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Remote Sensing of a Barrier Island

A combination of thermal-infrared, color and color-infrared imagery was more valuable for studying Padre Island, Texas, than a single imagery source operating at a specific wavelength.

INTRODUCTION

EACH OBJECT in the environment inherently possesses a variety of properties and characteristics which are capable of detection by a specially designed sensor. One such characteristic is the interaction of electromagnetic radiation with the object. Electromagnetic energy produces a wide range of manifestations of the environment. Each of these provides different and, sometimes, complementary information. Various wavelengths and intensities of electromagnetic energy are absorbed, reflected and emitted by all objects in accordance with spectral distributions unique to that object. Knowledge of these spectral signatures can be utilized to sense effectively the object and gain valuable information concerning its composition and external characteristics.

ABSTRACT: *Thermal-infrared imagery and color-infrared and conventional color photographs were generated over Padre Island, Texas, a barrier island off the south Gulf Coast of Texas. This imagery was used to examine the island's physical and cultural features. A major goal of this study was establishing the potential of each sensor in acquiring data by the formation of object signatures on the imagery. Detailed characteristics and basic trends of the island's physiography were established from the imagery. The distribution of the vegetation cover, development of vegetated and bare sand dunes, detection of water bodies and the characteristics of wind tidal flats and hurricane washover channels were examined. The effectiveness of the sensors in presenting information concerning the environment is evaluated and compared.*

To exploit the vast reservoir of environmental electromagnetic energy for remote sensing, images must be generated by a sensor. Subsequently, these images must be evaluated by an interpreter. Recent technological improvements in remote sensors, sensor platforms and recording media have greatly enhanced the capability of collecting data concerning the environment. The effectiveness of today's multi-spectral reconnaissance collection capabilities have enormously increased the volume, quality and sophistication of remote sensing outputs. But this increase in quality of data remains as only potential information until it is interpreted and evaluated by man. The capability of assimilating the data and interpreting its significance continues to lag although the use of computers for data manipulation and display offers considerable potential for the future.

A gap exists, then, between ability to generate imagery and the capability of interpreting it. This gap is further widened by the lack of knowledge concerning the signatures registered on imagery. Automated, computer-assisted interpretation is the potential bridge of this gap, but the bridge must be anchored solidly on a footing of known image signatures. To identify these image signatures, extensive analysis of acquired data associated with environmental phenomena must be accomplished. This study offers some progress in that direction. It presents the results of the interpretation of three types of remote sensing outputs: (1) thermal-infrared imagery (the prime sensor), (2) color-infrared photographs, and (3) conventional color photographs. The latter two were used as collateral reference imagery. The signatures produced by objects on the imagery were defined and evaluated. The evaluations were cross-correlated between the three types of sensor imagery.

Study Area

GENERAL DESCRIPTION

The area selected for this study was the northern portion of Padre Island, Texas. Padre Island is a little-developed, offshore barrier island located along the southeastern portion of the Texas Gulf Coast. The island extends in a great sweeping arc from near Corpus Christi—where it joins Mustang Island—south and west to Port Isabel. See Figure 1 for the location of the study area. It terminates approximately seven miles north

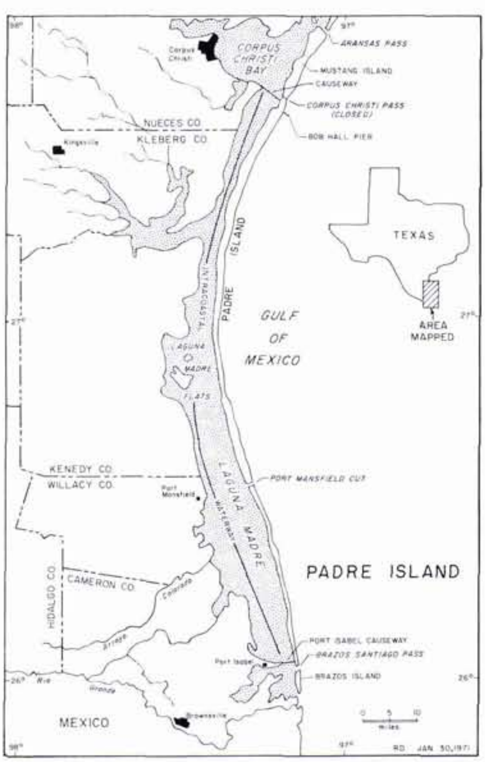

FIG. 1. Map of Padre Island, Texas.

of the mouth of the Rio Grande River. The island is separated from the mainland by Laguna Madre, a shallow, hyper-saline lagoon. The width of Padre Island tapers from over two miles at its northern end to about one-half of a mile at its southern end. Elevation of the island ranges from sea level to approximately 50 feet above mean sea level. Cultural development on the island is generally limited to the extreme northern and southern ends. About 30 miles from the southern end, the Island has been breached by a man-made channel. This is known as the Port Mansfield ship channel.

ISLAND DEVELOPMENT

The southern portion of Texas consists of a coastal plain which slopes gently to the south where it is flooded by the Gulf of Mexico. The barrier island deposits which form Padre Island originate from several geologic formations which underlie the coastal plain. Additional sediments are added by stream deposition from rivers like the Colorado, Guadalupe, and Nueces. The sediments are eventually deposited in belts parallel to the Gulf Coast.[1] The younger formations outcrop close to the Gulf Coast. The older formations outcrop further inland. Their location evidently indicates that the barrier island deposits are a relatively recent (Holocene Age) development.

As the barrier island complex reaches maturity, the island eventually migrates landward and joins the mainland. This stage is characterized by the filling in of the lagoon with sediment transported by the wind from the island. This lagoonal filling is evident along the landward margin of Padre Island between the latitudes of 26°48′N and 27°00′N. In this axis extensive sand and mud tidal flats join the island with the mainland. The geologic forces which continue to build and alter the physiography of Padre Island are the results of wave action, wind, ocean currents, and hurricanes.

CLIMATE

The climate of Padre Island is semiarid with an average rainfall of 26 inches at the north end of the island. Rainfall decreases southward to as little as approximately 20 inches per year. The temperatures in the study are average from 56° to 62° for January, and 82° to 86° during July.[2]

Sensor Imagery Utilized

The primary sensor imagery utilized in this study was 70-mm format thermal-infrared imagery taken by an infrared line scanner.* Collateral imagery consisted of color-infrared photographs and conventional color photographs generated with 35-mm cameras. The color-infrared was exposed on Kodak Ektachrome Infrared Aero Film Type 8443. The conventional color film used was Kodachrome II. A Kodak Wratten Filter 12Y and a Tiffen Polarizer were used respectively with the color-infrared and conventional color photography. The Kodak Wratten Filter 12Y is yellow and attenuates wavelengths in the blue (340 nanometers to 500 nanometers). The Polarizer was used to reduce glare from the water and sand.

Imagery Collection Methods and Procedures

The three types of imagery utilized in this study were collected during two different reconnaissance missions. The thermal-infrared imagery was collected on October 28, 1968, between the hours of 0700 and 0800. The initial leg of the mission was flown along the Laguna Madre coast of Padre Island from Corpus Christi south to the Port Mansfield Ship Channel. The return flight was along the Gulf Coast side of the island from the Port Mansfield Ship Channel north to about Corpus Christi. The mission was flown at an altitude of 2,000 feet. The color-infrared and conventional color photographs were collected on May 12, 1970, between 1245 and 1815 hours. The flight lines were similar to those used in the thermal-infrared mission. Aircraft altitude was 500 feet during this second mission. The color-infrared and conventional color imagery were taken with a handheld camera and produced a degree of obliquity in the photos.

Basic Orientation

Due to the unconventional nature of color-infrared photographs and thermal line-scan imagery, a slightly different approach and thinking is required for imagery interpretation. Color-infrared film differs from ordinary color film in that the three image layers are sensitized to green, red and infrared istead of blue, green and red. In the final color transparency the blue lightwaves are attenuated by the use of the yellow filter. The original green images as blue. The red images as green and the infrared appears as bright red or magenta. The original colors are shifted to longer wavelengths and present a new rendition of the subject.

In field use, color-infrared photographs have demonstrated a vast potential in crop identification and the detection of diseased or insect infested crops. Manzer and Cooper demonstrated the use of color-infrared in potato disease detection.[3] Color-infrared has also been used for water detection and shoreline analysis. Schneider has reported on its use in water resources studies by the U.S. Geological Survey.[4]

Thermal-infrared imagery is similar to conventional photographs only as pictorial representation of an imaged thermal scene. The imaged gray scale densities on black-and-white film represent relative levels of reflected and emitted infrared radiation rather than visible light. To understand and exploit the information presented on infrared imagery, a comprehensive knowledge must be acquired of the thermal behavior of the imaged object and its responses to temporal and environmental changes. For this reason all major observations are presented with an explanation of the phenomenon.

The thermal-infrared imagery was collected by an electro-opto-mechanical line scanner which senses and collects infrared radiation propogated by the environment and electronically records these emissions on film. To perform these functions, the line scanner typically consists of four basic components: (1) scanner optics, (2) detector, (3) recording unit, and (4) power supply. The scanner optics collect the emitted radiation and focus it upon the detector. The detector transfers the infrared energy into an electrical signal which is amplified and transmitted to the recording unit. The recording unit converts the electrical signal into visible light. The light fluctuates in proportion to the original infrared signal and is then used to record an image of the original infrared scene on black-and-white film, or by some other means such as a cathode ray tube (CRT).

Because the thermal-infrared image is a graphical display of shades of gray, it must be determined whether the interpreted imagery is negative or positive. The infrared imagery used during this study is a negative transparency, thus the *warmer* areas or those emitting relatively more infrared energy, image darker in tone. The *cooler* areas which are emitting less energy, image lighter. In

* The thermal infrared imagery was generated by a CCC-1 Bendix Thermal Mapper operating in the 8μm to 14μm range. Aircraft altitude was 2,000 feet and its ground speed was about 150 miles per hour. The instantenous field of view (resolution) was 2.5 milliradians. The lateral scan angle is 120°—or 60° on either side of the aircraft nadir.

interpreting a positive image such as the prints presented with this paper, it is necessary to adjust and consider the lighter shades as *warm* and the darker areas as *cool*.

During the last decade, the use of thermal-infrared imagery has expanded to many areas. Colwell and Olson have reported its use in vegetation analysis.[5] Hirsch has reported substantial successes in the use of thermal imagery in wild forest-fire locating systems.[6] Detection of thermal water pollution using infrared imagery has been demonstrated by Van Lopik, Pressman and Ludlum.[7] Other uses include detection of water sources and measurement of soil temperatures.

Imagery Interpretation Results

LAND/WATER CONTRAST

One of the more apparent contrasts on the thermal-infrared imagery is between the waters of the Gulf of Mexico and the bare beach terrain. The water was emanating a large amount of infrared energy and thus images *warm*. In comparison, the bare beach images *cool* because it was emitting less infrared energy than the water.

Due to the considerable land-water contrast evident on the imagery of Padre Island shown in Figure 2, it is logical to assume that it was probably taken during the night or early daylight hours. This deduction is based on the known diurnal temperature cycle of water and bare soil. As bare soil is exposed to solar radiation, it tends to be heated more rapidly and intensely. At night, bare soil surfaces rapidly lose a significant portion of their absorbed infrared energy and become cool. Bodies of water react very differently to incident radiation. Water generally maintains a more stable temperature profile compared to earth materials. Water surfaces tend to warm more slowly than bare terrain and cool more slowly if the source of radiation is reduced.

Further explanation of the land-water contrast can be attained by analyzing the specific interaction of electromagnetic energy with each type of surface. Water is transparent and allows the incident energy at most wavelengths to penetrate easily and be absorbed at great depths. Because of the deep penetration, a great volume of water is heated. The fluidity of water allows the heat to be circulated throughout the system. On the other hand, ground surfaces are opaque at these wavelengths and incident energy is transmitted beyond the surface layer only by conduction. This restricts the heat to a more limited area of a solid. Solids do not possess a fluidity which allows rapid heat exchange.

Because the temperature of an object is an extremely important factor in predicting the object's signature on infrared imagery, it is necessary to examine the specific relationship between temperature and infrared emittance as explained by the Stefan-Boltzman Law that is defined as:

$$W = \epsilon \sigma T^4$$

where W is the radiant emittance, measured in watts/cm^2 of the radiating surface, ϵ is an emissivity factor representing the object's radiatio efficiency, σ is the Stefan-Boltzman constant 5.673×10^{-12} watt/(cm^2)(deg^4) and T is the absolute temperature in °K. This law states that with all other factors constant, the amount of infrared energy emitted by an object is directly pro-

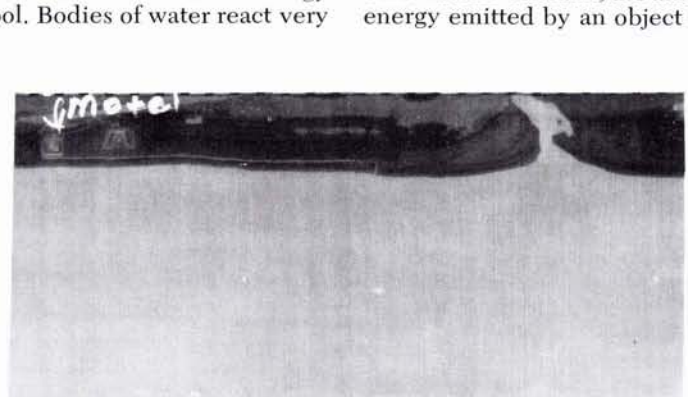

FIG. 2. The land/water contrast is evident on this thermal-infrared image. Also note the contrast in emittance between Packery Channel in the upper right of the image and the Gulf water. The retaining wall stretching along the beach displays the *warm* concrete signature.

FIG. 3. Water forms and degrees of moisture are sharly delineated by the black-and-white reproduction of the color-infrared photograph.

portional to the fourth power of the temperature.[8] This relationship demonstrates how critical temperature is in producing an object's signature on infrared imagery.

WATER

Detection and evaluation of water in the study area was satisfactorily accomplished with all three types of imagery. Infrared imagery and color-infrared photographs displayed the best capability for detecting the presence of small bodies of water. On the other hand, conventional color photographs displayed the greatest potential for water analysis and penetration.

On the infrared imagery, the wash-over channels and other water on the island appeared extrememly *warm* in contrast to the *cool* appearance of the bare soil and the less *warm* appearance of the vegetation. Due to this marked contrast, all surface water on the island could easily be detected. In addition, different bodies of water varied notably in the intensity of infrared emittance. Inland water, e.g., hurricane channel, imaged warmer than that of the Gulf. This contrast could be seen in the comparison of the smaller ponds, channels, and passes with the Gulf. There are several reasons for this contrast. The smaller bodies of water, especially the ponds and hurricane channels, are shallow, thus allowing the incident radiation during the day to heat the water to a higher temperature. In addition, the inland water has less chance to mix with other water. Some examples of the contrast in infrared emittance between inland water and the Gulf are shown in Figure 4. The difference is seen in the comparison of the water in Packery Pass with the Gulf. This pass is located to the north of Padre Island Causeway between latitudes of 27°36′N and 27°39′N.

On the color-infrared photographs, inland water and the Gulf imaged in variations of blue. The blue rendition of the water permits a more exacting delineation of the land/water interface. It was especially efficient in delimiting some of the shallow, slightly inundated areas where an optimum sensitivity to the various degrees of water and moisture was required. As an example, the original of Figure 3† displays five shades of blue from the very light blue rendition of the fairly dry sand to the deep blue rendition of the water. Each shade represents a finer delineation of the water content suspended within or on top of the beach.

Conventional color photographs provided the greatest penetration and differentiation in color rendition of the water. Figure 4 shows the capability of conventional color in differentiating between the color variations of the water near the outlet of Port Mansfield Ship Channel. The contrast in color between the water being released through the channel and the Gulf is due to the transported sediment load.

CULTURAL FEATURES

Two image signatures which are common to cultural areas are: (1) asphalt/concrete,

† Color photographs submitted with this article are reproduced here in black and white. —*Editor.*

FIG. 4. Differentiation in water rendition due to sediment transport is best delineated with conventional color of which this is a black-and-white reproduction. Sediment accretion behind the southernmost jetty of Port Mansfield Cut displays the vector of the longshore current.

and (2) man-made sources of heat, e.g., a furnace. Both of these signatures are evident in the developed portions of Padre Island.

In the built-up area on the northern end of Padre Island, the concrete/asphalt signature is produced by parking lots, developed roads and a concrete retaining wall. These signatures are shown in Figure 2. On the thermal-infrared imagery the concrete wall shows as an extremely *warm line* running parallel to the shoreline. The concrete retains energy during the night and continues to emit strongly during the early morning hours. Several reasons account for this. First, concrete has a high heat capacity. Heat capacity is the ability to absorb energy and radiate it slowly over a prolonged period of time. Second, the surface of the wall is relatively rough, thereby increasing the potential absorption and emission capability. In contrast, an object with a well polished or smooth surface reflects a large amount of the incident solar radiation during the day. A good reflector will emit strongly for only a short period of time after the sun has set because most incident energy is reflected rather than being absorbed and re-emitted. Another reason for the wall having such a strong signature is because two sides or planes of emission are exposed to the line of sight of the scanner. The exposure of both sides to the scanner increases the volume of energy which is incident upon the scanner.

The *warm* concrete/asphalt signature is also emitted by the paved roads and the parking lots surrounding the motels in the area. Due to the geometry and placement of these surfaces on the imagery they do not appear as *warm*, or contrast as sharply with the bare sand as does the retaining wall. These surfaces consist of one plane of emission and are further removed in distance from the infrared scanner.

Approximately 11.5 miles south of the Padre Island Causeway is a small petroleum installation which displays signatures typical of cultural activity, especially in an industrial area. Figures 5 and 6 show thermal-infrared and conventional color photos of the petroleum site. The site consists of a distillation unit, five petroleum

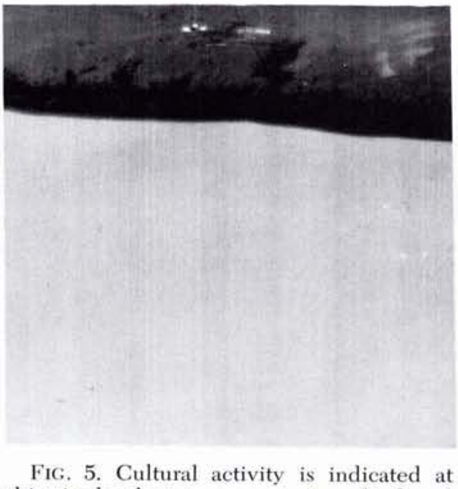

FIG. 5. Cultural activity is indicated at this site by the intense emission of infrared energy. Note *warm* signature of tanks and cooling water.

FIG. 6. A conventional color photograph (this is a black-and-white reproduction) provides complementary coverage and best rendition of ground truth of the industrial site imaged by the thermal-infrared in Figure 5. Change detection is displayed by the removal of one of the five tanks previously imaged by the thermal-infrared.

tanks, a pond for cooling water and an associated road network. The distillation unit consists of heat producing subsystems, including a furnace. These objects image as three intense *hot* spots. Intense emission in the infrared is characteristic of industrial areas which generate a great amount of heat. Five tanks are located near the distillation unit. Because of their *warm* signatures, the tanks are assumed to be full. If the tanks were empty, they would normally image *cool* because they are constructed of metal and have a smooth, unpainted surface. This type of surface makes a good reflector and would enable the tanks to assume the ambient temperature if they are empty.

On the imagery, near the termination of the road leading from the beach to the petroleum site, are two *cool* spots; these are sheds with tin roofs. An unpainted metal surface such as these tin roofs will normally display a *cool* signature at night due to a low emissivity, low temperature and low heat capacity. Due to the high reflectivity of metal, it will normally image *cool* in the 800–1400 nanometer (8 to 14 micrometer) atmospheric window during the day as well as the night. A thermal-infrared scanner operating at the shorter or reflected infrared wavelengths would respond differently to the infrared reflection from the tin roofs. It would sense and record more of the reflected infrared energy and these metal surfaces would appear hotter.

Comparison of the infrared emittance from the undeveloped road leading to the site from the beach, and the emission propagated from the unpaved parking area in the location of the site provides important information concerning the effect of surface compactness on the image signature. Although both of these surfaces are identical in material composition, they emit different intensities of infrared energy. The parking area and the road surface in the immediate area of the site appear *warmer* because they receive more traffic and are more compact than the road leading to the beach. Normally, during the night or early morning hours, a compacted, compressed surface will image *warmer* than a loose surface Compactness tends to increase an object's heat capacity.

HURRICANE CHANNELS

Hurricane channels are a prominent landform in the study area. They are formed by a breach in the foredunes during a storm surge. Hurricane channels are more common in the southern portion of the island because the increased aridity in the area and subsequent sparseness of vegetation make the terrain more vulnerable to erosion. Figure 7 shows a hurricane channel imaged on a thermal-infrared photograph.

At the termination of the hurricane channels, the sediment which was transported by wave action through the foredune

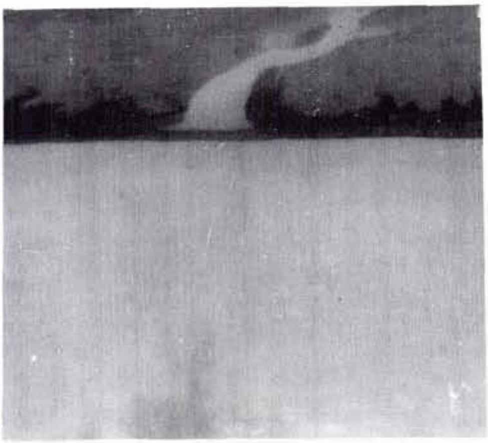

FIG. 7. Thermal-infrared imagery shows the hurricane channel cut off from the Gulf by a sand bar. The bar is evidence of the depositional work of the longshore current system.

ridge is spread in a form called a hurricane washover fan.[9] Figure 8 (color-infrared) shows a washover fan generated by two hurricane channels and spread over areas of the barrier flats. Visible in Figure 8 are probable areas of saline soil appearing almost white in color. The detection of salinity has enhanced the value of color-infrared photographs for use in agriculture.

BEACH AREA

The beach area is sharply defined on the thermal-infrared imagery as a *cool* continuous trip bordering the Gulf. Both the Gulf waters and the vegetation on the foredune image *warm* and easily delineate the beach interface. Generally, the width of the beach area increases as it extends to the south. The additional width is the result of foredune leveling by blowouts, washovers, hurricane channels and the establishment of a hurricane beach.

Due to the action of the waves and the wind, different portions of the beach normally manifest different degrees of wettness. Immediately adjacent to the water, the area is subjected to continual inundation by the surge of water from breaking waves. Further inland and comprising the greatest portion of the beach is a strip which is occasionally inundated by a surge of water and normally is damp. Beyond this damp strip, an area of dry sand appears. This portion is infrequently inundated by Gulf water and consists mainly of dry, eolian sand which was transported from the forebeach.

The three beach areas of different wettness appear different in contrast and are easily delineated on the thermal-infrared imagery and color-infrared and color photographs. Although each type of imagery provides adequate means of differentiation between the three areas, color-infrared provides the greatest contrast for delineation. The color (reflected) infrared images all three portions of the beach in different shades of blue, ranging from very deep blue in the continually inundated areas to an ex-

FIG. 8. A washover fan is shown developed at the termination of a hurricane channel. The near-white blotches are areas of saline soil which are easily detected with color-infrared photographs of which this is a black-and-white reproduction.

FIG. 9. Areas of different moisture content are delineated on the color-infrared photograph of which this is a black-and-white reproduction. Vegetation is differentiated by intensity of infrared reflectance. In the background, blowouts taper to the northwest indicating a prevailing southeast wind.

tremely light blue/white in the dry areas. A good example of this observation is shown in Figure 9. The delineation of degrees of moisture in the sand is easily seen in the beach area and also can be detected further inland where differences in moisture content appear.

Although lacking the preciseness of color-infrared photographs, the thermal-infrared line-scan imagery also makes possible the detecting and delineating of areas of different moisture content. The portion of the beach subjected to continual inundation by the wave surge appears *warm.* Inland, the beach appears *cooler* except for the superposition of man-created signatures such as vehicle tire indentations. These indentations compress the sand over a period of time and develop a *warmer* appearance. Adjacent to and extending into the foredunes, the dry, eolian sand appears still *cooler.* The bare sand signature is also recorded in the blowout areas of the foredunes. The *cool* appearance is caused by dryness, high reflectivity and lack of compactness.

Color photographs also displayed potential for use in moisture detection and delineation. The beach areas of different moisture content are delineated by a progressively darker shade of brown. However, the contrast and delineation was not as well defined as on the color-infrared photography.

Along portions of the beach, the wave action close to the shore has formed a relatively steep-sided, well developed berm on the forebeach. The berm and the portion of the beach seaward from it images as *warm* compared to the rest of the beach. There are several reasons for this. The beach seaward of the berm has a slightly greater slope than that on the other side of the berm. In addition, due to the increased elevation of the terrain landward of the berm, most of the waves that inundate the beach seaward of the berm are not capable of reaching beyond the raised point. Due to the increased slope and the increased moisture, the beach seaward of the berm tends to appear *warmer* than the remainder of the beach. The presence of moisture increases the total infrared emittance from the area. The greater slope increases the amount of emitted radiation which reaches the scanner.

The role of the beach slope in determining the amount of infrared radiation that reaches the scanner can be better appreciated by examining Lambert's Law of Cosines. This law states that when the radiating body is a plane, the radiant intensity emitted for all wavelengths varies as the cosine of the angle between the line of sight and the normal to the surface of radiation. The larger the angle between the scanner line of sight and the normal to the surface, the less infrared radiation will be received from that surface.[8] Figure 10 displays the effect of Lambert's Law

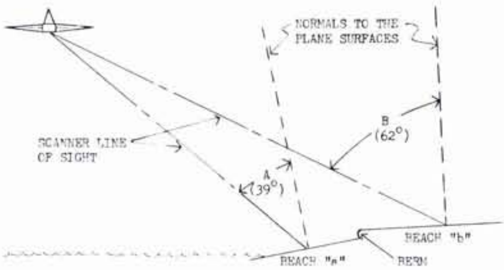

FIG. 10. Lambert's law of cosines.

as it applies to the image of the area adjacent to the berm. The total emittance E_a received from a is related to the base emittance E_o:

$$E_a = E_o \cos A$$

where the angle A is indicated in the figure. Using the angles shown in the figure,

$$E_a = 0.77715\ E_o$$
$$E_b = 0.46947\ E_o.$$

SHORE CURRENTS

The interpretation of the erosion and deposition of sediment along the island coast serves as an effective indicator of the existing current system. All of the hurricane channels are cut off from the Gulf by an accumulation of sediments. These sediments form a straight and narrow sand bar between the channel and the Gulf. The formation of these bars substantiate the sediment depositional force of the longshore current operating along the coast of Padre Island.

The currents continually deposit sediment along the shore of the island as well as in front of the hurricane channel until it is completely sealed off from the Gulf. The accumulation of sediments which block the channels are apparent in Figure 7. Additional accretion of sediment substantiating the existence of the longshore current system is seen behind the southern jetty of the Port Mansfield Cut on the thermal-infrared imagery. This accumulation of sediment is formed by the northward flowing current.

At approximately 35 to 40 miles south of the Padre Island Causeway, at a latitude of 27°03′, there is a marked increase in debris which has been washed up onto the beach by wave action. The debris consists of a large amount of driftwood and other visible but unidentifiable accumulations of objects, probably shells. The debris was not recognizable on the thermal-infrared imagery but was easily detected on the color and color-infrared photographs.

The deposition of debris on the beaches in this area is the result of a convergence of the longshore currents along the south Texas coast. The combination of the prevailing southeast winds and the concave shaped Texas shoreline create ideal conditions for the formation of two separate longshore currents. One current flows southward from the upper Texas coast and the other flows northward from the lower Texas-Mexican coast. The two longshore currents converge at a location along the Padre Island coast at approximately 27°N. The location of this conversion point has been confirmed by other researchers working on Padre Island.[10] At this point excess water returns seaward while many of the objects which were transported by the current are deposited on the beaches. As the prevailing wind changes with the season, the exact location of convergence also migrates. Debris deposition here is largely the result of longshore convergence.

FOREDUNES

The infrared imagery provided the best means of observing the general location and the overall continuity of the foredunes. The windward side of the foredune ridge facing the Gulf is fairly regular and normally is void of an vegetation. The leeward side appears irregular with some dunes extending into the barrier flats. The leesides are almost entirely covered with vegetation although vegetation decreases to the south on the island. The bare sand on the windward side images *cool* whereas the vegetation on the leeward side images *warm*.

One of the predominant trends observed during the interpretation of the foredunes is the NW-SE orientation of the blowout tongues. These tongues consist of masses of bare sand transported and spread over the vegetated barrier flats. They originate from large gaps in the foredune ridge. The directional orientation of the blowout tongues is indicative of the prevailing southeast wind. The lower infrared emittance from the bare, dry sand comprising the blowout tongues, sharply contrasts with the *warm* appearance of the adjacent vegetation of the barrier flats. Figure 9 shows a blowout tongue with the tip extending to the northwest.

VEGETATION

All three types of imagery provided a variety of information concerning vegetation

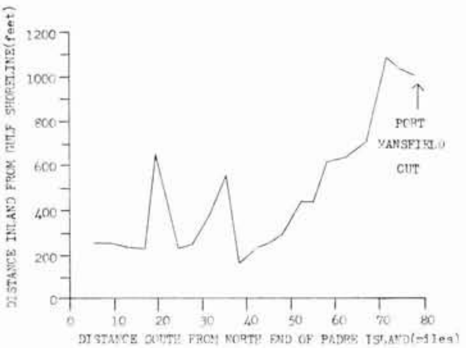

FIG. 11. Retrogradation of vegetation cover from Gulf shoreline as a function of latitude.

cover. Color, and especially color-infrared, provided the best means for detailed analysis of the vegetation cover. On the other hand, thermal-infrared imagery provided an excellent means with which to determine the overall vegetation cover by clearly delineating the boundaries and extent of vegetation growth.

Using the infrared imagery for evaluation of trends, the vegetation was determined to be more extensive in the northern portion of the study area. This is primarily due to the greater annual precipitation in the north. Figure 11 shows the trend of the vegetation cover as a function of latitude. The data supporting the trends shown in Figure 11 was developed from measurements taken on the thermal-infrared imagery. A measurement was taken at approximately every 2.5 miles of ground distance along the flight line. These measurements were used to determine the retrogradation of vegetation from north to south.

A rapid retrogradation and overall decrease of vegetation cover begins approximately 42 miles south of the Padre Island Causeway. The change in vegetation is due to decreased rainfall and is manifested by development of hurricane channels, inland runway channels, blowout tongues and retrogradation of the foredunes. All of these features attest to the greater vulnerability of the southern portion of the test area to erosional forces. In the northern portion of Padre Island, the vegetation was relatively stable except for two areas where extensive washovers occurred. In the north the vegetation cover began 200 to 300 feet from the shoreline as opposed to over 1000 feet in the extreme southern areas. The presentation of this data in graphical form quickly identifies basic trends in the island's foredune vegetation cover.

Thermal-infrared imagery provides the capability of evaluating the thickness or density of vegetation cover. Dense areas, possessing an extensive vegetation cover, image *warmer* while sparse vegetation cover images relatively *cool*.

For purposes of detailed analysis of vegetation, color-infrared photographs displayed the greatest potential of the three sensors. Although an intensive study of the vegetation on Padre Island was not within the limits of this study it was apparent from the rendition of the spectrum of color on the infrared photographs that a variety of vegetation categories were imaged. Most of the vegetation was imaged in shades of greenish-blue. The remaining vegetation imaged as a variation of magenta, red and pink. The variety of color rendition on the color-infrared photographs provides it with more potential in discriminating between vegetation type and vigor than either the conventional color photographs or the thermal-infrared imagery.

The semi-arid climatic conditions of the area results in the predominance of the bluish-green rendition of the vegetation. The flora is xerophitic and appears a dull green in true color. The plants are not highly reflective in the infrared; they are more characteristic of a desert vegetation on color-infrared photographs.

LAGOON AREA

In contrast to the Gulf shoreline, the Laguna Madre coast of Padre Island is extremely irregular. The irregularity is due to the continual transport of sediment into the lagoon. The sediment forms extensive mud flats which encroach upon the lagoon waters. Unlike the Gulf coast of the island, there is no marked difference in infrared emittance between the lagoon and the adjoining sediment. This is primarily due to a gradual and uniform increase in moisture from the mud flats to the shallow waters of the lagoon.

The lack of contrast is especially evident in the southern portion of the study area due to the extensive mud flats. In the northern portion of the study area, the Laguna Madre shoreline is more sharply delineated due to the lack of the mud flats and more direct contrast between the sand and the lagoon water. The shifting dunes comprised of bare, dry sand, image *cool*. This *cool* signature contrasts with the *warmer* appearance of the lagoon. In all areas of the island, the thermal-infrared imagery is very effective in differentiating between the shifting sand dunes, the mud and sand flats and the lagoon waters.

The shifting sand dunes located in the back-island regions normally consist of desert type dunes such as barchans and seifs. The more common of these dunes is the barchan. These crescent-shaped barchans have their horns pointing down-wind. The orientation of these horns indicate the direction of sand movement and the orientation of the prevailing wind. On Padre Island, the horns of the crescent are oriented to the northwest, in consonance with the prevailing southeast wind.

Conclusion

This study has been an attempt to show the information gathering and extraction capability of thermal-infrared imagery, and to a lesser extent, color-infrared and conventional color photographs. All three sensors displayed significant capability in providing valuable information concerning the environment. Thermal-infrared imagery provided an effective means of determining general trends in vegetation cover, water detection and sediment movement. Intrepretation of these trends provided information concerning offshore currents and existing wind systems. Thermal-infrared imagery also displayed an outstanding capability of detecting inherent heat sources. The ability to detect intense heat can be used to indicate industrial activity in developed areas. Color-infrared photographs provided the best means for water (moisture) and vegetation detection and delineation. It also presented the most potential for detailed vegetation analysis, e.g., determination of plant communities and vigor. Conventional color was most effective in water penetration and analysis and presented the most accurate rendition of (eye response to) the original scene.

The potential uses of information gained from a systematic interpretation of sensor imagery are vast, and valuable to man in many disciplines. The use of Padre Island as the study site provided an opportunity to evaluate the effectiveness of the sensors in a dynamic environment consisting of infrequently imaged physical features. The results of the exploration provided supplemental data on Padre Island's physiography from imagery interpretation.

This study shows that beach investigations are enhanced by the use of remote multisensor imagery. Each sensor can make valuable contributions to data collected. Multisensor imagery increases the interpreter's workload but gives him added clues and information in solving image signatures. The results derived from a combination of imagery are more valuable than that from a single source operating in a narrower range or at a specific wavelength.

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