POSITIONING MARITIME BOUNDARIES WITH CERTAINTY – A RIGOROUS APPROACH

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ABSTRACT

The United Nations Convention on the Law of the Sea (UNCLOS) outlines the provisions under which a Coastal State may establish the outer limits of its Territorial Sea, Contiguous Zone and Exclusive Economic Zone. Although there are other factors, the precision to which the outer limits may be computed is largely dependent on the precision of the points forming the Territorial Sea Baseline (TSB), the precision of the intersecting distances from the TSB, and the geometry of TSB points used in the intersection computation. Whilst the quality of the intersection points may be easily determined given the precision of points on the TSB, unless a user navigating at sea has access to information about the quality of these points, an element of uncertainty will continue to prevail in the real time positioning of maritime zone boundaries.

In recent years, rigorous geodetic methodologies for handling uncertainty in the delimitation of maritime boundaries have been proposed (Leahy et al. 2001; Horemuž, et al. 1999; Vaniček 1999; Sjöberg 1996). However, little work has been done to resolve uncertainty in the context of positioning boundaries in real time. This paper describes a rigorous method for providing a measure of uncertainty in the positioning of maritime boundaries. In principle, this method combines the precision of the user's position with the spatial behaviour of uncertainty in the points making up a maritime boundary to provide a complete measure of positioning uncertainty. The paper concludes with a discussion of how this approach can be used to provide confidence and certainty in the positioning of stakeholders' interests, and in the mutual use of marine spaces.

1 INTRODUCTION

Unlike most cadastral boundaries on land, the position of maritime boundaries cannot be determined by a hierarchy of evidence of intention, or by physical monuments. Rather, maritime boundaries exist as virtual objects without visible or tangible demarcation. Accordingly, the location of maritime boundaries must be realised through the use of navigation and positioning instruments, such as the Global Positioning System (GPS).

Whilst GPS serves as an efficient and reliable means for positioning and navigation, the application of GPS to realise a maritime boundary is not without uncertainty. In the first instance, a measure of positional uncertainty arises as a result of the GPS receiver's ability, or inability, to accurately determine the boundary's true position. Classically, it is the error associated with the GPS measurements that separates the observed value from the truth. The nearness of the GPS position to the boundary's true location is a measure of accuracy. A lesser accuracy results in a greater positional uncertainty.

In the second instance, the positional uncertainty is further amplified by the errors associated with the delimitation of the maritime boundary. Except for maritime boundaries which are defined by explicit spatial positions on the ellipsoid, the horizontal accuracy of a maritime boundary is subject to measurement errors in the normal baseline points from which the boundary was computed. As such, the realisation of the boundary's true position becomes uncertain. The total degree of uncertainty is proportional to the boundary's spatial accuracy *and* the accuracy obtained from the GPS derived position.

This paper presents an overview of the sources of uncertainty and the geodetic methodology for managing positioning error. These methods provide a practical approach for determining the level of uncertainty upon the definition and positioning of maritime boundaries.

2 UNDERSTANDING BOUNDARY POSITIONING UNCERTAINTY

Classically, an uncertainty principle prevails in maritime boundary positioning, and deals with our lack of knowledge of the error in a given position. To simply visualise the uncertainty in a maritime boundary, prior knowledge of the error contained within the boundary points is required. Determining the uncertainty upon realising a boundary further requires a measure of the positioning tool's ability to accurately locate the user on or near the boundary. Overcoming the effect of uncertainty in real time therefore requires knowledge of (1) the errors in the maritime boundary delimitation process and (2) those that affect the precise positioning of GPS receivers.

2.1 Maritime Boundary Delimitation Errors

Except for those boundaries which have an explicit spatial definition, the delimitation of maritime boundaries is subject to uncertainty. The fundamental causes of uncertainty in the delimitation of maritime boundaries are a function of the accuracy of mapping the normal baseline, the exactness to which the delimitation algorithm embodies the legally adopted principles and the geometry of the points defining the normal baseline (Leahy et al., 2001). The most significant source of inaccuracy is likely to be the precision to which the normal baseline was mapped (Leahy et al., 2001). Experience teaches that these inaccuracies are the result of error in the measurement of the normal baseline points.

As defined under Article 5 of UNCLOS (United Nations, 1997), the normal baseline is:

> *"…the low-water line along the coast as marked on large-scale charts officially recognised by the coastal State…"*

In Australia, the normal baseline is legally defined within National maritime legislation as the line formed along the foreshore at the tidal datum of Lowest Astronomical Tide (LAT). LAT is the lowest level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions.

However, locating Australia's coastline (the low-water line as shown on current Australian charts) is not a simple task and has historically been based on different methods of survey and legal principles. Leahy et al. (2001) note that a large percentage of the Australian coastline was defined well over 100 years ago using a tidal plane that differs to the legally adopted LAT. Hence, depending on the gradient of the foreshore and the selection of a tidal plane, the location of the coastline can be rather inaccurate. Couple this with the natural processes of accretion and erosion and the error in the baseline increases even further.

A key function of the Australian Maritime Boundaries Information System (AMBIS) is to manage the precision, stored in terms of standard deviations, of the computed coordinates of Australia's normal baseline (AUSLIG, 2001). The precision of the location of the points defining the normal baseline in Australia is highly variable, ranging from metres to several kilometres (Leahy et al., 2001). In certain areas, the precision of the normal baseline measurements is unknown. In the sections that follow, a procedure for using the precision of the normal baseline points to determine the uncertainty in positioning maritime boundaries in real time will be presented.

2.2 GPS Positioning Errors

GPS positioning is based on determining the distance, or range, between the receiver's antenna and each satellite's antenna. The receiver computes this observable based on a time difference (or synchronisation) between the arrival of the satellite's pseudorandom noise (PRN) ranging code and the receiver-generated replica code. The range is therefore the time difference multiplied by the speed of light.

Like any measuring instrument however, GPS positioning is subject to various systematic and random errors directly affecting the raw measurements. Fundamentally, the observed range is biased by the lack of synchronisation between the satellite clock, which governs its signal generation, and the receiver clock, which governs the generation of the replica code (Langley, 1997). Hence, the biased range, known as the *pseudorange*, is an estimate of the true, geometric distance. In addition, the pseudorange is further influenced by the effects of tropospheric and ionospheric refraction, atmospheric absorption, multipath, and receiver noise.

Finally, to compute the receiver's position, the receiver must determine the position of each satellite using the Keplerian elements describing the satellite's orbit contained within the broadcast ephemerides. However, these elements are given in terms of a *predicted* future orbit based on prior observation and modelling. As such, there will always be some error in the broadcast ephemeris. Strictly speaking, this error must be accounted for.

Whilst many of the aforementioned errors in GPS positioning can be minimised when differential techniques are employed, this paper provides a methodology for handling broadcast ephemeris error and the errors contained within the pseudorange measurements made by a single GPS receiver operating in real-time, autonomous mode.

3 MARITIME BOUNDARY GEOMETRY

Uncertainty in the location of a maritime boundary is directly related to the way in which the boundary was established. Accordingly, the means for handling the error in the delimitation process requires an understanding of the method for geometrically defining the location of each boundary point. Fundamentally, there are three types of maritime boundary: (1) those which are computed from measurements to natural features, (2) those which have an explicit spatial definition, and (3) those which are a combination of the previous two.

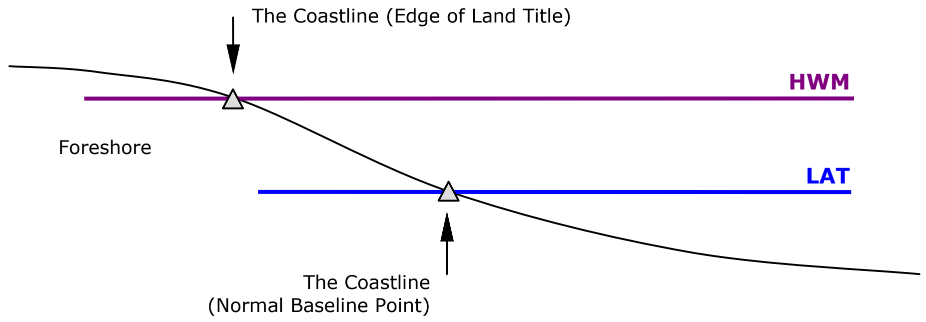
3.1 Type 1 – Computed

The computed maritime boundaries of interest in this paper are those which are determined by intersecting the foreshore with a tidal plane (i.e. coastline definition), and those derived by distance offset from the TSB.

Tidal Plane – Foreshore Intersection

The coastline may be determined by locating the points along the foreshore at which the level of a particular tidal plane is predicted to fall. Figure 3.1 shows the concept of locating points at which the tidal planes of High Water Mark (HWM) and LAT intersect the foreshore.

Figure 3.1. The tidal plane – foreshore intersection



Since there are a variety of tidal planes currently in use, the definition of the term 'coastline' has a variable meaning. Therefore, the spatial location of coastline points must be managed in the context of the tidal plane in question.

Distance Offset

As implied in the Scientific and Technical Guidelines (United Nations, 1999) prepared by the Commission on the Limits of the Continental Shelf (CLCS), the method of *Envelopes of Arcs* (Boggs 1930) is used to offset zone boundaries from the normal baseline. Following the alternative method of rolling a circle along a baseline described by Leahy et al. (1999), the delineation of a maritime zone boundary using this method is shown by Figure 3.2.

Where a maritime boundary is to be offset from a straight baseline, the method of *Tracés Parallèls* is used. This method involves the segmentation of a straight baseline into a predetermined number of points, and the subsequent construction of a normal from each point which is extended the required zone width (w). This method is shown in Figure 3.3.

Figure 3.2. Construction from a Normal Baseline Point (Leahy et al., 1999)

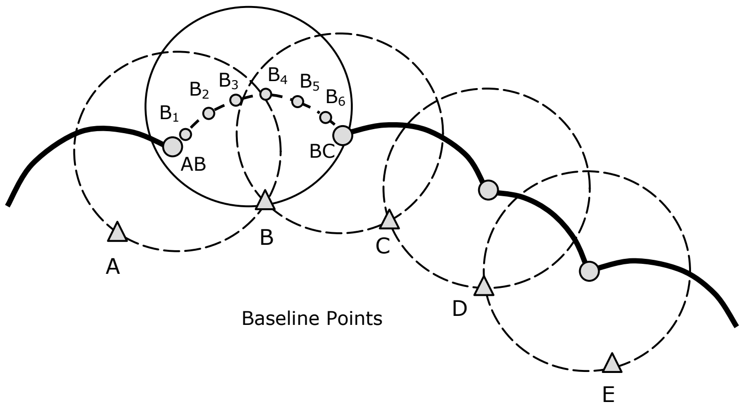
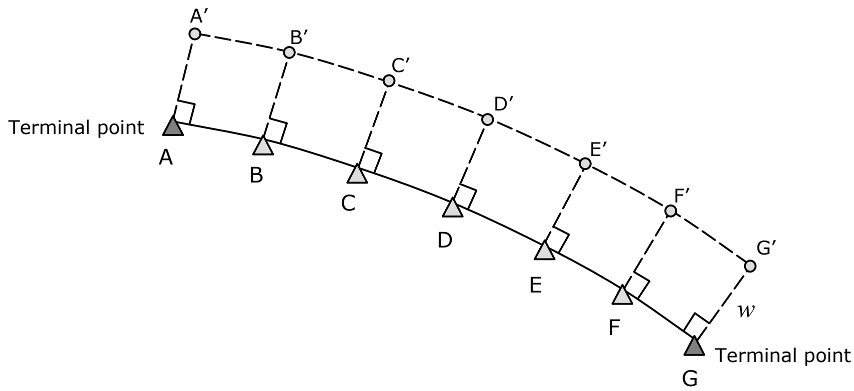
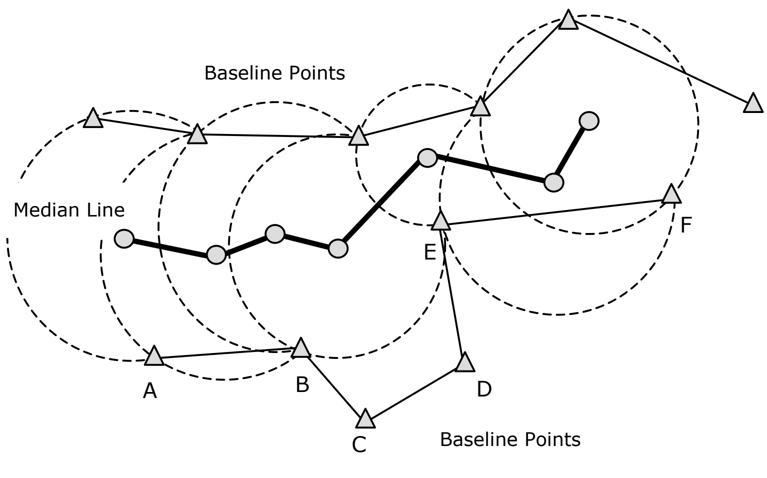


Figure 3.3. Construction from a Straight Baseline (Murphy et al., 1999)



To determine the location of points making up a "median line" between two geographically opposing baselines, the method of rolling a circle along the baseline is again used. As the circle is rolled, the radius of the circle is increased or decreased until the circle can be defined by three baseline points. The centre of the rolling circle scribes out the median line. Figure 3.4 shows the delineation of a median line using this method.

Figure 3.4. Construction of a Median Line (Leahy et al., 1999)



3.2 Type 2 – Explicit

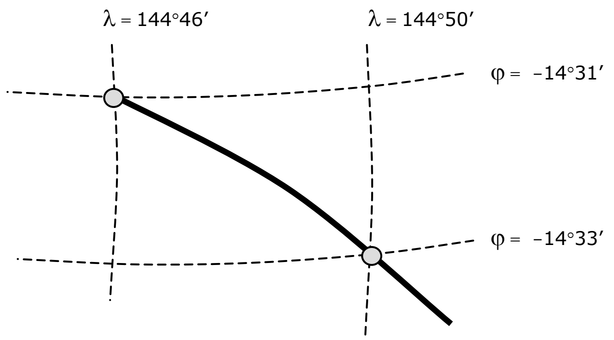
Maritime boundary points may be defined by explicit spatial descriptions. These can include a point on the ellipsoid, given in terms of latitude and longitude, or as a function of the intersection of particular meridians, geodesics, loxodromes or parallels. Such boundaries are defined using textual descriptions and contain little or no uncertainty. For example, sections (c) and (d) of the definition for the *Dead Dog Creek to Barrow Point* Preservation Zone in the Great Barrier Reef Marine Park state (GBRMPA, 2002):

> *"... (c) thence north-westerly along the geodesic to the point of latitude 14°33' south, longitude 144°50' east; ..."*

> *"... (d) thence north-westerly along the geodesic to the point of latitude 14°31' south, longitude 144°46' east; ..."*

Figure 3.5 shows the delimitation of (c) and (d) described above.

Figure 3.5. Explicit boundary (geodesic)



3.3 Type 3 – Combined

Finally, maritime boundaries may be established as a line defined by a combination of computed and explicit types. Figures 3.6 and 3.7 show two typical examples.

Figure 3.6. Baseline and Explicit

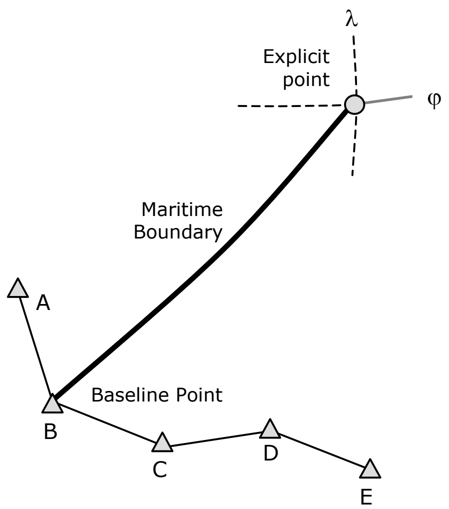
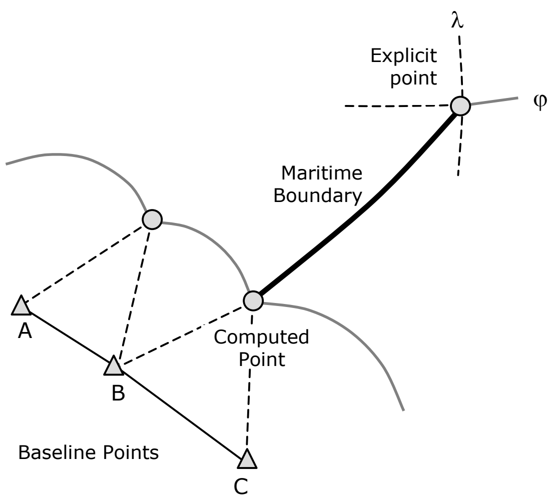


Figure 3.7. Computed and Explicit



4 ALGORITHMS FOR HANDLING ERROR

In positioning a maritime boundary in real-time, the solution is expressed as a function of measurements. Since random errors exist in both (1) the location of the baseline points from which a maritime boundary is computed and (2) the broadcast ephemeris and pseudorange measurements, it is shown that the quality of the solution is a function of both of these sources of error. To quantify the level of error in the positioning solution (given the random errors contained within the measurements), the method of variance-covariance propagation is used. In general, the relationship between the measured and computed quantities can be given by:

$$\delta = \mathrm{Ax} \qquad (1)$$

where

- δ is the calculated quantity for the linearised function Ax,
- A is the linearised mathematical model relating δ to x, and
- x represents the measurements.

The law of propagation of variances and covariances for linearised functions is given by (Mikhail 1981):

$$\mathrm{V}_\delta = \mathrm{A}\mathrm{V}_\mathrm{x}\mathrm{A}^\mathrm{T} \qquad (2)$$

where

- V_δ is the variance matrix for the computed quantities, and
- V_x is the variance matrix for the observed measurements.

§4.1 and §4.2 describe the algorithms for handling error in maritime boundary delimitation and absolute GPS position determination respectively.

4.1 Error Propagation in Maritime Boundary Delimitation

As described in §3, the means for handling the error in a maritime boundary is dependent on the way in which the location of each boundary point is geometrically defined. In this context, the general law of variance-covariance propagation described above is applied relative to the boundary delimitation algorithm.

Distance Intersection

Consider Figure 3.2. The location of points AB and BC are solved for using the method of distance intersection from baseline points A and B, and points B and C respectively. The error in point AB is determined using the variances of baseline points A and B. Similarly, the error for boundary point BC is derived from the variances of baseline points B and C.

The solution for propagating the variances from two baseline points to an intersection point is given in two parts.

Step 1

Using equation (2), the variances from the two baseline points are propagated into the two distances (used to perform the intersection) by:

$$V_d = BV_pB^T \tag{3}$$

where B is the linearised matrix relating the intersection point P_i to baseline points P_1 and P_2, given by:

$$B = \begin{bmatrix} \frac{\partial f}{\partial \varphi_1} & \frac{\partial f}{\partial \lambda_1} & \frac{\partial f}{\partial \varphi_2} & \frac{\partial f}{\partial \lambda_2} \\ \frac{\partial f}{\partial \varphi_1} & \frac{\partial f}{\partial \lambda_1} & \frac{\partial f}{\partial \varphi_2} & \frac{\partial f}{\partial \lambda_2} \end{bmatrix}$$

f is a general function that allows the distances to be computed from points P_1 and P_2 to point P_i . V_p is the variance matrix for points P_1 and P_2, given by:

$$V_p = \begin{bmatrix} V_1 & V_{12} \\ V_{21} & V_2 \end{bmatrix}$$

V_1 is the variance matrix of baseline point P_1,

V_2 is the variance matrix of baseline point P_2,

V_{12} is the covariance between P_1 and P_2, and $V_{21} = V_{12}^T$.

Step 2

The least squares solution of the distance intersection problem yields the precision of the coordinates for the intersection point from:

$$V_i = (A^T V_d^{-1} A)^{-1} \tag{4}$$

where A is the linearised (Jacobian) design matrix relating the intersection point P_i to baseline points P_1 and P_2, given by:

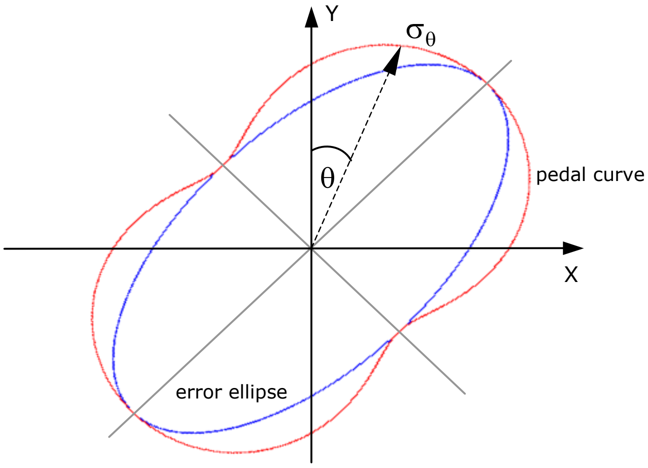
$$A = \begin{bmatrix} \frac{\partial f}{\partial \varphi_1} & \frac{\partial f}{\partial \lambda_1} \\ \frac{\partial f}{\partial \varphi_2} & \frac{\partial f}{\partial \lambda_2} \end{bmatrix}$$

V_d contains the variances for distances d_1 and d_2, given by equation (3). f is a general function that allows the distances to be computed from points P_1 and P_2 to point P_i . Note that this method may also be used to determine the variances of median line points.

Radial Offset

Consider Figure 3.2. The locations of points B_1 through to B_6 are determined by radial offset from baseline point B. Hence, the error in the boundary formed by points B_1 through to B_6 is derived solely from baseline point B. In this case, the propagation of variances from B to points B_1 through to B_6 is achieved by using the pedal curve. Figure 4.1 illustrates the pedal curve.

Figure 4.1. The pedal curve



In Figure 4.1, the semi-major and semi-minor axes of the error ellipse represent the maximum and minimum precision in the position of the point to which the error ellipse applies. The pedal curve enables the precision of the point in any arbitrary direction θ to be determined (σ_θ) (Cooper, 1974).

In maritime boundary delimitation, the polar equation of the pedal curve may be used to propagate the variances of both normal baseline points and straight baseline segmentation points. Figures 4.1 and 4.2 show the resultant error belts formed by radial offset from the normal baseline and segmentation points on a straight baseline respectively.

Figure 4.2. The propagation of error from normal baseline points

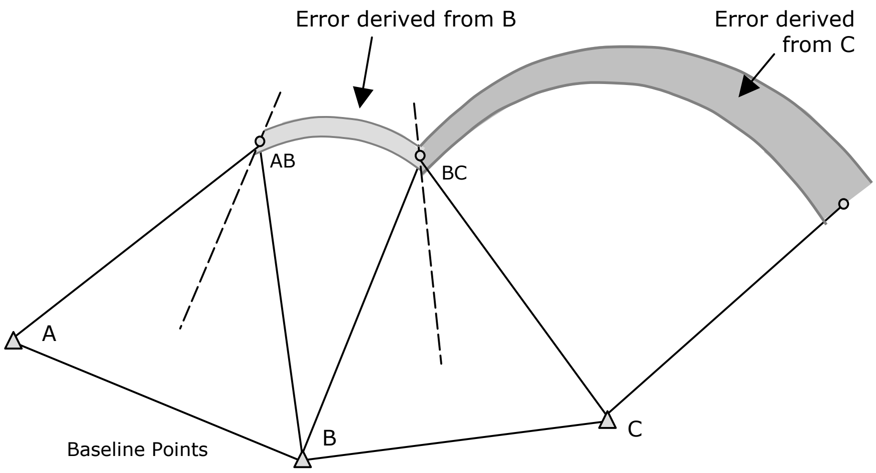
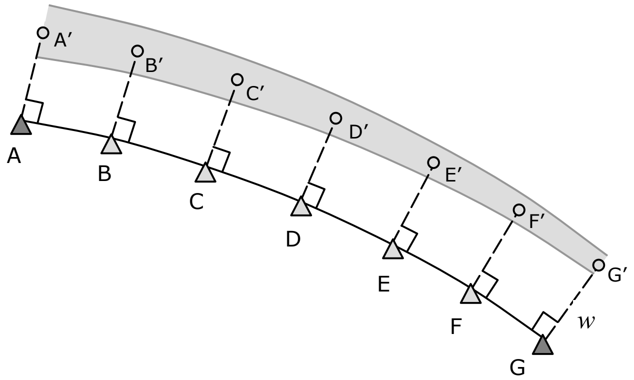


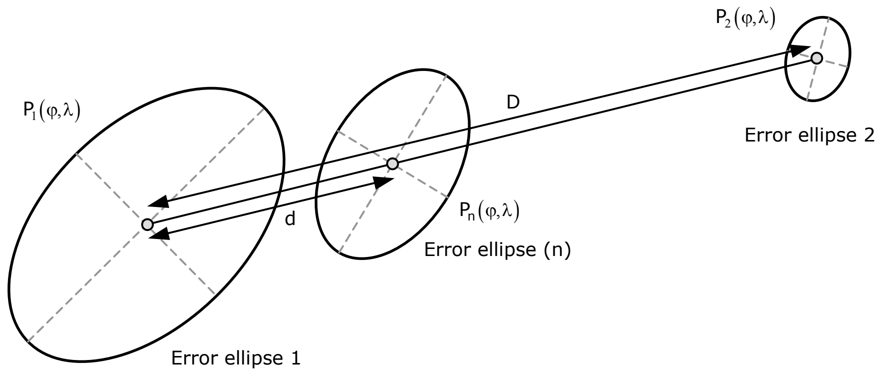
Figure 4.3. The propagation of error from a Straight Baseline



Combined types

Where the error must be determined along a line defined by two end points of differing quality, such as those determined via different methods of boundary definition, the concept of proportioning the error according to the mathematical relationship between the two end points can be used. Figure 4.4 illustrates the proportioning concept.

Figure 4.4. Error ellipses for boundary points P1 and P2 and the ellipse for P(n)



The variance matrix of point P_n can be computed using equation (2), where A is the matrix relating the random point P_n to points P_1 and point P_2, and V is the variance matrix for points P_1 and P_2.

Determining the error in a straight baseline segmentation point is one example where this concept is used, whereby point P_n is at segmentation distance *d* from point P_1. To illustrate the nature of error in other examples, Figures 4.5 and 4.6 show the error belt formed by points defined by different methods of geometrical definition, having variable levels of spatial accuracy. Note in these examples that the explicit points have zero error.

Figure 4.5. Baseline and Explicit

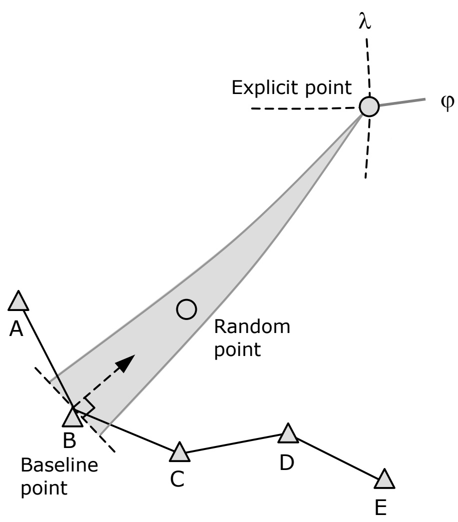
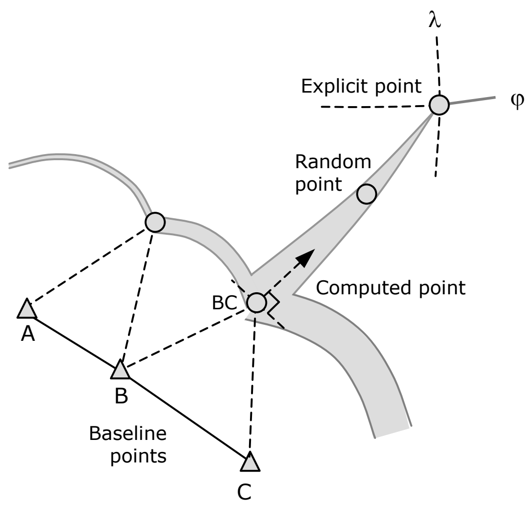


Figure 4.6. Computed and Explicit



4.2 Absolute GPS Positioning

To determine the precision of GPS in deriving an absolute position in real time, we must take into consideration the random errors affecting the geometric solution as described in §2.2. For this example, the errors considered are those assumed to be present in the broadcast ephemeris and those which directly affect the pseudorange measurements.

The least squares solution of the code observation problem yields the precision of the coordinates for the receiver position (r) from:

$$V_r = (A^T V^{-1} A)^{-1} \tag{5 }$$

where

A is the Design matrix,

V is the full variance matrix of GPS measurements.

The full variance matrix of the GPS measurements is populated with a variance matrix comprised of the pseudorange observables and a variance matrix for each set of satellite coordinates as determined from the broadcast ephemeris. The full variance matrix is given by:

$$V = \begin{bmatrix} V_\rho & 0 \\ 0 & V_{sv} \end{bmatrix}$$

where

V_ρ is the variance matrix of the pseudorange measurements, and

V_{SV} contains the variance matrices for the satellite coordinates.

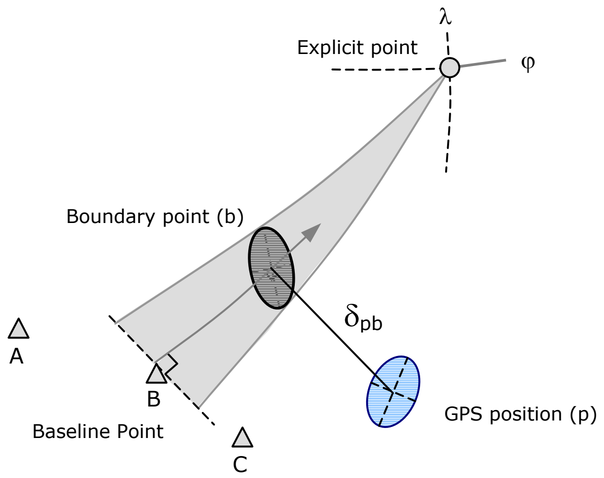
5 POSITIONING MARITIME BOUNDARIES WITH CERTAINTY

This section presents the overall positioning solution for determining the probability of a user's position being on or near a given maritime boundary. The positioning solution is given in the contexts of positioning boundaries at sea and positioning the coastline.

5.1 Positioning Boundaries at Sea

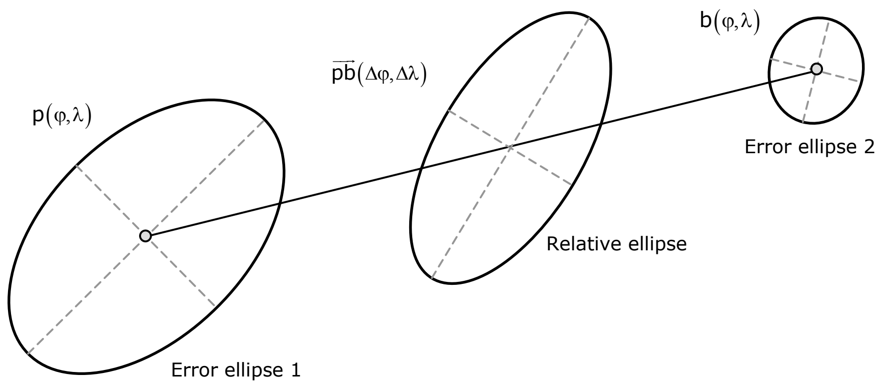
The method for determining the precision to which a user is able to locate a maritime boundary is based on the precision of the distance between the user's position and the nearest point along the boundary. Practically, this distance is the perpendicular offset, or shortest distance, from a boundary segment. Figure 5.1 illustrates a typical example.

Figure 5.1. Precision of GPS position with respect to a maritime boundary



To compute the precision to which the user's position (p) is determined with respect to a maritime boundary, we need the variance matrix of the vector δ_{pb} . This variance matrix produces the *relative error ellipse*, which expresses the precision of point (b) with respect to point (p). Any errors common to the two points are removed as a result of their geometrical difference. Figure 5.2 illustrates the concept of the relative error ellipse.

Figure 5.2. Error ellipses for points (p) and (b) and the relative error ellipse



Hence, the relative error ellipse is a measure of how precisely the user at (p) can determine their location relative to the boundary.

The vector δ_{pb} is formed by the GPS position (p) and the closest point on the boundary (b). The variance matrix V_{pb} for the vector δ_{pb} can be computed using equation (2), where A is the matrix relating the GPS position (p) to boundary point (b) and V is the combined variance matrix for points (p) and (b), given by:

$$V = \begin{bmatrix} V_b & 0 \\ 0 & V_p \end{bmatrix}$$

V_b is the variance matrix of the boundary point, derived according to the method of boundary delimitation, and

V_p is the variance matrix of the user's position given by $(A^T V^{-1} A)^{-1}$ in equation (5).

5.2 Positioning the Coastline

To determine the error involved in positioning the coastline, the concept of fitting a point (given in three-dimensional space) on a plane is considered. The plane in this case is the tidal plane of interest and, since we are concerned with *realising* the coastline, the point is one on the foreshore defined in real time using GPS.

The solution for determining whether point (p) lies on a plane is given by the vector dot product:

$$n \bullet (x - p) = 0 \qquad (6)$$

where

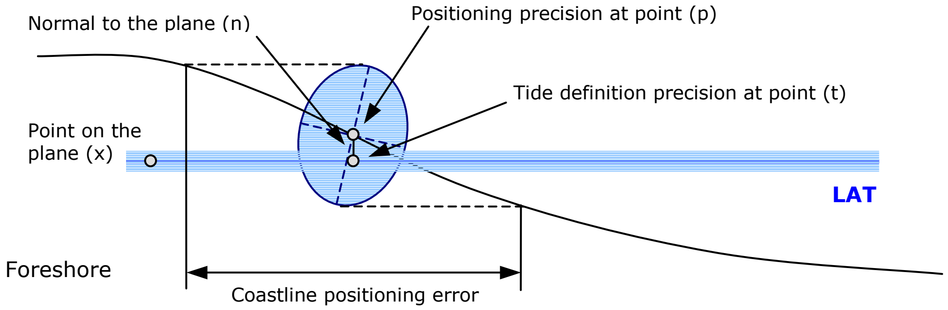
the plane has been defined from three tide gauge bench marks,

n is the normal to the plane (from point p), and

x is a point on the plane (such as a tide gauge bench mark reference)

Hence, equation (6) is satisfied if point (p) lies on the tidal plane which is at a specified height defined relative to tide gauge bench marks. If the gradient of the foreshore is known, the error in the horizontal location of the coastline (as determined by GPS) may be quantified as illustrated by figure 5.3.

Figure 5.3. Coastline positioning error



However, the gradient is not always known in real time and we must also consider the effect of error in the definition of the tidal plane in question. Whilst the error in the definition of tides may be relatively small at tide gauge benchmarks, where the benefit of many years of observation and modelling is present, tide heights at random locations may be subject to large error as a result of unaccountable site specific perturbations.

To compute the precision to which the user is able to locate the intersection of a tidal plane and the foreshore, we need the variance matrix of the normal n. This variance matrix produces the relative error ellipse, which expresses the precision of point (p) with respect to point (t). Using equation (2), the variance matrix V_n for the normal n can be computed by:

$$V_n = AVA^T \qquad (7)$$

where A is the matrix relating the GPS position (p) to point (t) on the plane, and V is the variance matrix for points (p) and (t), given by:

$$V = \begin{bmatrix} V_t & 0 \\ 0 & V_p \end{bmatrix} \qquad (8)$$

where

V_t is the variance matrix of the tidal plane definition at point (t), and

V_p is the variance matrix of the user's position given by $(A^T V^{-1} A)^{-1}$ in equation (5).

6 IMPLICATIONS FOR A MARINE CADASTRE

In the marine environment, maritime boundaries are created to define public use areas, conservation areas, marine parks, native title claims, commercial mining leases, farming leases, administrative areas, jurisdictional areas and sovereign extent – to mention a few. Accordingly, maritime boundaries are critical to the clear and unambiguous legal definition, management and security of these interests. Handling the legal, technical and business aspects of maritime boundaries is the specific purpose of a marine cadastre (Todd, 2001).

In contentious cases, the prosecution of offenders in the marine environment places significant weight on their position relative to a maritime boundary. As we have seen however, the realisation of maritime boundaries is often corrupted with error – sometimes in the magnitude of kilometres. Failing to take into account both the precision of the offender's location and the accuracy to which the boundary has been delimited cannot be justified. Confidently arguing the actual location of a person relative to a maritime boundary must therefore be dealt with using probabilities or confidence indicators.

To support this need, the design of a marine cadastre must cater for the management of metadata to describe the quality aspects of marine feature geometry. Accordingly, Australian industry research and development activities have identified the Open GIS

Consortium (OGC) specification for Feature Accuracy Metadata (OGC 1997) as the most effective model for managing quality information within a marine cadastre. In short, the accuracy specification supports the management of absolute, relative and value accuracy, metadata accuracy, vertical linear, horizontal circular, and 3D spherical error, covariance matrices, confidence probabilities and normal error distributions of geometrical features.

For the activities of data integration, boundary definition, maintenance and reinstatement, algorithms are required to rigorously handle the precision and accuracy of marine feature geometry. The algorithms presented in this paper offer a rigorous means for managing marine cadastre data and accuracy metadata based on this specification. The next phase of this research will look at implementing these algorithms as "Web Services", so as to simulate marine cadastre data-management and boundary positioning tasks over an Internet framework.

7 CONCLUSION

This paper presents a rigorous methodology for determining the uncertainty in positioning a maritime boundary in real time. It is argued that the uncertainty in positioning maritime boundaries is a function of the accuracy to which maritime boundaries are delimited and the errors associated with absolute GPS positioning.

To correctly account for the error in a given maritime boundary, the various methods for geometrically defining maritime boundary points have been discussed. Accordingly, algorithms for handling the error in maritime boundary delimitation have been described. To provide a measure of confidence in using GPS to position a maritime boundary, a methodology for combining the precision of an absolute position determination with the error associated with a maritime boundary has been presented. The positioning solution offers a simple, yet rigorous approach for reinstating the location and spatial extent of marine interests, with a measure of confidence, in real-time.

In the context of a marine cadastre, the error propagation algorithms described herein provide an appropriate means for managing the relevant aspects of boundary accuracy metadata.

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