GEOSPATIAL INFORMATION FOR JOINT MILITARY OPERATIONS IN THE LITTORAL ZONE

by

STEVEN DOUGLAS FLEMING

(Under the Direction of Roy A. Welch)

ABSTRACT

In order to successfully support current and future U.S. military operations in coastal zones, geospatial intelligence must be integrated to accommodate force structure evolution and mission requirement directives. Coastal zones are complex regions that include sea, land and air features for which the military requires high-volume databases of extreme detail within relatively narrow geographic corridors. Unclassified, commercial remote sensing data in the form of images acquired from aircraft, unmanned aerial vehicles (UAVs) and satellites are increasingly being used to populate coastal zone databases. Geographic information systems (GIS) are also being employed to integrate and analyze geographic data for military operations. This study was undertaken in conjunction with the National Geospatial-Intelligence Agency (NGA) to assess: (1) the suitability of commercially available images for littoral warfare (LW) operations and mandatory LW feature extraction; and (2) the applicability of GIS analysis, modeling and map generation for use in LW operations, providing products that show the possibilities for future employment. With respect to the former objective, results indicate that spatial resolution is more important than spectral resolution for effectively populating LW databases. Large-scale color and color-infrared photos scanned at pixel resolutions from 0.15 m to 1.2 m and QuickBird and Ikonos panchromatic satellite images (0.6- and 1.0-m pixel resolution, respectively) are the most suitable data for visual LW feature extraction and mapping at scales of 1:1,000 to 1:10,000. With respect to the latter objective, results indicate that GIS-based analysis products and perspective scene representations of the operational environment will greatly assist commanders deployed in littoral regions. Military decisions regarding sea, land and air regions should not be addressed independently. Geospatial information and analysis capabilities provide military planners the means to assess littoral zones with an effective and integrated digital warfighting tool.

INDEX WORDS: Remote Sensing, GIS, GPS, High-Resolution Satellite Imagery, United States Marine Corps (USMC), Littoral Penetration Point (LPP)

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DEDICATION

In Memory of

Bill Alexander Fleming

1930 – 2002

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CHAPTER 1

INTRODUCTION

America's military force structure is dramatically changing as collectively our armed forces undergo a major transition from what the Department of Defense (DoD) calls the Legacy Force* (built with industrial-age based technologies) to the Objective Force* (designed to capitalize on information-age based technologies)[1]. Traditional "stovepipes" between services are being eliminated and replaced with integrated systems that allow joint forces (combined Army, Navy, Air Force and Marine organizations) to seamlessly execute required tasks.

Looking toward the future, service planners are working alongside equipment acquisition teams to develop new employment tactics, techniques and procedures. Parallel to force structure developments, mission requirements continue to change focus. In order to successfully support future military operations, important planning tools must be integrated to accommodate both force structure evolution and mission requirement directives. One of the key tools used for planning is **geospatial information**. As part of ongoing research being conducted by the Center for Remote Sensing and Mapping Science (CRMS) for the National Geospatial-Intelligence Agency (NGA) (formerly the National Imagery and Mapping Agency (NIMA)) on geospatial databases in support of littoral warfare (LW), my work examined this integration, addressed the critical

[1] *Introductory Note: The introduction and literature review include a number of military-specific terms (indicated by [*] in the text) that are likely to be unfamiliar to those outside of military circles. Appendix 1 lists and defines these terms and/or acronyms. Most of these terms are further defined in JV2010 (JCS, 1997).*

challenges brought about by change and proposed realistic solutions for the use of geospatial information in the future.

Major Research Objectives

In order to achieve "full spectrum dominance" [*], operational and tactical commanders must gain and successfully exploit information superiority (JCS, 1997). Once done, U.S. Forces possess over their adversary(ies) unmatched battlespace awareness[*] – a joint "common operational picture" (COP)[*] of the environment, friendly force operations and enemy activities. In this, knowledge about the environment serves as the foundation. More importantly, the integration of geospatial data – digital maps, images and terrain data – is the cornerstone to this concept; it is at the core of all other decision-making information on the modern battlefield (Figure 1.1).

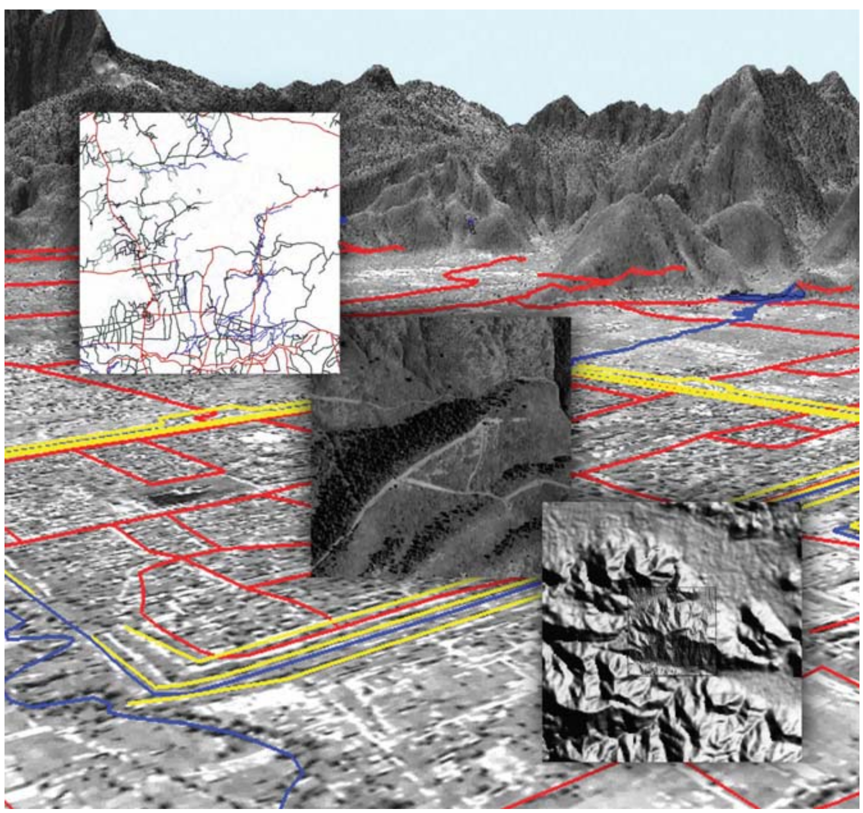


Figure 1.1. The integration of geospatial data (NIMA, 2003)

Efficient methods for collecting and integrating geospatial data and effectively generating useful products have not been fully developed. My research focused on generating effective methodologies of employing geospatial information for joint military operations in the littoral region. The three major objectives of my research were:

1. to evaluate the feature data collection utility of current and evolving commercial sensor systems with potential military applications for littoral operations;
2. to establish example modeling and terrain visualization protocols for littoral regions, employing design and/or operating functions planned for use as part of the Commercial Joint Mapping Toolkit (C/JMTK)[*]; and
3. to demonstrate the value of a digital geographic information system (GIS) database developed according to military specifications for planning and execution of littoral operations.

In order to meet the above objectives, this dissertation is structured to include a brief introduction to the study area, a literature review, two manuscripts, a summary and set of conclusions. The manuscripts focus on unclassified images for military operations in coastal zones and GIS applications for military operations in coastal zones submitted for publication in: (1) *Photogrammetric Engineering and Remote Sensing (PE&RS)*; and (2) *ISPRS Journal of Photogrammetry and Remote Sensing*, respectively.

Study Area

Joint operations are conducted from four spatially unique regions – hydrographic, topographic, aeronautic and space (JCS, 1997). Designed around their required missions, the Marine Corps' force structure supports operations in the first three of the four – referred to in this research as the sea, land and air. In support of unit readiness requirements, our United States Marine Corps (USMC) bases facilitate integrated training in these regions. Camp Lejeune, North Carolina, one such base, served as the study area for this project. A detailed description of the operational environment there, the largest such facility in the world (Pike, 2003a) and an ideal location to address the three research objectives, is provided in Chapter 3 as part of a formal journal manuscript.

Camp Lejeune makes important use of digital geospatial information during daily operations. The base has what is called an Integrated Geographic Information Repository (IGIR) (GISO, 2001). Established in 1992, it is a GIS database designed to integrate geographic data about Camp Lejeune into one shared resource that serves as a strategic component of the base command's information infrastructure. Previously, Camp Lejeune utilized many different, yet related sources of geographic information where different database formats, datums and map projections prevented accurate interchange of available data. Today, the IGIR is a comprehensive resource of environmental, installation infrastructure and military training information (GISO, 2001). It is comprised of innovative computer hardware, software and a telecommunications infrastructure which provides a diverse means to create, maintain, organize, access, interpret and analyze geographic data. With ArcGIS as the primary interface tool, base personnel from over 100 different organizations can access more than 350 different layers of information (AutoCAD files, image files and GIS data) (GISO, 2001). The repository actively supports the base command as an aid in critical decision making by supplying geographic information for natural and cultural resource management, environmental planning and compliance, military exercises, facilities management, disaster preparedness and recovery/emergency response.

CHAPTER 2

GEOSPATIAL INFORMATION USE IN MILITARY OPERATIONS:

A CRITICAL REVIEW

Introduction

The U.S. military has used geospatial information in every conflict throughout its history of warfare. Until the last quarter century, geospatial information used by commanders on the battlefield was in the form of paper maps. Of note, these maps played pivotal roles on the littoral battlegrounds of Normandy, Tarawa and Iwo Jima (Greiss, 1984; Ballendorf, 2003). Coastal digital geospatial data were employed *extensively* for the first time during military actions on Grenada in 1983 (Cole, 1998). Since then, our military has conducted littoral operations numerous times – twice in the Persian Gulf region (Operation Desert Storm (McCaffrey, 2000) and Operation Iraqi Freedom), Panama and Somalia – while preparing for many other like contingencies (Cole, 1998, Krulak, 1999). United States forces have and will continue to depend on maps – both analog and digital – as baseline planning tools for military operations in coastal zones that employ both Legacy and Objective Forces (Murray and O'Leary, 2002).

Important catalysts involved in transitioning the U.S. military from dependency on analog to digital products include: (1) the Global Positioning System (GPS); (2) unmanned aerial vehicles (UAVs); (3) high-resolution satellite imagery; and (4) GIS (NIMA, 2003). In addressing these four important catalysts, this review is first structured to include a summary of geospatial data collection technologies, traditional and state-of-art, relevant to littoral operations and, second, examine GIS integration of these data for use in military environments.

Geospatial Data Collection Technologies

Three major data collection categories used in populating coastal GIS databases include: (1) field data collection and GPS; (2) aerial reconnaissance; and (3) satellite reconnaissance. Discussed here, these collection methods provide a complementary mix of platforms and technologies for gathering information about coastal regions.

Field Data Collection and GPS

There are numerous methods of collecting raw data in the field for direct input into littoral warfare geospatial databases. These methods are most often used when the required data do not exist in any other readily available format, such as maps, photographs or satellite images. Field data also are frequently collected when "ground truthing" of remotely sensed data is required. Traditional manual surveying techniques make use of levels and theodolites for directly collecting field measurements. Modern digital equivalents of these manual techniques have been developed so that data collected are stored in digital format ready for direct input into a GIS. Examples here include total stations (high-precision theodolites with electronic distance measurement (EDM) and data logger capabilities), hand-held laser range finders and digital compasses (Figure 2.1).

A universal military locating system, GPS, was designed and fully introduced to the military by the late-1980s. During this time, global missions for U.S. forces expanded dramatically, often requiring immediate information about “place” anywhere on Earth.

Joint operations between services became the norm for how America's military planned and executed tasks. A common system for providing key location data for friendly

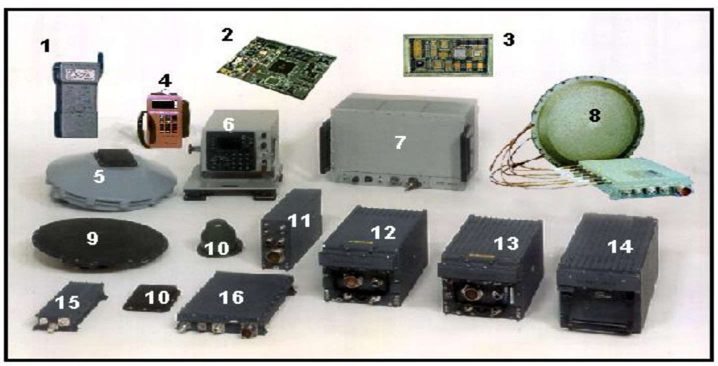
Figure 2.1. TOPCON's electronic distance measurement (EDM) instruments (TOPCON, 2004)

units, enemy targets and critical terrain was required.

Joint U.S. combat operations in Grenada (1983) demonstrated the need for improved positioning technology. Although U.S. forces prevailed as a result of large amounts of non-standard geospatial data between services, the conflict was not an efficient, well-coordinated effort by any measure of warfighting (Cole, 1998). Since then, GPS integration and employment has accelerated, becoming the answer to many location-based challenges brought about by mission and interoperability changes.

The GPS, including satellites and monitoring equipment, undergoes constant improvement cycles to increase accuracy, reliability and capability. Currently, military GPS receivers reliably provide position accuracies to within one meter (GPS JPO, 2000). These receivers have been made smaller, more accurate and easier to use. Microelectronics have made them very affordable so that every individual, weapon system and command post can share the technology, making available the benefits of a reliable, accurate worldwide navigation and positioning (Huybrechts, 2004).

The GPS user equipment segment consists of the military GPS receivers, antennae and other GPS-related equipment. Global positioning system receivers are used on aircraft, ships at sea, ground vehicles or hand-carried by individuals. They convert satellite signals into position, velocity and time estimates for navigation, positioning and time dissemination. Most of the user equipment is employed by more than one service with very few (if any) having utility for a single service. Figure 2.2 shows and names the primary tools in the DoD suite of GPS equipment.



1. Combat Survivor/Evader Locator (CSEL)
2. GRAM-SAASM
3. Selective Availability Anti-Spoofing Module (SAASM)
4. Precision Lightweight GPS Receiver (PLGR)
5. FRPA Ground Plane (FRPA-GP)
6. Standard Control Display Unit (CDU)
7. Receiver 3S
8. GPS Antenna System (GAS) -1
9. Controlled Radiation Pattern Antenna (CRPA)
10. Fixed Radiation Pattern Antenna (FRPA)
11. Miniature Airborne GPS Receiver (MAGR)
12. Receiver OH (MIL-STD-1553)
13. Receiver UH (ARINC 429)
14. Receiver 3A
15. Antenna Electronics AE-4
16. Antenna Electronics AE-1/AE-1A

Figure 2.2. Department of Defense GPS Equipment (GPS Office, 2001)

System devices and GPS-aided weapons have been employed in numerous warfighting applications including navigation and positioning, weapon guidance, targeting and fire control, intelligence and imagery, attack coordination, search and rescue, force location, communication network timing and force deployment/logistics (NAVSTAR, 2001). Major benefits of GPS realized in these applications include: (1) improved position accuracy; (2) more accurate weapon placement; (3) enhanced systems performance; and (4) time synchronization (GPS JPO, 2000). Table 2.1 provides a detailed listing of benefits derived from GPS employment.

Table 2.1. Military Benefits Resulting from GPS Employment

Improved Position Accuracy	**Accurate Weapon Placement**
Mine Countermeasures	Saved Ordnance
Search and Rescue	Improved "Kill Ratios"
Special and Night Operations	Increased Efficiency
Intelligence Assessments	Demoralized Enemy
Logistics Support & Tanker Ops	Reduced Exposure to Hostile Fires
Enhanced Systems Performance	**Time Synchronization**
Standoff Land Attack Missile	Command and Control
Patriot	Secure Communications
Artillery and Armored Vehicles	Coordinated Operations
Sensors	Joint Operations
Attack Aircraft	Special Operations

The GPS has a bright future; it is being improved to preserve the advantages it brings to the battlefield and to prevent its vulnerability to attack (GISDevelopment, 2004). The vulnerability of GPS includes terrorist use as demonstrated by the tragic events of September 11, 2001 where al Qaeda loyalists exploited GPS technology in guiding airliners into their targets on the U.S. mainland.

Changes designed to better support the warfighter in an evolving threat environment are planned. They will provide more flexibility through more portable systems as well as military anti-jam capability, meaning that GPS accuracy will be maintained closer to the target in a high jamming environment. In this, the GPS has recently been linked to laptop computers and personal data assistants (PDAs – also known as personal data organizers; Figure 2.3). Overall, GPS will provide a more secure, robust military signal service, assuring acquisition of the GPS signal when needed in a hostile electronic environment (Kimble and Veit, 2000). Ongoing changes will deny an enemy the military advantage of GPS, thereby protecting friendly force operations and preserving peaceful GPS use outside an area of operations (SPAWAR, 2001).

Figure 2.3. Military GPS portability on laptops (left) and PDAs (right)

Aerial Reconnaissance

There are numerous methods of collecting data via aerial reconnaissance for use in military operations in littoral zones. Some methods have been used for many years while others make use of relatively new technologies. Included here is a discussion of two primary methods of employing airborne reconnaissance platforms to populate LW databases: (1) air photos and digital images; and (2) sensor data obtained with UAVs.

Air Photographs and Digital Images

Aerial photographs have been traditionally used for over 75 years in mapping littoral regions (NOAA, 1997). Taken from specially designed aerial camera systems, several different types of aerial photographs have been used routinely by military intelligence sources. These include simple black and white (panchromatic), color and color-infrared. Color-infrared systems assist military analysts in camouflage detection mandates.

Current aerial photographs show changes that have taken place since the making of a map. For this reason, in military operations, maps and aerial photographs complement each other. More information can be gained by using the two together than by using either alone. Detailed in Table 2.2, aerial photographs provide many advantages over an analog map for military applications.

Table 2.2. Advantages of Aerial Photographs over Analog Maps
(FM 3-25.26, Map Reading and Land Navigation)

Photos provide a current pictorial view of the ground that no map can equal.
Photos are more readily obtained; it may be in the hands of the user within a few hours after it is taken. A map may take months to prepare.
Photos may be made for places that are inaccessible to ground soldiers.
Photos show military features that do not appear on maps.
Photos provide a day-to-day comparison of selected areas, permitting evaluations to be made of enemy activity.
Photos provide a permanent and objective record of the day-to-day changes with the area.
Photos are often used to obtain data not available from other secondary sources, such as location and the extent of certain areas of interest.

Over the past decade, digital images have been used increasingly in populating coastal zone databases. Scanning analog photographs or collecting scenes with digital cameras mounted on aircraft are the two primary means of generating digital images. In the latter use, digital cameras for collecting panchromatic, color and color-infrared images are designed around a matrix (array) of charge-coupled device (CCD) imaging elements (Figure 2.4). Camera features such as completely electronic forward motion compensation (FMC) and 12-bit per pixel radiometric resolution ensure image quality (Z/I Imaging, 2004). Significant advances in sensor technology have stemmed from subdividing spectral ranges of radiation into bands (intervals of continuous wavelengths), allowing digital camera sensors in several bands to form multispectral (MS) images. For MS data, the total bandwidth normally ranges between 0.4 and 0.9 μms for visual and near infrared (IR). An advantage over aerial photos, digital images enable rapid image enhancement, zoom viewing and classification via supervised or unsupervised methods.

Figure 2.4. The Digital Mapping Camera (DMC) from Z/I Imaging Corporation.

Another popular technology, imaging spectroscopy (also known as hyperspectral remote sensing) allows a sensor on a moving platform to gather reflected radiation from ground targets where a special detector system records up to 200+ spectral channels simultaneously over a range from 0.38 to 2.5µm (JPL, 2004). With such detail, the ability to detect and identify individual materials or classes greatly improves. Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS), one such hyperspectral sensor, operated since 1987, consists of four spectrometers with a total of 224 individual bandwidths, each with a spectral resolution of 10 nm and a spatial resolution of 20 m (Lillesand and Kiefer, 1999).

A new form of digital imagery, light detection and ranging (lidar) is a very powerful and versatile remote sensing tool. It has a broad range of applications and is extremely well suited for coastal zone monitoring. One noteworthy application of lidar technology is the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system (Guenther *et al.*, 1998). This bathymetric mapping application uses a technique known as airborne lidar bathymetry (ALB) or airborne lidar hydrography (ALH) where lidar is employed to rapidly and accurately measure seabed depths and topographic elevations, surveying large areas and far exceeding the capabilities and efficiency of traditional coastal survey methods (Guenther *et al.*, 1998).

In addition to these digital technologies, thermal remote sensing, operating primarily in the 8-14 μm but also in the 3-5 μm wavelength region of the spectrum produces data that aid in identifying materials by their thermal properties. Finally, radio detection and ranging (radar), an active microwave system, has been flown on both military and civilian platforms because of its ability (for certain wavelengths) to penetrate clouds. Aircraft-mounted synthetic aperture radar (SAR) is the most popular radar device used in littoral mapping operations.

Sensor Data Obtained with UAVs

Although the use of aerial photographs and digital images for littoral applications has seen modest increase over the past few years, UAV exploitation has grown tremendously. The ability to provide real-time or near real-time data about the terrain they fight on and the enemy they face has always been a goal of the military intelligence community (Mahnken, 1995). Unmanned aerial vehicles have made that goal a reality at many levels of war, becoming a valuable tool for Army and Marine Corps planners and ground commanders in preparation and execution of missions. With increasingly more UAVs populating the littoral battlespace, coupled with robust communications systems for distribution of the information they gather, these data may soon be available to every soldier and marine.

Unmanned aerial vehicles are remotely piloted or self-piloted aircraft that carry cameras, sensors, communications equipment or other payloads (Reinhardt *et al.*, 1999).

Not a new idea, the UAV has been employed by military units since the late 1950s (Pike, 2003b). Until the last 15 years, however, their usefulness was viewed as limited because the analog data they collected were not accessible (in most all cases) until after they returned from their missions. Digital technology changed this paradigm. As a result, since the early 1990s, DoD has employed UAVs to satisfy surveillance requirements in close range, short range and endurance categories. Initially, close range was defined to be within 50 km; short range was defined as within 200 km; and endurance range was set as anything beyond. By the late 1990s, the close and short range categories were combined. The current classes of these vehicles are the tactical UAV and the endurance category.

Numerous digital multispectral, hyperspectral and radar sensor platforms are used on-board both tactical and endurance UAVs for military applications in littoral regions. As the ability to move data quicker and in greater volume improves, military commanders now receive current details of battlefield events like never before. Commanders are trained warfighters; they have a basic understanding of aerial photos/video, but are *not* trained in the interpretation of IR and radar data. For simple utility purposes, much of the tactical data gathered for military use by these systems are high-resolution multispectral images, predominantly from the visual portion of the electromagnetic spectrum. Average spatial ground resolutions now routinely achieved by these systems are on the order of one metre. Systems collecting IR, thermal and radar data are quickly approaching similar resolutions (FAS, 1996).

In all cases of UAV employment, tactical control stations (TCS) are used to control the vehicles and their on-board systems. The TCS is the hub where all software and communications links reside as well as connectivity links to other battlefield command, control, communication, computers and intelligence (C4I) systems (FAS, 1999b).

Tactical commanders routinely control UAVs from within their command posts. Three tactical UAVs (TUAVs) are discussed here. The Pioneer was procured beginning in 1985 as an initial UAV capability to provide imagery intelligence for tactical commanders on land and sea at ranges out to 185 km. Used temporarily by the Army, it is currently only used by the U.S. Navy (FAS, 2000a). The Outrider was designed to provide follow-on, interim support to Army tactical commanders with near-real-time imagery intelligence at ranges up to 200 km (Figure 2.5). This system, still in limited use, helped developers create the systems' capabilities requirement for future TUAV design (FAS, 2000b). The resulting product, now in extensive use, was the Joint Tactical UAV or Hunter (Figure 2.5). This system was developed to provide ground and maritime forces with real-time and near-real-time imagery intelligence at ranges up to 200 km and extensible to 300+ km by using another Hunter as an airborne relay (FAS, 2001a). Detailed capabilities of these three systems are provided in Appendix 2, Table A.

Figure 2.5. The Outrider (left) and Hunter (right) Tactical UAVs (TUAVs) (from FAS, 2000b and FAS, 2001a, respectively)

Complementing TUAVs, Endurance UAVs have seen tremendous application and experienced great success over the past five years for military commanders, particularly in Afghanistan and Iraq. The medium altitude endurance UAV is called the Predator (Figure 2.6). This vehicle provides imagery intelligence to satisfy Joint Task Force and Theater commanders at ranges out to 830 km (FAS, 2001b). Global Hawk (Figure 2.6) and Darkstar are high altitude endurance UAVs. These latter two vehicles are used for missions requiring long-range deployment, wide-area surveillance or prolonged acquisition over the target area. They are both directly deployable from the continental United States (CONUS) to any theater of operations (FAS, 1999a; FAS, 2001c). Detailed capabilities of these three systems are provided in Appendix 2, Table B.

Figure 2.6. The Predator (left) and Global Hawk (right) endurance UAVs (from FAS, 2001b and FAS, 1999a, respectively)

Micro unmanned aerial vehicles (MAV) are currently under development. Experiments are being conducted to explore the military relevance of MAVs for future operations and to develop and demonstrate flight-enabling technologies for very small aircraft (less than 15 cm in any dimension) (FAS, 2000c). As portable systems capable of receiving and utilizing image data proliferate the littoral battlefield, data volume will continue to be a challenge. Communication systems designed to monitor, control and filter bandwidth at different levels of warfighting (strategic, operational or tactical) will play critical roles in "moving" the data.

When combined, the aerial reconnaissance data collection methods provide an important resource for populating LW databases. These technological benefits offered by the various systems are a tremendous improvement to the intelligence assets available to military forces only a few years ago.

Satellite Reconnaissance

There are a growing number of satellites orbiting the earth, collecting coastal data and returning it to ground stations all over the world. Satellite remote sensing has the ability to provide complete, cost-effective, repetitive spatial and temporal data coverage. Tasks such as the assessment and monitoring of littoral conditions can be carried out over large regions. Classified and, increasingly, unclassified, systems have and continue to be successfully used by intelligence organizations to provide critical information to military units.

<u>Classified Systems</u>

Satellite imaging systems have long been the workhorse of the military intelligence community. Classified satellite systems are primarily used for the collection of intelligence information about military activities of foreign countries. These satellites can detect missile launches or nuclear explosions in space and acquire/record radio and radar transmissions while passing over other nations. There are four basic types of reconnaissance satellites: (1) optical-imaging satellites that have light sensors designed to detect enemy weapons on the ground; (2) radar-imaging satellites that are able to observe the Earth through cloud cover; (3) signals-intelligence or ferret satellites that are sophisticated radio receivers capturing the radio and microwave transmissions emitted from any country on Earth; and (4) relay satellites that make military satellite communications around the globe much faster by transmitting data from spy satellites to stations on Earth (Galactics, 1997). The first two will be discussed in detail as part of this review.

Starting in the 1960's, the U.S. began launching reconnaissance satellites. The first series was called Discoverer. As these satellites circled the Earth in polar orbits, on-board cameras recorded photographs (Pike, 2000). The next series of U.S. spy satellites was given the code name Keyhole, or KH for short. They mostly performed routine surveillance or weapons targeting. Traveling in elliptical orbits at low altitudes of 140 km at perigee, they either took wide-area photographs of large land masses or close-up photos of special interest objects (MacDonald, 1995; Pike, 2000). The early KH satellites – Corona, Argon, and Lanyard – were used through the early 1970's to assess the Soviet Union’s long-range bombers and ballistic missile production and deployment (MacDonald, 1995; Pike, 2000). The resulting photographs were used to produce maps and charts for DoD and other U.S. government mapping programs.

In June 1971, the KH-9 satellite deployed. Weighing 30,000 pounds and placed in an orbit that at times came within 150 km of the Earth, it was nicknamed Big Bird because of its extraordinarily large size (Figure 2.7). Big Bird employed two cameras to obtain both area-surveillance images and close-up photos. On the latter photos, it was reported that objects as small as 20 cm could be distinguished (MacDonald, 1995; Pike, 2000). The Big Bird satellites were launched at the rate of about two a year from 1971 to 1984; 19 successful launches were followed by one failure, on April 18, 1986, in which the booster exploded after takeoff. The Big Bird's major limitation was its relatively short life span, which started out at some 52 days. By 1978, it was extended to 179 days and the average orbital life was 138 days with a maximum of 275 days achieved in 1983 (MacDonald 1995; Pike, 2000).

In the early 1970s, another major U.S. classified initiative, the Defense Satellite Program (DSP), was established (Figure 2.7). The satellites from this program, a key part of North America's early warning system, detect missile launches, space launches and nuclear detonations. Operated by Air Force Space Command, the satellites feed warning data to North American Aerospace Defense Command (NORAD) and U.S. Space Command early warning centers at Cheyenne Mountain Air Force Base, Colorado. The first launch of a DSP satellite took place in the early 1970s and, since that time, they have provided an uninterrupted early warning capability to the United States. The system's capability was demonstrated during Desert Shield/Storm when the satellites detected the launch of Iraqi SCUD missiles, provided warning to civilian populations and coalition forces in Israel and Saudi Arabia (USAF, 2004).

Figure 2.7. Artist renderings of two classified satellites
(Big Bird - left and DSP - right)

In December of 1988, NASA launched the $500-million Lacrosse satellite. Lacrosse's main attribute, like most spy satellites, is its image sensor. Lacrosse uses SAR technology, allowing it to see objects only one metre across. That level of detail is necessary to identify military hardware. When doing imaging, instead of providing a constant stream of images, like most radars, Lacrosse records a series of snapshots as it arcs over the Earth (Pike, 2000). Lacrosse also beams microwave energy to the ground and reads the weak return signals reflected into space. This allows the satellite to "see" objects on Earth that would otherwise be obscured by cloud cover and darkness. In order to send out these signals, however, Lacrosse has very substantial power needs. It meets these needs with solar panels larger than would be found on most satellites its size. Lacrosse uses a rectangular antenna, 15 m long and 3 m wide, which is very different from the standard mechanical antenna (Pike, 2000). This antenna is covered by rows and columns of small transmitting and receiving elements that help Lacrosse pick up the faint return signals bouncing back from the Earth. Today, the National Reconnaissance Office continues to design, build, launch and operate classified satellites. Its future looks promising with over $25 billion planned for the next two decades (USAF, 2004).

Unclassified Satellite Systems Producing High-Resolution Images

Although the military has had and continues to have its share of classified satellite programs, commercial systems are now producing data with comparably high spatial resolution (Behling and McGruther, 1998). Historically, remote sensor data with spatial resolutions corresponding to 0.5 – 10 m are required to adequately define the high frequency detail that characterizes the urban scene (Welch, 1982). Littoral warfare databases demand similar detail, as many of the features found in the urban scene are common to LW data sets. Because of their ability to provide high-resolution spatial data, these systems are useful in most mapping applications of littoral zones at large scale.

Resulting images are primarily characterized by significant *spatial* resolution improvements over the well-known Landsat and SPOT satellite images and are useful for mapping applications at large scale (DigitalGlobe, 2004; SpaceImaging, 2004). Three noteworthy high-resolution systems – Ikonos, QuickBird and OrbView-3 - have some unique qualities (Table 2.3 and Figure 2.8). In September 1999, with the successful launch and deployment of Ikonos by Space Imaging, high-resolution satellite images exploded onto the commercial market scene (SpaceImaging, 2004). Just over two years later (October 2001), DigitalGlobe launched the QuickBird satellite (DigitalGlobe, 2004). Ikonos provides panchromatic and 4-band multispectral images of 1 and 4-m resolutions, respectively, whereas QuickBird generates panchromatic images of 0.61 m and multispectral images of 2.44 m pixel resolutions.

OrbView-3, launched in June 2003, has very similar technical capabilities as the Ikonos and QuickBird satellites. The greatest advantage is its repeat cycle, re-visiting (through sensor "pointability") ground tracks every three days to provide extraordinary temporal resolution required for assessing rapidly occurring changes on the Earth's surface (such as flooding or volcanic activity). All of these systems provide high-resolution multispectral data that are suitable for mapping, change detection and the assessment of threats. Stereo images suitable for generating digital elevation models (DEMs) and large-scale mapping also can be obtained (Dial and Grodecki, 2003; Haverkamp and Poulsen, 2003).

Table 2.3. High-Resolution Satellites and their Sensor Systems (Wilson and Davis, 1998; DigitalGlobe, 2004; Orbimage, 2004; and SpaceImaging, 2004)

SYSTEM	Ikonos	QuickBird	OrbView-3	NEMO (planned capabilities)
Date of Launch	Sept. 1999	Oct. 2001	Jun. 2003	Not Determined
Orbital Parameters	Altitude: 681 km Inclination: 98.1 degrees Orbit type: sun-sync. Orbit time: 98 min	Altitude: 450 km Inclination: 98 degrees Orbit type: sun-sync. Orbit time: 93.4 min	Altitude: 470 km Inclination: Orbit type: sun-sync. Orbit time: 98 min	Altitude: 605 km Inclination: TBD Orbit type: sun-sync. Orbit time: TBD
Sensor Parameters	Spatial Resolution 1m (pan) 4 m (XS) Spectral Resolution Panchromatic 0.45 - 0.90 um Multispectral #1: Blue 0.45 - 0.52 #2: Green 0.52 – 0.60 #3: Red 0.63 - 0.69 #4: Near IR 0.76 - 0.90 Radiometric Resolution: 11 - bit Swath Width: 11 km at nadir	Spatial Resolution 61 cm (pan) 2.5 m (XS) Spectral Resolution Panchromatic 0.445 - 0.90 um Multispectral #1: Blue 0.45 - 0.52 #2: Green 0.52 – 0.60 #3: Red 0.63 - 0.69 #4: Near IR 0.76 - 0.89 Radiometric Resolution: 11 - bit Swath Width: 2.12 degrees (nominal 16.5 km at nadir – can be 14 – 34 km; altitude dependent)	Spatial Resolution 1m (pan) 4 m (XS) Spectral Resolution Panchromatic 0.45 - 0.90 um Multispectral #1: Blue 0.45 - 0.52 #2: Green 0.52 – 0.60 #3: Red 0.625 - 0.695 #4: Near IR 0.76 -0.90 Radiometric Resolution: 11 - bit Swath Width: 8 km at nadir	Spatial Resolution 5 m (pan) 60 or 30 m (XS) Spectral Resolution Panchromatic 0.45 - 0.90 um Multispectral 200 bands from 0.4 to 2.5 um Radiometric Resolution: 11 - bit Swath Width: unknown
Data Parameters	Scene Size: 13km by 13km	Scene Size: 16.5 km by 16.5 km in-orbit stereo pairs	Scene Size: User defined	Scene Size: unknown

Figure 2.8. Left to right: Ikonos, QuickBird and OrbView-3 high-resolution satellites (SpaceImaging, 2004; DigitalGlobe, 2004; Orbimage, 2004)

Future Systems for Littoral Operations

The Office of Naval Research (ONR) and the Naval Research Laboratory (NRL) have initiated a Hyperspectral Remote Sensing Technology (HRST) program to demonstrate the utility of a hyperspectral Earth-imaging system to support Naval needs for improved characterization of the littoral regions of the world (Wilson and Davis, 1998). One key component of the HRST program will be the development of the Naval EarthMap Observer (NEMO) satellite system to provide a large hyperspectral database for ocean and littoral areas (See Table 2.3). The NEMO system is designed to provide for improved identification of features imaged in water by combining a high-resolution Panchromatic Imager (5-m resolution) and the Coastal Ocean Imaging Spectrometer (COIS) to record co-registered images for a 30-km swath width from an altitude of 605 km. The COIS will provide images of littoral regions at 30- or 60-m spatial resolution in 210 spectral channels over a bandpass of 0.4 to 2.5 μm.

A unique aspect of NEMO will be an on-board processing system (Wilson and Davis, 1998). It essentially is a feature extraction and data compression software package known as the Optical Real-Time Spectral Identification System (ORASIS). The ORASIS employs a parallel, adaptive hyperspectral method for real time scene characterization, data reduction, background suppression and target recognition. The planned use of ORASIS will be essential for management of the large amounts of data expected from the NEMO Hyperspectral Imagery (HSI) system and for developing Naval products under HRST. The combined HSI and panchromatic images are expected to provide additional information to aid in the operation of Naval systems in the littoral environment. Specific areas of interest for the Navy include bathymetry, water clarity, bottom type, atmospheric visibility, bioluminescence potential, beach characterization, underwater hazards, total column atmospheric water vapor, and detection and mapping of sub-visible cirrus (Wilson and Davis, 1998).

Integration and Application of Data in Littoral Environments

Geographic information system technology allows for the use of digital data in developing and employing tailored, current battlefield information to Marine commanders operating in littoral regions. Over the past ten years, DoD has done work in GIS, focusing primarily on database design/population and software development (Satyanarayana and Yogendran, 2001). Numerous digital data formats are available for incorporation into large-scale littoral mapping projects. Previously discussed, many of these are the result of various data collection methods currently in use; they facilitate military and civilian organizations supporting DoD in this effort.

Limited GIS analysis has been effectively demonstrated for garrison operations at Camp Lejeune. The need arose to select a mechanized assault course to provide a specific type of experience to Marines stationed at the base. Using GIS analysis techniques, a USMC planning team was able to evaluate and select a course layout/route. Their work also facilitated the completion of a preliminary review required by the Environmental Protection Agency (EPA) within a few weeks instead of months, the time it typically takes to manually compile and analyze the required data (GISO, 2001). In this way, training was neither delayed nor prevented. Similar techniques were used to assess environmental impacts of projects to install a natural gas pipeline, implement fiber optics cable for base-wide communications and expand existing tank trails and maneuver areas. This afforded base personnel from multiple organizations with the impressive capability to successfully answer questions related to geographic inventory, analysis and modeling (GISO, 2001). Although garrison operations are important, this example does not demonstrate the possible applications of GIS for military commanders. The remainder of this review will focus on the relevant GIS functions for use in combat operations followed by a discussion of current and planned developments of GIS technology for our armed services.

GIS and its Role

Two major components of a GIS include: (1) a geographic database; and (2) software that includes different types of analysis functions. These spatial analysis functions distinguish a GIS from other information systems (Peuquet and Marble, 1990).

The analysis functions use the spatial and non-spatial attributes in the database to answer questions about the changing world, facilitating the study of real-world processes by developing and applying models (Burrough and McDonnell, 1998). Such models often illuminate underlying trends in geographic data, making new information available and communicated through digital maps. The organization of databases into map layers provides rapid access to data elements required for geographic analysis.

There are four major groups of analytical functions: (1) data query; (2) overlay operations; (3) neighborhood analysis; and (4) connectivity operations (Aronoff, 1991; Maguire *et al.*, 1991; Lo and Yeung, 2002). Critical to military operations, the rapid, selective retrieval, display, measurement and reclassification of information from a database (data query) are fundamental to every GIS (Figure 2.9). Overlay operations are important as well to military decision makers. Just as plastic acetate attached to a map has been historically used to show different components of the battlefield, overlay functions efficiently integrate layers of geospatial data and result in the creation of new spatial elements (Figure 2.10).

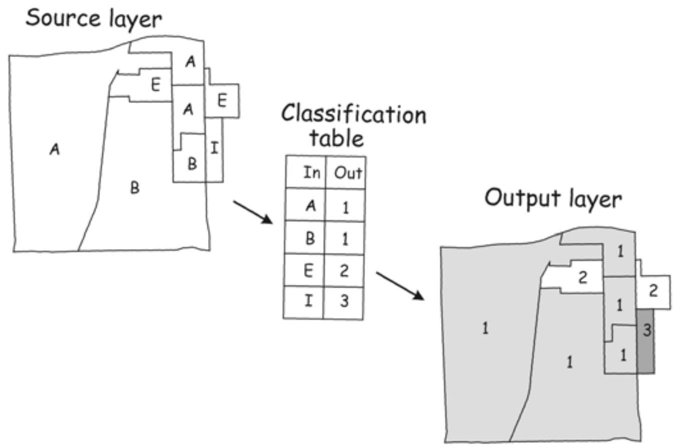


Figure 2.9. The data query and reclassification operation allows a user to take a source layer as foundation spatial data and generate a new output layer (Bolstad, 2004)

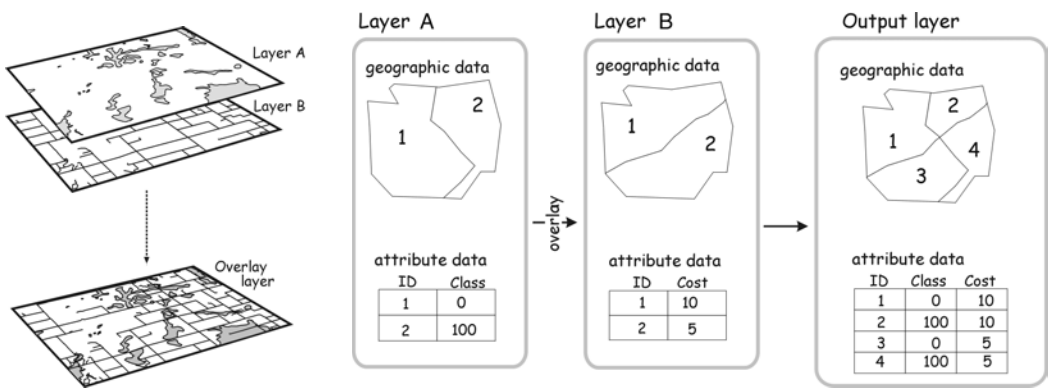


Figure 2.10. An overlay operation – where two source layers are joined ("unioned") in order to produce a combined output layer (Bolstad, 2004)

Neighborhood analysis involves the search and assessment of geospatial data surrounding a target location followed by calculation and/or assignment of a value. DEM generation – the interpolation of a continuous surface from discrete points of elevation for terrain analysis – is an example of a neighborhood analysis that is important in military applications. Finally, connectivity operations are based on interconnecting logical components of a process or model. Those important to military operations include intervisibility (Figure 2.11), seek (or stream) functions (Figure 2.12), buffering (Figure 2.13) and spread analysis.

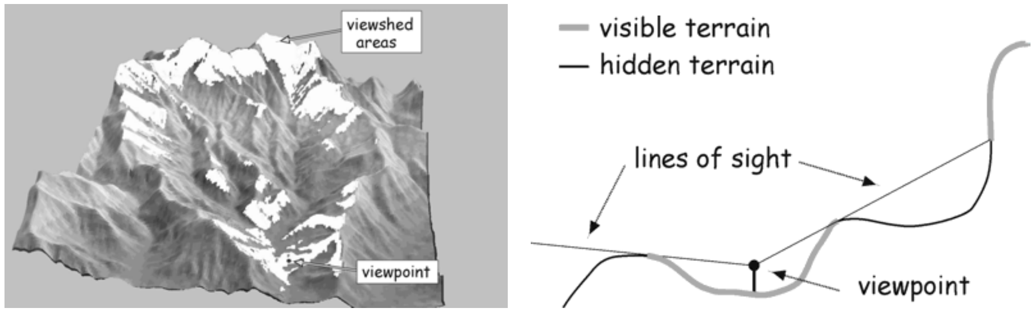


Figure 2.11. Intervisibility operations enable "line-of-sight" analysis (Bolstad, 2004)

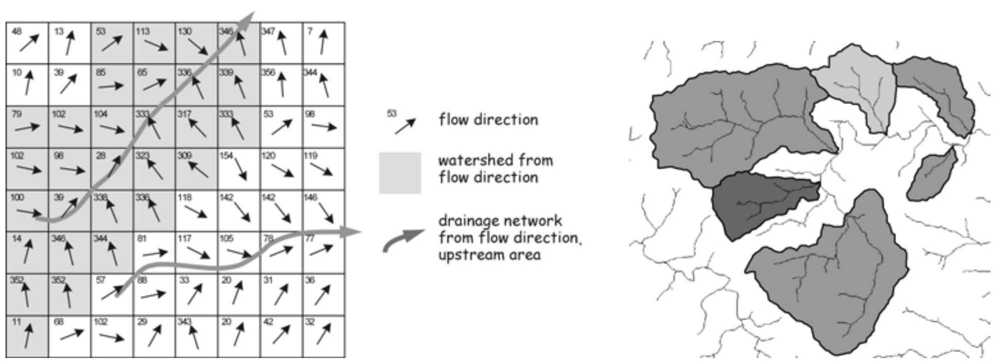


Figure 2.12. Watershed analysis allows the user to determine the direction of water flow over the terrain (Bolstad, 2004)

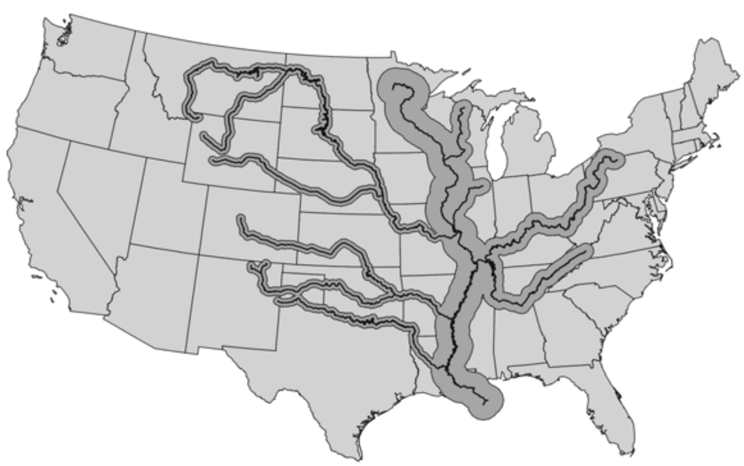


Figure 2.13. Connectivity operations allow for buffers to be placed around critical terrain. In this example, buffers are generated for major U.S. rivers (Bolstad, 2004)

Buffers, calculated circular or square areas from a given point or series of points, are frequently required in combat planning/execution to establish radii or zones around critical locations and key terrain (e.g., weapon impact areas and search & rescue boxes) (ESRI, 1998; ESRI, 2002a). Spread functions evaluate phenomena that accumulate with distance (Aronoff, 1991). One final military application of this type of analysis is terrain trafficability – predicting the time needed to traverse terrain with variable conditions. The trafficability, or ease and speed of movement, varies with the type of ground cover, topography, mode of transport and season of travel (Aronoff, 1991).

Current and Future Military Applications in Armed Services

Substantial research efforts are ongoing by each service employing digitization and GIS analysis to aid in combat decision-making by commanders and their staffs. Full digitization of the battlefield, however, will demand an extensive technological leap – the complete embracing of digital geospatial data and the means of exploiting it with GIS at all levels of war. This condition is, arguably, some time from now. For the foreseeable future, paper maps and GIS will be complementary. The defense community has only been using digital data in training and combat for a few years, primarily confined to strategic and air systems (JCS, 1997). Its use on the battlefield, long predicted, only recently has been leveraged by deployable systems (PEO-C3S, 1997). Tremendous growth is now being realized as the importance of GIS technology on the battlefield is recognized. For the USMC, GIS allows for efficient representation of the ever-changing, littoral battlespace and provides for rapid transmission of that information over their robust communications infrastructure.

In contrast, paper maps, have two major limitations. First, they often do not adequately provide relevant information to individual commanders leading diverse organizations on complex missions and, second, they quickly become out-of-date and therefore, inaccurate. Every paper map represents a compromise between the needs of differing users, none of whom receive the ideal product. Employing GIS, users are able to create (or have created) custom products that depict information that they need (Evans *et al.*, 2000). The modern battlefield changes rapidly; the analog map product cannot. This is a critical limitation on today's fast-moving battlefield where weapon systems are capable of significant alteration of the real world. Geographic information systems help solve this problem only if the problem is clearly acknowledged and effectively addressed. In this, three things must happen. First, proper GIS models of the real world must be developed, validated and implemented. Second, data must be properly maintained. Finally, human intervention must apply a "sanity check" after each step in the decision process; where problems are determined, inspections of the models and/or data are required.

At the direction of NGA, an effort to leverage and consolidate GIS technology for military commanders (in all services) is now being developed. Northrop Grumman is the prime contractor for NGA's Commercial/Joint Mapping Tool Kit (C/JMTK) Program. The C/JMTK will be a standardized, commercial, comprehensive tool kit of software components for the management, analysis and visualization of map and map-related information. The commercial software companies involved in this plan include the Environmental Systems Research Institute, Inc. (ESRI), Leica Geosystems, Analytic Graphics, Inc. (AGI), and Great Circle Technologies. The planned foundation of the

C/JMTK is ESRI's ArcView/ArcObjects framework (which includes Spatial Analyst, 3D Analyst, and Military Overlay Editor (MOLE)), extended by the ArcSDE database engine and distributed by the ArcIMS Internet server. This product will provide a seamless package that will give unprecedented capabilities in viewing map and map-related information along with tools to support the analysis and storage of map data (Birdwell, et. al, 2004). The program plans to integrate the best of government and industry into a common, long-term solution that will advance operational mission application development into the next generation of interoperable systems for the warfighter (ESRI, 2003).

Taking full advantage of such inventions as the C/JMTK, it is envisioned that the Objective Force will operate on four warfighting tenets: (1) see first; (2) understand first; (3) act first; and (4) finish decisively (JCS, 1997; Figure 2.14). Unprecedented intelligence, surveillance and reconnaissance capabilities coupled with other ground, air and space sensors networked into a common integrated operational picture will enable forces to accurately see individual components of enemy units, friendly units and the terrain. Data integration systems will enable decision makers to have a synthesized Common Operational Picture (COP) (JCS, 1997). Using the COP, Objective Force commanders will be able to leverage the intellect, experience and tactical intuition of leaders at multiple levels in order to identify enemy strengths and conceptualize future plans. As commanders decide on a course of action, they will be able to instantaneously disseminate their intent to all appropriate levels, affording maximum time for subordinate levels to conduct requisite troop leading procedures. The time gained through effective use of these information technologies should permit Objective Force units to seize and retain the initiative, building momentum quickly for decisive outcomes.

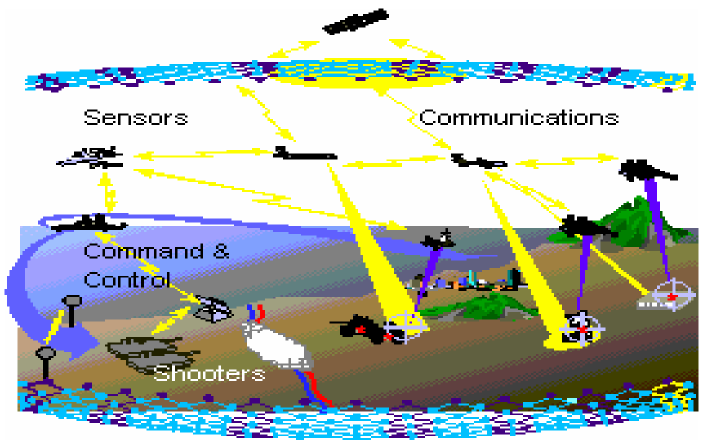


Figure 2.14. “See – Understand – Act - Finish” (JCS, 1997)

Seeing and understanding first gives commanders and their units the situational awareness to engage at times and places with methods of their own choosing. Objective Force units will be able to move, shoot and reengage faster than the enemy. It is planned that target acquisition systems will see farther than the enemy in all conditions and environments. The intent, here, is to deny the enemy any respite or opportunity to regain the initiative. Objective Force units will be able to understand the impact of events and synchronize their own actions. Finally, Objective Force units should finish decisively by quickly destroying the enemy’s ability to continue the fight. Units will be able to maneuver by both ground and air to assume tactical and operational positions of advantage through which they will continue to fight the enemy and pursue subsequent military objectives.

Although these advances will not eliminate battlefield confusion, the resulting battlespace awareness should improve situational knowledge, decrease response time, and make the battlefield considerably more transparent to those who achieve it. The integration of geospatial technologies and GIS will likely provide an improvement in lethality. Commanders will be able to attack targets successfully with fewer platforms and less ordnance while achieving objectives more rapidly and with reduced risk. Strategically, this improvement will enable more rapid power projection. Operationally, within the theater, these capabilities will mean a more rapid transition from deployment to full operational capability. Tactically, individual warfighters will be empowered as never before, with an array of detection, targeting and communications equipment that will greatly magnify the power of small units. As a result, U.S. Forces will improve their capability for rapid, worldwide deployment while becoming even more tactically mobile and lethal.

Conclusions from Literature Review

There are numerous critical and advanced image data collection technologies that now define unprecedented military intelligence, surveillance and reconnaissance capabilities. These advances enhance the detectability of features and targets across the littoral battlespace, improving distance ranging, "turning" night into day for some classes of operations, reducing the risk of friendly fire incidents (fratricide) and further accelerating operational tempo[*] (JCS, 1997). On the horizon, improvements in information and systems integration technologies will significantly impact future military operations by providing decision makers with accurate information in a timely manner. The fusion of information with the integration of sensors, platforms and command organizations will potentially allow operational tasks to be accomplished rapidly and more efficiently.

The purpose of this review was to provide a better understanding of geospatial information for applications in littoral regions by first examining image data collection techniques followed by exploring the role of GIS on the modern battlefield. From this review, it is clear that we have more data than we know what to do with; we can store more data than we can use; we can move data faster than it can be applied; we know when the data are uncorrupted; and our weapons, although very good at minimizing collateral damage, are not as precise as the coordinate data we can currently provide. Two additional questions, however, remain: (1) what information do the data provide; and (2) how can the military best use that information? The two manuscripts that follow help to answer these critical questions.

CHAPTER 3

UNCLASSIFIED IMAGES FOR MILITARY OPERATIONS IN COASTAL ZONES[1]

[1] Fleming, S. and R. Welch. To be submitted to *Photogrammetric Engineering and Remote Sensing*.

UNCLASSIFIED IMAGES FOR MILITARY OPERATIONS IN COASTAL ZONES

ABSTRACT

In order to successfully support current and future U.S. military operations in coastal zones, geospatial intelligence must be integrated to accommodate force structure evolution and mission requirement directives. Coastal zones are complex regions that include sea, land and air features for which the military requires high-volume databases of extreme detail within relatively narrow geographic corridors. Increasingly, unclassified commercially available remotely sensed data in the form of images acquired from conventional aircraft, unmanned aerial vehicles (UAVs) and satellites are being used to populate coastal zone databases. This study was undertaken in conjunction with the National Geospatial-Intelligence Agency (NGA) to assess the suitability of commercially available images for littoral warfare (LW) operations and provide data that show the probabilities for extracting mandatory LW features from the various images. Results indicate that spatial resolution is more important than spectral resolution for effectively populating LW databases. SPOT or Landsat TM images should not be used for LW feature collection as only about 50 percent of all mandated features can be effectively identified. Large- to medium-scale color and color-infrared photos scanned at pixel resolutions from 0.15 m to 1.2 m, QuickBird panchromatic satellite imagery (0.61-m resolution), closely followed by Ikonos satellite image data of 1-m pixel resolution, are the most suitable data for visual LW feature extraction. These images contain adequate detail for mapping at scales of 1:1,000 to 1:10,000.

INTRODUCTION

America's military force structure is dramatically changing as, collectively, the U.S. armed forces undergo a major transition from what the military has termed, a "Legacy Force" – built with industrial-age based digital platforms and systems – to an "Objective Force". The latter is designed to capitalize on information-age based technologies such as satellite imagery, digital maps, state-of-art communications and global positioning systems (GPS)(JCS, 1997). At all three major levels of command – strategic, operational and tactical – commanders are utilizing data collected by spaceborne and airborne systems to successfully attain real-time (or near real-time) knowledge about the geography of potential battlefields and both the capabilities and intentions of adversaries operating therein (NIMA, 2003) (Figure 3.1).

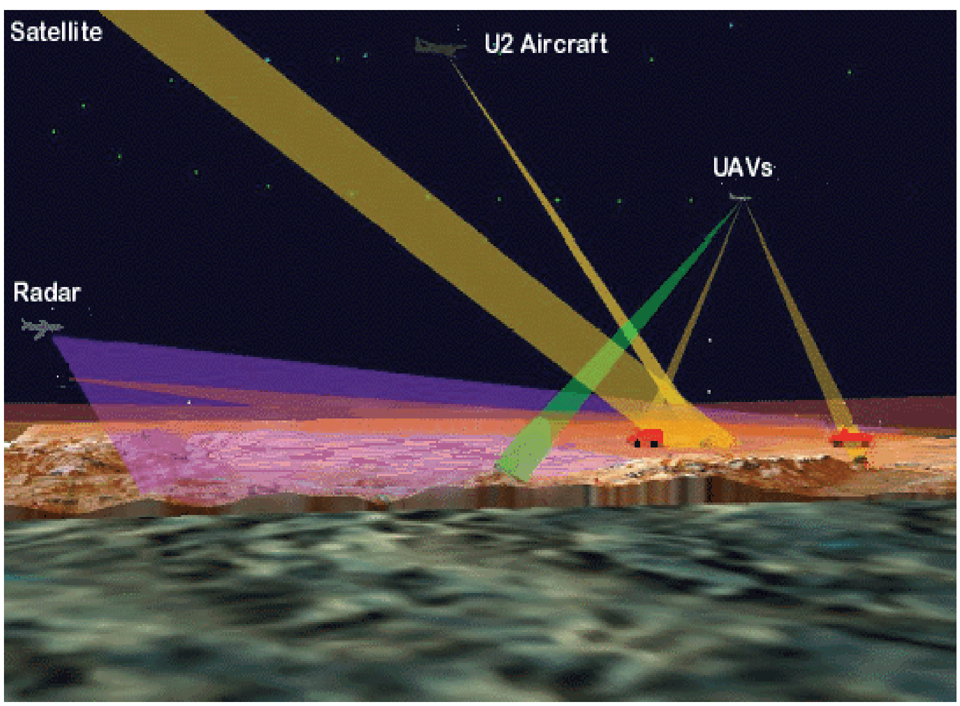


Figure 3.1. The integration of data from spaceborne and airborne systems (adapted from NIMA's Geospatial Intelligence Capstone Document, 2003).

One battlespace of concern is the coastal zone – a complex region that includes sea, land and air features. It is important to note that in coastal regions of potential conflict there is a growing requirement for detailed databases of designated 3-8 km wide corridors referred to as littoral penetration points (LPPs). These LPPs extend from the 15-20 m depth curve to 5-10 km inland (Figure 3.2; NIMA, 2002). The National Geospatial-Intelligence Agency (NGA), formerly the National Imagery and Mapping Agency (NIMA), specifies that littoral warfare (LW) databases for LPPs must include features compatible with 1:5,000-scale map products plotted to within +/- 5 m of their correct planimetric positions as referenced to the World Geodetic System of 1984 (WGS84) datum (Zimmer, 2002). Increasingly, unclassified commercially available remotely sensed data in the form of images acquired from conventional aircraft and satellites are being considered for use in constructing these coastal zone databases.

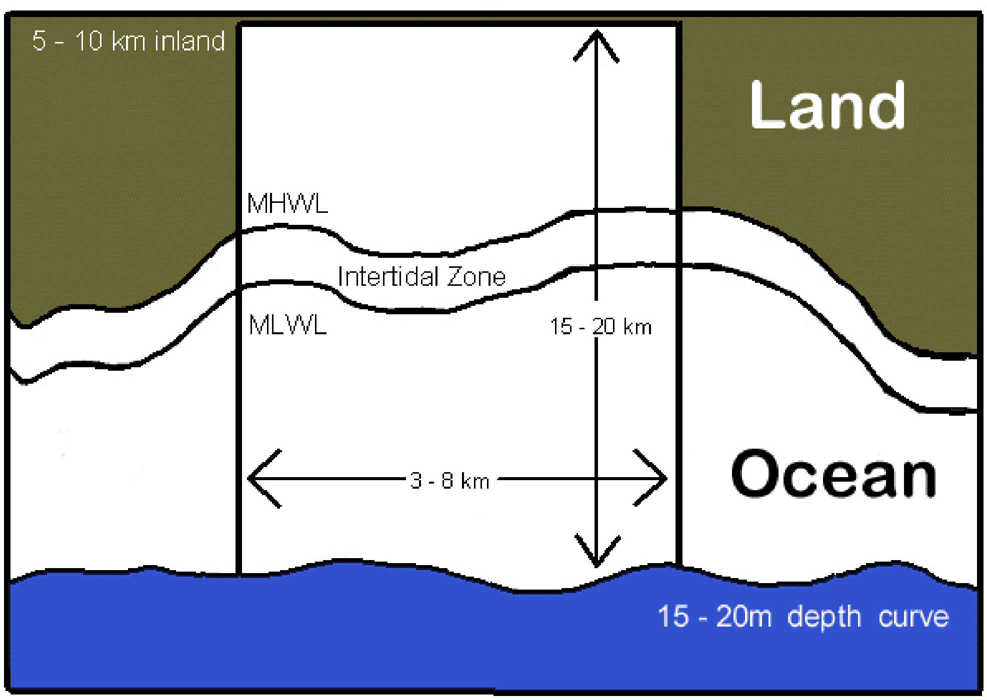


Figure 3.2. Schematic of a littoral penetration point (LPP) as defined by NGA.

In September 1999, with the successful launch and deployment of Ikonos by SpaceImaging, high-resolution satellite imagery exploded onto the commercial market scene (SpaceImaging, 2004). Just over two years later in October 2001, DigitalGlobe launched the QuickBird satellite (DigitalGlobe, 2004). Unclassified high-resolution satellite images now provide a legitimate alternative to classified satellite images and aerial photographs for many applications. Table 3.1 provides an assessment of high-resolution satellite imaging systems, noting the advantages and disadvantages inherent in their use.

Table 3.1. Inherent Advantages and Disadvantages of
High-Resolution Satellite Systems Relative to Aircraft-Mounted Systems.

Advantages	Disadvantages
Operational 365 days of the year	Image spatial resolution is low (when compared to large scale aerial photographs)
No extra expense is incurred in attempting more than one capture; no aircraft, cameras or other expensive equipment are required	The typical off-nadir viewing angle of up to 25° may not be acceptable in a dense urban area – or where the DTM is not perfect
Satellite orbit and sensor pointability enable frequent re-visit times (~ every 4 days)	The reliability of capture and delivery of images is an unknown quantity
Imagery is post-processed relatively quickly. Footprint is sufficient to reduce the need for block adjustment and the creation of image mosaics	Production processes required for high-resolution satellite images may be different to those of traditional photogrammetric data capture – extra equipment, different production flow-lines and more training may be required
No air traffic control restrictions apply; satellite can easily access remote or restricted areas	Strong possibility of cloud cover in tropical regions; completely cloud-free images will be rare in these areas

High-resolution satellite images are primarily characterized by significant *spatial* resolution improvements over past-generation satellite images (e.g., Landsat and SPOT). Ikonos, for example, provides panchromatic and multispectral images of 1- and 4-m resolution, respectively, whereas QuickBird generates panchromatic images of 0.61-m and multispectral images of 2.44-m pixel resolutions (SpaceImaging, 2004; DigitalGlobe, 2004). These systems provide high-resolution and multispectral data that are suitable for monitoring and assessment of threats, mapping and change detection and also stereo images suitable for large-scale mapping (Dial and Grodecki, 2003; Haverkamp and Poulsen, 2003). The spatial, radiometric, spectral and temporal resolutions of Ikonos and QuickBird images are noted in Table 3.2.

Table 3.2. Ikonos and QuickBird Resolutions:
Spatial, Radiometric, Spectral and Temporal.

Resolution Type	Ikonos	QuickBird
Spatial	1m (Panchromatic) 4 m (Multispectral)	0.61m (Panchromatic) 2.5 m (Multispectral)
Radiometric	11 bit	11 bit
Spectral	**Panchromatic** 0.45 - 0.90 µm **Multispectral** #1: Blue 0.45 - 0.52 #2: Green 0.52 – 0.60 #3: Red 0.63 - 0.69 #4: Near IR 0.76 - 0.90	**Panchromatic** 0.445 - 0.90 µm **Multispectral** #1: Blue 0.45 - 0.52 #2: Green 0.52 – 0.60 #3: Red 0.63 - 0.69 #4: Near IR 0.76 - 0.89
Temporal	Re-visit rate is 3 to 5 days off-nadir and 144 days for true-nadir	Re-visit rate is 1 to 3.5 days depending on latitude at 70-cm resolution and maximum off-nadir angle

Recent evaluations of QuickBird panchromatic images indicate that the detail is sufficient to allow base mapping at scales of 1:2,400 to 1:4,800 and consistent with National Image Interpretability Rating Scale (NIIRS) Level 5/6 specifications (~0.2-m to 0.6-m pixel resolution) (Pike, 1998; Emap International, 2002). The intelligence community utilizes the NIIRS to determine the quality of images and performance of imaging systems. Through a process referred to as "rating" an image, the NIIRS is used by image analysts to assign a number which indicates the interpretability of a given image. Thus, the NIIRS concept provides a means to directly relate the quality of an image to the interpretation tasks for that it may be used. As urban and littoral zones in populated regions contain “high frequency” detail, QuickBird images routinely show small features necessary for mapping at scales of 1:5,000 and larger, such as street centerlines, curb lines, building rooflines, sidewalks, fences and tree/shrub lines (Emap International, 2002).

A major advantage of near-nadir, narrow-angle satellite images is the negligible displacements due to relief. Consequently, in most instances (other than extreme relief), the high-resolution satellite images can be considered orthoimages suitable for mapping, database construction and monitoring/change detection with minimal geometric pre-processing by the user. In pre-launch assessments and subsequent post-launch studies with real images, for example, accuracies of +/- 2 m were realized with GCP-controlled stereo images (Li, 1997; Zhou and Li, 2000; Li *et al.*, 2002; Grodecki and Dial, 2002).

Because of their high resolution and their short revisit cycle (~ 3-4 days), Ikonos and QuickBird satellites generate images suitable for shoreline mapping and change detection in the intertidal zone (Di *et al.*, 2003). However, despite the interest in automated feature extraction techniques, visual interpretation and analysis will be required for the foreseeable future to map shorelines and extract the high level of detail required for potential LPP databases. As open-source images may be used for this work, the objective of this study is to evaluate and rank the suitability of unclassified aerial photographs and commercially available satellite images collected over a study area at Camp Lejeune, North Carolina for the extraction of features typical of those found in the littoral zone and required for the construction of LPP databases.

STUDY AREA

Camp Lejeune (34° 35' N latitude, 77° 18' W longitude) – the largest U.S. Marine Corps (USMC) base in the world – occupies an area of 619 km^2 near Jacksonville, North Carolina (Figure 3.3). Military forces from around the world come to Camp Lejeune on a regular basis for bilateral and NATO-sponsored exercises. There are 54 live-fire ranges, 89 maneuver areas, 33 gun positions, 25 tactical landing zones and a state-of-the-art Military Operations in Urban Terrain (MOUT) training facility (Pike, 2003). As part of the Marine's training infrastructure, Camp Lejeune maintains 23 km of beach capable of supporting amphibious operations.

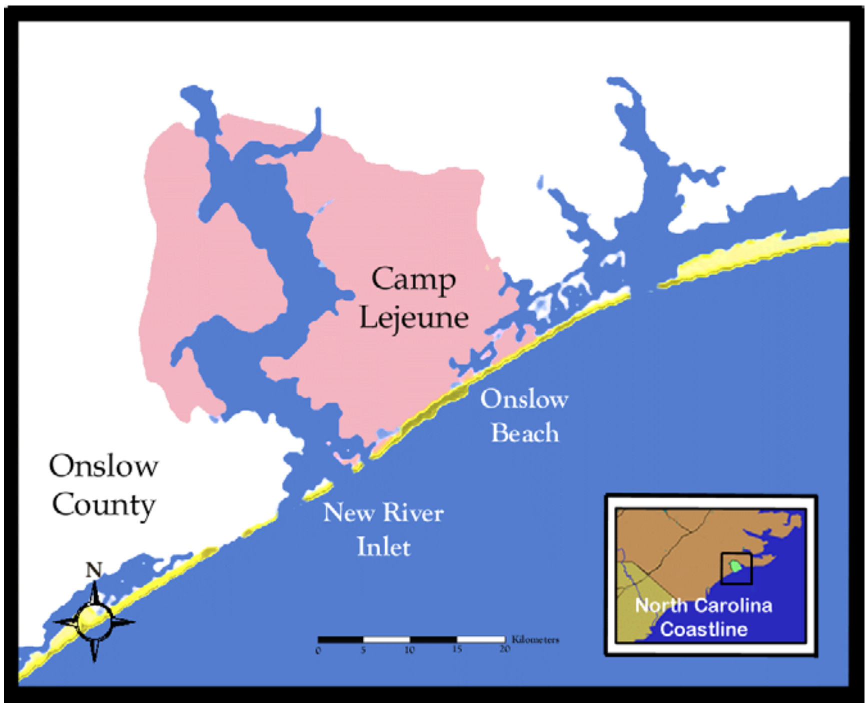


Figure 3.3. Camp Lejeune is located on the Atlantic coast of North Carolina. The study area was Onslow Beach, vicinity of New River Inlet.

The Atlantic Ocean frontage of the base is separated from the mainland by the Intracoastal Waterway. Onslow Beach, the designated LPP site for this project, is part of the Camp Lejeune coastline, and extends northeast for about 10 km from the New River Inlet. The sandy beach has a gently sloping gradient of approximately 5 degrees from a distinct line of sand dunes seaward to depths of greater than 15 m (Figure 3.4). The offshore limit of the study area was defined by the 15-m depth curve. The Intracoastal Waterway separates Onslow Beach and the sand dunes from the mainland.

Inland from the Intracoastal Waterway, terrain is relatively flat, with elevations reaching a maximum of 16 m above mean sea level (MSL). Hardwood and coniferous forests predominate, interspersed with marshes, bare ground, grasslands and built-up areas. A well-established transportation network (improved/gravel roads and vehicular trails) interconnects the region, including cross-country exits along the entire beach (NIMA, 1998).

Figure 3.4. Onslow Beach at Camp Lejeune slopes gently seaward from a line of 5-m high sand dunes. The average beach width is 70 m from the low water to the dune line. Risley Pier can be seen in the background.

GEOGRAPHIC AND IMAGE DATA USED IN RESEARCH

The NGA, the USMC and the Naval Oceanographic Office (NAVOCEANO) provided data for this project. These data sets may be categorized as: (1) remote sensing data; and (2) map and database products. Remote sensing data included SpaceImaging Ikonos images (panchromatic and multispectral), DigitalGlobe QuickBird images (panchromatic and multispectral), SPOT panchromatic images, Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper, Plus (ETM+) images (panchromatic and multispectral), USGS digital orthophoto quarter quadrangles (DOQQs) and scanned color and color-infrared air photos. The latter photographs were recorded under the USGS National Aerial Photography Program (NAPP). Complementing these data, map and database products included Camp Lejeune's Integrated Geographic Information Repository (IGIR), NGA's Littoral Warfare Data (LWD) Prototype 2 data set and the LWD feature specification list for 550 features in 11 different categories where each feature is alphanumerically coded with a Feature Attribute Coding Catalog (FACC) identifier (Chan, 1999; NIMA, 2000; GISO, 2001).

The majority of the data used in this research were the digital images from QuickBird, Ikonos, SPOT and Landsat and the scanned aerial photographs listed in Table 3.3. In total, these data exceeded 18 gigabytes (Gb). Although much of these data were collected at different times, all were geo-referenced to the World Geodetic System of 1984 datum (WGS 84). The Ikonos images were collected in May 2000, whereas the QuickBird images were collected in May 2003. The true color photography was completed in September 1999 and the DOQQs were developed in September 2001. Of note, the color aerial photographs were provide by NGA in digital format, scanned to provide 15-cm pixels. From these data and using Leica Geosystems' ERDAS Imagine software, the merging of panchromatic and multispectral satellite images was accomplished by the CRMS, generating multiple pan-sharpened, false-color images of high spatial resolution (Table 3.3) (Di *et al.*, 2003). Ikonos panchromatic and multispectral images were merged, producing a multispectral image with 1-m spatial resolution. This same procedure was followed with SPOT and Landsat images, yielding two multispectral images, one with 10-m and the other with 15-m spatial resolution.

Table 3.3. Remote Sensing Data Used in Research.

Image	Spatial Resolution	Spectral Bands	Radiometric Resolution	Acquisition
Scanned True Color Photographs	0.15 m	B, G, R	8-bit	Sept 1999
Scanned Color-Infrared Photographs	1.2 m	B, G, R, IR	8-bit	Sept 1999
DOQQs	~ 1 m	Pan	8-bit	Sept 2001
QuickBird Panchromatic Images	0.6 m	Pan	11-bit	May 2003
QuickBird Multispectral Images	2.5 m	B, G, R, IR	11-bit	May 2003
Ikonos Panchromatic Images	1 m	Pan	11-bit	May 2000
Ikonos Pan-sharpened Images	1 m	B, G, R, IR	11-bit	Feb 2003
Ikonos Multispectral Images	4 m	B, G, R, IR	11-bit	May 2000
SPOT Panchromatic Images	10 m	Pan	8-bit	Sept 1994
Landsat TM Panchromatic Images	15 m	Pan	8-bit	Sept 1999
Landsat TM Pan-sharpened Images	15 m	B, G, R, IR	8-bit	Feb 2003
Landsat TM Multispectral Images	30 m	B, G, R, IR	8-bit	Sept 1999
Landsat TM-SPOT Pan-sharp. Images	10 m	B, G, R, IR	8-bit	Feb 2003

METHODOLOGY

A procedure for ranking the image data in terms of potential for extracting features and populating LW databases was developed. Four basic steps were involved: (1) feature selection; (2) establishment of image evaluation criteria; (3) comparative evaluations of images; and (4) consolidation of image evaluations and assessment of results.

Feature Selection

The initial list of littoral features with FACC identifiers was not tied to Camp Lejeune, nor was it referenced to what could be observed on remotely sensed images. Consequently, it was necessary to consider which features were "observable", "possibly observable" or "not observable" on the images of the Camp Lejeune study area based on: (1) likely presence within the study area (e.g., marsh features are present, therefore “observable”); and (2) size as compared to the spatial resolution of the available images. For example, a 0.5-m buoy is likely “not observable” on a 0.6-m QuickBird image, whereas a 10-m helipad would be “observable”. The “observable” and “possibly observable” features were consolidated into a single list of 279 features. From this list, 50 representative point, line and area features in 11 different FACC categories corresponding to aeronautical (AEN), aids to navigation (ATN), defense fortifications and structures (DFS), ground transportation (GTR), inland water (IWA), ocean environment (OEN), physiography (PHY), ports and harbors (PHR), population (POP), utilities (UTL), and vegetation (VEG) were selected as a basis for comparative evaluation of the suitability of the various images for populating LW databases (NIMA, 2000) (Figure 3.5).

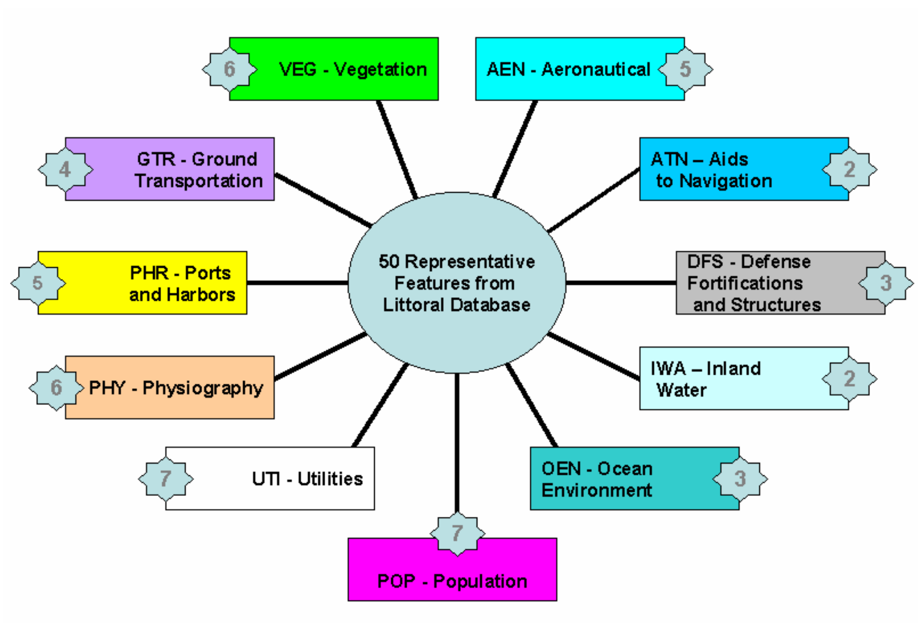


Figure 3.5. Distribution of the 50 representative features across the 11 different categories. The number of selected features from each category is indicated accordingly.

Ground coordinate (X,Y) locations of the 50 features were established from rectified images. This was done to insure that different evaluators would view each feature at a unique, common geographic coordinate on each of the images. Camp Lejeune's Integrated Geographic Information Repository (IGIR) Catalog compiled in July 2001 and NIMA's LWD Prototype 2 data set were frequently referenced in order to establish the correct locations for all 50 features.

Image Evaluation Criteria

Critical to this end, one must appreciate the linkage between interpretability of digital imagery and scale. Scale has been a fundamental measure of the utility and quality of hardcopy images for many decades. However, a digital image file does not have scale *per se*; it can be displayed and printed at many different scales. The scale of digital images is a function of the device and processing used to display or print the file, not necessarily an unalterable property of the image file itself (Comer *et al.*, 1998). Interpreters tasked with extracting features from digital images are interested in knowing what enlargement factors or view scales will yield the best results. Ultimately, enlargement factors and view scales are tied to the resolution of the images, i.e. a "high-resolution" image can be subjected to much greater enlargement factors and hence viewed at larger scale than an image of lower resolution (Welch, 1972; Moore, 2003). Thus, assuming the extraction of littoral features will be accomplished by image analysts in the near term, it was deemed important to establish a rating system that was compatible with NIIRS standards and provided viewing scale (on the computer screen) thresholds that could be associated with the different types of images (Pike, 1998). The rating system determined suitable for this project provided six levels as noted in Table 3.4.

Table 3.4. Image Quality Rating System Based on NIIRS System.

1	High Interpretability	Small features are well-defined. Sharp edges. Image will withstand magnification to scales larger than 1:2,000.
2	Medium-High Interpretability	Small features are adequately defined. Image will withstand magnification to scales larger than 1:5,000.
3	Medium Interpretability	Small features are visible, but not clearly defined. Image will withstand magnification to scales of 1:5,000 to 1:10,000.
4	Medium-Low Interpretability	Small features poorly defined. Image will withstand magnifications to scales of about 1:15,000.
5	Low Interpretability	Small features are not defined/visible. Blurred edges. Image will withstand magnification to scales of about 1:25,000.
6	Not Visible/ No Interpretability	Features not visible, therefore, no Interpretability.

Comparative Evaluation of Images

An image evaluation program was developed to facilitate on-screen image analysis. This program works within ESRI's ArcView/GIS suite and allows an evaluator to simultaneously view a reference image and two other images of choice for comparative assessment (Figure 3.6). Image scales (on the monitor) can be set at any value from 1:100,000 to 1:250 in order to determine optimum viewing scales for the feature. Evaluation results are automatically recorded in a spreadsheet format for future analysis.

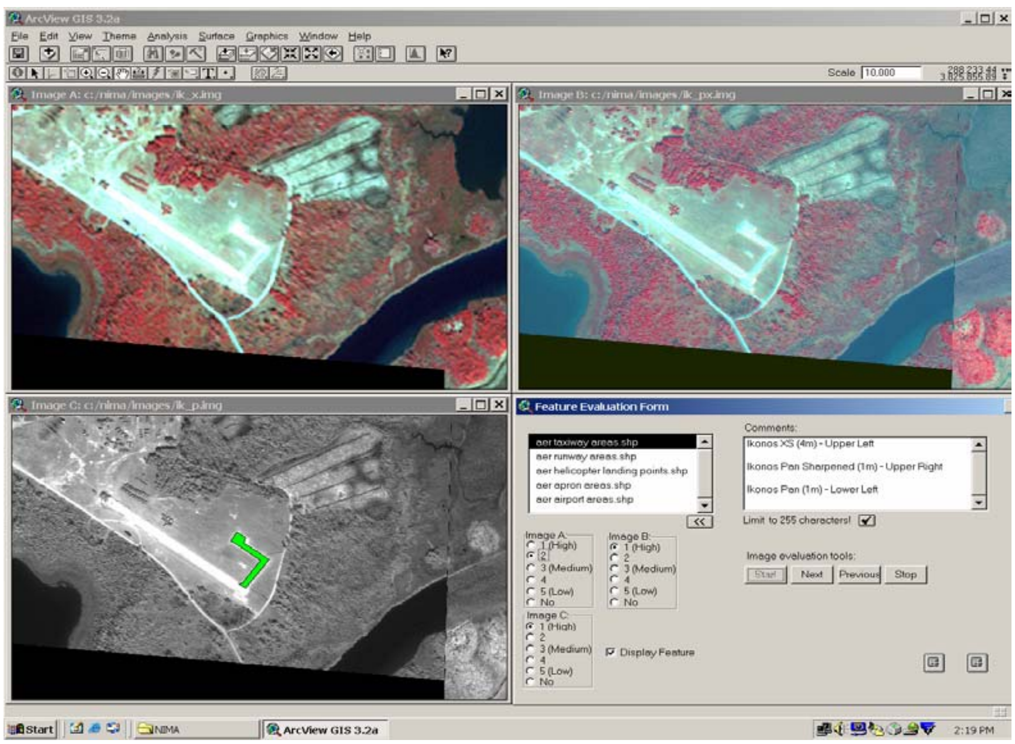


Figure 3.6. Three images can be simultaneously displayed and evaluated at specific scales for given features. In this figure, the airport apron and runway are shown on the reference image, an Ikonos panchromatic scene (1-m, lower left), an Ikonos multispectral scene (4-m, upper left), and an Ikonos pan-sharpened scene (1-m, upper right). The panel in the lower right quadrant provides options for program interaction and for image evaluation on a scale from 1 to 6.

Four individuals with experience in remote sensing, mapping and GIS were trained in common evaluation criteria and employed to conduct the image evaluations. In order to standardize image viewing on desktop monitors, display resolution was set at 1280 x 1024 x 24 bits and cubic convolution specified as the re-sampling algorithm. The evaluators determined optimum viewing scales for the features on each type of image. Optimum viewing scale is defined here as the on-screen scale (by "zooming" in and/or out) where the evaluated feature is most clearly observed. Upon determining the optimum viewing scale, a subjective image quality rating of 1 to 6 (as noted in Table 3.4) was assigned. All 50 features were independently evaluated on each of the images. Figure 3.7 illustrates how a pier feature appears on the various images. The average optimum viewing scale for the pier on the true color image was determined to be 1:625 with a quality rating of 1, whereas an optimum viewing scale of 1:3,300 was determined for the pier on the Ikonos pan-sharpened image and given a quality rating of 3.5.

Consolidation of Image Evaluations and Assessment of Results

In Table 3.5, the assessments of the four evaluators are provided for *average* optimum viewing scale, *average* image quality rating and the percent of features visible on the images evaluated. As might be expected, it is immediately evident that there is a strong relationship between spatial resolution and these other factors. This observation is further reinforced when optimum viewing scale is plotted against pixel dimension (Figure 3.8). The linear relationship on a log-log plot is a convenient means for quickly estimating the appropriate scale to display images of a particular type and resolution, which used in conjunction with the other data in Table 3.5 provides immediate

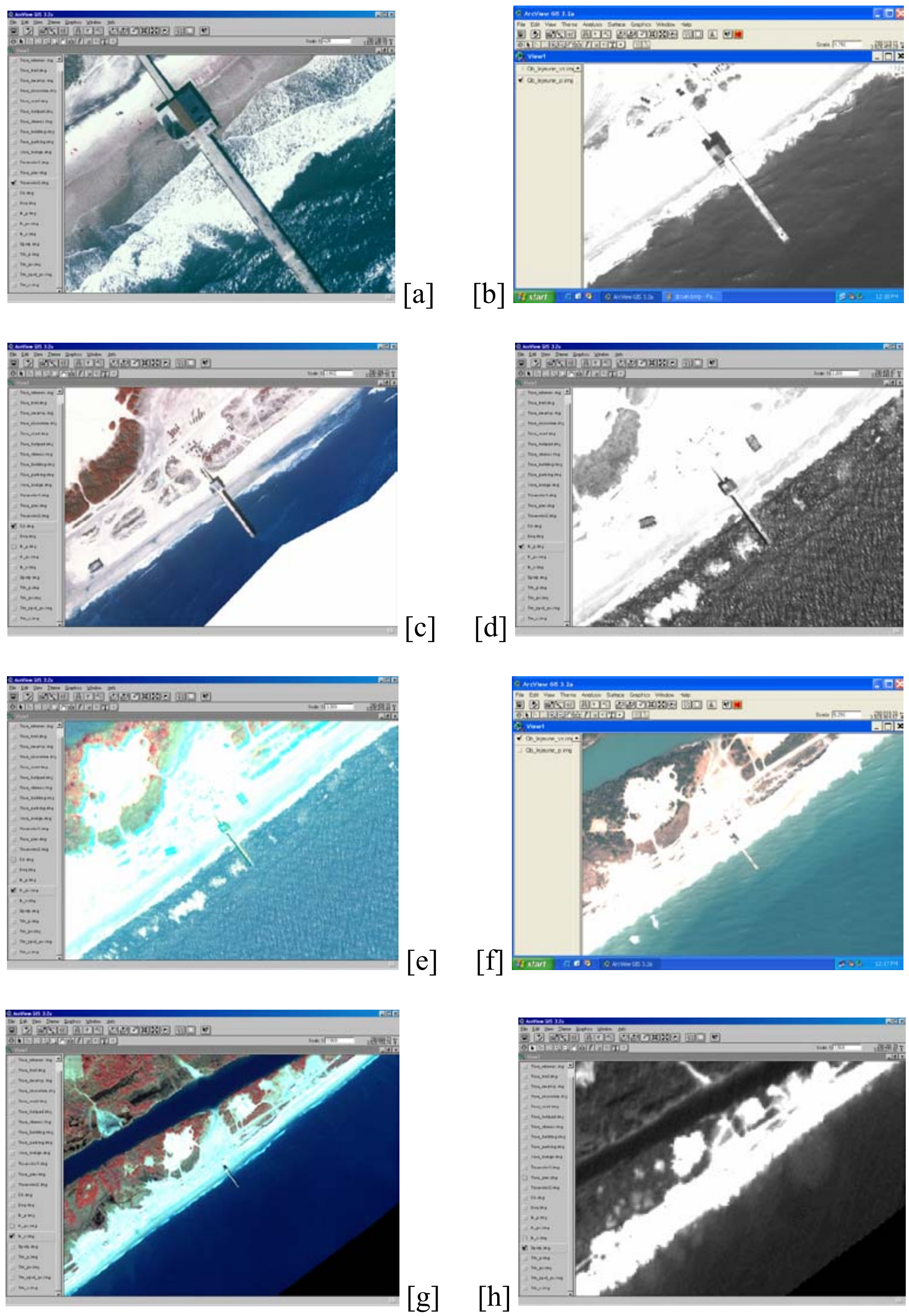


Figure 3.7. The details of Risley Pier are shown here on eight of the thirteen different images used in research. Note how crisp and clear the details are when viewed on large-scale color photographs [a] scanned at a resolution of 0.15 m. Quality of detail continues to diminish as spatial resolution is degraded (QuickBird panchromatic [b], color-infrared photographs [c], Ikonos panchromatic [d], Ikonos pan-sharpened imagery [e], QuickBird multispectral [f] and Ikonos multispectral imagery [g]). Risley Pier is not detectable on the SPOT panchromatic image [h].

Table 3.5. Quantitative Summary of Image Evaluation Results. Average values computed from the consolidation of four independent image evaluations.

Image	Spatial Resolution	Average Optimum Viewing Scale (1/x)	Average Image Quality Rating	Percent of Features *Visible* on Image
True Color Photographs	0.15 m	500	1.18	94%
QuickBird Panchromatic Images	0.6 m	1500	2.07	90%
Color-Infrared Photographs	1.2 m	1750	2.07	86%
Ikonos Panchromatic Images	1 m	1900	2.80	86%
DOQQs	~ 1 m	2000	3.10	86%
Ikonos Pan-sharpened Images	1 m	2300	2.97	86%
QuickBird Multispectral Images	2.5 m	3700	2.71	86%
Ikonos Multispectral Images	4 m	6200	4.02	80%
SPOT Panchromatic Images	10 m	17300	4.80	54%
Landsat TM-SPOT Pan-sharp. Images	10 m	25600	5.43	52%
Landsat TM Panchromatic Images	15 m	26200	5.33	52%
Landsat TM Pan-sharpened Images	15 m	29800	5.44	52%
Landsat TM Multispectral Images	30 m	48300	5.39	48%

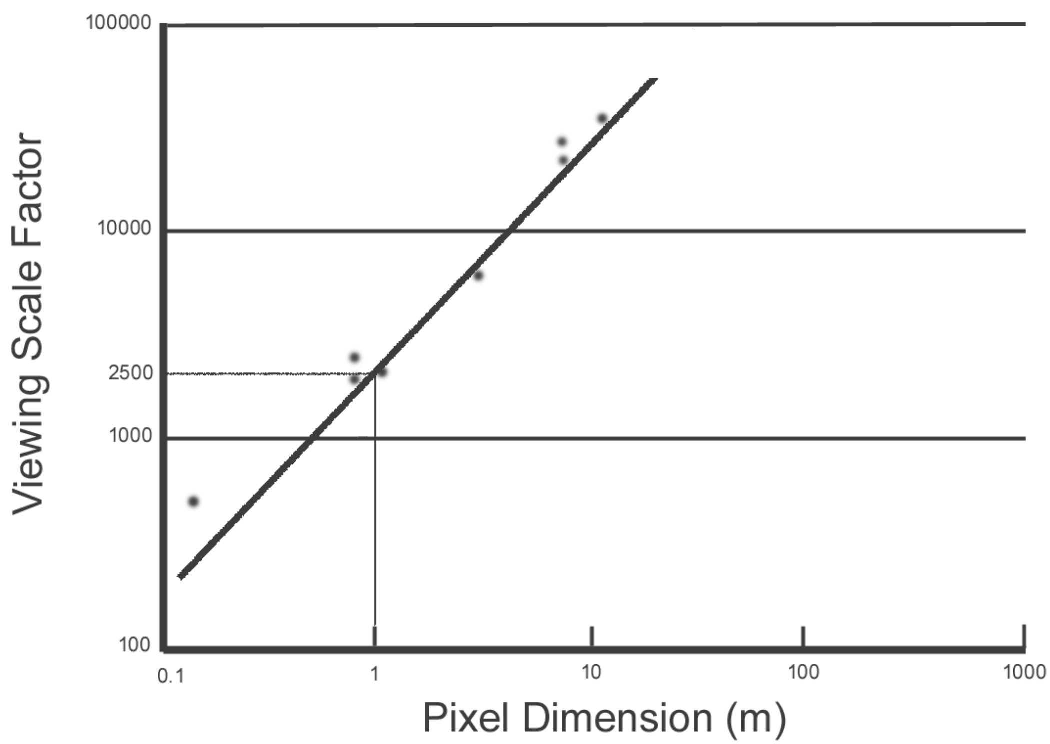


Figure 3.8. Optimum viewing scale for extracting features as a function of resolution (pixel dimension). Images with pixel resolutions of better than 1.0 m, and preferably better than 0.5 m, are needed for compiling detailed LW databases and map products.

indication of the suitability of the images for littoral feature extraction. For example, an image resolution of 0.6 m (e.g., QuickBird panchromatic) or better is required to detect/identify better than 90 percent of the features representative of those required for LW warfare operations and 1 m or better (e.g., Ikonos panchromatic) to detect/identify more than 85 percent. Images such as those obtained from Landsat or SPOT are of relatively little value for preparing detailed databases of potential LPPs. The higher resolution images (better than 1 m) allow viewing scales of 1:2,500 or larger on the computer monitor and permit planimetric positional accuracies of better than +/- 5 m to be realized as stipulated for LW products at scales of 1:5,000 and larger. As shown in Table 3.6, features within the categories corresponding to AER, ATN, DFS, IWA, OEN, POP and UTI require images with spatial resolutions of 1-m or better that will permit viewing scales of 1:2,500 or larger, whereas features from categories corresponding to PHY, PHR, GTR and VEG can be extracted from images with spatial resolutions of 2.5 m or better displayed at viewing scales of between 1:2,500 and 1:3,500.

CONCLUSIONS AND RECOMMENDATIONS

Large- to medium-scale color and color infrared photos scanned at pixel resolutions from 0.15 m to 1.2 m and QuickBird panchromatic satellite images are best viewed at scales of 1:600 to 1:3,000 and are the most suitable data for LW feature extraction and mapping at scales of 1:1,000 to 1:10,000, closely followed by Ikonos satellite image data of 1-m pixel resolution. In practice, it appears image data with pixel resolutions of better than 0.5 m are needed for compiling detailed LW databases and map products. When collecting AEN, DFS, IWA, POP and UTL features, images must be able

Table 3.6. Assessment by Category of Image Evaluation Results. Qualifying comments provide specific notes on features within each littoral warfare category.

Optimum Viewing Scale (OVS)	Category Code	Littoral Warfare Category	Qualifying Comments	Features in Database (Total: 512)
	AER	Aeronautical	Features evaluated visible at all viewing scales.	50
	ATN	Aids to Navigation	No quantitative comparison possible; none of these features evaluated visible at any viewing scale.	32
Larger	DFS	Defense Fortifications and Structures	Majority of these features evaluated visible at most viewing scales; 40 % of features not visible on 10 - 30 m resolution images.	18
Than	IWA	Inland Water	Features evaluated visible at all viewing scales. Multispectral sensor desired.	44
1 : 2,500	OEN	Ocean Environment	Very difficult to detect submerged features. 66 % of these features not visible at any viewing scale.	47
	POP	Population	15 % of these features not visible at any viewing scale. 66 % of features not visible at resolutions greater than 4 m.	69
	UTI	Utilities	30 % of these features not evaluated visible on images with resolutions of 0.6 - 4 m. No features visible on images of 10 m resolution.	73
1 : 2,500	PHY	Physiography	Features evaluated visible at most viewing scales; 50 % of features not visible on images with resolutions of 10 - 30 m.	51
To	PHR	Ports and Harbors	Features evaluated visible at most viewing scales; 60 % of features not visible on images with resolutions of 10 - 30 m.	52
1 : 3,500	GTR	Ground Transportation	Features evaluated visible at most viewing scales; 33 % of features not visible on 30 m resolution images.	51
	VEG	Vegetation	Features evaluated visible at all viewing scales. Multispectral sensor desired.	25

to withstand magnifications to viewing scales of at least 1:2,500, and preferably 1:1,000 or larger. This implies that spatial resolutions (as measured by pixel dimension) of better than 1.0 m are required for the detailed interpretation and delineation of these five feature categories. Additionally, when collecting PHY, PHR, GTR and VEG features, images must be able to withstand magnifications to viewing scales of at least 1:3,500, but not necessarily withstand magnifications greater than 1:2,500. This implies that spatial resolutions (as measured by pixel dimension) of between 4.0 m and 1.0 m are required for the detailed interpretation and delineation of these four feature categories. As it is likely that many potential LPPs will be located in denied areas (defined here as an area where manned or unmanned aircraft is not possible, desired or permitted), QuickBird panchromatic and Ikonos panchromatic images displayed at scales of approximately

1:1,500 offer good potential for compiling LW databases of acceptable completeness and accuracy. Because spatial resolution has proved to be far more important than spectral resolution for effectively populating LW databases, SPOT and Landsat images cannot be considered particularly useful for LW feature collection as they permit identification of only about 50 percent of all features found in the LWD specification list. These pixel resolution and viewing scale thresholds should serve as critically important guidelines for **efficient** extraction of littoral features.

In all cases (regardless of the data source), when conducting detailed coastal zone studies or compiling geographic databases, large data volumes associated with high-resolution images can be problematic. The NGA must be able to rapidly access the best imagery to successfully complete their mission. Data from classified military satellites and other restricted sources were not used in this project. Clearly, the addition of data from these would add more complexity to the data volume problem. Although sorting data is a necessary and important task, the NGA cannot afford to spend precious time retrieving and evaluating the suitability of all possible combinations of image, text and map data sets for each of the potential LPPs around the world. Based on this study, the successful generation of LWD products for LPPs will depend on the availability of skilled personnel with ready access to current high-resolution images at pixel resolutions of better than 1.0 m. In the unclassified domain, these image requirements can be fulfilled with products from Ikonos, QuickBird and comparable satellite systems.

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Requirements (NIMA, 2002). The authors wish to express their appreciation of Dr. Richard Brand's (NIMA) initiative and assistance throughout the project and to Dr. Scott Loomer for his valuable input. The cooperation of numerous Marine Corps and civilian personnel at Camp Lejeune permitted field checks to be completed and database entries to be verified. We would particularly like to thank Master Sergeant Russell Dominessy and Ms. Frances Railey. Finally, we gratefully acknowledge many individuals at The University of Georgia who worked with the CRMS in evaluating images, consolidating data, creating merged digital imagery and organizing paperwork. These include: Dr. Tommy Jordan, Dr. Marguerite Madden, Dr. E. Lynn Usery, Jinmu Choi, Yanfen Le, Yangrong Ling, Thomas Litts, and Virginia Vickery.

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CHAPTER 4

GIS APPLICATIONS FOR MILITARY OPERATIONS IN COASTAL ZONES[1]

[1] Fleming, S., T. Jordan, M. Madden, E.L. Usery and R. Welch. To be submitted to *ISPRS Journal of Photogrammetry and Remote Sensing*.

GIS APPLICATIONS FOR MILITARY OPERATIONS IN COASTAL ZONES

ABSTRACT

In order to successfully support current and future U.S. military operations in coastal zones, geospatial information must be integrated and analyzed to meet ongoing force structure evolution and new mission requirement directives. Coastal zones in a military-operational environment are complex regions that include sea, land and air features that demand high-volume databases of extreme detail within relatively narrow geographic corridors. Static products in the form of analog maps at varying scales traditionally have been used by military commanders and their operational planners. The rapidly changing battlefield of 21st Century warfare demands dynamic mapping solutions. Commercial geographic information system (GIS) software for military-specific applications is now being developed and employed with digital databases to provide customized digital maps of variable scale, content and symbolization tailored to unique demands of military units. Research conducted by the Center for Remote Sensing and Mapping Science (CRMS) at The University of Georgia demonstrated the utility of GIS-based analysis and digital map creation when developing large-scale (1:10,000) products from littoral warfare (LW) databases. The methodology employed – selection of data sources, establishment of analysis/modeling parameters, conduct of analysis, development of models and generation of products – is discussed. Based on observations and identified needs from the National Geospatial-Intelligence Agency (NGA), formerly the National Imagery and Mapping Agency (NIMA), and the Department of Defense (DoD), prototype GIS models for military operations in sea, land and air environments

were created from multiple data sets of a study area at U.S. Marine Corps Base Camp Lejeune, North Carolina. Results of these models, along with methodologies for developing large-scale LW databases, aid NGA in meeting LW analysis, modeling and map generation requirements for U.S. military organizations.

INTRODUCTION

The U.S. military is undergoing tremendous change in order to capitalize on information-age technologies. Leaders are now beginning to apply digital data depicting real-time information about military situations in regional security environments, thereby improving warfighting assessments and decisions. This information includes dynamic weather, image, map, force structure and logistics conditions (NIMA, 2003) (Figure 4.1). United States Marine Corps (USMC) commanders, in particular, are using these technologies to achieve a better understanding of coastal zones, with specific interest on littoral penetration points (LPPs). The National Geospatial-Intelligence Agency (NGA), formerly the National Imagery Mapping Agency (NIMA), defines an LPP as a 3 - 8 km wide lane, extending offshore from the 15 to 20-m depth curve to 5 – 10 km inland (Welch *et al.*, 2003). Historically, in order for commanders to make assessments about these corridors, tremendous effort was necessary to manually consolidate many different analog products created at varying scales to provide a “snapshot” of the battlefield. Today, image processing and GIS techniques permit the rapid generation of LPP snapshots as shown in Figure 4.2. Recognizing that a number of studies have addressed independent military solutions using digital geospatial data, the objective of this study is to demonstrate the utility of GIS analyses, modeling and map creation from a littoral warfare (LW) database of a study area at Camp Lejeune, North Carolina for developing large-scale (1:10,000) products that integrate sea, land and air environments.

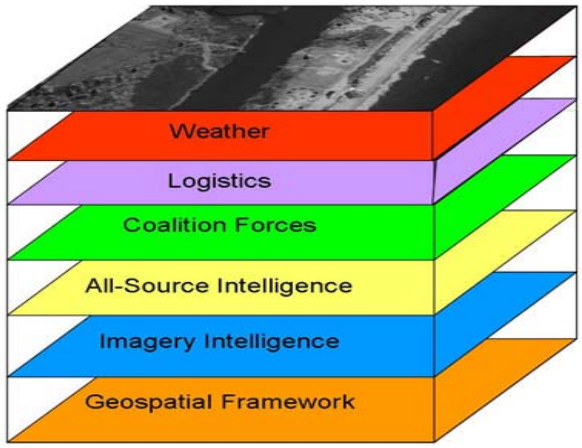

Figure 4.1. Fusion of geospatial data on the modern battlefield (adapted from NIMA, 2003).

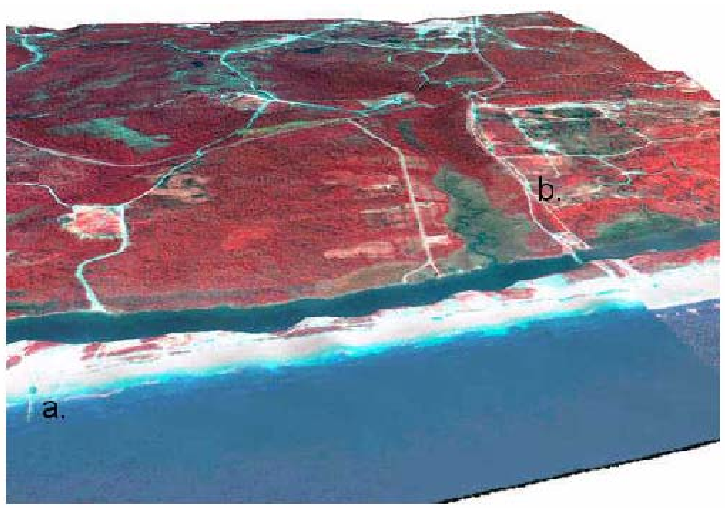

Figure 4.2. An aerial perspective view of the approach to Onslow Beach, Camp Lejeune, North Carolina, created by draping a pan-sharpened Ikonos image over a digital elevation model of the study area. Shown are: Risley Pier – a feature in the intertidal zone [a]; and Onslow Beach Road [b].

Background

The need to understand terrain has always been an essential requirement for military commanders. This understanding has been supported by paper maps enabling military operations for hundreds of years. The imperative to evolve the paper map to the digital environment has included military advances such as motorized vehicles, aircraft and now, digitization (ESRI, 1998). Regardless of the catalyst, the primary need for a map is to support situational awareness; all commanders and their staffs need to understand the battlefield. The map acts as the spatial framework upon which a common situational display is built.

Paper maps have two major limitations. First, they often do not adequately provide relevant information to commanders on complex missions. Second, they quickly become out-of-date and, therefore, inaccurate. Every paper map represents a compromise between the needs of various military commanders, none of whom receives their “ideal” product. Likewise, the real world of the modern battlefield changes rapidly while analog maps remain static. Because map production is costly, not every change results in a new map. These two limitations are detrimental to effective operations on today's fast-moving battlefield where integrated weapons/systems and units are capable of significantly changing the landscape in a short period of time.

Substantial research efforts are ongoing by the Department of Defense (DoD) whereby digitization and use of GIS are being employed to minimize the limitations of analog maps in an attempt to improve combat decision-making (ESRI, 2003). Full digitization of the battlefield, however, will demand the complete embracing of digital geospatial data and the means of exploiting these data with GIS at all levels of war (PEO-C3S, 1997). For the foreseeable future, paper maps and GIS will be complementary, since the military has only been using digital data in training and combat for a few years – primarily confined to strategic and air systems (JCS, 1997; JCS, 1999).

Tremendous growth in use is now being realized as the importance of digital technology on the battlefield is recognized. Within the USMC, GIS permits efficient representation of the features found in the ever-changing, littoral battlespace. Spatial databases, the central storage component in a GIS, accommodate the dynamic conditions of these areas by providing benefits such as a uniform repository of geospatial data, rapid data entry and editing, rich feature context, facilitation of dynamic map display and the capability for many users to edit the data simultaneously (Zimmer, 2002).

Capitalizing on these benefits and at the direction of NGA, an effort to consolidate GIS technology for military commanders (in all services) is now being developed by the Northrop Grumman Corporation (Northrop Grumman, 2002). Called the Commercial/Joint Mapping Tool Kit (C/JMTK), it is designed to be a standardized, commercially-developed, comprehensive tool kit of software components for the management, analysis and visualization of defense-related map and map-related information (ESRI, 2003). When fully deployed, it will provide a seamless package that will give unprecedented capabilities in viewing military map information, along with the tools to support the analysis and storage of map data (Birdwell, et. al, 2004). It is expected to further advance all operational mission application development – not just in littoral regions – into the next generation of interoperable systems for the warfighter (ESRI, 2003).

The rapid exploitation of feature data is critical to operations in the littoral zone. In this context, proper GIS database design, appropriate analysis procedures and effective product generation are needed to facilitate military decision-making capabilities (Zeiler, 1999). Consequently, this project used many of the same software tools found in the

C/JMTK to construct specialized large-scale map products and detailed analyses that demonstrate the potential of GIS for providing useful information about the LPP. Based on observations and identified requirements from NGA and DoD, prototype GIS models of specific sea, land and air environments were created from multiple data sets of a study area at Camp Lejeune, North Carolina. Results of these methodologies for developing large-scale LW databases will assist NGA in meeting needs for future missions conducted by the USMC, sister services and governmental agencies.

STUDY AREA

Camp Lejeune is the largest USMC base in the world, occupying an area of 619 km^2 in coastal North Carolina (Figure 4.3). Separated from the mainland by the Intracoastal Waterway, the ocean frontage of the base includes 23 km of beach and sand dunes (Pike, 2003a). Onslow Beach, a portion of coast extending approximately 10 km north of New River Inlet, is "key terrain" [1] for this study (Figure 4.4).

The "sea environment" of the study area for this research extends from the offshore limit of the 15-m depth curve to the onshore limit of the intertidal zone – the region extending along a shoreline between the high and low waterlines. This zone at Camp Lejeune is characterized by a gently sloping beach gradient of approximately 5 degrees (Figure 4.5a).

Inland, the study area extends 10 km. West of the sand dunes, the terrain is relatively flat with elevations reaching a maximum of 16 m above mean sea level (MSL). The landscape within two km of the coast is interspersed with cypress stands, coastal marshes, bare ground and grasslands (Figure 4.5b). The soil in these lowlands is

[1] a military term meaning any locality, or area, the seizure or retention of which affords a marked advantage to either combatant.

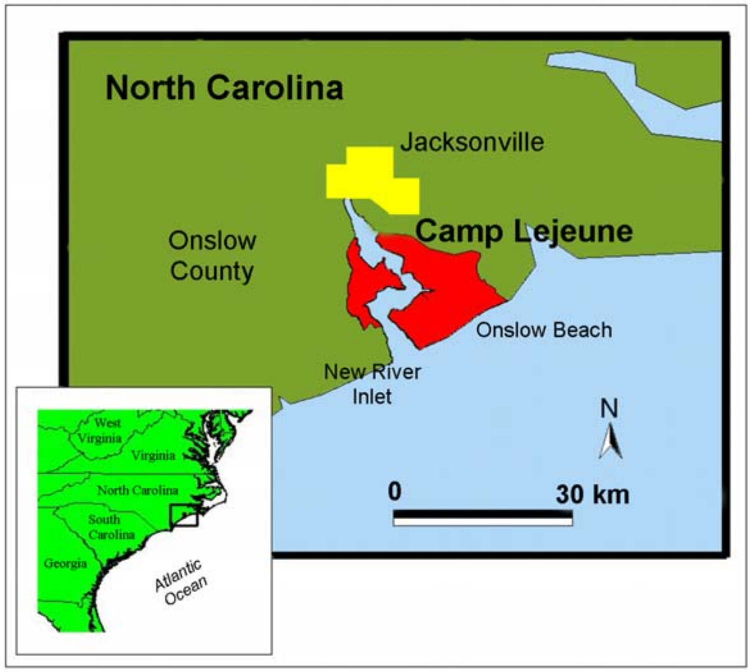

Figure 4.3. Camp Lejeune is located on the Atlantic coast of North Carolina.

Figure 4.4. QuickBird pan-sharpened image of the study area.

predominantly sandy in nature except for the marsh areas where silty soils exist. Further inland (2 – 10 km from the coast) are modest stands of deciduous and coniferous forests with some small lakes, mixed scrub and grasslands (Figure 4.5c). Soils here, sandy in some remote areas, are mainly silty clays and loams. Heavy clay concentrations are rare.

Although the majority of the region is covered by natural features, the study area also includes some cultural features. Small buildings along the beach and other military features exist, including helicopter landing zones, ammunition and equipment storage areas, bivouac sites and a small airstrip. Additionally, a well-established transportation network that includes a mix of improved roads, gravel roads, vehicular trails and walking trails interconnects the region. Access from the beach to this network is possible via cross-country exits between sand dune formations. These beach exits connect vehicular trails extending across the Camp Lejeune training area, most of which are suitable for vehicle traffic. In densely forested areas further inland, heavy vehicles are frequently confined to the established transportation networks (Figure 4.5d) (NIMA, 1998b).

Overall, the study area provides a good example of a littoral environment that is capable of supporting amphibious operations and provides an excellent training site for U.S. and foreign forces engaged in bilateral exercises. Lessons learned here can be applied to LPP assessments in other coastal areas throughout the world.

METHODOLOGY

A procedure for demonstrating the effective use of GIS in generating large-scale products from LW databases employing commercial GIS software was developed. Three basic feature steps were involved: (1) database preparation; (2) map product design; and (3) development of GIS applications for littoral operations.

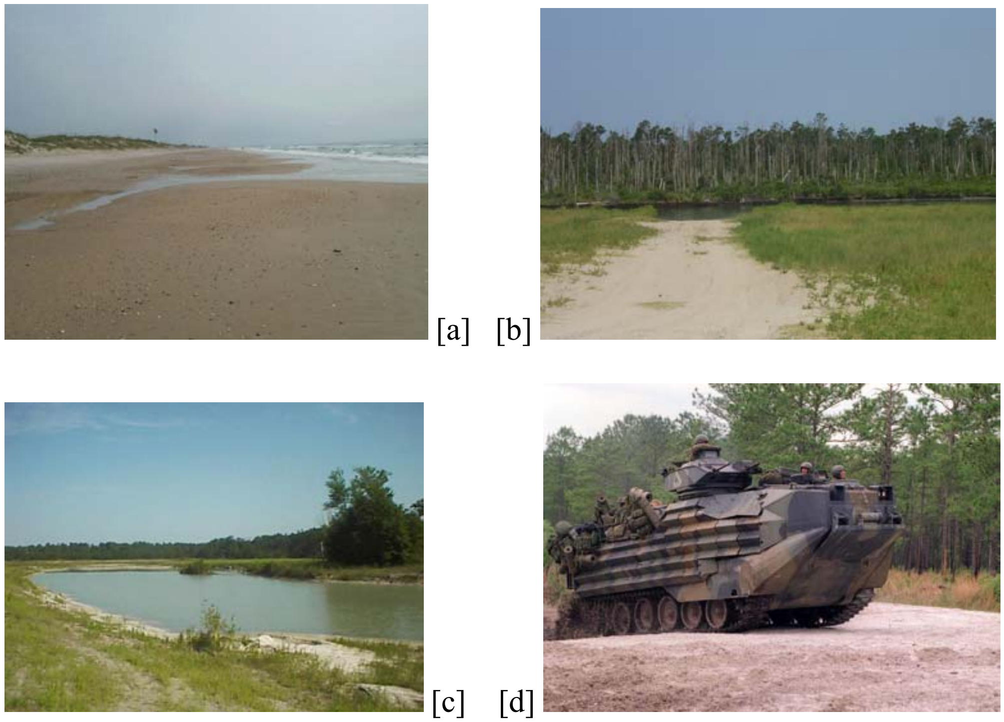

Figure 4.5. Onslow Beach at Camp Lejeune slopes gently seaward from a line of 5-m high sand dunes. Beach widths average 70 m from the low water to the dune line [a]. Lowlands on the base are characterized by cypress stands, marshes, grasslands and some bare ground [b]. Further inland, stands of deciduous and coniferous forests and occasional lakes predominate [c]. A well-established transportation network exists, supporting vehicular movement through heavily wooded areas [d].

Database Preparation

The NGA, USMC and Naval Oceanographic Office (NAVOCEANO) provided data for this project and database preparation was the initial task. This task required definition of the area of study and the collection, sorting and inventory of map, database and remote sensing source materials. Index sheets for maps and photographs that provide a ready reference were prepared and various data sets that give the most up-to-date information about the LPP identified. The data sets for this project were organized into map/database and remote sensing data totaling over 18 gigabytes of digital files. These data are discussed below.

Maps and GIS Databases

Maps and GIS database products used in this research are listed in Table 4.1. The NGA contributed NIMA and U.S. Geological Survey (USGS) paper maps at scales of 1:50,000 and 1:24,000; NAVOCEANO provided National Oceanic and Atmospheric Administration (NOAA) charts produced at varying scales. The GIS data were provided primarily by the USMC at Camp Lejeune. The Integrated Geographic Information Repository (IGIR) is a local GIS database designed to integrate geographic information about Camp Lejeune into one shared resource that serves as a strategic component of the base's information infrastructure (GISO, 2001). The IGIR has evolved over the last ten years and now provides comprehensive data on environmental features, natural/cultural resources, military training facilities, communications and security and disaster preparedness requirements. The LWD Prototype 2 data set from NIMA and the National Elevation Dataset (NED) produced by the USGS were provided by NGA and incorporated into the project as additional sources (NIMA, 1998a). Both were leveraged in the construction of a digital elevation model (DEM), the former serving as a resource for bathymetric data, whereas the NED was used in establishing elevations for the land portion of the study area.

Table 4.1. Camp Lejeune Map and Database Products.

Map and Database Products
Camp Lejeune's Integrated Geographic Information Repository (GISO, 2001)
NIMA LWD Prototype 2 data set (NIMA, 1998a)
LWD Specifications and Feature List found in 11 different feature categories (each identified with a Feature Attribute Coding Catalog (FACC) number) (Chan, 1999)
DIGEST/FACC Version 2.1 (NIMA, 2000)
USGS/NGA map and chart products (1:50,000 and 1:24,000 scale)
NOAA Digital Nautical Charts (1:80,000 scale)

Image Data

The majority of image data used in this research were high-resolution satellite images from QuickBird and Ikonos (Table 4.2). Additional satellite images from SPOT and Landsat also were periodically referenced. From these panchromatic and multispectral scenes, the CRMS used Leica-Geosystems ERDAS Imagine software to create four pan-sharpened images. Quickbird panchromatic and multispectral images were merged, producing a multispectral image with 0.6-m spatial resolution. This same procedure was followed with Ikonos panchromatic and multispectral images, yielding a 1-m multispectral image. Finally, a Landsat panchromatic image was merged with both a Landsat multispectral image and a SPOT multispectral image, resulting in two multispectral images, each with 15-m spatial resolution (Fleming and Welch, 2004). Lidar data with 3-m post-spacing obtained over a portion of the Camp Lejeune coastline were used in the development of a current, continuous elevation data set. United States Geological Survey digital orthophoto quarter quadrangles (DOQQs) and scanned true color/color-infrared aerial photographs were used to complement the satellite images. Finally, ground photographs were collected and integrated into the reference image data set.

Table 4.2. Camp Lejeune Remote Sensing Products.

Remote Sensing Data Products
Space Imaging Ikonos images (panchromatic and multispectral)
DigitalGlobe QuickBird images (panchromatic and multispectral)
SPOT panchromatic images
Landsat ETM+ multispectral image data
USGS digital orthophoto quarter quadrangles (DOQQs)
Lidar data
Scanned color and color-infrared air photos
USGS National Aerial Photography Program (NAPP) air photos

Sea-Land DEM

A primary requirement for the construction of detailed maps and the preparation of GIS analyses of the LPP was the availability of a continuous sea-land DEM of reasonable accuracy. Unfortunately, although data sources as noted in Table 4.3 existed for the sea, intertidal zone and land areas of the LPP, they were referenced to different horizontal datums and the vertical (bathymetric and elevation) values were not referenced to a common sea level. More importantly, at large-scale, coastline topography frequently shifts due to tide and seasonal climate dynamics and often results in poorly represented intertidal zones. Thus, one of the initial tasks was to integrate the data sets to produce a *current* sea-land DEM. A more detailed description of the process highlighted here can be found in Welch *et al.*, 2003.

Integration of the DEM was accomplished by first converting all horizontal coordinates to the WGS 84 / NAD 83 datum, and vertical coordinates to MSL. In the latter case, depth soundings of varying density obtained from the LWD Prototype 2 data set for the channel of New River and the ocean area between the 15-m depth curve and Onslow Beach were subjected to interpolation using a kriging algorithm to create a regular 10-m grid of bathymetric data. Because the zero elevation for these data was mean low water (MLW) – on average, 0.59 m below MSL – a constant of 0.59 m was added to bathymetric values in order to “raise” them to MSL. A MSL shoreline, which did not exist in the LWD Prototype 2 data set, was then produced by manually digitizing the waterline depicted on a rectified panchromatic Ikonos image acquired at the time of mid-tide on May 4, 2000.

Table 4.3. Bathymetric and Elevation Data Sets Contributing to the Sea-land DEM (MSL=mean sea level, MLW=mean low water; MLLW=mean low-low water)

Data set	Format	Source	Resolution	Elevation Ref.	Vertical Datum	Horiz. Datum
Littoral Warfare Data Prototype 2 Level A	Soundings	NAVOCEANO	Variable (points)	MSL	NAVD 88	NAD 83
Littoral Warfare Data Prototype 2 Level B	Land Contours	NIMA	Vector	MLW	NAVD 88	NAD 83
National Elevation Dataset (NED)	Grid	1952 USGS Topo Maps	30-m	MSL	NAVD 88	NAD 27
Digital Nautical Chart (DNC)	Soundings	NOAA Charts	Variable (points)	MLW	NAVD 88	WGS 84
Lidar	Grid	NASA/NOAA Aircraft	3-m	MLLW	NAVD 88	None

A digital surface model (DSM) for the intertidal zone along Onslow Beach was produced from lidar data recorded by the National Aeronautic and Space Administration (NASA)/NOAA from an aircraft operating at 700 m above MSL. The lidar data were referenced to MSL. A median filter was employed to remove spikes caused by buildings and trees, leaving a DSM that closely approximates a DEM for the intertidal zone and coastal region inland to the Intracoastal Waterway (Figure 4.6).

The DEM for the inland portion of the study area was extracted from the USGS NED data referenced to MSL (USGS, 2003). Because significant morphologic changes had occurred along the beach and at the mouth of the New River since the topographic maps were produced in 1952 (USGS, 1952), the values from this DEM seaward from the Intracoastal Waterway to MSL were "masked" by the intertidal zone DEM to create a merged inland/intertidal zone DEM. This DEM was then mosaicked with the bathymetric DEM. The resulting continuous sea-land DEM retained bathymetry data from MSL seaward, lidar data from MSL to the Intracoastal Waterway and NED data from the Intracoastal Waterway inland (Figure 4.7).

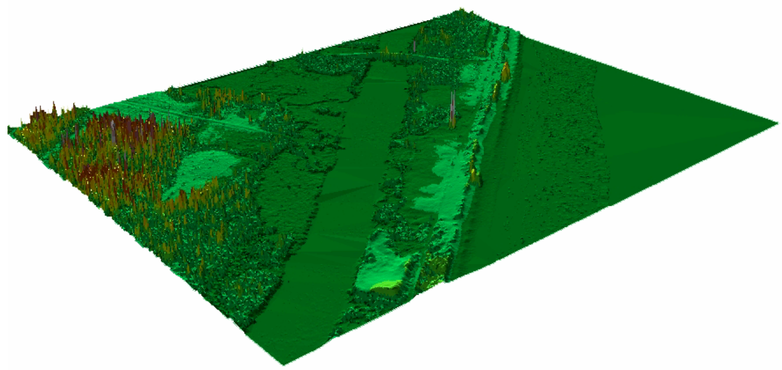

Figure 4.6. Looking north along the coast at a digital surface model derived from lidar data reveals details of the shoreline and in-shore areas including waterways, trees and manmade objects such as towers.

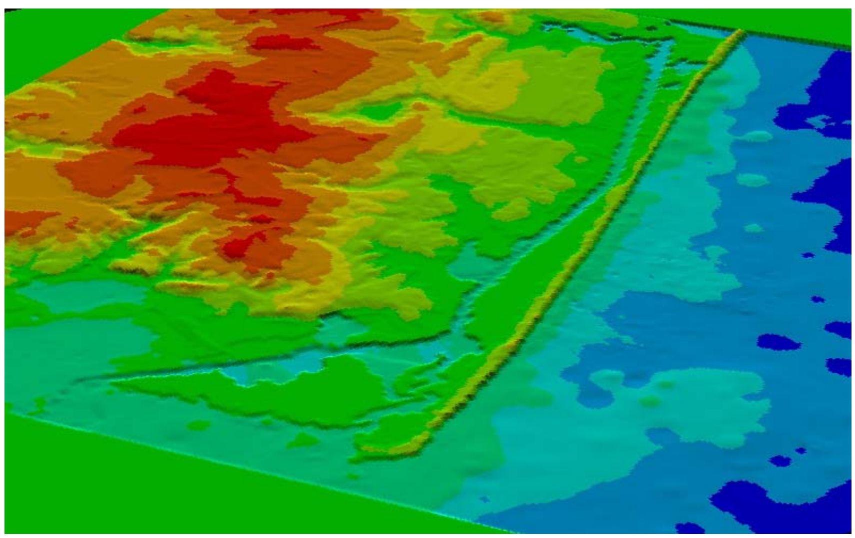

Figure 4.7. The sea-land DEM (looking north along the coast) was compiled from the best available elevation and bathymetric data for the study area and represents a continuous elevation model that is suitable for LPP analysis. In this figure, blue shades define bathymetric elevations, the lightest shade of green approximates intertidal zone elevations and darker greens through red detail the land elevations.

Map Product Design

Cartographic products that aid in military decision-making must address various components of the dynamic battlefield. Information needed and portrayed on maps allows these conditions to be assessed. In this regard, the static military map of years past is not sufficient and a prototype product representing the LPP was needed. A graphical layout of such a product was created (Figure 4.8). This prototype, 153 x 91 cm in size, contains a detailed base map in the middle which serves as the common centerpiece for planning and executing missions *across* levels of command in a fighting force. As considerable detail must be represented and most LPPs will be relatively small areas, scales of 1:10,000 or larger are appropriate, with 1:5,000 or larger preferred. Features found in LW databases were identified and assigned proper codes/symbology on the base map . At a minimum, these include contours (bathymetric and land) at an interval of 2 m and salient features in the intertidal zone and on-shore areas (e.g., waterlines, vegetation cover, wetlands, hydrography, lines of transportation, airfields, cultural features and obstacles).

Since digital and analog map products may be employed by both U.S. and foreign military units, it is desirable to provide coordinate reference systems familiar to all concerned because the need to recover both plane and spherical coordinates compatible with their navigation and fire control systems is critical. For U.S. forces, WGS 84 is the appropriate horizontal datum, with both the Universal Transverse Mercator (UTM) coordinate system and the Military Grid Reference System (MGRS) superimposed at intervals of 100 to 1000 m, depending on the projected scale of the displayed maps. Both of these plane coordinate systems were included on the prototype map. For many allied and coalition forces, spherical coordinates are necessary to effectively employ their weapon systems. Therefore, provisions were made to enable the determination of latitude and longitude values. Perpendicular axes across the map were graduated in degrees, minutes and seconds at 15-second intervals.

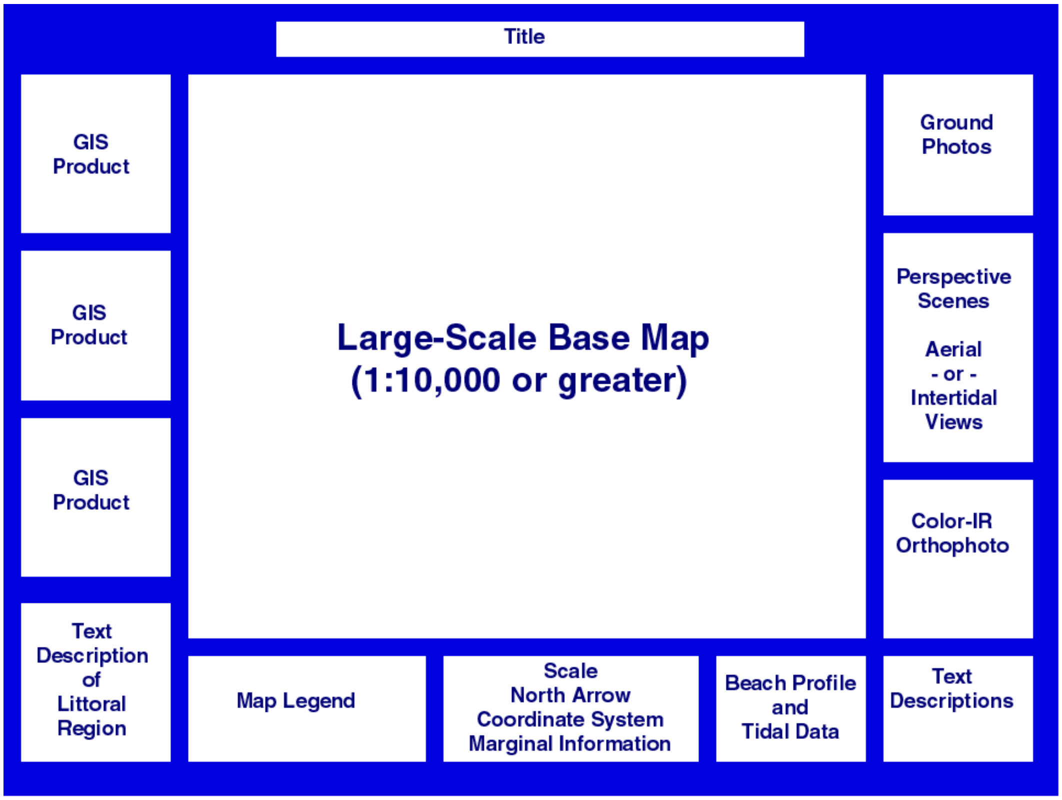

Figure 4.8. Template of final map product.

Finally, critical information requirements needed by individual operational or tactical commanders in order to accomplish *their* directed missions were deemed important. Products that provide this information can be placed in inserts surrounding the base map (Welch *et al.*, 2003). These marginal data products were developed from the revised LW database. Included here are: (1) a cross-sectional profile extending from approximately the 10-m depth curve to MSL; (2) tide tables for the designated operational period; (3) ground photographs; (4) inset maps at scales of 1:50,000 to 1:250,000 created using GIS analysis functions that depict command-specific applications (e.g., vegetation density, soil trafficability and heavy vehicle mobility); and (5) both vertical and perspective aerial views of the LPP.

More details of the production process outlined here and an example prototype combat chart are provided in Welch *et al.* (2003). Relevant to this paper, however, is the concept that proper GIS analysis procedures and modeling techniques are required to create the products detailed in (4) and (5) above. The remainder of this manuscript discusses the use of two software tools found in the C/JMTK – ESRI ArcGIS and ERDAS Imagine – in demonstrating the potential of GIS analysis and modeling techniques to provide important information about LPPs.

Development of GIS Applications for Littoral Operations

Maps and associated database products provide a basis for GIS modeling and the generation of critical information needed by Marine commanders. These modeling results can be included as inset maps along with vertical and perspective aerial views of LPPs on combat charts. Examples of GIS analysis with the Camp Lejeune data sets are provided here for the sea, land and air environments. Specifically, these examples include: (1) modeling sea level and shorelines in the littoral zone; (2) vegetation and vehicle mobility assessments; and (3) aerial perspective scenes and fly-over animations.

Modeling Sea Level and Shorelines in the Littoral Zone

Although shoreward operations are important, getting to shore is arguably the more critical of the two. In this context, mobility in and around the shoreline is a significant challenge to Marine commanders and their planning staffs.

Assessing entry points in intertidal zones is not a new problem for the USMC, dramatically illustrated by a brief review of the Battle of Tarawa (November '43/Central Pacific Campaign in WWII) where some 1,500 men were either killed or wounded during the landing at Red Beach 2. Most of these casualties occurred when trying to transition the Marines from "afloat to afoot" with major difficulty due, in large part, to failures in comprehending the effects of the irregular tides on the barrier reef surrounding Tarawa Atoll (Ballendorf, 2003).

GIS-based modeling offers tremendous potential towards providing a basis for understanding the dramatically changing conditions of this critical region of military operations (Millett and Evans, 2002). In this study, two products were generated through integration and modeling techniques using ArcGIS and Imagine software: (1) shoreline delineations; and (2) perspective scenes of tide levels.

The shoreline, as drawn on a typical map, is represented as a single line that is usually tied to a nominal location of the water-land interface at MSL (Di *et al.*, 2001; Ingham, 1992). However, this line is only accurate three to four times each day, depending upon local tidal flow conditions (NOAA, 1997; NOAA, 2003). In actuality, changing tides in coastal environments results in different shorelines depending upon the scale at which the data are viewed (NOAA, 2003). Critical to tactical operations in the littoral environment, planimetric mapping at large scale (1:1,000 to 1:10,000) must include the correct delineation of all intertidal features. The use of multiple lines and various color shades (e.g., yellow indicating sand on the beach) can effectively define the shorelines associated with different tidal conditions and the changing variations of exposed beach areas.

In order to define multiple shorelines reflecting tidal conditions at Camp Lejeune, a model of the intertidal zone was created which enabled visualization of tidal effects on the beach area. A reference image (QuickBird Panchromatic) was draped over the sea-land DEM that had been re-sampled to 1-m post spacing. The draped image was then viewed orthogonally from a projected height of 200 m above ground level (AGL) (Figure 4.9). On 20 May 2003 (date of image collection), the tidal range from mean low water (MLW) to mean high water (MHW) was 0.68 m. Using the Imagine Floodwater Module, different tide stages ranging the full tidal range from 0.34 m below to 0.34 m above MSL (Δ of 0.68 m) were portrayed (ERDAS, 2000). This module allows one to simulate "filling" a DEM "with water" to selected elevation levels. In Figure 4.9, for example, light green shading indicates the MSL fill level established using the flywheel function of the Floodwater Module. The software was then employed to adjust the water fill to 0.34 m above and below MSL. At each fill stage, vectors of the shoreline were collected by tracing the coastline on the screen display. These unique vectors depicting different tidal stages where then imported into ArcGIS and employed to produce cartographic representations of the changing shoreline (Figure 4.10). The darker yellow area represents the beach area between MLW and MSL, while the lighter yellow area represents the beach area between MSL and MHW. Upon viewing such a map with multiple shorelines depicted, commanders can readily determine where tide levels (as a function of beach slope and tidal range) support and/or deter amphibious operations.

Some commanders prefer visualizing the battlefield over interpreting what the battlefield may look like from a map. In an attempt to meet this requirement, perspective views were created of the LPP in order to demonstrate the capability of GIS technology in rendering visualizations of tidal effects on the beach area. In this simulation, a 1-m pan-sharpened, color-infrared Ikonos image (acquired in May 2000) was draped over

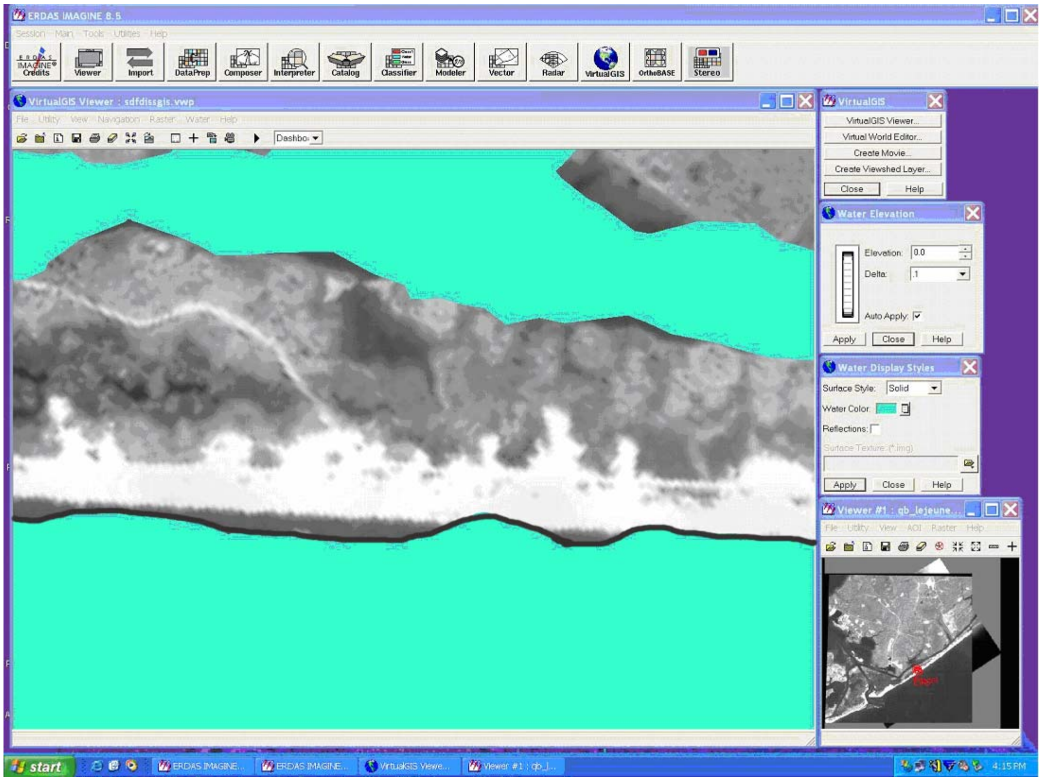

Figure 4.9. Mean sea level tidal stage "filled" using ERDAS Imagine Floodwater Model.

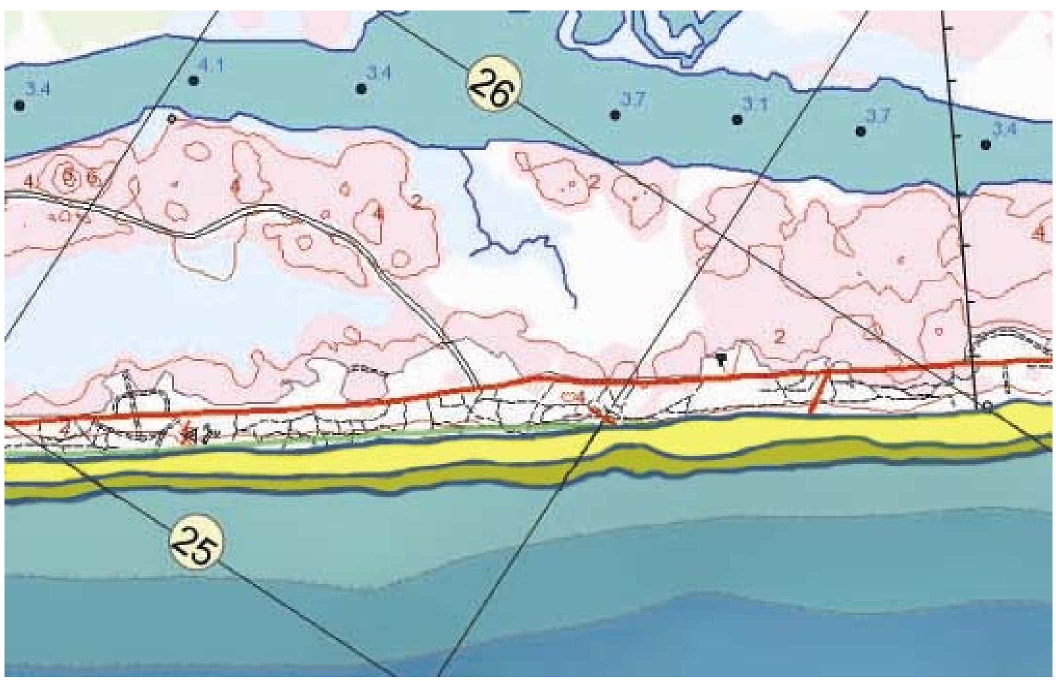

Figure 4.10. Tide stages on Onslow Beach. Light yellow shading on the beach represents the beach from MSL up to the MHW line; the dark yellow shading represents beach from MSL down to the MLW line.

the sea-land DEM. Scenes were observed from a viewpoint 30-m AGL with a view angle of 45 degrees to grid north (NE). Again, employing the Floodwater flywheel function, a tidal range was evaluated from 2 m below to 2 m above MSL. This low elevation (2 m below MSL) was determined by combining the lowest low-tide mark at Camp Lejeune during May 2000 (-0.59 m) with the average Landing Craft Utility (LCU) draft depth (~1.4 m). The high elevation (2 m above MSL) was approximated by estimating a tidal surge during a spring tide condition. Snapshots ("screen captures") were collected to depict the change in water levels for the different tidal stages (Figure 4.11). These types of images reveal overland flow of tidal waters at the proposed LPP, enabling decision-makers to readily visualize (in 3-D) where water levels affect amphibious operations.

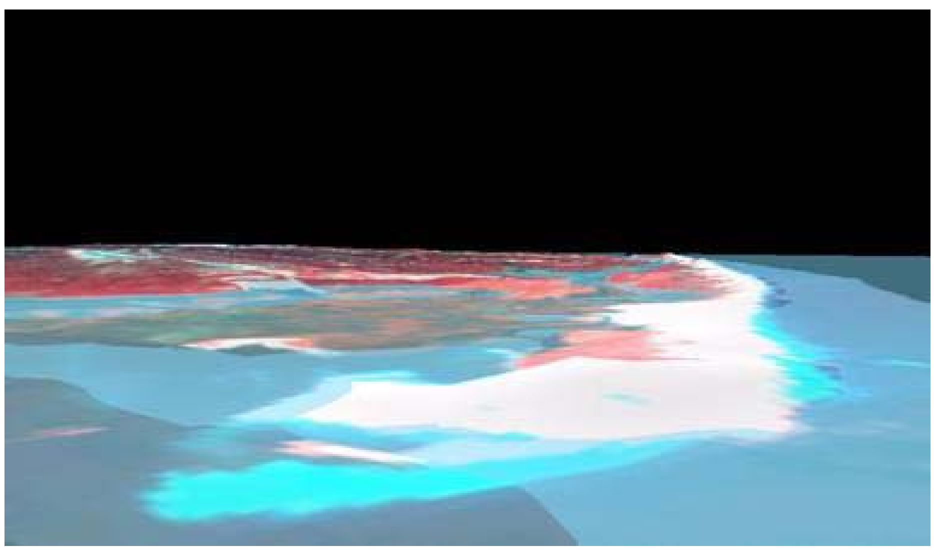

Figure 4.11. MSL tidal stage is illustrated in this Virtual GIS 3D flood simulation. This type of visualization is useful for determining areas that may be exposed or treacherous at different times during a given day. It is also possible to assess errors or inconsistencies in the DEM that should be addressed and corrected.

Vegetation Cover and Vehicle Mobility

Vehicle mobility – how well a unit's mounted force can traverse terrain – is a major concern to Marine ground commanders. Vehicle mobility in relatively flat terrain is primarily a function of vegetation density and soil trafficability (Department of the Army, 1994). In terrain where dramatic elevation change exists, slope becomes an additional consideration and mandates the use of an elevation model. Since the Camp Lejeune area has very little relief, only two unique products were necessary to assess vehicle mobility using ArcGIS software: (1) a vegetation density map; and (2) a soil trafficability map.

A map categorizing tree and shrub density with respect to heavy vehicle movement – the vegetation density map – was produced first using information contained in Camp Lejeune's LWD Prototype 2 database and augmented by manual photointerpretation of color-infrared digital orthophotos (pixel size = 1.2 m) prepared from aerial photographs acquired in March of 1998 (NIMA, 1998a). Tree size and density are critical factors of concern for vehicular movement. Specifically, large trees growing close together and/or smaller yet very dense vegetation can restrict the movement of wheeled and, in some cases, tracked vehicles. A visit to Camp Lejeune was made by the CRMS personnel in August 2002 to examine the study area in order to validate the interpretation work and verify the data in the LWD database.

Vegetation density for large trees at least six inches in diameter at breast height (dbh) was assessed as dense (>50 percent coverage), medium (>15 percent to <=50 percent coverage), sparse (>5 percent to <=15 percent coverage) or open (<=5 percent coverage). Scrub/brush density (with dbh generally less than 15 cm) was likewise assessed as dense, medium, sparse or open. Non-forested areas were classified as beach, bare ground, open marsh, developed, roads or water to provide information on the relative openness of the ground cover. The resulting vegetation density map provides information on cover and concealment as well as limits to vehicular movement inland from the initial beachhead (Figure 4.12).

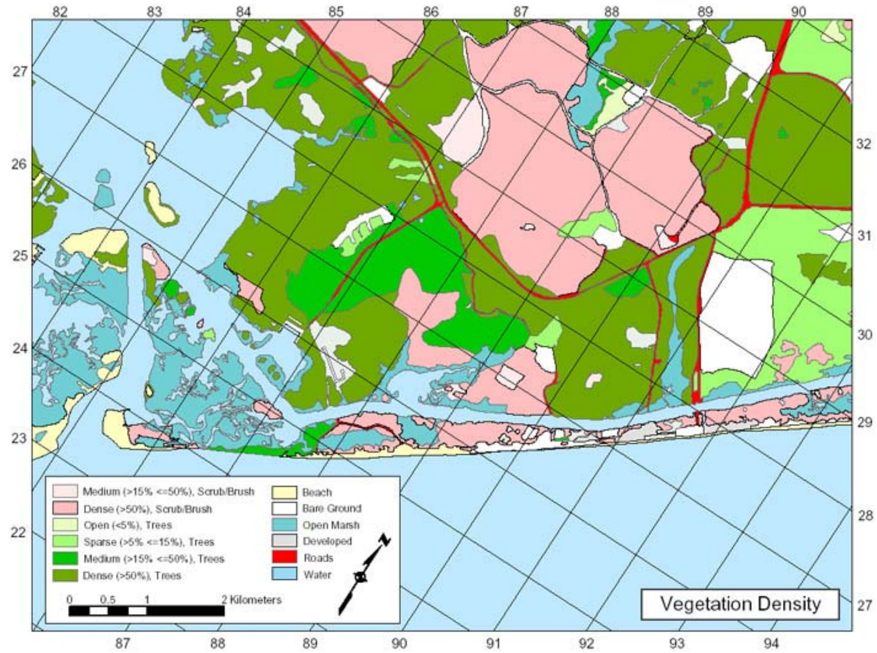

Figure 4.12. Vegetation density was derived from the vegetation and land cover layers of the GIS database.

Soils were evaluated for their ability to support the weight of tracked vehicles (trafficability) under *wet* conditions typical of those likely to be encountered during the month of May, the month in which most of the image data over the area were collected. In May, rainfall at Camp Lejeune averages about 4 inches.

Based on information on soils trafficability provided in “Planning and Design of Roads, Airfields and Heliports in the Theater of Operations”, soil composition (sand, silt and clay) and moisture are the major factors influencing substrate support for vehicles as they move along road networks or cross-country over relatively flat terrain (Department of the Army, 1994). The majority of the soils found in the Camp Lejeune LWD Prototype 2 database were, in order of soil moisture holding capacity, silty sands (SM), poorly graded sands (SP), well-graded sands (SW) and inorganic clays (CH) (NIMA, 1998a). A soil textural triangle, which takes into account soil groups and the relative percent of sand, silt and clay of a soil type, was used to assign rule-based ratings of "Good", "Fair" and "Poor" to areas on the map classified by soil type (USMA, 2001). The map of reclassified soils shows variations in wet soil trafficability in terms of support for heavy vehicles (Figure 4.13). The majority of the study area (76 percent) was deemed "Fair" in terms of soil condition for heavy vehicle trafficability. Only 10 percent of the study area, coinciding primarily with the beach and dunes, was classed as "Good" trafficability conditions, while 14 percent was "Poor" due to drainages along creeks and low-lying wetlands.

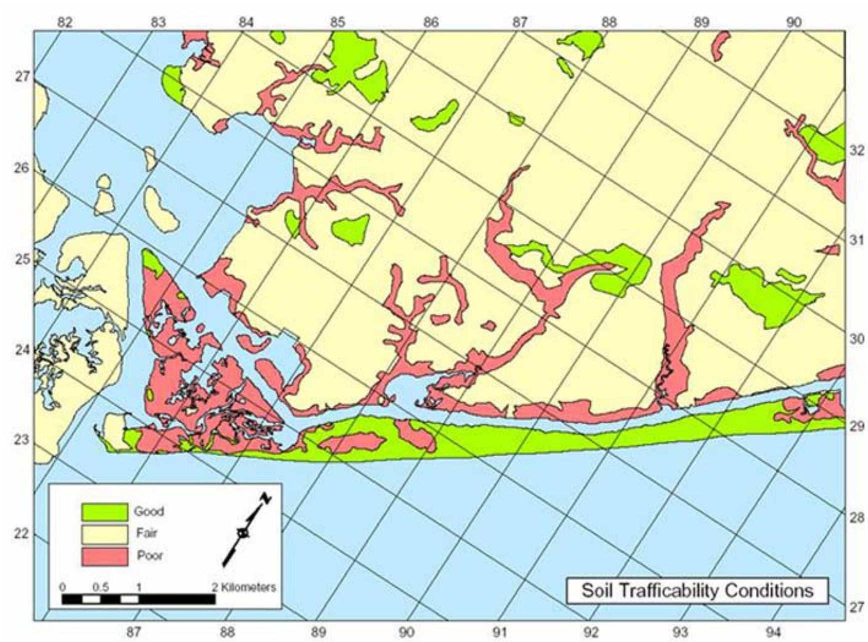

Figure 4.13. Reclassification of the soils data layer provided data on soil trafficability under wet conditions.

A final heavy vehicle mobility map for wet conditions was produced by intersecting the vegetation density and soil trafficability maps (Figure 4.14). Specifically, areas with medium, sparse or open vegetation (with the exception of marshes) that were spatially coincident with “Good” soils conditions were rated “Good” for heavy vehicle mobility; areas with medium, sparse or open vegetation (with the exception of marshes) coincident with “Fair” soil conditions were rated “Fair”; and areas with any type of vegetation coincident with “Poor” soil conditions, as well as dense vegetation and marshlands, were rated “Poor”. From this GIS analysis, it is evident that a commander’s flexibility for uninhibited movement across the ground area is limited. A Marine commander using this modeling tool would likely deploy heavy vehicles along an axis of advance where good and fair conditions would be maximized (indicated by the arrows on Figure 4.14). The mobility map demonstrates the utility of a GIS database, analysis and modeling in a land environment whereby the inherent functions of a GIS enable the generation of an effective product to assist commanders in making decisions about route selection/attack axis.

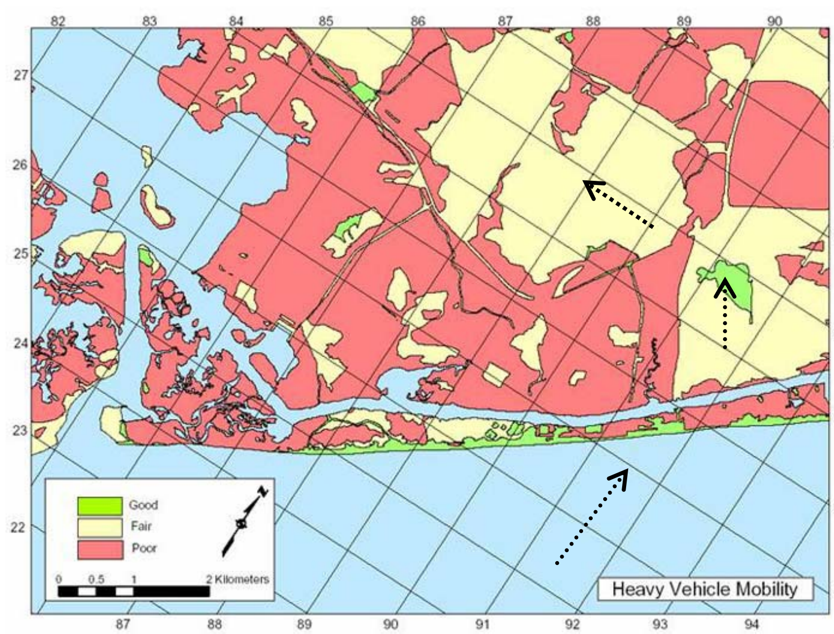

Figure 4.14. A heavy vehicle mobility map for the Camp Lejeune LPP was generated by combining the vegetation density and soil trafficability data sets using GIS analysis techniques. Arrows indicate a potential axis of advance that maximizes optimal terrain conditions.

Fly-Over Animation

In the 21st Century, more so than ever before in the history of warfare, sea and land military operations depend on successful air operations. Unmanned aerial vehicles (UAVs) are extremely critical to this end as they provide real-time and near real-time aerial perspective views and fly-overs of the battlefield (Reinhardt, et. al, 1999; Pike, 2003b). When UAVs are not available, however, GIS technology can closely replicate this information for field commanders. Coupled with high-resolution satellite images and/or aerial photographs, the sea-land DEM permitted the development of perspective views and fly-overs for the LPP at Onslow Beach that simulate data return from UAVs. As an illustration of generating a perspective scene, an Ikonos pan-sharpened, color-infrared image (1-m pixel) was draped over the sea-land DEM using the Imagine software (Figure 4.15). A vertical exaggeration of 5x was applied to the DEM to enhance local relief. This view was generated to simulate a viewing altitude of approximately 350 m above MSL with a downward look angle of –31 degrees.

Animation techniques were next employed to simulate UAV fly-overs of the Onslow Beach area created from a sequence of perspective views of the terrain. The first fly-over covered the entire LPP study area analogous to what is termed a limited area of operations for a unit commander. In preparing this product, the sea-land DEM with 10-m post spacing was displayed in Imagine with a vertical exaggeration of 5x and draped by a 1-m Ikonos pan-sharpened, color-infrared image. The fly-over parameters were set for an altitude of 200 m, field-of-view (FOV) of 75 degrees, a downward look angle of -31 degrees and a speed varying at rates of 40 to 110 km/h. A total of 160 frames were generated to provide a movie file (.mov) with a runtime of 90 seconds that can be viewed on a computer display.

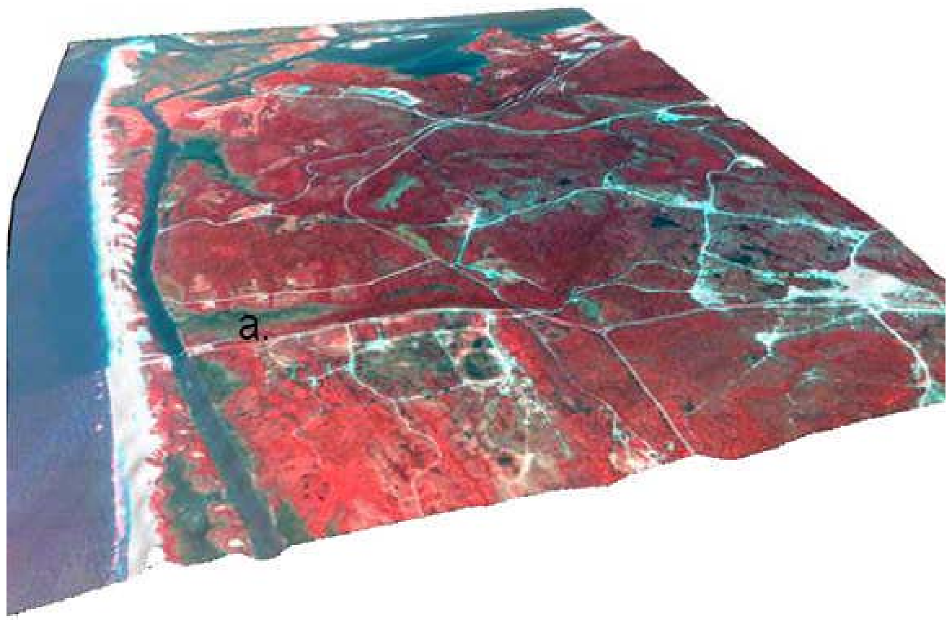

Figure 4.15. Aerial perspective view looking southeast along Onslow Beach created by draping a pan-sharpened Ikonos image over the sea-land DEM of the study area. Shown at [a] is the location of Onslow Beach Road.

A second fly-over, also saved in movie file format, was generated along the shoreline from Onslow Beach Road to the New River Inlet (USGS, 1952). Color-infrared aerial photographs of 1:40,000 scale scanned at 1.5-m pixel resolution were draped over a DEM with 3-m post spacing produced from the lidar data. A flight path was established using parameters that included an altitude of 60 m above MSL, FOV of 45 degrees and an equivalent ground speed of 40 km/h. A total of 60 frames were generated along the coastline.

These two fly-overs demonstrated the value of image processing, animation and simulation techniques for visualizing and exploring the battlefield. Aerial perspective scenes and fly-over generation can be quickly compared to real-time (or near real-time) scenes collected by UAVs often under the direction of operational and tactical commanders. Assuming common resolution and view orientation between live UAV video feeds and simulations presented in this research, comparisons should reveal completed or ongoing battlefield changes. The strength of these types of products is the ability to create or replicate airborne visualizations similar to image and video data now available at all levels of command.

CONCLUSION

A number of studies have addressed independent digital solutions for military needs, but few have focused on the merits of generating and integrating GIS-based analysis products into a collective decision-making tool. In this study, a methodology was developed and employed to assist in rapidly creating a large-scale map prototype from multiple geospatial data sources for commanders operating in coastal zones. Three major environments found in the littoral region – sea, land and air – were examined.

The mapping tool used by tactical and operational Marine units should be built around a dynamic large-scale combat chart. The chart must include multiple coordinate systems and proper military features. Supporting the chart, products can be placed around the margin such as tide profiles and tables, ground and aerial photographs/images of significant military objectives, perspective views and inset maps based on required analyses deemed important to operations by commanders.

Many of these products make frequent use of a seamless sea-land DEM. It must feature bathymetric and elevation data of sufficient accuracy to permit the generation of waterlines in the intertidal zone for MLW, MSL and MHW.

Establishing data sets that detail bathymetric conditions is more cumbersome than collecting similar data for land areas. Final integration of these data (e.g., bathymetric soundings) with lidar data of intertidal zones and upland DEMs, each tied to a different vertical reference, can be a difficult and time-consuming task. Recognizing this, defense mapping organizations should prioritize and allocate sensor and assessment resources accordingly, thereby enabling timely collection of bathymetric data followed by efficient integration of all required information.

All three environments – sea, land and air – merit the attention of Marine commanders. Shoreline delineations provide improved maps of intertidal zones at large-scale, detailing how tide levels will impact amphibious operations. Perspective scene modeling of these shorelines reveals overland flow of tidal waters at LPPs, enabling 3-D visualizations of water levels from which conclusions about mission impacts can be made. Effective vehicle trafficability estimates are critical information as well. Geographic information system functions enable the analysis of data vital to the development and generation of these products. In this regard, proper GIS database construction and data modeling are necessary to assist commanders in route and/or attack axis selection. Finally, aerial perspective scenes and simulated "fly-overs" provide a realistic view of the landscape by draping properly rectified satellite or aerial images over co-registered, detailed and accurate DEMs. These products are quickly compared to real-time (or near real-time) video and scenes collected by UAVs and/or satellite images.

Analysis and modeling capabilities of a GIS provide military commanders the means to rapidly integrate data sets, assess conditions, plan strategies and evaluate options. The overall success and reliability of large-scale, LWD products created from image processing and GIS tools ultimately depends on the availability of skilled personnel with ready access to current data. This research provided examples of improved digital data sets, map products and analysis procedures that can be used by NGA for future LWD military applications.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

This research focused on developing methodologies of employing geospatial information for joint military operations in the littoral region. Many advanced data collection technologies define unprecedented military intelligence, surveillance and reconnaissance capabilities. Three of these – GPS, sensors on UAVs and high-resolution satellite images – enhance the detectability of features and targets across the littoral battlespace, improve distance estimation, reduce the risk of fratricide and further the speed of operations. A number of studies have addressed independent digital solutions that make limited use of these data for military needs. However, methods for efficient collection and integration of the information and effective generation of useful military decision-making tools have not been fully developed. It is envisioned that the work undertaken for this dissertation will help provide answers to what information the data provide and to how the military can best use that information. To this end, three major research objectives were achieved: (1) to evaluate the utility of current and evolving commercial sensor systems for feature data collection and potential military applications for littoral opeations; (2) to establish modeling and terrain visualization protocols for littoral regions, employing some of the operating functions planned for use as part of the C/JMTK; and (3) to demonstrate the value of a digital GIS database (developed according to military specifications) for planning and execution of littoral operations.

In addressing the first objective, unclassified aerial photographs and commercially available high-resolution satellite images provide a wealth of information for mapping and constructing databases of potential LPPs. In practice, image data with pixel resolutions of better than 0.5 m are needed for compiling detailed LW databases and map products. Large- to medium-scale color and color infrared photos scanned at pixel resolutions from 0.15 m to 1.2 m and QuickBird and Ikonos panchromatic satellite images are best viewed at scales of 1:600 to 1:3,000. These data are suitable for LW feature extraction and mapping at scales of 1:1,000 to 1:10,000. When collecting aeronautical, military, inland water and urban features for LW databases, images must be able to withstand magnifications to viewing scales of at least 1:2,500, and preferably 1:1,000 or larger. This implies that images with spatial resolutions of better than 1.0 m are required for detailed interpretation and delineation. In addition, when collecting port, harbor, transportation and vegetation features, images must be able to withstand magnifications to viewing scales of at least 1:3,500 or spatial resolutions of between 1.0 m and 4.0 m to properly interpret and delineate features.

As it is likely that many potential LPPs will be located in denied areas, QuickBird and Ikonos panchromatic images displayed at scales of approximately 1:1,500 merit consideration for compiling LW databases of acceptable completeness and accuracy. Because spatial resolution has proved to be far more important than spectral resolution for effectively populating LW databases, SPOT and Landsat images cannot be considered particularly useful for LW feature collection. They permit identification of only about 50 percent of all features found in the LWD specification list. These pixel resolution and viewing scale thresholds should serve as critically important guidelines for **efficient** extraction of littoral features.

In addressing the second objective, ArcGIS and Imagine software, both part of the C/JMTK suite, provide sufficient data analysis, modeling and terrain visualization functions for use in littoral regions. All three major environments found in the littoral region – sea, land and air – were examined in detail as part of this research. Critical to each, a seamless sea-land DEM is necessary for analysis and visualization in military operations. In the sea environment, databases produced for construction of LPP DEMs should feature bathymetric and elevation data of sufficient accuracy to permit the generation of waterlines in the intertidal zone for MLW, MSL and MHW. Delineations of shorelines provide commanders improved maps of intertidal zones at large-scale detailing how tide levels will impact amphibious operations. Complementing these maps, perspective scene models reveal overland flow of tidal waters at LPPs from which conclusions about mission impacts can be made. In the land environment, effective vehicle trafficability estimates for units that have come ashore are critical information to USMC commanders and their staffs. Geographic information system functions enable the development and generation of these products that assist commanders in route and/or attack axis selection. Finally, in the air environment, aerial perspective scenes and simulated "fly-overs" provide military commanders a more realistic view of geospatial data as compared to a planimetric presentation of the same information. These products can be quickly compared to real-time (or near real-time) video and scenes collected by UAVs and/or satellite images.

In addressing the third objective, a digital GIS database makes use of accurate, time-sensitive geospatial information, thereby providing revolutionary decision-making tools to military commanders operating in littoral regions. Analysis and modeling capabilities of a GIS allow military commanders the means to rapidly integrate data sets, assess conditions, plan strategies and evaluate options. In this study, methodologies were developed and employed to create large-scale maps from multiple geospatial data sources. Digital maps (from which analog maps can be plotted on commercial hardware) for use by tactical and operational Marine units are most effective when designed around a large-scale combat chart that includes: (1) UTM, MGRS and latitude-longitude coordinate grids; (2) hydrographic, vegetation, wetland, intertidal, lines of transportation, aeronautical and cultural features; (3) a cross-sectional intertidal zone profile corresponding to an assault lane; (4) tide tables; (5) ground photos of significant military objectives; (6) vertical and perspective aerial views prepared from both satellite and aerial images; and (7) inset maps depicting GIS-based analyses as required by operational and tactical commanders. The overall success and reliability of large-scale, LW products created from image processing and GIS tools ultimately depends on the availability of skilled personnel with ready access to current data, especially high-resolution images (~1-m pixels). In the unclassified domain, these image requirements can be fulfilled with products from Ikonos, QuickBird and comparable satellite systems.

In all cases, large data volumes associated with high-resolution images from multiple sources, varied data formats, data integration processes and complex output designs are problematic. Of particular note, establishing data sets that detail bathymetric conditions is more cumbersome than collecting similar data for land areas and integrating these data (e.g., bathymetric soundings) with lidar data of intertidal zones and upland DEMs each tied to a different vertical reference is a difficult and time-consuming task. Recognizing this, mapping organizations must prioritize and allocate sensor and assessment resources accordingly, thereby enabling timely collection of bathymetric data first, followed by efficient integration of all other required information. It follows, that at the national level, NGA must be able to rapidly access the best imagery to successfully complete assigned missions. Taking into consideration that data from classified military satellites and other restricted sources were not used in this project where the addition of these data would clearly add more complexity to the data volume problem, the NGA cannot afford to spend precious time retrieving and evaluating the suitability of all possible combinations of image, text and map data sets for each of the potential LPPs around the world.

This research provided examples of improved digital data sets, map products and procedures that can be used by NGA for future military applications in littoral zones. It is anticipated that further research with database and software platforms will continue to result in more efficient and productive solutions for ongoing mapping and modeling challenges of military operations in the coastal environment. On the horizon, improvements in GIS and integration technologies will likely have a significant impact on future military operations by providing decision makers with even more accurate information in a faster manner. In order to take full advantage of these opportunities, however, the complete embracing of digital geospatial data and the means of exploiting it with GIS at all levels of war is required.

Although these solutions will not eliminate battlefield confusion, the resulting battlespace awareness should improve situational knowledge, decrease response time, and make the battlefield considerably more transparent to those who use it. The integration of geospatial technologies and GIS will likely provide an improvement in lethality. Commanders will be able to attack targets successfully with fewer platforms and less ordnance while achieving objectives more rapidly and with reduced risk. Strategically, this improvement will enable more rapid power projection. Operationally, within the theater, these capabilities will mean a more rapid transition from deployment to full operational capability. Tactically, individual warfighters will be empowered as never before, with an array of detection, targeting and communications equipment that will greatly magnify the power of small units. As a result, U.S. Forces will improve their capability for rapid, worldwide deployment while becoming even more tactically mobile and effective.

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APPENDIX 1

MILITARY TERMS USED IN DISSERTATION

Battlespace Awareness – Full understanding of all activities on the battlefield.

C/JMTK – (Commercial Joint Mapping Toolkit) A standardized, commercial, comprehensive tool kit of software components for the management, analysis and visualization of map and map-related information.

COP – (Common Operational Picture) term indicating that multiple levels of war have access to and use common information; a common view of the battlefield.

JFQ – (Joint Forces Quarterly) A professional military publication produced by the Office of the Chairman of the Joint Chiefs of Staff.

Full Spectrum Dominance – term indicating friendly forces control all components of the battlefield.

Legacy Force – A military force built with industrial-age based technologies.

Objective Force – A military force built designed to capitalize on information-age based technologies.

OPTEMPO – (Operational Tempo) often indicating a fast speed of action(s).

UAV – (Unmanned Aerial Vehicle) A remotely piloted or self-piloted aircraft that carries cameras, sensors, communications equipment and/or other payloads.

APPENDIX 2

UNMANNED AERIAL VEHICLE INFORMATION

CHARACTERISTICS	***Pioneer***	***Hunter***	***Outrider***
ALTITUDE:			
Maximum (km,	4.6 km 15,000 ft	4.6 km 15,000 ft	4.6 km 15,000 ft
Operating (km,	<4.6 km <15,000 ft	<4.6 km <15,000 ft	1.5 km 5,000 ft
ENDURANCE (Max)**:**(hrs)	5 hrs	11.6 hrs	>4 hrs (+ reserve) @ 200 km
RADIUS OF ACTION:(km,nm)	185 km 100 nm	267 km 144 nm	>200 km >108 nm
SPEED:			
Maximum(km/hr, kts)	204 km/hr 110 kts	196 km/hr 106 kts	204 km/hr 110 kts
Loiter(km/hr,kts	120 km/hr 65 kts	>165 km/hr >89 kts	167 km/hr 90 kts
Cruise(km/hr,kts	120 km/hr 65 kts	<165 km/hr <89 kts	111-139 km/hr 60-75 kts
CLIMB RATE (Max)**:**(m/min,fpm)	[N/A] [N/A]	232 m/min 761 fpm	488 m/min 1,600 fpm
DEPLOYMENT NEEDS:	Multiple* C-130, C-141, C-17 or C-5 sorties Ship: LPD	Multiple* C-130 sorties	Single C-130 (drive on/drive off) Ship: LHA/LHD (roll on/roll off)
PROPULSION: Engine(s)	One Recip; 2 cylinders, 2-stroke	Two Recips: 4-stroke	One Recip; pusher prop
· Maker	- Sachs & Fichtel SF 2-350	· Moto Guzzi (Props: 1 pusher/1 puller)	· McCulloch 4318F Short Block/Diesel
· Rating	19.4 kw 26 hp	44.7 kw 60 hp	37.3 kw 50 hp
· Fuel	AVGAS (100 octane)	MOGAS (87 octane)	Heavy Fuel (JP-8)
· Capacity (L, gal)	42/44.6 L 11/12 gal	189 L 50 gal	48 L 12.7 gal
WEIGHT:			
Empty(kg, lb)	125/138 kg 276/304 lb	544 kg 1,200 lb	136 kg 300 lb
Fuel Weight(kg, lb)	30/ 32 kg 66/ 70 lb	136 kg 300 lb	39 kg 85 lb
Payload(kg, lb)	34/ 34 kg 75/ 75 lb	91 kg 200 lb	27 kg 60 lb
Max Takeoff(kg, lb)	195/205 kg 430/ 452 lb	726 kg 1,600 lb	>227 kg >500 lb
DIMENSIONS:			
Wingspan (m,ft)	5.2 m 17.0 ft	8.9 m 29.2 ft	3.4 m 11.0 ft
Length(m,ft)	4.3 m 14.0 ft	7.0 m 23.0 ft	3.0 m 9.9 ft
Height(m, ft)	1.0 m 3.3 ft	1.7 m 5.4 ft	1.5 m 5.0 ft
AVIONICS:			
Transponder	Mode IIIC IFF	Mode IIIC IFF	Mode IIIC IFF
Navigation	GPS	GPS	GPS and INS
LAUNCH & RECOVERY:	Land: RATO, Rail; Runway, (A-Gear) Ship: RATO; Deck w/Net	RATO, Unimproved Runway (200 m)	75m x 30m x 10m "box" (dependent on weight and altitude)
GUIDANCE & CONTROL:	Remote Control/Preprogrammed	Remote Control/Preprogrammed	Prepgmd/Remote Con/Autopilot & -land
SENSOR(S):	EO or IR	EO and IR	EO and IR (SAR growth)
DATA LINK(S):			
Type	Uplink: C-band/LOS & UHF Downlink: C-band/LOS	C-band/LOS	C-band/LOS (Digital growth)
Bandwidth:(Hz)	C-band/LOS: 10 Mhz UHF: 600 MHz	20 MHz	4.4·5.0/5.25·5.85 GHz
Data Rate:(bps)	C-band/LOS & UHF: 7.317 kbps	7.317 kbps	Full Duplex: 9,600 baud
C2 LINK(S):	Through Data Link	Through Data Link	Through Data Link

Table A. Tactical UAVs (from FAS, 2000b).

CHARACTERISTICS	Tier II, MAE UAV ***Predator***	Tier II+, CONV HAE UAV ***Global Hawk***	Tier III, LO HAE UAV ***DarkStar***
ALTITUDE:			
Maximum (km,	7.6 km 25,000 ft	19.8 km 65,000 ft	>13.7 km >45,000 ft
Operating (km,	4.6 km 15,000 ft	15.2-19.8 km 50,000-65,000 ft	>13.7 km >45,000 ft
ENDURANCE (Max)**:**(hrs)	>20 hrs	>40 hrs (24 hrs at 5,556 km/3,000 nm)	>8 hrs (at 926 km/500 nm)
RADIUS OF ACTION:(km,nm)	926 km 500 nm	5,556 km 3,000 nm	>926 km >500 nm
SPEED:			
Maximum(km/hr, kts)	204-215 km/hr 110-115 kts	>639 km/hr >345 kts,	>463 km/hr >250 kts
Loiter(km/hr,kts	120-130 km/hr 65- 70 kts	639 km/hr 345 kts,	>463 km/hr >250 kts
Cruise(km/hr,kts	111-120 km/hr 60- 65 kts	630 km/hr 340 kts	>463 km/hr >250 kts
CLIMB RATE (Max)**:**(m/min,fpm)	168 m/min 550 fpm	1,036 m/min 3,400 fpm	610 m/min 2,000 fpm
DEPLOYMENT NEEDS:	Multiple* C-130 sorties	AV: Self-Deployable,GS: Multiple* C-141, C-17 or C-5 sorties	Multiple* C-141, C-17 or C-5 sorties
PROPULSION: Engine(s)	One Fuel-Injected Recip; 4-stroke	One Turbofan	One Turbofan
· Maker	- Rotax 912/Rotax 914	- Allison AE3007H	- Williams FJ 44-1A
· Rating	63.4/75.8 kw 85/105 hp	32 kN 7,050 lb static thrust	8.45 kN 1,900 lb static thrust
· Fuel	AVGAS (100 Octane)	Heavy Fuel (JP-8)	Heavy Fuel (JP-8)
· Capacity (L, gal)	409 L 108 gal	8,176 L 2,160 gal	1,575 L 416 gal
WEIGHT:			
Empty(kg, lb)	544 kg 1,200 lb	4,055 kg 8,940 lb	1,978 kg 4,360 lb
Fuel Weight(kg, lb)	295 kg 650 lb	6,668 kg 14,700 lb	1,470 kg 3,240 lb
Payload(kg, lb)	204 kg 450 lb	889 kg 1,960 lb	454 kg 1,000 lb
Max Takeoff(kg, lb)	1,043 kg 2,300 lb	11,612 kg 25,600 lb	3,901 kg 8,600 lb
DIMENSIONS:			
Wingspan (m,ft)	14.8 m 48.7 ft	35.4 m 116.2 ft	21.0 m 69 ft
Length(m,ft)	8.1 m 26.7 ft	13.5 m 44.4 ft	4.6 m 15 ft
Height(m, ft)	2.2 m 7.3 ft	4.6 m 15.2 ft	1.5 m 5 ft
AVIONICS:			
Transponder	Mode IIIC IFF	Mode I / II / IIIC / IV IFF	Mode IIIC IFF
Navigation	GPS and INS	GPS and INS	GPS and INS
LAUNCH & RECOVERY:	Runway (760 m/2,500 ft)	Runway (1,524 m/5,000 ft)	Runway (<1,219 m/<4,000 ft)
GUIDANCE & CONTROL:	Prepgmd/Remote Control/Autonomous	Preprogrammed/Autonomous	Preprogrammed/Autonomous
SENSOR(S):	EO, IR, and SAR	EO, IR, and SAR	EO or SAR
DATA LINK(S):			
Type	C-band/LOS; UHF/MILSATCOM; Ku-band/SATCOM	Ku-band/SATCOM; X-Band CDL/LOS	Ku-band/SATCOM; X-Band CDL/LOS
Bandwidth:(Hz)	C-band/LOS: 20 MHz UHF/MILSATCOM: 25 kHz Ku-band/SATCOM: 5 MHz C-band/LOS: 20 MHz Analog	UHF/SATCOM: 25 kHz Ku-band/SATCOM: 2.2-72 MHz X-band CDL/LOS: 10-120 MHz	UHF/SATCOM: 25 kHz Ku-band/SATCOM: 2.2 MHz X-band CDL/LOS: 10-60 MHz
Data Rate:(bps)	UHF/MILSATCOM: 4.8 kbps Ku-band/ SATCOM: 1.544 Mbps	UHF/SATCOM: 19.2 kbps Ku-band/SATCOM: 1.5-50 Mbps X-band CDL/LOS: 274 Mbps	UHF/SATCOM: 19.2 kbps Ku-band/SATCOM: 1.5 Mbps X-band CDL/LOS: 137 Mbps
C2 LINK(S):	UHF/MILSATCOM	UHF MILSATCOM/SATCOM/UHF/LOS/CDL/LOS	UHF MILSATCOM/SATCOM/LOS/LOS

Table B. Endurance UAVs (from FAS, 1999a; FAS, 2001b; FAS, 2001c).

UAV ACRONYMS

ADR Air Data Relay
A-Gear Arresting Gear
AV Air Vehicle
AVGAS Aviation Gasoline
CDL Common Data Link
CGS Common Ground Segment
EO Electro-Optical
FLIR Forward-Looking Infrared
GCS Ground Control Station
GDT Ground Data Terminal
GPS Global Positioning System
GSE Ground Support Equipment
HAE High Altitude Endurance
IFF Identification Friend or Foe
INS Inertial Navigation System
IR Infrared
JP Jet Petroleum
kHz Kilohertz
LHA Landing Helicopter Amphibious
LHD Landing Helicopter Dock
LOS Line of Sight
LPD Landing Platform Dock
LRE Launch & Recovery Equipment
LRS Launch & Recovery System
MAE Medium Altitude Endurance
MHz Megahertz
MMF Mobile Maintenance Facility
MMP Modular Mission Payload
MOGAS Mobility Gasoline
MOSP Multi-mission Optronic Stabilized Payload
MPS Mission Planning Station
PCS Portable Control Station
RATO Rocket-Assisted Takeoff
RRS Remote Receiving Station
RVT Remote Video Terminal
SATCOM Satellite Communications (Military)
TML Truck-Mounted Launcher
UHF Ultra High Frequency

Table C. List of Acronyms in Support of Tables A and B