# A Fully Automated Sea Boundary Delineator

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## ABSTRACT

Although the problem addressed in this paper may arise on land, it is typically found in a maritime context, when one is trying to determine the limits of the Territorial Sea, Extended Zone and Economic Exclusion Zone, as well as the so-called Median and Equidistant Lines. To delineate on a map the boundaries of those zones, that is, to trace a line that lies at a constant distance from another line or set of lines, is a problem that in pre-computer times was solved with a ruler, a compass, a calculator, and perhaps a procedure for computing the intersections of lines on the ellipsoid. As with most geometric applications, this process changed with the arrival of the computer. Since then the technical literature has recorded experiences with partially automated solutions that parallel the manual method. As with their manual predecessors, computer applications can be characterized by their point-to-point mode as well as for the interactive selection and sorting of the resulting intersections. Some of those solutions, herewith designated as PTP (Point-To-Point) for the sake of brevity, have been turned into commercial offerings while others are strictly in-house products. Using a variety of PTP solutions, government agencies have argued cases of boundary conflicts between sovereign states or between internal jurisdictions of a country. This paper offers another solution to the delineation problem, with the key distinction of being a fully automated procedure. Furthermore, because the entire input line contributes simultaneously to the solution, the proposed solution is more of a global solution as opposed to a point-to-point. Its main component is waterlining, a device used in the past to denote water in maps. A second major component, a Medial-Axis Transformation, must be used in the delineation of the Median and Equidistant Lines. The advantages of full automation are discussed vis-à-vis the interactive mode of the currently used PTP solutions. Lastly, remarks are made with regard to the principle of Straight Baselines, its raison d'être, and its superfluousness should a global method of delineation be available.

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## 1 WATERLINING

The delineator reported in of this paper is a special application of a computer procedure for tracing lines at a constant distance from other lines. The delineator is essentially a computer procedure for *waterlining*, unless a Medial-Axis Transformation (MAT), described later, is invoked.

In Neumann (1997) waterlines are defined as *lines representing water, drawn parallel with the edge of a water feature, which decrease in proximity and strength away from this edge*. From the middle 18th Century until the beginning of the 20th Western cartographers used that device to mark out bodies of water (Figure 1). However, the craft has not been completely abandoned: the Bundesamt für Landestopographie, Wabern, Switzerland, still applies it with its usual flair to the rivers of its 1:25,000 series. Other than that, waterlining is occasionally found in books and magazines to render maps with an antiqued appearance (NGS, 1994). More on waterlining can be found in Christensen (1999).


Figure 1. Part of Sheet 42, Ordnance Survey of Ireland, One Inch Map Series, July 1868. Enlarged 200%

With the author's software (Waterlining and Medial-Axis Transformation, WL&MT for short) waterlines can be generated with a variety of options. The most important in the context of this paper is that of positioning the waterlines either on a projection plane or on a given ellipsoid. In the first case the distances are measured along straight lines; in the second along arcs of geodesics. The first option is acceptable provided that the distance to be spanned with the waterlines is small and that a right and proper cartographic projection is used. The software generates the waterlines intervals according to the selected options, either in plane or in spherical units. Similarly, the direct results of WL&MT are files with either plane or spherical coordinates. Measured against a typical surveying or cartographic task, such as a transformation between datums, the cost of running WL&MT is very high, and much more so if the determination is done on the ellipsoid.

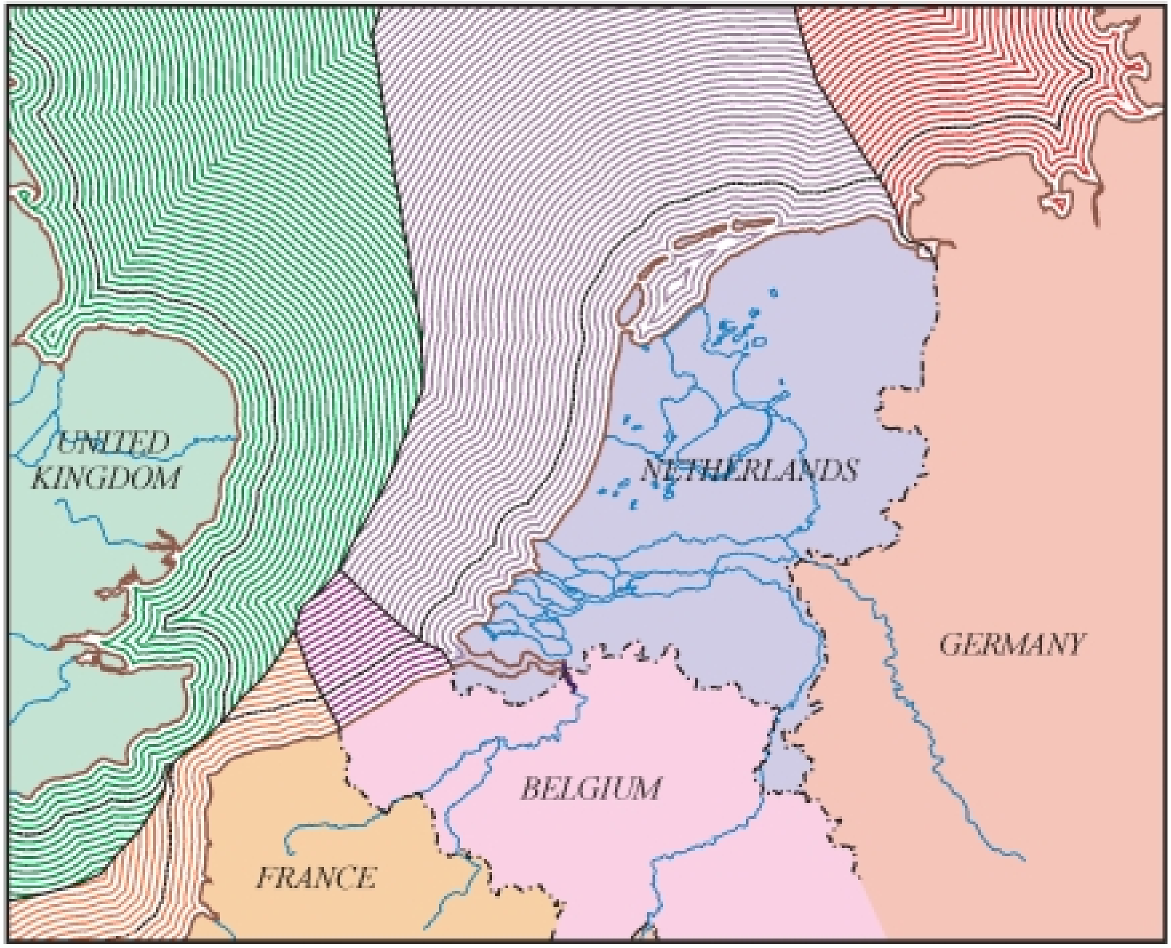


Figure 2. Extended Zone, Median and Equidistant lines in the Straits of Dover and in the North Sea. Shorelines and land boundaries from Data Bank II.

## 2 DETERMINATION OF A SEAWARD BOUNDARY BY WATERLINING

However onerous, the determination of seaward boundaries by WL&MT is extremely simple. Given a line $\boldsymbol{S}$, consisting of a shoreline and associated islands; any land boundaries that reach $\boldsymbol{S}$, and the distance $\boldsymbol{D}$ at which the boundary must be determined, the software creates waterlines $W_i$ at intervals $d_i$ until:

$$\boldsymbol{A} = \sum_{i=1}^{i=N} d_i \geq \boldsymbol{D} \qquad [1] \text{ and}$$

$$\boldsymbol{A} - \boldsymbol{D} < d_i \qquad [2]$$

where

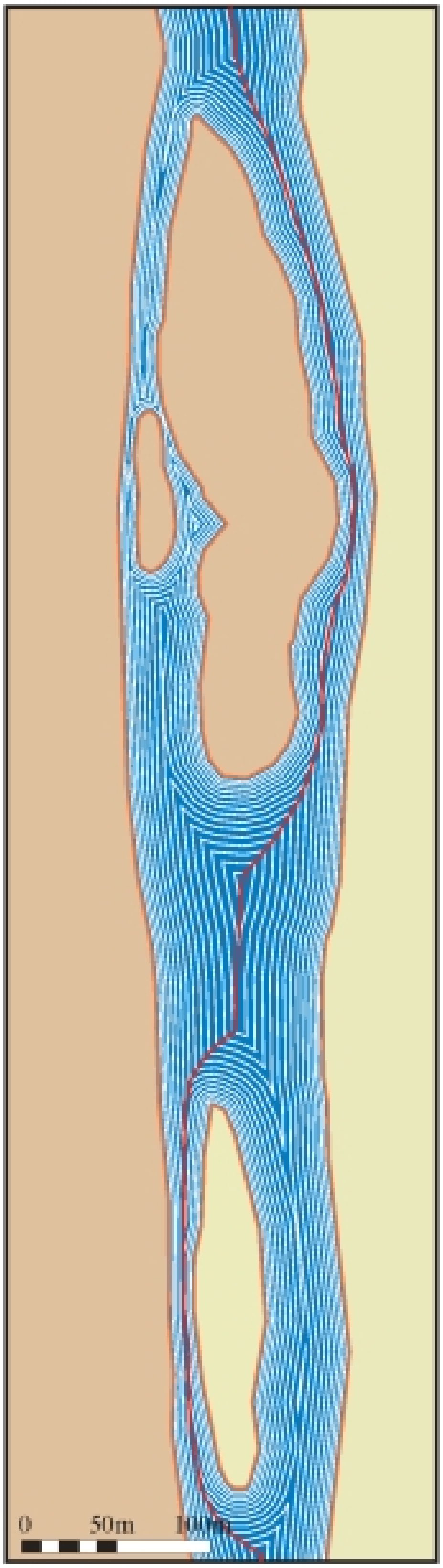

Figure 3. International river Boundary

$d_i$ = the distance between waterline $W_i$ and $W_{i-1}$, with the shoreline considered as waterline $W_0$,

N is the number of waterlines created that verifies [1] and [2].

Once $W_N$ has been determined, it is erased (even if $\boldsymbol{A} = \boldsymbol{D}$) and a new waterline $W_N$ is traced at a distance $d_i' = d_i - (\boldsymbol{A} - \boldsymbol{D})$. The requested boundary is waterline $W_N$ . It is clear then that in the case of seaward boundaries only the waterlining module of WL&MT is used. This description applies to both the planar case and the ellipsoidal case, although in the second case the computations of distances and positions are more complicated (Christensen, 1998b). The author has developed two different methods to work on the ellipsoid, but has not settled on which is superior. To reach that conclusion a larger and more powerful computer than the one currently available to the author will be needed. If the objective is to determine Median Lines and/or Equidistant Lines, see Maling (1989), pp. 531-533, ownership codes must accompany the shorelines. More on this later. In addition, it is necessary to compile a specifications file that contains, inter alia, the mode of operation (ellipsoidal or plane), starting interval $d_1$ (distance between the shoreline and the first waterline), the type of variation to apply in the determination of the subsequent intervals $d_i$ and the maximum distance $\boldsymbol{D}$.

In the toolbox of a modern Geographic Information System there is one command, buffering, whose product is very much like waterlines on the plane. In fact, provided the buffering function can deal with any complex configuration of shoreline and islands, a plane area can be waterlined by the repeated executions of the buffer function, that use as input the result of the previous execution. The author is not aware of any GIS that allow buffering on the ellipsoid.

The repetition of operations, essential to waterlining, is necessary because the geometric operations can create the next line in sequence only if the interval

$d_i$ (or buffer distance if buffering is used) is of the order of the irregularities in the previous line. As with each repetition the waterlines became less irregular, something the reader can verify in any old map and in the figures of this paper, it is then possible to increase $d_i$ in a measure proportional to the number of intervals *i* already determined.

On a plane operation WL&MT traces a single line at a given distance from another with an error ε that depends on the errors of the real arithmetic of the system and the diameter of the line's minimax box. The final error on the boundary depends on the type of the requested boundary. If it is a seaward boundary, the error is proportional to the expression $\varepsilon \sqrt{N_{\max}}$, which usually amounts to less than the least significant digit in the input data set. The final error in the case of a Median or Equidistant Line is discussed in the next section.

As noted earlier, two methods have been developed for the ellipsoidal mode of WL&MT. Each method has its own source of errors, but the primary cause of the errors is the same: the dropping of high order terms in ellipsoidal formulas, a limitation imposed by the weak performance of the computer the author is using. The errors in the first method have been reported in Christensen (1998b). To date, those of the second method have been examined only superficially.

## 3 DETERMINATION OF THE MEDIAN AND EQUIDISTANT LINES BY MEANS OF ATTRIBUTE-LOADED WATERLINES

As mentioned in the previous section, the waterlining module of WL&MT is all that is required to delineate any of the seaward boundaries. However, the Medial-Axis module as well as a special postprocessor are required to materialize the boundaries designated by Langeraar (1984), cited by Maling (1989, pp. 531-533) as Median Line (the line that runs at equal distances between two opposite coasts) and Equidistant Line (the extension into the sea of a land boundary that reaches the shoreline). The distinction between those lines is germane to the manual and semi-automated approaches. The distinction, however, is lost for WL&MT and its postprocessor, as the reader will verify in the next paragraph.

In order to automatically derive a Median or Equidistant line, the input shorelines must carry ownership codes, one for each of the states sharing the shoreline. For the case of Figure 2, five different codes were required. WL&MT reads in the codes as non-graphic attributes of the shorelines and passes them from one waterline to the next. At this point is necessary to introduce the concept of *breaks*, which are the vertices of shorelines and waterlines on the divide of the ownership codes. Once the whole area enclosed by the shorelines and the map frame has been waterlined, the Medial-Axis Transformation (MAT) is invoked. The result is a set of lines (arcs) diversely known as medial-axis, centerline and skeleton (Blum, 1973). By logical inferences, MAT traces the arcs of the medial-axis along certain vertices of the waterlines. As only some of those arcs define the boundary in question, upon completion of the MAT, the postprocessor is invoked, to compile the boundary with those arcs that run along the breaks. See Figures 2 to 5. The postprocessor also capture the arcs that join the medial-axis with the breaks in the shoreline and with the seaward boundary if there were one. The postprocessor is able to perform this operation regardless of the relative positions of the states, whether side-to-side (Equidistant Line) or opposite across a river (Figure 3) or an arm of the sea (Median Line). Both cases are treated the same way (Figure 4, from Christensen, 1998b). Additionally and for the purpose of illustration, the waterlines themselves can be colored according to the ownerships codes, as shown in the figures that accompany this article.

The conclusion of the above previous description is that every vertex P of a Median or Equidistant Line coincides with a break in a waterline $W_i$. In Figure 5 it is possible to see that the error of the boundary at point P is equal to no more than half the interval $d_i$ used to generate $W_i$. As this error can be predicted, it can be reduced by a power of two by running the waterlining module in a self-calibrating mode, an option whose effect can also be seen in Figure 5 right.

With respect to the figures that illustrate this paper, it must be noted that their sets of waterlines have been thinned. Otherwise they could not have been plotted in a distinctly manner. Thinning was particularly severe in the case of Figure 4, which resulted from an ellipsoidal computation. The density of waterlines actually required to obtain the results with the errors reported in Christensen, (1998b) was ten times greater that the illustrated.

## 4 THE IMPLEMENTATION

The author planned developing WL&MT in 1993, with a number of applications in mind, which at the time did not include the maritime boundary delineation problem. That discovery came later, as a consequence of a discussion by James J. Wolfe on the Mississippi Boundary Case (Wolfe, 1983). For a review of the applications so far found for WL&MT, see Christensen, (1999).

WL&MT, together with the small additions needed to run the boundary delineator, runs under the AIX operative system in a 10-years old RS6000 machine. The software, written in three different languages, FORTRAN, C, and xEagle, consists of more than 50,000 lines. As boundary delimitations are not an everyday task, processing times are not of paramount concern. Nevertheless, the following figures may give the reader an idea of the cost in computer resources incurred during a boundary determination. Most of the time spent on any of the boundary delineation cases is due to the waterlining step, which is proportional to the square of the product of the number of waterlines and the average number of vertices in a waterline. The other two steps, MAT and the postprocessor, run on times linear with the number of waterlines and arcs in the medial-axis. With a modern RISK machine, such as the current entry model of the IBM RS6000 series, the planar computation of the boundary of the Exclusive Economic Zone would take approximately 20 minutes for a shoreline with 2000 vertices.

The quoted elapsed times may seem excessive when compared with those required to run Point-To-Point (PTP) procedures, to be described next, or those of simple geodetic algorithms. However, one must also include the expense of the skilled operator required during the interactive steps of a PTP solution. Anyway, as noted before, time is a relatively unimportant consideration in this kind of problem.

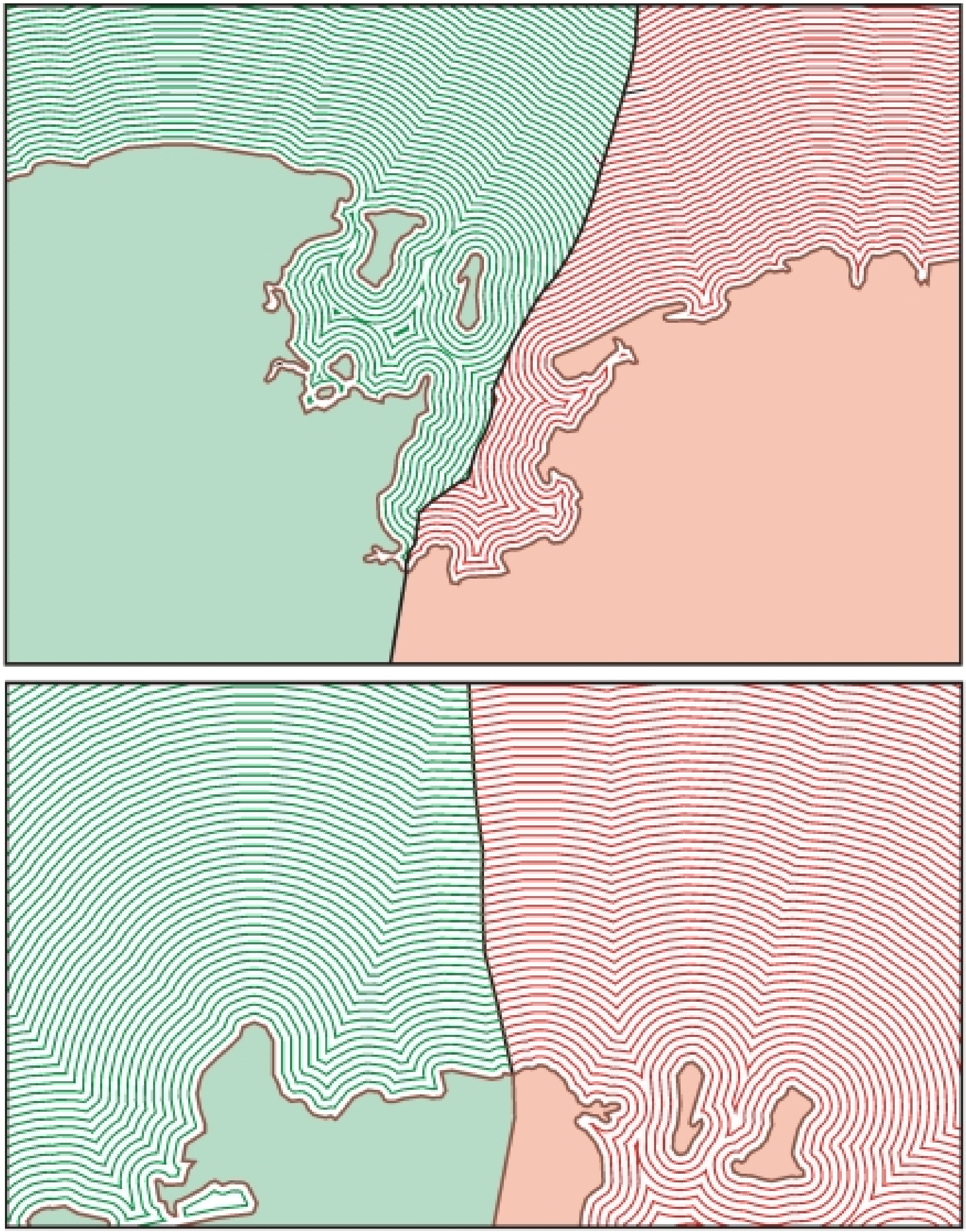

Figure 4. The Median Line Case (Top) and Equidistant Line Case (Bottom)

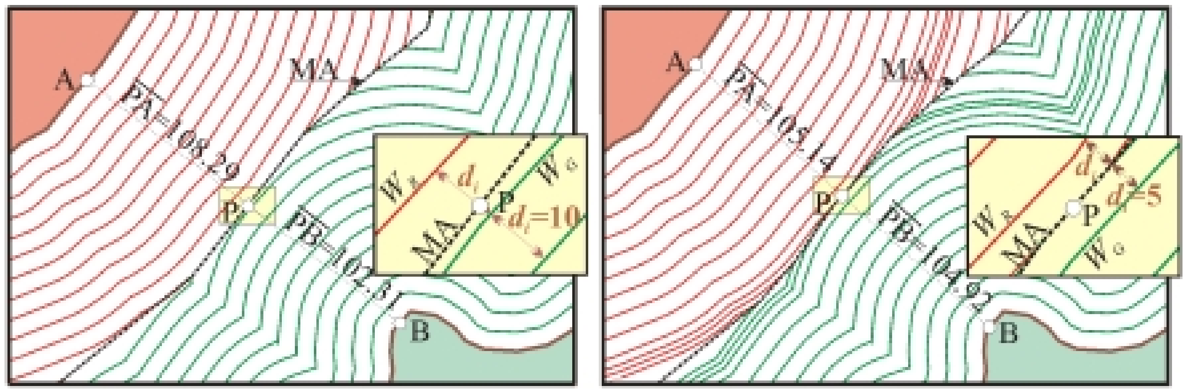

Figure 5. Verification of Medial-Axis position in the uniform (left) and self-callibration modes (right)

## 5 THE POINT-TO-POINT SOLUTIONS

PTP methods are an alternative way to generate boundary delimitations. They are essentially geodetic calculators, their main and only function being the computation of intersections between geodesics; see for instance Carrera (1987). A PTP execution starts with the manual selection of the shoreline vertices considered strictly necessary for the boundary determination. A selection, by the way, which is tantamount to a one-sided declaration of mini-Straight Baselines. The computer process that follows may be organized in one or more steps. In either case, each step yields a number of intersections between geodesics, of which only a fraction may lay along the boundary in question. A qualified operator has to decide which of these intersections can be safely dropped. Because the decision is made strictly by visual inspection and the intersections can number anywhere from a few to a great number, a good graphic display and well-designed interactive commands are of paramount importance to PTP approaches.

If one examines the list of software in Appendix 2 of IHB (1990), it is clear from the descriptions given (section 9, 168-172) that most of the items listed, if they are not simply descriptions of a geodetic algorithm, are of the PTP kind.

## 6 AN APPRAISAL OF THE BOUNDARY DELINEATOR AND THE USE OF STRAIGHT BASELINES

In contrast with PTP approaches, WL&MT can be characterized as fully automated and global. Additionally, one can consider it a gradual approach. Here g*radual* expresses what is evident in this paper's figures: that the boundary is determined in successive steps, each of them producing a closer approximation to the boundary than the previous one. *Fully automated* needs no explanation. *Global* refers to the fact that all the shoreline points are used in the computation. In other words, that WL&MT maintains data integrity.

Unlike gradualism, which is in the nature of waterlining, full automation and data integrity are not strictly necessary characteristics, as demonstrated by PTP solutions. It is clear, however, that full automation and data integrity are highly beneficial attributes. Automation means independence of operator decisions, and together with data integrity make WL&MT immune against claims of arbitrariness as well as unconcerned with captious argumentations. Once the shoreline and land boundaries are accepted by all parties involved, -- through a process that is outside the context of this paper-- there is no room left for captious arguments. While there is likely to be little opposition to the notion of striving for full automation, there may be differences of opinion on the question of data integrity. Why to use all shoreline points if only a well selected few would suffice?

Of course, if the parties in the boundary dispute all agree that, for instance, the outline of a bay is absolutely and undoubtedly superfluous for a boundary delineation, the bay could be closed with a straight baseline before running a PTP or WL&MT (with the only benefit for WL&MT being quicker results). However, as noted before, the replacing of an accident with a straight line is not always accepted, even if conducted according to the codification of the Principle of Straight Baselines.

The Principle of Straight Baselines has many critics because of the difficulties of establishing cause of the difficulties in the way of a comprehensive codification. Geographers and International Law experts have tried to include all possible cases of well-grounded straight baselines in the LOS Convention and associated documents. But Geography, although a queen, is not an exact science. It is very difficult if not impossible for geographers and other experts to anticipate all coast configurations and, consequently, to formulate their instructions in a clear and definitive way. In this predicament geodecists and geometricians can do nothing, except perhaps to avoid introducing more ambiguities into the problem.

Faced with the potential problems created by the application of the principle of Straight Baselines, one is tempted to ask, why this principle is still being advocated? In 1951, when the Anglo-Norwegian case was being argued, accepting that principle could have been a prerequisite, as at that time no one could afford to compute a sea boundary without simplifying the shorelines. Much has changed in the last 50 years. With very fast computers and a set of GIS-like functions it is now possible, as WL&MT demonstrates, to avoid the use of straight baselines and to obtain well structured and precise sea boundaries by means of a highly demonstrative process.

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