ABSTRACT

Title of Thesis: How Many Bits? Radiometric Resolution as a Factor in
                          Obtaining Forestry Information with Remotely Sensed
                          Measurements.

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In this study, Landsat 7 and IKONOS data were compared to determine if

higher quantization is beneficial for forestry remote sensing. An industrial forestry site

in central Virginia was chosen for analysis because of its large variation in standing

biomass. Data were selected and processed so that the measurements were as

comparable as possible to one another. The processing steps included spatial

aggregation, pixel alignment, and calibration to planetary reflectance.

Due to several aspects of study design and execution, the results are

inconclusive. The registered data sets were found to differ by more than 1-2%, which

is above the theoretical limits based on their radiometric resolutions. Lessons learned

from this study are that to investigate radiometric resolutions, extreme care must be

taken to understand the consequences of every data processing step and that all

differences in the compared datasets cannot be overcome.

HOW MANY BITS?
RADIOMETRIC RESOLUTION AS A FACTOR IN OBTAINING FORESTRY
INFORMATION WITH REMOTELY SENSED MEASUREMENTS.

by

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CHAPTER I: INTRODUCTION

The question of whether 8-bits is enough to evaluate the Earth's land conditions with satellite remote sensing is often talked about and debated in the remote sensing field, but rarely evaluated. This is, in part, because "it depends" upon the particular remote sensing application. In this study, the number of radiometric quantization levels needed to evaluate variations in forest vegetation is examined.

An industrial forestry site in central Virginia was analyzed because of the large variation in forest cover present. Landsat 7 imagery and IKONOS imagery serve as the means to evaluate whether increased radiometric precision might improve remotely sensed assessments of forested areas.

For this study, the aggregated IKONOS sensor data is assumed to be "reality", and the Landsat 7 satellite is evaluated in comparison to this "reality". The differences in sensor sensitivity, as a function of spectral band (blue, green, red, near infrared), will judge whether Landsat 7 has adequate radiometric precision for forestry analysis or whether higher radiometric resolutions would be valuable. By measuring the associated changes in reflectance of the two sensors, it is possible to evaluate the need for increased radiometric quantization.

The result of this study, which compares radiometric resolution for aggregated Landsat 7 and IKONOS data, should better inform scientists in planning for further satellite missions. As of yet, we do not fully understand what observation measurements are needed in all remote sensing applications. In this case, this study will contribute to understanding the needs of observations for forest studies. Although this study will not provide all the answers, it is a step in this direction, as it will provide

some insight into one of the major considerations that scientists and engineers

encounter when designing a sensor for terrestrial remote sensing.

CHAPTER II: BACKGROUND

Over the past century, applications of terrestrial remote sensing have moved from qualitative, visual analyses to more quantitative interpretations (Liang, 2003; Swain & Davis, 1978; Colwell, 1960).

Previous Studies

In initial efforts to address the question of satellite sensor radiometric resolution, aircraft multi-spectral scanner data were used (Morgenstern et al. 1976). Morgenstern, et al. (1976), in their study, used a simulation classifier and a set of aircraft-collected spectral responses from agricultural fields. They looked at noise equivalent reflectance (NEΔρ), which is a term that quantifies how much reflectance in a signal is caused by random noise. It is related to radiometric resolution in that the lower the NEΔρ value, the higher the quantization level can be set by the sensor engineer without the signal being overly contaminated by random noise. They found that an increase in noise equivalent reflectance (NEΔρ) from 0.5 to 2.0 percent:

1. Decreased the overall classification accuracy from 90 to 87 percent;

2. Decreased classification accuracy in highly stressed corn from 53 to 37 percent;

3. Decreased classification accuracy from 94 to 85 percent in soybeans.

The Morgenstern et al. (1976) study addressed the specific question of how field-center classification accuracy was affected by changes in Noise Equivalent change in Reflectance (NEΔρ). The authors also warned readers that the actual classification accuracy was a complex function of many factors, only one of which was noise equivalent change in reflectance (Morgenstern et al. 1976).

It is worth noting that Landsat Multispectral Scanner (MSS) had a NEΔρ ~2 percent, while Landsat Thematic Mapper (TM) had a NEΔρ ~0.5 percent. Although these NEΔρ figures of merit are presented as "fixed" sensor characteristics, they are variable, as a function of solar zenith angle. As seen in Figure 1, the 30m Landsat 7 ETM+ sensor has a NEΔρ less than 0.5 percent in bands 1-4 up to 75 degrees solar zenith angle and in most bands up to 50 degrees solar zenith angle (Arvidson et al., 2002).
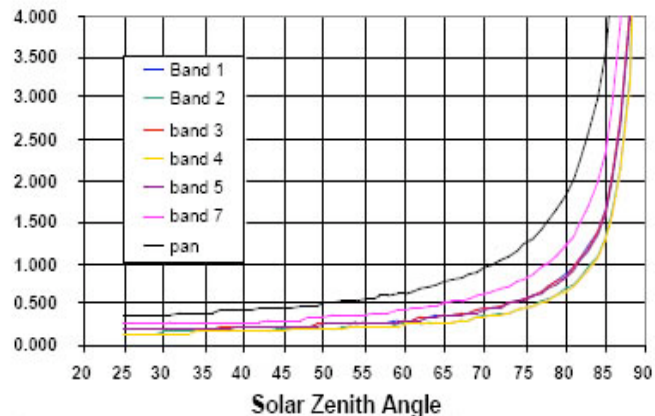

Figure 1- ETM+ Exoatmospheric Noise Equivalent Change in reflectance (in % reflectance) for high gain, exoatmospheric reflectance of 0.05 and level 0R data. (source: Arvidson et al., 2002).

Tucker (1980) used *in situ* collected reflectance data and compared quantization levels at 16, 32, 64, 128, 256 and 512 (2^4 to 2^9 bits) digital counts for Thematic Mapper bands 3 and 4. This study was conducted to evaluate the benefits that higher radiometric resolution data provides for monitoring vegetation resources. By using *in situ* data and a simulation model to make the comparison, Tucker found that 256 quantizing levels gave a 1-3 percent improvement in its coefficient of determination (r^2) per channel over 64 quantizing levels, and that 256 quantizing levels gave a 1 percent improvement in r^2 per channel over 128 quantizing levels. No improvement was found for 256 versus 512 quantizing levels.

For glaciological studies, where it is very important that the sensor detects slight differences in image brightness, radiometric resolution becomes very consequential (Bindschadler and Vornberger 2000). In an attempt to compare different sensors' ability to differentiate ice-sheet topography, Bindschadler and Vornberger (2000) composed a qualitative and quantitative study whereby they compared spatial and radiometric resolution combinations of four sensors for glacial observations. The four sensors used in their study were AVHRR, SPOT, Landsat TM, and RESURS-01, all having 8-bit quantization, except for AVHRR which has 10-bits. In summary, after comparing all relevant factors, including quantization, radiometric resolution, saturation threshold, solar irradiance, and spatial resolution; the authors concluded that:

1. AVHRR held the advantage of highest quantization, but only at twice the radiometric resolution of Landsat TM. AVHRR never saturated, but it suffered because of its relatively course spatial resolution;

2. Landsat TM has a much higher spatial resolution than AVHRR. Its radiometric resolution ranked second in the comparison, but it saturated quickly;

3. RESURS-01 has a spatial resolution between AVHRR and TM, but by applying its 8-quantization over a wider range of radiance, it had the worst radiometric resolution in the study;

4. No SPOT data was actually used in this study, but its radiometric resolution falls third in the study. Nevertheless, with SPOT's 20-meter pixel resolution, it should prove very useful in defining small-scale features.

More recently, Masek et al. (2001) used the numerical method of entropy to compare radiometric resolution between Landsat 7 Enhanced Thematic Mapper

(ETM+) and Landsat 5 Thematic Mapper (TM) data. Although both these sensors have 8-bit quantization, Landsat 7 employs two alternate gains that permit enhancing radiometric resolution in the high gain mode. This study was undertaken to evaluate the potential advantages of Landsat 7's two-gain state characteristic. The two-gain state was introduced so the sensor could better image very bright objects in the high gain state or very low reflecting objects in the low gain state by simply selecting what dynamic range to telemeter to the ground receiving station. As expected, ETM+ high gain proved superior to the older, single low gain TM system used on Landsat 5. Given typical reflectance spectra, the simulated ETM+ entropy distribution showed increased information content in all bands, except 1 and 5, in which the sensors have most closely gain attributes. It is those bands that the high-gain state of Landsat 7 replicates those of Landsat 5, meaning that when that sensor is set to high gain, the bits that are telemetered down to earth correspond to the eight bit gain that Landsat 5 will telemeter.

Although not relegated to solely a study of radiometric resolutions, Legleiter et al. (2002) did a comparative study where the authors tested differing sensor resolutions for mapping in-stream habitats. They compared hyperspectral imagery against simulated multispectral data where they did classifications with different sensor resolutions and determine what data types improved their classification accuracy's the most. The sensor resolutions that were under investigation in this study were spatial resolution, comparing a 1 meter pixel to a coarsened 2.5 meter pixel; spectral resolution, comparing hyperspectral data to multispectral data; and radiometric resolution, comparing 11-bit data to linearly rescaled 8-bit data. To control for other confounding factors, like varying signal-to-noise which describes the purity of the

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signal, only two sensors were used in this study (the airborne multispectral sensor ATLAS, the airborne hyperspectral system PROBE-1) and all variations that are not native to the sensor were simulated. The largest improvement, reported in this paper, was the use of hyperspectral data over multispectral data with a classification accuracy improvement of 7.2 percent. The second biggest improvement was made by using higher spatial resolution data over the lower, 2.5 meter pixel, improving the classification by 4.7 percent. Lastly, the smallest improvement was made by the increased radiometric resolution, with the 11-bit data improving the classification by only 0.8 percent over the 8-bit data.

Elmore and Mustard (2003) compared the capabilities of the EO-1 Advanced Land Imager (ALI) data with the capabilities of Landsat ETM+ for measurements of vegetation cover. The analysis defined the precision and accuracy of ALI and ETM+ for making quantitative measurements of earth for semiarid ecological studies. This comparison was accomplished to determine if it is valid to substitute EO-1 ALI for Landsat ETM+ data without loss of quality in vegetation analysis. In a comparative assessment, ALI performed superior in every aspect of the study, including detecting more variability in areas of high reflectance, having better estimates in percent green cover, and reporting fewer negative values in regions of low cover. Not only were the improvements in ALI attributed to having more spectral bands and a higher signal to noise ratio (SNR), but also to a higher radiometric resolution (12-bits vs. 8-bits). In this study, and in others, the conclusion was that ALI meets or exceeds ETM+ performance (Elmore & Mustard, 2003; Lobell & Asner, 2003).

Summary and Conclusions from Previous Studies

In most cases, having a higher radiometric resolution is undoubtedly helpful for distinguishing characteristics of features and for extending a sensor's capability. Unfortunately, it is nearly impossible to have all the data characteristics that are desired with one sensor. For example, it would be optimal if a sensor had high quantization, high spatial resolution, and a large swath width. Unfortunately though, due to data download and memory constraints, high cost, and other factors, current sensor technology is not up to the challenge. Having high quantization is a trade-off for other desirable characteristics. Most of the time, radiometric resolution appears less important than spectral or spatial resolution, and increasing the quantization above 8-bits shows virtually no improvement. But this might not be the case for forestry remote sensing.

CHAPTER III: CURRENT STUDY

Introduction

Previous studies often have not found radiometric resolution to be an important factor in the capability of remote sensing systems to discriminate land features. Nevertheless, the case of forest canopies may differ. During the growing season, forests are very low reflectors of visible and shortwave infrared radiation as well as moderate reflectors of near infrared light (broadleaf canopies tend to be more reflective than needleleaf) (Running et al., 1994). Therefore, it may well be that the radiometric resolution of the data are more important for forest analyses. Studies have shown the great practical utility of IKONOS imagery for forest mapping in mid-Atlantic regions mostly due to the high spatial resolution that gives the user the ability to augment traditional mapping approaches and may provide, in many cases, a cost-effective alternative (Goetz, 2003). In this study IKONOS observations are used as the "truth" by which to evaluate whether Landsat 7 ETM+ observations have adequate bit density to observe variations in forest canopy.

The Study Site

The site examined - an area in Powhatan County, Virginia (see figure 2) - was selected because it contains forest stands of varying ages and in differing stages of regrowth. Furthermore, there was little residential and no retail business in the area so consequently the stands were relatively undisturbed except for times of clearing. The scenes that were chosen to be compared for the study were acquired in September 1999 (Landsat 7) and October 2000 (IKONOS). With only one year separating the two images and both towards the end of the growing season, the vegetation has only

minimally changed and the stands are at a similar stage of seasonality. In addition, in

between the acquisition of the two dates, there was one plot that was cleared in the

scene pair, so that area could be used as a control for the results, as it is known that
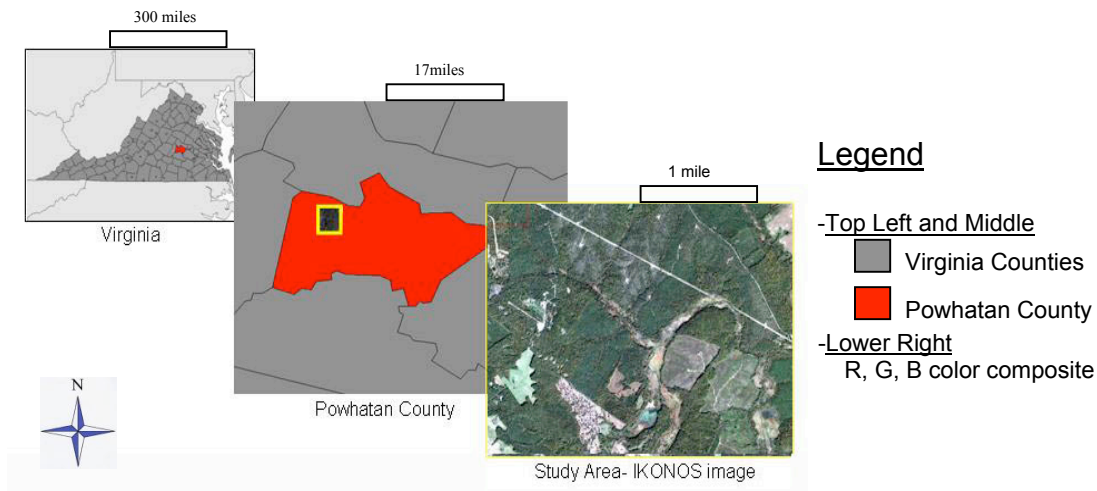
there was a dramatic change in that area.

Figure 2- Study Area

The area for this study had a high degree of variability in forest stand age (see

figure 3a) due to timber farming. The land is flat and mostly forest, with several areas

of clearing for timber extraction and others for residential yards (figure 3b). The roads

going through the lands are mostly dirt, with a one being paved (figure 3c). The stand

ages vary by a great degree, possibly up to 60 years. In one plot, towards the center of

the study area, the area was cleared about the time that the images were acquired, so the

land was dirt and showed high reflectivity in the visible part of the spectrum. Presently,

about 5 years later, the vegetation in that particular area is regrowing with all being

very young and a large mixture of species. Over the whole study area, there are

hundreds of different types of trees, with the dominant species being Oak, Pine,

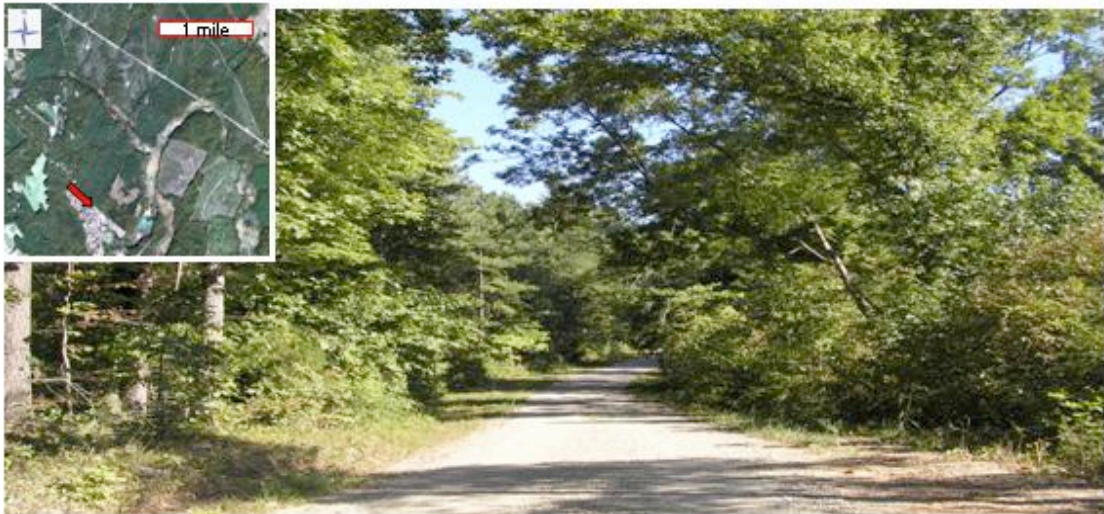Juniper, Sweetgum, Maple, Birch, and Sassafras.

Figure 3- a) Stands in various ages of growth b) Farming lot and c) residential road

Data Sets employed

The IKONOS and Landsat 7 sensors have several similar measurement characteristics that make them suitable for a comparison of radiometric precision. These include a near-polar, sun synchronous orbits with both having a descending nodal crossing time of approximately 10 AM, and similar spectral bands passes (see table 1) for the four shortest wavelength bands of ETM+. IKONOS does not have any other multispectral bands so the comparison of the short-wave infrared (SWIR) band is not possible.

Table 1
Comparison of Landsat 7 and IKONOS visible and NIR spectral band passes

Band	Landsat 7 spectral range (nm)	IKONOS spectral range (nm)
(1) Blue	450 - 515	445 – 516
(2) Green	525 – 605	506 – 595
(3) Red	630 – 690	632 – 698
(4) NIR	775 – 900	757 – 853

In addition to there being similarities, there also are some differences between the sensors. The largest of these differences is the spatial resolution. Landsat 7 provides moderate resolution[1] at 30 meters (multispectral), whereas IKONOS was designed to be the first high-resolution commercial satellite, providing spatial resolution of 4 meters for its multispectral bands, a near factor of 10 finer resolution. Secondly, the Landsat 7 platform has a fixed viewing angle, only viewing up to 7.5 degrees off nadir at its edges, while the IKONOS sensor can be positioned to image at a large variety of viewing angles, including those close to the Earth's horizon. Much of the

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[1] The classification "moderate" is not always agreed upon by scientists. Sometimes Landsat 7 data is classified as being "high resolution", and finer spatial resolution data such as IKONOS is considered "hyperspatial".

reason for having such a variable viewing angle is because of the much smaller swath width of the IKONOS (11 km at nadir) sensor compared to the Landsat 7 sensor (183 km). With IKONOS being a terrestrial environmental monitoring system and having such a small swath width, it becomes necessary to view at wide angles and monitor more land than when viewing exclusively at nadir. The last noted difference between the sensors, and the one analyzed in this study, is radiometric resolution. Landsat 7 ETM+ downlinks 8 bits, in two alternate gains, versus IKONOS which acquires 11 bit digitized radiometry and then compresses the data for telemetry.

The potential off-nadir constrast was overcome by selecting an IKONOS image that was not acquired at a large off-nadir view (see table 3 in Data Selection section). The largest difference to surmount was the spatial resolution. Since this was a study of radiometric quantization, it was first imperative to equalize the spatial resolution so that what was being determined in the analysis is a factor of the radiometric resolution difference, and not due the spatial resolution. Explained in more detail later, both datasets were aggregated to 60 meters to control for that concern.

To answer the question posed in this study, Landsat 7 and IKONOS data were chosen to be used for the comparison. There were two main reasons for using these datasets for the study. First, and necessary for the study, these two sensors produce similar observations in time and spectral composition, while varying in radiometric precision, particularly after they have been aggregated. Secondly, both these datasets are commonly used for terrestrial remote sensing studies and have become a standard in the industry, with Landsat being the classic moderate resolution earth resource satellite

and IKONOS being the first high resolution commercial satellite. Both these systems are widely used and the data is readily available to the public and private sector.

Definition of Terms

Since terminology can get confusing, it is useful to clearly define terms being used in this paper.

Radiometric Resolution

In remotely sensed data, radiometric resolution is defined as the amount of energy required to increase a pixel value by one quantization level or 'count'. Radiometric resolution involves two components that are related to the design of a system sensor. The first element is random signals (or noise), that are present in the sensor systems optics, mechanics, or electronics. The noise can be related to reflectance and thus, is referred to as noise equivalent reflectance (NE_). The second one involves the number of quantizing levels present in the analog-to-digital (AtoD) converter. Determining sensor's quantizing ability largely depends upon the amount of random noise that is involved in the sensor (Tucker, 1980). In summary, radiometric
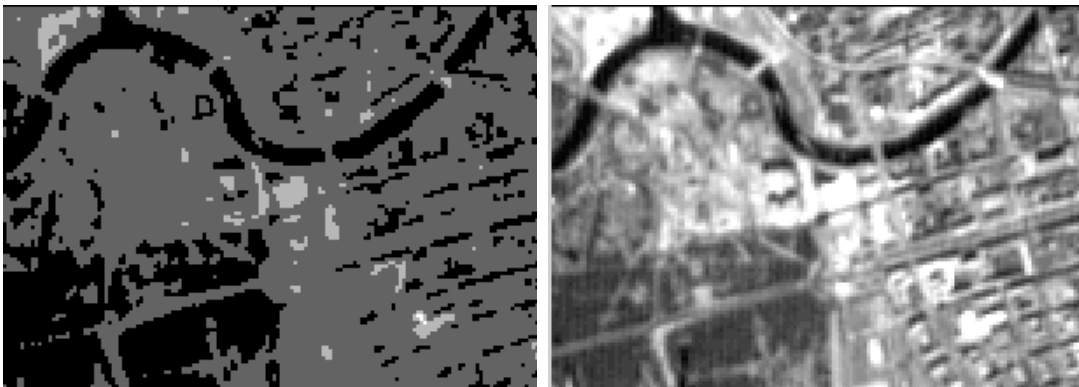

Figure 4 - Comparison of two SPOT images (courtesy of SPOTIMAGE) of central Berlin. Left image has low radiometric resolution and the right image has a higher radiometric resolution and provides much more information. (source: http://www.uni-kiel.de/castle/ch3/s3l7p040.htm, last accessed 12/8/2005).

resolution determines how finely the sensor can distinguish between objects of similar reflection. The higher the radiometric resolution, the better we can distinguish even subtle differences in reflection (see figure 4).

Quantization

It refers to the number of individual levels used to digitize a range of radiometric values. This is done by sorting the magnitude at a particular sampling instant into increasingly fine binary values within the overall dynamic range (Landgrebe, 2003). For example, a 3-bit system has 2^3, or 8 possible values, namely levels 0-7, while a system with 12-bit quantization will have 2^{12}, or 4096 distinct values. Although digitizing using a small number of quantization levels does not make a huge difference to the visual quality of an image (given that we can only see on the order of 30 shades of gray), a numerical analysis will suffer greatly if only a few quantization levels are used. Early aircraft systems typically had an 8-bit system indicating 256 different shades of gray. Landsat MSS, the first spaceborne system, had 6-bit quantization; and more modern systems have 10 to 12-bit quantization, based on much higher signal to noise (S/N) ratios possible (Landgrebe, 2003).

Dynamic Range

This is a concept that pertains to any imaging system, whether it is a handheld camera, or a satellite remote sensing system. In accordance with radiometric resolution, dynamic range is the other factor that characterizes what the change in reflectance ($\Delta\rho$) will be for a sensor. Based on the brightest and darkest objects that will be encountered, the dynamic range is set by the system designer to capture the desired range of values. Usually, such desired range of brightness values covered

depends on the type of applications that it will be used for. If a sensor is used for applications that it is not originally designed for, saturation may occur. An example would be using a terrestrial monitoring system in glacial environments, where the dynamic range might not be sufficient (or high enough) to capture the very bright pixels that reflect off of snow and ice. Some sensor systems, including Landsat 7, have dual gain systems that can shift from one dynamic range to another, depending on what is being imaged.

Radiometric Resolution, Dynamic Range, and Δρ

Radiometric resolution and dynamic range are the two factors that determine what the change in reflectance (Δρ) will be for a system. Although they work together, it is important not to get radiometric resolution and dynamic range confused. As explained above, radiometric resolution is the factor that defines how precisely an object's reflectance can be detected while dynamic range is the radiometric extremes that a sensor is set to observe.

The change in reflectance (Δρ) is the smallest increment of reflectance that can be detected by the sensor. To determine Δρ, both radiometric resolution and dynamic range of a system have to be considered. For example, the minimum radiance (LMIN) that Landsat 7 is set to detect is -6.4 W/m^2/sr/μm (units of absolute radiance) and the maximum radiance (LMAX) it is set to detect is 196.5 W/m^2/sr/μm, in band 2. Subtracting the difference between LMAX and LMIN for this band, the resulting dynamic range is 202.9 units of radiance. Moreover, given that Landsat 7 has 8-bit quantization, it is simply a matter of dividing 202.9 by 256 to get a Δρ of 0.793 for

band 2. Therefore this means that for every quantization level in band 2, there is a change in reflectance of 0.793.

Information concerning the conversion of DN values to spectral radiance is found in the Landsat Data Users Handbook (LPSO, 1998) for Landsat. Also, Space Imaging provides equivalent information for the IKONOS sensor (Peterson, Gerlach, & Hutchins, 2001).

CHAPTER IV: DATA AND METHODS

Introduction

A potentially difficult aspect of this study is to demonstrate that either of the two remotely sensed observation sets (Landsat 7 or IKONOS) measure some specific aspect of forests (e.g biomass, canopy closure, stand age, etc). Such a study, although interesting, would require detailed field measurements for the study area under investigation that is beyond the scope of this MA thesis. However, a relative assessment of a specific remote sensing system's capacity to distinguish variations in the same forest canopies can be conducted by simply comparing one system's capability to measure radiometric detail versus another.

In this study, digital number data are calibrated and converted to top-of-atmosphere reflectance. The image pixels from each sensor are aggregated to 60 meters to compare radiometry of the images at a common spatial resolution. However, when the image pixels from each sensor are aggregated to 60 meters to compare the radiometry, IKONOS presents a considerably higher radiometric resolution. When the Landsat and IKONOS scenes were aggregated, the radiometric resolution increased to roughly 0.05% reflectance for the Landsat 7 data, and 0.0002% reflectance for the IKONOS data (see table 2). Finding the radiometric resolution after aggregation was

Table 2 - Landsat 7 and IKONOS 60 meter radiometric resolutions, in % reflectance

	Band 1	Band 2	Band 3	Band 4
Landsat 7	0.04303	0.04718	0.04351	0.06651
IKONOS	0.00023	0.00019	0.00024	0.00025

simply a matter of dividing the difference between the minimum and maximum
reflectance by the new quantization per each band.

The IKONOS observations, when aggregated to 60 meters, provided a change
in reflectance (Δ_) of ~ 0.0002%. Given this measurement precision, the IKONOS data
can be viewed as "truth", that is to say this is about as fine a level of radiometric
precision as one can hope to achieve currently with satellite land remote sensing
technology (Goward et al., 2003a).

Data Selection

The goal when choosing images was to find two images that were as similar as
possible. Several issues were considered to achieve such similarity:

Phenology

First, and the most obvious consideration, was to find two images that were
from the same time in the growing season. Given that Landsat 7 has a much more
robust archive than IKONOS, it was easier to simply choose an adequate IKONOS
image and then to find a compatible Landsat 7 image that was nearly time-coincident.
Both images were late in the growing season, with Landsat 7 being acquired September
30, 1999 and the IKONOS image being acquired on October 10, 2000. In addition, by
visual inspection, in neither of these images did the vegetation appear to have started to
senesce.

View Angle

It was imperative to pay attention to view angle because if the two sensors
looked at the same scene from quite different view angles, the radiance reaching the

sensors would have had different radiometric results, causing questionable results. Spatial related problems, such as bi-directional reflectance and parallax, could easily occur. Take, for example, both sensors viewing a scene in the principle plane of the sun, one having the sun behind the viewer and the other having the sun in front of the viewer. In such case, the sensor is viewing the scene from two totally different perspectives, with the first sensor having backscatter and the latter having forward scatter; the radiance reaching the platform will be different. Another view angle problem that could occur is parallax. This occurs when a sensor is viewing far off-nadir and besides seeing the target from above, the target is also being viewed at its side. In this study, parallax was not an issue because the IKONOS image had an off-nadir viewing angle of 6.7 degrees and the Landsat image was viewed off-nadir even less at 5 degrees. With both sensors viewing the land surface at similar angles as well as the sun azimuth and elevation being alike (see table 3), the two datasets had very comparable radiance reaching the sensor.

Cloud-Cover

An ideal scene pair would have little or no cloud contamination, either cloud or shadow. In this study, visual inspection was employed to insure cloud-free imagery since there were not many things that could be done to correct this problem if it was present. After receipt of the images, they were subjected to further digital enhancements to evaluate for presence of haze or cirrus contamination. Neither image appeared to have much haze contamination.

Data Selected

The data selected for this study was fairly easy to find mostly attributed to a

large archive of data for both sources. The three main concerns were all accounted for

and the criteria for selecting images were all met. As seen in table 3, all scene

collection variables are analogous.

Table 3 - Landsat 7 and IKONOS scene collection details.

	Acquisition Date	Projection/ Datum	Pixel Size	Sun Azimuth	Sun Elevation	Off-Nadir
Landsat 7	9/30/1999	UTM, WGS84	28.5 meters	150 degrees	45 degrees	5 degrees
IKONOS	10/10/2000	UTM, WGS84	4 meters	158 degrees	43 degrees	6.7 degrees

Analysis Methods

Developing Comparable Observations

A study of radiometric resolution can be complicated when two of the sensors

being compared have different spatial resolutions. To isolate the comparison between

sensors' spectral resolution and not spatial resolution, both datasets were aggregated to

60 meters, which is an even integer of both an IKONOS and a Landsat 7 pixel.

Radiometric resolution is a combination of sensor system noise and the number of

quantizing levels present in the sensor system (Tucker, 1980). When aggregations of

pixels occur, the system noise is reduced by $(1/N)^{1/2}$, where N is the number of pixels

being averaged (Schott, 1997: 352). When pixels are aggregated the resultant bit level

quantization is no longer the original quantization (8-bits for Landsat 7 and 11-bits for

IKONOS), but something more.

Aggregation affects quantization such that when the data are averaged, the

resultant data has values falling between the original steps, so the average data step size

is reduced. For example, the Landsat 7 data were aggregated such that 4 pixels became

1 pixel (2*2). By doing that (in floating point), the step size was reduced from 1 DN to

_ DN, which increased the quantization by 2 bits, raising its original quantization of 8-

bits to 10-bits. For IKONOS, the aggregation was much more dramatic, with 225

pixels becoming 1 pixel, and the original quantization of 11-bits increased to a new

level of 18.8-bits. For this reason, this study is not a comparison of 8-bits versus 11-

bits, but a comparison of lower quantization of Landsat 7 versus the much higher

quantization of the IKONOS satellite.

Spatial Aggregation

In order to accurately compare the radiometry between IKONOS and Landsat 7,

spatial aggregation was required. There are several methods, such as nearest neighbor

or cubic convolution resampling, used in remote sensing to resize and align pixels. In

such methods, either the closest neighboring pixel value is taken or a weighted average

method is employed. For this study, since the attempt was to approximate the

integrated reflected energy, it was decided to utilize the approach of aggregation where

an average of all surrounding pixels is used equally. Since it was necessary to take

both datasets to a common geometric resolution that was in simple integer units of each

other, both datasets were aggregated to 60 meters. Not only did this make each pixel

spatially comparable, but it also reduced the noise in the data and minimized the

modulation transfer function (MTF) effect (Brian Markham, personal communication).

Since it is important not to loose precision in the aggregation process; before the

aggregation was done, the digital numbers were converted into floating point data. The

process of making it floating point was done so when aggregated, the results did not

undergo the negative effects of rounding a DN up or down so it is a whole number, but rather gave the result with more precision. If the aggregation was not done in floating point, the increased radiometry due to aggregation would have been lost.

Georegistration

Georegistration is necessary any time a comparison is being done between two sets of images. This was pertinent to the study because if georegistration was not accomplished before any comparative analysis was done between the scenes, it was possible (and likely) that the pixel in one scene was not at the same geographic position the other one was in the other scene. It is very easy to think that change is happening between the pixels, but in reality, it is just a result of looking at two different locations. Although geodetic ground accuracy is very good for both IKONOS and Landsat 7, to be absolutely sure that the pixel location and alignment where as close as possible, georegistration was needed. The image-processing software that was employed for georegistration was ENVI, version 4.1. Nine ground control points (GCP's) were selected in an image-to-image manner and the root mean square error (RMSE) was 0.209223. The IKONOS image was used as the base, the warping method was RST (Rotation, Scaling, Translation), and the resampling was done by cubic convolution. After georegistering the two images to one another, the Landsat image was subset to the size of the IKONOS image since all further studies were based on the subset.

Radiometric Calibration

Although many remotely sensed data are distributed and analyzed in Digital Numbers (DN's), DN's are not suitable for comparative analysis (Goward et al., 2003b). This is especially the case when the comparison is between differing sensors.

In simple terms, DN's are what radiance the sensor is receiving from the ground, with no attention given to sensor and solar geometry differences. To overcome this hurdle, there are two steps that need to be taken with the digital numbers. The first step was calculating to radiance, which transformed the data into comparable physical units. The second step was calculating to reflectance, which compensated for different incident solar irradiance. With ETM+, the equations used for calculating to spectral radiance and surface reflectance were simply found in the Landsat Data User Handbook (LPSO, 1998). On the other hand, Space Imaging supplies their calibration constants in the form of documents found on the internet (Peterson et al., 2000; Peterson, 2001), or often times they can be found more easily in published papers (Goward et al., 2003b*).* Calibration equations used for both sensors are listed in table 4.

Table 4- Calibration equations used for IKONOS and Landsat 7

IKONOS

From DN to Radiance

$L_\gamma = (DN/Cal. Coeff/10)/(Bandwidth/1000)$
Band 1- B1/63.3/0.0713
Band 2- B2/64.9/0.0886
Band 3- B3/84.0/0.0658
Band 4- B4/74.6/0.0954

To Reflectance (283 Julian Day, solar zenith = 46.64)
$P_p = (\pi*L_\gamma*d^2)/(ESUN_\lambda*\cos\theta_s)$
Band 1- $(\pi*L1*0.996)/(1939.429*0.68658)$
Band 2- $(\pi*L2*0.996)/(1847.400*0.68658)$
Band 3- $(\pi*L3*0.996)/(1536.408*0.68658)$
Band 4- $(\pi*L4*0.996)/(1147.856*0.68658)$

Landsat 7

From DN to Radiance

$L_\gamma = ((LMAX_\gamma - LMIN_\gamma)/Q_{cal\ max}) * Q_{cal} + LMIN_\gamma$
Band 1 - $((191.6 - -6.2)/255) * B1 + -6.2$
Band 2 - $((196.5 - -6.4)/255) * B2 + -6.4$
Band 3 - $((152.9 - -5.0)/255) * B3 + -5.0$
Band 4 - $((157.4 - -5.1)/255) * B4 + -5.1$

To Reflectance (273 Julian Day, solar zenith = 44.31)
$P_p = (\pi*L_\gamma*d^2)/(ESUN_\gamma*\cos\theta_s)$
Band 1 - $(\pi*L1*1.002)/(1970* 0.71557)$
Band 2 - $(\pi*L1*1.002)/(1843* 0.71557)$
Band 3 - $(\pi*L1*1.002)/(1555* 0.71557)$
Band 4 - $(\pi*L1*1.002)/(1047* 0.71557)$

Visual Inspection

Initially, by just visually comparing the two datasets at their aggregated

resolutions, I originally thought that the differences being seen were due to increased

precision between pixel values (figure 5). This would show that without doing

anything quantitative to the data, a scene could be displayed with more precision with

IKONOS than with Landsat 7. Looking closely reveals that contrary to there being

more gray values displayed with IKONOS than with Landsat, the Landsat 7 data is

simply smoothed, whereas the IKONOS data has not been. What appears to be more

"gray values" in the data is just a mirage. In the processing of the data, after the two

datasets where aggregated to 60 meters, the Landsat 7 scene was georegistered to the

IKONOS scene and the pixels were warped by cubic convolution resampling. The

observable fact that is being seen in figure 5 is not a difference in precision, but rather
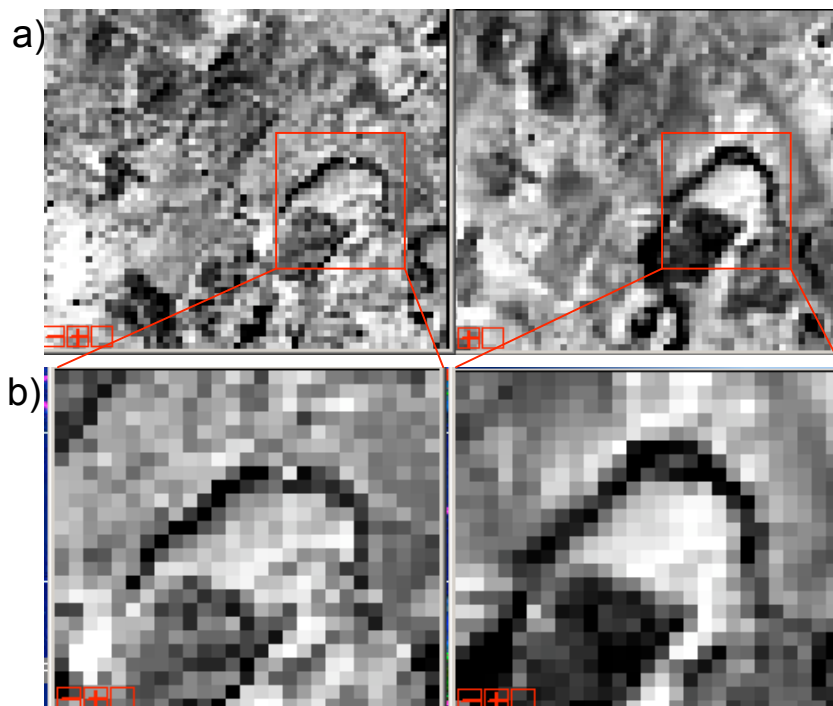
the smoothing effect that is due to the resampling method.

Figure 5- a) IKONOS (left) and Landsat 7 (right) full image at 60
meters b) IKONOS and Landsat 7 zoomed in. Near Infrared band used.

Principal Components

To obtain more information about the dimensionality (# of bands needed to get usable data) of the data, a Principal Components analysis was performed to both the IKONOS and Landsat 7 scenes. As expected, each dataset was narrowed down to only two important components, with the first two principal components for IKONOS comprising over 98% of the variability in the scene and the two first principal components for Landsat 7 comprising over 99% of the variability in the scene. However, the other two principal components left in each scene were more interesting to the study. For IKONOS, although only the first two principal components were statistically significant, there was still some interesting imagery (extra radiometry) left in the 3rd and 4th components (figure 6). As for Landsat 7, after the two primary
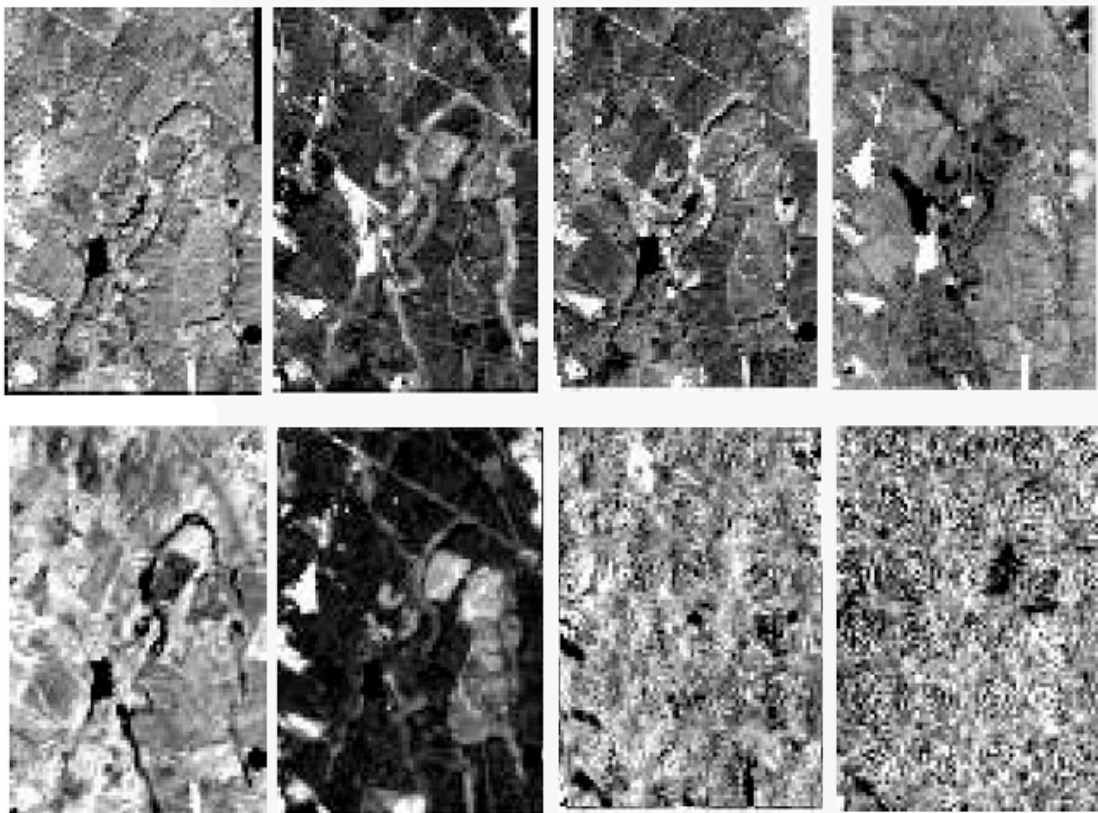

Figure 6 - Principal Component bands 1-4 for IKONOS (above) and Landsat 7 (below) at 60 meters.

components were made, there just was not enough spare radiometry in the data for anything visible in the other two components (figure 6).

Scatterplots

Scatterplots are a graphical way to see how closely the two images approximate each others' reflectances. With scatterplots, it is also very easy to visually see how much of one images' reflectance correlates to the other images reflectance. Ideally, if both sources of data have all the same image collection factors (including pixel sizes, spectral responses per band, filter characteristics, etc.) and imaged with the same solar geometries and atmospheric conditions, then the scatterplots should be along the 1:1 line with no variance along that line (ie. r^2 of 1). Deviations from that 1:1 line and subsequent variances reflect differences between the data being compared, and can be used to make inferences about the similarity or differences being observed.
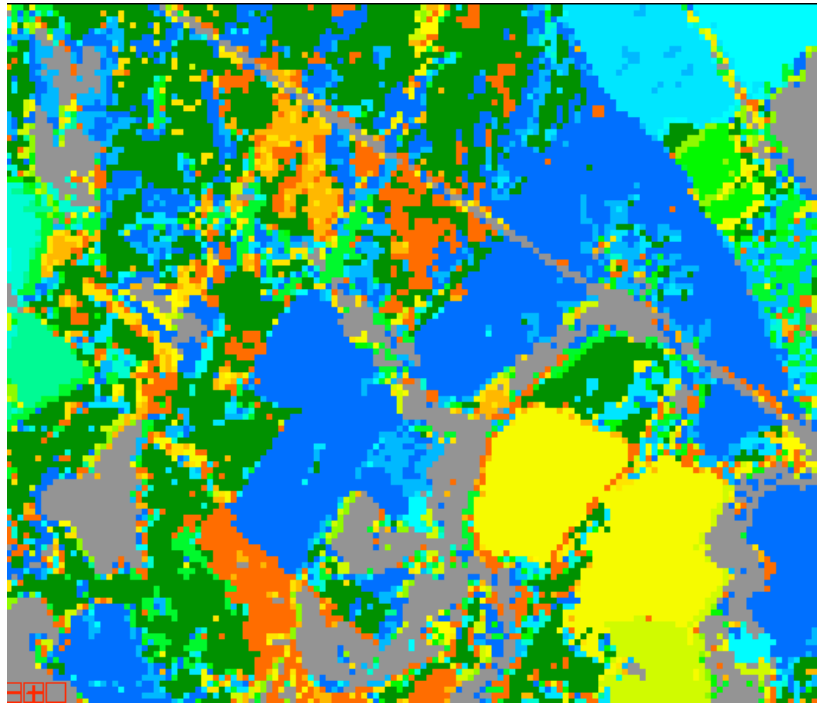
Image Differencing

Image differencing was performed between the aggregated images to see if there was more detail that could be seen by the higher resolution IKONOS over Landsat 7. This method of image differencing is rather simple and visually very explanative. By doing a simple image difference, and controlling for factors such as forest variability, seasonality, and differing sensor characteristics, it should have been possible to deduce the difference in the radiometry that was due solely to varying radiometric precision. This was accomplished by selecting areas in the paired IKONOS and Landsat 7 images that have been stable, and by selecting spectral bands that were most similar. The paired images were not corrected for atmospheric differences, so it was accepted that this could also be a contributor.

Correlations to Disturbance

As stated previously, the goal of this study was to determine whether higher radiometric resolution data could provide more information for forestry remote sensing than the readily used Landsat 7 standard of 8-bits. The most assured way to determine this was to look at the imagery and see if you can see more detail in the higher radiometric resolution data that cannot be observed in the lower radiometric resolution data.

Earlier in this paper, it was explained how one of the major goals of this study was to determine if higher radiometric resolution data could discriminate more attributes of a forest, like biomass, canopy closure, age variations, etc. than could lower resolution data. In this study, to determine age variation, a disturbance map for the area was used (see Appendix I for creation method) showing when areas in the image have been clear cut (see figure 7). By having the disturbance data available, it was known at what stage of regrowth certain patches were at within the image. By knowing the date when certain patches were disturbed in the imagery, it was simply a matter of resolving if we could see those patch age gradations better in the higher resolution IKONOS data than can be seen in the lower radiometric resolution Landsat 7 data.
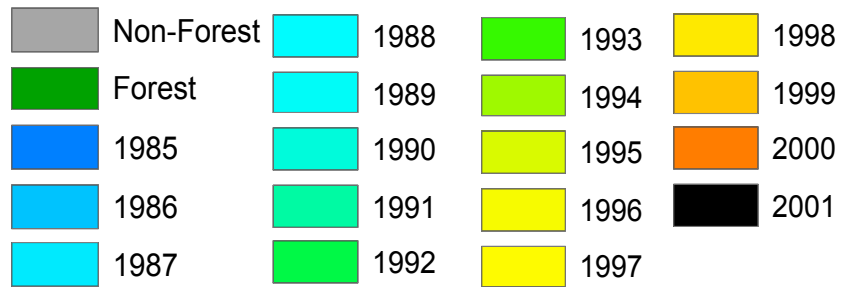
Year Disturbed

Non-Forest	1988	1993	1998	
Forest	1989	1994	1999	
1985	1990	1995	2000	
1986	1991	1996	2001	
1987	1992	1997		

Figure 7 – Disturbance map of area

CHAPTER V: RESULTS

The goal of this study was to evaluate the necessity of higher radiometric

resolutions in measuring forestry information.   To answer the question of whether

higher resolution data are needed to evaluate forestry would be a significant

improvement to our present understanding of bit-quantization. The design of the study

was to determine if more information could be found in higher resolution data

compared to lower resolution data. More specifically, the question of whether Landsat

7 has sufficient quantization, or if the higher resolution IKONOS satellite is better for

forestry studies was posed.

Scatterplots

At the aggregated resolution of 60 meters, the scatterplots (see figure 8) show

that ETM+ and the IKONOS data closely approximate each other's reflectance,

especially for bands 1-3 (visible bands). In those cases, IKONOS reflects slightly

higher than ETM+. In band 4 (NIR), the opposite occurs where not only does the

reflectance deviate more so than in the visible bands, but in this band, the Landsat 7

ETM+ sensor records higher values. Although this could be problematic when making

a comparison between the data sources, especially if the Normalized Difference

Vegetation Index (NDVI) is being used, these results had been seen in previous studies

and the source of this difference is known. It can be attributed to the fact that these two

sensors do not have identical spectral band passes (figure 9), and consequently do not

provide exactly the same spectral radiance values (Goward et al., 2003b).   For this

study, where the effect of higher radiometric resolution was being observed for forestry

remote sensing, what was of more interest though was the distribution of points (r^2

value) for each band. Bands 1-3, the r^2 value was around 0.5. This means that about _ the spectral radiance was explained and the other half was unknown.

As explained above, one cause could have been that the IKONOS and Landsat 7 sensor do not have exactly the same spectral response curves. Another cause could have been seasonality, but with the acquisition dates only being ten days apart, this was assumed not a big contributor to the difference. Things that are not included, but also could have been causal were the fact that these images were acquired one year apart or differing atmospheric conditions during acquisition. The rest of the variance that was not due to seasonality or different spectral responses was caused by 60-m aggregated IKONOS having higher radiometric resolution than the 60-m aggregated Landsat 7 data. With this metric of using scatterplots it is hard to quantify what the difference is, but combined with other test, it says concretely that there are differences between the data sources.
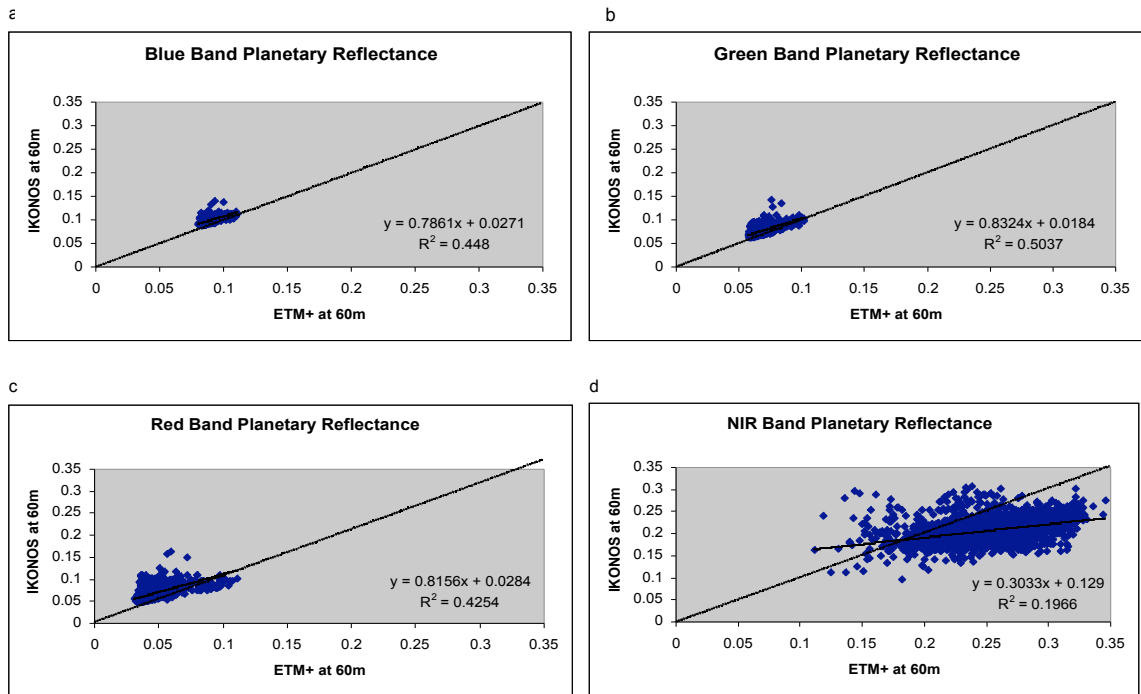
Figure 8 - Scatter plots of IKONOS and Landsat 7 ETM+ at 60 meters. a) band 1- Blue b) band 2-Green c) band 3- Red and d) band 4- Near Infrared.
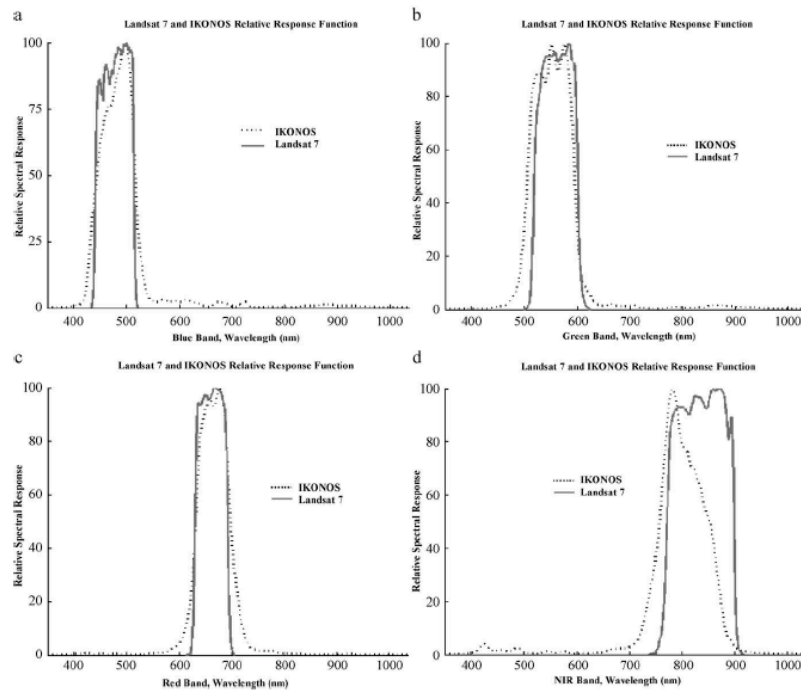

Figure 9 - Relative spectral response functions for Landsat 7 ETM+ and IKONOS a) blue spectral band, b) green spectral band, c) red spectral band and d) near infrared spectral band. Note the differences particularly for the red and near infrared bands.

Image Differencing

One way to quantify how much of the signal difference was due to a difference in radiometric resolution was by doing image differencing. By being careful to pick areas in the scene that have not changed between the two successive years, it should have been possible to quantify the change that was due to differing quantization. Since the green band has the highest r^2 value (see figure 8) between the data and close spectral response curves (see figure 9), this band was chosen to first work with.

By doing an image difference over the whole image and using band 2 (green) statistics, the histogram showed that IKONOS is approximately 2% (0.02) brighter than the Landsat 7 image for this location (see figure 11a), as was previously noted in the scatterplots. However, this varies between –3% and - 1%, which indicates that there are other differences between the data. Additionally, as can be seen in figure 10, three areas that represented the most stable areas in the image were chosen. For each of the stable areas, the change algorithm was again run and the change was 1-2 % (see the histograms in figure 11 b,c,d). This would mean that after all the processes to equalize the datasets; there still is roughly 1-2% difference between the images. This difference was initially thought to be due to differing radiometric resolutions, but after further thought, it was determined that it cannot be due solely to this difference.

Since the radiometric resolution after aggregation for Landsat 7 was roughly 0.05% reflectance and 0.0002% for IKONOS (table 2), it is impossible to have 1-2% of the variability being attributed to radiometric resolution. Based on these radiometric resolutions, there is a theoretical limit to how much of the variability can be due to varying quantization. The result does not make theoretical sense- the difference in

radiometric resolution can only account for no more than roughly 0.04% of the difference. With the amount calculated to be 1-2%, there is some other attribute of the data that is having most of the influence.

The same analysis was done for the red band (figure 12) and again, the same results were concluded. As can be seen in figure 9, this band has the closest spectral response curves. Although this band does not have as close an r^2 value (see figure 8), the results were similar. Over the whole image, IKONOS is again about 2% brighter and varies between –3% and 0%, or 3% more variable than the Landsat data. By looking at the peak of the curve, you see how the data reflection (ie. brightness) compares to that of the opposing data, and by looking at the spread, you can see the variance between the datasets. Furthermore, looking at the stable forest sites, again there is 1-2% difference and again, it is above the theoretical limit, so therefore the difference must be due to some other factor or factors of the data.

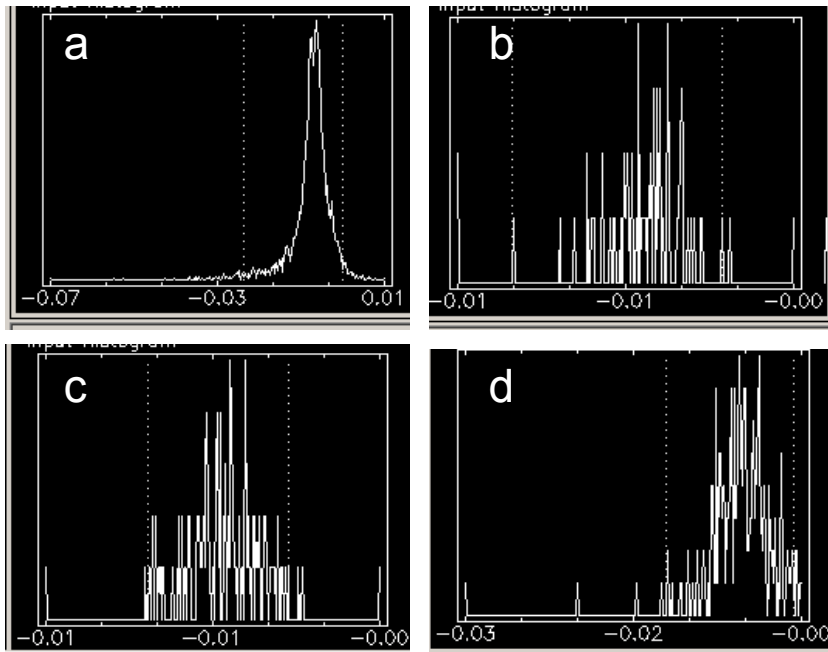**Figure 10-** Three most stable chosen areas

Figure 11 - Histograms of image difference for a) whole image and b,c,d) stable image subsets using band 2 (green) statistics.
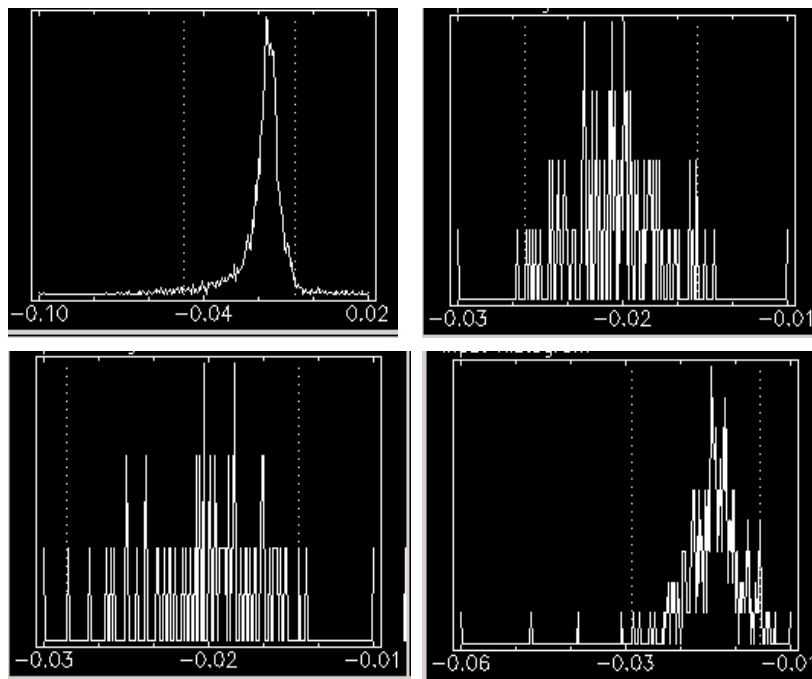

Figure 12 – Histograms of image difference for a) whole image and b,c,d) stable image subsets using band 3 (red) statistics

Disturbance Assessment

The most definitive way to determine if the increased radiometric resolution was beneficial for forest remote sensing was by looking at the imagery and considering if it was possible to discriminate more meaningful differences that correspond to physical attributes in one dataset over the other. For this study, a disturbance map (figure 7) that shows in what year a forest stand was cleared for timber was used to make that judgment. The easiest way to determine this was to look at boundaries in the disturbance map and then see if those boundaries could be seen in the imagery.

When looking at the imagery and comparing it to the disturbance map, however, it was not evident there was an advantage of using one data type over the other in locating boundaries. Take for example figure 13, where there are adjacent stands that were disturbed in 1985, 1987, and 1993. In such area, IKONOS did not seem to be any better than Landsat 7 in differentiating the different stands. There did appear to be a difference between the images, but it was not radiometry related. The cause of the visual difference was once again, a smoothing effect of the Landsat 7 data, much like what was observed in figure 5. This effect was caused by a methodology mishap. As said previously, the first thing that was done to the data was aggregation of both datasets to 60 meters, and after that the data was georegistered and warped. Doing it in this order was a mistake because after the data was aggregated, the data was then georegistered to improve coregistration. In the warping process, following the georegistration, the Landsat 7 pixels were resampled by cubic convolution, which negated the aggregation and smoothed the pixels. The reason why Landsat 7 had this

appearance and not IKONOS is because IKONOS was used as the base image, so only

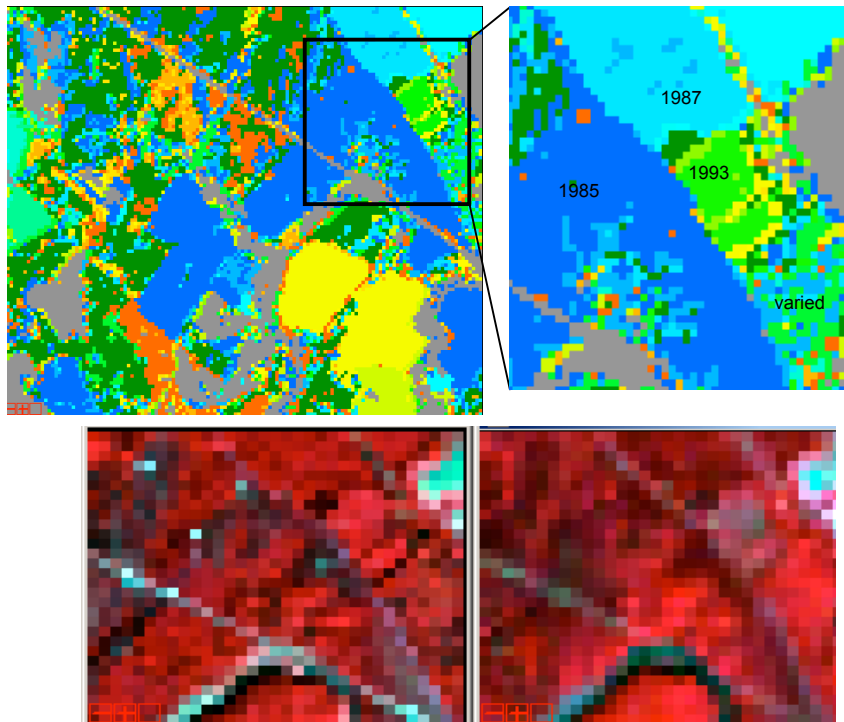the Landsat 7 imagery underwent cubic convolution resampling.

Figure 13 – Disturbance map above with zoom-in on right. Bottom left is IKONOS at 60 meters and bottom right is Landsat 7 at 60 meters. In this example it is hard to notice any difference in the ability to determine boundaries between the imagery. Band combination for the imagery is near-infrared, red, green.

To see the results per band, the imagery was displayed separately for the green,

red, and near-infrared to see if the disturbance could be seen in one band more easily

than in another band (figure 14). Again, what was initially thought to be more

variability displayed in each band of the IKONOS data was in fact not true, and can be

verified by looking at the scatterplots (see figure 15) of the two data sources. The

scatterplots show almost identical variability in each of the three bands selected. This

means that what was thought to be differences in the visual inspection of the

disturbance map was something else.

To double check, I selected the bottom right corner of the disturbance map of the near-infrared band in figure 14 (see figure 16). Visually, it appears that in IKONOS there certainly are more gray values, whereas in the Landsat 7 subset, it looks like there are only a few color variations. Again, though, when looking at the scatterplots of the imagery, it becomes apparent that they produce similar results. If there was truly less Landsat 7 radiometry in the image as is appears, then when looking at the scatterplots of the data, there would be more "binning" of the data for Landsat 7 than for IKONOS. This is a one of those perfect examples of lying with imagery. It certainly was not the intention to distort or skew the results by presenting the results visually, but when analyzed using statistics instead of visual subjectiveness, the truth becomes apparent.
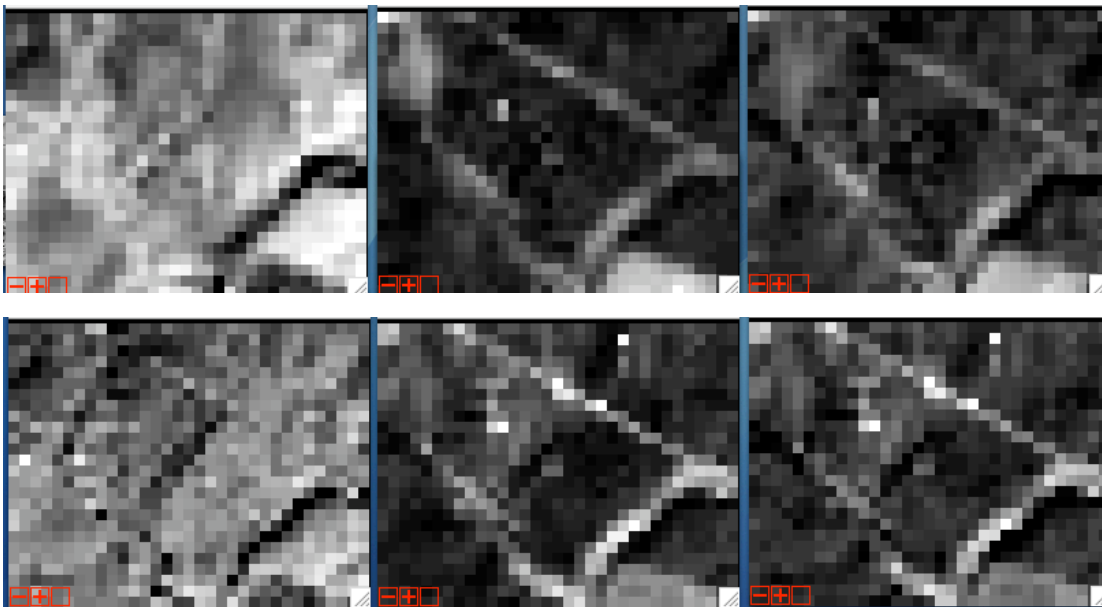

Figure 14 – Disturbance map in near-infrared (left), red (middle), and green (right). Landsat 7 (upper row) and IKONOS (lower row)
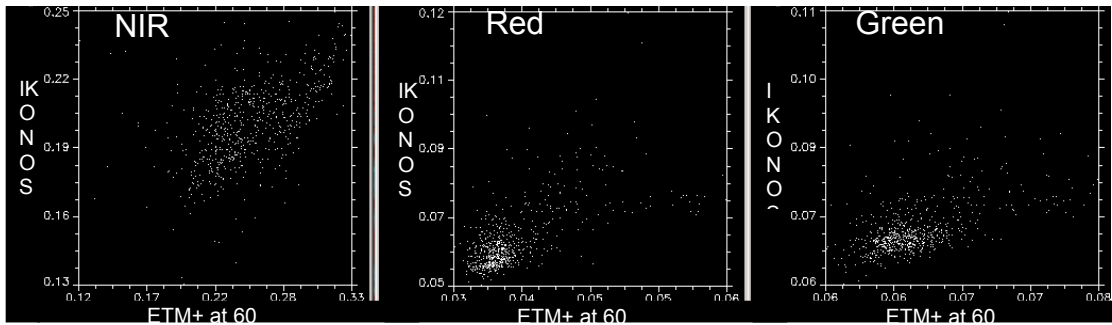
Figure 15 – Scatterplots, in % reflectance, of image subsets that were used in disturbance map.

Discussion

This study was accomplished with the motivation to learn of the enhanced

abilities that higher resolution, higher quantized data can provide for monitoring forest
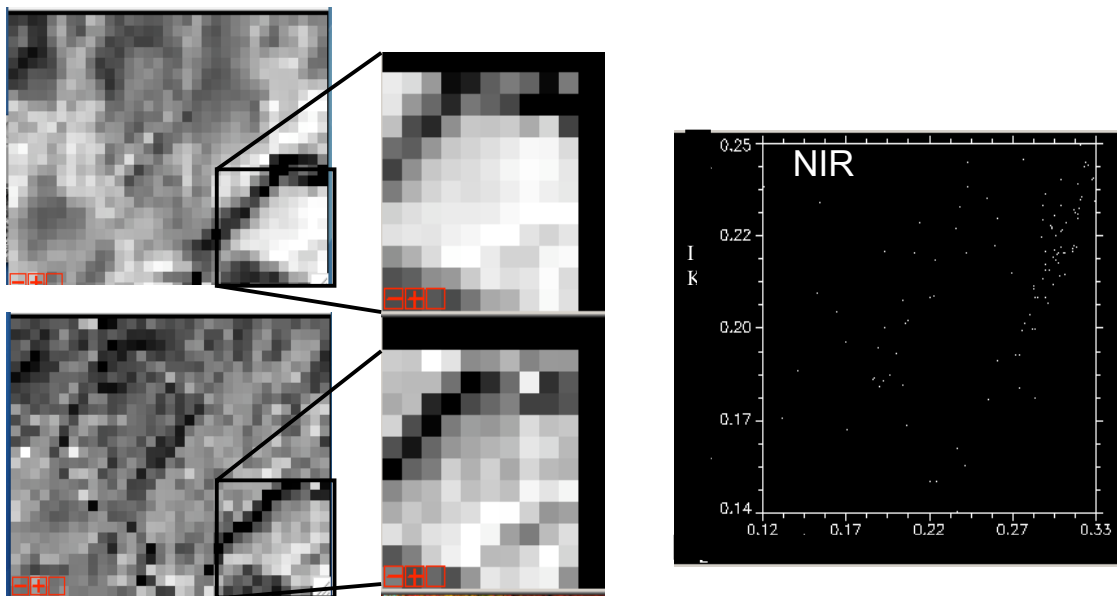

Figure 16 – Zoom-in on the area that visually looks different and the associated scatterplot of the data that quantitatively shows similarity.

resources.

Overcoming issues for comparability

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An initial concern was bi-directional reflectance (BRDF) for the IKONOS image because of its ability to view so far off of nadir view. If the sun and view angle where not similar to one another, BRDF would have been a concern producing differences in the observations (Walthall, Norman, Welles, Campbell, & Blad, 1985). The first IKONOS image that was considered, luckily, only had a off-nadir view angle of 6.7 degrees, which matched well with the paired Landsat 7 image that was viewed off-nadir 5 degrees. Additionally, the sun azimuth and sun elevation angle were also very close (see table 2).

Spoken about previously, there are differences in the spectral band passes for these two sensors, especially for the near infrared band. This differentiation appears to originate from the differing spectral band pass that the two sensors have. The part of the electromagnetic spectrum that these instruments are designed to detect in can be very problematic if they are not considered. For this study, the problem was easily handled by avoiding using the near infrared band for direct comparisons, like in the case of image differencing.

Additional considerations when choosing data sources for forestry remote sensing

Although this study was only interested in radiometric resolutions for forestry analysis, other characteristics of the sensors should not be overlooked when considering which satellite to use for analysis. One such example is the available bands that a remote sensing system can detect in. In the case of Landsat 7, there are six reflective bands; whereas with the IKONOS sensor, it only has four reflective bands that correlate most closely to the first four bands of Landsat 7, respectively being Blue, Green, Red,

40

and Near-Infrared. The fact that the IKONOS sensor lacks these additional reflective

bands is important to the ability to detect forestry information (Goetz et al., 2003: 205).

Price (1984) showed in a study that compared the Thematic Mapper (TM) sensor to the

older Multispectral Scanner Sensor (MSS) that Landsat TM bands 5 and 7, in respect to

their ability to distinguish change, are superior to the shorter wavelength bands 1, 2,

and 3. IKONOS, much like the MSS sensor, lacks those two longer wavelength bands.

The same can also be said for spatial resolution. IKONOS having a much

higher spatial resolution, at 4 meters, is considerably finer than Landsat 7's 30 meter

multispectral resolution. For forestry analysis, and most analysis in general, having

increased spatial definition is advantageous for discriminating features, especially when

those features are smaller, like some patches of forest in Europe or the eastern United

States. In the Legleiter et al. (2002) study, the authors showed that in fact, having

increased spatial resolution is more beneficial than having increased radiometric

resolution. A good example is in the above section where correlations to disturbance

were made. If IKONOS was being looked at in its full resolution (like in figure 10), it

would be much easier to distinguish the boundaries, while at its aggregated resolution it

was not always easy. Once again, building the best sensor not only is restricted by

download capabilities and cost, but is dependant on the mission of satellite.

CHAPTER VI: SUMMARY AND CONCLUSIONS

Over the course of this study, there were some issues that came up that were insurmountable and others that came up where the methodology was incorrect. Given the results, it is not possible to determine whether "more bits are better".

One issue that was brought up by the committee reviewing the paper was that when looking at figure 14, where the disturbance maps were being compared in the separate bands, it appeared that there was a difference in the Landsat 7 image from the IKONOS image that did not appear to be radiometry related. It looked as if the Landsat 7 imagery had some smoothing affect. After talking about the methodology, the order in that the processing was done caused a large problem.

Another issue that was noticed that led to the results of this study being inconclusive was the amount by which the variability (1-2%) was shown in the histograms of the image differences. Since the radiometric resolution after aggregation for Landsat 7 was roughly 0.05% reflectance and 0.0002% for IKONOS (table 2), it is impossible to have 1-2% of the variability being attributed to radiometric resolution.

Although in this study the spatial resolutions were equalized by aggregating both datasets to 60 meter, it would be most favorable to use datasets with more similar native resolutions. It was noticed in this study that aggregating the spatial resolution is not independent from affecting the radiometric resolution and changing one of the resolutions by a large degree also drastically affects the other. Perhaps the best way to test the effects of varying radiometric resolutions is to use the same dataset from the same sensor, aggregate by several different factors, and then make comparisons. Doing it in this manner would eliminate all factors that can cause comparison problems.

An inclusive result is still a result that can be learned from. In doing such a comparison of data types, one must be very careful what attributes are being manipulated and every consequence of that manipulation needs to be fully understood. Unfortunately, in this study, not all of those consequences were totally understood. Additionally, what is learned from this study is that there are limits to what barriers can be overcome. These two datasets, although both having similar mission goals, have too large of differences to equalize.

CHAPTER VII: APPENDIX

I.   Disturbance map produced by Chengquan Huang, University of Maryland
        Geography Department.

For each image, dating from 1985 to 2001, core mature forest pixels were selected and the mean and standard deviation were calculated for the six Landsat 7 reflective spectral bands. The Euclidean distance was calculated to the core forest pixels using the mean values and the normalized standard deviation values. Then, for each pixel, the temporal profile was analyzed for each created index value for the 1985-2001 period, and a large jump in the index value indicated the occurrence of a disturbance.

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