CHAPTER 116

COASTAL ENGINEERING APPLICATIONS OF AERIAL REMOTE SENSING

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ABSTRACT

This paper reviews the important coastal engineering applications of aerial remote sensing techniques and provides a current state of the art summary of the utilization of aerial remote sensors in coastal engineering studies. The sensors discussed include conventional black and white aerial photographs, black and white infrared aerial photographs, color and color infrared aerial photographs, multispectral aerial photographs, satellite photographs, infrared imagery, multispectral imagery, and radar imagery.

The field of coastal engineering is considered in a broad context to include all important applications of aerial remote sensing that relate to coastal engineering problems. The use of remote sensors to monitor coastal changes, study coastal landforms, examine storm effects, map coastal areas, determine nearshore hydrography, and monitor the environmental effects of coastal engineering projects, a topic of considerable current concern, is described.

The important characteristics of the various aerial remote sensors are described briefly. The advantages and limitations of the aerial remote sensing techniques for different coastal engineering studies are noted. The review and state of the art summary of the applications of the aerial remote sensors can be used by coastal engineers as guidelines in employing the sensors in future coastal engineering investigations.

INTRODUCTION

A considerable amount of literature exists which describes various applications of aerial remote sensing techniques in the field of coastal engineering. The increased interest in aerial remote sensors as a tool in coastal engineering investigations is indicated by the increasing number of papers describing the use of these techniques that have been presented at the Coastal Engineering Conferences in recent years. It is quite probable that the uses of aerial remote sensors in coastal engineering will continue to expand in the future as coastal engineers become more familiar with the techniques and improvements in aerial remote sensing techniques are developed.

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Aerial remote sensing techniques have several important advantages over other possible approaches to many coastal engineering studies. In many instances, a savings in the cost of data collection can be achieved. In other coastal engineering studies, the use of aerial remote sensing techniques makes it possible to collect data that could not be obtained by any other method or only at a cost that would be prohibitive. The use of aerial remote sensors also makes it possible and economically feasible to obtain more complete data on certain coastal conditions and processes than can be obtained by alternative data collection techniques. The continuous coverage of the terrain available with aerial remote sensors also permits very limited field observations to be used to characterize conditions over very large areas.

Certainly one of the most important advantages of aerial remote sensing techniques is a direct result of the aerial vantage point that is inherent in all of these techniques. The use of the aerial vantage point provides an overall view of terrain features that can be very useful in analyzing coastal landforms and processes. The aerial remote sensors provide synoptic coverage of the terrain that permits the coastal engineer to examine the relationship between various coastal features and processes. The continuous coverage and the aerial vantage point that are provided by the aerial remote sensors are particularly important in analyzing rhythmic coastal features such as sand waves that cannot be observed easily on the ground.

A variety of aerial remote sensors are available for use in coastal engineering applications. The most common sensors include black and white, black and white infrared, color, and color infrared aerial photographs, multispectral aerial photographs, satellite photographs, infrared imagery, multispectral imagery, and radar imagery. Each of these sensors has characteristics and capabilities that make it particularly suitable for certain types of coastal engineering investigations. It is imperative that coastal engineers be sufficiently familiar with the primary characteristics of the various sensors if the optimum sensor for a particular coastal engineering application is to be selected. Consequently, the following paragraphs describe the important characteristics and coastal engineering applications of the various sensors and summarize the advantages and limitations of the sensors.

APPLICATIONS OF AERIAL REMOTE SENSORS

Black and White Aerial Photographs

Conventional black and white or panchromatic aerial photographs have been used for many years in various coastal engineering applications. At the present time, black and white aerial photographs are the most widely used aerial remote sensor, primarily because these photographs are readily available for coastal areas. Black and white aerial photographs have been used both as graphic display tools or maps to illustrate coastal features and as a source to extract quantitative data concerning various coastal features and processes. Because of the aerial vantage point, aerial photographs have a unique capability to depict many coastal features and processes. In many instances, the relationship between various coastal features and processes can be examined more thoroughly from aerial photographs than from ground observations.

One of the most useful coastal engineering applications of black and white aerial photographs is to detect and measure changes in dynamic coastal landforms by comparing photographs taken with some time lapse. Aerial photographs are made by various governmental agencies and private firms for many different purposes, and consequently several coverages of aerial photographs taken over the past 30-40 years exist for most coastal areas in the United States and many other areas of the world. Therefore, several increments of change in coastal features can be determined by making measurements on each set of available photographs. Aerial photographs can be used to determine changes that result from long-term coastal processes and from short-term effects such as storms and hurricanes. If an effort is made to minimize the detrimental effects of the inherent errors in aerial photographs caused by scale variation, tilt, and relief distortion, accurate measurements of coastal changes can be made. An important recent development in the use of aerial photographs for coastal engineering studies is that the Coastal Engineering Research Center has initiated a program to compile a list of all existing aerial photographs of coastal areas in the United States.

Athearn and Ronne (1963), Cameron (1965), El-Ashry (1963 and 1966), El-Ashry and Wanless (1965, 1967, and 1968), Moffitt (1969), and others have described the results of studies which used panchromatic aerial photographs to determine changes in coastal landforms. Stafford (1968 and 1971) presented a detailed description of a procedure for conducting beach erosion surveys by making measurements on comparative aerial photographs. The results obtained in conducting an erosion survey along the entire 330-mile length of the North Carolina Coast were presented by Langfelder, Stafford, and Amein (1968 and 1970).

Many other coastal engineering applications of panchromatic aerial photographs have been described by various investigators. Examples of these applications include studies of wave refraction patterns, rip currents, coastal mapping, land use mapping, storm effects on coastal landforms, water current direction and velocity, coastal landform and geomorphology research, and wave patterns. Sonu (1964) reviewed the use of black and white aerial photographs in studies of coastal processes.

Black and White Infrared Aerial Photographs

Black and white infrared aerial photographs have been used in certain coastal engineering applications for many years. For coastal applications, the primary characteristic of infrared photographs is that they produce a sharp contrast between water bodies and the beach. This feature is the result of the marked difference in reflectance characteristics of water and earth materials in the near infrared wavelengths. Water bodies photograph in a dark gray or black tone which contrasts distinctly with the white to light gray tone of the materials composing the beach and other land features. Consequently, black and white infrared aerial photographs are very useful in shoreline delineation studies and particularly in locating the shoreline or waterline at different stages of the tide. By taking aerial photographs at specific levels of the tide, the location of the water line corresponding to any desired tidal stage can be determined. Black and white infrared aerial photographs have been used extensively by the National Ocean Survey and its predecessor, the U. S. Coast and Geodetic Survey, for various coastal mapping applications. Consequently, there are several coverages of black and white infrared aerial photographs available for many areas along the coast of the United States. It should be noted that black and white infrared aerial photographs can be used very effectively in conjunction with panchromatic aerial photographs in examining changes in coastal landforms.

Another characteristic of black and white infrared aerial photographs that can be useful for certain applications in the coastal environment is that these photographs have better haze penetration capability than panchromatic photographs. This capability results from the fact that the near infrared radiation used to expose black and white infrared film has a significantly longer wavelength than the visible spectrum radiation used to expose panchromatic film. The longer wavelength radiation is less susceptible to atmospheric scattering by thin clouds, fog, haze, dust, or air pollution than the shorter wavelength visible spectrum radiation in accordance with Rayleigh's Law. The increased haze penetration can be useful in a variety of coastal engineering applications in urbanized areas where air pollution is common or in areas where meteorological conditions frequently produce fog or haze.

Color and Color Infrared Aerial Photographs

Color and color infrared aerial photographs have been used in several coastal engineering applications. The addition of color to the aerial photograph provides a supplementary detection and discrimination capability that can be very useful in investigating many coastal features and processes. The additional cost of color or color infrared aerial photographs as compared to black and white photographs can be justified by the additional information content of color photographs in many coastal engineering applications. Several studies have shown that color photographs are most appropriate for some coastal engineering applications and color infrared photographs are the optimum type of aerial photograph for other coastal engineering applications. Thomas (1971) compared the coastal engineering applications of color and color infrared aerial photographs using the southern coast of Long Island, New York, as a study site. He found that color photographs were best for investigating underwater phenomena such as sediment patterns, water depths, and mapping shoal areas. Color infrared aerial photographs were found to be best for examining coastal features on land and for coastal vegetation studies. Consequently, obtaining both color and color infrared aerial photographs should be considered for comprehensive coastal engineering studies if the added expense can be justified.

Color aerial photographs have been used extensively by the National Ocean Survey in preparing and revising coastal charts because of their ability to provide water penetration and show submerged features. Color aerial photographs have been found to be useful in planning hydrographic surveys, in conducting storm damage surveys in coastal areas, and in revising nautical charts made obsolete by storm induced changes in coastal landforms.

Several studies of water penetration and water depth determination using color aerial photographs have been conducted in recent years. Much of the work in investigating the water penetration characteristics of color aerial photographs has been a preliminary step toward developing a technique for depth determination. Geary (1968) and others have described successful tests of water depth determination from color aerial photographs. Many studies have documented the superior water penetration capability of color aerial photographs as compared to color infrared photographs (Thomas, 1971). A special color film in which the blue sensitive emulsion layer was eliminated has also been used in depth penetration studies, apparently with considerable success. However, Ross (1969) and others have cast considerable doubt on the utility of a non-blue sensitive color aerial film for depth penetration applications. Several investigators have discussed important considerations in selecting the proper photographic techniques to achieve maximum depth penetration and to record subsurface details with color aerial photographs. Several studies have shown that a higher than ordinary exposure of the aerial film is necessary to produce maximum depth penetration, and this usually results in overexposure of the film for surface features. It is also important to have an understanding of the light transmission characteristics of water in planning depth determination projects using color aerial photographs. Continued development of techniques for determining water depths from aerial photographs can be expected.

Color aerial photographs have been used successfully in determining water current direction and velocity by photogrammetric techniques. Color aerial photographs have also been used in examining the flow patterns of water discolored by suspended sediment, pollutants, or dye. James and Burgess (1970) described a very sophisticated technique for investigating ocean outfall dispersion based on an analysis of color aerial photographs of a dye tracer. Waste concentrations, dispersion coefficients, and water current direction and velocity were determined by this technique.

Color infrared aerial photographs have some of the same characteristics commonly associated with black and white infrared aerial photographs. Color infrared photographs have better haze penetration than color photographs and they also give a sharper line of demarcation between water bodies and land features. These properties can be useful in several coastal engineering applications. The sensitivity of color infrared aerial film in the near infrared portion of the spectrum and the high reflectance of vegetation in the near infrared band cause vegetation to appear in a deep red or magenta color on color infrared aerial photographs. The variation in infrared reflectance characteristics of different vegetation species is sufficient to permit the differentiation of vegetation species by examining the intensity of the reddish color of vegetation on color infrared aerial photographs. Color infrared aerial photographs have been used extensively for mapping marshland vegetation species in the coastal zone (Pestrong, 1969). Color infrared aerial photographs may also be useful in monitoring the environmental effects of various activities in marshlands, estuaries, and other coastal areas.

Multispectral Aerial Photographs

Multispectral or multiband aerial photographs have only recently begun to be utilized for coastal engineering applications. Multispectral aerial photographs consist of two or more photographs of the same area that have been exposed by using different portions of the electromagnetic spectrum. Multispectral aerial photographs produced by multiple lens cameras with different film and/or filter combinations have an increased capability for the detection and analysis of various coastal features and processes. This increased detection capability results from the fact that multispectral photographs provide additional information on the interaction of terrain features and the electromagnetic energy employed in making the photographs. The selection of the different film and filter combinations can be made in such a manner that the maximum amount of information for a particular coastal engineering application can be obtained from the multispectral aerial photographs. In coastal areas, one wavelength band could be chosen to give maximum water penetration, another wavelangth band chosen to provide the maximum capability to delineate the land-water boundary, another wavelength band could be chosen to provide the maximum capability to discriminate between coastal vegetation species, and the other wavelength band or bands selected to optimize the capability to detect some other coastal feature or process of interest to the investigator. Research has shown that four multispectral photographs consisting of the blue, green, red, and near infrared bands are adequate for many applications.

Pestrong (1969) examined the utility of multispectral aerial photographs in investigating several aspects of the coastal environment, including water depth penetration, land-water boundary delineation, drainage feature mapping, and vegetation mapping. He found that four photographs consisting of color, color infrared, black and white infrared, and a photograph in the 550-630 millimicron wavelength band would constitute an optimum multispectral system. Ross (1969), Wenderoth (1969), and Yost and Wenderoth (1968 and 1971) have used multispectral aerial photographs extensively to investigate the water depth penetration capability of aerial photographs. Several important aspects of the depth penetration problem such as photographic techniques for achieving maximum penetration, the effects of suspended particulate matter on penetration, and the attenuation characteristics of light in various wavelength bands in different types of coastal water have been examined and the results have been reported. It has been shown that the light transmission characteristics of water are an important factor that must be considered in planning multispectral aerial photography missions for coastal engineering applications that involve water penetration.

Recently considerable progress has been made in the analysis techniques for multispectral aerial photographs. The development of various image enhancement techniques and particularly the additive color viewing approach has greatly increased the capability to extract data on different features depicted in the multispectral aerial photographs. Available techniques and equipment can be used to combine the multispectral photographs in combinations that simulate regular color, color infrared, and other false color images. Therefore, the multispectral aerial photographs and the additive color viewing technique can be used to obtain the maximum amount of information about the coastal zone terrain and thus provide essential data for coastal engineering investigations. Multispectral aerial photographs and additive color viewing appear to have considerable potential in coastal zone vegetation studies and this approach may be useful in examining the environmental effects of some coastal engineering projects.

Satellite Photographs

Satellite photographs have been used in examining certain coastal and oceanographic phenomena that can be observed from satellite altitudes. Fortunately, a number of important coastal and oceanographic features are visible on satellite photographs. The primary advantage of satellite photographs is the large area of coverage provided by each photograph. The large area of coverage permits features and processes that occur on a large scale to be observed in their entirety rather than in small segments as is commonly the case with ground observations or even other aerial remote sensors. Therefore, the photographs are suited ideally to the analysis of large coastal phenomena such as littoral currents, suspended sediment patterns, river effluent dispersion, and regional coastal landform studies. Satellite photographs can provide synoptic coverage of large scale coastal features and processes that can be used to evaluate the relationship between various landforms and features observed in the photographs. Satellite photographs may be particularly useful for providing more complete information on small scale problems that are created by large scale processes whose role is not completely understood or which cannot be observed using low altitude aerial remote sensors or ground observations.

The combination of the high altitude and the small scale that is used in producing satellite photographs results in a relatively low resolution as compared to other photographic aerial remote sensors. Satellite photographs commonly have a resolution in which the smallest features that can be observed are in the 200-300 feet range. Although the low resolution limits the type of coastal features that can be examined on satellite photographs, the resolution is not a severe handicap when large scale features are being investigated.

The applications of satellite photographs to coastal engineering studies have been severely restricted by the fact that the photographs have been available for only limited areas. However, the Earth Resources Technology Satellite (ERTS) program to obtain repeat coverage with multispectral satellite photographs on an 18-day cycle for most coastal areas promises to open a new era in the coastal engineering applications of satellite photographs. The repeat coverage will be particularly useful in investigating large time-varying coastal zone phenomena. The amount of satellite photography that will be available for study will increase dramatically as the ERTS and Skylab missions are conducted. Also, the combination of multispectral satellite photographs and analysis techniques such as additive color viewing offers considerable potential for coastal engineering applications.

One of the most important investigations of coastal processes by the use of satellite photographs was conducted by Mairs (1970). This study was based on an analysis of Apollo 9 photographs and it involved a detailed analysis of the origin, movement, and dissipation of turbid water plumes near Cape Hatteras, North Carolina. The observed plumes were concluded to be the ebb tide discharge of highly turbid water containing sediment derived from the bottom of Pamlico Sound. Mairs (1970) concluded that satellite photographs were a useful tool in studying coastal water circulation, flushing, and mixing patterns.

Nichols (1970) described several coastal processes that can be examined on satellite photographs, including turbid water plumes being transported by currents and circulation patterns. He noted the need for and the difficulties encountered in collecting adequate ground truth data to use in calibrating data extracted from satellite photographs.

Lepley (1968) investigated coastal water clarity by examining Gemini mission satellite photographs. The primary objectives of this study were to estimate the portion of the world's coastline that had sufficiently clear water to permit mapping of nearshore topography by using aerial remote sensing techniques and to investigate the feasibility of using satellite photographs to obtain data on water clarity. Lepley (1968) concluded that 35 percent of the world's coastal waters were sufficiently clear to allow mapping of sea floor topography to depths of 20 meters by aerial photographic techniques.

The satellite remote sensing data that will be generated in the near future appears to have considerable potential for coastal engineering applications. The availability of almost complete coverage of coastal areas at 18-day intervals will provide a capability for monitoring large scale coastal processes that has not previously existed. Hopefully, the apparent potential of this sensor will be realized in the near future so that this new tool can provide essential data needed in conducting comprehensive coastal engineering investigations.

Infrared Imagery

Infrared imagery is a non-photographic sensor that is produced by an optical-mechanical scanning device. The scanner is equipped with a detector which senses radiation in the infrared band. The infrared detector changes the incoming radiation into an electrical signal which can be recorded on magnetic tape or amplified and converted into an image on photographic film. The scanner is designed to scan a narrow band of terrain perpendicular to the flight line of the aircraft. As the aircraft travels along the flight line, successive scan lines provide continuous coverage of a band of terrain beneath and on each side of the aircraft. The infrared detector can be selected to provide sensitivity in the portion of the infrared spectrum where the maximum amount of information on a particular application can be obtained. The size of the infrared detector can also be selected to provide the proper balance between spatial resolution and thermal sensitivity. Taylor and Stingelin (1969) have presented an excellent description of the operating characteristics of infrared scanners.

An important characteristic of infrared energy is that bodies emit radiation in proportion to their temperature. Therefore, the intensity of the infrared energy emitted by an object can be used as an indication of the temperature of the body. The gray tone or film density of the infrared imagery represents the intensity of the infrared emission and the temperature of terrain objects depicted in the imagery. On positive prints of infrared imagery, white or light gray tones represent high temperatures and dark tones represent low temperatures. Consequently, infrared imagery is often referred to as thermal imagery or thermal infrared imagery. The fact that infrared imagery can be used to obtain data on temperature makes this sensor an ideal tool for a variety of applications in which temperature is an important variable. Some infrared scanners have provisions for the scanner to observe the infrared emission of a body having a known temperature incorporated into the device. This provides a technique to calibrate the gray tone of infrared imagery. The ability to quantify the gray tones on infrared imagery greatly increases the utility of the imagery. Taylor and Stingelin (1969) have reported that temperature differences as small as one degree centigrade can be detected on infrared imagery.

An important characteristic of infrared imagery is that it has day and night capability. Infrared imagery does not require sunlight for illumination because the infrared energy emitted from the terrain is a function of the terrain temperature. Generally, infrared imagery is made at a time when the feature of primary interest has maximum temperature contrast with the surrounding terrain. By having day and night capability, infrared imagery is less restricted than aerial photography if coverage during a particular tidal stage or other specific time period is desired.

Infrared imagery has been used only to a limited degree for coastal engineering applications. Because of the relation between the gray tone of infrared imagery and temperature, infrared imagery is particularly applicable to studies in which temperature is an important variable. In the coastal environment an important terrain feature that is particularly temperature sensitive is water. Thus, most coastal applications of infrared imagery have involved investigations of various characteristics of water bodies that can be indicated by temperature differences. Studies of water pollution, thermal pollution, and tidal flushing of coastal water bodies are investigations in which infrared imagery can be used successfully.

Several studies of water currents in the coastal environment have utilized infrared imagery. Some of these studies have monitored the movement of cool groundwater being discharged by springs into warmer ocean water to evaluate current patterns. Other studies have examined current patterns by relying on the existence of natural water temperature differentials or heated industrial effluent and noting the movement of these water masses.

Taylor and Stingelin (1969) investigated current patterns in the Merrimack River estuary of Massachusetts by using infrared imagery taken at night. In particular, the effect of tidal stage on current patterns was of interest and infrared imagery taken at different tidal stages was examined. The movement of polluted water and the boundary between river water and sea water under the influence of tidal action was also evident on the infrared imagery.

Taylor and Stingelin (1969) and others have demonstrated the tremendous potential of infrared imagery for thermal pollution studies in the coastal environment. The dispersion patterns of thermal effluents can be easily traced on the infrared imagery. The influence of tidal currents on thermal effluent dispersion can be investigated by using infrared imagery taken at different tidal stages. As more nuclear and fossil-fueled power plants are constructed in coastal areas and possibly offshore, infrared imagery will provide a powerful tool to monitor the effects of the thermal discharges of these plants in the coastal environment. Infrared imagery can also be used effectively in a variety of environmental studies such as monitoring industrial effluents, determining oil pollution sources and dispersion patterns, and examining certain aspects of tidal marsh ecology.

Multispectral Imagery

Multispectral imagery is a relatively new remote sensing tool that has not been used to a significant degree in coastal engineering applications. The basic concepts and the equipment used in obtaining multispectral imagery are similar to those used in obtaining infrared imagery. However, multispectral imagery is a more comprehensive sensor because data is collected in several bands of the spectrum. The spectral range that can be covered in obtaining multispectral imagery ranges from the ultraviolet through the visible region to the infrared band. The multispectral scanner collects data in a number of spectral bands over this range.

The mode of operation of a multispectral scanner is quite similar to that of an infrared scanner. The optical-mechanical scanner scans an area beneath and on each side of the flight path. Each scan line covers a narrow band perpendicular to the flight line. As the aircraft moves forward successive scan lines combine to provide continuous coverage of the area. The incoming radiation is separated into several discrete wavelength bands and transmitted to detectors sensitive to the proper wavelength band. The intensity of the radiation in each band is translated into an electrical signal by the detector and the electrical signal for each spectral band is stored on magnetic tape. Multispectral scanners having the capability to obtain data in as many as 24 discrete bands have been developed. Multispectral imagery in approximately five to seven bands is adequate for most applications.

When the multispectral data that is stored on tape is returned to the laboratory, the data in any of the spectral bands can be transformed into a photographic image. The gray tone or film density of the image corresponds to the intensity of the energy reflected or emitted in each particular band. It should be recognized that the energy emanating from the terrain represents primarily reflected energy in the ultraviolet, visible, and near infrared bands and emitted energy in the infrared spectral regions. Multispectral imagery commonly includes the infrared portion of the spectrum, and the infrared region is frequently separated into two or more bands corresponding to the infrared windows in the atmosphere.

The availability of data in several spectral bands provides a unique capability for discriminating between objects and for detecting the presence of specific features. The individual multispectral images reflect the spectral reflectance and emission characteristics of the terrain in each spectral band. Thus, the multispectral images can be used for detailed studies of terrain properties. Since many terrain features have unique spectral signatures or spectral signatures that are somewhat different from the signatures of the surrounding terrain, the multispectral images which reflect the spectral response of the terrain can be used to identify specific features.

One of the most advantageous aspects of multispectral imagery is the analysis techniques that are available. The multispectral data stored on tape can be processed and used as input to computer programs to analyze the data. By comparing the characteristics of the spectral response of the terrain with known spectral response data obtained from field measurements, the computer can identify certain terrain features. For instance, the ratio of the spectral response at different wavelengths may be used to identify certain features. Also, the computer output consisting of the predicted occurrence of selected features can be printed in a map showing the distribution of the features. This approach provides a degree of automation in the interpretation and analysis of aerial remote sensing data that is not available with other remote sensors. This technique is a powerful tool for analyzing multispectral imagery. However, it should be recognized that information on the spectral response of the features of interest must be known so that the computer analysis system can be calibrated.

One important and potentially very useful coastal engineering application of multispectral imagery that has been reported is water depth determination. Polcyn and Sattinger (1969) have described a technique for using multispectral imagery to map shallow water depths. The technique consists of the computer analysis of the energy reflected from the bottom at two different wavelengths. The depth determinations produced by the computer analysis are used to print a map of water depths. Thus, the computer performs the data analysis and also produces a convenient presentation of the water depth data. Even though the water depth data may not be sufficiently accurate for some detailed coastal engineering investigations, the technique appears to have considerable potential for applications where data on water depths are required. It should be noted that this technique is in an early stage of development and considerable improvement in the method may be forthcoming in the near future. Combining a laser device for measuring water depths with the multispectral technique provides a method of calibrating the water depth data and improving the accuracy of the depth determinations.

Techniques for using multispectral imagery and computer processing to classify vegetation have been described by several investigators. The successful use of multispectral imagery and computer processing has been reported for a number of other applications. These techniques have been used to classify soils, investigate hydrologic features, and many other similar applications. It appears that these techniques may also be useful in investigating various aspects of the coastal environment other than water depths and vegetation. All that is required is that the features to be investigated have a sufficiently unique spectral signature that the presence of the feature can be predicted from an analysis of the multispectral imagery. Another requirement is that information on the spectral response of the feature of interest must be known and this information can be obtained from field measurements.

When the existing and potential uses of multispectral imagery and computer processing techniques are considered, this approach appears to have considerable potential for coastal engineering applications. Also, it is quite likely that the quality of multispectral imagery and available analysis techniques for multispectral imagery will realize significant improvement in future years. Consequently, multispectral imagery will probably be used more widely for coastal engineering applications in the future.

Radar Imagery

In contrast to all photographic sensors, infrared imagery, and multispectral imagery which are passive sensors, radar imaging systems are active sensors. This means that the radar sensor provides its own source of illumination rather than relying on reflected energy from the sun or emitted energy from the terrain. This property provides radar imaging systems with a day or night capability. The radar system transmits a pulse of energy in a narrow beam perpendicular to the flight path of the aircraft and monitors the returning or reflected signal. The returning signal is processed and used as input to a cathode ray tube device which produces a photographic image. Successive impulses of radar energy are transmitted from an antenna and the reflected signals are monitored to provide continuous coverage of a band of terrain on one side of the aircraft. Because the radar imaging system is an active sensor which illuminates the terrain with radio waves and monitors the reflected signal, it measures the reflective characteristics of the terrain.

The radar imaging system is a side-looking device which scans a band of terrain on one side of the aircraft. Radar imagery is frequently referred to as SLAR or SLR imagery which are acronyms for side-looking airborne radar or side-looking radar. Although the view of the terrain taken by the radar system is similar to the view in an oblique aerial photograph, the radar imagery is produced in a format that has a uniform scale. Mosaics of radar imagery can be compiled to provide continuous coverage of large areas.

Another important characteristic of radar sensors is that the long wavelengths that are commonly used are not significantly attenuated by the atmosphere even when clouds, fog, haze, or air pollution are present. This provides radar imaging systems with an all weather capability. Only heavy precipitation has the effect of degrading radar imagery. When the all weather and day and night capability are considered in combination, radar imaging systems have considerable versatility. The all weather capability can be a particularly advantageous characteristic in tropical areas where cloud cover is almost constant. The successful use of a radar imaging system in a tropical environment has been demonstrated in the Darien Province of Panama where good quality radar imagery was obtained in an area where it has never been possible to obtain complete aerial photographic coverage.

Some of the radar imaging systems have provisions to control the polarization of the signal that is transmitted and received by the sensor. For instance, a signal polarized in a horizontal plane can be transmitted, and a signal polarized in a horizontal plane can be received. Alternatively, a horizontally polarized signal can be transmitted and only vertically polarized signals received. The radar images produced by these two polarization combinations are defined as like and cross polarized images, respectively. It has been shown that having both a like and a cross polarized image can increase the ability to detect linear features associated with natural terrain and cultural development. One typical radar system provides adjacent like and cross polarized radar images for analysis and interpretation.

The synthetic aperture radar system operates in a slightly different manner and provides radar imagery with higher resolution than other radar systems. The primary characteristic of the synthetic aperture system is that the electronic equipment used for radar energy transmission and receiving is designed to produce a synthetic or fictitious antenna in space so that the flight path of the aircraft acts as an antenna in transmitting and receiving the radar pulses. The longer synthetic antenna improves the resolution of the imagery and provides for uniform resolution throughout the entire band of coverage. In the synthetic aperture radar system, the energy reflected from the terrain is received, changed into an electrical signal, and stored on film. The filmed data is processed optically in the laboratory to produce the radar imagery.

Radar imagery is usually produced at a relatively small scale. Also, the resolution of the best radar imagery available on the civilian market is approximately 50 feet. Thus, radar imagery is rather limited when detailed analyses of terrain features are contemplated. On the other hand, the small scale radar imagery is particularly advantageous for conducting reconnaissance surveys of large areas. The side-looking radar imagery provides a wide band of coverage for each flight line which can be a useful feature.

Imagery produced by side-looking airborne radar systems has been employed by geoscientists for numerous applications related to geologic studies, geologic mapping, and terrain evaluation. However, the coastal engineering applications of radar imagery have been limited. However, it has been shown that many coastal landforms and features can be identified on radar imagery. Radar imagery can be used as as a map of coastal areas and the imagery can be interpreted to obtain data on the geology and other characteristics of coastal terrain.

One of the most extensive applications of radar imagery in coastal studies has been described by MacDonald, et al. (1971). This study involved an investigation of the use of radar imagery in coastal mapping and coastal geomorphology studies in Panama. The advantages and disadvantages of radar imagery in coastal studies were discussed and the types of coastal landforms visible on radar imagery were described. The importance of the all weather capability of radar sensors in obtaining satisfactory coverage of perennially cloud covered tropical areas was emphasized. The coastal landforms and features identified and examined on the radar imagery included tidal mud flats, estuarine features, surf, beach ridges, and a variety of other beach features. The low spatial resolution and lack of data on water depths, nearshore processes, and submerged features were noted as limitations of radar imagery in detailed coastal studies.

Lewis and MacDonald (1970) investigated the characteristics of estuarine drainage patterns by using radar imagery. The primary features examined were estuarine meanders consisting of oblong channels separated by depositional spurs. These landforms provide information on the balance between marine and fluvial processes and on other characteristics of the coastal environment. Other investigators have noted that radar imagery is very useful in delineating drainage patterns.

Orr and Quick (1971) investigated the use of radar imagery and other aerial remote sensors in coastal terrain studies. Radar imagery was found to be the optimum sensor for conducting a regional analysis of coastal terrain. A number of coastal landforms and features could be identified on the radar imagery. A ranking of the capability of radar imagery and several other aerial remote sensors in investigating various aspects of the coastal environment was presented.

Radar imagery with its day or night and all weather capability has the potential to be a useful sensor in selected coastal engineering investigations. Radar imagery can be particularly useful for coastal mapping in cloud prone tropical areas and in extreme northern or southern latitudes which have long periods of darkness. Radar imagery can also be advantageous in conducting reconnaissance surveys of long sections of coastline. For certain types of coastal studies, radar imagery may be useful as a supplement to other aerial remote sensors. Improvements in radar imaging systems to increase the resolution may be available in the future.

Other Aerial Remote Sensors

Several other aerial remote sensors have been developed and used for certain coastal and oceanographic applications. Some of these sensors may prove to be useful for selected coastal engineering investigations. The sensors that appear to have the greatest potential for coastal engineering applications are described briefly in the paragraphs below.

Laser devices for determining water depths from aircraft have been developed recently. These devices are in a state of testing and development and information on the characteristics and accuracy of the devices is rather limited. The laser depth ranging devices may be particularly useful for calibrating water depth data obtained from other aerial remote sensors such as multispectral imagery or multispectral aerial photographs. Practical laser devices to differentiate between suspended sediment and true bottom may also be developed in the near future. Laser devices for measuring water depths appear to have considerable potential for coastal engineering applications, particularly if further development of the technique can improve the accuracy of the depth data obtained. It should be noted that laser devices for obtaining ground surface profiles or cross-sections of land features are available.

Meteorological satellites have had a tremendous impact in the field of meteorology and these satellites have also produced a considerable amount of data that is useful in oceanographic applications. Data on weather conditions obtained from meteorological satellites may be useful to coastal engineers in developing synoptic weather charts for use in wave propogation studies. Meteorological satellites can also be useful in examining severe storms such as hurricanes and relating the storm location to wave conditions and storm damage along coastlines.

Scientists at the U. S. Geological Survey have developed and tested a prototype model of an airborne fluorometer (Stoertz, et al., 1969). The device has the capability to measure fluorescence from dyes in aqueous solution in daylight from an airborne platform. The device can be very useful in monitoring dye tracers in water current and dispersion studies in bays and estuaries. The device can be used with clear or turbid water and very low concentrations of dye tracer can be detected. The airborne fluorometer appears to have considerable potential for coastal engineering applications such as hydrodynamic investigations and water pollution studies. Further improvements to overcome some of the problems with this new aerial remote sensor may be forthcoming.

Several other aerial remote sensors may have potential in certain coastal engineering studies. These include infrared radiometers, radar scatterometers, active microwave sensors, passive microwave sensors, and microwave scatterometers. Although not an aerial remote sensing technique, terrestrial photogrammetry which is closely related to aerial photogrammetry also has potential in coastal engineering investigations both in the laboratory and the field.

CONCLUSIONS

Each of the aerial remote sensors has characteristics which make it particularly suitable for certain coastal engineering applications. Therefore, it is important to have an adequate knowledge of the capabilities of the aerial remote sensing techniques so that the optimum sensor can be selected for a particular application. By employing the type of aerial remote sensor that is most appropriate for a given task, coastal engineers can take maximum advantage of aerial remote sensing as an analysis tool, and considerable economic savings or improvements in data collection capability can frequently be realized in conducting coastal engineering investigations. Hopefully, the information presented herein can be used by coastal engineers as guidelines in employing aerial remote sensing techniques in future coastal engineering investigations.

Several of the aerial remote sensors appear to be particularly notable from the standpoint of future potential. Satellite remote sensing data that will be collected by the ERTS program in a multispectral format and with repeat coverage provided on an 18-day basis appears to be a particularly useful tool for monitoring large scale coastal processes of interest to coastal engineers. Image enhancement techniques such as additive color viewing should provide an improved capability to extract coastal engineering data from multispectral aerial and satellite photographs. The potential coastal engineering applications of multispectral imagery and computer processing techniques also appears to be substantial.

The field of aerial remote sensing has experienced rapid development in the past ten years, and this trend will probably continue in future years, although possibly at a slower pace. Consequently, significant improvements in the aerial remote sensors that currently exist can be expected to occur in the future. Also, new aerial remote sensors that are not available presently will probably be developed. The improvements that occur in the future may produce higher quality aerial remote sensing data, or they may consist of better techniques for analyzing aerial remote sensor data. The improved and new aerial remote sensors may improve the capability of these sensors for coastal engineering applications. The future developments in aerial remote sensors should be monitored closely to detect new techniques that are applicable to coastal engineering investigations.

One important factor that must be considered in coastal engineering investigations which employ aerial remote sensors is the provision for obtaining adequate ground truth data to calibrate the information obtained from the aerial remote sensors. For best results, ground truth data should be collected simultaneously with the aerial remote sensing mission, although this is not always possible. Obtaining current ground truth data is particularly important when coastal processes that are heavily time dependent are under investigation. There is little doubt that many aerial remote sensing missions have been less than completely successful because of inadequate ground truth data. The expense of obtaining aerial remote sensing data has been essentially wasted on some projects because of the lack of satisfactory ground truth data that could have been obtained at minimal additional cost. It is important to make detailed plans for the ground truth data collection program so that unanticipated problems will not prevent satisfactory data from being collected. In some instances, the type of ground truth data that can be collected at reasonable cost may be a significant factor in selecting the type of aerial remote sensor that should be employed. It should be noted that one of the primary advantages of aerial remote sensing techniques is that they permit limited field observations to be extended throughout the area of coverage, and it is the ground truth data that form the basis for this process.

NOTE CONCERNING ILLUSTRATIONS

The oral presentation of this paper was accompanied by illustrations consisting of black and white and color 35mm slides. These slides illustrated several aerial remote sensor displays of coastal features. Because of the loss in quality that would result from the printing of the color illustrations in a black and white format, the decision was made to delete the illustrations in printing the paper. The interested reader is referred to the publications listed in the bibliography and other aerial remote sensing publications for illustrations of the aerial remote sensor displays of coastal zone landforms, features, and processes of interest to coastal engineers.

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