CHAPTER 219

BEACH PROFILE ANALYSIS AROUND INDIAN RIVER INLET, DELAWARE, U.S.A.

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ABSTRACT: The purpose of this study is to examine the recent shoreline history at Indian River Inlet, Delaware using beach profile data. Indian River Inlet was stabilized in the late 1930's with two parallel rubble mound jetties. The stabilization resulted in considerable modifications to the surrounding beach environment, leading to the construction of a sand bypassing system in 1990. The profiles adjacent to the inlet are first examined with the standard tools, such as shoreline change, volume change, and sand budget. Then, details are given on the use of Principal Component Analysis (PCA) in the coastal field, an explanation of its function, and the differences between the complex and non-complex versions. Results are presented for areas north and south of the inlet in both 2-mode and 3-mode versions of Complex Principal Component Analysis (CPCA). The results illustrate the ability of CPCA to detect moving features within the profile data, including its direction and speed, as bypassed sand is seen moving to the north.

INTRODUCTION

The Delaware Atlantic coastline, a sandy shore that spans approximately 24 miles, is an area of constant transformation. Significant littoral drift rates, man-made structures, remediation efforts, and occasional battering by large storms all effect the coastline. Thus, the beach profiles are 'dynamic' in character, changing continuously. These profile variations occur in both the subaqueous and subaerial elements of each profile, as wave energies constantly move sand on, off, or alongshore. In effect, changes in profiles can reveal a vast amount of information, both long and short term, about the coastline.

The focus of this study is the profiles adjoining Indian River Inlet (as shown in Figure 1), which is one of the most unique features along the Atlantic Coast of Delaware. After several failed attempts to keep the Indian River Inlet open by dredging alone, a 152 meter (500 foot) wide inlet was constructed in the late 1930's. The goal being to establish a stable passage way from the inner bays (Rehoboth and Indian River) to the Atlantic Ocean, increase bay salinity, reduce stagnation, and increase the tide range (Thompson and Dalrymple, 1976). The

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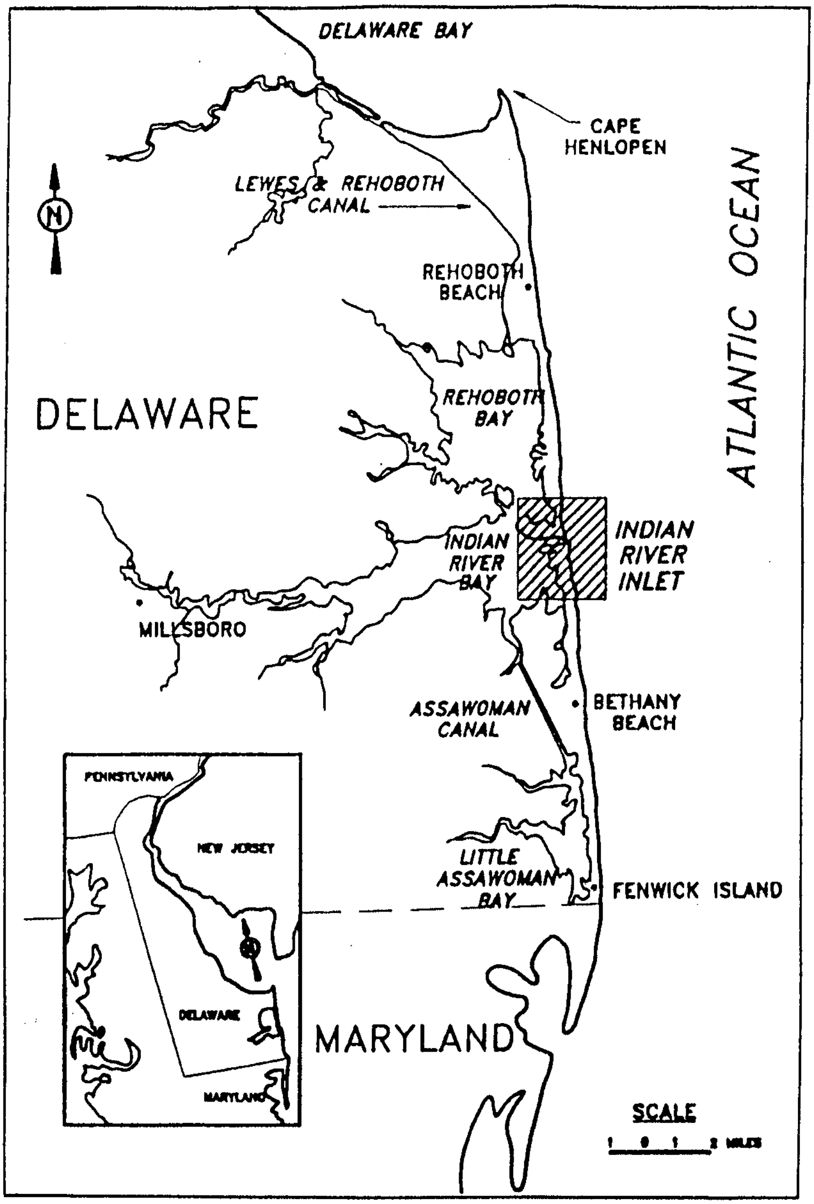


Figure 1: The Atlantic Coast of Delaware

inlet is stabilized by two parallel rubble mound jetties, originally extending a distance of 472 meters (1550 feet). 185 meters (600 feet) of this length extended seaward of the ocean shoreline at the time of construction. There have been significant problems with the engineered inlet over the years, including erosion of channel banks west of the jetties, accelerated scour along the jetties, and massive downdrift erosion, due to the predominant northward drift (Gebert *et al.*, 1992). The main concern related to the downdrift erosion is the threat it poses to the Route 1 highway traveling parallel to the shoreline. In fact, by 1954, a dune scarp had been created that was, in places, less than 60 meters (200 feet) from the roadway. From 1957 to 1990, mitigation of the beach erosion was accomplished by dredging of the flood tidal shoal and back barrier deposits. Approximately 380,000 m^3 (49,700 yd^3) of sand was placed on the north beach approximately every five years. Since February of 1990, however, a fixed sand bypassing system was constructed to pump sand from the southern shore and "slurry" it across the inlet to the northern shore. The system mines the south accretional fill by using an eduction unit deployed by a crane. Through May of 1995, approximately 350,000 m^3 (456,000 yd^3) have been pumped across the inlet at a cost of \$2.11 per m^3 (\$1.62 per yd^3). The system is performing well and is relatively inexpensive to run.

The objective of the present study is to investigate many aspects of the beach profile at Indian River Inlet through the use of the newest analytic methods and the most recent field data available. We want to determine what the profiles north and south of the inlet reveal about the region and to answer questions such as:

- What happens to the bypassed sand?
- Is enough sand being pumped?
- Can we identify moving forms or sandwaves?

To do this, we consider the early performance of the bypassing plant through shoreline changes, evaluation of littoral drift, and other standard analytical tools. We also explore the use of complex principal component analysis (CPCA), in both 2-mode and 3-mode versions, to evaluate propagating features that exist within a bathymetry.

FIELD DATA COLLECTION

Profile data sets are considered on both the north and south side of Indian River Inlet collected by the U.S. Army Corps of Engineers, Philadelphia District. The profiles span from 1984 to 1994, with an average of two surveys per year. 28 profile lines are taken in the range from 1524 meters (5000 ft) south of the inlet to 1524 meters (5000 ft) north of the inlet, as shown in Figure 2. 17 of the lines are located in the northern portion of the study area, while 11 are located in the south. As shown in Figure 2, some profile lines extend far offshore, while others only advance to the water line. The station numbers provided are the distance in hundreds of feet (30.5 m), from the respective jetty centerline. Survey points were taken randomly during each survey, thus requiring linear interpolation in both the alongshore and cross-shore directions for much of the analysis. Examples of the bathymetries north and south of the inlet are shown in Figure 3. Notice the scour hole that is evident at the tip of the northern jetty.

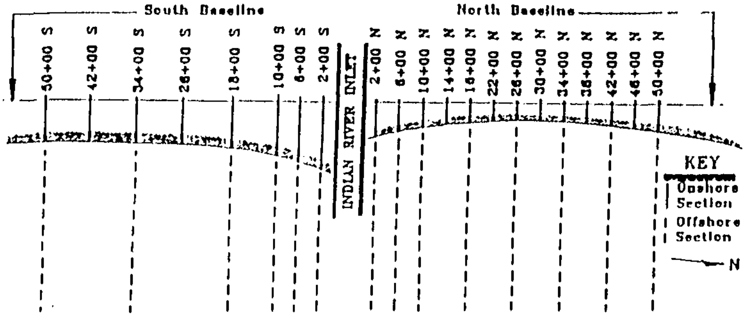
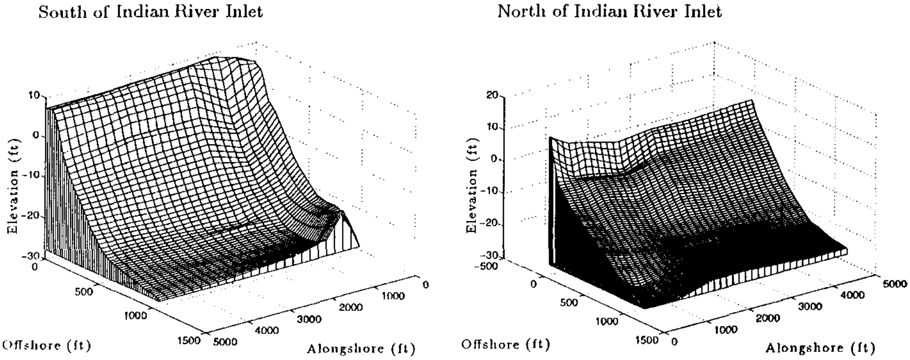


Figure 2: Profile lines north and south of Indian River Inlet


South of Indian River Inlet

North of Indian River Inlet

Figure 3: Sample bathymetries (October 1994) for north and south of Indian River Inlet. Offshore grid intervals are 152.4 meters (500 feet); alongshore, 304.8 meters (1000 feet); and elevation, 3.05 meters (10 feet).

SHORELINE CHANGE

The simplest way to examine what is occurring on a given region along the coast is to evaluate the change in shoreline position. This 1-line analysis quantifies beach behavior and allows for comparison of pre- and post-bypassing. Cumulative shoreline change plots for four profile stations in the range extending up to 305 meters (1000 feet) away from the inlet in both the north and south directions are shown in Figure 4. The figure illustrates the shoreline behavior at various stations through time. Watson *et al.* (1993) have computed similar results for a shorter interval of time. For this study, the pre-bypassing interval is from November of 1984 to October of 1989. The initial survey of November 1984 takes place after a large beach fill of 35,781 m^3 was placed between stations 0+00 to 30+00. Surveys measured after October of 1989 are considered post-bypassing. Since we only have a total of four years of data after bypassing start-up, only the short-term performance of the system can be determined.

North of the inlet the trend had been towards progressive retreat, as expected due to the influence of the inlet and the northward littoral drift. Only once, during the winter season from September 1987 to March 1988, did a substantial shoreline advance occur. This was most likely due to the net reversal of littoral drift in the winter months (response to "northeasters") and thus the trapping of some sediment in the shadow of the jetty. The general shoreline retreat was evident until approximately 1035 meters (3400 feet) from the jetty. At this distance, the effect of the inlet was lessened and larger seasonal variations tended to dominate. The bypassing operation was started with the aid of a 133,800 m^3 (175,000 yd^3) fill (evident in the March 1990 survey) obtained from the flood shoal . The initial increase in beach width was not retained due to the spreading of the beach fill, but the shoreline for the stations just north of the inlet seems to have stabilized since bypassing initiation.

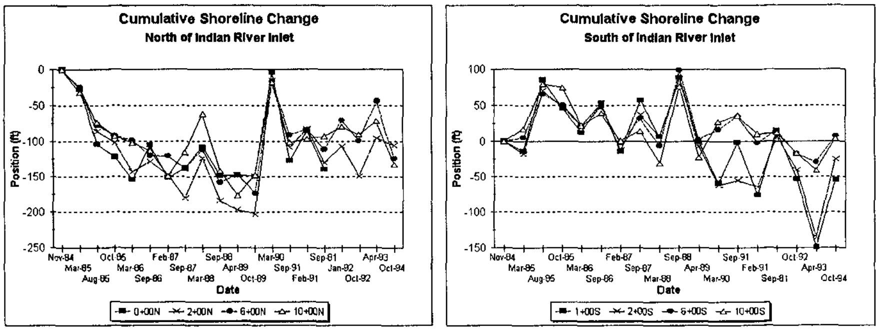


Figure 4: Cumulative shoreline plots showing relative distance from original shoreline position with time for the first four profile stations both north and south of Indian River Inlet.

South of the inlet, pre-bypassing, the trend had been overall stability with some slight accretion. The accretion, if any, was at a much lower rate than the erosion to the north. Again, at around 1035 meters (3400 feet), the effect of the inlet seemed to be minimized as the overall change in beach width was small. After bypassing start-up, Stations 1+00 and 2+00 exhibited immediate effects of the sand mining. Proceeding southward, the next two stations (6+00 and 10+00) show a slight lag in the response to the mining and a smaller shoreline retreat. Notice as well that all stations recover quickly from the effect of the mining. Sand bypassing influence is also typically seen to about 1035 meters (3400 feet) south of the inlet.

VOLUME CHANGE AND SAND BUDGET

Next, volume changes for the areas between profile stations were computed. From these volume changes, a standard sand budget analysis was calculated for the northern region by assuming that the only sediment entering the area was due to bypassing or beach fills. The results from this analysis, shown in Figure 5, yield a measure of the local transport rate. The littoral drift is found to be dominantly northward, as expected, at a rate of approximately 79,500 m^3 (104,000 yd^3) per year. This value was found to be consistent with values found in the past by other methods (Lanan and Dalrymple, 1977; U.S. Army Corps of Engineers, 1984).

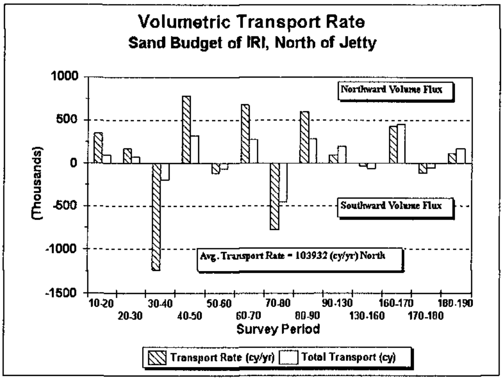


Figure 5: Local volumetric transport rate for north of Indian River Inlet.

THE HISTORY OF PRINCIPAL COMPONENT ANALYSIS

Many geophysical phenomena derive from interactions between traveling waves of different spatial scales and temporal frequencies. Principal component analysis (PCA) was developed to explore these spatial and temporal relations with the primary advantage of its ability to express the complicated variability of data into the fewest possible number of modes. Thus, applying this idea to beach profiles, beach changes can be described by linear combinations of space and time through the breakdown of data into spatial and temporal dependence (e.g. Winant *et al.*, 1975; Aubrey, 1979). Winant *et al.* (1975) found that most of the variation in a profile configuration is accounted for by the first three eigenfunctions, which corresponded to the "mean beach," "bar-berm," and "terrace" functions. However, PCA detects standing oscillations only, such as the standing phenomena of the shift from summer to winter profiles in seasonally sampled data (Winant *et al.*, 1975), not traveling waves. Therefore, PCA can not identify a coherent form moving through the data, such as a rapidly traveling bar as a sand wave alongshore.

Complex principal component analysis (CPCA) was developed for meteorological applications (e.g. Wallace and Dickinson, 1972; Barnett, 1983) and has been used to detect a fast moving sand bar by Liang and Seymour (1991). CPCA has also been shown to out-perform PCA by capturing more of the variance in fewer terms by Liang, White, and Seymour (1992). CPCA has considerable potential for being widely used to detect propagating features, yet its limitations as an analysis technique have not been well explored.

Both of the methods discussed above account for only one spatial direction when evaluating the temporal changes in the data set. This assumes the movement is directed in two independent directions and therefore, the analysis is limited to looking at only individual cross-shore or alongshore "lines." However, what if there is two dimensional movement of sand, as expected in response to a coastal structure or a beach nourishment? Then the 2-dimensional analysis may be rendered inadequate. So, in a further expansion of PCA, the analysis was carried into a third dimension allowing the break down of data into three separate components. This so-called 3-mode PCA was started for mathematical psychology applications, such as the evaluation of multiple personality patients

(Tucker, 1966; Kroonenberg and DeLeeuw, 1980). For the case of a coastal region, 3-mode PCA allows a bathymetric survey to be divided into two spatial directions (cross-shore and alongshore) and a temporal dependence. The technique was applied to a beach fill site in Spain by Medina *et al.* (1992).

In the next section, we apply the 2-mode CPCA tool to the beach profile data of Indian River Inlet and develop a 3-mode CPCA model to examine movement occurring in multiple directions within a bathymetry. The 2-mode CPCA is shown to not only detect the moving forms as well as standing forms, but also distinguish between them.

2-D COMPLEX PRINCIPAL COMPONENT ANALYSIS

To apply CPCA, the data field must first be augmented in a manner such that propagating features within it may be detected. This is done by deriving a complex data matrix, where the real part is simply the original data field and the imaginary part is the Hilbert transform, which represents a filtering operation upon the data in which the amplitude of each spectral component is unchanged, but each components phase is advanced by $\pi/2$. If g(t) is a real-valued function of time, we can define an analytic function

$$z(t) = g(t) + ih(t)$$

where h(t) is the Hilbert transform of g(t) given as:

$$h(t) = \mathcal{H}(g(t)) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{g(t')}{t'-t} dt' \tag{1}$$

Using the complex data, we can compute complex eigenvectors (functional decompositions of the data) and eigenvalues (portions of the variation represented by each eigenvector). The goal is to expand the data, $z(x,t)$, into two dimensions (in this case offshore and time) as:

$$z(x,t) = \sum_{i=1}^{n} a_i \, g_i(t) \, e_i(x) \tag{2}$$

n=number of desired modes
a_i=normalizing factors (eigenvalues)
g_i=temporal eigenfunctions
e_i=spatial eigenfunctions

This is done through computation of the correlations between the spatial locations to develop a complex correlation matrix, as shown in Equation 3, where n_t is the total number of surveys and the large brackets denote a time average. The eigenvalues and eigenvectors are then determined from the complex correlation matrix.

$$A_{ij} = \langle \, z_j(t)^* \cdot z_i(t) \, \rangle_{n_t} \tag{3}$$

The 2-mode CPCA is used to look at an alongshore profile lines north of Indian River Inlet in the hope of identifying migrating features. Because of the random sampling of the data, many profile lines had to be discarded for various reasons (e.g. did not extend far enough offshore, a given survey was missing, etc.). The results shown below are for an alongshore profile line located approximately 76 meters (250 feet) from the baseline. The complex correlation between the complex time series at given alongshore grid points are shown in Figure 6a. Each complex correlation is plotted in vectorial format where the real portion (magnitude) is indicated in the vertical direction of the vector and the imaginary portion (phase) is indicated in the horizontal direction. A vector pointing upwards (downwards) indicates that the two time series are in-phase (out-of-phase). For example, a vector pointing to the right indicates a lag of 90 degrees. The complex correlation between the time series delineates the propagation of a moving "bump" through the domain. Figure 6b shows the resulting spatial eigenvectors for the alongshore line, plotted in vectorial format as in Figure 6a. The numbers correspond to the percent of variance retained by each eigenvector. The top panel is the first eigenvector which represents the mean alongshore profile and accounts for 98% of the variance. The eigenvector is almost entirely real valued, which signifies that no extensive movement is associated with it, and exhibits a depression in magnitude near the inlet entrance. The second eigenvector identifies a definite progressive feature, which represents 1% of the total variance. Imagine the movement as a spinning motion indicated by vectors "rotating" through space. The second eigenvector then represents a moving form that augments the mean alongshore profile. Similarly, the third eigenvector, which indicates no coherent movement, modifies the mean further.

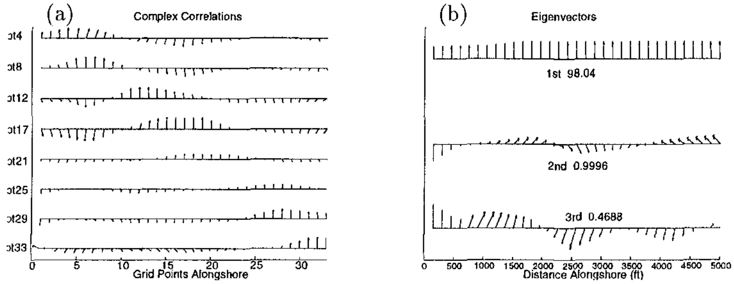


Figure 6: (a) Complex correlation between time series for alongshore grid points. Notice that the vector is normalized to one when a time series is correlated to itself; i.e. the time series of point 4 is perfectly related to itself. (b) Eigenvectors computed by CPCA for an alongshore profile line North of Indian River Inlet. Spacing intervals in the distance alongshore are 152.4 meters (500 feet).

Once the eigenvectors and eigenvalues have been determined, we are able to define both a spatial ($\theta_i(x)$) and temporal ($\phi_i(t)$) phase function as:

$$\theta_i(x) = arctan\left[\frac{\mathcal{I}m(e_i(x))}{\mathcal{R}e(e_i(x))}\right] \qquad \phi_i(t) = arctan\left[\frac{\mathcal{I}m(g_i(t))}{\mathcal{R}e(g_i(t))}\right] \tag{4}$$

The spatial derivative of the spatial phase function then provides a measure of the "local" wavenumber. Similarly, the time derivative of the temporal phase function is directly proportional to the "instantaneous" frequency. Therefore, CPCA not only allows us to identify a moving form, but also determine the direction and the rate at which it is moving. The spatial and temporal phase functions for the same alongshore profile line, as presented in Figure 6, are shown in Figure 7. The numbers correspond to the approximate wavenumber

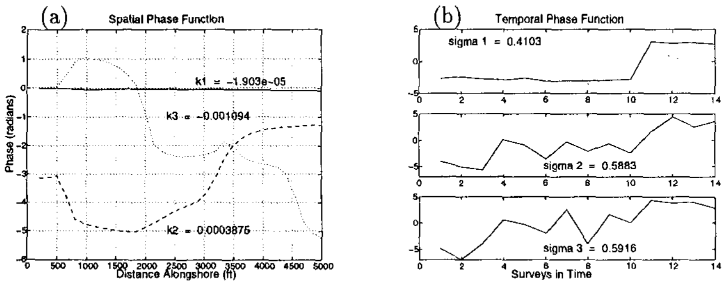


Figure 7: (a) Spatial phase function for alongshore location north of Indian River Inlet. Spacing intervals in alongshore distance are 152.4 meters (500 feet). (b) Temporal phase function for the same location.

and frequency of each eigenvector component. By using these values, the second eigenvector indicates a feature that is moving northward at the rate of around 1.68 meters (5.5 feet) per day. Therefore, over this time period, CPCA reveals that sand was relatively quickly moved out of the area to the north.

3-D COMPLEX PRINCIPAL COMPONENT ANALYSIS

The 2-mode CPCA appears to be very useful for many cases. However, what if 2-dimensional movement of sediment is expected, as mentioned earlier. The 3-mode CPCA is applied to the nearshore region, where significant movement is occurring, for both north and south sides of the inlet. In 3-mode CPCA, we begin with a <u>set</u> of data matrices or rather, a large 3 by 3 cube of data, which can also be thought of as a collection of 2-mode matrices (Figure 8).

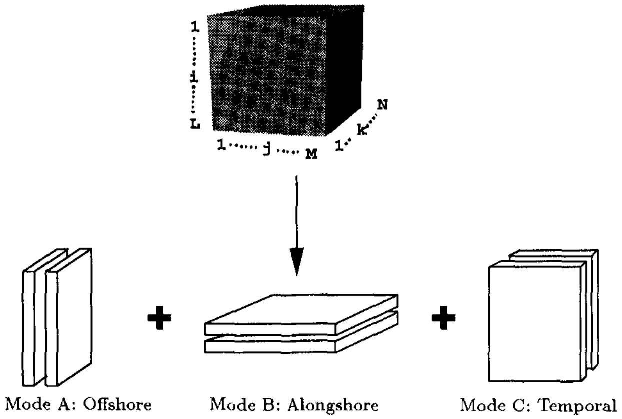


Figure 8: Schematic breakdown of a 3-mode data set into 2-mode submatrices.

Again, after Hilbert transforming the data in time to generate a complex data set, we seek to expand the data in two spatial dimensions and time by:

$$z(x,y,t) = \sum_{m=1}^{s} \sum_{p=1}^{u} \sum_{q=1}^{v} e_m(x)\, f_p(y)\, g_q(t)\, C_{mpq} \tag{5}$$

where

s, u, v are the number of components in the 3 modes, respectively
e, f, g are the offshore, alongshore, and temporal eigenfunctions, and
C_{mpq} is the core matrix (normalizing factors)

Rewriting Equation 5 in matrix form we arrive at

$$Z(x \times yt) = E(x \times s)C(s \times uv)[F(y \times u)' \otimes G(t \times v)'] \tag{6}$$

where $\otimes$ denotes the Kronecker product and the dimension of the matrices Z and C are augmented to be two dimensional arrays. The core matrix, C, is no longer a simple diagonal matrix of eigenvalues as in 2-mode analysis, but a complex combination of elements that describe the basic relations that exist between the various collections of variables as expressed through their components (Kroonenberg and DeLeeuw, 1980).

The cross-shore and alongshore eigenvectors for the nearshore region north of the inlet are presented in Figure 9. For simplicity, only the real part of each eigenvector is shown. To illustrate the relative importance between both the variables and components, the eigenvectors shown have been weighted. These eigenvectors can be thought of as the average form of all cross-shore or alongshore profile lines in the region. In the cross-shore direction, we see the mean is easily identifiable. The second component, typically referred to as the "bar-berm" function is significantly reduced in importance due to the larger fluctuations occurring in the alongshore direction. In the alongshore eigenvectors, the mean is characterized by a dramatic depression that occurs near the inlet. The second and third components highlight sizable changes in the alongshore direction.

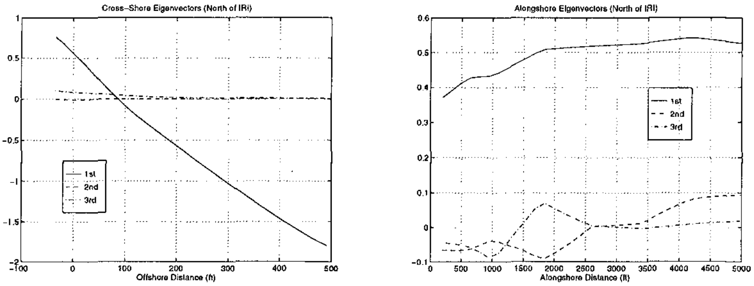


Figure 9: The real portion of cross-shore and alongshore eigenvectors computed from 3-mode CPCA. Offshore distance is spaced at 30.5 meters (100 feet), while the alongshore distance is spaced at 304.8 meters (1000 feet).

The eigenvector components can also be combined to represent various features of the bathymetry. These *eigenvector combinations* are products of the different alongshore, cross-shore, and temporal components. Similar to a large puzzle, if we have three components in each variable, then there are 27 combinations that make up a complete bathymetry. The three combinations that capture the highest amount of variance are shown in Figure 10. The real part of each combination is shown on the left and the imaginary part of the combination on the right. The top panel shows the combination A1O1, which is defined as the product of the first eigenvector in the alongshore direction (A) and the first eigenvector in the cross-shore direction (O). This combination represents the mean bathymetry and the real part is characterized by the erosion located at nearshore region of the inlet entrance. The middle panel shows the A1O3 combination, corresponding to the product of the first alongshore eigenvector and the third cross-shore eigenvector. This combination modifies the mean bathymetry most notably in the shoreline area where bypassing has a significant effect. The lower panel, which contains the A3O3 combination (same nomenclature as before), is perhaps the most intriguing. A large "bump" appears on the real portion of the bathymetry, while the imaginary portion depicts a wave-like phase rotation. This imaginary "hot spot" of movement indicates that the feature is in motion. Notice that the magnitude of the imaginary bathymetry decreases as we proceed offshore. Therefore, the alongshore movement is strongest at the nearshore area and becomes less severe further offshore.

The eigenvector combinations for the region south of Indian River Inlet are shown in Figure 11. The nomenclature remains the same as for the combinations north of the inlet. Again, the top panel represents the mean bathymetry and shows a build up of sediment in the area adjacent to the southern jetty. The A2O3 and A2O1 combinations illustrate changes that are occurring once again in the neighborhood of the inlet entrance. The difference between the two is that the imaginary portion of A2O3 identifies more of a movement in the alongshore direction, while the imaginary portion of A2O1 identifies more of a movement in the cross-shore direction. This may mean that, after bypassing occurs, the large eduction hole that remains recovers by receiving sediment from both the alongshore and offshore elements of the bathymetry.

CONCLUSIONS AND SUMMARY

An in-depth analysis of the profiles at Indian River Inlet, Delaware has been accomplished by using standard analysis tools and Complex Principal Component Analysis. Early returns of the sand bypassing system seem to be positive. The shoreline analysis reveals that the north shore has been stabilized by the bypassing and the south shore recovers quickly from the eduction process. The littoral drift indicates sand is moving to the north and that a larger amount of sand could be pumped each season. Generally, sand moves quickly to the north as evident from both the shoreline variation and CPCA analysis. As shown, CPCA has considerable potential, but needs further investigation on a more finely sampled data set.

ACKNOWLEDGMENTS

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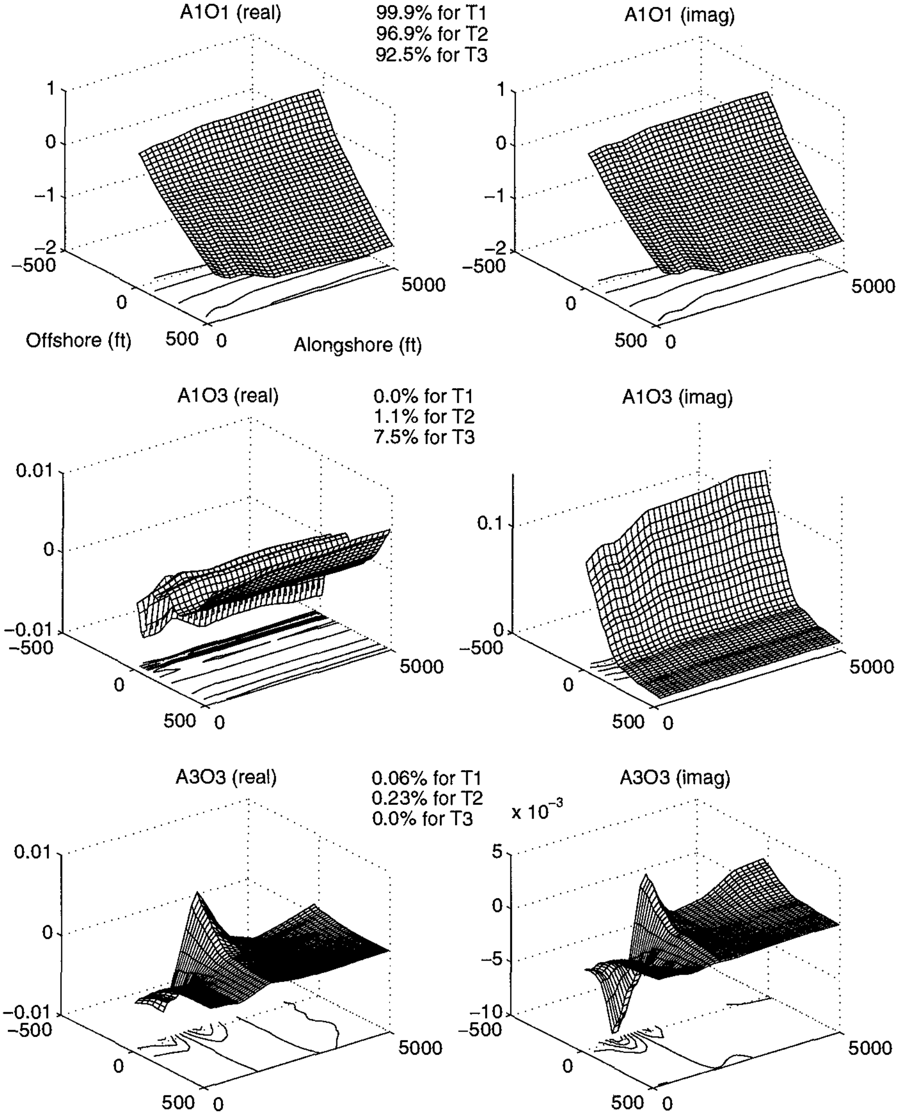

Figure 10: Eigenvector combinations north of Indian River Inlet. The numbers (or core matrix values) included represent the percent of variance captured by each eigenvector combination for a given temporal component. The offshore range is spaced at 152.4 meters (500 feet) and the alongshore range covers 1524 meters (5000 feet).

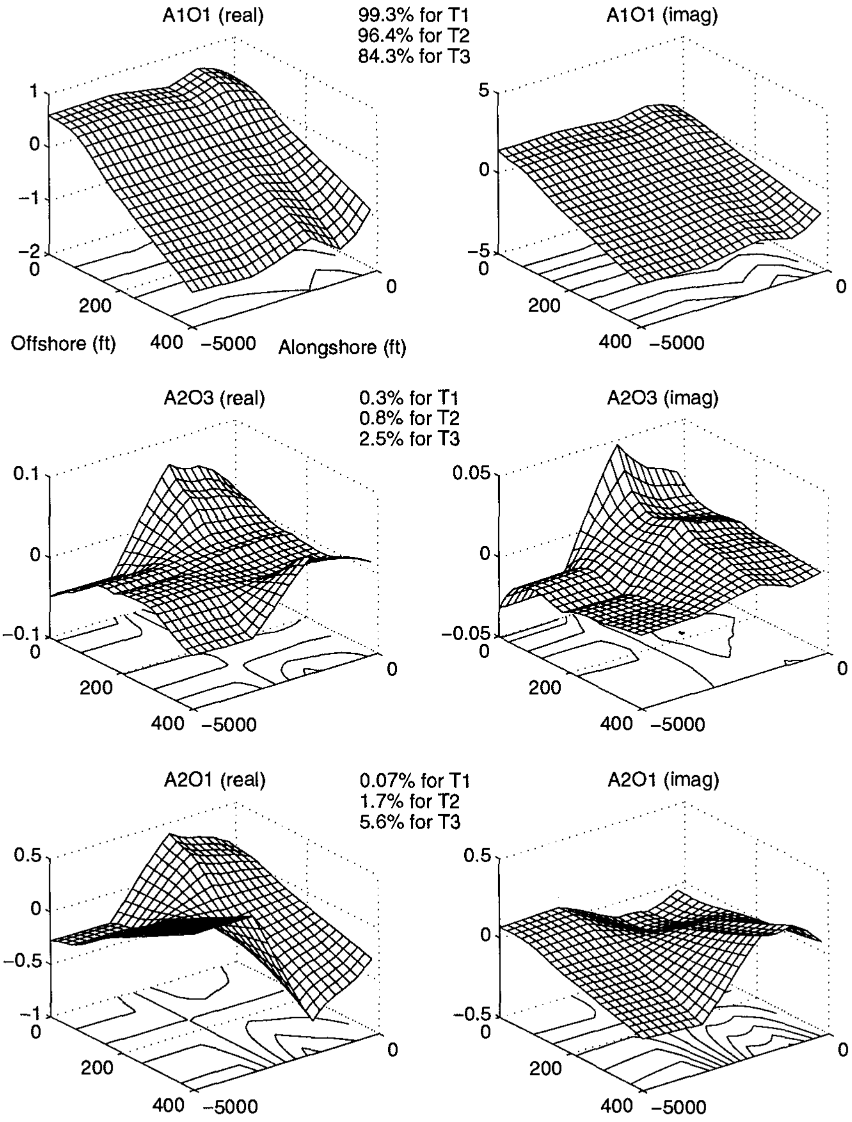

Figure 11: Eigenvector combinations south of Indian River Inlet. The numbers (or core matrix values) included represent the percent of variance captured by each eigenvector combination for a given temporal component. The offshore range is spaced at 61 meters (200 feet) and the alongshore range covers 1524 meters (5000 feet).

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