NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

VEGETATION IDENTIFICATION WITH LIDAR

by

Michael F. Helt

September 2005

Thesis Advisor:	R.C. Olsen
Second Reader:	Alan Ross

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE: Vegetation Identification With LIDAR			**5. FUNDING NUMBERS**
6. AUTHOR(S) Michael F. Helt			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT

LIDAR data taken over the Elkhorn Slough in Central California are analyzed for terrain. The specific terrain element of interest is vegetation, and in particular, tree type. Data taken on April 12th, 2005, were taken over a 10 km × 20 km region which is mixed use agriculture and wetlands. Time return and intensity were obtained at ~2.5 m postings. Multi-spectral imagery from QuickBird was used from a 2002 imaging pass to guide analysis. Ground truth was combined with the orthorectified satellite imagery to determine regions of interest for areas with Eucalyptus, Scrub Oak, Live Oak, and Monterey Cyprus trees. LIDAR temporal returns could be used to distinguish regions with trees from cultivated and bare soil areas. Some tree types could be distinguished on the basis of the relationship between first/last extracted feature returns. The otherwise similar Eucalyptus and Monterey Cyprus could be distinguished by means of the intensity information from the imaging LIDAR. The combined intensity and temporal data allowed accurate distinction between the tree types, and task not otherwise practical with the satellite spectral imagery.

14. SUBJECT TERMS Identifying vegetation with LIDAR			**15. NUMBER OF PAGES** 83
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

VEGETATION IDENTIFICATION WITH LIDAR

Michael F. Helt
Captain, United States Marine Corps
B.A., Kent State University, 1996

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
September 2005

Author: Michael F. Helt

Approved by: R.C. Olsen
Thesis Advisor

Alan Ross
Second Reader

Rudy Panholzer
Chairman, Department of Space Systems
Academic Group

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

LIDAR data taken over the Elkhorn Slough in Central California are analyzed for terrain. The specific terrain element of interest is vegetation, and in particular, tree type. Data taken on April 12th, 2005, were taken over a 10 km × 20 km region which is mixed use agriculture and wetlands. Time return and intensity were obtained at ~2.5 m postings. Multi-spectral imagery from QuickBird was used from a 2002 imaging pass to guide analysis. Ground truth was combined with the orthorectified satellite imagery to determine regions of interest for areas with Eucalyptus, Scrub Oak, Live Oak, and Monterey Cyprus trees. LIDAR temporal returns could be used to distinguish regions with trees from cultivated and bare soil areas. Some tree types could be distinguished on the basis of the relationship between first/last extracted feature returns. The otherwise similar Eucalyptus and Monterey Cyprus could be distinguished by means of the intensity information from the imaging LIDAR. The combined intensity and temporal data allowed accurate distinction between the tree types, and task not otherwise practical with the satellite spectral imagery.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

Special Thanks to

Dr. R.C Olsen,
Angela Puetz,
&
Eric Van Dyke

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. PURPOSE OF RESEARCH

A major element of maneuver warfare is mobility. Without it, ground forces are unable to reach their objective and complete the mission. There are many factors that influence the mobility of ground forces such as terrain, existing roads, weather, natural and manmade obstacles, etc. One of the many potential impediments to mobility is vegetation. The vegetation of the battlefield is often studied in great depth in order to determine how it will have an effect on the off-road movement of vehicles and personnel.

The remote study of vegetation is often inconclusive and inaccurate when conducting mobility studies since much of the desirable data is hidden beneath the treetops. This is especially true when studies are conducted using satellite or unmanned aerial vehicle photogrammetric images.

The use of LIDAR systems can perhaps reveal much of the information hidden amongst the foliage and identify treetop heights and foliage density.

This can potentially be taken one step further and give the ability to identify species of vegetation by using the statistical characteristics of the foliage. With the dimensions and types of vegetation known, the tree trunk girth or diameter can be estimated. Mobility analysis will be much more accurate and areas can be more easily designated as go or no-go for wheeled and tracked vehicles.

B. OBJECTIVE

The objective of this thesis is to determine if different types of vegetation can be identified using a combination of satellite imagery and LIDAR data. This will be accomplished using a 2002 QuickBird image and a LIDAR mapping survey of the Elkhorn Slough Wetland area north of Monterey, California.

II. BACKGROUND

A. LIDAR (LIGHT DETECTION AND RANGING)

LIDAR or LIght Detection And Ranging is the optical analogue to the more familiar Radar or Radio Detection And Ranging. The primary difference is that the radiation used by LIDAR is laser light with wavelengths that are 10,000 to 100,000 times shorter than that used by conventional radar; usually from the ultraviolet to the infrared wavelength[1].

LIDAR uses pulses of laser light striking the surfaces of the earth or intended target and measuring the time of pulse return. The time of the pulse return is then translated into distance[1], Figure 1.

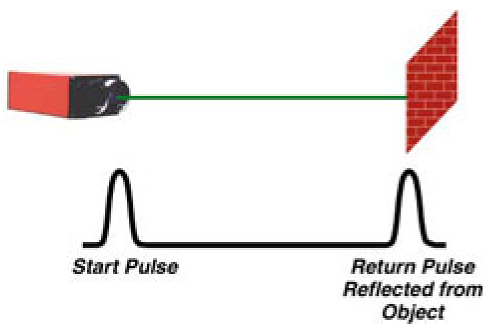

Figure 1. Simple LIDAR Example, Pulse Return

LIDAR systems also have the capability to capture intensity of the reflected data in addition to the x-y-z coordinates. Reflectance percentage values differ depending on the type of surface they hit (i.e. snow may reflect 90%, black asphalt 5%), and are called LIDAR intensities. This data may be processed to produce a geo-referenced raster file, which is ortho-metric and looks somewhat like a conventional image. These images are useful for identification of broad land use and serve as additional data for post-processing[1].

The LIDAR laser scanner can be mounted on the bottom of an aircraft (similar to an aerial camera) along with an Inertial Measuring Unit and Airborne GPS, Figure 2. The basic components of a LIDAR system are a laser scanner and cooling system, a Global Positioning System (GPS), and an Inertial Navigation System (INS). The laser scanner that is mounted in an aircraft emits infrared laser beams at a high frequency. The scanner records the difference in time between the emission of the laser pulses and the reception of the reflected signal. A mirror is mounted in front of the laser. The mirror rotates and causes the laser pulses to sweep at an angle, back and forth along a line. The position and orientation of the aircraft is determined using a phase differenced kinematic GPS. Several ground stations (differential GPS) are located within the area to be mapped. The orientation of the aircraft is controlled and determined by the INS[1].

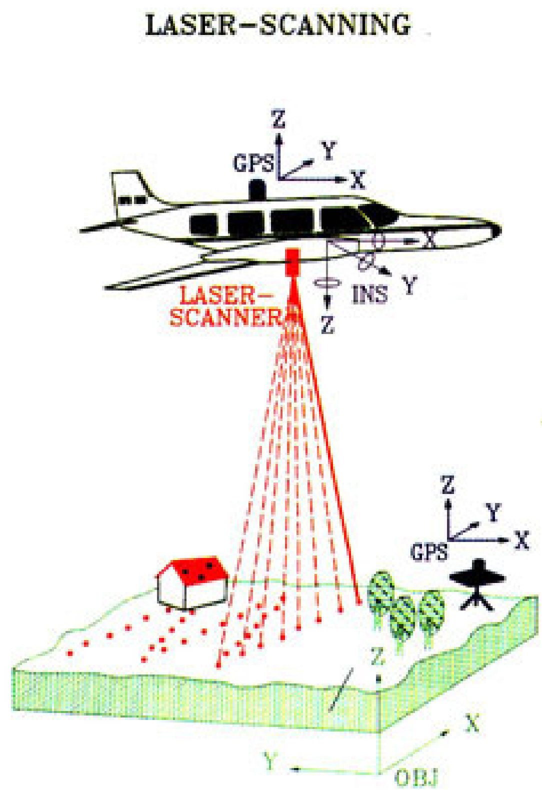

Figure 2. LIDAR Scanner Example (From: http://www.sbgmaps.com/LIDAR.htm)

Current LIDAR systems are capable of a laser repetition rate of 25,000-50,000 pulses per second. In addition to rapid pulsing, modern systems are able to record up to five returns per pulse as illustrated below, Figure 3. The laser pulse sometimes hits more than one object on its trek to the earth's surface. For example, it may pass through a vegetation canopy, touching leaves or branches before finding its way to the ground[1].

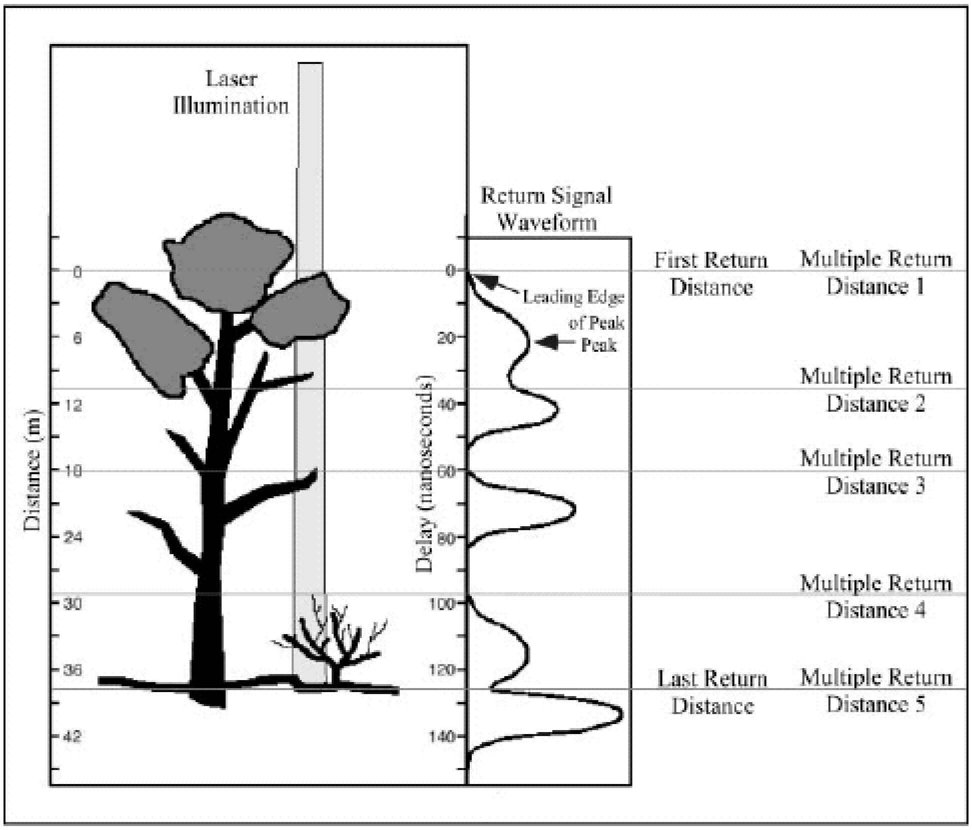

Figure 3. Example of a Multiple Return LIDAR Pulse (From: LIDAR Remote Sensing for Ecosystem Studies; MICHAEL A. LEFSKY, WARREN B. COHEN, GEOFFREY G. PARKER, AND DAVID J. HARDING)

These data sets are then available for high-resolution contour production, and bare-earth surface evaluations. This data provides the capability for LIDAR to distinguish not only the canopy and bare ground but also surfaces in between (such as a forest structure and under story). For example, in urban areas, the first pulse return (or 1st return) of LIDAR data measures the elevations of the canopy, building roof elevations, and other unobstructed surfaces. Depending on the surface complexity (variable vegetation heights, terrain changes, etc.), the data sets can be remarkably large: 200,000 points per square mile in suburban terrain, 350,000 points per square mile in forestland[1].

B. ADVANTAGES OF LIDAR

The advantages of using LIDAR, instead of traditional photogrammetry for topographic mapping pushed research to develop high-performance systems. LIDAR technology offers the opportunity to collect terrain data of steep slopes and shadowed areas such as the Grand Canyon and inaccessible areas such as large mud flats and ocean jetties[1].

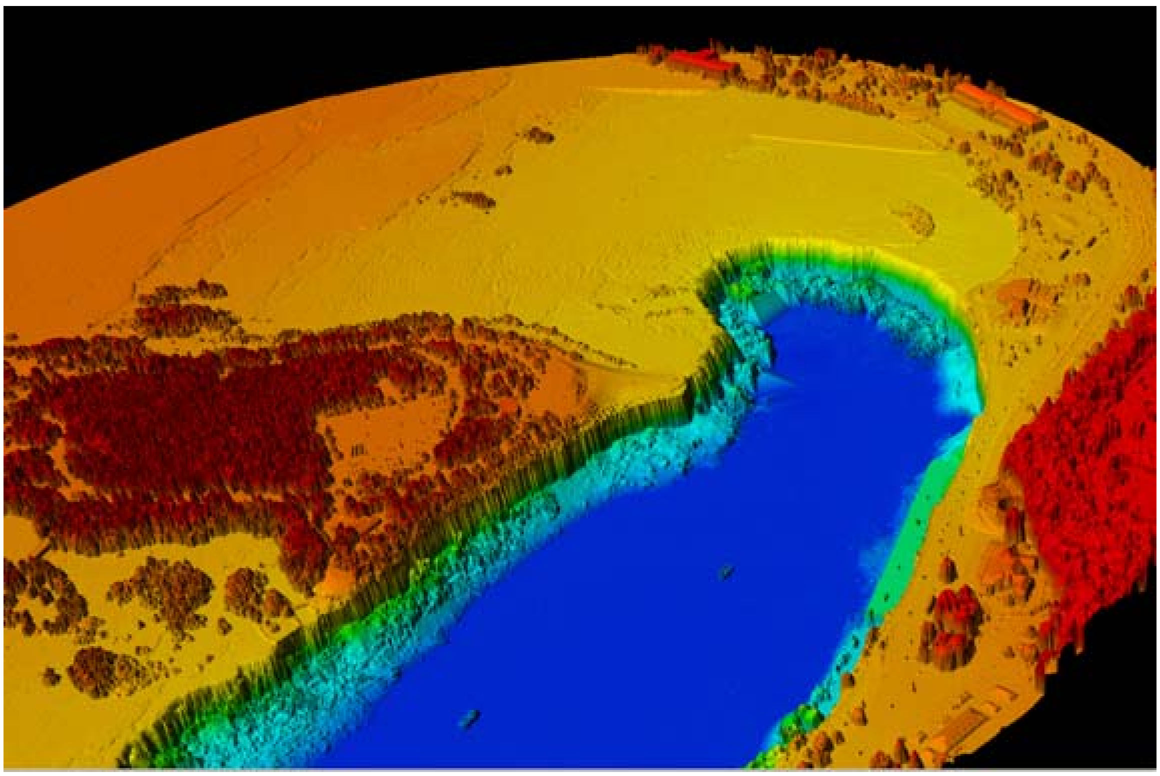

Figure 4. LIDAR Image of Niagara Falls (From: Optech Incorporated)

These LIDAR applications are well suited for making digital elevation models (DEM), topographic mapping, and automatic feature extraction, Figure 4. Applications are being established for forestry assessment of canopy attributes, and research continues for evaluation of crown diameter, canopy closure, and forest biometrics. Additional uses for wireless communication design, coastal engineering and survey assessments, and volumetric calculations are demonstrating the value of LIDAR data collection[1].

C. LIDAR VERSUS OTHER METHODS

Other methods for acquiring terrain elevation data include leveling, photgrammetric-derived contouring and radar. All of these approaches are expensive, and have limitations. Leveling is the traditional way of using surveyors on the land. This method is extremely expensive and takes an incredibly long time. It can provide high-resolution results, but is not practical for large area applications[4].

Photogrammetric-derived contouring is the current method used by the US Geological Survey (USGS) to create their digital elevation models (DEMs) which cover most of the United States. Optical photographs, often still from film systems, are analyzed using stereo parallax to build the DEM. The resolution of the DEM depends on the image resolution, but standard USGS Photogrammetric-derived contouring DEMs have a horizontal resolution of 30 meters and a vertical accuracy of 15 meters or better. Such specifications are insufficient for floodplain management[4].

Imaging radar data can be used to create digital elevation models in the same way optical systems are used, but generally not to any great accuracy. More recently, Interferometric Synthetic Aperture RADAR (IFSAR) approaches have been used[4], Figure 5.

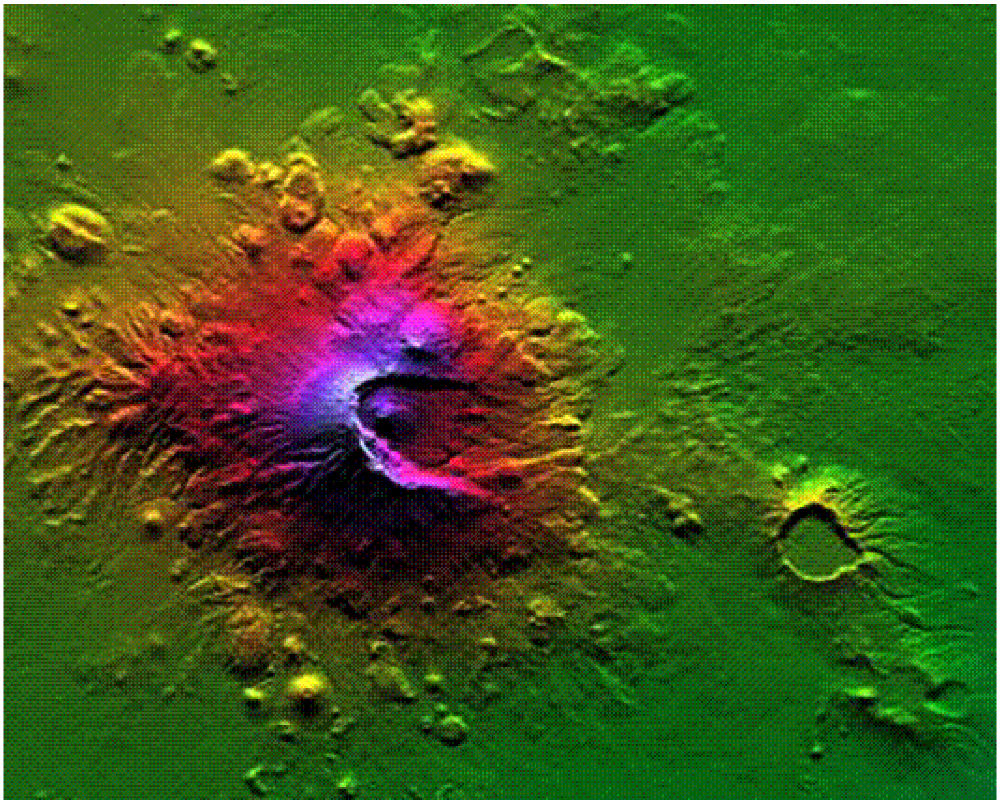

Figure 5. Interferometric Synthetic Aperture RADAR (IFSAR) Image of Mount Meru, Tanzania Taken by the Shuttle Radar Topography Mission (SRTM) (From: http://srtm.usgs.gov/)

IFSAR, uses the phase difference between two SAR images to calculate elevation, and accuracies of 10's of cm are possible. Current civilian radar satellites have relatively poor spatial resolution, however, and offer a horizontal resolution of 10-30 m. The longer wavelength of radar waves provides an advantage vis-à-vis LIDAR, because radar wavelengths can penetrate clouds and more vegetation than LIDAR[4].

D. MILITARY APPLICATIONS OF LIDAR

There are many LIDAR applications for military use. Mobility is a critical element of war fighting and maneuver warfare; mobility estimates can be challenging with standard aerial or satellite images. Since LIDAR has the ability to produce high-resolution digital elevation models, it can be extremely helpful in determining the slope and contour of avenues of approach.

Vegetation can be a potential natural obstacle to military movement. Typically, trees with a trunk diameter of approximately 8 inches and larger will impede the movement of an M1-A1 Abrahams Armored Tank. LIDAR data can estimate treetop height and perhaps tree trunk girth with its capability to receive multiple returns per pulse.

Before the start of Operation Iraqi Freedom, it was believed that the Iraqi Military Engineers were going to destroy several dams in order to flood large parts of the country significantly hindering movement of U.S. and allied forces. Many studies were completed to determine where the flood zones would be. These studies proved to be quite challenging and somewhat inaccurate due to the lack of precise digital elevations models. A LIDAR system mounted on a UAV (unmanned aerial vehicle) might have significantly reduced effort and inaccuracies in these studies.

III. THESIS

A. CAN LIDAR IDENTIFY TYPES OF VEGETATION?

The purpose of this thesis is to determine if LIDAR systems in conjunction with satellite imagery have the ability to distinguish between different types of vegetation.

Modern LIDAR systems have the ability to receive multiple returns per pulse. This capability not only gives the height of the vegetation, but also characteristics between the tops of the vegetation and the ground. This capability in conjunction with the intensity return can potentially enable the identification of types of vegetation. For example: The Hawthorn Tree in the figure below (left) should give multiple uniform returns from the treetop to the ground, Figure 6. The Palm Trees seen in the figure below (right) should give multiple returns from the treetop to a short distance down and then there should be a large void of returns between that and the ground, Figure 6.

The techniques that will be tested in this thesis include physically locating groups of vegetation species through on-the-ground site surveys and analyzing their foliage characteristics with the LIDAR data.

Vegetation can be characterized based on the density of its canopy or foliage affecting the ability of the LIDAR pulse to reach the bare earth. Foliage density is a relative value comparing the quantity of returns that are permitted to impinge on the bare earth.

Figure 6. Hawthorn Tree (left) Palm Trees (right) (From: http://www.domtar.com/arbre/english/p_aubep.htm www.stevedibler.com/ photos/Florida/Palm_trees)

Another method that will be used to identify different types of vegetation with LIDAR data is the foliage dispersion that will be compared with various types of vegetation. Each type of tree should have a characteristic range of foliage height that includes tree top height and foliage height above ground.

The foliage density and dispersion will be the two methods to statistically analyze and differentiate various types of vegetation with the LIDAR return data.

The LIDAR intensity of the multiple returns will be an additional technique for vegetation identification. Intensities are indicative of foliage densities and will be used to support conclusions derived from the initial LIDAR intensity analysis.

IV. AIRBORNE 1

Airborne 1 Corporation, located in El Segundo, California was contracted to conduct a LIDAR mapping survey of the Elkhorn Slough Wetland area north of Monterey, California in April of 2005. The figure below depicts the flight lines mapped by Airborne 1, Figure 7.

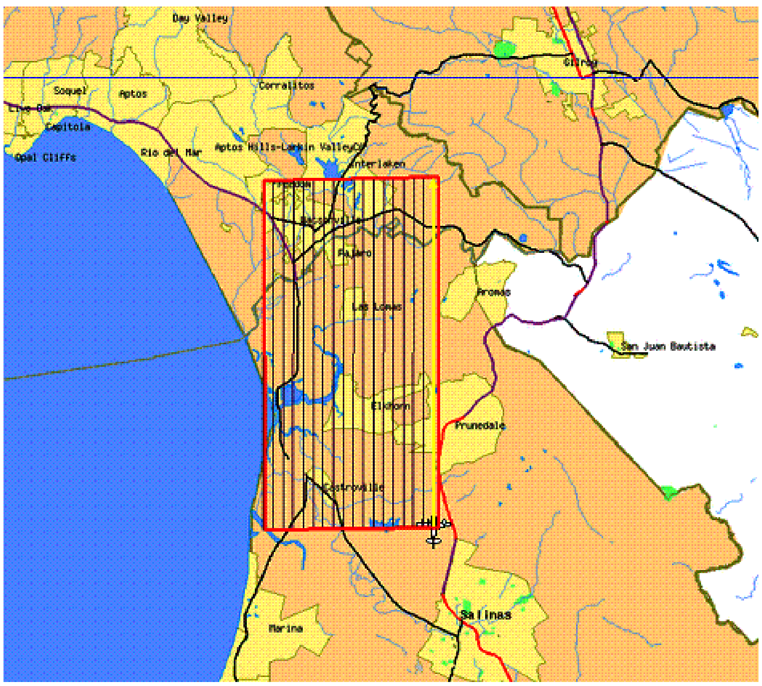

Figure 7. Location of LIDAR Mapping Survey(From:Airborne 1)

A. OPTECH ALTM (AIRBORNE LASER TERRAIN MAPPER) 2025

Airborne 1 utilized the Optec ALTM (Airborne Laser Terrain Mapper) 2025 in their aircraft in the mapping survey of the Elkhorn Slough. The ALTM 2025 collects 25,000 pulses per second and records 4 returns per pulse. An intensity value is also recorded for each return. The

ALTM 2025 operates in the near infrared spectrum at 1064nm and therefore is not visible with the naked eye.

Figure 8. Optech ALTM (Airborne Laser Terrain Mapper LIDAR) System (From: Optech.ca)

Operating altitude	250 - 2,000 m nominal
Elevation accuracy	15 cm at 1,200 m; 25 cm at 2,000 m (1 sigma)
Range resolution	1 cm
Scan angle	Variable from 0 to ± 20°
Swath width	Variable from 0 to 0.68 x altitude
Scan frequency	Variable, depends on scan angle; e.g., 28 Hz for ± 20° scan
Horizontal accuracy	Better than 1/2,000 x altitude
GPS receiver	Novatel Millennium
Laser repetition rate	25 kHz
Beam divergence	Variable, 0.2 mrad (1/e) or 1.0mrad
Laser classification	Class IV laser product (FDA CFR 21)
Eye safe range	250 m @ 1.0 mrad, 550 m @ 0.2 mrad nominal
Power requirements	28 VDC, 35 A
Operating temperature	10 - 35° C
Humidity	0 - 95% non-condensing

Table 1. Optech ALTM 2025 Specifications (From: Optech)

B. RAW DATA DELIVERED FROM AIRBORNE 1

The raw data that Airborne 1 provides consists of an X and Y coordinates and for each X, Y coordinate, the corresponding Z data that includes the four return values and four intensity values. This data is contained in a LAS file

Files conforming to the ASPRS LIDAR data exchange format standard are named with an LAS extension. The LAS file is intended to contain LIDAR point data records. The data will generally be put into this format from software (provided by LIDAR hardware vendors) which combines GPS, IMU, and laser pulse range data to produce X, Y, and Z point data. The intention of the data format is to provide an open format which allows different LIDAR vendors to output data into a format which a variety of LIDAR software vendors can use. Software that creates the LAS file will be referred to as “generating software”, and software that reads and writes to the LAS file will be referred to as “user software” within this specification[8].

The format contains binary data consisting of a header block, variable length records, and point data. All data is in little-endian format. The header block consists of a public block followed by variable length records. The public block contains generic data such as point numbers and coordinate bounds. The variable length records contain variable types of data including projection information, metadata, and user application data[8].

In order to make the information in the LAS file useful, it is necessary to process it so that it can be used in imagery analysis software such as ENVI 4.1

THIS PAGE INTENTIONALLY LEFT BLANK

V. LIDAR DATA PROCESSING

An IDL code written by Prof. R.C. Olsen was used to read information from the .las file header, and to extract x, y, z and intensity values for each of the LIDAR pulse returns. For each of the four LIDAR returns, a set of 4 binary files was created to contain the x, y, z and intensity values. Separate files were created for each value in order to mitigate problems with byte ordering issues when switching between Windows and UNIX based systems[6].

A second IDL code was written to regrid the irregularly gridded LIDAR data into a regular grid. Due to the extremely large size of the LIDAR data set, a Sun SunBlade 1000 workstation was used. (This is where the byte-ordering issue first appeared.) The 'gridding' of the data was accomplished using IDL's 'triangulate' and 'trigrid' routines. This IDL code produced an image band and an ENVI header file[6].

From IDL Online Help for the triangulation procedure, "The TRIANGULATE procedure constructs a Delaunay triangulation of a planar set of points. Delaunay triangulations are very useful for the interpolation, analysis, and visual display of irregularly gridded data. In most applications, after the irregularly gridded data points have been triangulated, the function TRIGRID is invoked to interpolate surface values to a regular grid[6]."

One of the parameters that can be set in the trigrid routine is the number of pixels in the x and y directions. These values were calculated using the min and max x and y

LIDAR coordinates. The LIDAR data was provided in a UTM projection system, with a North America 1983 datum. UTM coordinates are in units of meters, and a 2.4-meter pixel spacing was desired to match the resolution of the QuickBird imagery. Therefore, the range of x was divided by 2.4 to figure the number of pixels in the x direction. The number of pixels in the y direction was figured the same way. Since this was not always an integer number, some rounding occurred, and therefore the pixel size was not actually 2.4 meters. The actual pixel size recorded in the header file was calculated by dividing the range in the x / y direction by the number of pixels in the x / y direction[6].

Each LIDAR return was processed separately. In the original LIDAR data, the numbers of pulses for each return are not equal, meaning that there are not 4 returns from every spatial location. This became a problem in a few cases where the min x spatial location was different, which led to some output images covering a smaller spatial area. To fix this, the original LIDAR data was modified by adding one ‘point’ so that the min x spatial location was the same for every pulse return image. This forced the trigrid routine to interpolate values for the same spatial area for each pulse return. The synthetic point was given a z value equal to the nearest LIDAR pulse return[6].

After each pulse return image was created, the same process was used to create an intensity image for each pulse return. These 8 separate image bands were combined into one image using ENVI’s ‘save as’ feature[6].

The last processing step involved using ENVI’s mosaic tool to combine three sections of the LIDAR image into one large image covering the Elkhorn Slough area. Using the ENVI mosaic wizard, images were imported and arranged according to their geographic coordinates. The 3 image sections overlap by about 1000 m. The edges of the overlapping sections were ‘feathered’ together using the first and last 20 rows of the image sections. 20 rows correspond to approximately 48 meters. The image sections were re-sampled using the ‘nearest neighbor’ technique, and the output pixel size was set at 2.4 x 2.4 meters[6].

THIS PAGE INTENTIONALLY LEFT BLANK

VI. IDENTIFYING VEGETATION WITH LIDAR PULSE RETURNS

A. FOUR RETURNS PER PULSE -BANDS 1,2,3, AND 4

The Optech ALTM 2025 LIDAR System operates at 25,000 pulses per second and records four light returns per pulse. Pulses are saved as bands 1, 2, 3, and 4. An intensity value is also recorded for each return. The four bands are further classified into the first and last return of the extracted features, usually leaves, bands 3 and 1 respectively, and first and last return of the bare earth, bands 4 and 2 respectively, Table 2. Each return is recorded with an X,Y, and Z value. The X and Y are typically recorded as latitude and longitude and the Z as elevation above sea level.

The product of these four bands is a digital elevation model (DEM) with terrain and extracted feature elevation. Embedded within the terrain and extracted feature elevation are intermediate returns of the vegetation.

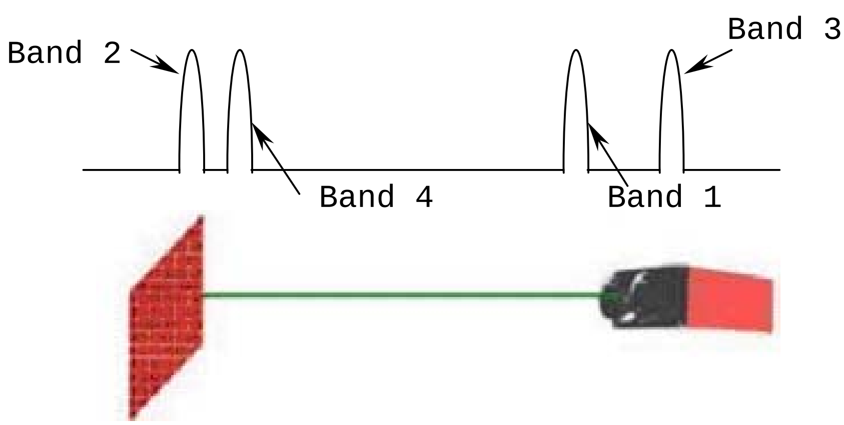

Figure 9. Four Returns per LIDAR Pulse are Recorded as Bands 1,2,3 and 4

Extracted Feature Last Return	Band 1
Bare Earth Last Return	Band 2
Extracted Feature First Return	Band 3
Bare Earth First Return	Band 4

Table 2. Four LIDAR Returns; Bands 1,2,3, &4

B. SELECTED AREA OF INTEREST

Depicted below are two images of the area of interest, Figure 10. On the left is a QuickBird Satellite image and to the right is a two-dimensional digital elevation model of the same area.

Figure 10. Visible Image Taken from QuickBird 2002 (left) LIDAR DEM of same area April 2004 (right)

Below is the same DEM in a three dimensional configuration, Figure 11. The LIDAR DEMs depicted illustrate the terrain contours very well, however the more pronounced terrain differences minimize the characteristic of the vegetation.

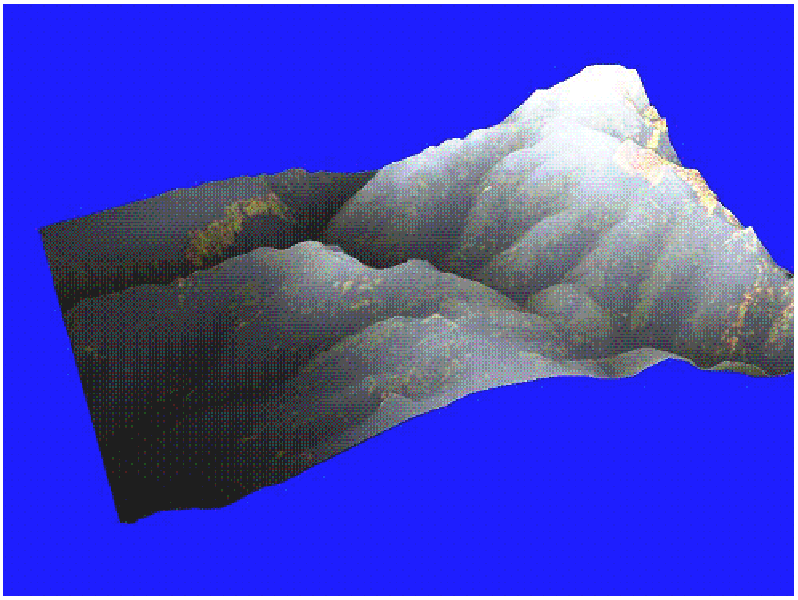

Figure 11. 3 Dimensional Digital Elevation Model of Area of Interest

C. REMOVAL OF DIFFERENCES IN ELEVATION OF TERRAIN

In order to highlight and concentrate on the vegetation it is necessary to eliminate the differences in the terrain and maintain the differences between the vegetation and the bare Earth. This is accomplished by subtracting the extracted feature last return (band 1) from the bare earth last return (band 2) and subtracting the extracted feature first return (band 3) from the bare earth first return (band 4). This will create two additional bands, Relative Last Return and Relative First Return. When plotted, these two bands will create a separate image that will depict only the vegetation heights above the bare earth.

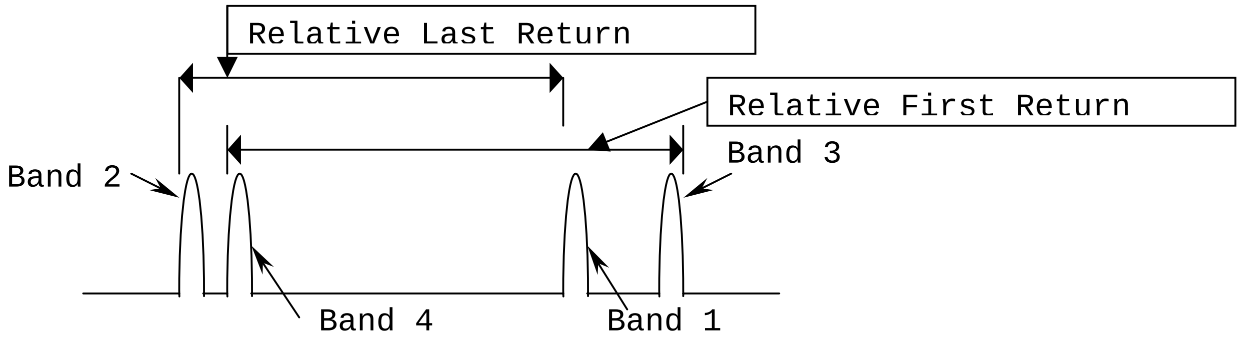

Figure 12. Differences in Terrain Removed in Order to Depict Vegetation Elevations Above Bare Earth

The figure shown below, illustrates 2 and 3 dimensional images taken from the same area of interest of vegetation heights above the ground with the differences in terrain elevation eliminated, Figure 13.

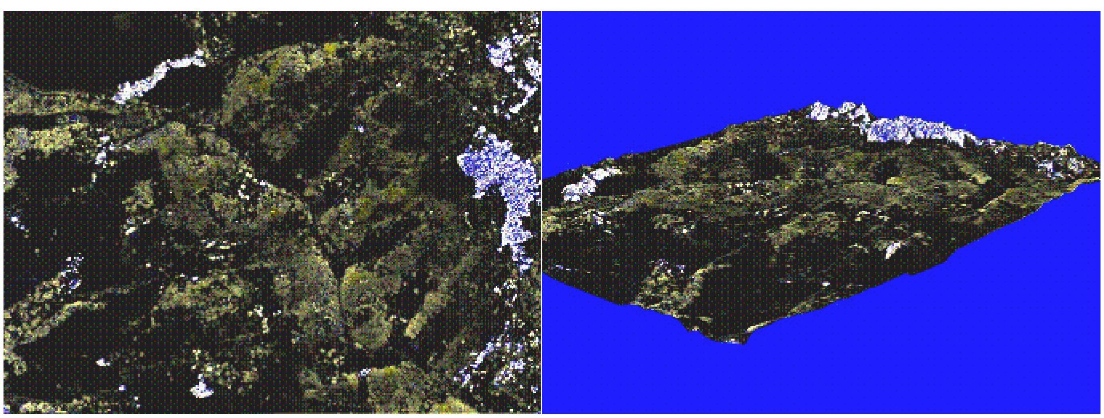

Figure 13. 2 Dimensional (left) and 3 Dimensional (right) Image of Vegetation Height Above Bare Earth

The area of interest depicted below has been thoroughly examined though several site surveys in order to identify various types and locations of vegetation, Figure 14. It has been discovered that there are three predominant types of trees in this area. They are the Eucalyptus Tree (Eucalyptus globus), California Scrub Oak

(Quercus dumosa), and the California Live Oak (Quercus agrifolia). These three species of trees are very abundant in this area and commonly grow in groups. Locations of groups of these trees have been verified by site surveys and are shown below, Figure 14. Common traits will be exploited to differentiate between these three types of trees.

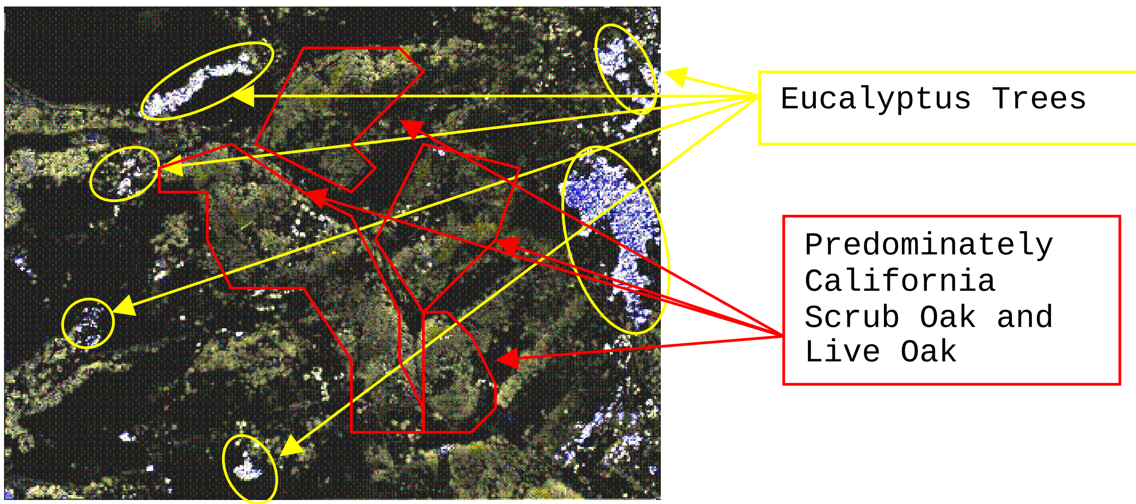

Figure 14. Confirmed Locations of Eucalyptus Trees and California Scrub and Live oaks

In order to gather baseline characteristics of various types of vegetation it was necessary to accurately locate groups of known species through several site surveys. The LIDAR data was then used to highlight these known locations of known species to determine baseline characteristics such as foliage height, foliage height range, foliage density, and intensity return. These known values were then used to locate vegetation with similar parameters in the LIDAR data. These locations were later checked by additional site surveys to see if they held that type of tree.

D. TYPES OF VEGETATION

1. California Scrub Oak (Quercus dumosa)

The California Scrub Oak is the smallest of the three trees in this area, growing up to three meters in height. Its foliage is thick compared to the Eucalyptus tree and ranges from about 0.25 to 3 meters above the ground, Figure 15.

Figure 15. California Scrub Oak (Quercus dumosa)

Several known locations of California Scrub Oaks were analyzed with the LIDAR data. The Relative First Return and Relative Last Return values of the Scrub Oak were used to analyze the characteristics of the vegetation. The histogram below shows the foliage dispersion of the California Scrub Oak, Figure 16. The average height of the foliage is about 1.4 meters above the ground and the maximum height is around 3 meters. The range of 0.25 to 3 meters will be used later to highlight regions of potential California Scrub Oak.

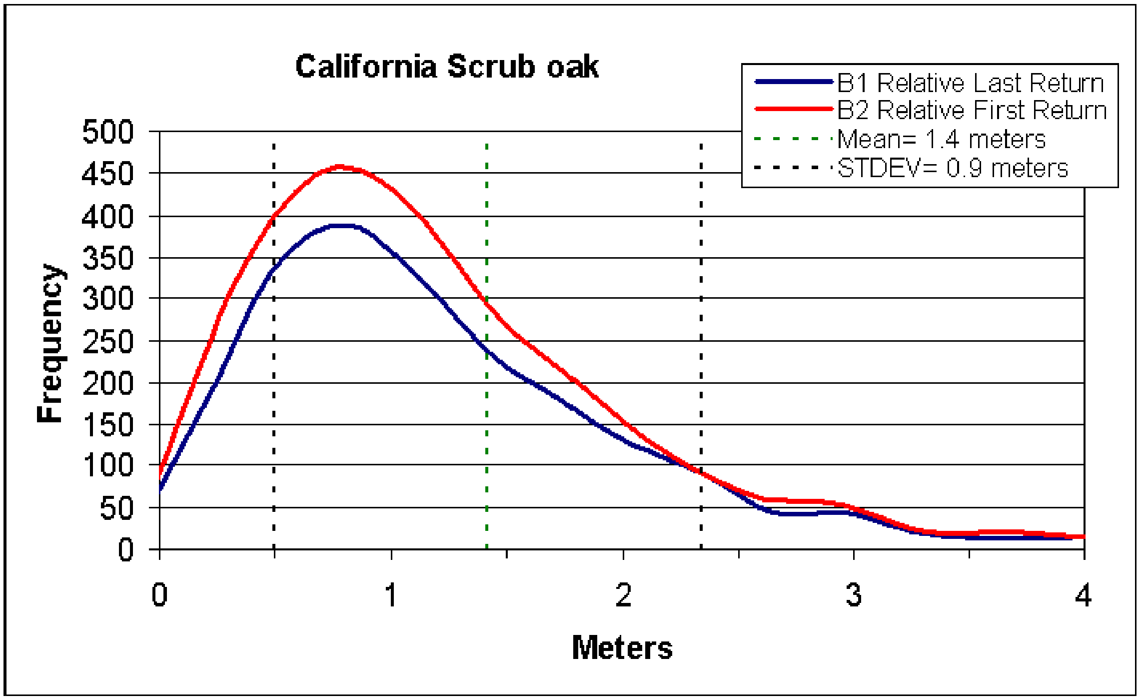

Figure 16. Histogram Depicting the Dispersion of California Scrub Oak Foliage, Relative Last Return and Relative 1st Return Each Contain 2070 Data Points

2. California Live Oak (Quercus agrifolia)

The California Live Oak is similar to the California Scrub Oak except it can grow to heights of 20m. It also has thick foliage compared to the Eucalyptus tree and usually ranges from about 3 to 14 meters above the ground.

Figure 17. California Live Oak

Several known locations of California Live Oaks were analyzed with the LIDAR data. The Relative First Return and Relative Last Return values of the Live Oak were used to analyze the characteristics of the vegetation. The histogram below shows the foliage dispersion of the California Live Oak, Figure 18. The average height of the foliage is about 7.25 meters above the ground and the maximum height is around 14 meters. The range of 3.0 to 15 meters will be used later to highlight regions of California Live Oak.

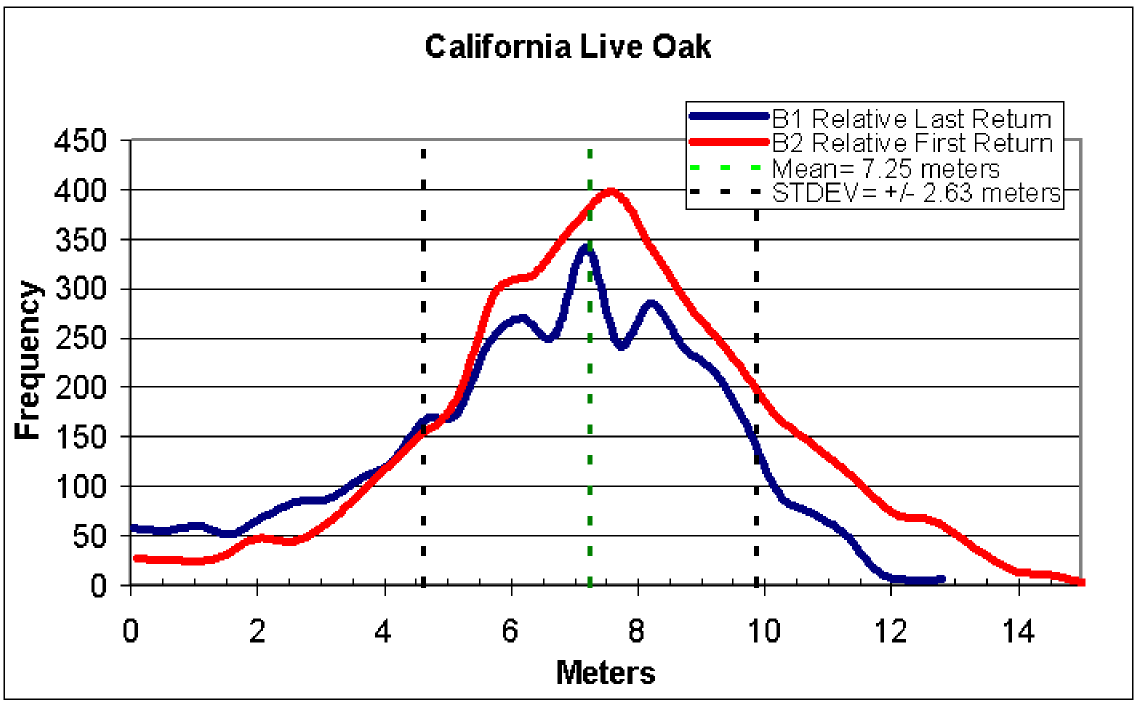

Figure 18. California Live Oak Foliage Dispersion Histogram, Relative Last Return and Relative 1st Return Each Contain 3530 Data Points

3. Eucalyptus Tree (Eucalyptus Globus)

The Eucalyptus tree is the tallest of the three trees in the area of interest. It can grow to heights of up to 70 meters and its foliage is relatively sparse compared to the California Oak Trees. Its foliage usually ranges from about 15 to 35 meters above the ground.

Figure 19. Eucalyptus Tree (Eucalyptus Globus)

Several known locations of Eucalyptus Trees were analyzed with the LIDAR data. The Relative First Return and Relative Last Return values of the Eucalyptus Trees were used to analyze the characteristics of the vegetation. The histogram below shows the foliage dispersion of the Eucalyptus Tree, Figure 20. The average height of the foliage is about 21.2 meters above the ground and the maximum height is around 35 meters. The range of 15 to 35 meters will be used later to highlight regions of Eucalyptus Trees.

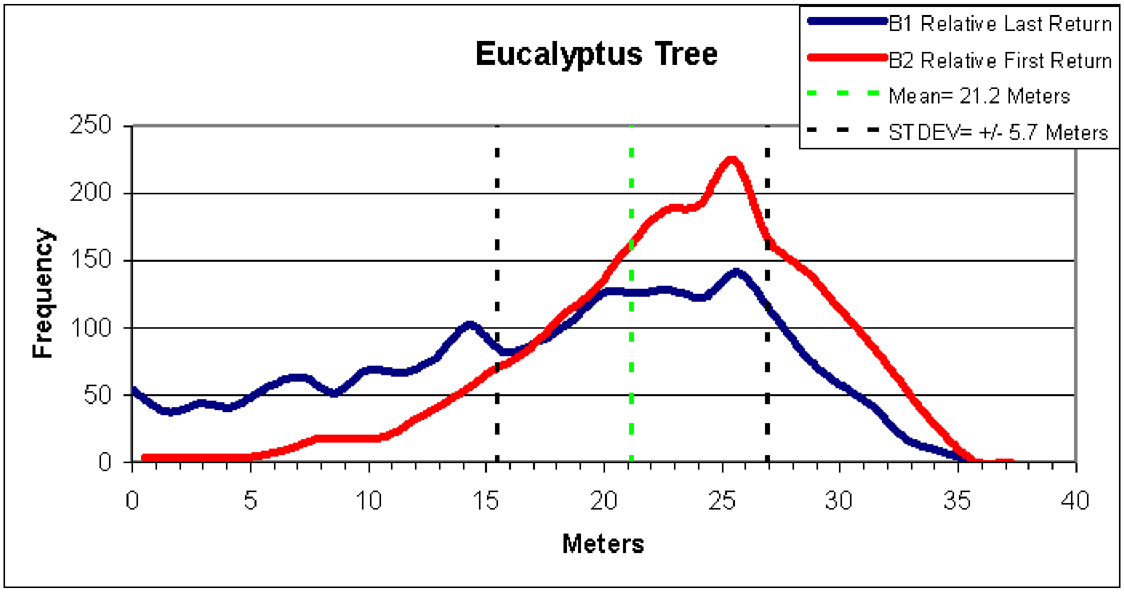

Figure 20. Eucalyptus Tree Foliage Dispersion Histogram, Relative Last Return and Relative 1st Return Each Contain 1909 Data Points

E. IDENTIFYING LOCATIONS WITHOUT VEGETATION

The next step in the analysis process is to discriminate between vegetated and non-vegetated regions. This is accomplished by highlighting regions where the difference between band 1 and band 2 are very small (less then 0.20m) AND the difference between band 3 and band 4 are very small (less then 0.20m). The figure below depicts regions of very short extracted features (less then 0.20m) in yellow, Figure 21. These can be classified as areas that do not have Eucalyptus, California Live Oak, and California Scrub Oak Trees.

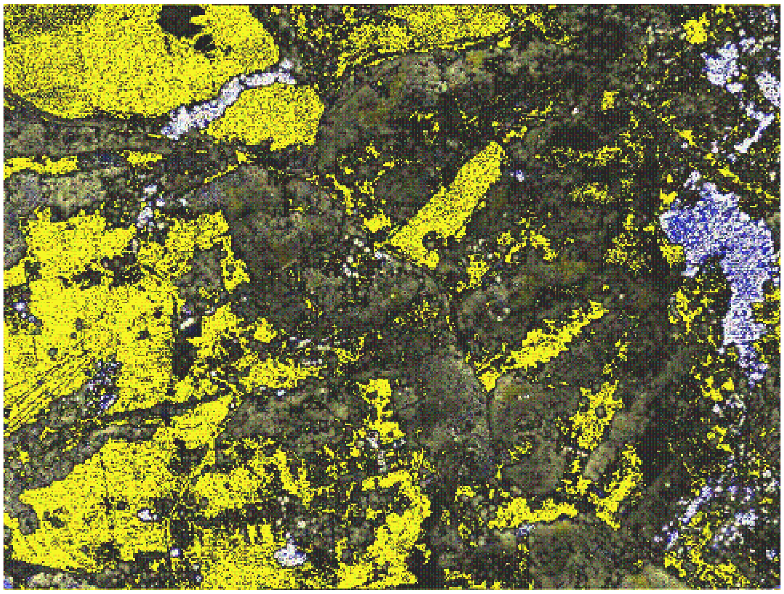

Figure 21. Bare Earth, Fields, and Areas With Vegetation Less Then 0.20 Meters Are Depicted in Yellow

F. IDENTIFYING LOCATIONS WITH CALIFORNIA SCRUB OAK

The height analysis illustrated above for the different tree types then led to an iterative approach to identifying tree types. To identify potential locations of the California Scrub Oak, vegetation within the height range of California Scrub Oak were highlighted. Vegetation ranging from 0.25 to 3 meters are depicted in green, Figure 22. These regions can roughly narrow down locations of California Scrub Oaks. This criteria does not uniquely identify California Scrub Oaks, however, all California Scrub Oaks in this area of interest will be located within the green regions.

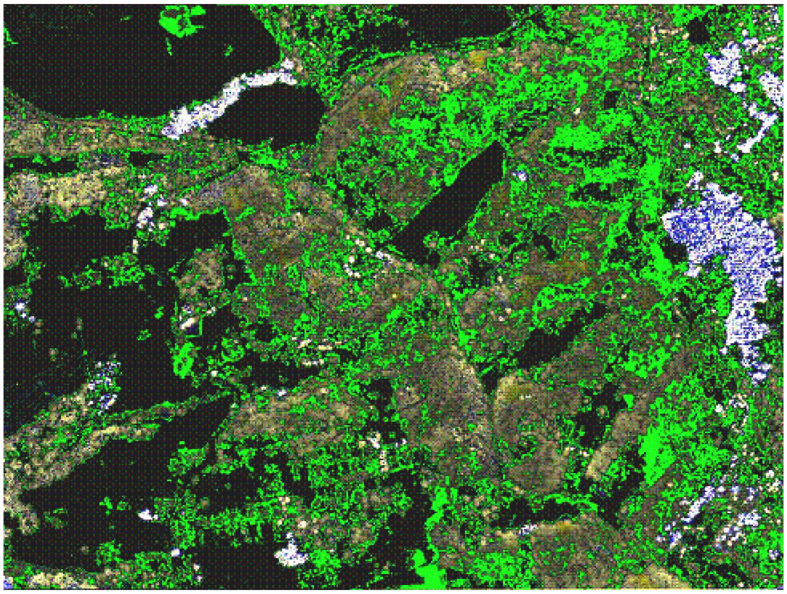

Figure 22. Green Depicts Vegetation Ranging From 0.25-3 Meters in Height

G. IDENTIFYING LOCATIONS WITH CALIFORNIA LIVE OAK

Similarly, to identify potential locations of the California Live Oak, vegetation within the height range of California Live Oak were highlighted. Vegetation ranging from 3 to 15 meters are depicted in red, Figure 23. These regions can roughly narrow down locations of California Live Oaks.

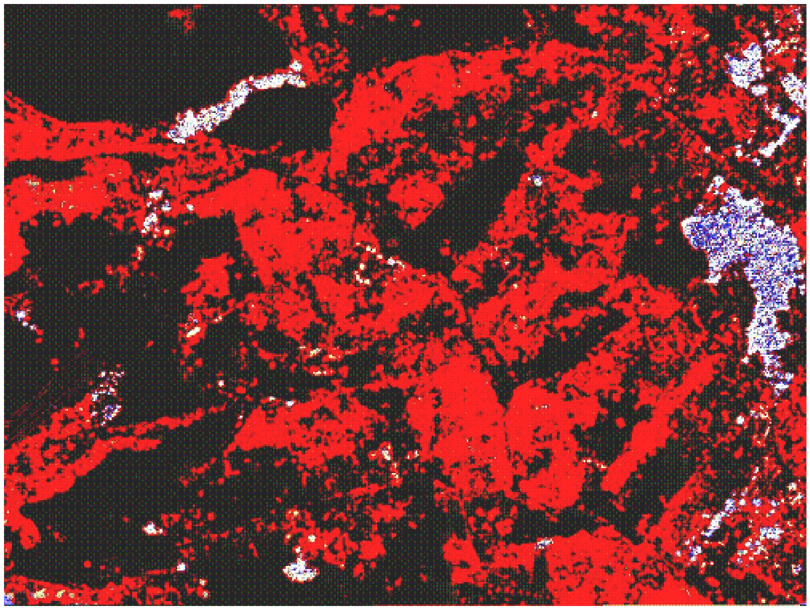

Figure 23. Red Depicts Vegetation Ranging From 3-15 Meters in Height

H. IDENTIFYING LOCATIONS WITH EUCALYPTUS TREES

To identify potential locations of Eucalyptus Trees, trees within that height range were highlighted. Vegetation ranging from 15 to 35 meters are depicted in blue, Figure 24. These regions can roughly narrow down areas where Eucalyptus Trees will be located.

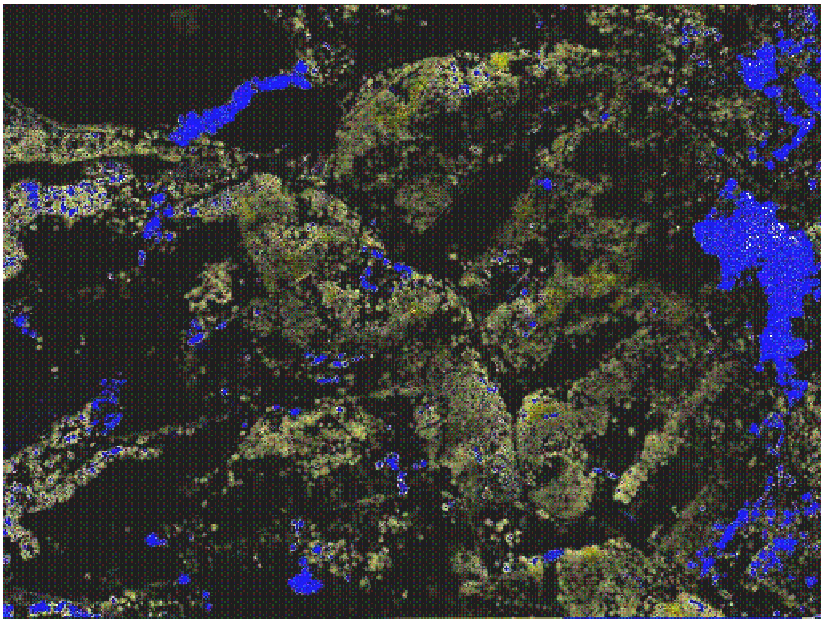

Figure 24. Blue Depicts Vegetation Ranging From 15-35 Meters in Height Above Ground

VII. FOLIAGE DENSITY ANALYSIS

The foliage dispersion range is the initial method used to narrow down locations of vegetation types. Although the colored regions do not identify the types of vegetation, they identify the parameters that match the foliage dispersion characteristics. From here these regions can be more closely analyzed. The next step is refining the colored regions using the foliage density characteristics, in particular, the relationship between the first and last returns for each foliage type.

The figure below depicts an X-Y scatter chart comparing the extracted feature returns of the Eucalyptus tree, California Live Oak, and California Scrub Oak for the training set, Figure 25. Sparse foliage will allow many of the last returns from the extracted features recorded on band 1 to penetrate through the foliage to the ground while the first return of the extracted feature will typically be recorded as a normal foliage return. When this occurs, the Relative First Return will likely be recorded as a normal height, but the Relative Last Return will be recorded as a much lower number compared to the Relative First Return. The Relative Last Return in sparse foliage is often recorded as a zero creating a vertical cluster of returns along the Y-axis of an X-Y scatter plot comparing the first and last returns of the extracted feature. This is evident in the figure below where the plot of Eucalyptus tree returns are concentrated in a vertical grouping along the Y-axis at X≈zero, Figure 25.

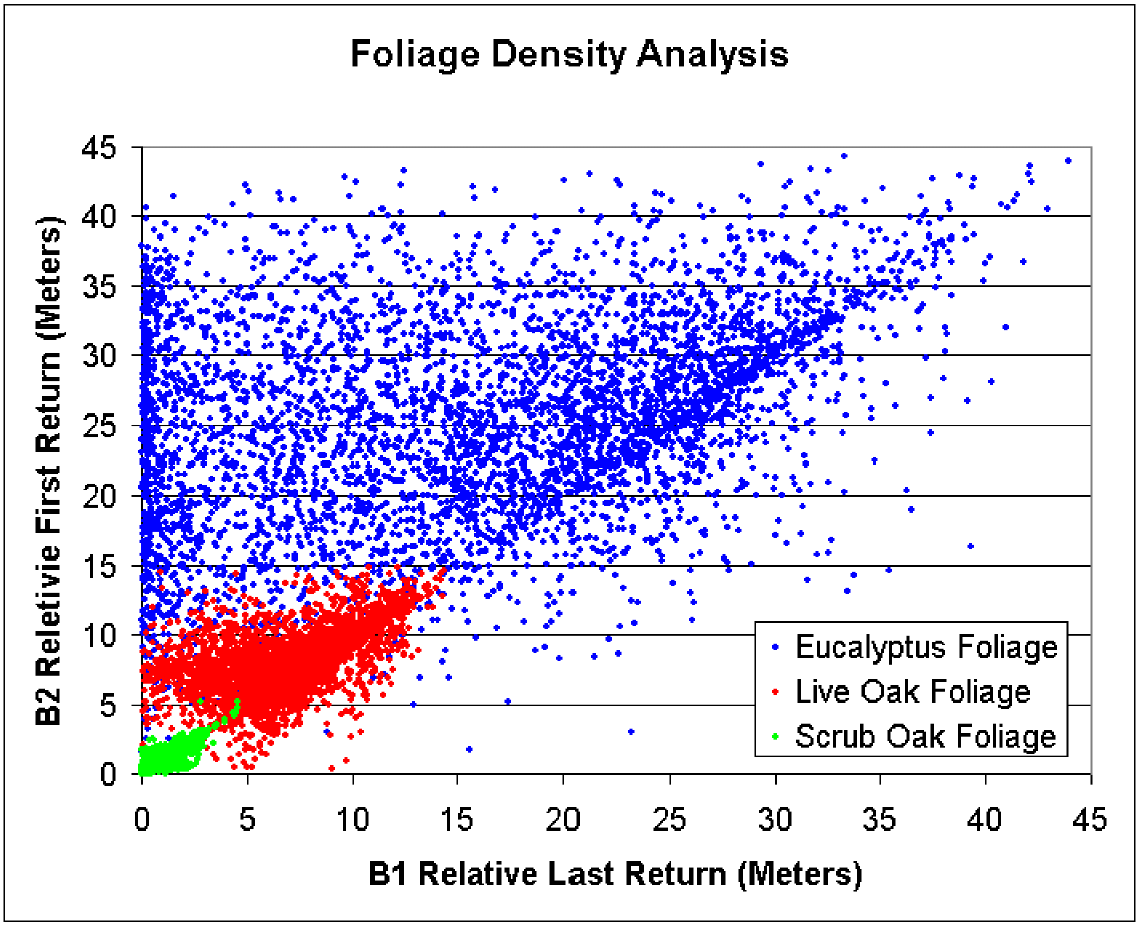

Figure 25. Foliage Density Analysis X-Y Scatter Chart, Comparison of Relative Last Returns (X) to Relative First Returns (Y)

The denser foliage will not allow as many of the last returns of the extracted features to penetrate to the ground, as does the sparse foliage. When this occurs, the first and last returns of the extracted features are similar in value. Assuming the first and last returns of the bare earth are near equal, bands 4 and 2 respectively, then the plot of the Relative Last Return compared to the Relative First Return of the denser foliage will be concentrated along a slope=1 line of the X-Y scatter plot indicating X≈Y. This can be seen in the figure above where the plots of the California Scrub Oak and California Live Oak are concentrated along the slope=1 line, Figure 25.

To further narrow the classification of vegetation, foliage density characteristics will be exploited.

Relatively dense vegetation can be located by highlighting regions where the difference between the value of Band 1-Band 2 and Band 3-Band 4 are small. This would indicate that the first and last returns of the extracted features did not penetrate the canopy to the ground. Furthermore, the heights of the vegetation will be maintained.

A. FOLIAGE DENSITY ANALYSIS OF CALIFORNIA SCRUB OAK

To further refine areas of California Scrub Oak, areas have been highlighted in green that are relatively dense and range from 0.25-3.0 meters in height. The regions in Figure 25 are encompassed by the previous green regions in Figure 22. The exception is that the dense foliage has been included and foliage that is considered sparse has been excluded. Only Relative Last Returns and Relative First Returns that are close in value and are grouped along the slope=1 line on the X-Y scatter chart shown in the figure above were highlighted to produce the image shown in the figure below, Figure 26.

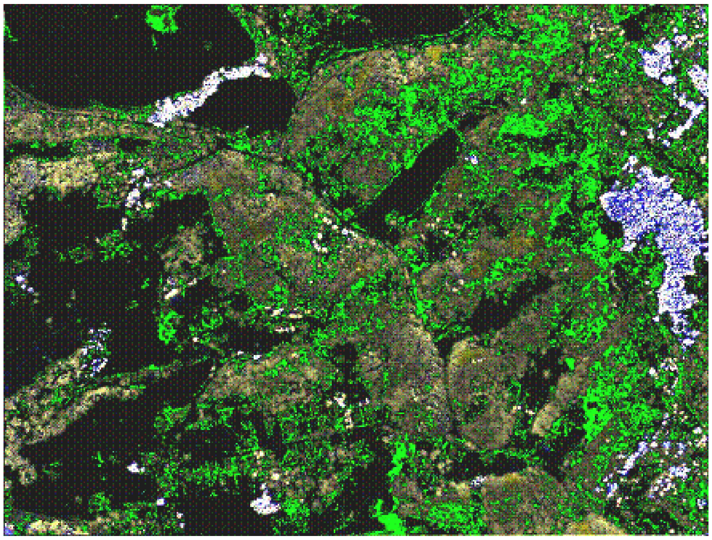

Figure 26. Dense Vegetation Ranging from 0.25-3.0 Meters Depicted in Green

B. FOLIAGE DENSITY ANALYSIS OF CALIFORNIA LIVE OAK

The same method to refine areas of California Scrub Oak was used to refine areas of California Live Oak. The height of the foliage is 3-15 Meters. The figure below depicts the refined regions that encompass the California Live Oaks, Figure 27.

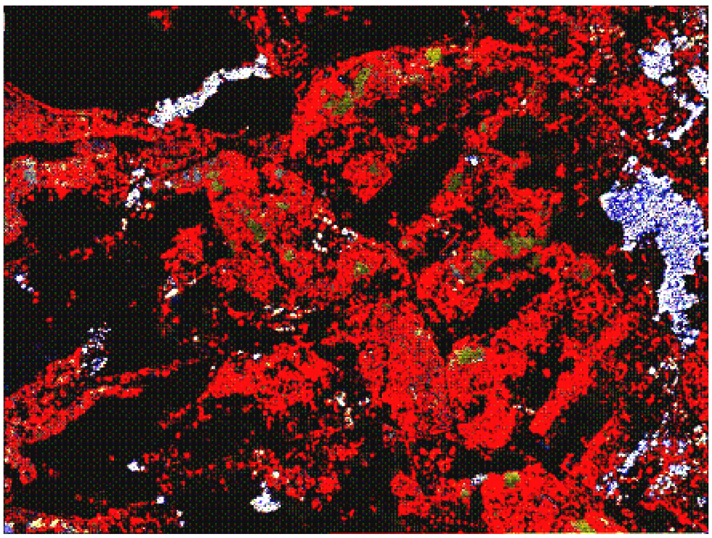

Figure 27. Dense Vegetation Ranging from 3-15 Meters Depicted in Red

C. FOLIAGE DENSITY ANALYSIS OF EUCALYPTUS TREES

To further refine areas of Eucalyptus Trees, regions have been highlighted in blue that are considered to have relatively sparse foliage and range from 15-35 meters in height, Figure 28. These blue regions are encompassed by the same blue regions depicted above in Figure 23 with the exception that the sparse foliage has been included and vegetation that is considered dense has been excluded. Only Relative Last Returns that are near zero in value and are grouped along the X≈0 line on the X-Y scatter chart shown in Figure 24 were highlighted to produce the image shown in Figure 28.

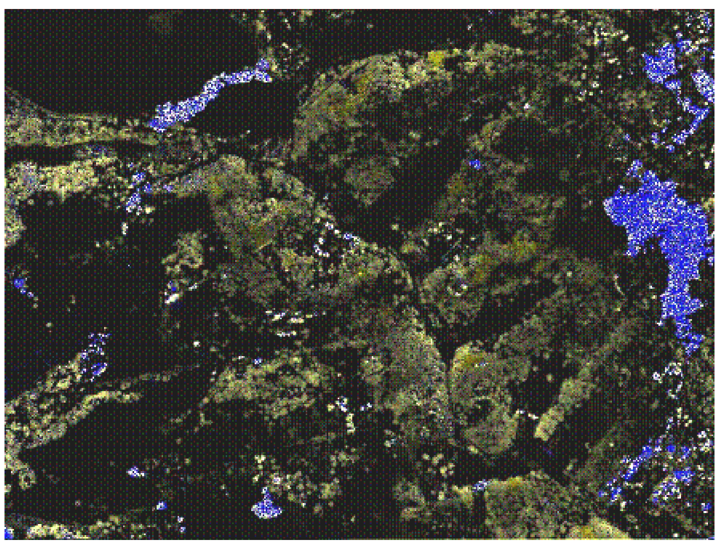

Figure 28. Sparse Vegetation Ranging From 15-35 Meters Depicted in Blue

The range of the foliage height above ground and the foliage density are two methods that can be used to classify or identify types of vegetation using the LIDAR returns. These two methods narrow down the locations of vegetation types based on their extracted feature and bare earth returns. It has been confirmed that these methods can accurately identify different types of vegetation through on site survey. A consolidated image of dense California Scrub Oaks, dense California Live Oaks, and sparse Eucalyptus Trees is shown below, Figure 29.

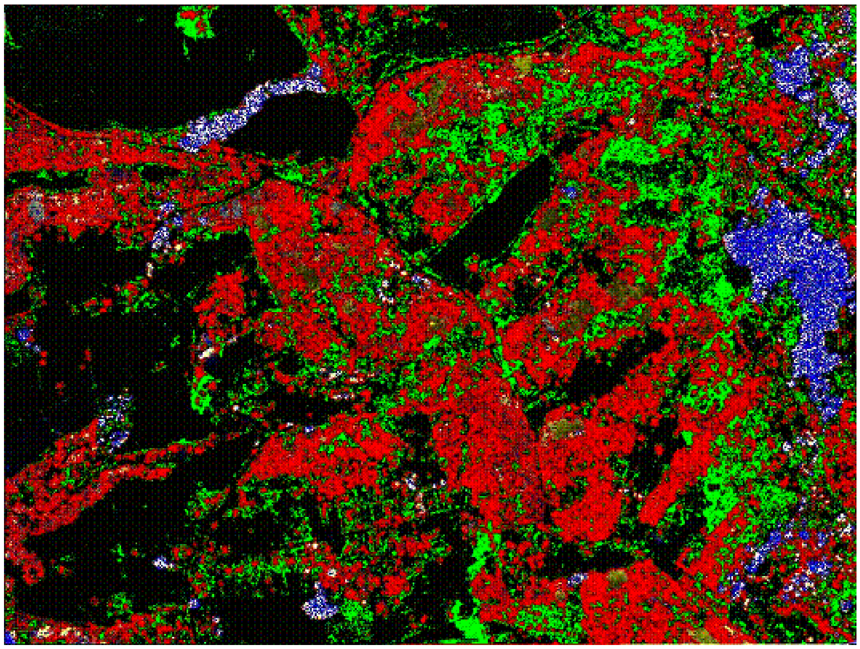

Figure 29. Dense California Scrub Oaks Shown in Green, Dense California Live Oaks Shown in Red, Sparse Eucalyptus Trees Shown in Blue

VIII. LIDAR INTENSITY ANALYSIS

The four returns from each LIDAR pulse also record an intensity value. The intensity values are additional information that can help confirm or support conclusions derived from the LIDAR data.

The Optech 2025 ALTM LIDAR System records an intensity value, or amplitude of each of the four returns and is plotted as an image, Figure 30. This feature provides additional information for further analysis of foliage density and terrain characteristics. In this image, band 1 is mapped to red, band 2 is mapped to green, and band 3 is mapped to blue. Band 4 is excluded in this image since Envi 4.1 only allows three colors in RGB images. Band 4 is also similar in intensity when comparing the three types of vegetation and was excluded to emphasize contrast between them.

A. FOLIAGE INTENSITY ANALYSIS

Vegetation with dense foliage characteristics will not allow as many of the returns to penetrate as deeply into the vegetation as sparse foliage. Returns that do not penetrate the canopy return with higher amplitude or with higher intensity since the returns collide with fewer obstructions. These types of vegetation will appear brighter when depicted on an image.

Returns that are permitted to penetrate further into the foliage will inevitably reflect with less intensity due to obstructions returning to the sensor. This phenomenon can be observed in the figure below where areas of Eucalyptus Trees show up darker then surrounding areas, Figure 30.

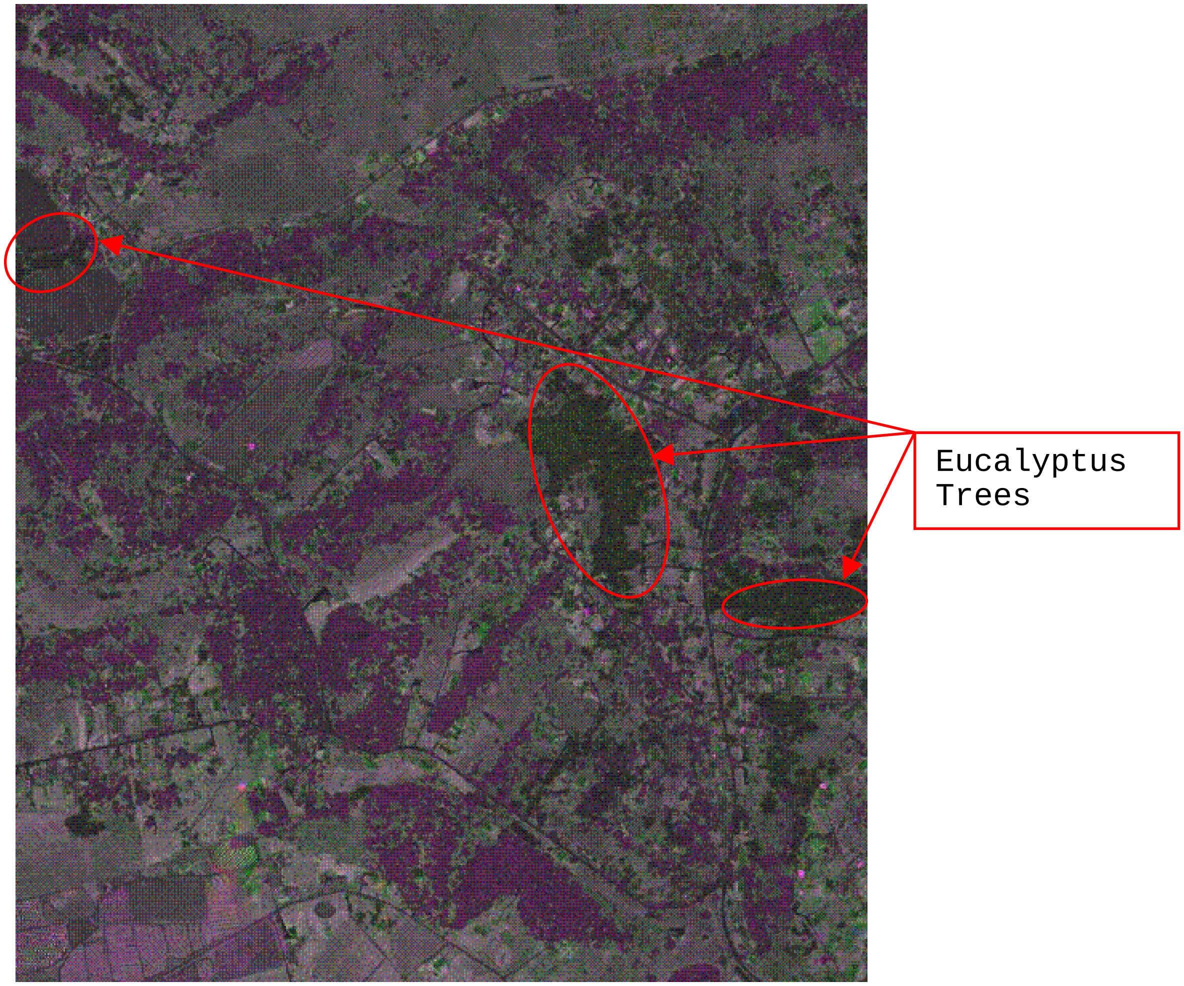

Figure 30. Image of Intensity Values Recorded from LIDAR Returns. Band 1 is mapped to Red, Band 2 is Mapped to Green, and Band 3 is Mapped to Blue

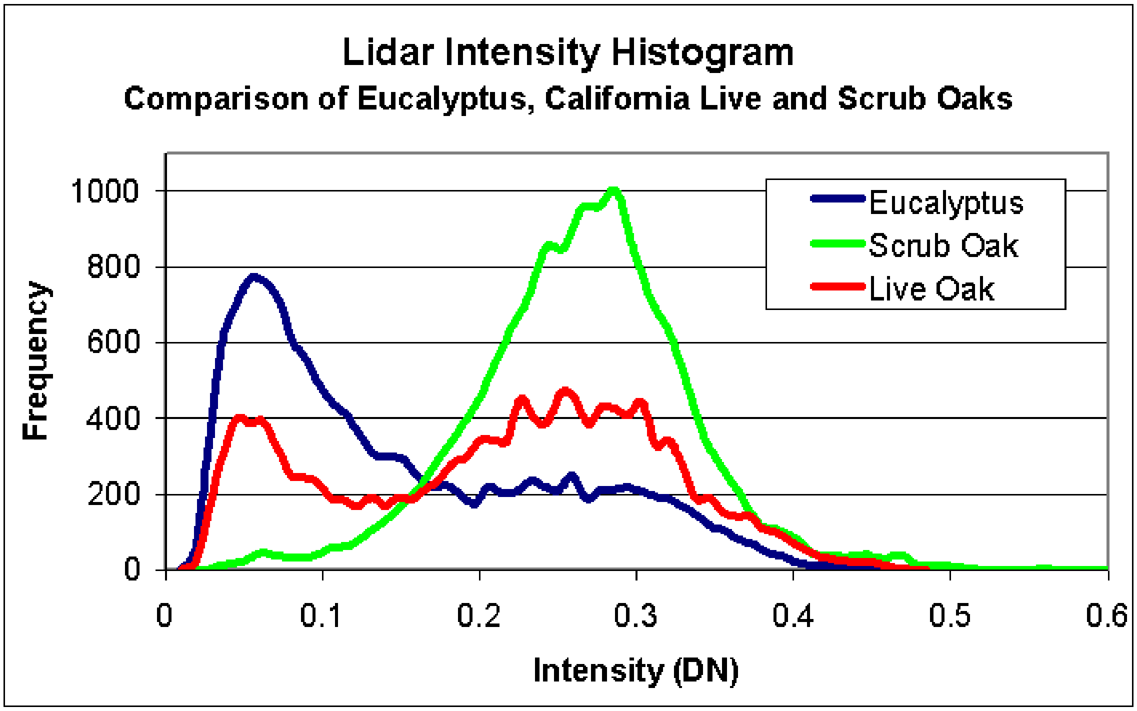

Figure 31. LIDAR Intensity Histogram Comparing Intensity Returns of the Eucalyptus Tree, California Live Oak, and California Scrub Oak, Sum of Bands 1,2,3 &4. Each Series Contains 12500 Data Points

B. INTENSITY COMPARISON OF EUCALYPTUS, CALIFORNIA LIVE AND SCRUB OAK

When the intensity returns of the Eucalyptus Tree, California Live Oak, and California Scrub Oak are more closely observed and compared, it is evident that there are differences in intensity returns. The histogram in the figure above depicts the frequency and intensity of the three types of trees, Figure 31.

The California Scrub Oak appears to be the brightest of the three. The foliage density of the Scrub Oak and Live oak are similar, but the Scrub Oak is much shorter. The first and last returns of the extracted features of the Live Oak and Scrub Oak are similar, however, since the Scrub Oak is closer to the ground, the first and last returns of the bare earth will have less opportunity to be blocked by foliage thus recording a more intense return.

The California Live Oak will appear brighter then the Eucalyptus tree because of its dense foliage, but slightly darker then the Scrub Oak because it is taller then the Scrub Oak.

The Eucalyptus Tree will appear the darkest of the three since it is the tallest and it has the sparsest foliage. The sparse foliage allows more opportunities for the first and last returns of the extracted features to reflect off of obstructions on their way to the sensor.

Intensity analysis is an effective tool used to compare foliage densities and also to support conclusions derived from the LIDAR return foliage density analysis. This technique will become more useful when the foliage dispersion between different types of vegetation is similar and difficult to differentiate using only LIDAR returns.

IX. IDENTIFYING VEGETATION WITH SIMILAR DIMENSIONS

The Comparison of Eucalyptus, California Live Oak, and California Scrub Oak Trees is relatively straightforward. The range of foliage heights is markedly different and the density is clearly different when comparing the Eucalyptus Tree to the Scrub and Live Oaks. These differences make identification reasonably simple when comparing the three types of trees. This process can become much more sophisticated when these parameters aren't so distinct.

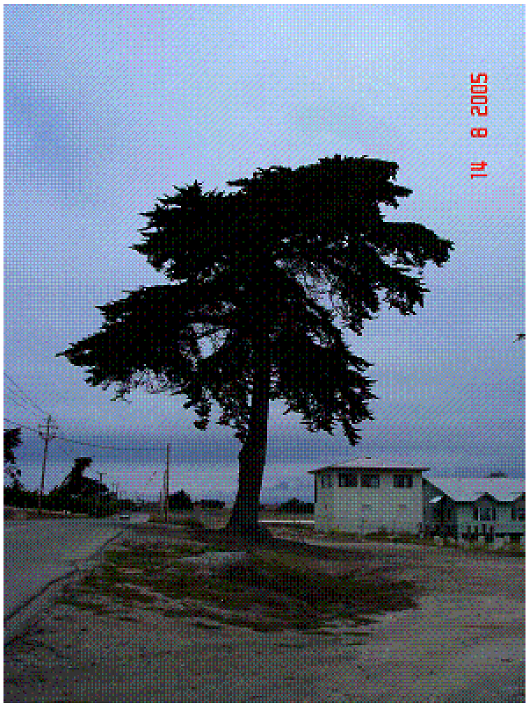

Figure 32. Monterey Cypress

A. LIDAR RETURN COMPARISON OF EUCALYPTUS AND MONTEREY CYPRESS

The similarities between the Monterey Cypress and the Eucalyptus Tree appear to be much closer when comparing the two with LIDAR data. Their foliage range is very similar and will be difficult to use the ranges as parameters to highlight them.

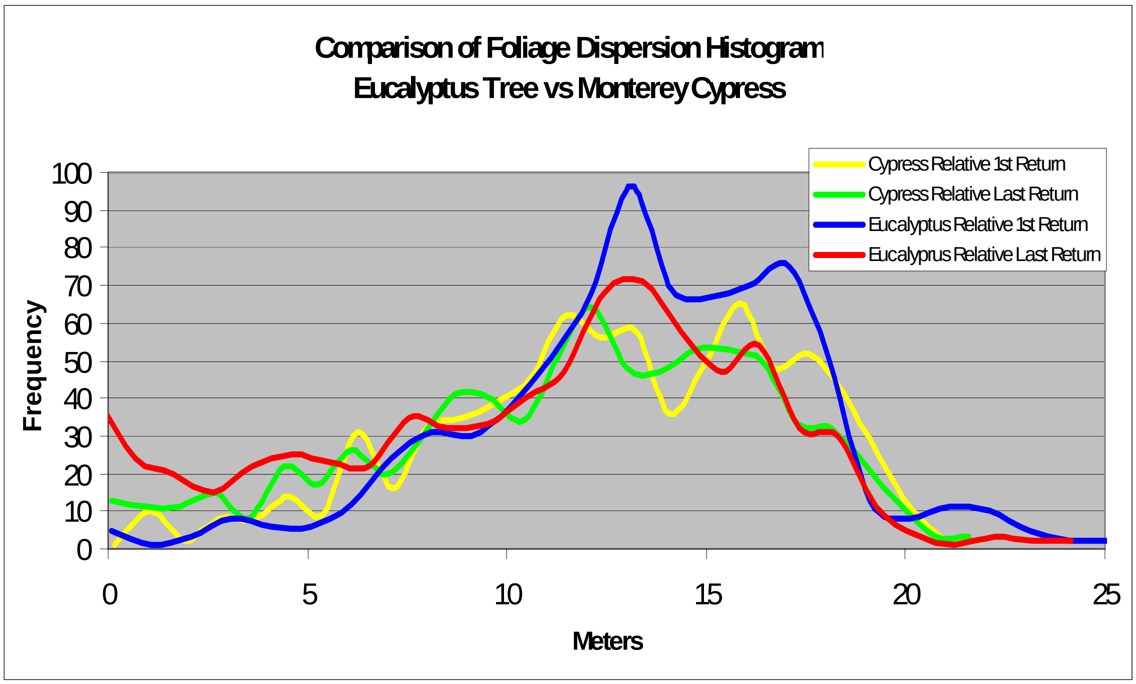

Figure 33. Foliage Dispersion Comparison of Eucalyptus and Monterey Cypress Trees. Each Series Contains 760 Data Points

The average height above ground of the Eucalyptus Tree is 12.6 meters with a standard deviation of 4.8 meters. The Monterey Cypress is almost identical with and average height above ground of 12.7 meters with a standard deviation of 4.6 meters. The foliage range cannot be used as a parameter to differentiate between Eucalyptus Trees and Monterey Cypress Trees. The only exception is that the maximum height of the Monterey Cypress tree in this area of interest was recorded to be 22.3 meters. The maximum height above ground for the Eucalyptus Tree in this area of interest was recorded to be 25.6 meters. All points that are higher then 22.3 meters will be highlighted as Eucalyptus.

B. FOLIAGE DENSITY ANALYSIS

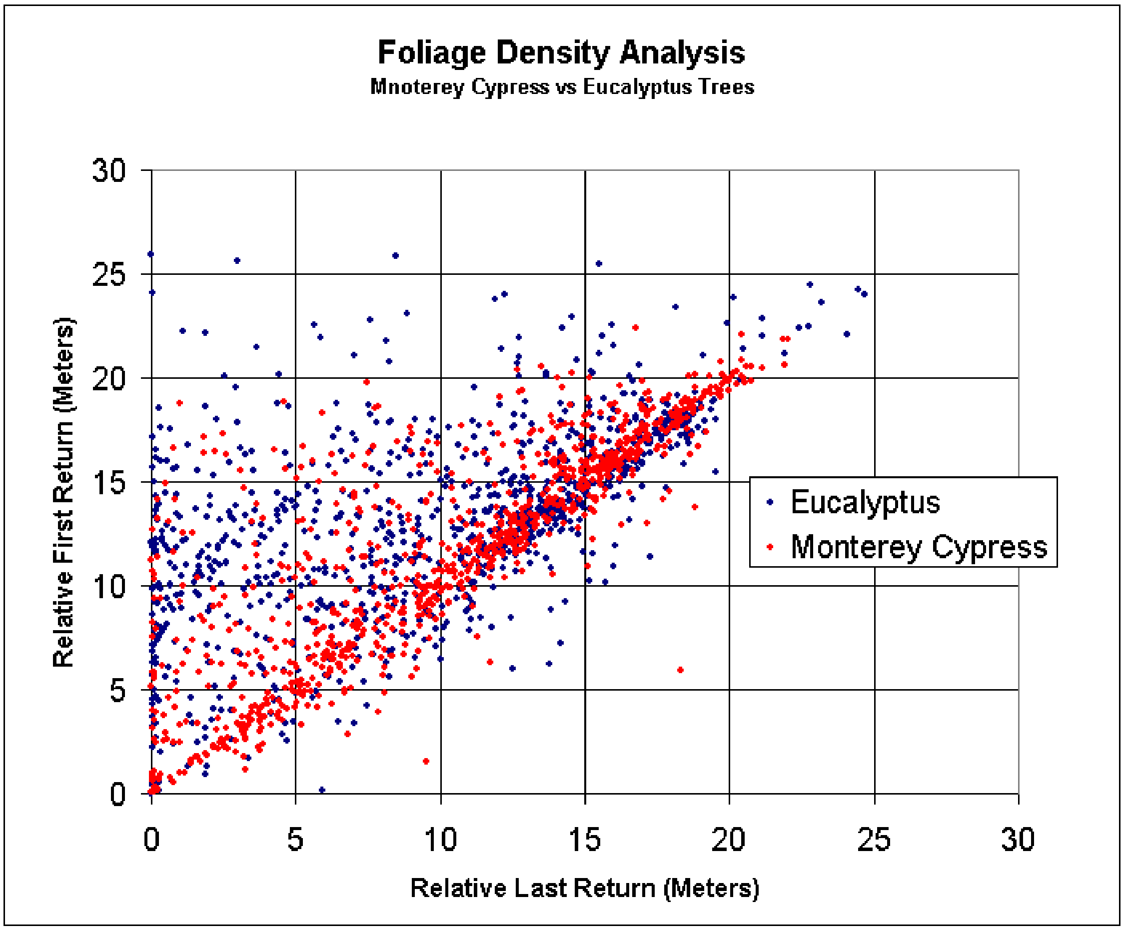

Figure 34. Foliage Density Analysis, Comparison of Monterey Cypress and Eucalyptus Trees

The foliage density of the Eucalyptus and Monterey Cypress can be compared to each other when the Relative Last Return and Relative First Return are plotted on an X-Y scatter chart, Figure 34. The sparser foliage of the

Eucalyptus Tree will allow more of the Relative Last Returns to reach the ground then the Monterey Cypress. This will cause more of the plotted data points to gather along the Y-axis where X=zero. Conversely, the Monterey Cypress data points will gather along a line where the slope=1 indicating X≈Y.

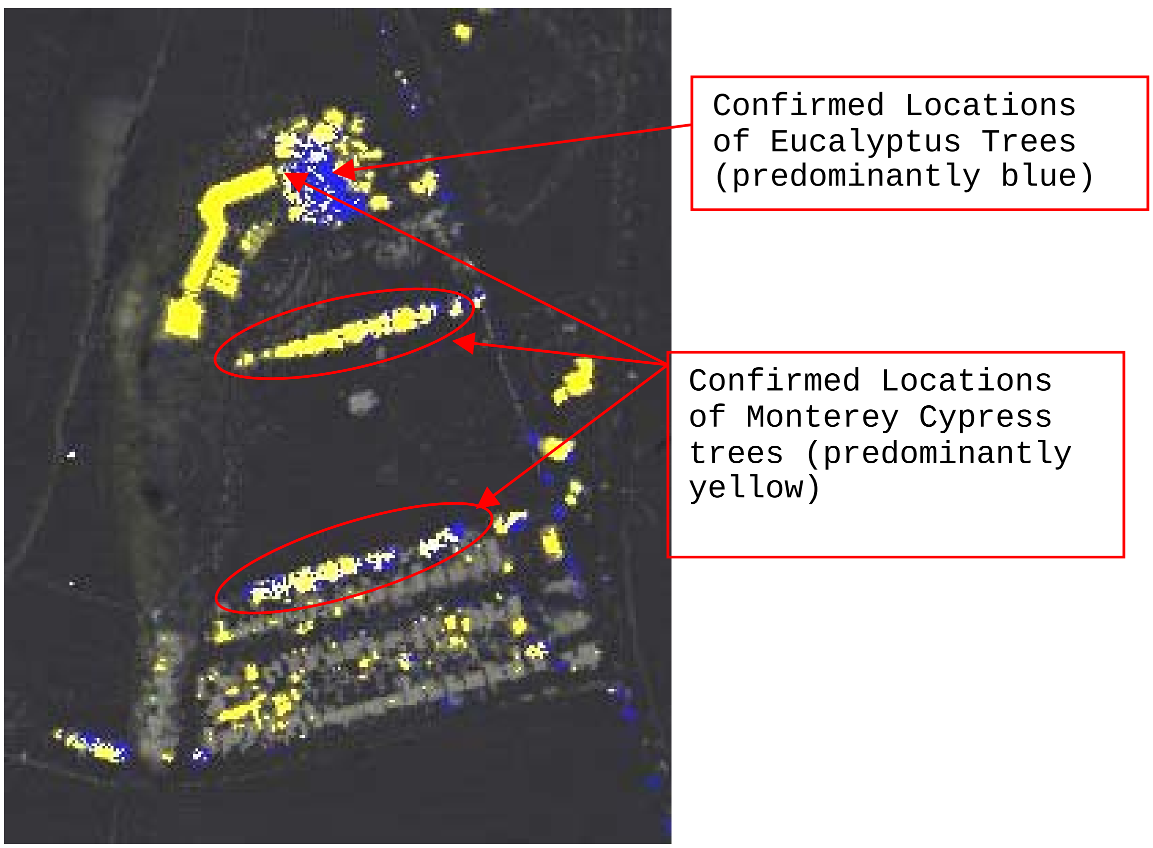

Figure 35. Vegetation With Monterey Cypress Foliage Characteristics Depicted in Yellow, Vegetation With Eucalyptus Tree Foliage Characteristics Depicted in Blue

In order to highlight regions of potential Monterey Cypress and Eucalyptus Trees, it was necessary to exploit their minimal differences in foliage density and foliage height range. Vegetation taller then the maximum height of the Monterey Cypress Tree (22.3 meters) were highlighted blue and considered potential Eucalyptus. The foliage that is considered dense or where the Relative Last Return is comparable in value to the Relative First Return is highlighted yellow and considered potential Monterey Cypress Trees. Finally, foliage that is considered sparse or where more of the plotted data points gather along the Y-axis where X=zero and where the X value is significantly less then its corresponding Y value are also highlighted in blue and are considered to be potential Eucalyptus Trees.

Depicted in the figure above are areas with confirmed locations of Monterey Cypress and Eucalyptus Trees, Figure 35. Although the Monterey Cypress Trees are not 100% highlighted in yellow and the Eucalyptus Trees are not 100% highlighted in blue, the difference between the two is apparent. This is especially true in the upper portion of the above figure where a group of Eucalyptus Trees is surrounded by a group of Monterey Cypress Trees, Figure 35.

C. INTENSITY ANALYSIS OF EUCALYPTUS AND MONTEREY CYPTESS

The intensity of the returns can be used to support assumptions concluded from the LIDAR foliage analysis. LIDAR intensity is helpful especially in the event of similar foliage characteristics where differentiating between types of vegetation with only LIDAR return data is difficult.

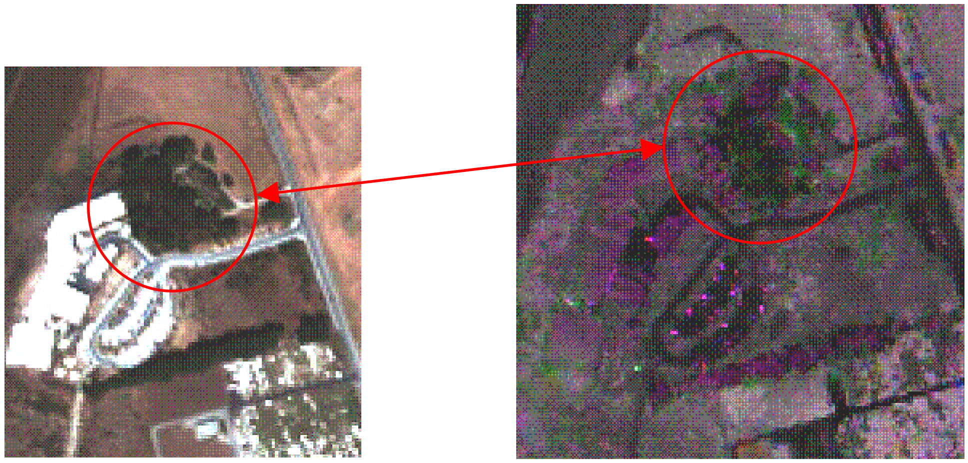

Figure 36. QuickBird image of Monterey Cypress and Eucalyptus Trees (left) LIDAR Intensity image of corresponding Quckbird Image; Eucalyptus Trees appear Dark, Cypress Trees Appear Purple; Band 1 is Mapped to Red, Band 2 is Mapped to Green, and Band 3 is Mapped to Blue (right)

Once the groups of vegetation with the foliage characteristics of the Monterey Cypress and Eucalyptus Trees have been have been identified with the LIDAR data, the intensity values can be applied to further verify the initial assumptions. The Sparse foliage of the Eucalyptus Tree will generate less intense returns then the Cypress Tree.

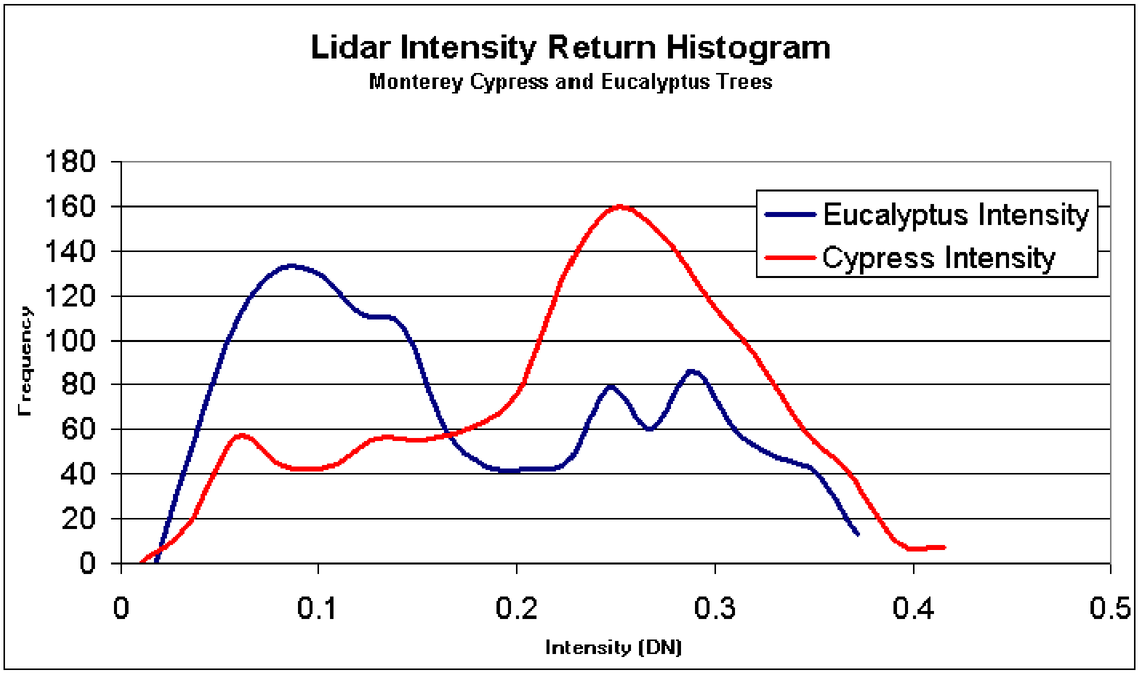

Figure 37. LIDAR Intensity Histogram for Monterey Cypress and Eucalyptus Trees, Intensity is Sum of All Four Bands for Each Tree. Each Series Contains 1230 Data Points

The figure above illustrates the difference in the combined intensities of bands 1,2,3, &4 between the Monterey Cypress and Eucalyptus Trees, Figure 37. This difference in intensities is generated from the variation in foliage densities and is evident when the individual bands are more closely examined.

The two figures below illustrate a histogram of the individual intensity returns of all four bands for the Eucalyptus and Monterey Cypress Trees. The first and last return of the bare earth, bands 4 and 2 respectively, between the two types of trees are similar in value. The average intensity value of the Monterey Cypress for band 4 is 0.257355 and .115475 for band 2. The average intensity value of the Eucalyptus Tree for band 4 is 0.284254 and 0.155708 for band 2.

Bands 1 and 3 record the intensity of the extracted features and compared to bands 2 and 4, are noticeably different in value between the Monterey Cypress and Eucalyptus Trees. The average intensity value of the Monterey Cypress for band 1 is 0.252667 and 0.244818 for band 3. The average intensity value of the Eucalyptus Tree for band 1 is 0.118934 and 0.091508 for band 3.

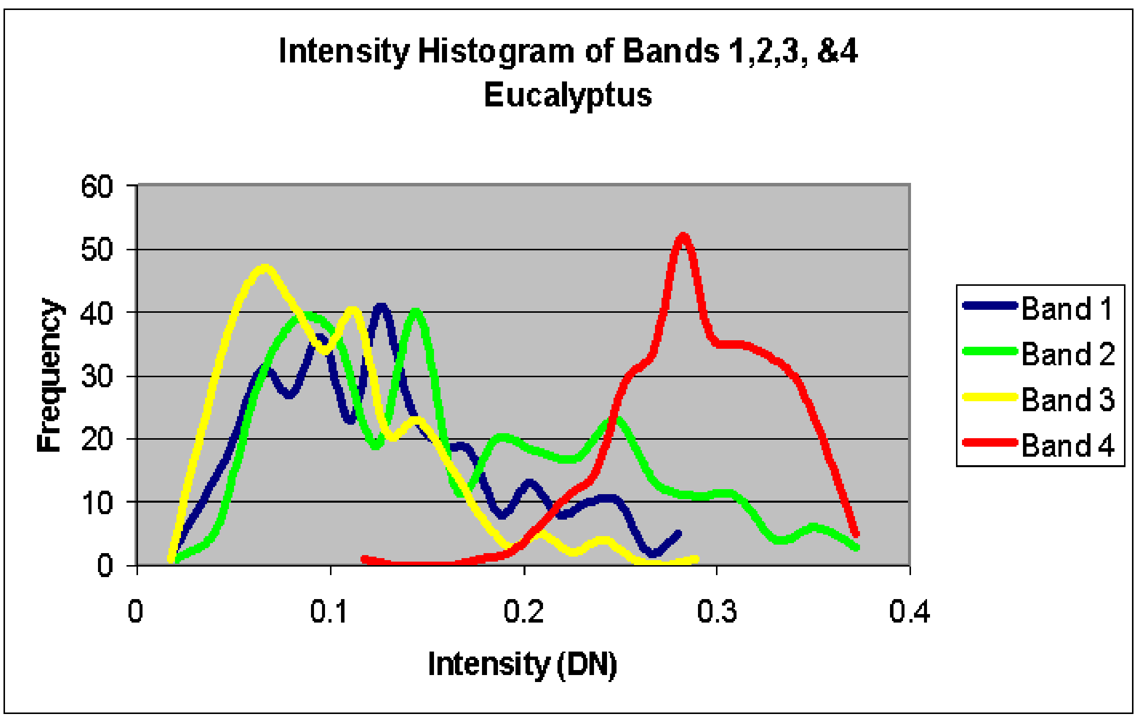

Figure 38. LIDAR Intensity Histogram of Bands 1,2,3, &4 for Eucalyptus Trees. Each Series Contains 300 Data Points

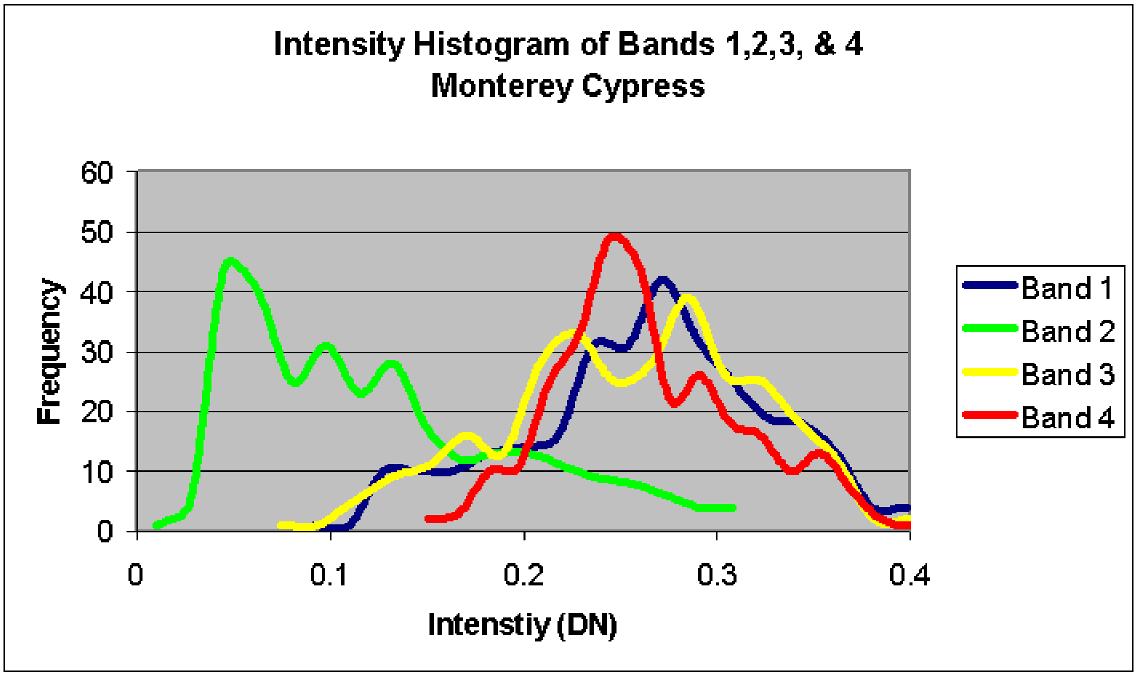

Figure 39. LIDAR Intensity Histogram of Bands 1,2,3, &4 for Monterey Cypress Trees. Each Series Contains 300 Data Points

Since the LIDAR intensity from bands 2 and 4 are similar in value for the Eucalyptus and Monterey Cypress trees, only bands 1 and 3 will be used to differentiate between the two types of trees. The figure below shows a comparison of the LIDAR intensities of the Monterey Cypress and Eucalyptus Trees using only band 1 and 3, band 1 is plotted on the X-axis and band three is plotted on the Y-axis, Figure 40.

D. INTENSITY COMPARISON OF BANDS 1 AND 3

The intensity of the Eucalyptus Tree recorded on bands 1 and 3 are both less intense then the intensities recorded on bands 1 and 3 for the Monterey Cypress Tree. When plotted on an X-Y scatter chart shown below, the less intense returns from the Eucalyptus gather in the lower left hand region of the chart and the more intense returns from the Monterey Cypress gather in the upper right hand region of the chart, Figure 40.

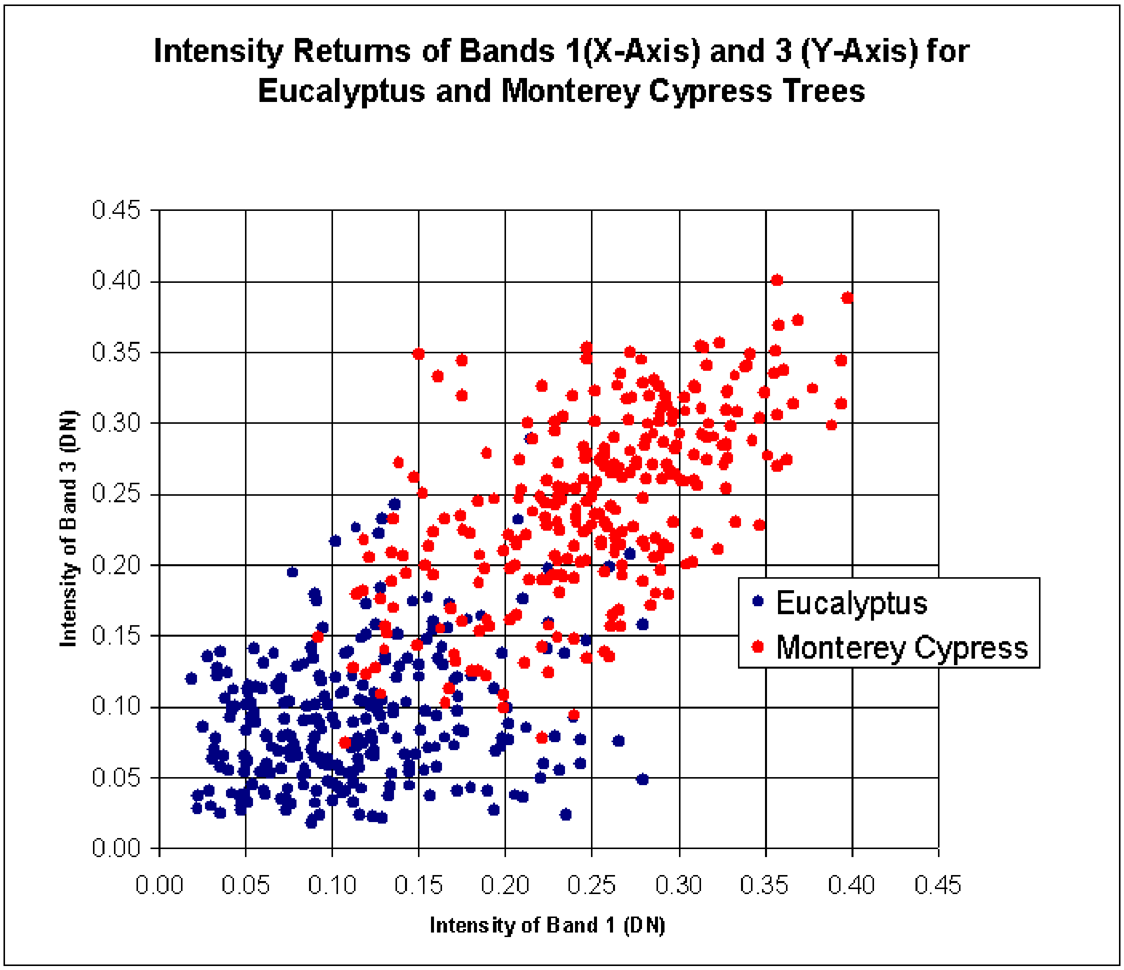

Figure 40. X-Y Scatter Chart Comparing the LIDAR Intensities of Eucalyptus and Monterey Cypress Using Bands 1 and 3

In order to exploit the different intensities of the two types of trees, an image is created using only band 1 and band 3. Bands 2 and 4 are excluded from the image in order to maximize contrast, image “A”, Figure 41. Band 1 is mapped to red and green and band 3 is mapped to blue.

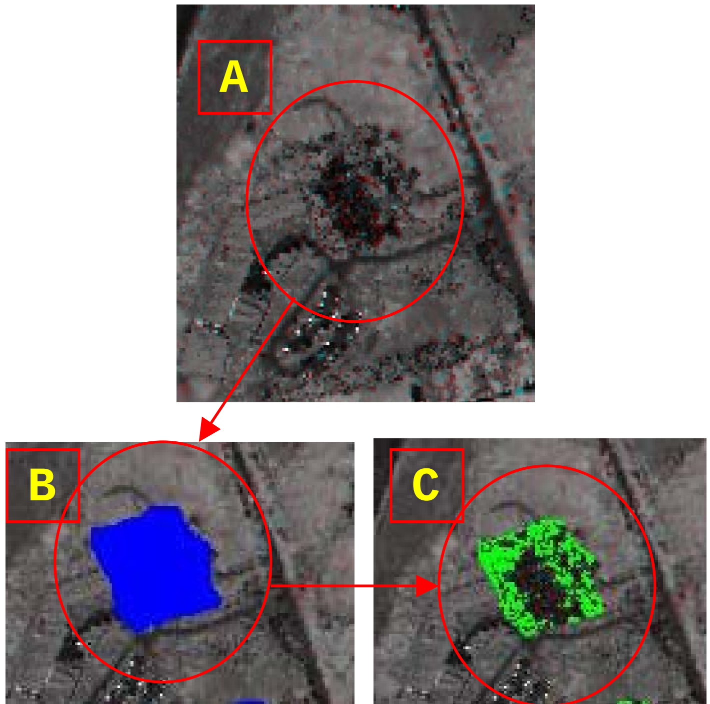

Figure 41. Intensity Image, Band 1 Mapped to Red and Green, Band 3 Mapped to Blue (A), Region of Interest Highlights Area in Blue With Foliage Characteristics of Monterey Cypress and Eucalyptus Trees (B), Intensity Characteristics of Monterey Cypress Highlighted in Green (C)

Areas with Monterey Cypress and Eucalyptus Tree foliage characteristics have already been identified with the LIDAR pulse return data. The next step in the analysis process is to confirm conclusions from the extracted feature analysis.

A region of interest highlights areas in blue that have the foliage characteristics of the Monterey Cypress and Eucalyptus Trees, image “B”, Figure 41. Within the region of interest, only the intensity values that are similar to the Monterey Cypress are highlighted and depicted as green in image “C”, Figure 41.

These areas have been confirmed by on the ground sites surveys to be the types of vegetation to be determined by the LIDAR return and intensity foliage analysis.

X. COMBINING LIDAR RETURN DATA WITH INTENSITY VALUES

As mentioned previously, differentiating types of vegetation with similar foliage dimensions with only LIDAR return data can be challenging. The intensity values play an instrumental role in supporting conclusions derived from LIDAR return data.

To optimize the capabilities of the LIDAR returns and intensity values, it is necessary to combine the two data sets so that false identification is minimized.

The first step is to locate vegetation with the desired foliage densities and dispersions. Pictured below in image “A” is a Relative Last Return/Relative First Return image; vegetation with Eucalyptus foliage characteristics are depicted in blue and vegetation with Monterey Cypress foliage characteristics are depicted in red, Figure 42. Although most colored regions appear to be correct in identifying the two types of trees, an intensity analysis will support this conclusion.

Next the red and blue regions of interest are exported to a LIDAR intensity image shown below; image “B”, Figure 42. The corresponding pixels are analyzed comparing the intensities of bands 1 and 3. Bands 1 and 3 are the extracted feature returns and normally appear less intense (dark) for sparse foliage and more intense (bright) for dense foliage.

Pixels within the same region of interest that are considered dark or less intense are colored yellow and pixels that are considered bright or more intense are colored green; image “C”, Figure 42.

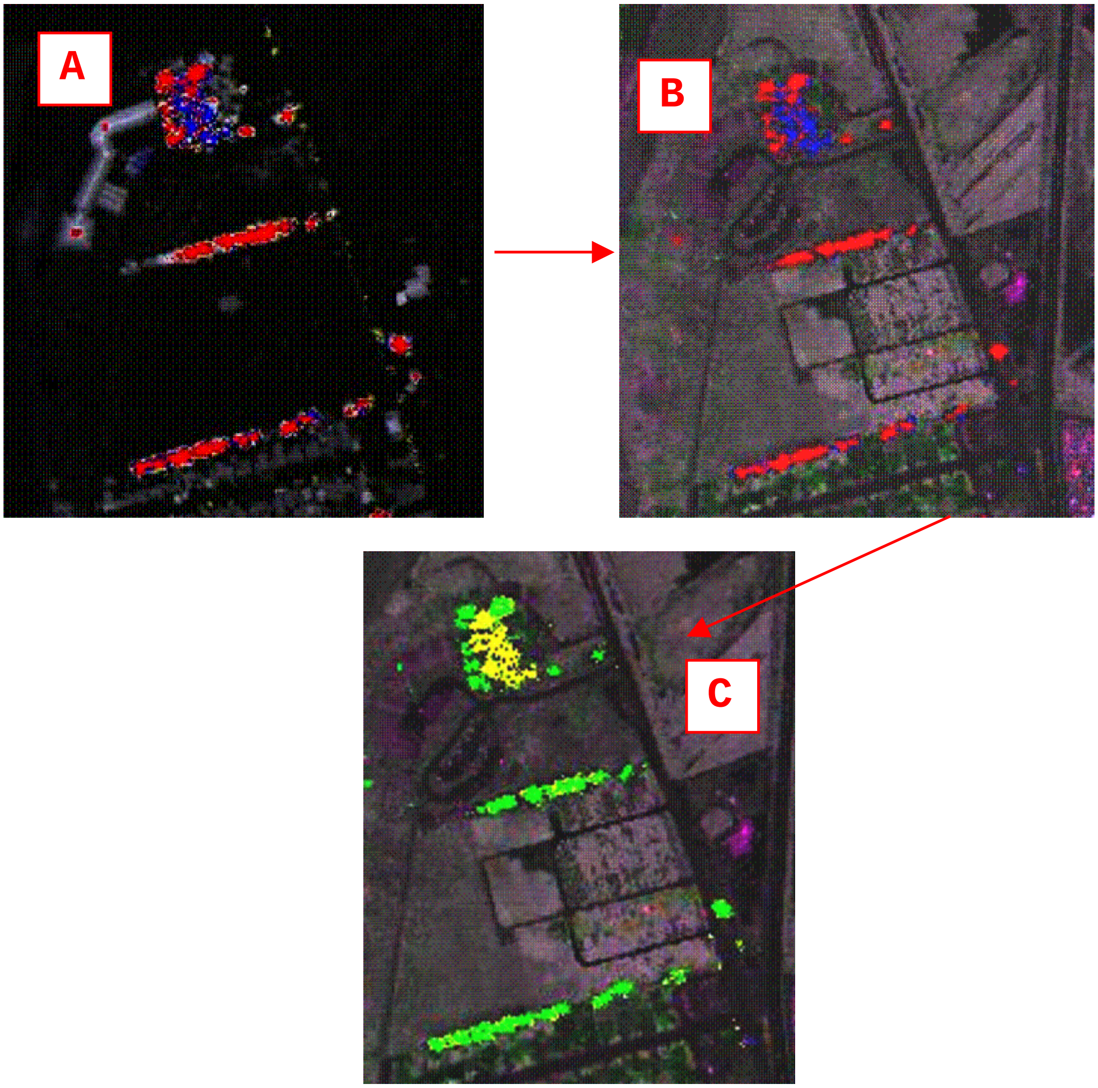

Figure 42. Relative Last Return/Relative First Return Image; Vegetation with Eucalyptus Foliage Characteristics are Depicted in Blue and Vegetation with Monterey Cypress Foliage Characteristics are Depicted in Red (Image A), LIDAR Intensity Image with Region of Interest Imported from Image A (Image B), LIDAR Intensity Image with Region of Interest Pixels Analyzed using Bands 1 and 3, Yellow Represents Areas with Foliage and Intensity Characteristics of Eucalyptus, Green Represents Areas with Foliage and Intensity Characteristics of Monterey Cypress (Image C)

The region of interest shown above in image “C” has both the foliage density/dispersion and intensity characteristics of the types of vegetation identified.

Vegetation identification is a step-by-step process starting with the analysis of foliage dispersion. This first step narrows the area of interest eliminating vegetation that does not match the estimated parameters of height and foliage range.

Once the dispersion range has been highlighted, foliage density can be exploited to further narrow the identification of vegetation.

Finally, the intensity analysis supports conclusions derived from the first two steps.

THIS PAGE INTENTIONALLY LEFT BLANK

XI. CONCLUSION

Vegetation identification can be performed with a high degree of accuracy using a combination of satellite images and LIDAR data. In order to accurately identify vegetation, basic characteristics need to be established. The treetop heights have to be determined along with the height range of the foliage. Furthermore, knowledge of the foliage density is used to narrow the identification of vegetation. These parameters are normally accomplished by on-the-ground site surveys locating various groups of vegetation.

Commonly, differences in terrain elevation can impede efforts of identification. To eliminate the terrain as a factor, the differences in terrain elevation are subtracted while maintaining the difference between the bare earth and the extracted features. Once that is accomplished, known foliage characteristics can be exploited.

Trees that are much different in dimensions can easily be separated with only LIDAR return data, such as the Eucalyptus and the Oak Trees; however, different species of trees are often very similar in dimension, such as the Monterey Cypress and Eucalyptus. With these similarities, special attention needs to be directed towards known differences such as foliage densities that can be compared with LIDAR return intensities.

With these tools, vegetation identification can be accurately accomplished, however detailed knowledge of vegetation needs to be collected and compared through on-the-ground site surveys. Site surveys of battlefields are normally not available during wartime operations and may make vegetation identification difficult without a database of foliage characteristics.

A solution to battlefield site surveys can be remedied through the collection of foliage characteristics within neighboring friendly territory assuming the same region contains similar types of vegetation.

With a baseline vegetation database established, mobility corridors can easily be identified using satellite images and a LIDAR system aboard an airborne platform such as an unmanned aerial vehicle or reconnaissance aircraft.

LIST OF REFERENCES

1. Spencer B. Gross, Inc, LIDAR (Light Detection and Ranging)

   http://www.sbgmaps.com/LIDAR.htm, Accessed 21 May 2005

2. LIDAR Remote Sensing for Ecosystem Studies; MICHAEL A. LEFSKY, WARREN B. COHEN, GEOFFREY G. PARKER, AND DAVID J. HARDING

3. Optech Incorporated

4. Producing Terrain Elevation Data with LIDAR, Colin McGuire

   www.personal.psu.edu/users/c/p/cpm171/Project3.html, Accessed 17 May 2005

5. Airborne 1 Corporation

6. Angela Peutz

7. USGS, Shuttle Radar Topography Mission

   http://srtm.usgs.gov/, Accessed 3 September 2005

8. ASPRS LIDAR Data Exchange, LASFORMAT

   http://www.lasformat.org, Accessed 7 September 2005

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Marine Corps Representative
   Naval Postgraduate School
   Monterey, California

4. Director, Training and Education, MCCDC, Code C46
   Quantico, Virginia

5. Director, Marine Corps Research Center, MCCDC, Code C40RC Quantico, Virginia

6. Marine Corps Tactical Systems Support Activity (Attn: Operations Officer)Camp Pendleton, California

7. Head, Information Operations and Space Integration Branch, PLI/PP&O/HQMC,Washington, DC