Moving Toward Achieving Consistency in Coastal GIS Shorelines with VDatum

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ABSTRACT

On two-dimensional maps and GIS, the shoreline is typically a snapshot of a coastline which is perpetually changing. Inevitable inconsistencies between shoreline delineations plague coastal GIS users as they seek to combine data from multiple sources and perform analysis. The goal of this project was to evaluate the results, in terms of consistency, of combining a shoreline definition based on the mean high water (MHW) tidal datum with a delineation technique that incorporates automation through the use of digital elevation models (DEMs). Differences between shorelines derived in this manner and those derived using more traditional methods were quantified. Finally, the ability to fully automate derivation of MHW shorelines from DEMs using ArcGIS was explored.

INTRODUCTION

The coastal zone is a continually changing environment, not only from year to year, but also by the month, day and even hour. Due to this constant state of change, there exists a legacy of inconsistency in the representation of the coastline in maps and digital data. As a result, performing mapping and analysis can be especially challenging for the user attempting to compare various GIS data layers from different sources.

The most promising answers to the problem of inconsistent shorelines plaguing coastal and marine GIS would combine a definition of shoreline which accounts for the dynamics of the oceans with a delineation technique that yields repeatable results (Parker 2001)(see Table 1). Given the constant advance and retreat of the land water interface due to changes in water levels brought on by waves and tides, it is easy to see why a definition of shoreline based on averaging of water levels adds consistency. Known as “tide coordinated shoreline,” this line occurs where the tidal plane (or average water level) intersects the shore (Shalowitz 1964; Li, Ma and Di 2002).

Further consistency can be achieved by automating the process of delineating the shoreline. Automation in tide coordinated shoreline extraction involves identifying a specified level within a digital elevation profile of the intertidal zone. The first step in such a process is to build an intertidal digital elevation model (DEM), incorporating elevation data from land as well as nearshore areas (Parker et al. 2001; Li, Ma and Di 2002). Determining the shoreline can then be thought of conceptually as adjusting the water level in the DEM to a height which corresponds to the desired tidal datum, using a hydrodynamic model to simulate water level (Parker 2001; Parker et al. 2001; Li, Ma and Di 2002).

Table 1 – Summary of shoreline mapping techniques as a combination of shoreline definition and delineation technique used. Cell shading is used to convey level of consistency in resulting shoreline representations. (As darkness increases, so does consistency.)

Delineation Technique ↓ Definition →	**Fast Line**	**Continually Shifting**
Manually Interpreted	**Land-water interface from non-tide controlled images** (USGS, NGA)	**Tide controlled photos, 3-D MHW extraction** (NOAA)
Automatically Detected	**Image processing** (edge detection, unsupervised classification)	**Intersecting water surface and land in DEMs** (VDatum)

Recently a software tool called VDatum, developed by the National Geodetic Survey (NGS), has made this method of capturing shorelines possible. VDatum is a Java-based application that incorporates tidal datum grids derived from hydrodynamic models developed by NOAA’s Coast Survey Development Laboratory (CSDL). The tool has the capability of translating the vertical referencing component of x,y,z coordinate data between 28 different vertical and 3-dimensional datums, including tidal datums (Milbert 2002). VDatum can be incorporated into a workflow in order to produce DEMs vertically referenced to tidal datums, which can then be used to automatically extract the line where the tidal plane meets the land surface.

PROJECT DATA

In order to explore the effectiveness of this method for consistently and accurately capturing coastal GIS shorelines, elevation data of very high accuracy and spatial resolution were obtained. Raw x,y,z data were collected with an Optech Airborne Laser Terrain Mapper (ALTM) 1233 (33 kHz) lidar system in October 2002. The lidar mission consisted of twelve flight lines with nearly 30 million data points (first return data), for complete coverage of the tidal zone within the study area (Figure 1). The tide level at the time of the data collection was sub-MLLW, resulting in the greatest exposure of bare land to the laser.

Secondary data, incorporated in this study for comparative purposes, included both digital elevation data and vector shoreline data. Comparison elevation data included pre-gridded lidar data for two time periods, October 1997 and April 1998, from the data archives of the Airborne Lidar Assessment of Coastal Erosion (ALACE) project. This data was downloaded via the World Wide Web at a user specified spatial resolution of 2 meters. Another source of elevation data included for comparison purposes was the USGS DEM 7.5 minute tiled data with a spatial resolution of 10 meters.

Vector shorelines delineated by more traditional methods were obtained for the study area with the intention of performing full quantitative analysis on their positions relative to the DEM derived shorelines. Sources were chosen on the basis of popularity within the GIS user community, perceived authority, and availability. These included:

- NGS photogrammetrically derived MHW line – Interpreted from metric quality vertical aerial photos taken concurrently with the 2002 lidar data used in this study. Vectors were compiled at a target scale of 1:20,000.
- USGS DLG Shoreline – From 1:24,000 scale 7.5-minute quads, non-tidally referenced and collected at an unknown stage of tide.
- National Wetlands Inventory (NWI) Shoreline – Digitized from 1:24,000 scale NWI map series. Non-tidally referenced, collected at an unknown stage of tide.
- NOAA ENC® (Electronic Navigational Chart) MHW Shoreline – MHW shoreline from NOAA ENCs. Compiled at scales ranging from 1:20,000 to 1:80,000.
- California State Lands Commission (SLC) MHW Shoreline – Scale indicated as 1:24,000. Described as a MHW shoreline mapped from satellite imagery.

Figure 1 – Location of the study area.

EXTRACTION OF TIDAL DATUM BASED SHORELINES

The process of rendering tidal datum based shorelines from the raw lidar data required interpolation of tidally referenced DEMs from the lidar data prior to creation of shoreline contours. Additional steps required prior to interpolation included aggregation, filtering, and formatting of point data using Microsoft® Access™, and multiple coordinate transformations using Corpscon for Windows® (ver. 5.11.08) and VDatum (ver. 1.06). No attempt was made to filter trees, buildings, or other objects protruding above the ground surface, thus resulting in elevation grids more accurately referred to as digital surface models (DSMs), though the generic term "DEM" is generally applied here.

ESRI's ArcGIS® ArcMap™ software was used to view lidar point data and interpolate all DEMs. Point data was imported directly from Access and interpolated using the Inverse Distance Weighted (IDW) method in the Spatial Analyst software extension, result was a set of tidally referenced DEMs (MLLW, MLW, LMSL, MHW, and MHHW). The Spline and Kriging methods were also attempted, but both repeatedly failed to run to completion. Various combinations of IDW input parameters (resolution, search radius, power, # of neighbors) were employed for the purpose of investigating resulting effects on shoreline contours.

The accuracy of the output DEMs was assessed by comparing known ground control against corresponding grid cell elevations. Each of the lidar DEMs was found to have an RMSE of under 0.5 meters, leading to the conclusion that the horizontal accuracy of resulting shoreline contours was acceptable for the purposes of this study.

With ESRI's Spatial Analyst, contours were generated at the zero elevation level for all of the output DEMs. For each of the five specified tidal datums, unique shorelines were contoured for each combination of IDW parameters used. In general, contour lines were continuous and unbroken, with the notable exception of the MLLW shorelines. Surprisingly, even though the lidar mission occurred at a sub-MLLW tide event, the contours generally represented ocean waves and swells rather than the land water interface (Figure 2). Considering the importance of the low water line on nautical charts, this result was disappointing.

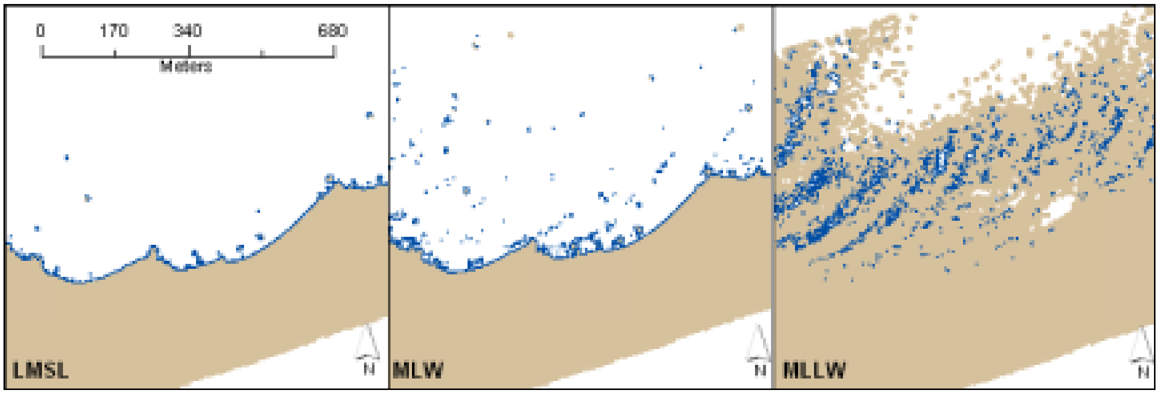

Figure 2 – Shoreline from three tidal datum referenced DEMs. Shaded areas are above datum level. In the MLLW DEM (far right), wave troughs are the only areas below the datum.

Overall the output shorelines based on the different tidal datums were roughly parallel and simulated the key stages of tide from lowest to highest (see Figure 3). Differently interpolated DEMs referenced to like tidal datums produced shoreline contours which were tightly clustered in most areas, although slightly greater variation was seen between delineations along rocky shores versus gently sloping beaches (Figure 4). Also, for some reason the shoreline contour from the "5m p3 s10" DEM appeared to be significantly offset from the rest of the shorelines (Figure 4).

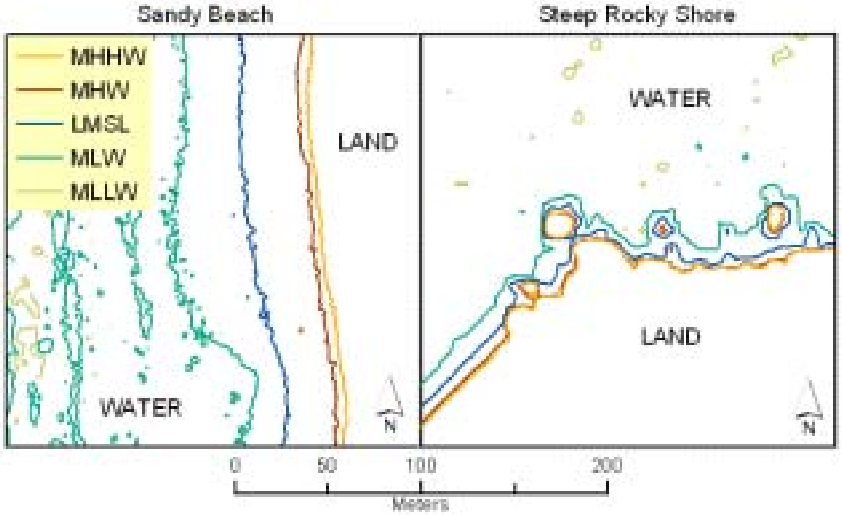

Figure 3 – Horizontal distances between shorelines from different datums were generally proportional to their vertical offsets. The vertical difference between MHW and MHHW is small compared to the other datums, and this relationship can likewise be seen in the horizontal spacing of these shorelines. However, an inverse relationship exists between slope and horizontal spacing.

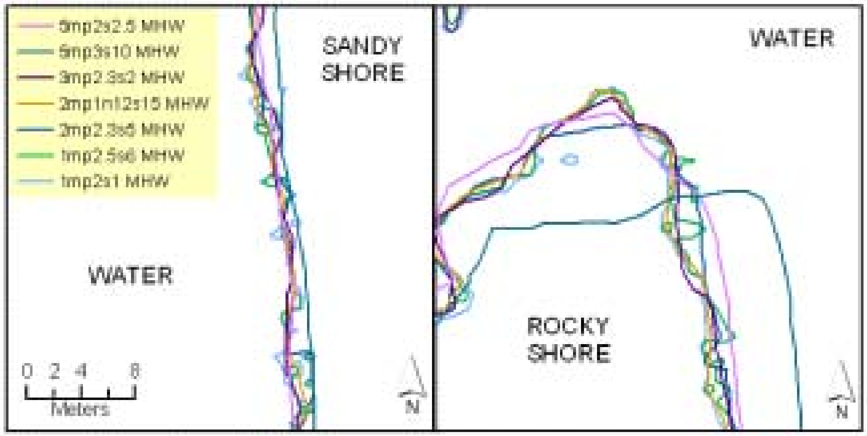

Figure 4 – Differences between MHW lines from lidar DEMs tended to be slightly greater along rocky shores than sandy beaches, but this is difficult to see without viewing the data at extremely large map scales (1:500 in this case). Also, the 5mp3s10 contour appeared to be significantly biased.

Some differences could be seen in shorelines based on the IDW input parameters used. Vectors resulting from DEMs with a high spatial resolution (1m, 2m) generally appeared excessively "jagged" and bore little resemblance to the smooth linework a trained operator might manually digitize, whereas shorelines contoured from DEMs with lower resolutions (5m) tended to be more cartographically pleasing (Figure 5).

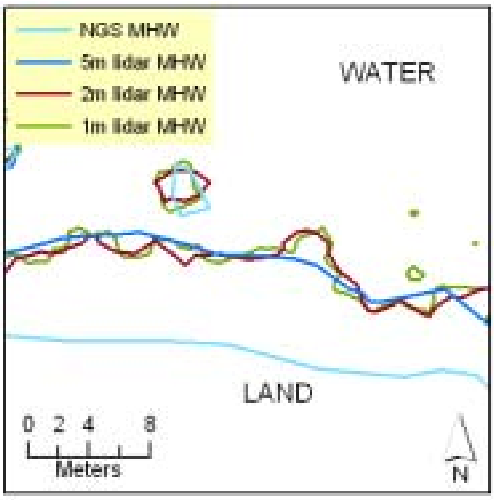

Figure 5 – Three MHW lines from lidar DEMs of different resolutions (1m, 2m, 5m) plus a manually captured MHW line, shown at an extremely large map scale. The 5m automatically extracted line bears the closest resemblance to the manually digitized line.

The IDW search radius also had an influence on output shorelines in some areas. Due to gaps in lidar data coverage where the sensor had difficulties picking up returns, small search radii produced regions of "NoData" cells in DEMs. When these areas were located adjacent to man-made shore structures such as bulkheads or piers (Figure 6), broken or discontinuous shoreline contours resulted. When large search radii were employed, gaps in the elevation data were effectively filled in during interpolation of DEMs, yet contours migrated seaward causing inaccuracies and awkwardly shaped man-made features.

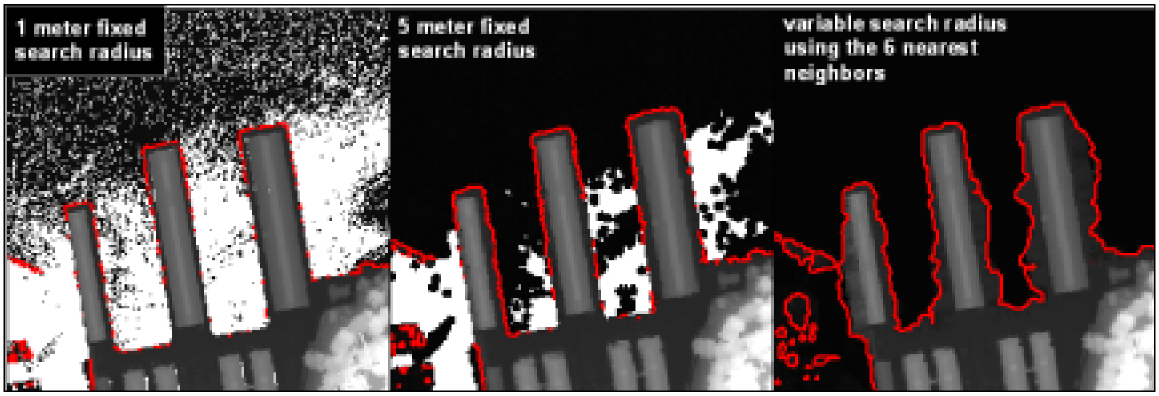

Figure 6 – Varying the interpolation search radius can impact the quality of extracted shorelines. Note the discontinuous nature of the shorelines when NoData cells are encountered (left, middle). The attempt to overcome this using a large search radius has its own problems, as land areas have unintentionally crept seaward here (right).

Finally, an unexpected side effect of the automatic extraction of shorelines from unfiltered DSMs appeared. Artificial islands resulted from data points collected on boats and wave caps during the lidar mission. These made it impossible to identify actual islets and rocks in the vector data, suggesting the need for further generalization and clean up.

COMPARISONS WITH SHORELINE DATA FROM OTHER SOURCES

After successfully creating tidal datum based digital shoreline vectors using raw lidar data as a source, their location and shape were initially assessed relative to other shoreline representations including the vector sources listed in the Project Data section above. Additionally, tidal datum based shorelines were contoured from pre-gridded lidar DEMs from 1997 and 1998, as well as USGS DEMs of unknown age, in order to evaluate the consistency of tidal datum based shorelines across time.

Initial visual comparisons of DEM-contoured MHW shorelines from the four different time frames in ArcMap (Figure 7) revealed greater variation than anticipated in their positions. This observation might indicate that actual geomorpological changes (natural erosion & accretion) along the coast could present the greatest challenge to mapping shorelines with consistency. The overall question might even be rephrased, “How does one keep shorelines in a GIS current?”

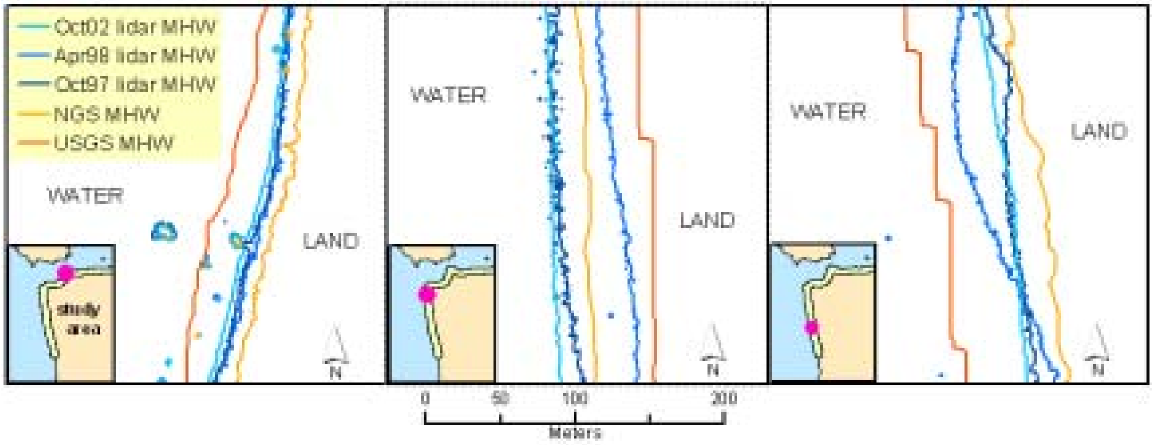

Figure 7 – Shorelines from pre-gridded lidar and USGS DEMs shown in relation to the MHW line extracted from the raw lidar (Oct '02), with the NGS photogrammetric MHW as a reference.

USGS DEMs were actually included in the study for dual reasons, both as an additional comparison elevation data source and as a means of demonstrating the results one can expect when applying the techniques of this study to the most widely available DEM data. Unfortunately, the extraction of shorelines from USGS DEMs referenced to tidal datums was not very successful. Besides not being able to obtain any MLW or MLLW shoreline at all, when shorelines were generated according to the other three tidal datums, the resulting contours were generated at nearly the same locations and were largely squared off, closely following grid cell boundaries (Figure 8). These results are likely due to the USGS practices of rounding elevations to the nearest whole integer (lack of precision) and assigning an elevation of zero to the entire sea.

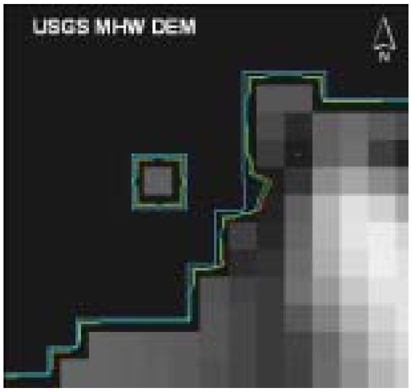

Figure 8 – MHHW, MHW, and LMSL shorelines from USGS DEMs, superimposed on a USGS 10m MHW referenced DEM. USGS uniformly assigns an elevation of "0" to water cells (black, above).

After viewing shoreline vectors obtained from the October 2002 lidar data relative to vectors from other sources, a quantitative analysis of the relative positions of various delineations was undertaken in order to compile objective conclusions on the overall success of extraction of tidal datum based shorelines from DEMs. The method chosen to quantify shoreline position utilized transect sampling (Figure 9), a technique commonly associated with shoreline change analysis and comparisons of shoreline positions mapped over time. The Digital Shoreline Analysis System (DSAS) version 2.1.1 (Thieler, Martin and Ergul 2003) was successfully used in conjunction with ArcView® GIS (version 3.3) to accomplish this task. The statistics used to assess shorelines were the mean (bias) and standard deviation, calculated manually using Microsoft Excel™. The calculated means expressed either landward (negatively signed) or seaward bias (unsigned, or positively signed). These statistical measures were used in favor of the RMSE since there is no standard, true, or accepted correct shoreline which can be used as a reference.

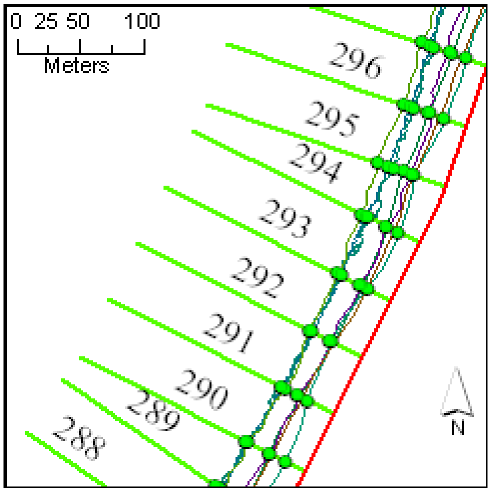

Figure 9 – Baseline (red), transects (green) and intersections used to determine relative shoreline position in DSAS. Transects are numbered sequentially and the intersections (sample points) are attributed with the transect number and shoreline IDs, enabling comparisons and statistics.

Nine MHW shorelines derived from 2002 lidar data were loaded into ArcView 3.3 and, using the DSAS software extension, orthogonal transects were generated extending from a baseline seaward through all shoreline vectors. The intersection points between the transects and shorelines were also automatically created by the software, and coordinates and attributes were saved in a dbf file. This dbf file was loaded into Excel and average intersections for each transect were calculated. These average points can be thought of as forming the average of the MHW lines derived from the 2002 DEMs. The average intersections were then used as a reference from which Euclidian distances to each of the nine lidar MHW lines were measured, either landward or seaward. Then mean and standard deviation statistics were calculated for each shoreline (Table 2).

As was previously noted, the “5m p3 s10” DEM produced a MHW line which was significantly offset from the other lines. This can clearly be seen in the statistics reported in Table 2 (SHORE ID #16). As was also noted, all of the other lidar MHW lines were tightly clustered regardless of interpolation parameters used, and this too is reflected in the table of statistics. Altough differences between the statistics are very small, the hierarchical organization which emerges when shorelines are ordered on their standard deviations is very interesting. DEM resolution was expected to play the greatest role in determining which lines deviated least from the average, but surprisingly all of the shorelines from 2 meter DEMs are at the top of the list with the lowest standard deviations, rather than the shorelines from DEMs with the smallest resolutions (1 meter).

Two additional shorelines from the 2002 lidar data were compared to the average MHW line. First, a DEM was interpolated from the original lidar data (z = ellipsoid heights) and uniformly adjusted to MHW based on a manually calculated offset using information from a single tide station, as a way of transforming the DEM to MHW without the benefit of VDatum. A shoreline contour was derived and loaded into ArcView 3.3. Using DSAS and Excel, a line comparison was performed and statistics generated. As expected, the "manual MHW" shoreline (SHORE ID #14 in Table 2) deviated from the average lidar MHW line far more than the others. Graphically observed in ArcView, the expected trend saw bias increasing the farther one goes from the point where the offset was calculated (SF Presidio). This exercise could be interpreted as pointing to the importance of VDatum when it comes to referencing DEMs to tidal datums.

The second comparison dealt with the issue of generalizing excessively detailed shorelines derived from DEMs with high spatial resolutions versus using lower resolution DEMs to generate cartographically pleasing shoreline contours that require no subsequent manual editing. The "1m p2.5 s6" MHW line (SHORE ID #8 in Table 2) from the 2002 data was generalized using the ArcGIS 8.3 ArcToolbox™ command "Simplify Lines" with a weed tolerance of 4 meters, then loaded into ArcView 3.3 with the DSAS extension. Again transects and intersection points enabled generation of statistics in Excel, which revealed (see Table 2, SHORE ID #26) that it is possible to use line generalization to improve an automatically generated shoreline while minimally affecting its overall position. Note that the line still sits higher in the hierarchy than any of the shorelines from the 5 meter DEMs.

Table 2 – Final statistics for all 2002 lidar DEM derived shorelines compared to the average lidar MHW line.

Statistical Comparison of Oct '02 Lidar MHW Shorelines

SHORE ID	Grid Parameters	Mean (m)	Std Dev (m)
11	2m p1 n12 s15	-0.0761	0.4087
10	2m p2.3 s5	-0.0411	0.4644
9	2m p2 s1.5	-0.1153	0.5077
8	1m p2.5 s6	-0.0727	0.5119
12	3m p2.3 s2	-0.0306	0.5576
7	1m p2 s1	-0.1825	0.6325
26	1m p2.5 s6 (generalized)	-0.0493	0.6341
17	5m p1 n12 s15	0.2086	0.6942
13	5m p2 s2.5	0.1654	0.7284
15	5m p1 n6	0.1452	0.7479
16	5m p3 s10	-1.7706	3.0033
14	5m p2 s2.5 manual MHW	-3.2821	4.4326

Comparisons with externally obtained vector shoreline sources, mostly delineated using more traditional methods, were statistically assessed next. MHW lines extracted from historic lidar DEMs and USGS DEMs were also included in this comparison. Vector shorelines were loaded into ArcView 3.3 and, once again with the DSAS ArcView software extension, transects were created and intersections formed with all shorelines included in the analysis. The transect intersections derived for this group of lines were compared to the average MHW line derived from the 2002 lidar data and stastistics were compiled (see Table 3).

Perhaps not surprisingly, the MHW line photogrammetrically derived from 2002 imagery (SHORE ID #3) was consistently the closest among traditionally extracted shorelines to the average line extracted from the raw 2002 lidar data. Only the MHW line from the 1997 lidar data (SHORE ID #5) had a lower standard deviation. However, the NGS MHW line also showed significant bias throughout the study area. This tendency becomes quite obvious of course when viewing the shorelines in ArcView 3.3.

Another surprising aspect of these results is the revelation that the two October MHW lines (1997 and 2002) were more consistent than the lines extracted from data collected six months apart (Oct. ‘97 and April ‘98) or temporally adjacent (April ’98 and Oct. ’02). Assuming there weren’t problems with the historic lidar datasets, this would suggest that the shoreline moves back and forth seasonally.

This would not be the first time seasonality of shorelines has been documented in research. According to Ruggiero, Kaminski and Plant, “There is a distinct seasonality in wave height, period and direction with increased wave heights and periods propagating from the south in the winter and lower waves and periods arriving from the north in the summer (1998, p. 7).” Furthermore, the California Beach Restoration Study (California Department of Boating and Waterways and State Coastal Conservancy 2002) goes on to explain how these factors result in beach retreat during the winter months and beach expansion and recovery during the summer.

The only other question pertaining to the comparison with MHW lines from the historic lidar data arises from the extreme nature of the differences between the April 1998 MHW line and the two October MHW lines. This is likely explained by the fact that the west coast of the U.S. experienced extraordinarily high erosion rates during the El Niño winter of 1997/98 (Ruggiero, Kaminski and Plant 1998). Therefore, the shoreline could be expected to fall significantly landward within the April 1998 lidar data.

A final observation would be that the table (Table 3) of comparison statistics between the alternate shorelines leaves the overall impression that there is a great deal of inconsistency between shorelines from traditional products, particularly if the range in values contained here is compared to the range in statistics which came out of the comparisons among the 2002 raw lidar data (Table 2). Given that all of these shorelines were delineated using different methods, and utilizing different definitions of exactly what constitutes a shoreline, this is not at all surprising. When one looks back at the statistics in Table 2, there is a glimpse of consistency which can readily be seen.

Table 3 – Comparison of shorelines from traditional sources, historic lidar, and USGS DEM to the 2002 lidar derived shorelines.

Statistical Comparison of Alternate Shorelines to Oct '02 Lidar

SHOREID	Shoreline Source	Mean (m)	Std Dev (m)
5	Oct '97 Lidar 2m grid adjusted to MHW	-3.3413	9.9283
3	NGS photogrammetrically interpreted MHW	-14.1238	15.8938
2	NWI Quad 1:24K shoreline	-6.2559	24.1454
6	Apr '98 Lidar 2m grid adjusted to MHW	-17.0226	27.6666
4	USGS DLG shoreline	-6.4924	32.6695
31	SLC 1:24K satellite MHW	-6.7042	33.7728
30	NOAA Electronic Nautical Chart (ENC) MHW	-24.6289	39.4601
1	USGS 10m DEM adjusted to MHW	-5.6897	39.8486

BRINGING VDATUM FUNCTIONALITY TO GIS

Given the role that VDatum can play in solving the problem of inconsistency in coastal GIS shorelines, it would seem quite beneficial to incorporate the VDatum functionality into widely available GIS software in order to make the tool more accessible to GIS users. In order to demonstrate the promise of VDatum capabilities in mainstream GIS software, the ModelBuilder extension in ArcGIS 9 (beta version) was used in an attempt to duplicate automation of tidal datum based shoreline delineation.

VDatum uses a grid-based transformation to perform coordinate conversions. For this reason, the application depends on geographically constrained grid files (gtx files), distributed in a proprietary format recognized only by the VDatum software. To replicate VDatum functionality in ArcGIS, these grids must be converted to a conventional raster format (Figure 10).

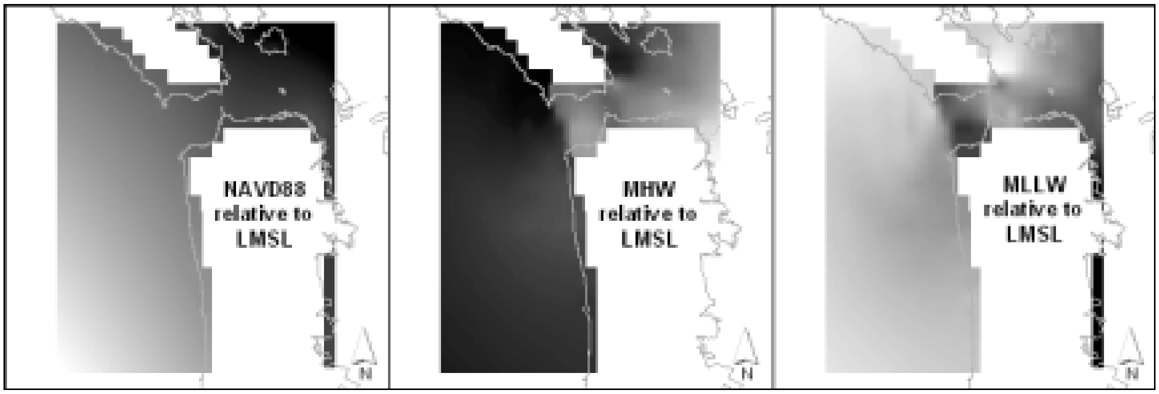

Figure 10 – VDatum transformation grids for the study area, converted to a GIS raster format. (Shoreline included for reference purposes only.)

For this project, VDatum gtx files for the study area were successfully converted to ArcInfo Grid format and resampled to 10 meter spatial resolution, a significantly higher resolution than that of the original gtx grids. Successful conversion of the VDatum transformation grids into a viable GIS raster data format meant that the VDatum processing sequence could be duplicated using standard raster data manipulation techniques. The process of automatically extracting tidal datum referenced shoreline from elevation data could then be accomplished by creating and implementing a GIS model using ArcGIS 9 ModelBuilder.

To test the approach, a model was created in ModelBuilder to extract MHW shoreline from an ellipsoid referenced DEM interpolated from raw lidar data (Figure 11). In addition to the input DEM, the model also incorporated three VDatum transformation grids plus the tools used to process the data, including the “Minus” and “Plus” raster processing commands in ArcGIS 9. Processing parameters were built in as well.

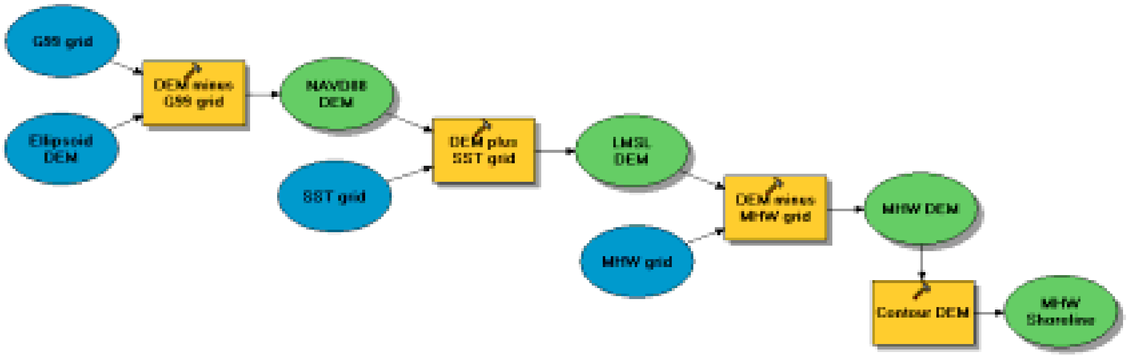

Figure 11 – Model constructed to automatically extract MHW shoreline using ArcGIS 9 ModelBuilder.

Once constructed, the model was run and a MHW shoreline was output in standard shapefile format. The results of the model were then evaluated against a MHW shoreline derived using the original VDatum data flow employed previously in this project. It is important to note that the ellipsoid DEM in the GIS model was interpolated using the exact same input parameters as the MHW DEM from the VDatum data flow. This was necessary to insure that differences seen in shorelines from the two methods were not due to differently interpolated DEMs.

The two MHW shorelines compared were expected to be similar, since they both originated from the same elevation source data. However, superimposition of the two shorelines surprisingly revealed that the MHW line output by GIS modeling of the tidal datum referencing was perfectly identical to the MHW shoreline obtained from the VDatum workflow, vertex by vertex. The ModelBuilder approach used to transform the raw lidar DEM to MHW and render shoreline flawlessly replicated the results given by the tedious method used throughout this project to process point data and interpolate tidal datum referenced DEMs prior to shoreline extraction. The capability of performing automated tidal datum transformations and shoreline extraction using GIS modeling in ArcGIS 9 ModelBuilder has been shown very successfully.

CONCLUDING REMARKS

To summarize the major accomplishments of this project, a source of great consistency in capturing coastal GIS shorelines has been shown by demonstrating a method to automatically extract tidal datum based shoreline from lidar DEMs. Tidal datum based shorelines were automatically extracted from lidar DEMs interpolated using a variety of IDW parameters, with very consistent results. Almost all of the MHW shoreline contours fell within one meter of each other on average. This contrasted greatly with the results shown in comparisons between shorelines currently used in coastal GIS applications from a variety of external sources. Those shorelines varied from the lidar shorelines by an average of over 30 meters.

By looking at MHW shorelines extracted from lidar data collected on other dates, it was shown that automated extraction of tidal datum referenced shoreline from DEMs only yields consistency using source data collected within a narrow timeframe. Just as a photo or satellite image captures the coast in a momentary state, so too does a DEM. However, a DEM is far more stable in its portrayal of the coast than an image showing the visible land-water interface, which fluctuates in terms of seconds rather than months.

Finally, the tidal datum based shoreline extraction principles demonstrated by this project were extended to ArcGIS 9 using ModelBuilder, thus demonstrating one means that coastal GIS users can immediately benefit from this research. As lidar becomes increasingly accessible to the GIS community, and as VDatum coverage expands to more parts of the United States coast, the methods and techniques introduced by this project may be implemented by even wider groups within the coastal GIS community. Perhaps as this occurs, debates over which shorelines are best will dissipate and users will enjoy the greater consistency they have sought all along.

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