Implementation of a TCARI Tidal Model Solution over an extensive coastal survey project in the Torres Strait: Why, How and an Analysis of the Results

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SUMMARY

Amongst the largest contracted coastal hydrographic survey projects awarded in recent years was the Royal Australian Navy/Australian Hydrographic Service (AHS) survey for the Torres Strait in Northern Queensland. This major program covered 6000km^2 of shallow and topographically complex coralline seabed, and was surveyed over two seasons in 2007 and 2008 using Airborne LiDAR Bathymetry (ALB). The survey had to meet the criteria for IHO Order 1b survey, which requires the same stringent horizontal and vertical positional accuracies for bathymetric data as Order 1a although relaxing the 1a target detection criterion, which specifies an ability to detect features in the order of 2m^3 in depths of up to 40 metres as a minimum acceptable standard. This data set ranged from above the high tide level to as much as 33 metres in the deepest parts of the survey in a region noted for extremely complex tides and demanding operational conditions.

Achieving this in such a highly complex and navigationally hazardous region, over such a large area, called for the use of ALB. Proving the hydrographic capabilities of LiDAR bathymetry was a satisfying sidebar to the delivery of charting-quality data for such a prominent and conscientious end customer. Delivery of charting data products in this environmentally very energetic region required a robust approach to the quality control of data acquisition in the field, and to quality assessment techniques in the post-processing and production delivery stages of the project.

This paper will introduce some of the techniques and steps employed by Fugro to ensure that data was consistent and within specification. Examples of methods applied to assess and address data artefacts, when outside or bordering tolerance, are covered.

Key words: hydrographic surveying; tides; modelling; offshore datums

1. TORRES STRAIT TIDAL REGIME

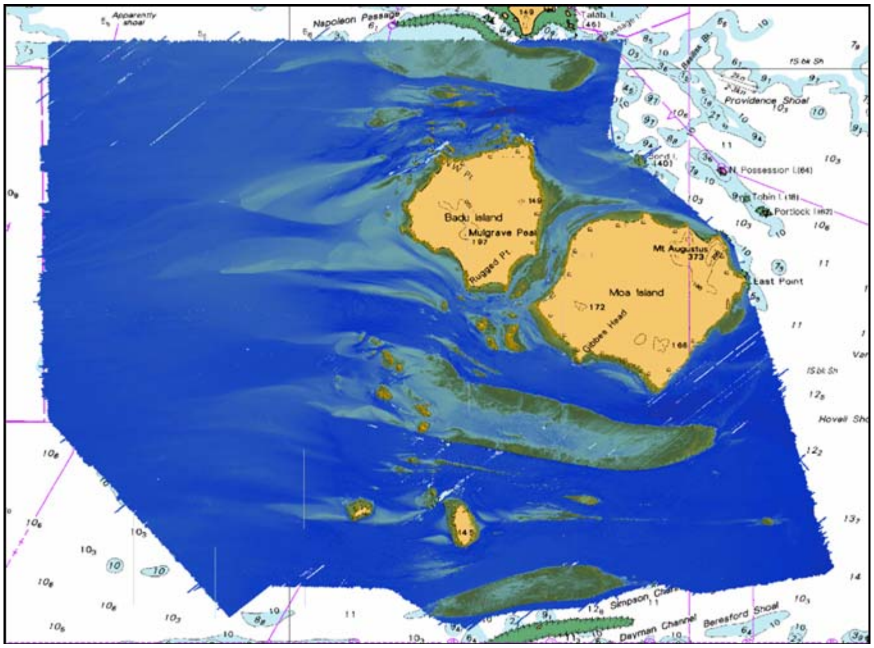
Without doubt, one of the most challenging aspects of the survey was the accurate depiction of the very complex tidal regime in the region. The Torres Strait is subject to a phenomenon which takes place very locally, whereby one class of dominant tidal constituents give way to dominance by another class, such that the nature of the tidal regime is semi-diurnal at one end of the survey area and diurnal at the other, with a broad region of mixed influences in the centre. This is also characterised by the change in the 'Age of Tide' which is simply the natural, usually regional time difference between theoretical astronomic spring tide and the actual highest tide. The problem with classic co-tidal modelling in this area was the fundamental variation occurring in various tidal constituents which meant there was no 'standard' tidal curve shape for the whole area.

In all, 16 stations (12 offshore; 4 onshore; 2 offshore sites supplied with redundant gauges due to their criticality in the plan) were occupied to determine the nature of the water levels during the conduct of the survey. Final levelling to the tide staffs and 25 hour observations were completed after all gauges were installed. In addition to the tide gauges, the tide program also included the installation of a met station on nearby Thursday Island, which was the main base for operations. The pressure data from this station was used for the correction to the final tide data when the units were retrieved and the data downloaded and processed. Fugro also conducted a series of wet tests of all tide gauges before deployment. Data was analysed to ensure conformity and accuracy of results across the entire suite of systems.

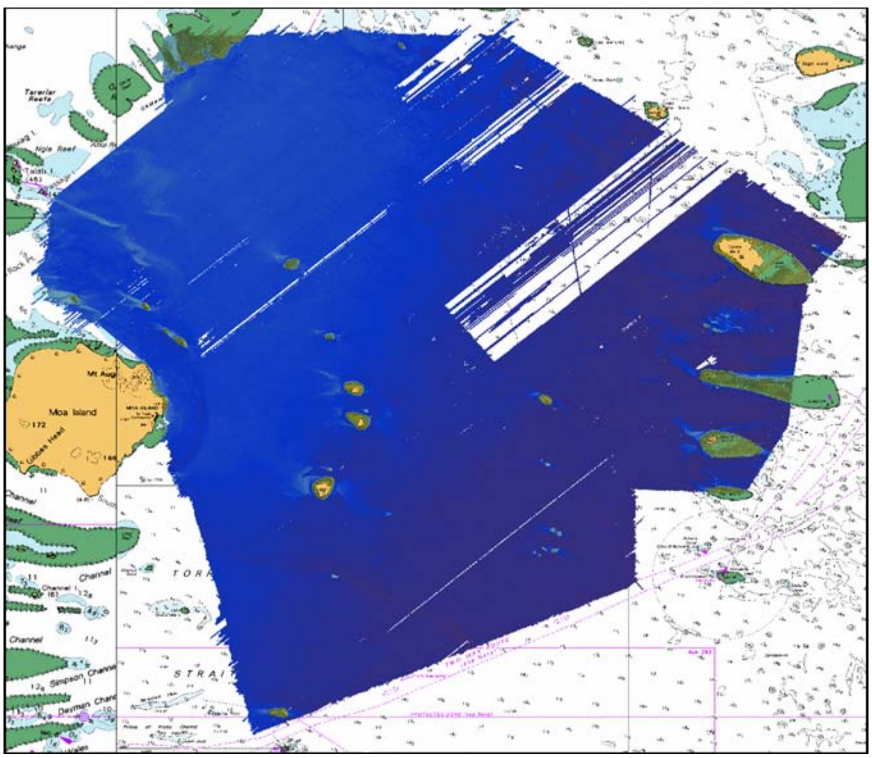
2. SCOPE OF THE SURVEY

In order to facilitate safer navigation and to provide freedom of manoeuvre, the Royal Australian Navy (RAN), set out an ambitious plan to expand the area of surveyed waters within the Torres Strait and northern Great Barrier Reef. This was intended to enhance the capacity of maritime enforcement vessels to protect and secure Australian waters from incursions by illegal foreign fishing vessels.

Seven areas were identified to be surveyed over two years totalling over 16,000 square kilometres. Hydrographic Instructions 436 and 437, the subject areas of this paper, represented two such areas in this scheme. Cognizant of the requirements and standards for work to be carried out for the provision of timely, modern quality charting surveys in the Torres Strait and northern Great Barrier Reef, a LiDAR survey was proposed to execute the work within the agreed timeframe and in compliance with the standards required. HI 436 was reported upon and presented on 24 April 2009, with HI 437 following on 6 July of the same year.


Napoleon Passage
Providence Shoal
Badu Island
Mulgrave Peak
Rugged Pt
Moa Island
Mt Augustus
Gibbes Head
East Point
Simpson Channel
Dayman Channel
Beresford Shoal

HI 436


Moa Island

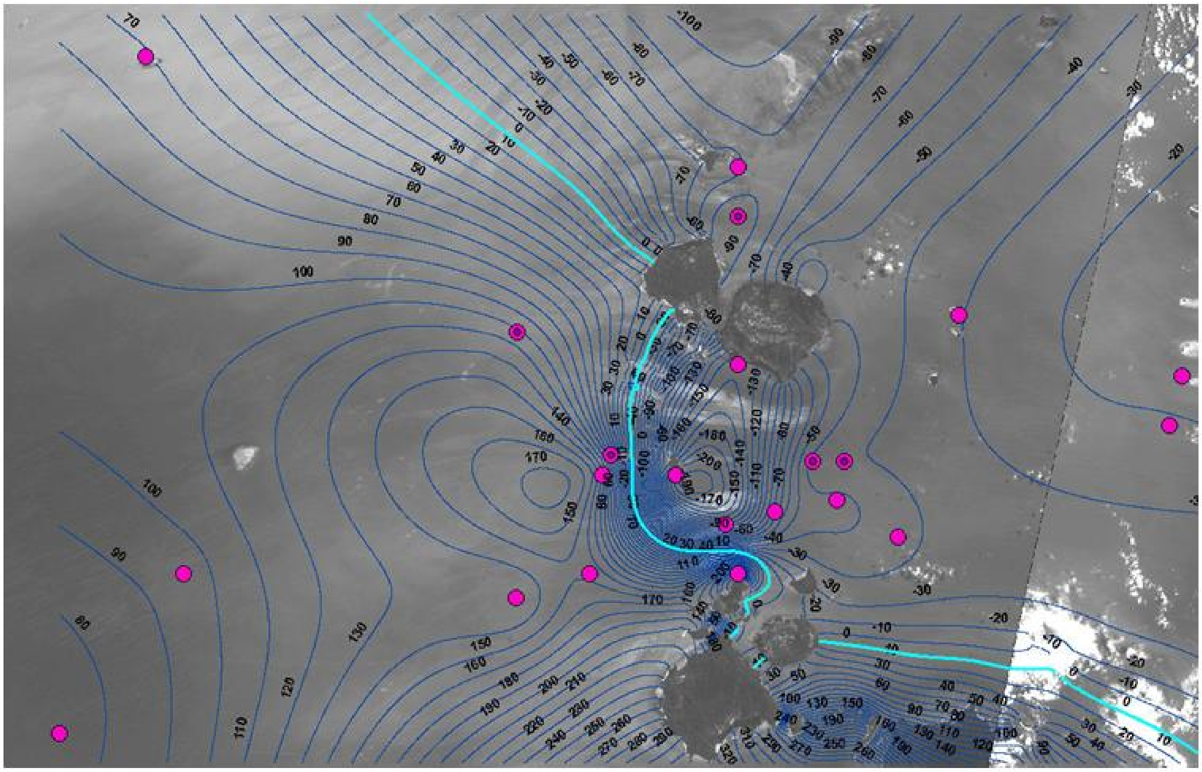
HI 437

2.1 Establishment of Vertical Control

The tidal campaign for this survey was regional in size and represented one of the largest logistic, engineering and physical science challenges of the project. Post-initial 2007 work in HI 436, it became apparent that the early Level of Effort (LOE) estimates would not succeed in solving for this very complex region. This led to the creation of a tidal plan which, once established, would cover both HI 436 and HI 437.

Standard Ports in NP 204 (ATT Vol 4 (at Thursday Island and Twin Island and as supplied by the Client)) provided a reliable source of predicted tides with full constituent breakdown, but the vast majority of other client-supplied data came from tide stations only temporarily occupied in the past (mostly for previous early surveys of the area).

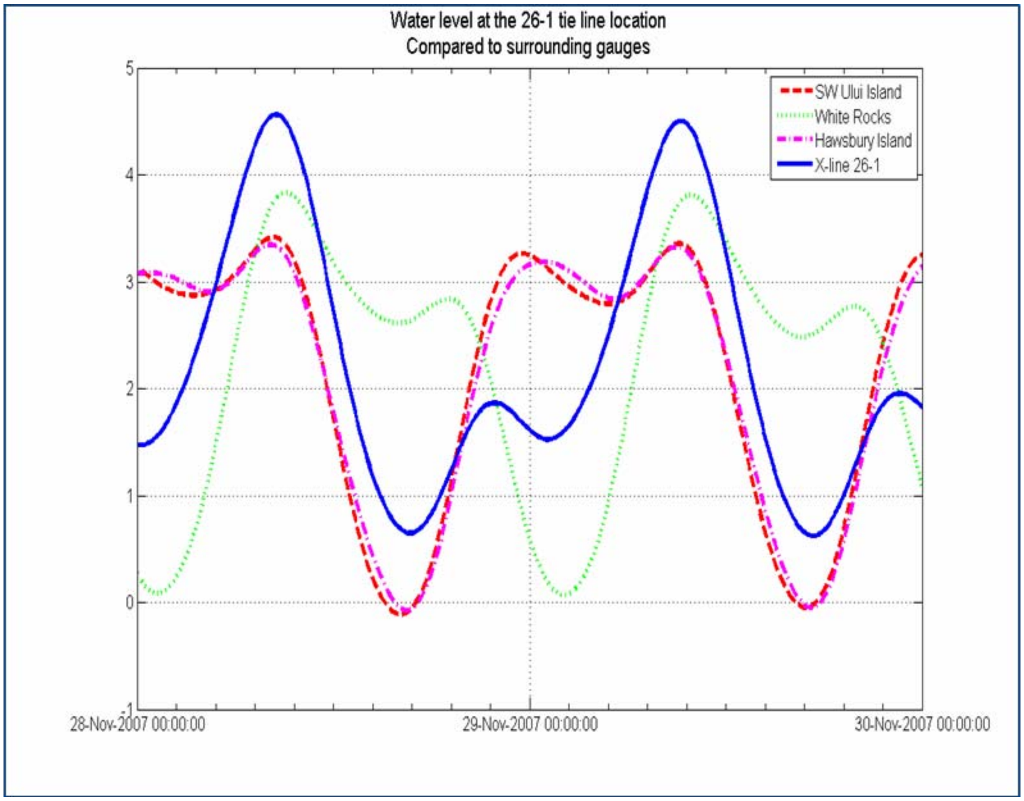
As was mentioned in the preamble, the Torres Strait is subject to a phenomenon which takes place very locally, whereby one class of dominant tidal constituents give way to dominance by another class, such that the nature of the tidal regime is semi-diurnal at one end of the survey area and diurnal at the other, with a broad region of mixed influences in the centre. This is also characterised by the change in the ‘Age of Tide’ which is simply the natural, usually regional time difference between astronomic spring tide and actual highest tide.



Age of Tide Dipole in the Torres Strait

In many regions and ports of the world this equates to roughly 1 or 2 days and can be seen in various published predicted Tide Tables. In this area however it is the ***rate of change of the age of tide*** which is *characteristic* of the change of tidal domain and this is what makes traditional spatial tidal correction methods difficult if not impossible to create for this area, such as discrete tidal zoning or co-tidal modelling. In the former, due to the rapid changes in range and phase, a great many very small zones would have to be designed for corrected bathymetric data to remain within survey vertical accuracy specifications. In the latter case, a standard or representative tidal curve is normally chosen for the entire area, and the phase and amplitude changes determined for various points calculated. However, the general shape of the curve remains the same, in other words the relative nature of the various constituents holds good for the vast majority of the time. This creates a network of similar predicted curves, created from real time observations from the primary tidal station and 'morphed' accordingly. This information is then typically taken as the fiducial nodes in a TIN and a linear interpolative method used to determine discrete values for the entire area under consideration, thus every bathymetric data point has, in theory, a unique tidal calculation applied to it. The problem with co-tidal modelling this area however remains the fundamental variations occurring to various tidal constituents which means there is no 'standard' tidal curve shape for the whole area.

Tidal variability is illustrated graphically below using an example of an actual flight line collected during acquisition of bathymetric LIDAR data with the Optech SHOALS 1000T operated by Fugro. Actual tide gauge data from the gauges surrounding the line in question are plotted to illustrate the range and phase issues and typical tidal error if the wrong process is chosen to reduce for tide.



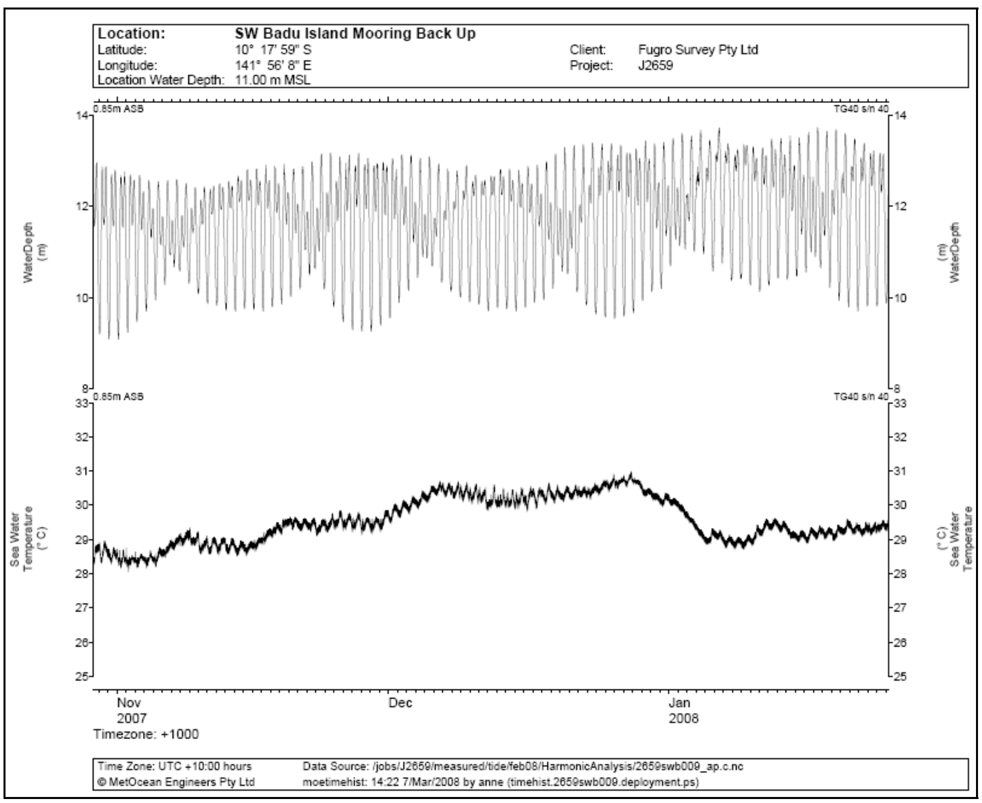
Gauge Comparison Data (Predicted tides only)

Due to the complexity of the area and the desire to create a modelled surface to which the bathymetric data would be reduced, a Tidal Constituent And Residual Interpolation (TCARI) method, originally developed by NOAA (Hess, 2003)[1] was used to build a continuous water level zoning model for these surveys. A description of the model and how it was progressed during 2007 and 2008 appears below. (It is important to include this early development work as it provides a full explanation for the rationale used thereafter.)

[1] *Hess, K., 2003. Water Level Simulation in Bays by Spatial Interpolation of Tidal Constituents, Residual Water Levels, and Datums. Continental Shelf Research, 23: 395-414.*

A wealth of historic tidal data was made available to Fugro through the Client from the Australian Hydrographic Office. Initially, 22 previously occupied stations with full or partial harmonic constituent data were provided. In order to provide this network with sufficient actual data from which to determine the 'real' modelled tide (the astronomic tide (predicted) plus the residual meteorological effects), it was concluded that an additional five tide gauges would be required in HI 436 during 2007; three offshore seabed gauges and two nearshore gauges which would be verified and supported by concurrent tidepole readings in order to ultimately verify the datum on the gauge records. This estimate proved insufficient to capture the complexity of the regime.

For 2008, Fugro GEOS undertook a radically more complex scheme in the continuing assessment of the level of effort and data required to adequately and successfully fuel a spatial constituent model such as TCARI. This was partly raised by concern that the seasonal variations in MSL were more marked than expected, so not only was there a spatial variation in MSL (as anticipated), there was also a very evident temporal variation, as observed in the records at the five MOE stations, exemplified in **Error! Reference source not found.**the SW Badu location:



Evident ramping in Tidal record at SW Badu Tidegauge – 29 Oct 07 – 25 Jan 08

This meant that a much fuller record of actual tide data was required to generate the residuals and to better populate the model for the derivation of the MSL surface and LAT.

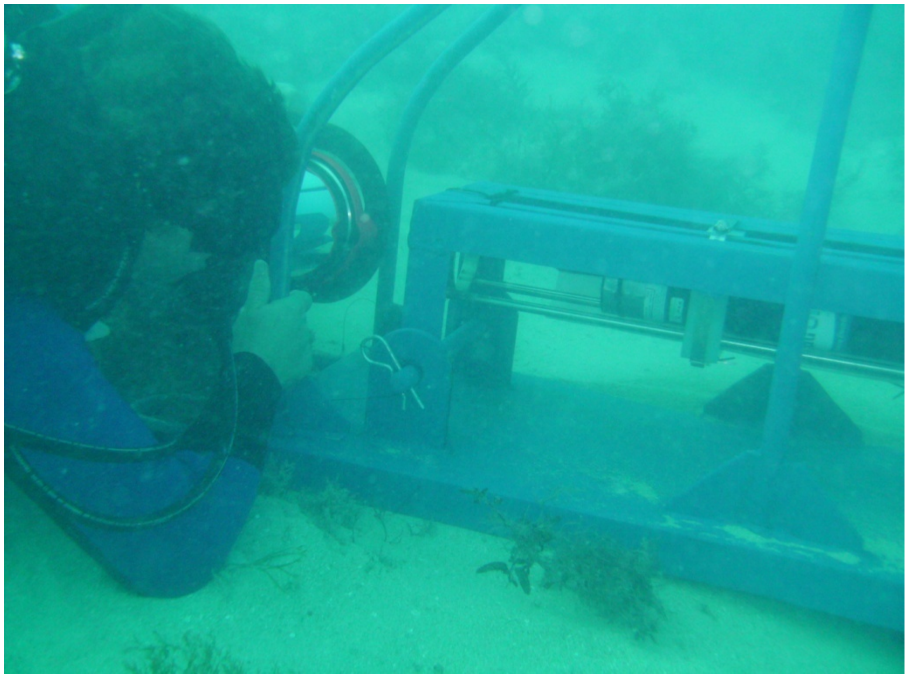
2.2 Tide Observations and Records

It was always the intent to install the tide gauge array for both HI436 and HI437 at the start of the LiDAR effort for Phase 2. If water clarity issues or adverse environmental conditions were present in HI436, Fugro planned to have the ability to continue working by moving to HI437 while waiting for better conditions to complete HI436, and vice versa.

A site reconnaissance trip to the Torres Strait was undertaken to identify locations for shore tide gauges, determine effort required at these locations, obtain permissions from local councils to install the gauges near the island communities, and perform some secchi disk measurements if possible. In addition to the tides, Fugro identified locations to install semi-permanent GPS stations in both HI436 and HI437 so that a PPK position could be computed, should it be required.

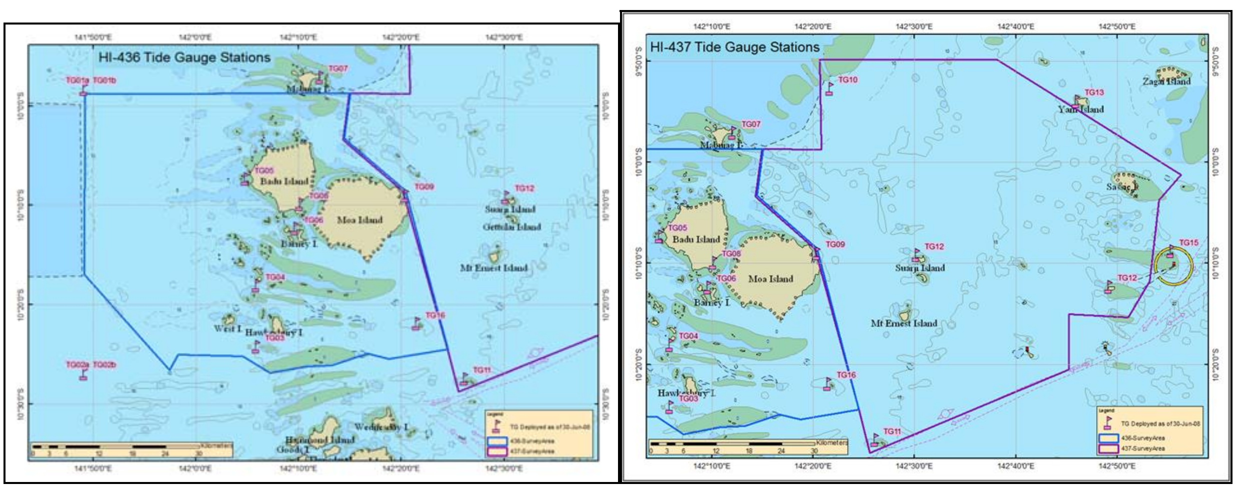
It was identified that gauges could be installed along the shoreline, or on manmade structures at Badu, Moa, Yam, Sue, and Mabuiag islands. At two other preferential sites, West and Twin Island, it was identified that there was no way to install a gauge along the shore, due to the extensive shallow reefs along the coastline and the inability to land a vessel safely on the coast to deploy the tide gauge. Therefore, a deep water, self-contained tide gauge was mobilized for the surrounding areas of West and Twin Island.

At Badu, Yam, and Sue, there were manmade structures which would facilitate protection for a shore gauge, as well as a method to install a tide pole for performing the 25 hour tide watch. A seabed gauge was installed very close to the shore at Mabuiag, so a set of tidal observations could also be planned there despite poor shoreside infrastructure. The sea bottom gauges were installed by lowering the tide gauge mounted in the anchor mooring to the sea bed, and then a final inspection by divers to ensure the system was resting on the bottom correctly. Each sea bed anchoring system had a final weight of approximately 250 kg to ensure the local currents did not move the tide gauge.



Checking the correct operation of an offshore tide gauge

The design of the moorings was such that the tide gauge could be lifted to the surface easily by removing release pins, and therefore allowing servicing if needed. A total of 18 offshore gauges and 4 onshore gauges were thus deployed for the survey areas, as shown below:



Tide gauge locations in HIs 436 &437

At Yam, Sue, and Badu Island, vented shore gauges were installed along with tide staffs. Of these stations, Badu and Yam Island were installed with Iridium satellite data transmission units so their data was broadcast daily back to the field office. Final levelling to the tide staff and 25 hour observations were completed after all gauges were installed. In addition to the tide gauges, the tide program also included the installation of a met station on Thursday Island. The pressure data from this station was used for the correction to the final tide data when the units were retrieved and the data downloaded and processed. A series of wet tests of all tidegauges was conducted before deployment. Data was analysed to ensure conformity and accuracy of results across the entire suite of the Aanderaa WRL7 systems.

2.3 Tide Modelling

The evolution of the considerable tidal modelling effort is succinctly stated in the table below:

Tide Model Summary

	Predicted Model 2007	**Predicted Model 2008**
Astronomic Tide	11 Harmonic Constituents (Amplitude and Phase) from • RAN Supplied Info	11 Harmonic Constituents (Amplitude and Phase) from • RAN Supplied Info • MOE Analysis
Residual	Difference between full harmonic curve and 11 constituent curve at: • RAN Supplied Info	Difference between full harmonic curve and 11 constituent curve at: • RAN Supplied Info • MOE Analysis
	Observed Model 2007	**Observed Model 2008**
Astronomic Tide	11 Harmonic Constituents (Amplitude and Phase) from • RAN Supplied Info • MOE Analysis	11 Harmonic Constituents (Amplitude and Phase) from • RAN Supplied Info • MOE Analysis • GEOS Analysis
Residual	Difference between real data and 11 constituent curve at: • MOE Gauges Only (2007)	Difference between real data and 11 constituent curve at: • MOE Gauges Only (2007) • GEOS Analysis Only (2008)

For 2007, data available was as follows:

- 22 RAN-supplied historic tidal station datasets with a minimum of 11 common harmonic constituents
- 5 real-data stations deployed (by MetOcean Engineering - MOE) for the surveys with full harmonic constituent data available and environmental residuals

For 2008, data available was as follows:

- 45 RAN-supplied historic tidal station datasets with a minimum of 11 common harmonic constituents
- 5 real-data stations (from the 2007 campaign) with full harmonic constituent data available and environmental residuals
- 16 Fugro GEOS real-data tide gauge stations (+2 redundant spares for critical boundary sites: total 18) were sown to fulfil the requirements for both survey areas.

3. TCARI

As mentioned earlier, the TCARI model was implemented in order to combat the variability in the tidal regime at the harmonic constituent level. The TCARI model consists of two main parts:

- The constituent interpolation (Astronomic Tide), and
- the residual

Both of these together gave the water level value applied to the survey point data. To build the model, it was first necessary to identify all common constituents from the harmonic analyses of

all the gauges in the area. The area was then divided into a 0.01^0 (approximately 1km) resolution

grid, and constituent amplitudes and phases were interpolated throughout the area using the Laplace equation with Neumann (no flow) boundary conditions at the shorelines. These constituents provide the astronomic tide for the area. During the field phase of this project the residual consisted of the difference between the common constituent solution and the full constituent solution at the gauges. Once final tides were available, the residual consisted of the difference between the common constituent solution and the verified tides at the gauges.

It should be stressed that, as the TCARI model is reliant on a common set of constituents at each gauge, such a mixed regime as that encountered in the Torres Strait effectively reduces this common population, so any prediction created by TCARI without actual water level information (i.e. the ability to derive the residual) leads to large misclosures compared to actual water levels. Where there are particularly dynamic changes in MSL over the course of the year, for example west of the Moa-Badu reef complex as witnessed from the original data collection during October 2007 – February 2008, large misclosures (due to the omission of dominant harmonic constituents such as Sa (Sun Annual) and Ssa (Sun Semi-annual) and climatic factors not taken into account by astronomic harmonic factors) are created.

Data capture during the campaign was conducted in three phases or deployments; from November 2007-January 2008; from June-September 2008 and from September 2008 –January 2009. The later 'break' was to account for a servicing and data download to be conducted mid-survey. Due to the need to 'stitch' both records at each station together to cover the period where the gauge servicing created a gap in cover, an iterative step was employed before final harmonic constituent values were derived. The process was thus:

- An initial harmonic analysis was conducted using the gauge data for the deployments.
- Using this data, a tidal prediction routine was generated to fill the data gap between deployments due to the servicing routine.
- The harmonic analysis was repeated using the 'seamless' data to generate coefficients and derive a complete record of water level files. (This process created the need for the iteration and subsequent steps below as it became clear that the predicted portion was not always a satisfactory match between the two datasets at each site.)
- The water level files were then separated again into deployment subsets by removing the predicted portion used to fill the gap between the deployments. To do this, the recorded start and end dates were used for each gauge.
- From these files, Fugro calculated the mean tide level correctors for each gauge/deployment.
- Next, the applicable MTL corrector for each gauge was applied for both the first deployment and second deployment.
- The prediction routine was then re-run for each gauge to fill in the gap between deployments using *full harmonic constituents* for that gauge.
- The first deployment, predicted gap, and second deployment were then re-merged into one file for each gauge.

The first step was then repeated:

- This version of the merged data, with vastly improved prediction portions 'closing' the first and second deployment real data, resulted in MTL corrected observed water level files as well as the site-specific correctors that were used for each gauge/deployment.

- A new set of harmonic constituents was then derived from the MTL corrected observed water level files.
- Once the new harmonic constituents were generated, the observed water level files were again split back into first and second deployments by removing the predicted portion.
- A final recalculation of the predicted portion using the new harmonic constituents was conducted and then remerged to include the first deployment, new predicted gap, and second deployment back into each file.

Common constituents used for the model included K1, K2, M2, M4, MS4, MSF, N2, O1, P1, Q1 and S2. For every time, latitude and longitude that a water level was required, the following occurred:

- The astronomic tide is calculated from the constituent amplitude and phase data. Bi-linear interpolation was used between grid nodes.
- The residual was calculated for the entire grid, using Laplace's equation and then interpolated to the Latitude and Longitude value for the data point in question
- The astronomic tide and residual were summed to give the water level

3.1.1 Summary of the Tidal Model

For a given longitude, latitude, and time:

1. Tide coefficients were calculated using Laplace surfaces for Amplitude (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MSF, MS4) and Phase (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MSF, MS4).
    - Laplace surfaces used nodes from 17 RAN historical stations, 5 MOE and 16 GEOS observed gauges.
2. Datum was determined using a Laplace surface of Datum.
    - Laplace surface used nodes from the 17 RAN historical stations.
3. Tide value was calculated by adding the tide coefficient (#1) to datum (#2).
4. Residual was calculated by creating a residual surface based upon the 5 MOE and 16 GEOS observed gauges using Laplace.
    - For each Observed gauge:
        a. Tide coefficients were calculated using Amplitude (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MSF, MS4) and Phase (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MSF, MS4) values retrieved from the Water Gauge Info files.
        b. Datum was retrieved from these Water Gauge Info files.
            - Note: Datum is 0 for Observed gauges. The reason for this is that the actual water level gauge data is not referenced to a datum.

c. Calculated tide value by adding tide coefficient (#a) to datum (#b).
d. Retrieved the water level for the given time using linear interpolation between closest time intervals.
e. Subtracted water level (#d) from tide value (#c).

- Use Laplace to create residual surface for residuals at 5 MOE and 16 GEOS Observed gauge locations.

5. Calculated prediction by adding tide value (#3) to residual (#4).

In all cases where a Laplace surface was used, the actual value was interpolated linearly from the 4 closest grid nodes. The reason for this is that the input Laplace surfaces came in the form of a matrix which was gridded every 0.01 degree.

4. ASSESSMENT OF MODEL PERFORMANCE AND PSEUDO GAUGE REINFORCEMENT OF TCARI

The model was endeavouring to create a spatial correction to a very complex tidal region. In order to confirm that the correct assessment of tide, with respect to space and time, had been made within acceptable tolerance, an empirical assessment was made of all survey blocks. This process was slightly iterative as resolution of the model was unintentionally weakened by design in certain places due to a more dynamic regime than anticipated and known errors in accurately determining the correct datum transfer values in others. In particular, the rapid change in datum and regime type in the approaches to Bligh Channel, north of Moa and affecting several blocks, exerted its own pressures on the model's ability to adequately interpolate the tide in this area.

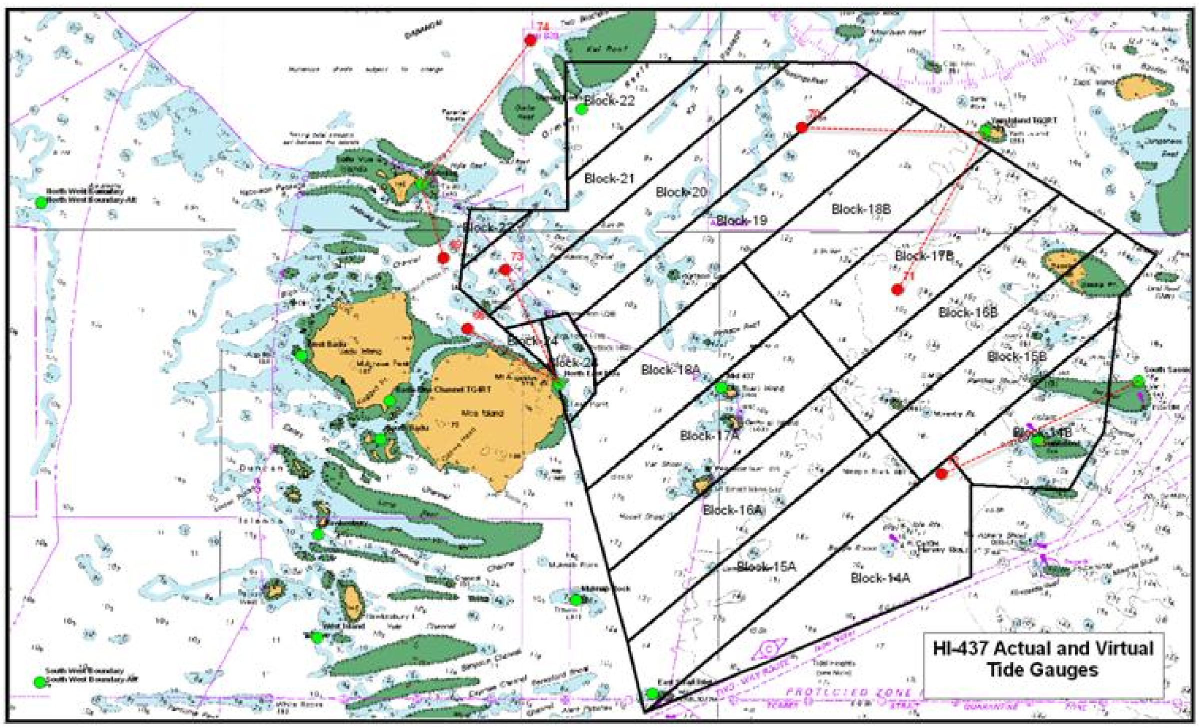
Another limitation was that drying areas were not part of the boundary conditioning solution for the model (just island landmasses) and so certain gauges were afforded too much influence in the interpolative process in the model. The main example of this with respect to HI 437 was the station at Mabuiag. Not only was the gauge sited on the north of the island and therefore facing away from the region it was supposed to provide tidal data for, it was also virtually surrounded by very extensive drying reef. This meant that the modelled tidal situation NE of Badu in the eastern end of Bligh Channel and further points east toward the more open water found in the rest of the survey area did not strongly reflect the actual datum relationship, phase, amplitude or indeed nature of the tide in that area.

A similar situation arose down the 'spine' of the survey area (see below) where the model's ability to accurately interpolate what was happening was limited by distance from the tide gauges established. This was further compounded by an inherent weakness in the datum transfer from Ince Point, essentially in a mixed tide regime, to other stations which were in a predominantly diurnal domain. A need to 'create' a 'pseudo-station' to provide a boundary condition beyond the northernmost fringes of the area created a third reason for augmentation of the original tide plan.

In order to reinforce the model therefore and to provide it with a theoretically more sound determination of the tidal situation in those areas where the empirical data was indicating a misclosure, seven ‘pseudo gauges’ were generated from actual gauges and inserted. These were created and ‘installed’ as follows:

Pseudo Station No.	Parent Station No.	Parent Station Name	Pseudo Gauge Lat (S)	Pseudo Gauge Long (E)	Block Applied To
68	59	Moa	10 05’.700	142 14’.880	OOA*
69	57	Mabuiag	10 01’.500	142 13’.440	OOA*
70	63	Yam	09 53’.748	142 34’.962	19/20
71	63	Yam	10 03’.408	142 40’.734	17B
72	65	Sassie	10 14’.376	142 43’.464	14A
73	59	Moa	10 02’.802	142 17’.124	21
74	57	Mabuiag	09 48’.606	142 18’.594	OOA*

OOA*: Out Of Area (boundary control outside of HI limits)



Actual (green) and Virtual (red) Gauges utilized in TCARI Model (with relationships indicated between virtual and actual gauges)

Resulting misclosures in the blocks concerned and indeed in surrounding blocks were found to be within specification for vertical accuracy (IHO Order 1). Insertion of the gauges had the desired effect of reducing the directional influence of a non-representative dataset and relieving the distances over which the interpolative part of the model was struggling to infer the water level in the more complex or remote parts of the survey. It was recognized that this amendment essentially corrected for an earlier miscalculation in the number of actual gauges required in order to meet specification, but since no less than 22 tidegauges were deployed in and around the survey areas, it was more a measure of the very dynamic nature of the area rather than any non-address of the issue or inability to tackle the tidal conundrum which created the need for the pseudo gauge 'installation'.

One last refining of the plan was considered but not put into practice due to insufficient time to properly test and evaluate the results. Although specification and accuracy requirements were met in the survey area, it was felt that the simple translocation of actual tidal data could have been improved by employing a co-tidal assessment to a local situation. Given that the surrounding gauges were tested for effectiveness in solving a tidal problem and just one 'best fit' used on each occasion, by inference the most representative curve was being selected for corrective action.

Using the harmonic analysis to determine not just MSL and the various constituents but also range and phase comparisons between defined events (such as MHHW or MHWI for example), a comparison between gauges could have been made in the same way that datum transfer at various gauges was used to create a datum surface in TCARI. Hence the model could yield range and phase correctors to a nominated, translocated gauge to create a pseudo, co-tidally corrected tidal node based on actual water levels and modeled, interpolated correctors.

4.1 Approximation of Chart Datum and reduction of LIDAR Data

Soundings obtained from LiDAR data for this survey were related with respect to the initial IR or Green laser return from the sea surface. In order to relate these relative soundings therefore to Chart Datum (LAT), temporal and spatial tidal modelling was necessary to reduce this surface through a series of correctors to datum. The tidal model used established a mean level by observation for each tide gauge location and, based on the tidal range at these points, a separate *relative* lowest astronomical tidal value for LAT was created. The determination of this value in an absolute sense was established through a datum transfer technique. This technique is described in the National Oceanic and Atmospheric Administration (NOAA) Special Publication NOS CO-OPS 2, "Computational Techniques For Tidal Datums Handbook" and specifically at Section 4.3.3 (Standard Method – Mixed Tides). It was acknowledged that it was vital that suitable standard port-quality stations for which a reliable LAT had already been established would have to be used to make this calculation for the 'family' of offshore gauges within the same regime.

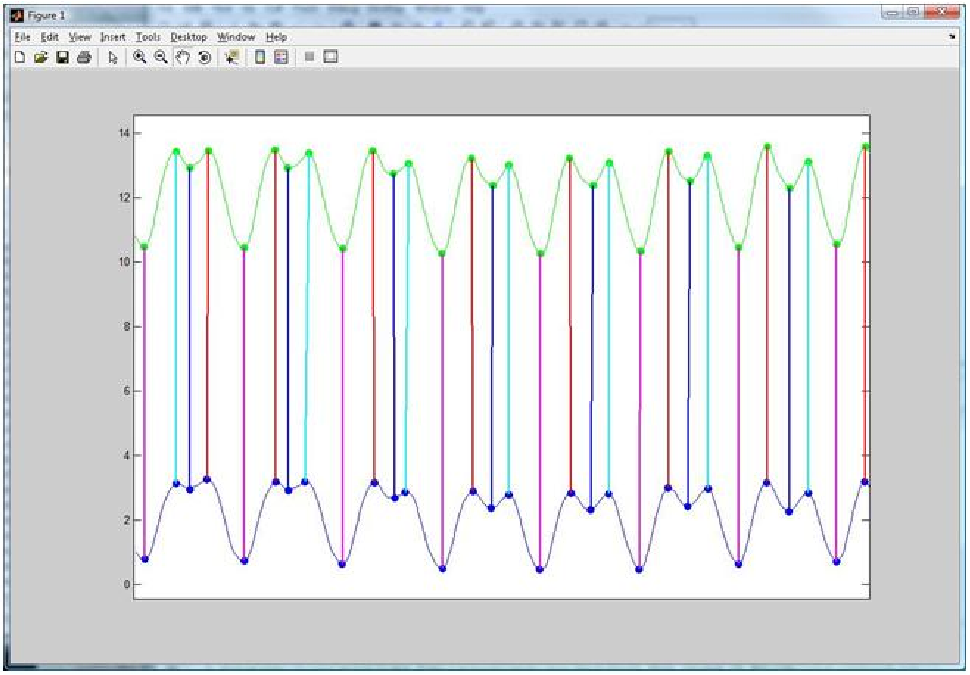
To take HI 437 as an example, this required the use of data from RAN stations 58140 (Ince Point) and 58230 (Booby Island). Ince Point lies to the south-west of the survey area in the region where mixed tides were prevalent and changes in regime most abrupt. Booby Island is considerably to the west of the survey area but nonetheless has an effect, having provided the western reference station of the datum transfer part of the overall TCARI model. Perusal of the changes to the main constituents of these stations reinforced the fact that the primary constituents highlighting a tidal regime change (and as illustrated succinctly by the abrupt change in the Age of Tide values) was evident in the following excerpt of constituents for Ince Point and Booby Island:

58140	INCE POINT	
(10 31' S 142 18' E)		
Constituents	**Amplitude (m)**	**Phase**
LAT	1.6900	
SA	0.0914	328.2968
O1	0.2629	9.9262
K1	0.5333	58.4741
M2	0.3656	111.8169
S2	0.4115	41.1153

58230	BOOBY ISLAND	
(10 36' S 141 55' E)		
Constituents	**Amplitude (m)**	**Phase**
LAT	2.4100	
SA	0.2780	313.4806
O1	0.4247	352.2939
K1	0.6901	44.0505
M2	0.7145	201.4671
S2	0.1385	322.5431

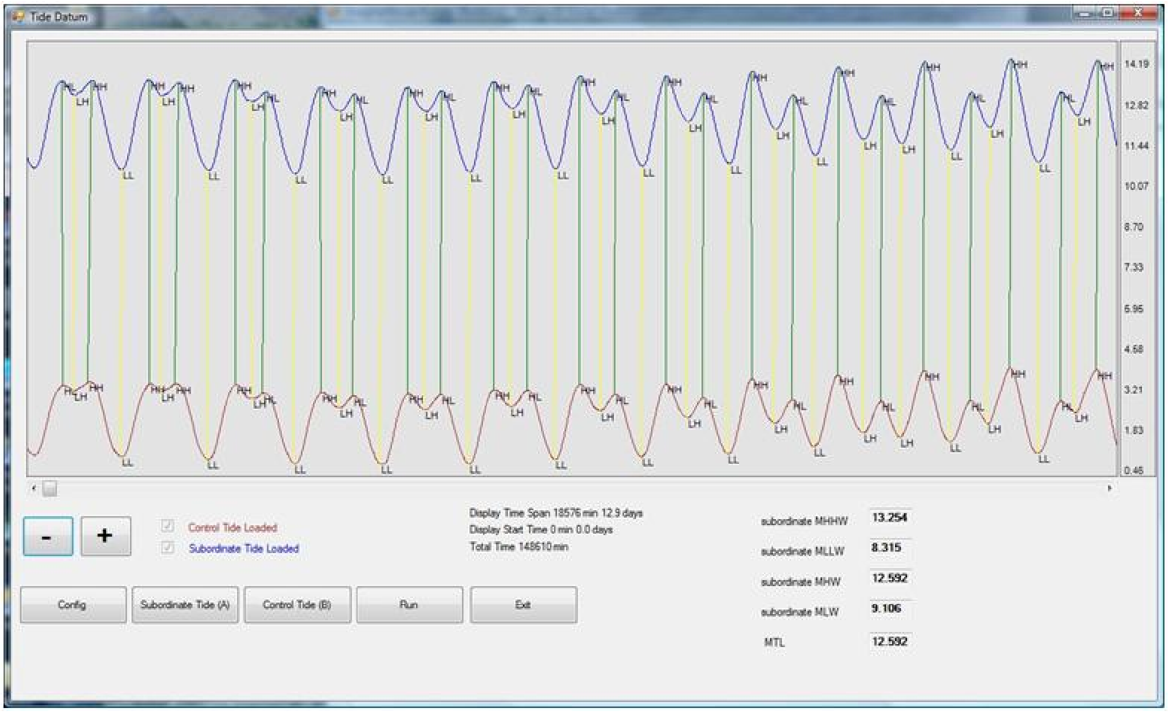
Major harmonic constituent shifts – Ince Point and Booby Island

In order to determine the values of LAT for the various offshore gauges located throughout the area, a technique utilizing Matlab software was established which related the appropriate peak-to-peak, trough-to-trough pattern between the primary gauge and the subordinate offshore gauge. The longest term possible comparison from available data was used to refine the derivation of Mean Tide Level values for the offshore stations. This was equated to Mean Sea Level; an inaccuracy which was acknowledged but mitigated through observation of tides over as long a term as possible to reduce the effect of variance in the high and low water diurnal inequalities creating asymmetric tidal curves and possible disparate values between MTL and MSL. The software allowed for a degree of flexibility in creating the associations between paired peaks and troughs where period and phase differed through the tidal cycle. This allowed creation of the associations necessary to make the MTL transfers thus:

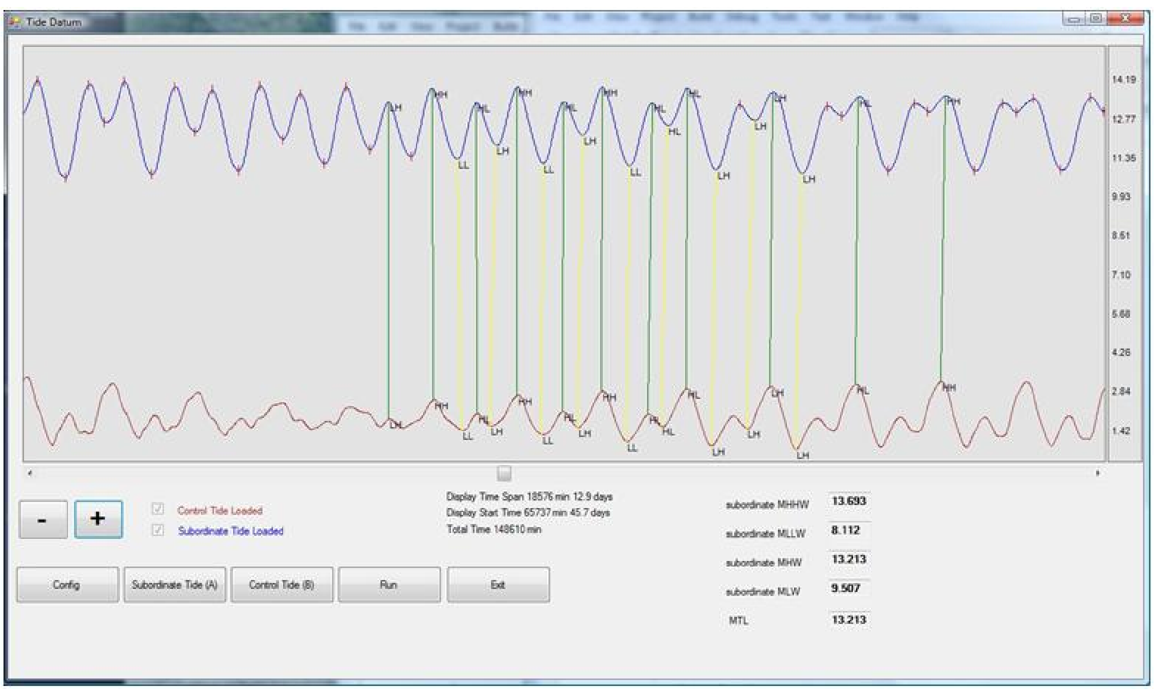


Example of Datum Transfer Analysis

This method was not without problems: if the subordinate gauge does not pattern well with the primary gauge, the transfer becomes statistically weak. An example of a good transfer and a poor transfer was possible by using data from the Northwest Boundary (TG01) GEOS gauge and comparing it with Booby Island (good result) and Ince Point (poor result):

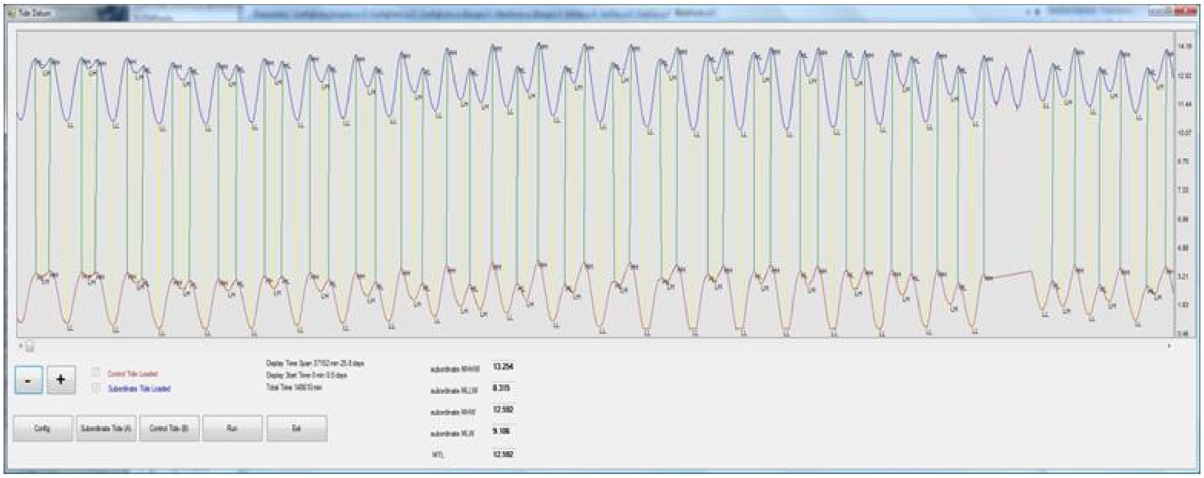


Datum Transfer Results with a suitable Primary Gauge



Datum Transfer Results with an unsuitable Primary Gauge

Even with a well-matched pair of gauges, phase comparison occasionally broke down before the conditioning parameters in the configuration file allowed acceptable match-ups to commence again. An example of this situation is shown below and highlights the degree of care and caution that had to be taken when validating this technique.



Gap in Splining due to Erroneous Gauge Data at Primary Gauge

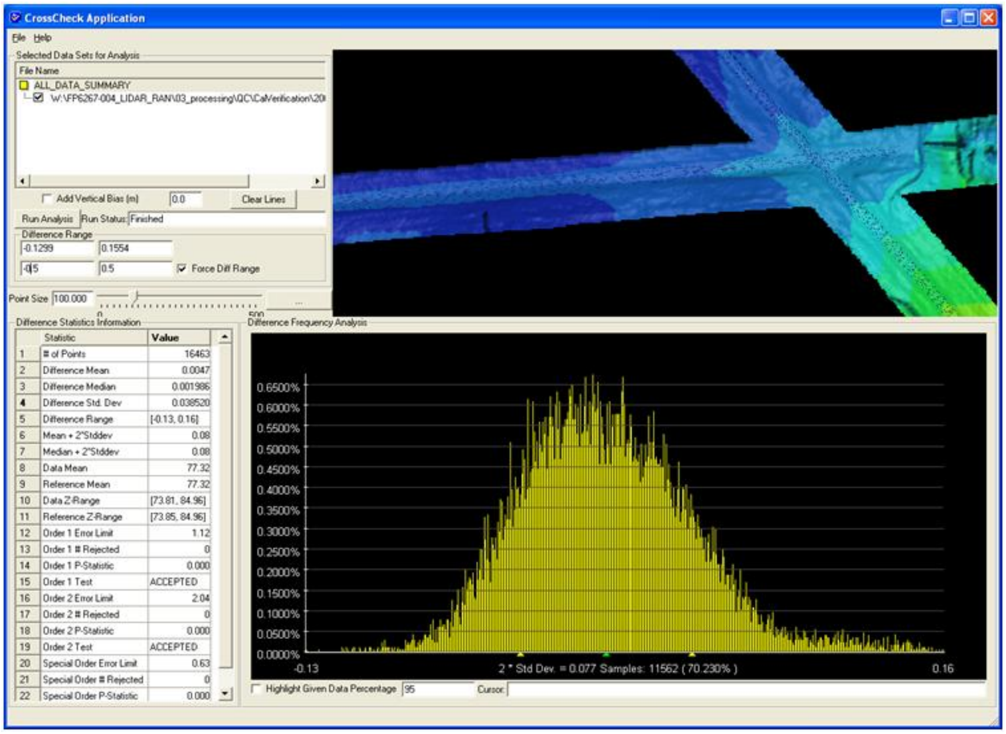
The following steps were used to determine a value for MTL (MSL) for the offshore gauges:

- The initial procedure was to use the constituents extracted from harmonic analysis of the actual gauge data and to run a tidal prediction program for a full 18.6 year cycle to extract an LAT value; this is normally referenced with respect to mean level.
- This relationship is then corrected with the calculated, absolute value for MTL/MSL to produce an offshore LAT value at the gauge.
- Throughout the survey area this process was repeated and an LAT datum surface created in the TCARI model.
- The model then used this data to determine the spatial and temporal predicted portion of the solution.
- To this was added the interpolated residuals created in TCARI to provide a tidal reduction value for each data point.

The water surface detected by LiDAR was thus corrected to a value with respect to this LAT surface. Additionally, the datum relationship to the reference ellipsoid was obtained at several shore stations by levelling in a tidepole, measuring the physical offset between the zero of the pole and the measuring point of the nearby tidegauge, establishing the gauge with respect to the reference ellipsoid and comparing this solution at each station with the computed relationship through the datum transfer method.

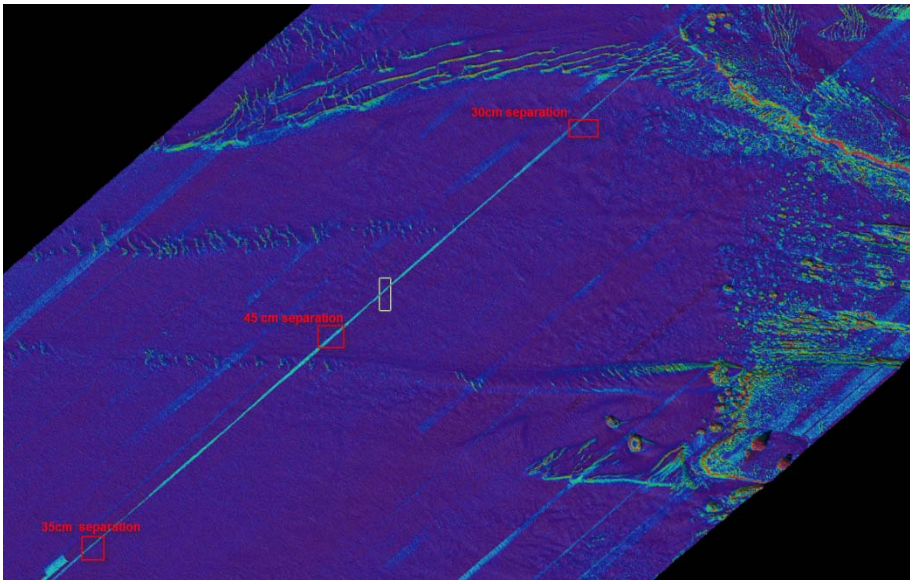
4.2 Spatial Analysis

A computational crossline analysis tool in IVS Fledermaus was used to statistically determine the overall correctness of the model, given that the crosslines and mainlines were obtained at different states of the tide.



Statistical Analysis of Cross Check Routines

This analysis formed the most fundamental QC check of the actual bathymetric data as it incorporated the entire pool of errors associated with each LiDAR shot. A complete record of crossline and surface comparison statistical analyses was carried out for each survey Block, by comparing the crossline and main dataset point data and determining the variance and distribution patterns/trends of the misclosures. The use of a standard deviation surface output available in the Fledermaus software suite allowed the surveyors to examine any dataset biases, systematic or gross errors detected. Geographic relationships between these errors and the location of the tidal model nodes (whether actual or 'pseudo') identified potential water level or datum calculation errors spatially such that remedial action could be carried out to achieve the accuracy tolerances required for the survey data.



Spatial Analysis of Standard Deviation Surface derived from the LiDAR Point Cloud

5. CONCLUSION

The complexity of the tidal regime prevalent in this region of the Torres Strait necessitated a constituent-level approach to the derivation of various tidal datums in a number of carefully selected tide gauge locations. Actual, long-period observations were necessary to derive not only the tidal harmonic constituents at a site but the determination of the mean level and its variance with time. Calculation of datum through long term comparison of predicted data modelled from actual harmonic analysis with fiducial, historic ‘primary’ nearby stations was a necessary step in determining MSL and thus a LAT (CD) surface, from which the TCARI modelled tides were referenced. By then reducing each point for a modelled astronomic tide, then applying residual value correctors through the TCARI model for the actual corresponding timeframe, the correct adjustment to the sea surface value with respect to the datum was achieved, and from this the actual soundings were obtained. The Laplace equation interpolative method was used to create the spatial interpolation emanating from the fiducial ‘sources’ (tide station nodes) for the entire LIDAR point cloud in this near-6000km^2 area. Data volumes themselves assisted in the creation of numerous areas of overlapping, temporally separated data, through which both crossline comparisons and area standard distribution surfaces were derived for QA purposes.

REFERENCES

[1] *Hess, K., 2003. Water Level Simulation in Bays by Spatial Interpolation of Tidal Constituents, Residual Water Levels, and Datums. Continental Shelf Research, 23: 395-414.*

BIOGRAPHICAL NOTES

Don Ventura is a charge hydrographic surveyor with Fugro Pelagos Incorporated of San Diego, California. Don is a retired Royal Naval officer and has 28 years of experience in the field of hydrography, oceanography and marine geophysics. He is currently supporting Fugro Pelagos' business marketing department but also provides operational and QA support to the Company's global Airborne Lidar Bathymetry business, which also includes frequent interaction with Fugro LADS Corporation in Adelaide. Past work experience during a 22 year Naval career included various appointments at sea and secondments to the United Kingdom Hydrographic Office and the US Naval Oceanographic Office, during which Don became increasingly interested in the training of hydrographic surveyors. He has also worked in support of NOAA's National Data Buoy Center at Stennis Space Center, Mississippi, specifically with the DART tsunami and TAO pan-Pacific oceanographic monitoring arrays. He lives in Louisiana with wife Jane and 2 grown-up daughters.

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