UNCERTAINTY ISSUES IN THE GEODETIC DELIMITATION OF MARITIME BOUNDARIES

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1. ABSTRACT

Uncertainties associated with the determination of maritime boundaries can be categorised under the three headings according to their cause, namely:

- the accuracy and precision of the baseline mapping;
- the exactness to which the algorithm adopted embodies the principles for the delimitation of maritime boundaries (as set out in the Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf (CLCS)); and
- the effect of the baseline geometry in propagating baseline precision into the strings of coordinates computed to delimit the boundaries.

Each of these factors is discussed in relation to the processes developed for the establishment of maritime boundaries in the Australian context. The discussion shows that the most significant source of inaccuracies in delineating boundaries is likely to be the precision to which the baselines were mapped.

While the development of a computer algorithm that faithfully embodies the principles set out by UNCLOS Article 4 is necessarily complex, the paper presents some alternatives to traditional procedures which the authors believe to provide the basis for more robust processes.

Finally, examples are given, based on boundaries established for the Australian Maritime Boundaries Information System (AMBIS), in which the precision of the computed coordinates is represented by the axes of error ellipses. The examples are chosen to illustrate the contribution made by the precision of the baseline coordinates and that of the varying geometrical relationship between baseline and boundary.

2. DEFINITION OF THE NORMAL BASELINE

Article 5 of the United Nations Convention on the Law of the Sea (UNCLOS) defines the normal baseline as being:

> *". . . the low-water line along the coast as marked on large-scale charts officially recognised by the coastal State."*
>
> *(United Nations, 1997)*

The normal baseline includes river closing lines and bay closing lines, as defined under Articles 9 and 10 respectively. The terminals of straight baselines, as provided for under the provisions of Article 7, are generally intended to coincide with points on the normal baseline.

For various reasons, the wording of the definition of the normal baseline included under Article 5 is deliberately vague, due to there being a number of definitions of low-water datum in use by various coastal States. There is also a degree of uncertainty regarding the requirement that the normal baseline be "*…marked on large-scale charts officially recognised by the coastal State*", as a number of coastal States have very little, if any, large-scale charting coverage of their coastlines. Many of these States depend upon medium to small-scale charts produced by other States, in many cases more than a century ago.

It is therefore not surprising that the precision to which a coastal State has mapped its territorial sea baseline, is highly variable. In Australia, the low-water line, or normal baseline, is explicitly defined in national maritime legislation as being the line corresponding with the level of Lowest Astronomical Tide (LAT) along the coastline. However, this legally binding datum definition has been in use for less than twenty years. A large percentage of the existing charting coverage of the Australian coastline, some 37 000 kilometres in length, depicts the low-water line as defined by surveys undertaken well over 100 years ago that were based upon a chart datum definition that differs from the LAT datum currently recommended for usage by the International Hydrographic Organisation (IHO), as legally implemented by Australia.

Delineation of the location of the normal baseline is subject to errors which fall into two categories, namely vertical and horizontal between which there is a high degree of correlation. Fundamentally, the mapping of the low-water line requires the determination of the location of an infinite string of points along the coastline at each of which sea-level is predicted to fall to a level corresponding with a pre-defined low-water datum, such as LAT. While there are several techniques available for defining the horizontal location of the low-water line, each of these is subject to errors associated with the definition of the tidal datum which include:

» The adequacy of the time period used for the acquisition of the tide gauge data and the rigour of the method used in the determination of the tidal constituents necessary for sea-level prediction. Generally speaking, the shorter the time period used for the acquisition of tide gauge data the less accurate will be the derived constituents with the consequence that predicted sea-level heights will also be less accurate.

» The spatial separation between the site at which tide gauge data is acquired and the location or region of the coastline where the tidal constituents derived from the tide gauge data are to be applied. Very generally, the validity of tidal constituents derived for a specific tide gauge location decreases in proportion to increasing spatial separation. This effect will be accentuated in areas where there are large tidal ranges possibly associated with constricted areas of the coastline or where there are large and complex offshore reef systems such as the Great Barrier Reef, or in areas where the tidal species is subject to rapid change, such as from semi-diurnal to diurnal.

The physical nature of the foreshore at any given location along the coastline is a critical factor in locating the normal baseline. A very flat foreshore gradient, for example 0.5% or less, will have a far greater effect on the location of the normal baseline as a result of errors in vertical datum definition than will sections of the coastline characterised by extensive vertically-faced rock platforms. An error of 0.5 metre in vertical datum definition in areas where the foreshore gradient is 0.5% will lead to an error in the location of the normal baseline of 100 metres (m), whereas along sections of coastline characterised by rock platforms the same vertical datum error may result in a positional error of only a metre or two.

Many areas of the northern Australian coastline are characterised by very flat foreshore gradients. In some of these areas the low-water line depicted on current charting coverage has been derived from surveys undertaken well over a century ago when absolute positioning was dependent upon astronomical techniques, which were estimated to be accurate to no better than about 0.5 – 1 nautical mile (M). As modern inshore sounding data was either non-existent or extremely sparse, for normal baseline delineation purposes there was no alternative other than to use the location of the drying line as depicted on old colonial survey fair charts. Drying line locations were transformed to the national geodetic datum by using empirical "rubber-sheeting" techniques which involved the registration of points of coastline detail as shown on the old fair charts with corresponding coastline detail as depicted on modern topographic mapping coverage. The horizontal errors inherent in the application of this technique were estimated to be 100-200 m. However, the drying line depicted on old fair charts was usually related to a low-water datum definition approximating the level of Indian Springs Low Water (ISLW), which differs from the LAT datum now legally in force. For practical reasons, the horizontal displacement of the location of the drying line due to the vertical datum difference, estimated to be up to 1 metre in some regions, was usually ignored due to the difficulty in quantifying this difference.

In some areas of northern Australia, notably along the coastline of Arnhem Land, the complete lack of any inshore sounding data necessitated the normal baseline being defined by either the mean high water coastline or the seaward edge of the foreshore flat symbol (as interpreted from the mapping photography) depicted on the 1:100 000 national topographic mapping series. Detailed hydrographic surveys undertaken more recently by the Australian Hydrographic Service in these areas indicate that the surveyed location of the normal baseline lies up to 3 M seaward of the provisionally chosen location.

Much of the data originally used to define Australia's territorial sea baseline (TSB) was derived from topographic maps, tide-controlled infra-red photography and Australian Hydrographic Service charts compiled during the period 1960-1980. In general the precision of these sources far exceeded that of earlier times. However, the Australian Surveying and Land Information Group (AUSLIG), which has functional responsibility for all issues relating to maritime boundaries, has been engaged in an extensive and ongoing program of TSB validation involving a detailed analysis of the reliability and quality of all existing TSB data.

Recent mapping of the line of LAT, or normal baseline, has been undertaken using a much higher degree of technical sophistication, including the application of the Australian Hydrographic Office's Laser Airborne Depth Sounder (LADS) system in areas too difficult or dangerous for the employment of the more conventional surface sounding techniques. Using harmonic constants derived from long period tide gauge observations now enables the instantaneous relationship between sea level and the level of LAT to be determined much more precisely. For large areas, or in regions where tidal characteristics are known to be complex, this precision can be enhanced through the simultaneous acquisition of data at a number of tide gauge sites.

In summary, the precision of the location of the normal baseline in Australia is highly variable. The horizontal standard deviation of points defining the baseline is estimated to range from a number of kilometres in areas characterised by very flat foreshore gradients but devoid of inshore hydrographic survey data to a metre or two in areas where the foreshore is relatively steep-to and has been the subject of modern hydrographic survey.

3. ALGORITHMS TO DELINEATE ZONE BOUNDARIES

The procedure for delineating the boundary of any maritime zone can be stated simply and concisely. UNCLOS Article 4 states:

> *The outer limit of the territorial sea is the line every point of which is at a distance from the nearest point of the baseline equal to the breadth of the territorial sea.*

This implies that the limit of the territorial sea be defined by arcs centred on critical points on the baseline and offset to the sections of straight baselines. This method has become to be known as the *envelopes of arcs* and referred to in the CLCS Scientific and Technical Guidelines (United Nations, 1999) and originally attributed to Boggs (1930). The method has subsequently been generalised to apply to all zone boundaries generated by distance from a baseline.

> *The application of the method of envelopes of arcs is independent of the actual breadth of the limit. Thus, although the method was originally*

> *designed as a tool to determine the outer limit of the territorial sea, its mathematical application remains equally valid to determine the outer limit of other maritime spaces based on metric criteria.*
>
> *United Nations(1999, p.27)*

While the procedure to be followed can be stated concisely, constructing a computer algorithm of sufficient robustness to apply the process accurately in all possible configurations of baselines is challenging. Experience in the Australian context has shown the complexities in the configurations of baselines to be almost endless. The logic used in construction of the algorithm needs to pay particular attention to the following situations:

» straight baselines interspersed with normal baseline (Murphy et al, 1999);
» sections of deeply indented baseline;
» the intersection of zone boundaries generated from mainland and island baselines; and
» the presence and influence of low-tide elevations (LTE's).

As the government agency with the functional responsibility for Australia's maritime boundaries, AUSLIG has developed the Australian Maritime Boundaries Information System (AMBIS) (Hirst et al, 1999). This system provides a national repository for the storage and management of maritime boundary information of interest to all levels of Australian government, including that relating to international maritime boundary treaty agreements and the meeting of legal obligations under the various provisions of the United Nations Convention on the Law of the Sea (UNCLOS).

During the period 1998-2000, the authors were involved in the development of algorithms and software for maritime boundary delimitation in support of the development of AMBIS (Collier et al, 2001). The experience has shown there are many opportunities for zone boundaries to be inaccurate if, in developing the algorithm, thought has not been given to all likely configurations of the TSB.

From the outset it was evident that the accepted procedure for generating territorial sea boundaries made for difficulties when the TSB was sinuous and/or zone boundaries generated from mainland and island baselines intersected. The view was taken that if a more robust basic algorithm for boundary delimitation could be found, it may go a long way in simplifying the handling of complex baselines.

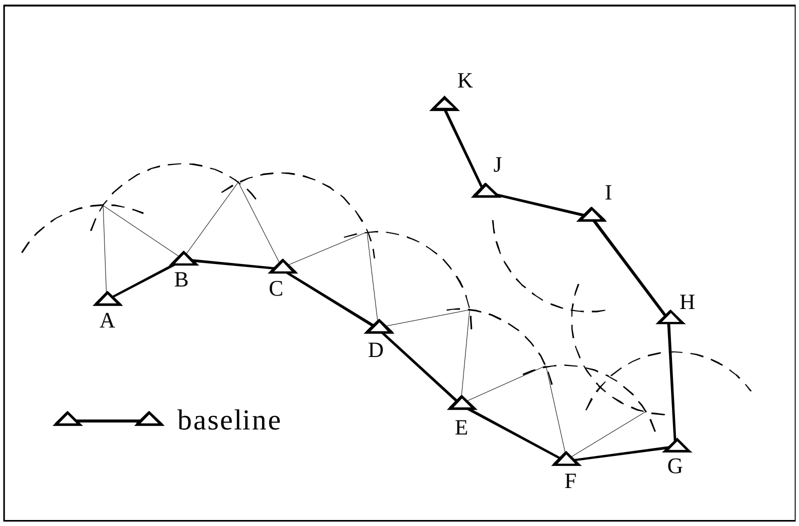


Figure 1

The traditional procedures for delineating maritime boundaries are as illustrated in Figure 1. Circular arcs of radius equal to the breadth of the limit (or zone width) and centred upon the points defining the TSB, are constructed as shown. The outer limit boundary is obvious for the arcs centred upon points A to F over the convex section of the baseline. In the concave section of the baseline (represented by points F, G, H, I) the outer limit boundary is less clear.

Figure 2 shows it is a relatively simple manual task to decide which sections of the arcs should be chosen as the boundary. However, to construct a computer algorithm to replicate what is to humans an intuitive skill is no easy matter. The intersections of the three arcs centred on points F, G and H need to be computed and the nine radial distances from points F, G and H. The intersection chosen is that for which all three distances are equal to the zone width. The fact that the radii of the arcs and distances are those of geodesics on a reference ellipsoid adds to the computational load and complexity.

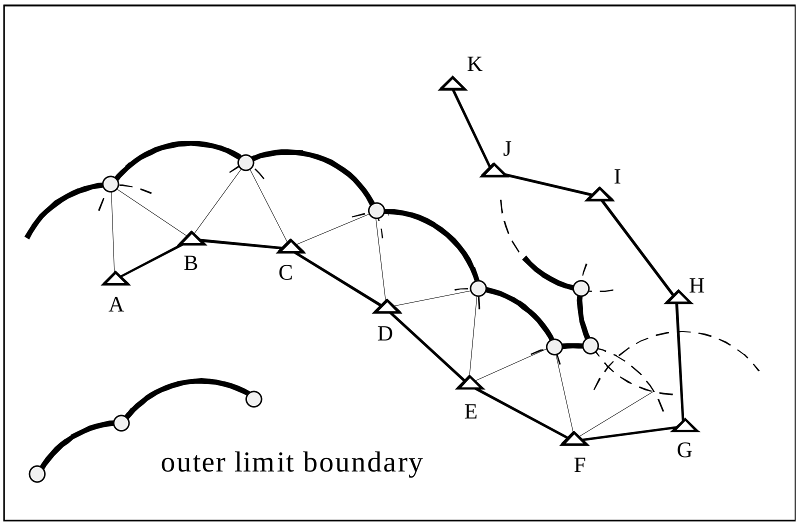


Figure 2

A further complexity that needs to be handled by the algorithm occurs when at some later stage the baseline turns back on itself to such an extent that the boundary intersects with itself. This is shown in Figure 3. Thus, in order to retain accuracy in the delineation of the boundary, the algorithm needs to include inbuilt checks that the most recently established section does not intersect with any earlier sections.

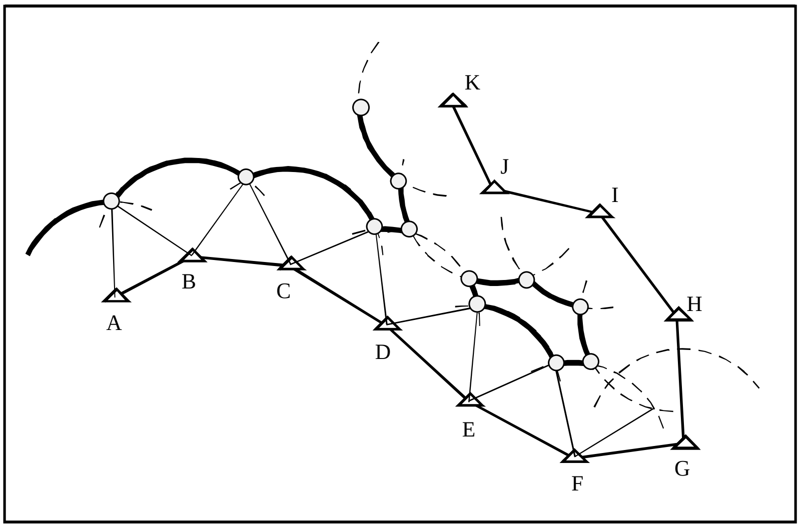
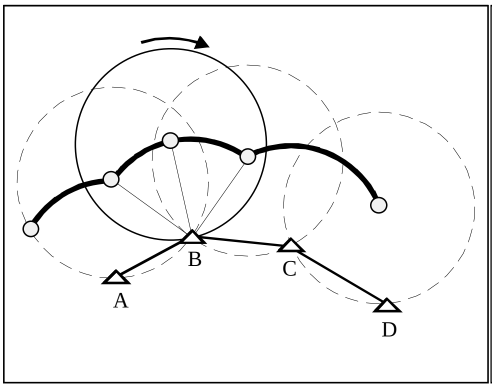


Figure 3

An alternative algorithm to that based on swinging arcs and determining intersections was adopted by the authors. In essence, the algorithm is based upon the construction of a circle of radius equal to the zone width which is then "rolled" along the baseline. Examples are shown in Figures 4a and 4b



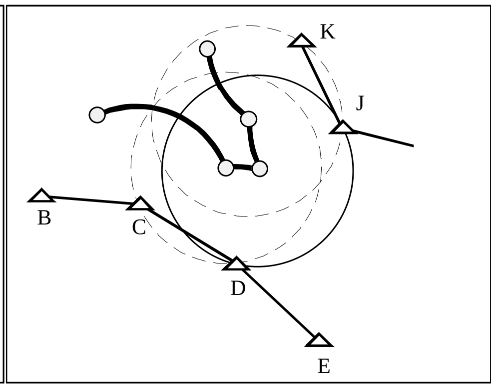


Figure 4a **Figure 4b**

In Figure 4a, the circle is initially located with its perimeter on point A and then pivots around until it meets point B. The locus of its centre delineates the first section of the boundary. The circle is then pivoted on point B until it meets C (an intermediate stage of this movement is illustrated by the circle drawn in a solid line). The process is continued with the circle pivoting on C and rotating to meet and rest on point D.

A critical advantage of the algorithm is illustrated in the movement of the circle when it is pivoting on point D. As shown in Figure 4b, the next point the circle rests on is J (rather than E). The circle then continues its movement along the sequence to K. Thus the algorithm immediately creates the final shape of the zone boundary for this section. When the baseline contains small indentations, the algorithm automatically identifies the critical points and does not visit the non-critical points. It also avoids the need to compute the intersections of arcs as is part of the traditional algorithm. More importantly, it avoids the requirement to continually check if the latest section of boundary intersects with earlier sections. The algorithm must however, be re-started on point E to ensure the boundary based on points E, F, G, H and I (in Figure 3) is computed.

One of the most challenging aspects of an algorithm for delineating zone boundaries involves the integration of mainland and island boundaries. Figure 5 shows a typical case. Here it is assumed that the zone boundary based on mainland baseline points 1 to 7 has been completed. The circle is then rolled around points 10 to 15 of the island baseline to generate the associated zone boundary - the “resting” positions of the circle are shown. The mainland and island zone boundaries intersect and these intersections need to be computed so that the two boundaries can be integrated.

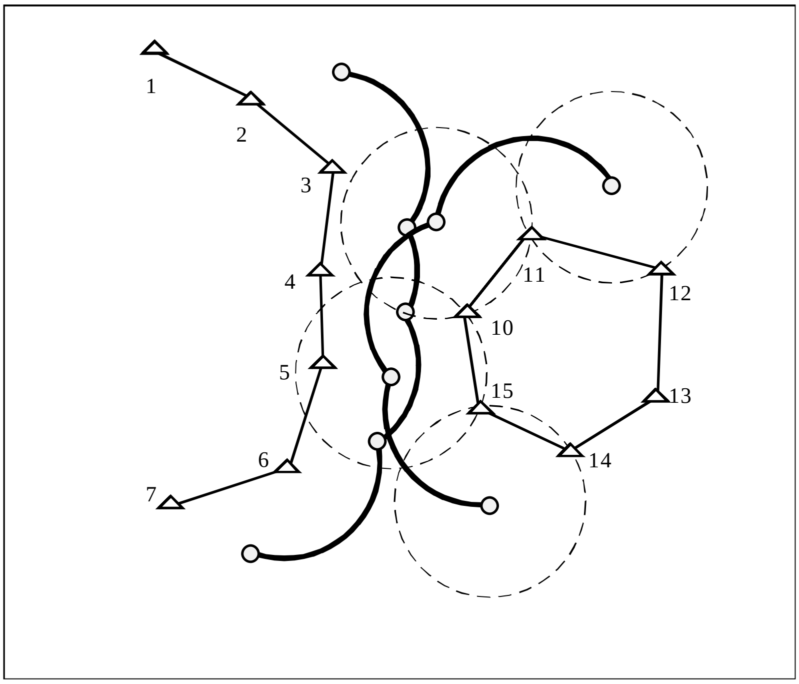


Figure 5

An alternative to this approach is to initially detect those islands that are in such proximity to the mainland that their zone boundaries will intersect. Thus, in the algorithm adopted, a pre-calculation is done to identify the shortest distance between mainland and island. This is the distance between points 4 and 10 in Figure 5.

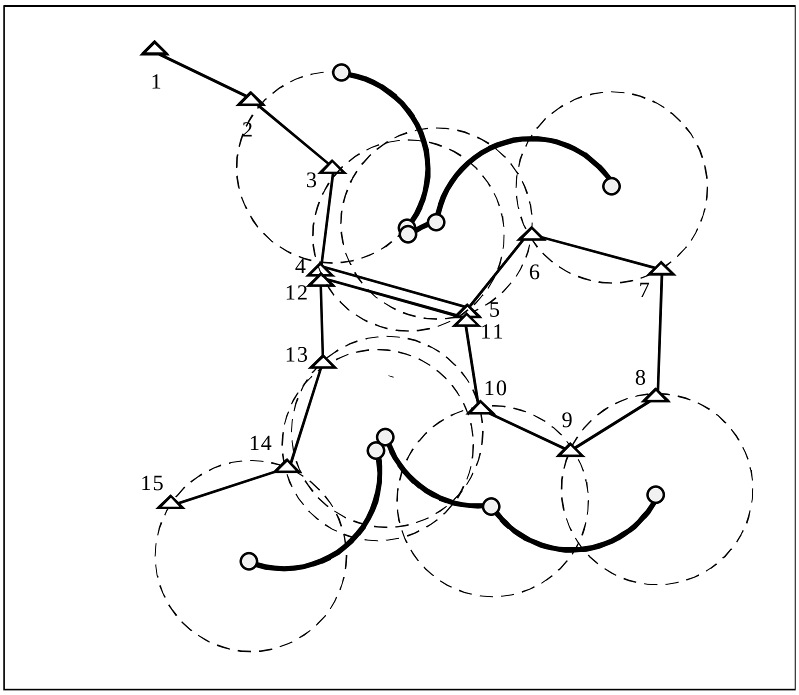


Figure 6

If the shortest distance is less than twice the zone width, the zone boundaries will intersect. The need to detect intersections can be avoided if the baselines are combined as shown in Figure 6. That is, it is considered that a land connection exists between points 4 and 10 and the two baselines are combined to reflect this. This is done by duplicating the baseline points at the original positions of 4 and 10 and then renumbering the points as shown in Figure 6. (Point 12 has the same coordinates as 4, point 11 has the same coordinates as 5).

The examples shown have been chosen to demonstrate some fundamental aspects of the algorithm and are of necessity, simple. Much more development is needed to cope with circumstances where there are multiple islands with intersecting zone boundaries – a situation further complicated if low-tide elevations are also to be considered. However, while these algorithms are basic, they proved to be computationally efficient and have a simplicity which engenders confidence that complex baselines can be handled accurately.

4. THE PRECISION OF COORDINATES DEFINING THE OUTER LIMITS

The line delineating the outer limit of a zone is made up of a series of points joined by arcs with radius equal to the breadth of the zone - referred to here as the "zone width". An example can be seen in Figure 1. The points on the boundary are located by "linear intersection" from a baseline that runs between two adjacent critical points on the baseline. Figure 7 shows a typical configuration.

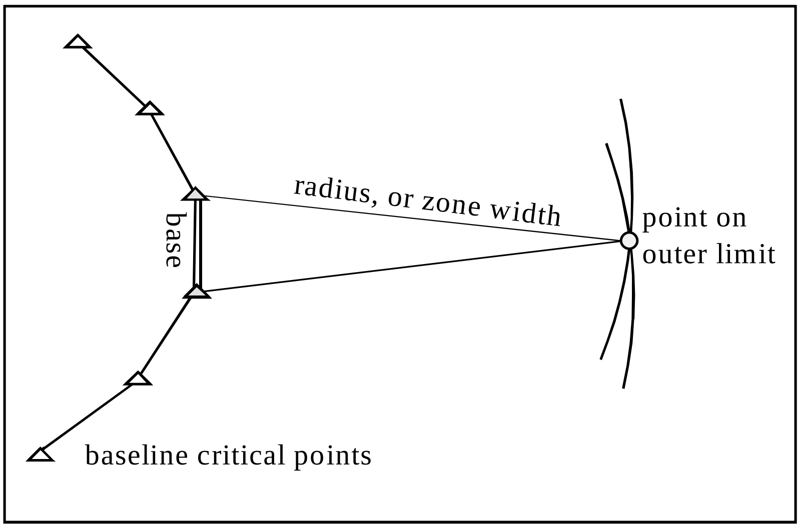


Figure 7

The precision to which the intersection points are determined can be estimated by solving for the intersection by the standard least squares technique used in geodetic network adjustment. The precision will be given in terms of the standard deviations of the coordinates (in metres in latitude and longitude) of the intersections. The three factors governing the precision of the location of the intersections are:

- the standard deviations of the coordinates of the critical points forming the baseline;
- the precision to which the intersecting radii are calculated; and
- the geometry of the intersection as represented by the angle between the intersecting radii.

As discussed in Section 2, the precision of location of the baseline points can vary widely and an accurate knowledge of the standard deviation of the coordinates will, in many cases, be difficult to obtain. If the Australian experience is any guide, some of the mapping of what has been taken to be the "low-water line" was completed over 100 years ago. In the best circumstance, the standard deviations in this case are likely to be of the order of 100-200 m. As mentioned earlier, where very flat foreshore gradients exist, the standard deviations will be much greater and possibly in the order of 1000-2000 m.

At the other end of the spectrum, where modern hydrographic surveying techniques have been used and coastlines characterised by vertically-faced rock platforms, it would be expected that standard deviations would be as low as 1 m.

In the sections which follow, it is shown that the precision to which the baseline is measured is the dominant factor in determining the precision to which the line of the outer limit can be computed.

The second factor that influences the precision of establishing the outer limit is that to which the intersecting radii are computed. This is not totally straightforward as the intersecting radii are geodesics on the surface of the reference ellipsoid. The computation is necessarily iterative and normally the configuration is badly conditioned. To retain rigour, the computation needs to be done in "high precision" and with a significant number of iterations to allow the computation to converge. If these factors are taken into account, the coordinates of the intersections can be computed to within less than a millimetre of the theoretical values. When compared to the likely magnitude of the standard deviations of the coordinates of the baseline points, any inaccuracies introduced in computing the intersection of radii will be insignificant.

The third factor that influences the precision to which the outer limit can be located is that of geometrical configuration. In comparison to traditional geodetic figures, this particular configuration is badly conditioned as it consists of an intersection of large radii from a very short base and there are no redundant measurements - see Figure 7. This will, however, allow location in the direction at right angles to the baseline to better than the standard deviation of the baseline points. In the direction of the baseline however the standard deviations will be of far greater magnitude.

The determining factor of this aspect of the precision of location of points defining the outer limit will be the ratio of the length of the base to that of the radii - the later being the zone width or breadth of the outer limit. A section of baseline along the Australian coast has been selected to illustrate typical base/radius configurations.

A section of normal baseline 203 km in length is defined by 8791 points which have been mapped with an average separation of 23 m. The outer limits of four zone widths generated from this section of baseline have been computed. Table 1 gives a summary of the number of critical points identified, the average length of the separation between critical points and the ratio of base length to radius. (The separation between critical points becomes the base from which radii are swung to intersect on the line of the outer limit.)

Zone width (M)	Number of critical points	Average length of base (metres)	Ratio base:radius
3	337	600	1:9
12	97	2100	1:11
200	45	4500	1:82
350	44	4600	1:140

Table 1

To illustrate the effect the “base to radius ratio” has on the precision of the outer limit coordinates, a number of computations were done to establish a point on the outer limit of the 12 M territorial sea. While the baseline points were mapped with an average separation of 23 m, the average separation of critical points (length of base) is 2100m. To cover the entire likely base to radius ratios met in practice, three computations were done with base lengths of 100 m, 2000 m and 4000 m. For the 12 M outer limit, these correspond to base:radius ratios of 1:222, 1:11 and 1:5.5 respectively.

For illustrative purposes, the standard deviation of the coordinates of the points defining the base was taken as 100 m. As mentioned earlier, these values are likely to be very different in practice. However, whatever the standard deviation of the baseline points, those for the points on the outer limit can be estimated by applying the scale of the actual values to the results shown here. The results are summarised in Table 2. For all practical purposes, the two standard deviations shown for each example are the semi-major and semi-minor axes of the standard error ellipse.

			Standard Deviations	
Radius (zone width)	Base length (separation of critical points)	Base/radius ratio	Orthogonal to base	Parallel to base
12 M ~ 22.2 km	100m	1:222	70.1m	999.5m
12 M ~ 22.2 km	2000 km	1:11	70.1m	842.4m
12 M ~ 22.2 km	4000 km	1:5.5	70.3m	616.7m

Table 2

The critical standard deviation is that for the location of the point on the outer limit in the direction orthogonal to the baseline. It can be seen this does not vary significantly with the range of variation in base to radius ratio likely to be found in practice. At first sight, the standard deviation of the location in the direction of the baseline seems to be of concern. This would be so in most geodetic positioning as similar precision is expected in all directions. In this case however, it is the distance to the baseline that is of interest.

Thus, of the three factors identified as contributing to the precision of the location of the outer limit (precision of baseline, accuracy of computation, effect of base to zone width), only the precision to which the baseline points are known is of consequence.

5. CONCLUSION

The paper proposes that the factors governing the accuracy to which maritime zone boundaries are delineated are those of the precision to which the normal baseline has been mapped, the robustness and completeness of the computer algorithm employed and the geometrical configuration used to solve for coordinates of points on the zone boundary. Experience has shown that the complexities of baselines are such that the development of algorithms that can handle accurately all cases needs to be done with great care. Two fundamental algorithms that differ from traditional practice are outlined. In the authors' experience these simplify the basic procedures and add considerable robustness to the total process.

Examples are given of the estimation of the precision of zone boundary coordinates following their establishment by algorithms based on those used for geodetic network adjustment. In this it is shown that the precision of coordinates defining the zone boundaries are almost totally determined by that of the baseline coordinates. The variation in geometrical configuration seen in the Australian context is not a significant factor.

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