Water Level Measurement and Tidal Datum Transfer Using High Rate GPS Buoys

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Key words: GPS Buoy, Tidal Datum Transfer, Cadastral Boundaries, MHWS, Sea Level

SUMMARY

The transfer of tidal datums using high rate GPS buoys offers advantages over traditional techniques, which may be limited by their practicality, efficiency and cost. This paper describes an experiment where two GPS buoys were deployed simultaneously near two tide gauges within Otago Harbour, New Zealand. The tide gauge records were used to verify, first, that GPS buoys can measure water levels, and second, test the accuracy to which a tidal datum can be transferred based on water levels estimated by the buoy. It was found that a datum could be transferred at similar accuracy to previous experiments, concluding that GPS buoys are a viable means of tidal datum transfer.

With rising sea levels and an increasing demand for coastal properties, cadastral surveyors and engineers need to be able to readily define cadastral boundaries both reliably and accurately. The use of GPS buoys has the following advantages for tidal datums transfer:

- Efficient datum connections between the GPS buoy and benchmark.
- Expedient and relatively easy data collection.
- Existing GPS equipment can be used.
- GPS buoys can be deployed in close proximity to the shore and do not have to be attached to an existing tide gauge instrument.

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1. INTRODUCTION

Tidal datums are used for a number of important purposes. They provide reference surfaces for navigational charts (e.g. chart datum, Chang and Sun (2004)); height datums (e.g. mean sea level, Hannah (1989)); as an indicator of climate change (Pugh, 2004) and as the basis for defining various coastal cadastral jurisdictional boundaries (Baker and Watkins, 1991). For some applications, a tidal datum must be transferred between locations and tide gauges have typically been used in the past. However, with GPS buoy technology being capable of estimating heights at the low centimetre level, it could provide a viable alternative method. A GPS buoy is essentially a GPS antenna mounted on a floating platform.

Traditional methods and techniques have limitations in practicality, efficiency, cost and accuracy (Goring, 2007). Dewar and Hannah (2005) discussed two general methods for transferring tidal datums using levelling (either spirit or GPS levelling) and tidal datum transfer techniques. Firstly, levelling can be undertaken using an established gauge as a starting point. Unfortunately today, terrestrial (or spirit) levelling is time consuming, expensive and typically requires extensive logistics, such as traffic management planning. Alternatively, GPS levelling, which measures ellipsoidal height differences, can overcome many of the problems associated with terrestrial levelling, but does require a high quality geoidal undulation model. Both levelling techniques ignore local sea surface effects. Secondly, tidal datum transfer methods can be used, where a temporary tide gauge is set up at a remote site and the datum transferred by comparing tidal observations at both the temporary and a nearby permanent gauge. Traditionally in cadastral surveying, a simple tide staff is used at the remote site, which can be inefficient and has a low level of accuracy due to the manual observations required. More generally, tide gauges may be difficult to install at many locations where it is difficult to rigidly fix them.

Using a GPS buoy to measure water levels offers many advantages over traditional techniques with its ability to determine heights relative to an absolute reference frame. While large scale GPS buoys have been used for long-term datum determination (e.g. Arroyo-Saurez *et al.*, 2005), there has been little research involving light-weight designs for short-term tidal datum transfers. However, Abidin (1999) did suggest that small systems using GPS did show potential for this type of application. The purpose of this study was to determine the viability of GPS buoy technology in transferring tidal datums. In particular, the ability of a high rate GPS buoy to measure the sea level was verified by determining its precision and accuracy relative to tide gauge observations. Furthermore, it aimed to demonstrate how accurately a tidal datum could be transferred using the sea levels estimated by the GPS buoy.

The experiment was undertaken in Otago Harbour - a 22 km long tidal inlet that is located on the eastern coast of the South Island of New Zealand. Existing tide gauges, located approximately 10 km apart, were used to provide a means of calibration and comparison. These were situated at two port facilities, Port Chalmers and the Dunedin Wharf (Figure 1).

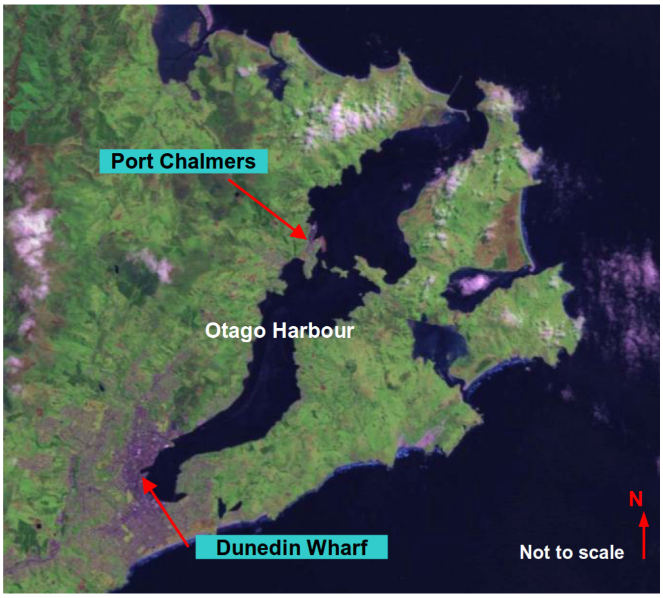


Figure 1: The Otago Harbour tide gauge deployment locations

2. WATER LEVEL MEASUREMENT USING GPS BUOYS

Since early designs in the late 1980's (e.g. Kelecy *et al.* (1994)) GPS buoy technology has rapidly progressed in both design and applications. This has been largely driven by their use for absolute calibration of satellite altimeters (Schone, 2001), with applications ranging from tsunami monitoring (Kato *et al.*, 2001) to river level monitoring (Moore *et al.*, 2000). Research has typically involved three types of design:

1. Lightweight wave rider, which must be tethered and operated from a boat
2. Autonomous lightweight wave rider, housing all the necessary equipment within the buoy
3. Autonomous, large scale buoy for use in long-term rugged environments

The advantages, disadvantages and applications of these designs are summarised in Table 1.

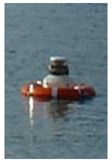
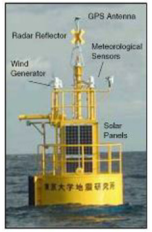
GPS Buoy Design	Description	Advantages	Disadvantages	Application Examples
Lightweight wave rider (antenna only)  e.g. (Key et al., 1998), (Cheng, 2005)	• A light-weight buoy usually using a life preserver as the floatation source • The buoy can be operated from a boat and only houses the GPS antenna • The antenna offset from the mean water level is small, typically positioned 50–250 mm above it	• Economical and simple to construct, with low cost materials that are readily available • Easily portable with their small size • No need to monitor and correct for the buoy's tilt • Low centre of mass	• Logistical support is required throughout the entire deployment (personal and boats) • Lack of versatility with the tether required • Deployment restricted in rough sea conditions • Short duration deployments only (Watson, 2005)	• Absolute altimeter calibration • Tidal Datum Transfer • Orthometric height transfer over water (measuring geoidal slope) • River and lake level monitoring • High frequency wave analysis • Mapping the sea surface
Autonomous lightweight wave rider   **e.g. (Parker, 2007)**	• A light-weight buoy as above, except it houses the GPS receiver, antenna and battery • Can operate autonomously, either: anchored, drifting or tethered	• As above • Reduced logistics considerations, with autonomous operation of up to 5 days	• As above • Reduced logistics considerations • Deployment time is still limited to short to medium terms	• As above • Verifying and calibrating tide gauges • Applications requiring autonomous (stand alone) operation for periods <1week
Autonomous, large scale  e.g.(Kato et al., 2001), (Arroyo-Saurez et al., 2005)	• A large, rugged buoy that houses the GPS system in addition to power storage and generation and data communications • Can operate autonomously for significant durations • The antenna reference point is typically 5-7 m above the mean water level (Watson, 2005)	• Can operate for long time periods and in rough sea conditions • Additional sensors can be integrated into the buoy, such as meteorological instruments (Watson. 2005)	• High Cost • Not easily portable • Can be difficult to measure and correct for buoy's tilt influencing the antenna's position above the water level. • Reliability issues with power and communications (Watson, 2005)	• Tsunami monitoring • Tidal Datum Determination • Absolute altimeter calibration • Long term tidal monitoring

Table 1: Advantages, disadvantages and applications of the three major GPS buoy designs. Table layout from Watson (2005)

3. METHODOLGY

3.1 GPS Buoy Design

The GPS buoy used in this study is of the wave rider style that was designed to operate autonomously. It consisted of a simple square block of polystyrene with the GPS box inserted into its centre. This box contained the GPS receiver (Trimble 5700) and battery, with the antenna (Trimble Zephyr Geodetic) fixed on top (Figure 2). Both the tether and shape of the buoy were key design considerations as they have the potential to influence the buoy's dynamics and therefore the mean vertical position above the water surface. In order to reduce any effects due to the anchor system's movement on the buoy's vertical position, the buoy was connected to a secondary float before being attached to either an anchor or pile.

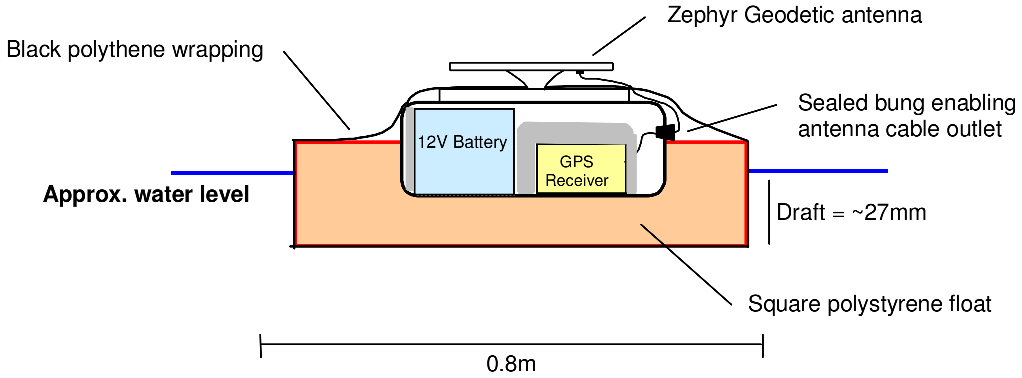


Figure 2: Sectional view of the GPS Buoy

3.2 Antenna Height Offset

Determining the height of the antenna above the mean water surface is a fundamental part of measuring absolute sea surface heights. In this experiment a spirit level and lightweight measuring rod were used to measure the height difference between the centre point on the top of the antenna and a bench mark that the water level had been raised to. This was carried out in a controlled environment using a temporary tank filled with fresh water with the buoy in its full deployment state. A correction for ocean salinity was made to the height difference between the antenna reference point (ARP) and mean water surface. The antenna offsets for the buoys were ~ 0.264 m ± 0.002m.

3.3 Deployment

Two GPS buoys were deployed simultaneously at Port Chalmers and Dunedin Wharf (Figure 1) within close proximity to existing tide gauges. Observations were made at a 5-second rate over a period of four days. Higher rates, such as 1 Hz are frequently used for GPS buoy data collection (Watson, 2005), however the difference in the precision and mean of the height difference between the tide gauge and GPS buoy was less than 1 mm when the higher rate was used. Because of the difficulties in processing and managing the increased data, 5-

second epoch observations were made. A minimum of 3 days is required for successful use of the range ratio method of tidal datum transfer (Grant and O'Reilly, 1986), with four days of tidal observations providing sufficient data to verify the GPS buoy's ability compared to the tide gauges. These observations were post-processed using GPS reference stations co-located with the gauges. Outliers were a common feature of the processed GPS heights and were identified by the clear jumps in the heights compared to the tidal pattern. These were possibly caused by the carrier phase ambiguities being incorrectly resolved and were removed. Figure 3 shows the GPS buoy being deployed at Port Chalmers.

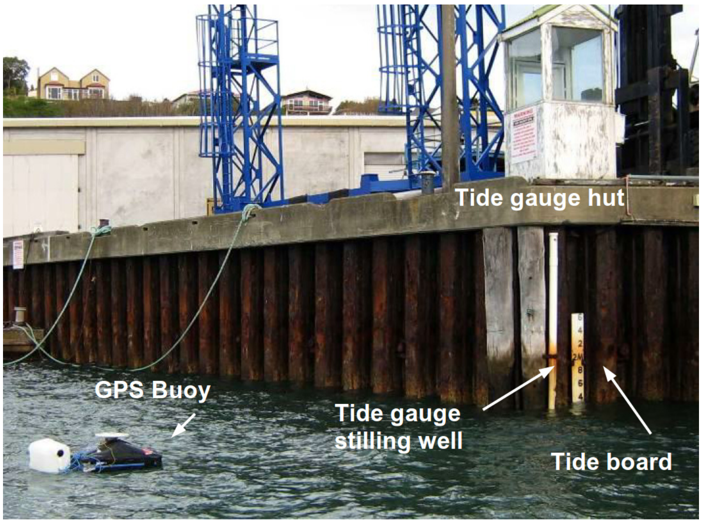


Figure 3: GPS Buoy deployment at the Port Chalmers tide gauge site

To directly compare the sea level observations from the tide gauge (relative to chart datum) and the GPS buoy (relative to the GRS80 ellipsoid), the observed heights are required to be reduced to the same reference surface. (Figure 4). In this situation the height difference between the ellipsoid and orthometric height datum at the reference station, (h_{REF} - H_{REF}), was used in combination with the geoidal undulation between this position and that of the buoy, ($\Delta N_{REF - Buoy}$), to determine ellipsoidal-orthometric separation at the buoy ($\sim N_{Buoy}$). The calculated offset to chart datum, (CD_{Offset}), was then applied to reduce the GPS buoy heights to chart datum ($GPSBuoy_{SSH}$).

The buoy should preferably be positioned within 200 m of the tide gauge being used for verification and the reference station (Watson, 2005). This both simplifies the GPS processing, as some errors in the GPS observables will be correlated between the two sites, as well as minimising the effects of geoidal undulation and dynamic sea surface topography (Figure 4). Sea surface topography is the difference in the mean sea surface due to the effects of wind, temperature, salinity and current between two locations. For most tidal datum transfer situations, there is often no orthometric height control close to the subordinate station and therefore the tidal observations and datum transfer must be made relative to another datum. A tide gauge is often referenced arbitrarily to a nearby benchmark so that when GPS buoys are used to transfer a datum, the reference height can be relative to the ellipsoid at the GPS base station benchmark or alternatively a geoid-ellipsoid separation model can be used to reduce the ellipsoidal height to an orthometric height surface.

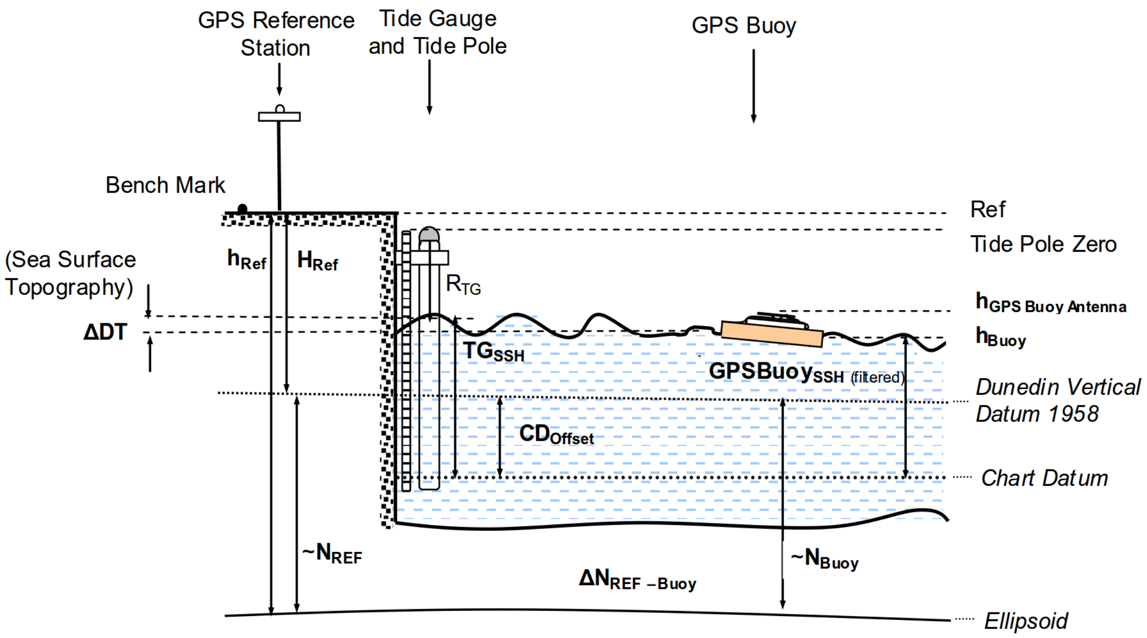


Figure 4: Datum connections and methodology for verification of the GPS buoy with the tide gauge

3.4 Verification

In order to verify the GPS buoy's ability to measure sea surface heights, filtered GPS heights were directly compared to those from the existing tide gauge at the location. The difference ($Difference_{TG-GPSBuoy}$) between the tide gauge and GPS buoy measured heights was computed as.

$$Difference_{TG-GPSBuoy} = TG_{SSH} - GPSBuoy_{FilteredSSH}$$

where TG_{SSH} is the tide gauge sea surface heights (relative to chart datum) and $GPSBuoy_{FilteredSSH}$ is the GPS buoy filtered sea surface heights. The GPS buoy heights required filtering to take into account the effect of the tide gauge's stilling well and different observation sampling rates, with the tide gauge taking the mean of every 30 seconds prior to the tenth minute. Upon analysis a 3 minute sampling period was selected and any outliers removed. This enabled both the precision as well as absolute and systematic biases between the two systems to be determined from these differences.

3.5 Tidal Datum Transfer

The range ratio method was used to transfer the tidal datum MHWS between Port Chalmers and Dunedin Wharf and vice versa. Three days of simultaneous GPS buoy observations were used. The high and low points required for this technique were determined by fitting polynomial curves to the extremities of the data (typically over a two hour period). The range ratio method assumes that the ratio of the vertical distances from the respective datum planes to mean high water springs (MHWS) at the reference and subordinate sites (i.e. MHWS/mhws) is equal to the ratio of the observed mean tidal range at the same two sites (i.e. MR/mr). Thus, the ratio is given as:

$$Ratio: \frac{MHWS}{mhws} = \frac{MR}{mr}$$

Marshall (2007) gives the full details of the tidal datum transfer procedures used. This method was chosen because of both its proven accuracy but also to enable a direct comparison to previous research undertaken by Dewar and Hannah (2005). However, other methods may be better suited to other sites depending on their physical and tidal characteristics. For example, in some locations only part of the tidal range can be observed because of the influence of mud flats. In this case the modified height difference method (Dewar and Hannah, 2005) could be used. The least squares method (Grant and O'Reilly, 1986) may be particularly suited to the high rate GPS buoy data, however this requires further investigation.

4. RESULTS AND ANALYSIS

4.1 GPS Buoy Verification

Differences between the tide gauge and GPS buoy sea surface heights were used to verify the ability of the GPS buoy in the manner described in Section 3. Table 2 summarises the precision achieved for two deployments. The first deployment (Initial Dunedin Wharf Test), logged data at 1 second to test the prototype, while the second deployment used two GPS buoys observing data simultaneously at Dunedin Wharf and Port Chalmers.

Deployment		Sampling Rate	Observation Period	1 σ (mm)	95% (mm)
1	Initial Dunedin Wharf Test	1 sec	~ 24 hours	±17	±33
2	Dunedin Wharf	5 sec	~ 4 days	±23	±43
2	Port Chalmers	5 sec	~ 3.75 days	±24	±47

Table 2: Summary of estimated precision of the height difference between the GPS buoy-tide gauge for three deployments.

The three deployments demonstrated standard deviations at the ~±2 cm level. This precision was ~1 cm higher than the majority of recent research involving this type of design. The reason for this is unknown, although a rougher sea state may have been a factor.

Figure 5 is an example of the unfiltered sea surface heights graph of the tide variation over the four days while Figure 6 graphs the difference between the tide gauge height and GPS buoy (filtered) height.

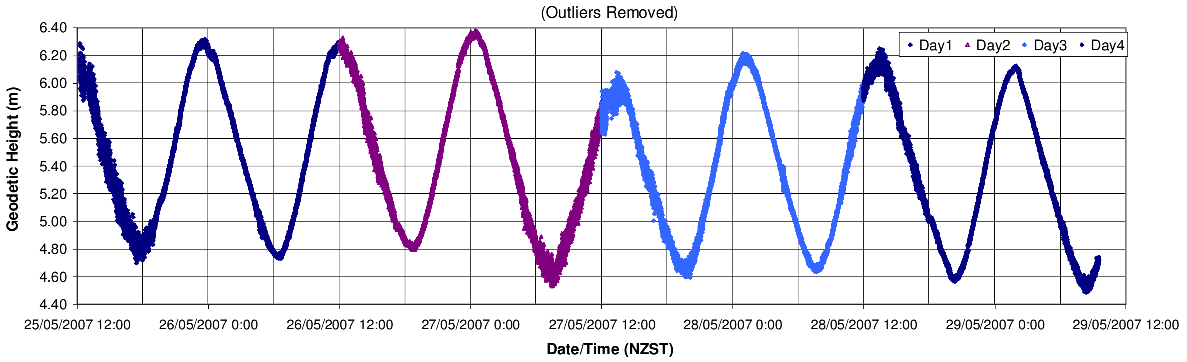


Figure 5: Dunedin Wharf deployment sea surface height estimates from the unfiltered GPS buoy data

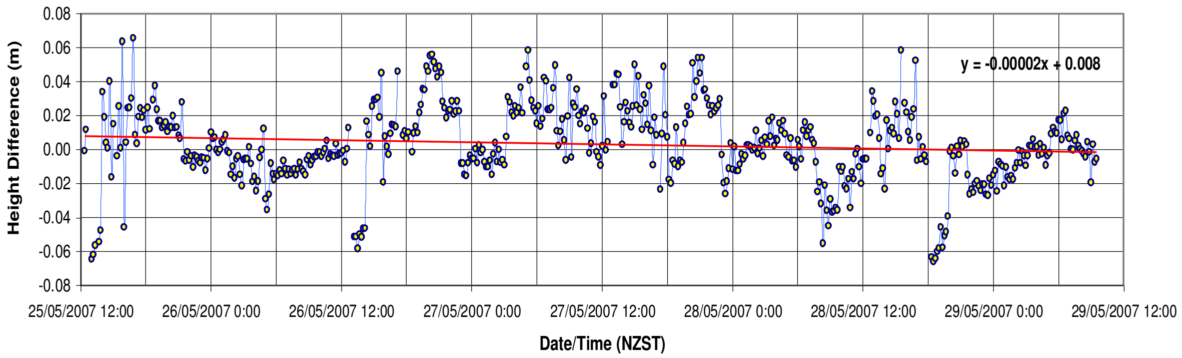


Figure 6: Dunedin Wharf deployment residual difference between the filtered GPS buoy data and the tide gauge

Deployment:		**Initial Dunedin Wharf Test**	**Dunedin Wharf**	**Port Chalmers**
Chart datum to ellipsoid offsets	Measured Datum Offsets (m)	4.322	4.322	4.450
	Mean $Difference_{TG-GPSBuoy}$ (m)	4.309	4.319	4.443
Absolute bias between TG and filtered GPS buoy SSH (reduced to CD)	Mean $Difference_{TG-GPSBuoy}$ (m)	+0.013	+0.003	+0.007

Table 3: Comparison of geodetic to chart datum offsets

Table 3 shows the mean difference (Section 3.4) between the tide gauge measurements relative to chart datum and those of the GPS buoy reduced to chart datum using the measured datum connections (Section 3.2). The mean bias between the two systems is small, being less than 7 mm for both simultaneous deployments. When considering the potential error budget, this appears to be insignificant.

Tidal Datum Transfer

The mean high water springs datum was transferred between Dunedin and Port Chalmers and vice versa using the process described previously. Residuals between the datum transferred and the long-term datum established were at the sub 10 mm level (Table 4).

Control to Subordinate Stations	**Dunedin to Port Chalmers (m)**	**Port Chalmers to Dunedin (m)**
MHWS datum transferred (above CD) [Reduced using measured datum connections]	2.153	2.170
Long-term MHWS datum (above CD) (LINZ, 2007)	2.14	2.18
Difference (m)	-0.009	+0.006

Table 4: Comparison of the MHWS datum transferred to that already established at Port Chalmers and Dunedin Wharf

Similar results were obtained by Dewar and Hannah (2005) who transferred the MHW datum using tide gauge data from the same locations as this project. Using the range ratio method and a similar two-day period of observations, a mean difference of ~10±21 mm was demonstrated, suggesting a similar level of accuracy. Although only two comparisons were obtained, the results do indicate that the GPS buoy is a viable data collection tool for tidal datum transfer.

5. DISCUSSION

Increasing demand for coastal properties and rising sea levels has heightened the need for reliable and accurate tidal datums to be defined for use by cadastral surveyors and engineers. Both MHWS and MHW are used to define coastal cadastral boundaries in New Zealand.

In some circumstances a mathematical approach, such as a tidal datum transfer, is not required. This is the case when the shore-line is steep and stable or the land value is low compared to the area that may be affected. In this case the tidal boundary can be defined using previous surveys or a re-survey of physical evidence, such as the face of a cliff, or edge of vegetation or driftwood. However, in other areas where a high value is placed on the ownership of the land the height of the seaward cadastral boundary must be defined with more accuracy and therefore a suitable tidal datum transfer procedure must also be used (Baker and Watkins, 1991) (Figure 7).

Typically a tide pole has been used by surveyors as part of the process to determine this coastal boundary at the subordinate site, with these observations then combined with those sourced from the permanent (control) tide gauge. However, the use of GPS buoys may have advantages in many situations. A particular environment where it may be particularly useful is in estuarine areas involving high value land, where there is little wave action and a flat gradient (Figure 7). The vertical error therefore has a large effect on the horizontal position of the boundary because of the slope. It should be noted that for best results a GPS buoy would need to be deployed at both locations to ensure the lower frequency observations from the control tide gauge does not degrade the quality of the transferred datum. However, typically a cadastral surveyor is expected to use a sole buoy at the subordinate station.

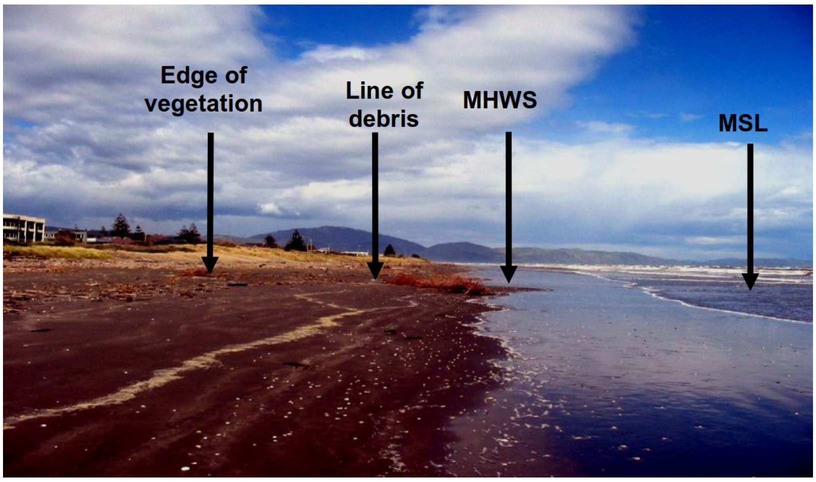


Figure 7: Photo of a coastline showing coastal cadastral boundary determination datums and concepts

The perceived advantages of the GPS buoy are:

- Efficient datum connections between the GPS buoy and benchmark eliminates the need for levelling to the tide gauge/staff and errors associated with this. This is probably one of the biggest advantages of high rate GPS buoys.
- Efficiency and time saved in data collection, with no manual observations required. This saves time, money and inconvenience.
- Existing GPS equipment as owned by a typical surveying firm can be used in combination with cheap readily available materials for buoy construction.
- Potential for increased accuracy in the datum transferred because of higher frequency observations. This is maximised by deploying a GPS buoy at both control and subordinate locations.
- They can also be deployed in close proximity to the shore, while not being required to be rigidly fixed as with traditional tide gauge instruments (Watson et al., 2007)

GPS buoys should also prove useful for hydrographic survey applications in areas where the installation of a tide gauge is difficult, such as establishing chart datum to be used as a reference point for the survey.

6. CONCLUSION

GPS buoy technology was successfully verified and applied to transferring a tidal datum within Otago Harbour. Increasing coastal development and sea level rise has highlighted the need for accurate tidal datums; however, existing methods of tidal datum transfer often have limitations. Although GPS buoy technology has been increasingly applied to many situations there has been little research investigating the use of light-weight designs for transferring tidal datums.

GPS buoys were deployed simultaneously at Port Chalmers and Dunedin Wharf tide gauges for four days allowing its observations to be compared against those of the gauges. These differences were less precise than expected, with a standard deviation at the ±2 cm level but with no significant bias between the two systems. The tidal datum MHWS was transferred and compared to that established from long-term tidal observations, with residuals at the 10 mm level.

It can be concluded that GPS buoys are a viable means of transferring tidal datums. The buoys were demonstrated to be simple and cheap to construct, while also being able to utilise typical GPS surveying equipment. It is therefore considered to have real potential for use in tidal data collection in many situations.

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BIOGRAPHICAL NOTES

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Practical experience: GPS surveying and mapping, deformation and control surveys, high precision vertical measurements, site engineering

International experience:
Establishing control surveys for the petroleum and exploration industry in North Africa, Middle East, Malaysia, Europe, and Scandinavia, 1989-1995
Collaborative projects with researchers at MIT, University of Colorado at Boulder, GFZ.

Activities in home and International relations:
Member, New Zealand Institute of Surveyors (NZIS), 1984-
Member American Geophysical Society (AGU), 1998-
Member New Zealand Geophysical Society (NZGS), 1998-
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