Examples of Mapping 'The Foot of the Continental Slope' with 'The Surface of Directed Gradient' Algorithm Using NOAA's ETOPO5 Data Base

By John Overton Bennett, Paradigm Imaging Inc, USA

The author first presented The Surface of Directed Gradient (SDG) Algorithm (developed by Professor Carl de Boor) at the 1996 GALOS Conference in Bali in a paper entitled 'Mapping the Foot of the Continental Slope (FCS) with Spline Smoothed Data Using the Second Derivative in the Gradient Direction (SDG).' Since that time the author has run the algorithm on data from several areas using the ETOPO5 data developed by NOAA (Bennett, 1998). The SDG Algorithm is a faithful translation of the United Nation's Law of the Sea Article 76 definition of the FCS as 'In absence of evidence to the contrary, the point of maximum change of the gradient at its base' (United Nations, 1993, pg 27, Article 27, 4.b) into a mathematical algorithm. For such data on a rectangular grid, the author has obtained an explicit mathematical function as a bi-cubic smoothing spline representation to the raw data. On occasions the ETOPO5 data are a bit noisy in some areas and requires some smoothing in order to map the location of the FCS in a meaningful way. The spline function representation of the data provides a useful smoothing parameter, p.

Two examples are presented. The first is of the United States Atlantic Coast that is a textbook example of where to use the United Nations legal definition of the Foot of the Continental Shelf (FCS). The SDG algorithm works very well and the computer traces out the FCS for most of the entire Atlantic Coast. The second example is of the North Slope of Alaska. This is a much more difficult area to apply the United Nations legal definition of the FCS. It was also much more difficult for the SDG to determine the FCS, because it is an undulating sub-sea terrain. Using data from this area the SDG found four possible candidates for the FCS.*

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* This is not necessarily the method of computing the Foot of the Continental Slope to be used by the United States Government. The examples presented in this paper represent no opinion or position of the United States Government. They are the observations of the author.

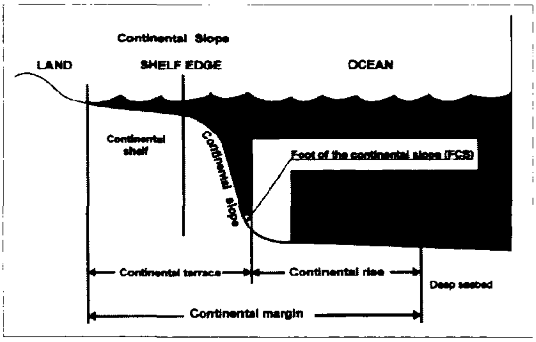

Figure 1: The foot of the continental slope as located on cross-section of continental shelf

base', into a mathematical algorithm. Figure 1 is a cross-section that shows the location of the FCS, the parameter under discussion.

This paper shows how the SDG algorithm computes the FCS by way of illustration without the mathematical equations and theoretical detail of the Bali GALOS (Bennett,1999) paper in order to make the SDG algorithm more easily understood.

Although there have been several data bases that have been developed since that of NOAA's ETOPO5, with finer resolution and more accurate water depth (z) values, the ETOPO5 data base is an inexpensive, complete world wide data base defined by latitude-longitude coordinates that can be converted to a rectangular grid. It provides a standard for comparing results of computing the FCS for areas in different parts of the world. A degree of latitude is 60 nautical miles (nm). Five minutes of latitude is 5 nm. The 5 in ETOPO5 indicates that the coordinates are 5 minutes of a degree. The degrees longitude range from 60 nm (5 minutes longitude about 5nm) at the equator to zero nm at the poles. By averaging the degrees of longitude over the area under consideration the latitude-longitude coordinates can by converted to a rectangular grid. (See Bennett, 1998, p 2) This is a fine enough grid to compute a reasonable first pass at computing the FCS anywhere in the world to determine what resolution requirements should be used for a more accurate computation of the FCS. A large part of the ETOPO5 database was obtained from the declassification of some United States Navy data sets.

An explicit mathematical bi-cubic spline function is obtained to represent the ETOPO5 bathymetric sea depth, z, in the area of interest. The ETOPO5 data are a bit noisy in some areas and require some smoothing of the spline function in order for the SDG to map the location of the FCS in a meaningful way

As new technology permits deeper offshore drilling for hydrocarbons and minerals, coastal countries have more reason to want to extend their mineral rights past the Exclusive Economic Zone (EEZ); thus the location of the FCS will become more important and crucial. The United Nation's Law of the Sea (U.N. LOS) gives the legal definition of the FCS to be, 'In absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient' (United Nations, 1993, pg. 27, Article 27, 4, b.).

Every coastal country owns its mineral rights out to the EEZ. Beyond the EEZ it must pay royalties to the United Nations for Third World Country development for any minerals found.

Briefly a country may claim mineral rights beyond its EEZ by one of the following 5 options:. (See de Wet, reference 5.)

1. 350 nautical miles from the coast line
2. 2,500 metermetre isobath plus 100 nautical miles
3. FCS seaward of the EEZ plus 60 nautical miles
4. 1 per cent rule: points each of which the thickness of the sedimentary rocks is at least 1 per cent of the shortest distance from such point to the FCS
5. 200-nautical mile Exclusive Economic Zone (EEZ)

Let M1=Maximum {1,2}

Let M2=Maximum {3,4}

then the outer limit of the continental shelf that can be claimed under UN Article 76 is given by:

Maximum [Minimum { M1, M2 }, 5].

For the full legal description of the determination of a country's mineral rights see page 27 of the United Nations publication (United Nations Publication, 1993).

Because two (3 and 4) of the four options above are dependent on the location of the FCS, it is clear that it is critical that the FCS be mapped accurately (For more detail see Cook and Carleton, 2000).

The FCS can extend a nation's mineral rights past the 200-nautical mile EEZ where the FCS is seaward of the EEZ of that country's coast, option 3. When this occurs, 60 nautical miles are added seaward of the location of the FCS to determine the extent of the coastal country's mineral rights. It is also possible to even go beyond the 60-nautical mile extension of the FCS where a substantial increase in sediment thickness via the 1 per cent rule, option 4. This would usually require reliable seismic data to verify sediment thickness. This is usually a much more expensive option than using ETOPO5 data to compute the FCS. Options 3 and 4 do not have any explicit constraints associated with them; however, options 1 and 2 are constraints that do bound the seaward extension of the mineral rights.
Having assembled documented evidence to make a claim via one or both of the above options 3 or 4, a country would then present a claim to the United Nation's 'Commission on the Limits of the Continental Shelf' (CLCS) for the right to extend its continental shelf based upon maps and other documentary evidence to support options 3 or 4 above. The United Nations has provided a useful publication with scientific and technical guidelines for countries submitting claims to the CLCS. (See United Nation's Publication Scientific and Technical Guidelines the Limits of the Continental Shelf: United Nations Publication, 1998) This publication lists the SDG algorithm and other viable methods to compute the FCS.

Example 1: US Atlantic Coast

An example from the US Atlantic Ocean to illustrate the implementation of option 3 to compute the FCS above will now be given.

What is needed is a worldwide digital bathymetric data set. It is fortunate that the worldwide ETOPO5 data set at its 5-nautical mile grid is about right to allow a first cut at determining any country's FCS.
NOAA's ETOPO5 data set has some shortcomings in resolution and accuracy; however, because of the high cost involved in obtaining new data, this is a good first cut for a country to decide how much more digital bathymetric data are needed to prepare maps to present to the CLCS.
The U.N.'s legal definition of the FCS, 'shall be determined as the point of maximum change in the gradient at its base' is very precise; but it is not easy to implement on paper bathymetric contour maps. See Figure 1 for a cross-section showing the location of the FCS. The legal definition of the FCS almost requires a digital environment for a meaningful implementation.
The definition of the FCS applies to well-defined continental slopes such as the U.S. Atlantic coast, which has a smooth drop off. It does not do well on an undulating sub-sea type terrain such as the North Slope of Alaska west of Prudhoe Bay, as in Example 2. For a continental slope with volcanic activity causing much jagged angularity, such as that of Japan, this definition does not apply well either. For areas such as these, the alternate legal option is needed of United Nation's Law of the Sea Article 76 definition of the FCS i.e. 'In absence of evidence to the contrary'

This legal definition was translated into a mathematical algorithm called the Surface of Directed Gradient (SDG) by de Boor and presented by Bennett (Bennett, 1998, references 1 and 2.) The input is digital bathymetric data sets on a rectangular grid and the resulting output is a second derivative surface is called the Surface of Directed Gradient (SDG). The crest of the highest ridge of this SDG surface locates the FCS wherever the U.N. legal definition is appropriate. FCS candidates arise from smaller ridges as in Example 2.
Other digital methods are also used to compute a second derivative surface from digital bathymetric data using the surface of maximum curvature (SMC). See Vanicek (Vanicek, 1994;Ou, 1996.) The author gave a paper comparing the two methods at the Advisory Board of the Law of the Sea (ABLOS) meeting September of 1999 in Monaco (Bennett, 1999).

The United States' FCS is computed using ETOPO5 data for the Atlantic Coast for latitude North from Florida at 29° to Delaware at 39° and for longitude West from 81° to 71°. See Figure 2 for a map showing the area of consideration.

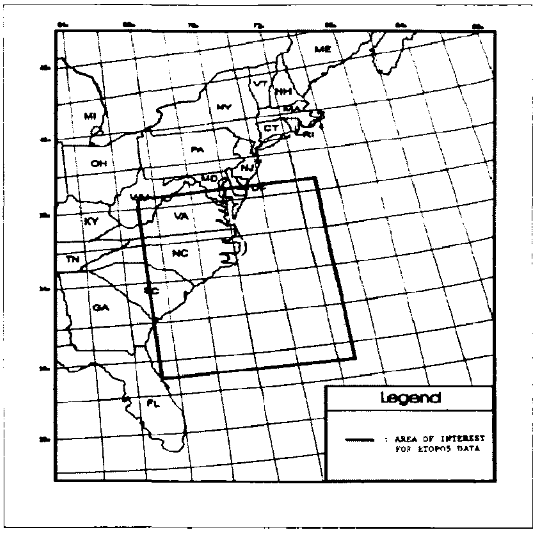

Figure 2: Map of US Atlantic Coast Study Area

Figure 3 is a 3-D net display of the raw ETOPO5 digital bathymetric data of the above area. The smoothing parameter, p, is between zero and including 1. If p=1.0 there is no smoothing. If p is close to zero there is maximum smoothing. In order not to lose the information content of the data set 'p' is bounded such that {.9 <p < =1}. If 'p <. 9', there is usually a severe loss of information content. There is no smoothing (p=1) of these raw data in Figure 3. For each different area where the FCS is to be determined, different amounts of smoothing must be used (i.e. a different value of 'p') to obtain the properly smoothed bi-cubic spline function defined on a rectangular grid to allow the SDG ridge crest to be mapped as a continuous location of the FCS that does not zigzag across the FCS. When the SDG algorithm was run on the raw data, the SDG obtained could not map the results with a simple plotting of each of the largest z values in the row of the array being considered but zigzagged on either side of the actual FCS. The spline function representation of the ETOPO5 data makes this smoothing of the data a simple adjustment of the parameter p.

A more elaborate crest of the ridge-tracing algorithm that discarded outliers too far from the last point found on the crest of the ridge is a possible solution. Another approach would be to smooth the data by decreasing the value of p until a reasonable FCS is found, then iteratively increase the value of p, until a credible FCS is found for the data with the higher information content.

Figure 4 is a 3-D net display surface of the spline smoothed ETOPO5. A small amount of smoothing (p = .999) was applied. This was just enough smoothing to do the job. Just the right amount of smoothing is

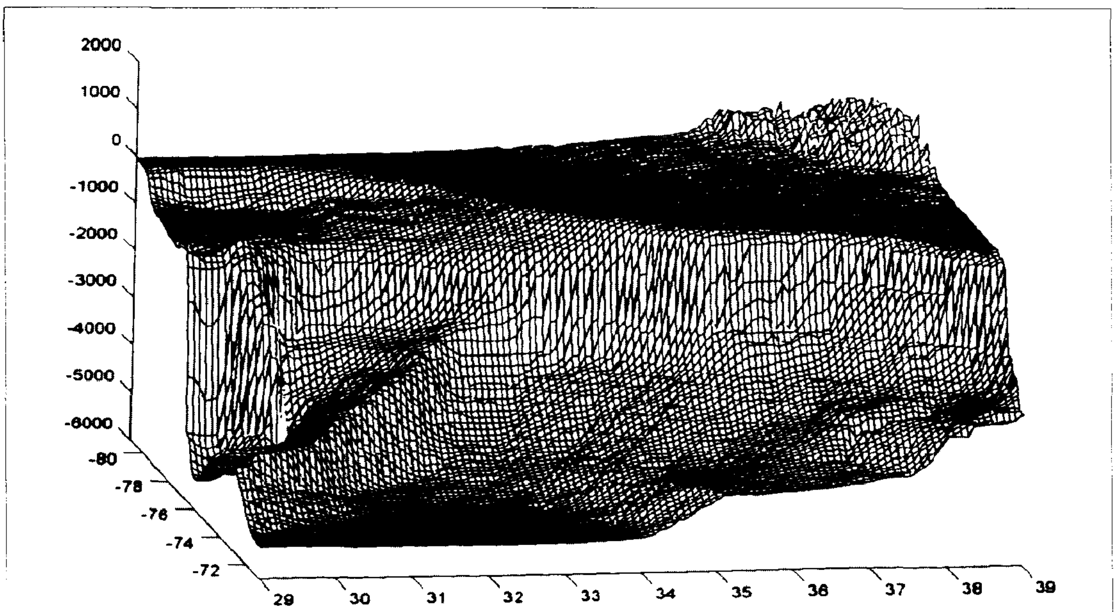

Figure 3: 3-D Net display of original NOAA ETOPO5 data of 10 degrees longitude by 10 degrees latitude portion of US Atlantic Coast Z = 0 is sea level 5-nautical mile grid interval (121 X 121 grid)

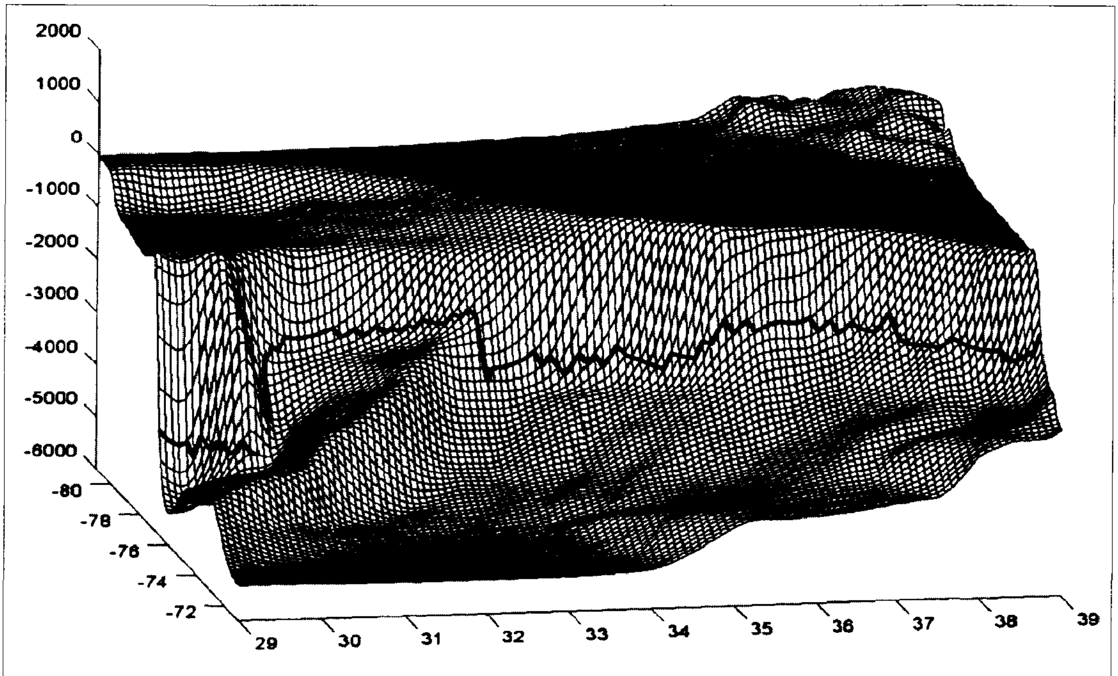

Figure 4: 3-D NET display of spline smoothed NOAA ETOP5 Data smoothing parameter, p=999 10 degrees longitude by 10 degrees latitude portion of US Atlantic Coast Z = 0, is sea level 5-nautical mile grid interval (121 X 121 grid)

needed to eliminate enough noise to compute the second degree surface and also not omit the needed information. The heavy black line in Figure 4 indicates the location of the FCS as determined by the SDG. Note the graphic location of the FCS to be: where the horizontal rows of diamonds in the 3-D net diagram are the largest and then where they begin to get smaller. This is a visual confirmation of the LOS legal definition of the FCS .i.e. where there is 'the maximum change in the gradient.'

This bi-cubic spline approach smooths out the noise and represents the data as an explicit mathematical function. This function could be useful in many areas of oceanography.
Figure 5 is a contour map of the same area as in the 3-D net diagram in Figure 4. This method requires the original data set to have a rectangular grid. The heavy black line in Figure 5 indicates the location of the FCS as determined by the SDG, which is shown in Figure 6.
The notation in labelling the grid lines of the figures is in longitude and latitude. The original co-ordinate units for the ETOPO5 data are as follows: x: degrees longitude, y: degrees latitude, and z: metres measured below sea level. These co-ordinates should be measured on a sphere. However, in displaying the data and results of this paper, a flat surface is used without a map projection. One degree of latitude on the y-axis is approximately 60 nautical miles, or 5 minutes of latitude are approximately 5 nautical miles. When converting to nautical miles from degrees on the x or longitudinal axis, the farther the distance is from the equator, the smaller is a degree of longitude resulting with zero at the North Pole.

Now that we have an explicit mathematical function that represents the ETOPO5 bathymetric data set with, if necessary, the noise removed, we proceed to apply the SDG. The approach of the SDG is to faithfully translate the UN legal definition of the FCS at each step to its equal event mathematical operation where the UN legal definition of the FCS can be implemented as the SDG algorithm on the bi-cubic spline bathymetric function that represents the digital ETOPO5 data.
Other approaches previously used to compute the FCS use the surface of maximum curvature and taking two-dimensional cross-sections; however neither of these are a faithful continuous implementation of the UN legal definition of the FCS.

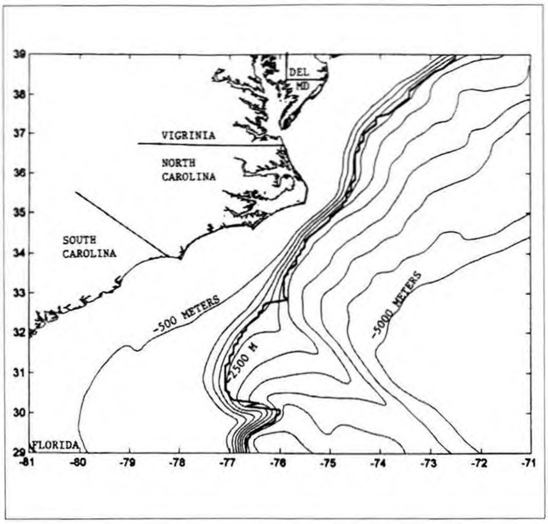

Figure 5: Contour map of the spline-smoothed NOAA ETOPO5 Data with smoothing parameters: p = .999 from 10 degrees longitude by 10 degrees latitude portion of US Atlantic coast contour interval = 500 meters 5-nautical mile grid interval (121 X 121 grid) Heavy line is a plot of the FCS as found by SDG

To follow the lead of the legal description of FCS as cited above, one must proceed in the direction of the gradient from any given point of the digital bathymetric data set. The computational procedure generates the surface by computing the Rayleigh Quotient (second derivative matrix computation) in the normalised gradient direction on the smoothed bi-cubic spline function at each point of the original data. The resulting surface is called the SDG. The location of the crest of the highest ridge of this surface is a good approximation to the determination of the FCS as can be seen in Figure 6.

Figure 6 is a 3-D net display of the SDG surface. The crest of the highest ridge, which is between 78° and 76° West longitude, outlines the location of the FCS. Note the hills on either side of the main ridge that could confuse the algorithm that was trying to map the crest of the ridge.
Figure 7 is the contour map of the SDG surface. The heavy black line in Figure 7 shows the location of the FCS.

Figure 8 is a map showing the bathymetric contours of the area. The map has a 500-metre contour interval. In Figure 8, the FCS is represented by the solid heavy black line. The EEZ is represented by the circled black line. Note between 29 and 30 degrees North latitude the heavy black line, which is the FCS, is seaward of the 200-nautical mile EEZ. North of 30 degrees North latitude the EES (circled line) is always seaward of the FCS (solid black line). According to option 3 on page 3 above of the United Nation's

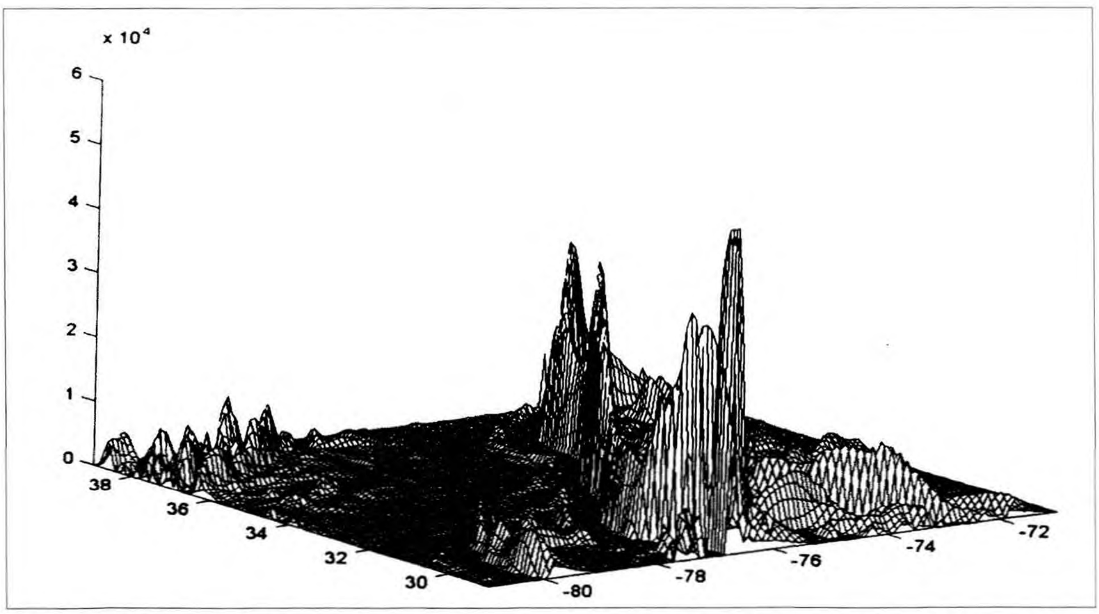

Figure 6: 3-D NET display of the 'SDG' from 10 degrees longitude by 10 degrees latitude protion of US Atlantic Coast 5-Nautical mile grid interval (121 X 121 grid) 'FCS' is the peak of the highest ridge

LOS, the United States is entitled to the additional mineral rights between the FCS plus 60 miles line (heavy dashed line) and the EEZ line (circled line). These extended mineral rights are indicated by the hatched area between the circled (EEZ) line and dashed heavy black line in Figure 8.

Although not shown on the map in Figure 8, options 1 and 2 of United Nations LOS i.e. 1) 350 nautical miles from shore and 2) 100 nautical miles seaward of the -2500 m isobath, respectively, would not limit the seaward extent of this possible U.S. claim as both lines would be well seaward of the heavy dashed line which represents the claim afforded to the United States by the United Nation's LOS under option 3 in this particular case. Note the correlation between the FCS (black line) and the 2,500 metre contour. For a detailed mathematical presentation of the SDG see Bennett (Bennett, 1998 refer-

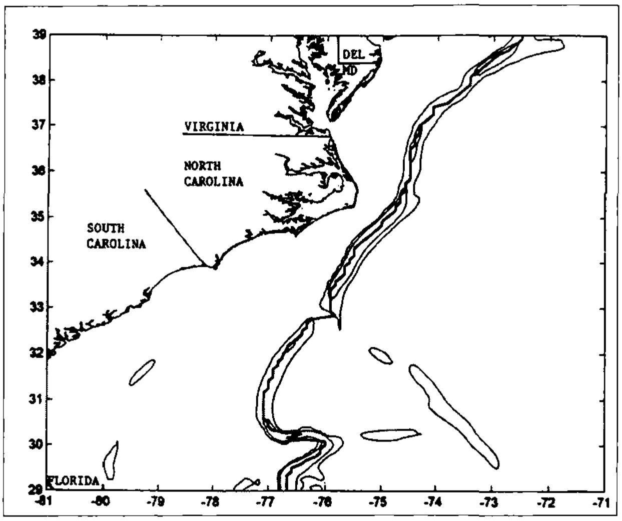

Figure 7: contour map of the 'SGD' using the spline-smoothed OAA ETOPO5 data with smoothing parameters: p = .999 10X10 degree portion of US Atlantic Coast 'FCS' is obtained from the crest of the highest ridge 5- nautical mile grid interval (121X121 grid) Heavy line is a plot of the 'FCS' as found by SDG

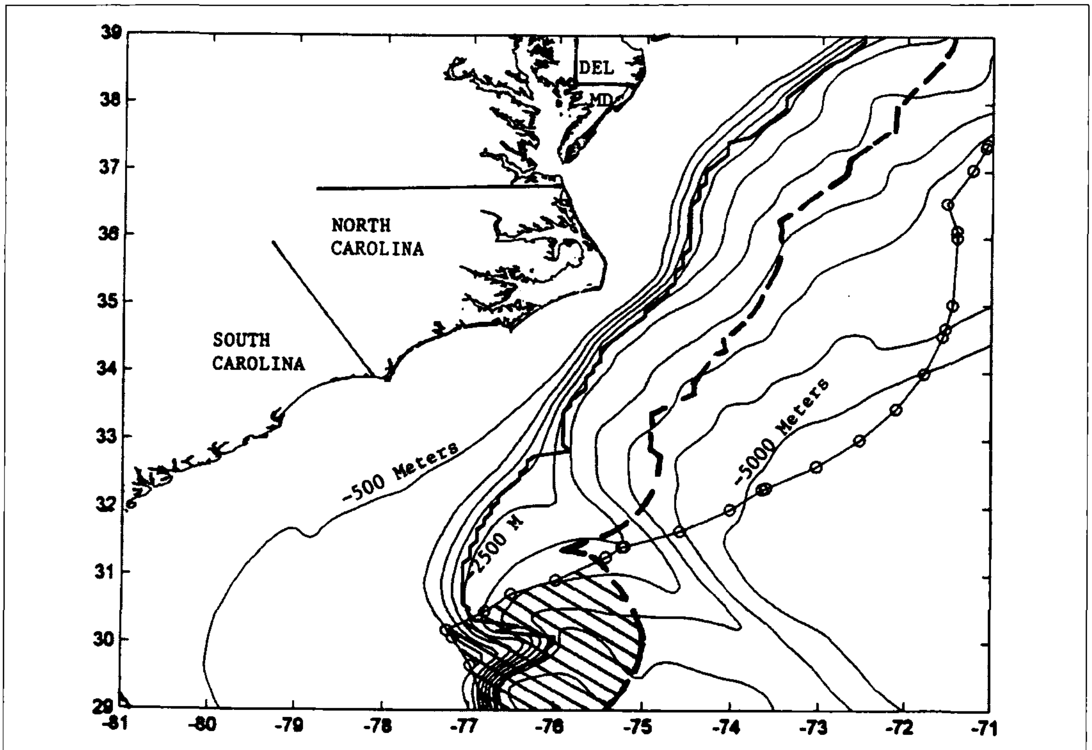

Figure 8: Map showing area where FCS is seaward of EEZ Contour map of the spline-smoothed NOAA ETOPO5 data with smoothing parameters: p = .999 from 10 degrees longitude by 10 degrees latitude portion of US Atlantic Coast contour interval = 500 meters 5- nautical mile grid interval (121X121 grid) Heavy line is a plot of the FCS as found by SDG dashed heavy line is the FCS plus 60 nautical miles circled line is extent of the exclusive economic zone (EEZ)

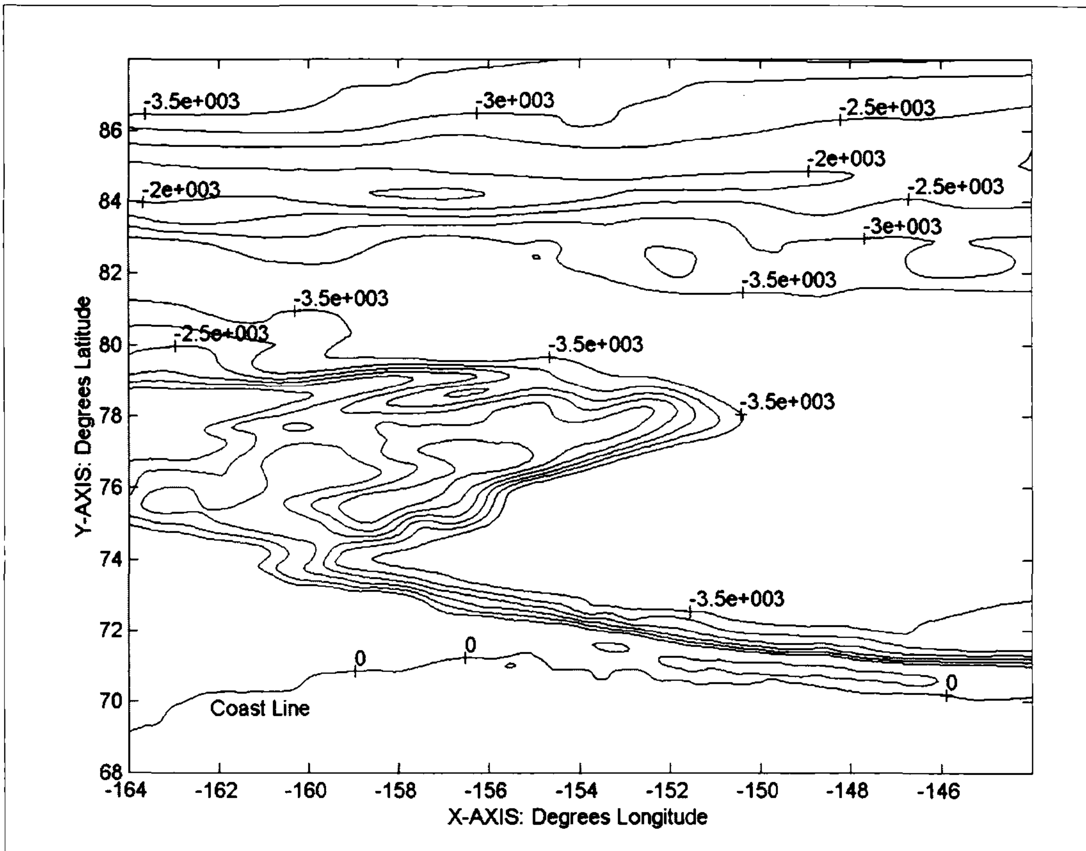

Figure 9: Contour map of North Slope, Alaska, CI = 500 meters

ences 1 or 2.) It is clear that the accurate location of the FCS is important to any coastal country whose FCS beyond the 200-nautical mile EEZ.

Although the United States is one of those countries that has not ratified the LOS, it should eventually. When this occurs, accurate digital location of the FCS will become increasingly more important to all coastal countries that wish to claim the entirety of their mineral rights. For any country to realise their full mineral rights they must first ratify the United Nations LOS. After a country ratifies the LOS it then has 10 years to submit its credentials for claims to extend their mineral rights.

Example 2: North Slope of Akaska

From what is a textbook example of the implementation of the SDG on the US Atlantic coast, we now turn to the North Slope of Alaska. It is not the classical continental shelf with a FCS that is readily classified by the UN legal definition of the FCS. The North Slope of Alaska has an undulating type of sub-sea topography. The area we will consider is from 68 degrees to 86 degrees North latitude and 146 to 164 degrees West longitude . Figure 9 is a contour map of this area under consideration.

The coastline is labeled with the 0 contour. The contour interval is 500 metres.

Note the 2,500-metre contours (labeled: '–2.5e+003') in the north part of the map. They would allow under option 2 above for expansion far beyond the 350 nautical mile limit (Shown in of Figure 13) option 1, if the FCS could be extended that far north.

Note also the steep drop off along the coast beginning in the eastern part (70° – 74° North) of the contour map in Figure 9. This is the primary FCS.

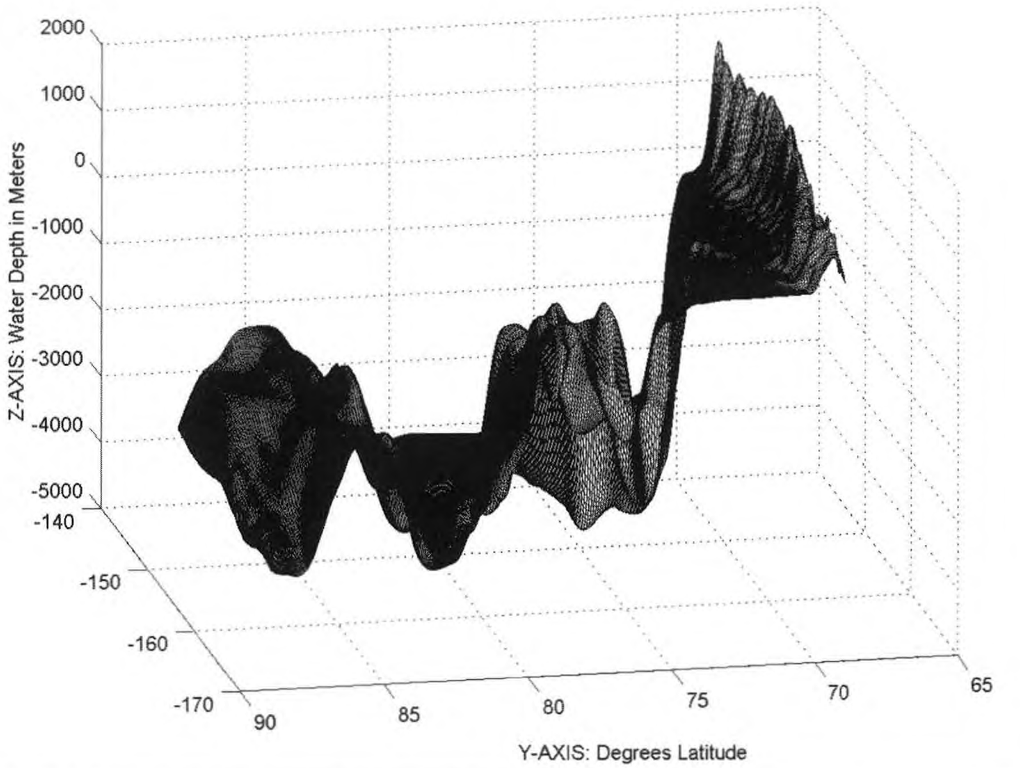

Figure 10: 3-D Net graph of North Slope, Alaska, p = .999

Figure 10 is a 3-D Net Graph, which shows the undulating sub-sea terrain north of the coast and suggests there could be several other candidates (76°, 79°,and 80°) for the FCS, several hundred miles north of the first and primary FCS. This will be the case.

We will now compute the SDG (Displayed in Figure 11) for the North Slope of Alaska inputting data as displayed in the 3-D Net Graph in Figure 10. Note the 4 distinct ridges at 72-74(FCS-A), 76(FCS-B), 78(FCS-C), and 80 (FCS-D) degrees north latitude in the 3-D Net Graph of the SDG in Ffigure 11. The crest of these four ridges FCS-A, FCS-B, FCS-C, and FCS-D are all candidates for locating a FCS.

Figure 12 is a contour map of the SDG that is presented as a 3-D Net Graph in Figure 11. Let us focus on FCS-A which starts at the eastern edge of the contour map in Figure 12 at about 72 degrees latitude. It is located by the crest of the ridge labeled FCS-A. The approximate EEZ is indicated by the single line labeled EEZ. FDS-A is seaward of the EEZ (200 nautical miles from shore) in the Eastern part of the map in Figure 12. At about 74 degrees North latitude and 160 degrees West longitude the EEZ and the FCS-A cross and west of this point the FCS-A is seaward of the EEZ. This invokes option 3 on page 5 above since the FCS-A is seaward of the EEZ; hence, an additional 60 nautical miles (double lines) is added to the location of the FCS-A. The additional mineral rights evoked by FCS-A are indicated on the maps in Figures 12 and 13 by the area bounded by the double line (FCS-A plus 60 nautical miles), the EEZ boundary and the western border of the map. This area is allowed because it is landward of the 350-mile limit, provided by option 1.
What is interesting about this North Slope of Alaska area is that there are in addition to primary FCS, FCS-A, there are three other possible candidates for FCSs. They are FCS-B, FCS-C, and FCS-D. Although

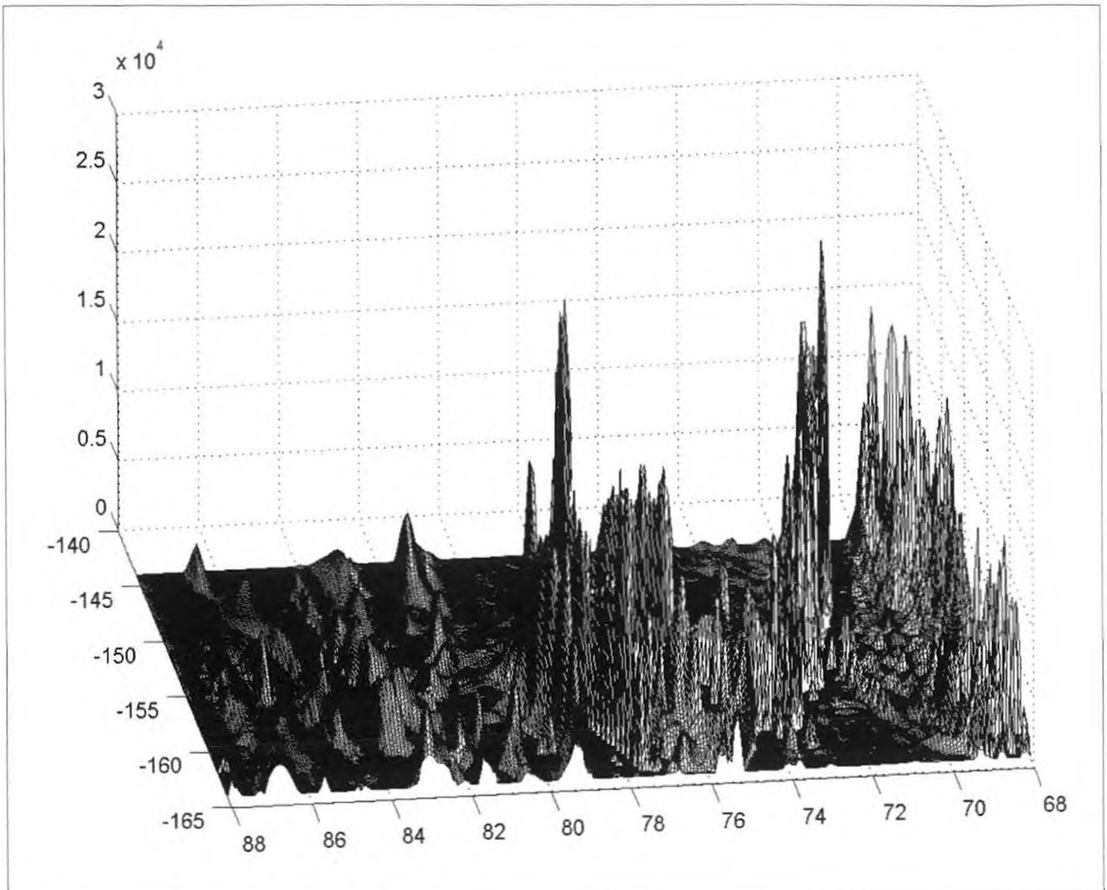

Figure 11: 3-D Net graph of SDG

FCS-C, FCS-D, and most of FCS-B are all seaward of the 350 Mile Limit they could be allowed by being landward the 2,500-metre contours plus 100 miles by option 2 on page 5 above.

Summary and Conclusions

1. The pre-processing of the NOAA's ETOPO5 worldwide bathymetric data set by bi-cubic spline smoothing provides an explicit mathematical function that can reduce the noise and retain most of the original information content of the data. This representation of the ETOPO5 data set as a mathematical bi-cubic spline function should provide valuable information about the world's sea floors to many areas of oceanography.
   This data smoothing is usually requisite to obtain good results in constructing any second derivative surface. Noisy data will always give poor results using gradient methods, because taking derivatives introduces angularity and magnifies the noise. There is a limit to the amount of smoothing that should be done. An estimate of the smoothing parameter 'p' can be found as a function of the grid interval (See reference 1 page 8). This smoothing parameter 'p' should not smooth out the original information content of the data. The optimal value of the smoothing parameter will vary depending on the individual data set. The explicit mathematical bi-cubic spline function used allows a possible display of the data at a finer grid than the grid on which it was originally received.
2. The SDG technique described in this paper can be implemented on any digital data set defined on a rectangular grid. If the data are from a triangulated grid, it must first be translated to a rectangular grid. The

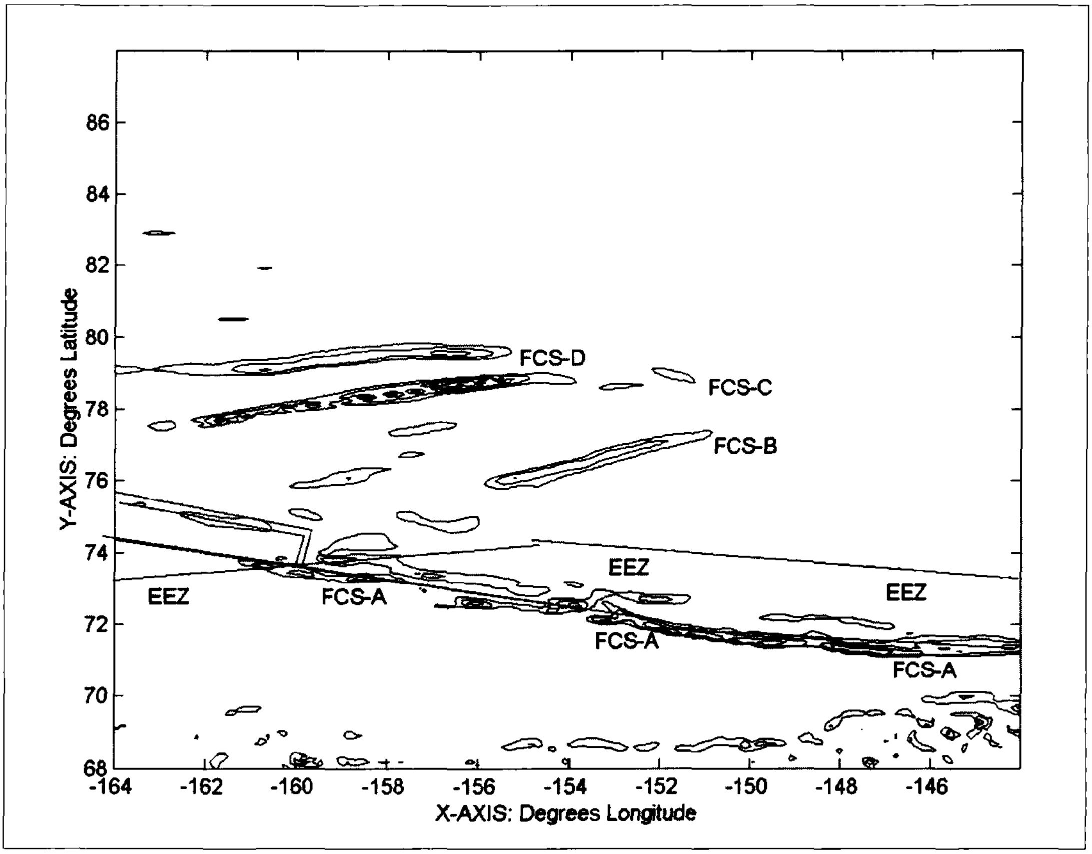

Figure 12: Contour map of SDG, North Slope, Alaska

author used the ETOPO5 data because it is a worldwide, public domain data set. It also provides a standard to compare different FCS in different parts of the world using the same bathymetric data set.

3. The SDG approach is an accurate, faithful mathematical modeling of the legal definition of the FCS.

4. The SDG does not have any spurious lobes and does not require scaling of the data to obtain accurate results, as do some other methods of computing the FCS on rectangular grids.

5. The United Nations, legal definition of the FCS will not locate the FCS in all cases. In particular, when a cross-section perpendicular to the contours of the continental shelf is the arc of a circle, the legal definition will not yield a FCS. Because of the uniform gradient in this case, there is no maximum gradient at the base. When the FCS is formed under normal sedimentation conditions, this situation will be rare. Where the FCS is located in undulating sub-sea terrain, such as in the North Slope of Alaska or very jagged, angular volcanism like on the coast of Japan, these cases may require the use of the 'In absence of evidence to the contrary' part of the UN's legal definition of the FCS. In Example 1 for the U.S. Atlantic Coast ETOPO5 data set used here, the SDG located the FCS quite accurately 95 per cent of the time for the entire coast. Example 2 is much more complicated. In addition to the primary FCS there are three other feasible FCS seaward of the primary FCS.

6. With new technology allowing deeper drilling and mining, coastal countries will become more interested in the accurate location of their FCS when seaward of the EEZ, in order to extend their mineral rights via the UN's LOS.

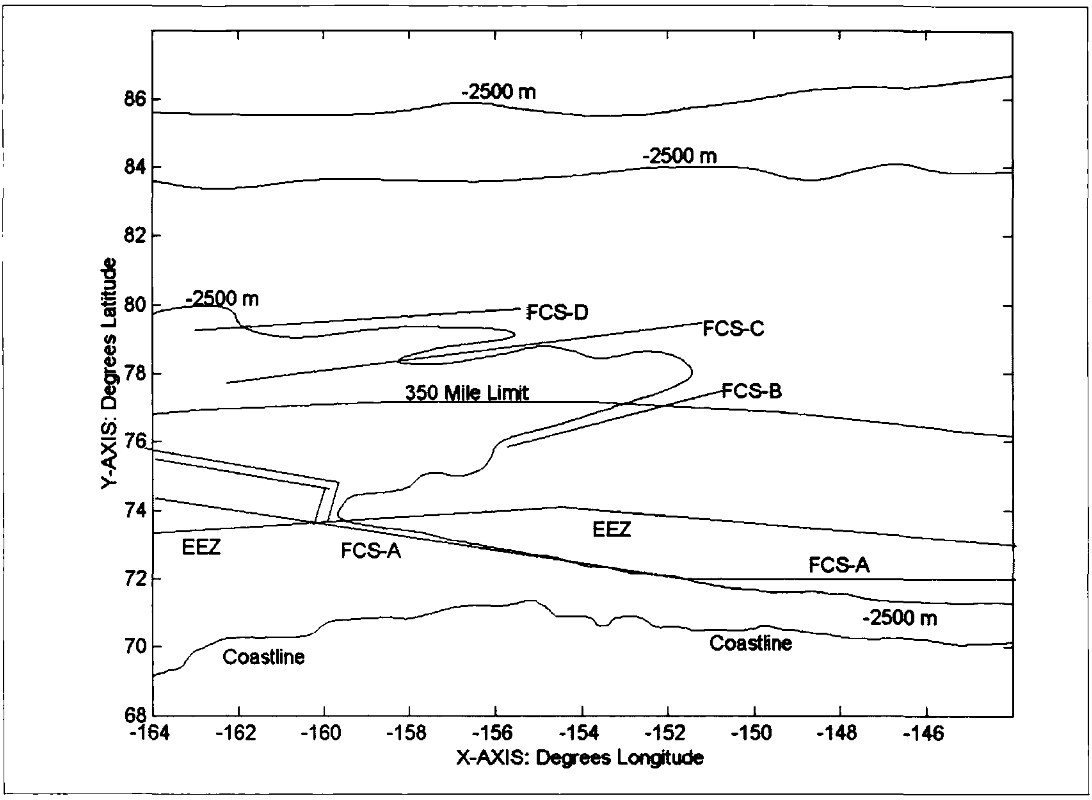

Figure 13: FCS map of North Slope, Alaska

7. The SDG is a continuous surface for the grid resolution of the data and thus is more reliable and accurate than any other method, which computes a series of 2-dimentional cross-sections, then finds the FCS at each point in the cross-section and finally connects the points.

8. It is hoped that the methods suggested in this paper and presented by the author (Bennett, 1998 references 1 or 2) will show how to utilise the information content of the NOAA ETOPO5 (or any other noisy rectangular digital data set) in many areas of oceanography and allow countries to use the SDG algorithm to compute their FCS where the U.N.'s LOS legal definition applies.

9. No country can claim their full mineral rights until they ratify the U.N. LOS.
   Once they ratify the LOS they have 10 years to present their claim to the UN Committee.

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Biography

John O Bennett graduated from the University of Oklahoma with a BA in Petroleum Geophysics and a MS in mathematics. After several years of graduate study and teaching in the mathematics department at the University of Texas, he completed a PhD in Mathematical Sciences at Rice University. His thesis was supported by a NASA grant in remote sensing. He then went to work for Exxon Production Research Company and set up their first image processing and remote sensing function. He then worked for Chevron designing filters and processing seismic data. He was supervisor of a computer-mapping group at Superior Oil. After their merger with Mobil he was Superintendent of Geologic Development for Mobil. He has been a mathematician with the US Government in the Department of the Interior's Minerals Management Service since 1989. In 1999 he started the Company Paradigm Imaging Inc. of which he is President and CEO.

pijob@comcast.net