Resolving Spatial Uncertainty in the Tidal Interface

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Abstract

The tidal interface or inter-tidal zone is that part of the coastal zone that falls between the extremes of Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT). It is an area of considerable interest and diverse human activity. The tidal interface possesses significant economic and commercial value while at the same time being a sensitive and delicately balanced environment. A number of competing and sometimes complementary rights, restrictions and responsibilities from private, public and commercial interests interact in the inter-tidal zone. The administration and governance of these interests in an equitable and sustainable manner is a complex and challenging task.

Virtually all activities in the tidal interface are spatially governed. More often than not, the defining boundaries relate to the line of intersection between a particular tidal datum and the land mass. For example, in Australia, freehold titles to coastal land parcels are limited in their seaward extent by the line of Mean High Water. On the other hand, government jurisdiction in the marine environment extends seaward from the line of Lowest Astronomical Tide. The difficulty with boundaries defined on the basis of tidal datums is that rigorous and consistent realisation of the line of intersection between a nominated tidal datum and the land mass is notoriously difficult, creating spatial uncertainty and the potential for conflict and dispute.

This paper describes and discusses the fundamental issue of dealing with spatial uncertainty in defining and realising boundaries which are linked to tidal datums. Some practical examples are presented to highlight the complexity of the problem. Having presented the background, a technical solution for realising the line of intersection between any given tidal datum and the land mass will be presented. Issues involved in implementing this solution will be described and its relevance and application to the development of a national marine cadastre will be discussed.

1. THE MARINE CADASTRE CONCEPT

The idea for a national marine cadastre stems from the broadly recognised need to improve administration and management of the marine environment from a spatial perspective. The marine cadastre aims to create a sustainable and equitable management system for spatially governed offshore rights, restrictions and responsibilities. In Australia, administration of offshore and coastal boundaries is shared by a complex mixture of federal, state and local government agencies, leading to overlapping jurisdictional responsibilities and considerable confusion for stakeholders. In response, a marine cadastre will provide a single, reliable and authoritative means for the delineation, management and administration of legally defined offshore boundaries at any scale.

The abundance and diversity of activity in the coastal zone and the complex nature of boundaries in the marine environment are illustrated in Figure 1. This figure demonstrates both the need for and the potential applications of a future marine cadastre.

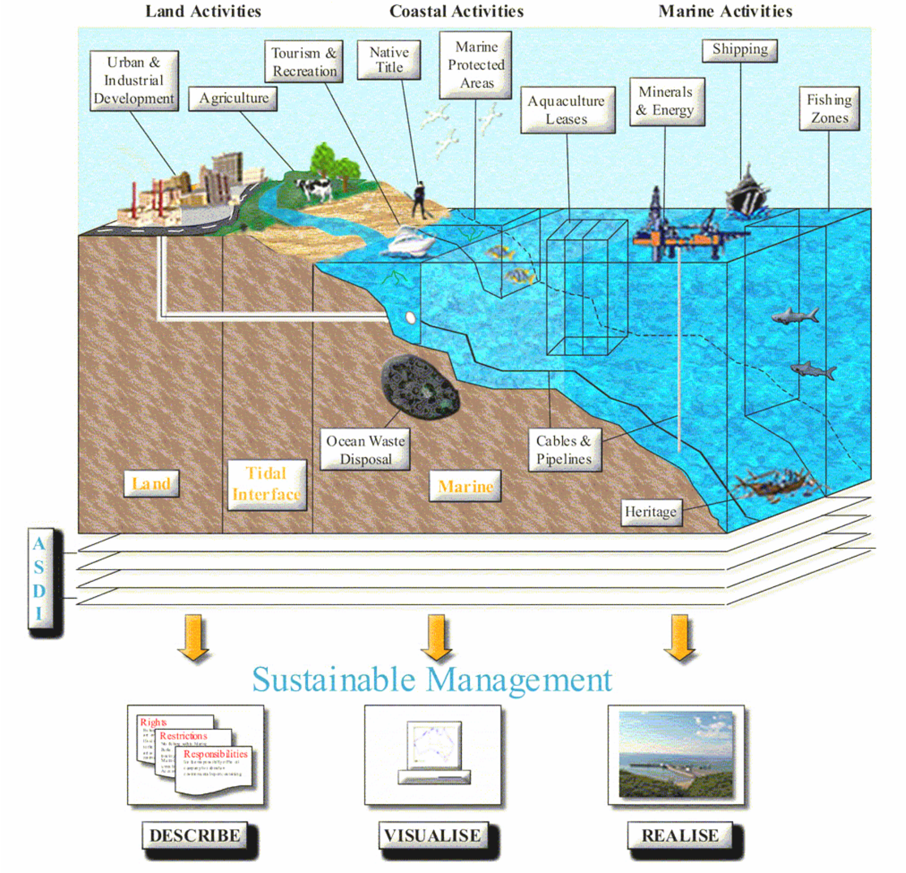

Figure 1: The Australian marine cadastre concept (Binns, 2003)

It is argued that a marine cadastre is vital to the long term sustainable management of Australia’s marine environment. The nation’s maritime jurisdiction is one of the largest in the world (16.1 million km^2). 85% of Australians live within 50 km of the coastline (ABS, 2004). In addition to supporting a wide range of recreational and public-good uses, Australia’s marine environment generates a significant proportion of the nation’s wealth, through shipping, fishing, aquaculture and natural resource extraction. It is vital to the national economy and the long-term sustainability of the ocean environment that this diverse mix of offshore activities is managed equitably.

The first marine cadastre research in Australia began in mid 2002 with the awarding of an Australian Research Council grant to a group of researchers from the University of Melbourne and committed industry and government partners. This project aimed to identify and define the main issues that will impact on the development of a future national marine cadastre. As a first step, the similarities and differences between the land cadastre and the marine cadastre were identified and considered (Binns, 2003). The features that distinguish the marine cadastre from the land cadastre were found to be (Collier, Leahy, Williamson 2001):

- The lack of *tenure* or ownership
- The inability to physically delineate boundaries
- The existence of three dimensional and sometimes four dimensional marine parcels
- The existence of overlapping rather than exclusive rights, restrictions and responsibilities
- The temporal nature of marine boundaries

At the same time as this research was being undertaken, a parallel research theme considered the *virtual* nature of offshore boundaries and addressed technical issues relating to spatial uncertainty in the realisation and visualisation of marine boundaries (Fraser et al., 2003).

A subsequent ARC grant took effect in mid 2004 and has allowed the research effort in marine cadastre issues to continue. The now expanded research team is pursuing objectives in four key areas covering a broad range of issues concerned with the implementation of Australia's marine cadastre. The four research areas are:

- The use of natural rather than artificial boundaries to define offshore jurisdictional limits
- The extension and application of the Australian Spatial Data Infrastructure to the marine environment
- Marine policy and security issues in relation to a marine cadastre
- Resolving issues in the definition of the tidal interface

The fourth of these research areas is the particular interest of the present authors and is the primary subject of this paper.

2. AMBIGUITY IN THE TIDAL INTERFACE

As shown in Figure 2, the tidal interface (otherwise known as the inter-tidal zone or foreshore) is that portion of the land mass that falls between the extremes of Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT). The horizontal width of this zone can vary dramatically, depending upon the steepness of the foreshore terrain and the magnitude of the tidal range. Where the foreshore slope is gradual and the tidal range is large, the inter-tidal zone can extend over a kilometre or more. If however the foreshore terrain is very steep, the lines of HAT and LAT can be practically coincident. In addition to showing the extremities of the tidal interface, Figure 2 also shows a number of other tidal datums that may be relevant in a marine cadastre, depending on the context and application at hand.

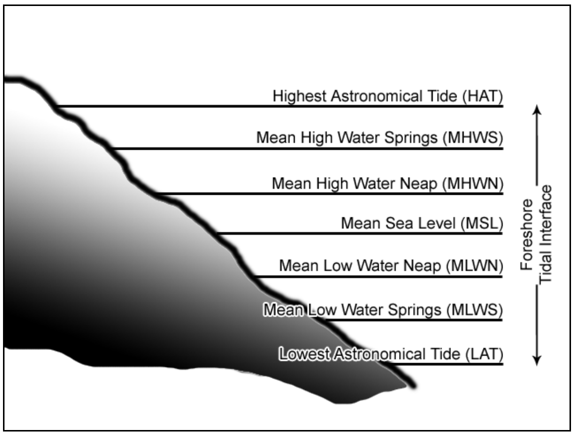

Figure 2: The Tidal Datums and the Tidal Interface

Coastal land parcels throughout Australia typically extend to the line of Mean High Water (Geoscience Australia, 2006), however international maritime boundaries defined under the United Nations Convention on the Law of the Sea (UNCLOS) are related to the line of LAT. The fact that, in Australia, different tidal datums are used to define different offshore (and onshore) boundaries has resulted in a number of different state and federal legislative definitions for the words such as *coastline* and *foreshore*. Typically, these terms are used to describe the line of intersection between a tidal datum and the terrain, but often no specific statement is made as to which tidal datum is being referred to. The words *coastline* and *foreshore* are therefore often shrouded in ambiguity from a spatial perspective.

The capacity to consistently and unambiguously realise the line of intersection between any nominated tidal plane and the land mass is a fundamental requirement of any marine cadastre. Wide ranging discussions at the national and international[1] level have clearly identified this as a research priority. It is widely agreed that only when a solution to this problem is found and implemented will it be possible to realise a functioning marine cadastre.

3. DEFINITION AND REALISATION ISSUES IN THE TIDAL INTERFACE

In Australia there is considerable inconsistency in terminology, particularly within legislative descriptions, when referring to the line of intersection of a tidal datum with the land mass. Definitions differ from one piece of legislation to the next and from jurisdiction to jurisdiction. By way of illustration, using four different Acts of Parliament from the state of Queensland, it can be seen from Table 1 that the definition of the word *foreshore* is by no means consistent. The first act refers to the *foreshore* as a single line on the tidal interface, whereas the others refer to it as being a region. Out of the three acts that refer to

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[1] "Administering the Marine Environment – The Spatial Dimension" organised by the UN Permanent Committee on GIS Infrastructure for Asia and the Pacific (UN-PCGIAP), held in Kuala Lumpur in May 2004.
"International Workshop on Marine Cadastre Issues" jointly organised by the Fédération Internationale des Géomètres (International Federation of Surveyors) and the University of New Brunswick, held at the University of New Brunswick in September 2003.

the foreshore as a region, two use the term *spring tide*, whereas the other is less prescriptive. Though these differences may appear minor, the ambiguity and uncertainty that is introduced when attempting to realise them in a spatial context is a real barrier to the successful implementation of a marine cadastre.

Table 1: Definitions of the Foreshore in Queensland (Todd, 2003)

Legal Entity	Definition of Foreshore
Administrative Boundaries Terminology Act 1985 - Sect 5	The high-water mark along the foreshore, shore, coastline or similar feature;
Coastal Protection And Management Act 1995 - Schedule 2	The land lying between high water mark and low water mark as is ordinarily covered and uncovered by the flow and ebb of the tide at spring tides.
Fisheries Act 1994 - Sect 4	Parts of the banks, bed, reefs, shoals, shore and other land between high water and low water.
Queensland Consolidated Acts - Volume 1 - Sect 3	The land lying between high-water mark and low-water mark at ordinary spring tides.

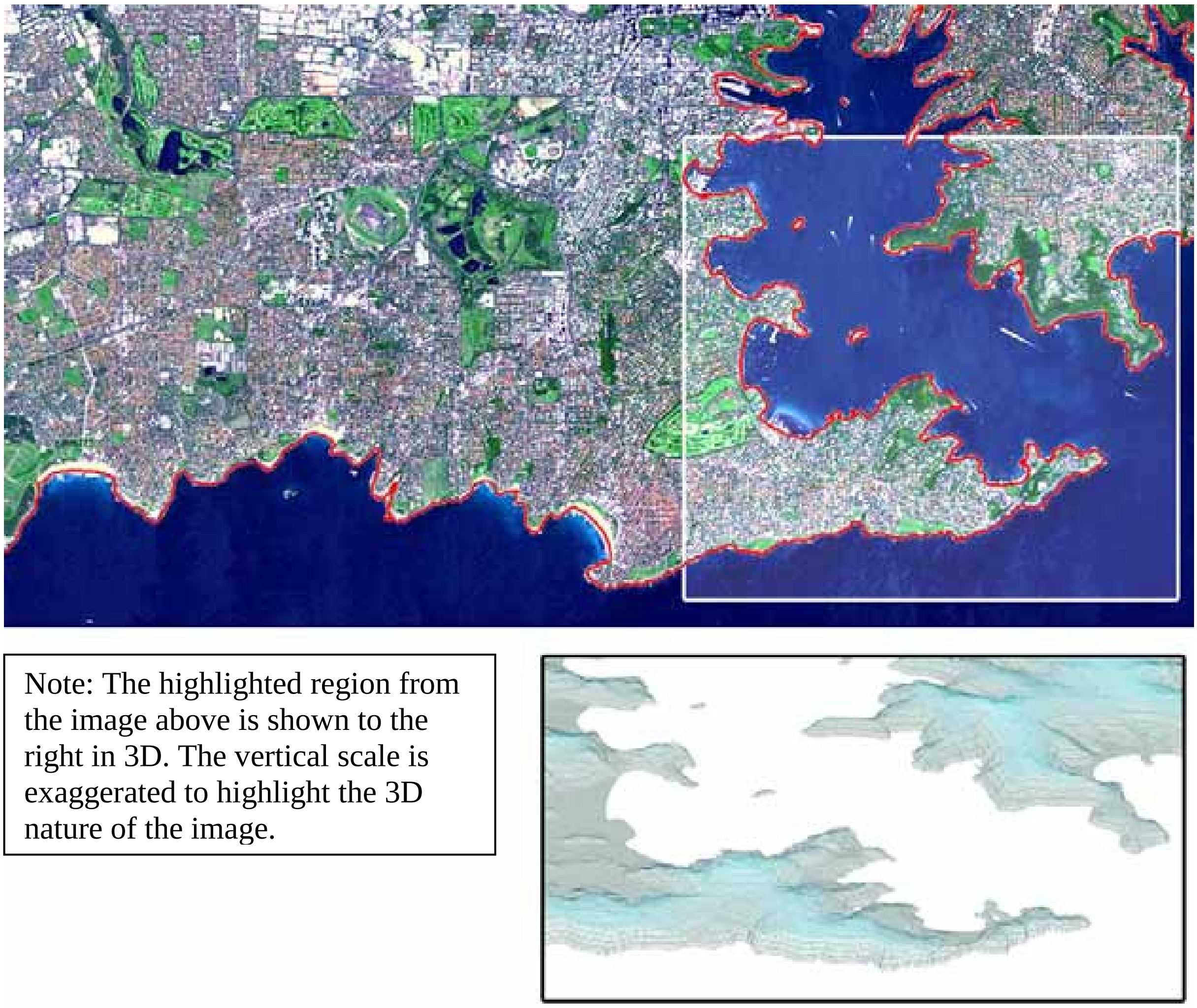
In addition to uncertainties in definitions and terminology, there are also significant inaccuracies associated with historical techniques used to spatially realise tidal plane intersections. Using LAT as an example, in the southern areas of Australia, positional accuracy of the line of LAT is said to be in the order of ±100 m. In the northern parts of the country, where the tidal ranges are larger and the foreshore terrain is often very flat, accuracy of LAT determination is closer to ±500 m (Hirst et al., 1999). Such levels of inaccuracy obviously disqualify the use of such data for the delimitation of accurate maritime boundaries. Thus it is needful to develop more efficient and more accurate ways of determining tidal plane intersections to support the marine cadastre concept.

Historically, two techniques have been employed for mapping tidal extremities, conventional surveying and aerial photogrammetry. For example, in the past, surveyors would use conventional techniques to locate points marking the most recent high water peak. These points would then be connected to delineate the line of high tide. This procedure was slow and inefficient. More recently, and for reasons of improved efficiency, aerial photogrammetry has superseded conventional surveying techniques as the preferred method for identifying tidal limits (Graham, 2003). The photogrammetric technique utilises visual features such as vegetation lines, berm crests, beach scarps, high water line and the wet sand line to approximate tidal extremities (Pajak, 2000). These two methods, along with other techniques that rely on directly capturing the coastline from visual evidence, are susceptible to short term fluctuations in wave and tide conditions and the problem that the tidal peak may not coincide directly with the time of data capture.

4. A NEW APPROACH TO REALISATION

The implementation of a marine cadastre in a practical sense will ultimately need to include a consistent and rigorous methodology for the realisation of the line of intersection between any nominated tidal datum and the land mass. The research being conducted at the University of Melbourne is focused on achieving this objective. The fundamental premise behind the research is that the methodology to be developed should be completely rigorous and repeatable, but fundamentally transparent to the user. To this end, the proposed technique will be principally mathematical and computational rather than relying on the more traditional techniques of interpreting imagery (from whatever source) and survey data. Of course this is a rather ambitious objective, especially given the inconsistency that currently prevails in relation to legislative definitions and the practical limitations on data acquisition, however the implementation of a consistent approach is a fundamental pre-requisite if the marine cadastre is to progress from concept to reality.

This new approach – hereafter referred to as the *automated foreshore and tide intersection model* (AFTIM) – relies on two sources of information. The first is the existence of an accurate and comprehensive digital terrain model of the foreshore and near-shore bathymetry. The second is a digital tide model that will allow the height of any nominated tidal datum to be determined for a given location. By combining these two sources of information, it is then possible to compute the 3D line of intersection between the land and the tidal datum for a given coastal region. The concept described here is illustrated in Figure 3 which displays the line of Highest Astronomical Tide in the Sydney region computed using AFTIM.



Note: The highlighted region from the image above is shown to the right in 3D. The vertical scale is exaggerated to highlight the 3D nature of the image.

Figure 3: The line of HAT for the Sydney Harbour region, illustrating the concept of a computationally determined line of intersection between a tidal datum and the land mass

4.1 Requirement 1 – Foreshore terrain model

A number of options exist for acquiring terrain data from which a foreshore digital elevation model (that also includes near-shore bathymetry) could be generated. These include:

- Existing topographic maps and bathymetric charts
- Dedicated terrestrial and hydrographic surveys
- Aerial photogrammetry
- Synthetic aperture radar (SAR)
- High resolution satellite imagery
- Airborne laser scanning (ALS) or Laser induced detection and ranging (LIDAR) systems

The first three of these techniques are largely unsuitable in the context of the requirements for AFTIM either because they are either not suited to data collection on a national scale, they are of inadequate accuracy or they do not allow simultaneous acquisition of foreshore terrain and bathymetry. The last three show some promise and will be discussed briefly below. Their potential as tools for acquiring terrain data in the inter-tidal zone arises particularly from their ability to *simultaneously* acquire both the shallow water bathymetry and the foreshore terrain.

The US National Geodetic Survey used SAR to complete shoreline mapping projects in Castle Bay and Resurrection Bay, Alaska using the satellite based RADARSAT system (Tuell, 1999). The direct acquisition of bathymetric data from SAR images is difficult, being complicated by the need to simultaneously collect data on wind speed, wind direction and surface water velocity (Robinson, 2004). This additional data can be used to correlate sea-surface roughness captured on the SAR image with bathymetric variations, but even still, it is difficult to obtain high accuracy bathymetric information. For this reason, alternative techniques have been sought.

High resolution satellite imagery provides another method for gathering foreshore terrain data. This method is based on the principle that the total reflected energy of electromagnetic waves from a water column varies with water depth (Leu and Chang, 2005). The drawback of this technique is that it also depends on the clarity of the water and the nature of the sea floor. Thus, regions with highly turbid water are not suitable for collecting bathymetric data using this method (Tripathi and Rao, 2002). For regions with low turbidity, supplementary data will need to be gathered on the sea floor, adding to the impracticality of using this method for gathering foreshore data for the AFTIM.

LIDAR is the most promising alternative for gathering foreshore terrain data as it directly measures the bathymetry. It has the advantage that it can penetrate clear water up to depths of 60 m (Wozencroft, 2003), which is more than adequate to map the land mass beyond the depth of LAT. Because of its high data acquisition rate and vertical accuracy, airborne LIDAR systems provide a very efficient tool for localised coastline mapping. However, for large scale (regional or national) applications a space borne LIDAR platform would be required in order to achieve adequate coastal coverage. Until such a platform exists airborne LIDAR will be required to collect data along sections of the coastline. The US Army Corps of Engineers investigated the use of airborne LIDAR to measure the impact of coastline sediment deposition in southern California, Florida and along the Lake Michigan shoreline (Wozencraft, 2003). The study confirmed the validity of LIDAR as a suitable tool for rapidly and accurately measuring coastal elevations on a local scale. Preliminary studies conducted by the authors using LIDAR data collected along a short section of the Queensland coast have further demonstrated the applicability of LIDAR for collecting foreshore terrain data.

4.2 Requirement 2 – Digital tide model

The second requirement for the AFTIM is the ability to accurately realise the height of any nominated tidal datum at any coastal location. Again, this is a complex and demanding requirement if an appropriate level of accuracy, consistency and coverage is to be achieved on a national scale. Below is a discussion of options and issues to be considered in the context of tidal datum generation for a marine cadastre.

One option for tidal datum modelling is to use an array of tide gauges to acquire the necessary tide height data. However, as shown in Figure 4, for a country as vast as Australia, the existing *permanent* tide gauge network is simply not sufficiently dense for this purpose. Thus the development of a comprehensive tidal model will generally require the installation of temporary tide gauges, which is a costly, time consuming and labour intensive exercise. The time consuming nature of the task is exacerbated by the fact that a full tidal cycle occurs only once every 18.6 years.

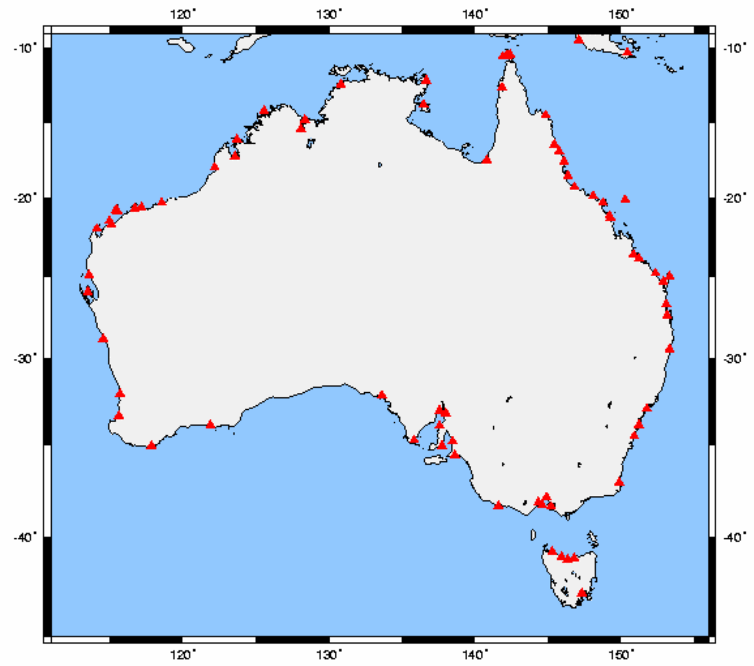


Figure 4 : Australian Tide Gauge Locations (National Tide Centre, 2006)

Notwithstanding the difficulties in acquiring appropriately dense tide gauge data, simple tidal models can be developed by linearly interpolating tide heights between tide gauges. However this technique is only adequate for straight sections of coastline. Where the coastal topography is non-linear, the tidal regime becomes more complex and simple interpolation between tide gauges is inadequate for accurately predicting tidal behaviour.

A more sophisticated approach to tidal modelling involves the computation and refinement of the harmonic constituents of a pre-defined global tide model. This process effectively "tunes" the harmonic constituents to local tide conditions by reference to data acquired from tide gauges specifically installed for the purpose. Of necessity, such an approach can only be applied on a local or perhaps regional scale, simply because of the requirement to install and maintain a network of temporary tide gauges for a considerable period of time.

Harmonic analysis is the process of decomposing a complex wave form into a series of sinusoidal components at particular frequencies. In the case of tidal modelling, harmonic analysis is used to isolate the separate astronomical effects that contribute to the overall tidal signature. Typically, least-squares estimation is used to calculate the amplitude and phase contribution of each constituent.

As shown in equation (1), the magnitude (height) of a particular tidal constituent at a given time and location is a function of the amplitude, frequency and phase of the contributing force (e.g. the declination of the moon). The phase is able to account for location by shifting the tidal frequency in time.

$$h(t) = A\cos(2\pi ft - \vartheta) \qquad \ldots(1)$$

where ;

h	is the height (magnitude) of a tidal constituent
t	is the time
A	is the amplitude of the contributing force
f	is the frequency of the force
ϑ	is the phase

To find the total tide height (*H*) at a specified time (*t*) requires that the contribution of each constituent be combined, as expressed in equation (2).

$$H(t) = h_0 + \sum_{i=1}^{n} A_i \cos(2\pi f_i t - \vartheta_i) \qquad \ldots(2)$$

where;

h_0	is the height of mean sea level relative to the local geodetic height datum
i	is the relevant tidal constituent (see Table 2 for definitions)

Expressing equation (2) in an explicit form as the sum of the major tidal constituents gives :

$$H(t) = h_0 + M_2 + S_2 + N_2 + K_1 + O_1 + M_4 + M_6 + S_4 + MS_4 \qquad \ldots(3)$$

A definition for each tidal constituent is given in Table 2.

Table 2 : Major Tidal Constituents (Boon, 2004)

Tidal Constituent		Definition	Frequency (degrees/mean solar hour)
h_1	M_2	Principal lunar semidiurnal	28.984
h_2	S_2	Principal solar semidiurnal	30.000
h_3	N_2	Larger lunar elliptic semidiurnal	28.44
h_4	K_1	Luni-solar declinational diurnal	15.041
h_5	O_1	Lunar declinational diurnal	13.943
h_6	M_4	First overtide of M_2	2 x M_2
h_7	M_6	Second overtide of M_2	3 x M_2
h_8	S_4	First overtide of S_2	2 x S_2
h_9	MS_4	A compound tide of M_2 and S_2	$M_2 + S_2$

The first five constituents listed in Table 2 combine to give a significant proportion of the total tidal signature in most locations. The next three are *shallow-water tides*, which, as can be seen, have frequencies which are an exact multiple of the frequency of the parent tides. The MS_4 constituent is an example of a *compound tide* which results from the interaction of two parent waves (M_2 and S_2). While there are other tidal constituents (particularly other shallow-water and compound tides) that could be included in Table 2, those listed account for major part of the tidal regime in most locations (Boon, 2004).

5. ISSUES IN IMPLEMENTING AFTIM

There is a compelling need to rationalise and unify legislative definitions for the *coastline*. While the term typically (though not uniformly) refers to the intersection of a tidal datum with the foreshore terrain, there is often ambiguity or uncertainty about which tidal datum is in view. Solution to this problem can only come through re-drafting and amendment of the relevant legislation. Obviously such a process will take considerable time and requires a will for consistency between state and federal jurisdictions. This may take place in due course and with appropriate lobbying of government, but in the meantime the proposed AFTIM can provide users of the marine cadastre with the flexibility to realise the line of intersection of any nominated tidal datum with the foreshore terrain.

Acquisition of data for the formation of a foreshore terrain model and the computation of a suitably accurate and comprehensive digital tide model represent significant challenges to the practical implementation of the AFTIM proposed above. However, it is argued that both of these difficulties will be overcome with time and planning and with improvements in relevant data acquisition technologies. In the meantime, existing foreshore terrain data and new terrain data acquired on a project by project basis can be used to develop localised foreshore terrain models wherever such data exists. While being less than ideal in terms of coverage, consistency, accuracy and extent, such an approach will allow early implementation and testing of the AFTIM. Likewise, existing tidal models and localised tide gauge information can be used in the early stages of AFTIM development while pending the computation of more sophisticated and extensive tidal models. Because a substantial period of time is required to collect sufficient tide data to model the full range of tidal behaviour, it will be necessary to institute programs for the collection of tidal data as a matter of priority. In the meantime, using existing terrain and tidal data will permit the approach to be implemented for testing purposes at a local scale and will allow implications for the marine cadastre to be identified and further investigated.

Perhaps the biggest challenge to fully realising the potential of AFTIM lies in the need to develop a solution that works nationally and at any scale. While it is possible within the confines of a research project to prove the concept in a local or even a regional context, the ultimate compilation of suitable national data sets for foreshore and tidal modelling will fall to government authorities. Of course priority can and should be given in this process to coastal areas of high property value and high levels of marine activity, such as Sydney Harbour and Port Phillip Bay.

A further issue in implementing AFTIM for marine cadastre purposes is the need to account for dynamic changes in the marine environment that necessitate re-computation of the line of intersection between a specified tidal datum and the foreshore terrain. Examples of such change include erosion and accretion of the foreshore which may occur naturally or as a result of human activity. In either case, changes in foreshore terrain imply the need to re-determine the location of the intersection of the tidal datum. Again, viewing the situation from a practical perspective, the only viable way to account for dynamic foreshore terrain variations in the short or long term is by regular re-acquisition of the relevant terrain data. In reality, routine, low-cost data collection will only be possible using space borne data collection systems of the future and a routine procedure for upgrading and maintaining the foreshore terrain model.

A similar situation, though less dynamic, is the requirement to account for changes in tidal extremities. An obvious cause will be sea level rise resulting from global warming. A recent article published in the Sydney Sun-Herald showed an inundation map for the Sydney basin resulting from projected future sea level rises. While such changes are expected to occur over very long time frames, they nonetheless need to be considered if a marine cadastre that shows tidal extremities is to be up to date and reflective of the true nature of the coastal environment.

In discussing the dynamic nature of the marine environment and in particular temporal variations in terrain and tidal extremes, a legal question arises that needs further consideration. Suppose an offshore boundary has been defined as a line parallel to the line of intersection of LAT with the foreshore. The question is: will that boundary move if the line of LAT moves as a result of foreshore erosion or accretion? This question of fixed and temporal maritime boundaries needs to be addressed by those experts in the interpretation of legislation and other legal instruments under which offshore boundaries are proclaimed.

6. IMPLEMENTATION OF AFTIM INTO THE MARINE CADASTRE

A marine cadastre will provide users with access to a single, definitive source of accurate and up to date spatial information relating to the location of legally defined offshore boundaries and the rights, restrictions and responsibilities associated with those boundaries. For example, the captain of a commercial fishing vessel may need to know where the geographical limits of a particular fishing zone are, at what times of the year fishing is permitted, what limitations apply to fishing procedures within that zone and to whom licence fees are payable. A marine cadastre could provide all this information instantaneously and in an on-line manner while the vessel is approaching the fishing area. At the same time, a recreational diver may search the marine cadastre for the location of a restricted area within the previously mentioned fishing zone, associated with a submerged shipwreck. Again rules governing access to the wreck and other relevant spatial information could be provided as part of such a query of the marine cadastre. Many other examples of applications of the marine cadastre could be outlined. However, most individuals, organisations and authorities with an interest in the marine environment readily recognise the potential benefits of such a system.

Of particular interest in the context of the proposal outlined in this paper is how the AFTIM concept can be implemented within a marine cadastre to further enhance its function and operation. Tidal datum intersections with foreshore terrain form the basis for the delineation of many offshore (and some onshore) boundaries. The AFTIM offers the ability to consistently and routinely delineate this most fundamental boundary. Its value will be particularly seen in the case of dealing with the ambulatory nature of the *coastline* in the event that boundaries are likewise regarded as ambulatory.

7. CONCLUSIONS

Historical techniques for delineating the line of intersection between a tidal datum and the foreshore terrain are labour intensive and largely unsatisfactory in the context of developing a marine cadastre. Recent technological developments provide the means to generate an appropriately accurate and high resolution foreshore terrain model and digital tidal model. A mathematical solution (called AFTIM) makes it possible to generate the line of intersection using two surface models and will provide a more rigorous and comprehensive solution for removing spatial uncertainty in the tidal interface.

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