Feature identification from commercial satellite images for military and homeland security operations in coastal zones

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Abstract. Supporting U.S. military operations and homeland security requirements in and around coastal zones, geospatial intelligence must be quickly integrated by tactical commanders to meet mission demands. Increasingly, unclassified commercial imagery and data acquired from conventional aircraft, unmanned aerial vehicles and satellites are being used by military and civilian analysts to populate coastal zone databases. This study assessed the suitability of commercially available satellite images for littoral warfare and homeland security operations. From the study, data that show the probabilities for extracting mandatory shoreline features from various images for maps produced at varying scale is provided. A prioritized list of image resources was also created for use in assisting military and civilian analysts to rapidly collect feature data from commercially available resources.

Keywords: commercial satellites, coastal zones, military, homeland security

1 INTRODUCTION

The coastal zone – a complex region that includes land, sea and air features – is receiving increased attention by the military and homeland security organizations as are the possibilities for using commercial high-resolution satellite images to identify features of importance in potential battlefield and emergency response scenarios. In this context, there is a growing requirement for rapidly populating detailed coastal databases. In a military context, these regions are designated 3-8 km wide corridors and referred to as littoral penetration points (LPPs). These LPPs extend from the 15-20 m depth curve to 5-10 km inland [1] (Figure 1). The National Geospatial-Intelligence Agency (NGA) 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.

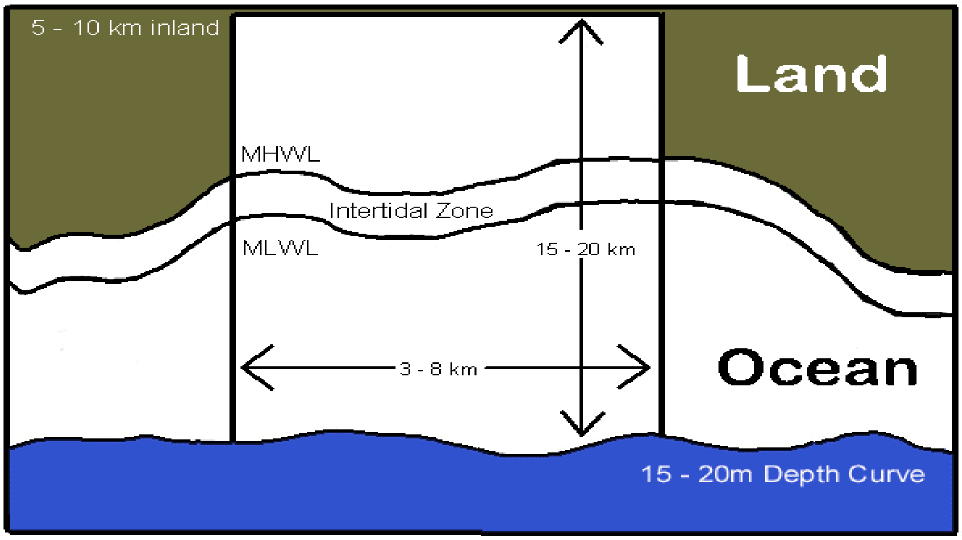


Fig. 1. Schematic of a littoral penetration point (LPP) as defined by NGA.

High-resolution satellite images from IKONOS and QuickBird appear to offer possibilities for meeting NGA requirements in feature population of coastal databases. QuickBird, for example, provides panchromatic images of 0.61 m and multispectral images of 2.44 m pixel resolution (e.g., Refs. [2-3]). 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 use with minimal across-track geometric pre-processing by the user. Because of their high resolution and their short revisit cycle (~ three days), IKONOS and QuickBird images are suitable for threat assessment, mapping and change detection in the coastal zone, assuming images recorded at appropriate tidal stages can be obtained (e.g., Refs. [4-9]).

The extraction of features of military and homeland security value still requires the use of visual rather than automated interpretation techniques. For example, the intelligence community utilizes the National Image Interpretability Rating Scale (NIIRS) to determine the quality of images and performance of imaging systems [10]. 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 which it may be used. Evaluations of QuickBird panchromatic images indicate that the detail is consistent with NIIRS Level 5/6 specifications (0.4 m to 1.2 m ground resolved distance (GRD)) and sufficient to allow base mapping at scales of 1:2,400 to 1:4,800 (e.g., Refs. [10-11]).

The objectives of this study were to: (1) assess the suitability of commercial IKONOS and QuickBird images for identifying features from a coastal study area and to compare their utility to aerial photographs; (2) show the probabilities for extracting mandatory shoreline features for the construction of coastal databases; and (3) demonstrate a procedure for quantitatively relating optimum viewing scale of digital images to pixel resolution.

2 STUDY AREA

In that the objectives of this work primarily support military requirements, Camp Lejeune, North Carolina was selected as the study site. Located at 34° 35' N latitude, 77° 18' W longitude, it is the largest United States Marine Corps (USMC) base in the world, occupying an area of 619 km ^{2} near Jacksonville, North Carolina (Figure 2). 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 [12]. As part of the Marine's training infrastructure, Camp Lejeune maintains 23 km of beach capable of supporting amphibious operations.

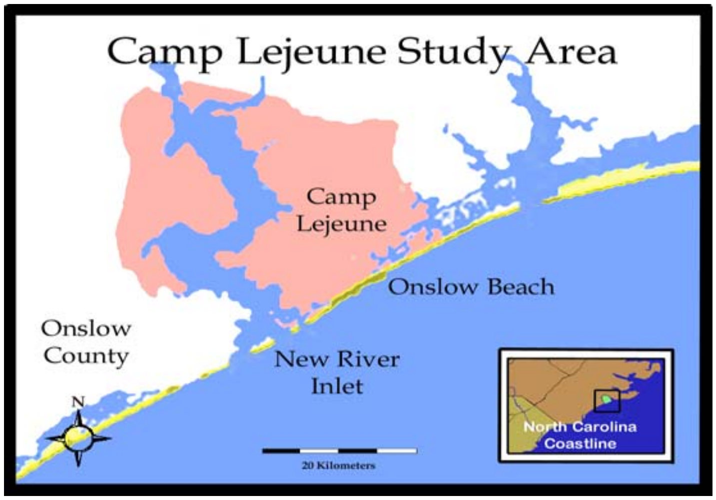


Fig. 2. Camp Lejeune is located on the Atlantic coast of North Carolina. The study area was Onslow Beach, vicinity of New River Inlet.

The Atlantic Ocean frontage of the base is separated from the mainland by the Intracoastal Waterway. Onslow Beach, the designated study 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 five degrees from a distinct line of sand dunes seaward to depths of greater than 15 m (Figure 3).

Fig. 3. 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.

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. Once the waterway has been crossed, 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 contains cypress stands, coastal marshes, bare ground and grasslands. The soil in here is predominantly sandy in nature except for the marsh areas where silty and loamy soils exist. Further inland (2 – 10 km from the coast) are small stands of deciduous and coniferous forests, mixed scrub and grasslands. Although the majority of the region is covered by natural features, the study area also includes some limited cultural features. Small buildings along the beach and other military features exist, as well as helicopter landing zones, ammunition and equipment storage areas, bivouac sites and a small airstrip. 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. 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. In such, lessons learned here can be applied to like assessments in other coastal areas throughout the world [13].

3 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’s IKONOS images (panchromatic and multispectral), DigitalGlobe’s QuickBird images (panchromatic and multispectral), SPOT panchromatic images, Landsat TM and 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 consisted of Camp Lejeune’s Integrated Geographic Information Repository (IGIR) Catalog (dated 7/ 01) [14], 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 (e.g., Refs. [15-16]). The 11 categories are broad feature sets, including: 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 (UTI) and vegetation (VEG) (also see Appendix 1). 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 1. 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 (WGS84). 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 provided by NGA in digital format, scanned at 15 cm ground resolution. From these data and using Leica Geosystems’ Imagine software, the merging of panchromatic and multispectral satellite images was accomplished by the CRMS in February 2003 (for IKONOS) and in August 2003 (for QuickBird), generating multiple pan-sharpened images. No longer a new technique, the pan-sharpening process provided images with desired qualities for coastal studies – high spatial and spectral resolutions [17].

Table 1. Remote Sensing Data Used in Research.

Image	Spatial Resolution	Spectral Bands	Radiometric Resolution	Acquired
Scanned True Color Photographs	0.15 m	B, G, R	8-bit	Sept 1999
QuickBird Panchromatic Images	0.6 m	Pan	11-bit	May 2003
IKONOS Panchromatic Images	1 m	Pan	11-bit	May 2000
DOQQ Images	~ 1 m	Pan	8-bit	Sept 2001
Scanned Color-Infrared Photographs	1.2 m	B, G, R, IR	8-bit	Sept 1999
QuickBird Multispectral Images	2.5 m	B, G, R, IR	11-bit	May 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 ETM + Panchromatic Images	15 m	Pan	8-bit	Sept 1999
Landsat TM Multispectral Images	30 m	B, G, R, IR	8-bit	Sept 1999

4 METHODOLOGY

A procedure for quickly and effectively 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 simple image evaluation criteria; (3) comparative evaluations of images; and (4) consolidation of image evaluations and assessment of results.

4.1 Feature Selection

The initial list of littoral features with FACC identifiers was not tied to the occurrence of these features within 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 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” whereas glacial features are not present and therefore, “not observable”); and, (2) size as compared to the spatial resolution of the best available images (e.g., a 0.1 m buoy is “not observable” on a 0.15 m scanned true color photograph, whereas a 0.8 m manhole cover would be “observable”). The “observable” features were consolidated into a single list of 279 features. From this list, 50 representative point, line and area features from all eleven FACC categories were randomly selected as a basis for comparative evaluation of the various images for populating coastal databases [16] (see Figure 4). Ground coordinate (X,Y) locations of the 50 features were established from rectified images. This was done to ensure 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 referenced in order to establish the correct locations for all 50 features.

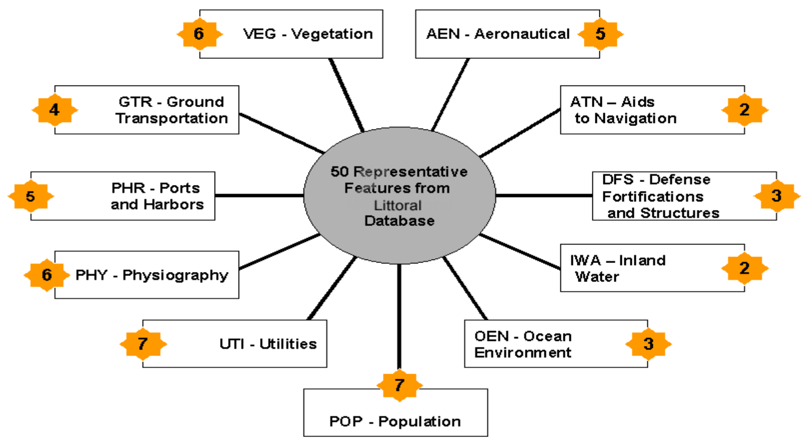


Fig. 4. Distribution of the 50 representative features across the eleven different categories. The number of selected features from each category is indicated accordingly.

4.2 Image Evaluation Criteria

The linkage between interpretability of digital imagery and scale has been a fundamental measure of utility and quality for many decades with hardcopy imagery. However, a digital image file does not have scale *per se*; it can be displayed and printed at many different scales. Scale of digital imagery 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 [18]. Image interpreters – both military and civilian – tasked with extracting features from digital images are interested in knowing what enlargement factors or viewing scales will yield the best results. Ultimately, enlargement factors and viewing scales are tied to the resolution of the imagery, i.e. a “high-resolution” image can be subjected to much greater enlargement factors and hence viewed at larger scales than an image of lower resolutions (e.g., Refs. [19-20]). Thus, assuming the extraction of coastal features will still be accomplished by image analysts (and not solely or partly by automatic feature extraction techniques) in the near term, it was deemed important to establish a simple rating system that provided viewing scale (on the computer screen) thresholds that could be associated with the different types of images. The rating system determined suitable for this project provided six levels as noted in Table 2.

Table 2. Image Quality Rating 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.

4.3 Comparative Evaluation of Images

In order to standardize comparative evaluations, an image evaluation program was developed to facilitate on-screen image analysis. This program worked within ESRI's ArcViewGIS 3.x and allowed an evaluator to simultaneously view a reference image and two other images of choice for comparative assessment (Figure 5). Image scales (on the monitor) could be set at any value from 1:100,000 to 1:250 in order to determine optimum viewing scales for the feature. Evaluation results were automatically recorded in a spreadsheet format for future analysis.

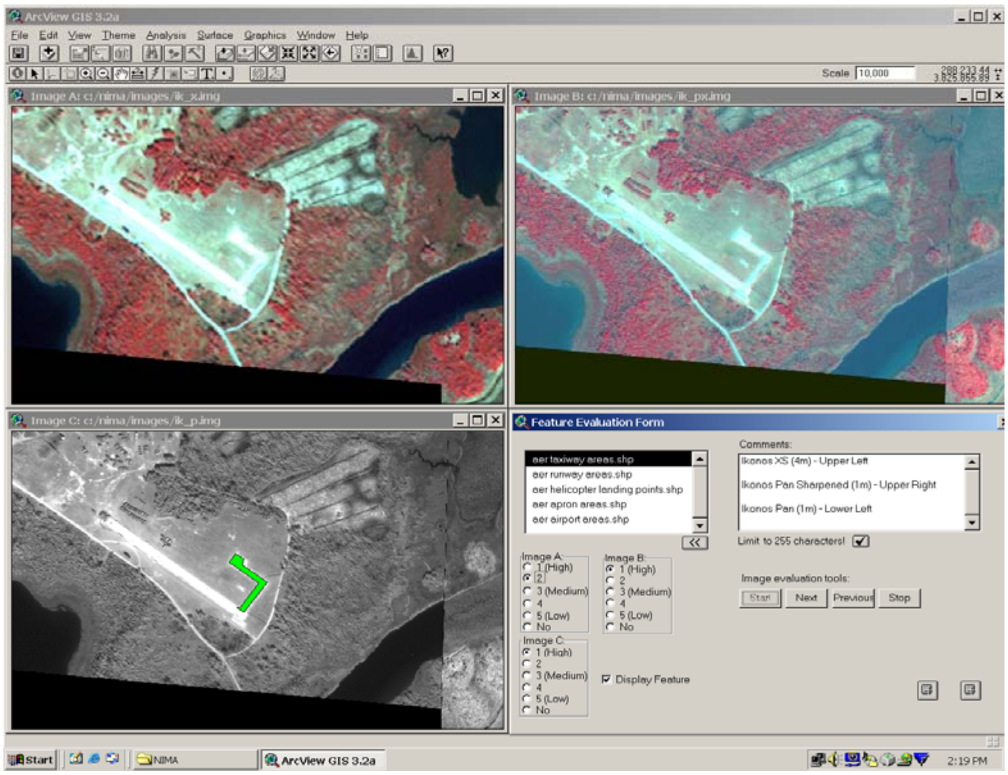
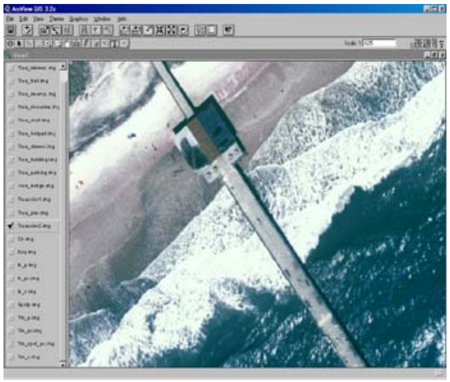


Fig. 5. Three images of different types can be simultaneously displayed and evaluated at specific scales for given features. In this figure, the airport apron and runway are shown on the reference image, an IKONOS panchromatic scene (1 m, lower left), an IKONOS multispectral scene (4 m, upper left), 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 prior training in image evaluation were employed to conduct the image assessments. In order to standardize image viewing on desktop monitors, display resolution was set at 1280 x 1025 x 32 bits and cubic convolution specified as the re-sampling algorithm. The trained 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 2) was assigned. All 50 features were independently evaluated on each of the 13 images. Figures 6a through 6d illustrate 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.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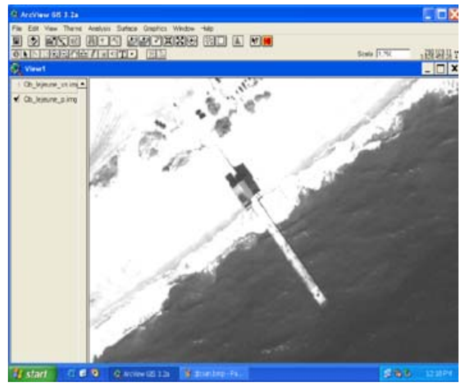


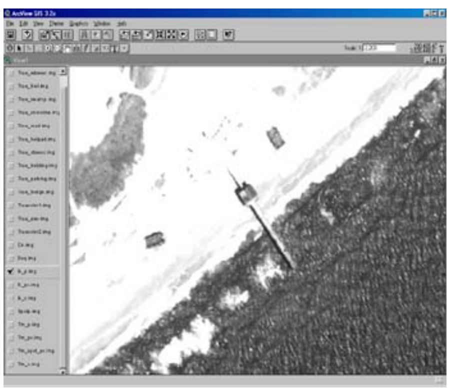
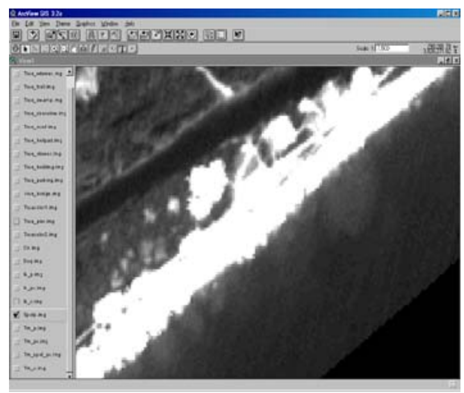

[c] [d]


Fig. 6. The details of Risley Pier are shown here on four 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] and IKONOS pan-sharpened imagery [c]. Risley Pier is not detectable on the SPOT panchromatic image [d].

4.4 Consolidation of Image Evaluations and Assessment of Results

A final average of the composite evaluations made by the analysts was computed. Shown in Table 3, these average assessments for each image at differing spatial resolutions provide *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 7). The linear relationship on a log-log graph 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, provides an immediate indication of the suitability of the images for littoral feature identification.

Table 3. 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**
Scanned True Color Photographs	0.15 m	500	1.18	94%
QuickBird Pan-sharpened Images	0.6 m	1350	2.05	90%
QuickBird Panchromatic Images	0.6 m	1500	2.07	90%
Scanned Color-Infrared Photographs	1.2 m	1750	2.37	86%
IKONOS Panchromatic Images	1 m	1900	2.80	86%
IKONOS Pan-sharpened Images	1 m	2300	2.81	86%
DOQQ Images	~ 1 m	2200	2.91	86%
QuickBird Multispectral Images	2.5 m	3700	2.93	86%
IKONOS Multispectral Images	4 m	6200	4.02	80%
SPOT Panchromatic Images	10 m	17300	4.80	54%
Landsat TM-SPOT Pan-sharpened Images	10 m	25600	5.43	52%
Landsat ETM + Panchromatic Images	15 m	26200	5.33	52%
Landsat ETM + Pan-sharpened Images	15 m	29800	5.44	52%
Landsat TM Multispectral Images	30 m	48300	5.39	48%

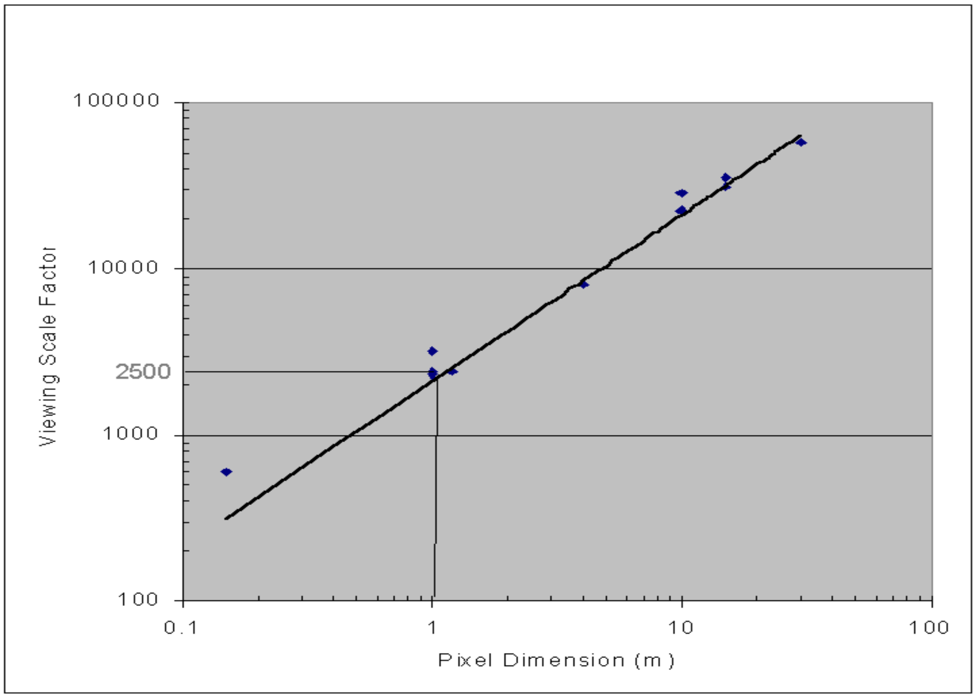


Fig. 7. Optimum viewing scale for extracting MSDS-Littoral features as a function of resolution (pixel dimension). Images with pixel resolutions of better than 1.0 m, and preferably better than 0.5 m, are needed for compiling detailed LW databases and map products.

For example, an image resolution of 0.6 m (e.g., QuickBird panchromatic) or better is required to detect/identify greater than 90 percent of the features representative of those required for littoral warfare operations and 2.5 m or better (e.g., QuickBird multispectral) to detect/identify more than 80 percent. Panchromatic and multi-spectral data from SPOT and Landsat showed little differentiation in visual feature extraction by image analysts. The derived pan-sharpened images compare equally to the source panchromatic images from QuickBird and IKONOS. Additionally, evaluations of the CIR photographs (1.2 m spatial resolution) rendered better image quality over the panchromatic satellite images of comparable scale (IKONOS panchromatic and pan-sharpened images at 1.0 m). This is likely due to negative effects of increased atmospheric attenuation traditionally inherent in satellite images. Data such as those obtained from SPOT or Landsat 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, as stipulated for littoral warfare products at scales of 1:5,000 and larger, to be realized. As shown in Table 4, features from the aeronautical, aids to navigation, defense fortifications and structures, inland water, ocean environment, population and utilities categories require images of the highest spatial resolution obtainable for viewing at scales of 1:2,500 or greater, whereas features from the ground transportation, physiography, ports and harbors and vegetation categories demand images with spatial resolutions of 2.5 m or better for optimum viewing at scales between 1:2,500 and 1:3,500.

Table 4. 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)
Larger Than 1 : 2,500	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
	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 imagery.	18
	IWA	Inland Water	Features evaluated visible at all viewing scales. Multispectral sensor desired.	44
	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 imagery with resolutions of 0.6 - 4 m. All evaluated features not visible when imagery resolution exceeded 10 m.	73
1 : 2,500 To 1 : 3,500	PHY	Physiography	Features evaluated visible at most viewing scales; 50 % of features not visible on imagery with resolutions of 10 - 30 m.	51
	PHR	Ports and Harbors	Features evaluated visible at most viewing scales; 60 % of features not visible on imagery with resolutions of 10 - 30 m.	52
	GTR	Ground Transportation	Features evaluated visible at most viewing scales; 33 % of features not visible on 30 m resolution imagery.	51
	VEG	Vegetation	Features evaluated visible at all viewing scales. Multispectral sensor desired.	25

5 CONCLUSIONS AND RECOMMENDATIONS

Commercially available satellite images are suitable for identifying features that comprise coastal databases. QuickBird panchromatic satellite images are best viewed by interpreters at scales of 1:600 to 1:3,000 and are the most suitable data for feature identification 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 coastal databases and map products. These pixel resolutions and viewing scale thresholds should serve as critically important guidelines for the most efficient extraction from image data of features from ground transportation, physiography, ports and harbors and vegetation categories. When collecting features from the aeronautical, defense fortifications and structures, inland water, population and utilities categories, 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 spatial resolutions (as measured by pixel dimension) of better than 1.0 m are required for the detailed interpretation and delineation of these 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 operation 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 coastal databases of acceptable completeness and accuracy. Because spatial resolution has proved to be 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 specification list. These pixel resolutions 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. Organizations must be able to rapidly access the best imagery to successfully complete their mission. Although sorting data is a necessary and important task, military and civilian image analysts cannot afford to spend precious time retrieving and evaluating the suitability of large images, text and map data sets for each of the potential LPPs around the world. Based on this study, the successful generation of coastal database products 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 aerial platforms, IKONOS, QuickBird and comparable satellite systems.

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