Each color level was digitized and stored in a separate channel. (Red, green, and blue filters were used with a Cohu 5000 series TV camera.) Although these 3 different images were stored in 3 separate channels, extreme care was taken to assure perfect registration when the images were superimposed to reconstruct the original color image.

B

With the three color-separated images stored on floppy disk, manipulations to the images could freely be performed. The infrared-to-green color ratio of the image was calculated by algebraically dividing the red channel by the blue channel pixel by pixel.

C
A. Full color image

B. Blue image (Green information)

Figure XIX
A. Green image (Red information)

B. Red image (IR information)

Figure XX
To extract the information produced in part B, the array processor's intensity transformation table (ITT) was adjusted so that the entire brightness range was fit between digital counts of 0 and 1. The DeAnza array processor stores information about each pixel as a "digital count," an integer value between 0 and 255. There is a brightness level which corresponds to each digital count; that is, the larger the digital count, the brighter that pixel is represented on the monitor.

Since the false-color image was digitized with color separation, each channel in memory stores a monochromatic image for each spectral band. The infrared image was stored in the red channel, the red in the green channel, and the green in the blue channel.

It is the nature of water to strongly reflect green radiation compared to its strong absorption of NIR radiation. Consequently, in images of water, the digital counts in the red channel are quite small compared to those in the blue channel. Conversely, the NIR reflectance of land is roughly the same as, if not greater than its green reflectance. As a result, the digital counts over land in both channels are very much the same in magnitude, with a tendency for the red digital counts to be slightly larger.

When the red to blue (actually IR to green) algebraic ratio was taken, the entire image was reduced to an array of counts between 0 and 2. Because the DeAnza truncates numbers to make them integers, the entire array then consisted of 0's and 1's (there were some 2's present also).

On a monitor which displays digital counts as 256 different brightness
Figure XXI, Examples of ITTs
Figure XXII, Ratio images
levels, no detail at all was noticeable to the eye. After adjusting the slope of the ITT, the monitor, which had been uniformly black, displayed water as jet-black and land as stark-white. The demarcation was dramatic.

This simple but effective image processing technique produced a demarcation line which was so pronounced that black pixels were exactly adjacent to white pixels all along the shoreline representation.
RESULTS

SECCHI DISK EXPERIMENT

The maximum depth into the water registered on the film was 21 inches with a relative over-exposure of 1 stop. At "proper" exposure (determined by NOAA standard operating procedure), the maximum penetration was 18 inches. So it is the conclusion of this experiment that under standard conditions (ie. on a clear day, with a 45 degree sun angle) the water penetration is approximately 18 inches +/- 3 inches depending on exposure.

ON-LOCATION SPECTRORADIOMETER EXPERIMENT & SEAWATER VS. LOCATION EXPERIMENT

The main results from these experiments are that the spectral behavior of water is very consistent relative to location, and that the spectral transmittance of seawater and pure water are almost identical. These results indicate that, for this application, the optical properties of water can safely be assumed to be constant.

WILD CUTOFF FILTER TRANSMITTANCE MEASUREMENT

The transmittance of the Wild filter "cuts off" at 712 nm (1/2 peak) and below. There is a peak transmittance gradation from the center (approximately 40%) to the edge (approximately 90%). Presumably, this "antivignetting" feature counteracts radial lens falloff in the film plane.

SEKONIC RESPONSE MEASUREMENT
The spectral response of the Sekonic is grossly inadequate for exposure determination in the B/W IR photography system. Almost all of the response of this exposure meter is in the near-ultraviolet and visible region, and almost none in the NIR region. This is exactly why simply filtering the Sekonic with a Kodak 89B filter has not given any results in the past.

NEAR INFRARED EXPOSURE METER DESIGN

Because of the results in the previous section, a new NIR radiometer/exposure meter was designed. This unit allows the user to accurately determine the exposure settings which are to be used in the aerial camera.

NIR EXPOSURE METER CALIBRATION

The responsivity curve of the new NIR radiometer/exposure meter, in V/Watt, was found to be approximately a straight line, with a very small positive slope. (See Fig. XV)

EXPOSURE METER ALGORITHM

This algorithm, which allows for the determination of usable exposure values, is based upon the behavior of radiation in the scene and on the responses of the camera and this new exposure meter. For an input of Volts (obtained from the exposure meter itself) this algorithm generates usable values of f-number and shutter speed.

IMAGE PROCESSING, COLOR RATIO

The infrared-to-green ratio of false-color infrared images enhances the demarcation line so that water and non-water are quite
distinguishable from each other.
DISCUSSION

At the outset of this research, the first priority was to identify which radiometric parameters of the scene could be considered constant and which could not. It was for this reason that the first three experiments were performed. Because of these experiments, as well as literature searches into the results of past research, it was determined that, for the purposes of this thesis, all of the scene components are very well behaved radiometrically. Reflectances of the land, foliage, and soil have proven to be relatively constant. The transmittance of water, and therefore the penetration thereof, has been proven to be somewhat wavelength dependent, but not adversely affected by weather conditions. That is, changes in weather conditions (relative to those of experiment I) could only serve to reduce the indicated water penetration.

It was found, as it was indicated in the first three experiments, that imaging at longer wavelengths (approximately 970 nm) would greatly improve the ability to accurately locate the demarcation line. As this route is not an immediately practical one for NOAA to follow, it is suggested that further research be conducted in this area. A silver-halide photographic system with sensitivity in this range, as compared to other technologies, would be ideal because of its superior resolution capabilities. One consideration is the low level of radiation in this wavelength region which reaches the air station. Such a film would need to be quite sensitive because of this behavior.
With the scene characteristics rather well defined, it was the purpose of the next several experiments to determine the radiometric behavior of the elements of the imaging system. Because the only severe discrepancy found in this system was with the Sekonic exposure meter, the new exposure meter of experiment VII was developed. All of the radiometric behaviors of the scene and of the imaging system found thus far were used in the mathematical analysis of the new exposure meter.

Because the radiance reaching the air station is always much more intense in the visible region than in the NIR region (see Fig. XVI) the Sekonic, by its nature, always gives exposure settings that would result in under exposure. A correction table was devised which adjusts exposure values given by the Sekonic to uniformly increase the exposure. The critical problem in doing this is that changes in radiance in the visible region may not correspond linearly with changes in the NIR. As was found in the second experiment, the main influence on atmospheric transmittance is its water content. Changes in water content will affect the atmospheric transmittance in the NIR much more strongly than in the visible. The humidity, therefore, will strongly affect the exposure needed to register an image on the 2424 film, while it may not affect the reading given by the Sekonic. This argument is the main justification for developing the new NIR exposure meter.

The technique for image processing false-color images is indeed very promising for NOAA's purposes. The experimentation of this thesis in this area is for the most part, however, ground-work for further research. There is much investigation and development
required before this technique can be applied in NOAA’s demarcation procedure.

As was indicated, the demarcation by this method is so pronounced that black pixels and white pixels were adjacent to one another along the shoreline. These pixels, however, are too large and thus the resolution too low for such precise requirements. With higher resolution apparatus, this problem can be overcome. Secondly, although water and land become quite distinguishable in general, some areas which were obviously water in the original image were represented as land in the ratio image, and vice versa. This problem can also be overcome by controlling the digital count truncation. Once the color ratio is performed, the digital counts should be stored as real numbers, and multiplied by 255 to re-expand the range.

If this color-ratio method were put into use, two major benefits would result. Primarily, the guesswork would be removed from shoreline location cartography. Secondly, since the false-color IR film used in the camera is processed into the final transparency, the printing process would be eliminated. There would be no more need to supply arbitrary guidelines to the laboratory technician in the printing process.
CONCLUSIONS

It is a conclusion of this thesis that in order to eliminate NIR penetration due to faulty exposure, the NIR exposure meter should immediately be put to use in all demarcation photography assignments. Since past exposure determination techniques have proven to be completely inadequate, use of this new exposure meter will greatly improve the consistency of the final photographs. If the 2424 film is continued to be used, it is recommended that the film be reversal processed and the printing process be eliminated completely. This would at least eliminate subjective exposure manipulation by the lab technician.

It has also been concluded that there will always be a water penetration of up to 21 inches if the B/W IR film is continued to be used. This is due to the inherent nature of water. For this penetration to be minimized, a new imaging system will need to be adopted. The simplest way to accomplish this is to develop a film which is sensitive to the 40 nm wide wavelength region centered at 970 nm. If a film like this is used, the maximum water penetration will be reduced to about 1 inch or less. This would improve the demarcation capability tremendously.

Finally, if such a film is not developed for this purpose and present methodology is continued to be used, it is recommended that the color ratioing technique be vigorously investigated and ultimately used to process demarcation photos. False-color IR film is readily available in aerial format. The only investigation which needs to be performed is the location of a high resolution processor with the
mathematical capabilities described in the "discussion" section. Once such a device is located, mathematical analysis would need to be performed in order to assure appropriate numerical demarcation.
REFERENCES


APPENDIX A

For the total flux, $\phi$, reflected from a Lambertian surface, the radiant intensity, $I$, as a function of angle of reflection is expressed:

$$I = \frac{d\phi}{d\omega}$$

$$I(\theta) = I(\theta=0) \cos \theta$$

$$d\phi = I(\theta) d\omega$$

$$d\phi = I(\theta=0) d\omega \cos \theta$$

$$\phi = I(\theta=0) \int_{\theta} \cos \theta \, d\omega$$

where $\int_{\theta}$ means the integral taken over the hemisphere of reflection made up of the azimuthal angle $\theta$ and the radial angle $\sigma$.

$$d\omega = \frac{dA}{r^2}$$

$$dA = r \, d\theta \, r \sin \theta \, d\sigma$$

$$d\omega = \frac{r^2 \sin \theta \, d\theta \, d\sigma}{r^2} = \sin \theta \, d\theta \, d\sigma$$

$$\phi = I(\theta=0) \int_{\theta} \cos \theta \, d\omega = I(\theta=0) \int_{\theta} \cos \theta \sin \theta \, d\theta \, d\sigma$$

$$\phi = I(\theta=0) \int_{0}^{\pi/2} \int_{0}^{2\pi} \cos \theta \sin \theta \, d\theta \, d\sigma$$

$$\phi = I(\theta=0) \pi$$
KODAK AEROCHROME Infrared Film 2443
(Estar Base)

KODAK AEROCHROME Infrared Film 3443
(Estar Thin Base)

Note: Critical users of these two films should determine the actual sensitometric characteristics of their particular batch of film by using their own specialized techniques. The keeping conditions for these films have an effect on their sensitometric response.

Spectral Sensitivity Curves
Process EA-5

Sensitivity = Reciprocal of the exposure (ergs/cm²) required to produce a density of 1.0 above D min.
Measurements were confined to the 400- to 700-nanometer region.

Spectral Dye Density Curves
Process EA-5

Spectral densities of dyes yielding an Equivalent Neutral Density (END) of 1.0 with D 5000 viewing illuminant.
Measurements were confined to the 400- to 700-nanometer region.

Characteristic Curves
Process EA-5

Exposure: Daylight through a KODAK WRATTEN Filter No. 12
(500-900 nm); 1/50 second
Process: EA-5 Chemicals
(120°F First Developer)
Development: Stuax A Filters

Modulation-Transfer Curve
Process EA-5

Illuminant: Tungsten (2850 K) + Corning Filters 5900 and 3966 + KODAK WRATTEN Filter No. 12
Process: EA-5 Chemicals
I was born and raised in Pittsburgh, Pennsylvania and moved to Frederick, Maryland at the age of 7. I finished elementary and high school in Frederick, and in 1981, entered RIT in Rochester, New York. I attended RIT for my first two years, and because of dwindling financial resources, took a one-year leave of absence to work. During this year, I worked as a newspaper photographer and as an industrial photographer simultaneously, and then as a photo counselor the following summer. I returned to RIT to complete my Junior year and, in the summer before my Senior year, took a job at NOAA to begin research for this thesis. The completion of this thesis marks the conclusion of my academic career at RIT.