

AUGMENTING THE UTILITY OF NSW LONGEST TIDE GAUGE RECORDS WITH CONTINUOUS GNSS TECHNOLOGY

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Abstract: The tide gauge records available from Fort Denison, Sydney Harbour (since 1886) and the Pilot Station, Newcastle (from 1925) in NSW are two of the longest continuous tide gauge records in the southern hemisphere. By virtue, these records are of considerable international importance in relation to sea level rise research.

Tide gauge data provides a measure of the water level “relative” to a fixed, land-based reference mark. What is often not known, however, is whether or not the land upon which the tide gauge is positioned is actually moving. There are in fact many processes that can contribute to the land moving including solid earth tides, plate tectonics, glacial isostatic adjustment and localised factors that contribute predominantly to subsidence (e.g. aquifer extraction, reclamation and development loadings). In order to determine a rigorous estimation of sea level change, these processes need to be taken into account, i.e. is the sea level rising or the land falling? Although other researchers had noted discrepancies between the Fort Denison and Newcastle tide gauge records, Watson (2011) identified that the Pilot Station gauge record was likely contaminated by subsidence due to a range of separate coal mine workings at depths of 20-70 m in the vicinity of the gauge site.

During the past 12 months, various NSW Government agencies have worked collaboratively to install a Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) at both gauge sites in order to accurately and continuously measure landform movements. With accurate time series knowledge of the landform movements, “relative” tide gauge measurements can be readily adjusted to measure the absolute changes in ocean water levels over time. The GNSS CORS installed at Fort Denison and Pilot Station, Newcastle, have been integrated into the state government’s CORSnet-NSW network managed by Land and Property Information to deliver high-accuracy positioning data for NSW.

This paper outlines the scientific value associated with augmenting these long tide gauge records with GNSS and provides an insight into the difficulties encountered in considering the installation of these units in sensitive, heritage-listed, harsh marine environments.

Introduction

The coastal zone with such a rich diversity of beaches, estuaries, headlands and foreshore landscapes, is one of the key environmental assets in Australia. In addition to its environmental value, the coastal zone is also home to a large proportion of the population and one of the key national recreational amenities, tourism drivers and peak economic margins.

Of all the impacts from climate change, the projected rise in mean sea level is the most significant concern for coastal zone managers. Depending on the rate and scale of sea level rise, the environmental, social and engineering consequences within low lying inter-tidal areas, in particular, will be profound (Watson and Lord, 2008).

There is widespread measured evidence of a global average rise in mean sea level during the 20th century of the order of 17 ± 5 cm (IPCC, 2007). Scientific projections (post IPCC, 2007) lean toward an upper bound global rise in mean sea level of the order of 100 cm over the course of the 21st century (ISC, 2009). The advent of satellite altimeters that have

been measuring changes in the world's ocean water surface since late 1992, with improved global accuracy and reliability, have focussed attention on measured global trends that appear to be increasing at rates exceeding 3 mm/yr, generally in line with the upper bound projections of global average sea level rise (IPCC, 2007).

Notwithstanding, there remains considerable uncertainty in predicting sea level rise into the future, due in part to uncertainties over the rate of loss and contributions attributable to melting of glaciers and ice sheets and more principally to uncertainties over the context and scale of future global greenhouse gas emissions driving climate change. Greater consideration is now being given to observed and projected regional variability in global mean sea level rise (Meyssignac and Cazenave, 2012). As a result there is now a heightened emphasis on monitoring sea level rise with improved accuracy.

The importance of augmenting tide gauge records with accurate measurements of the vertical landform movements at the gauge site is a rapidly emerging area of scientific endeavour. Noting concern over the likelihood of mine subsidence contaminating the long historical record at Newcastle and possibly the later (after the mid-1990s) portion of the Fremantle record, Watson (2011) recommended upgrading the Fremantle, Fort Denison, and Newcastle tide gauges with collocated Continuous Global Positioning System (CGPS) technology to enable direct measurements of land movements at each site in order to improve our regional understanding of "eustatic" sea level rise (i.e. sea level rise due to changes in the volume of the oceans).

In mid 2012, following considerable cross-government agency collaboration, continuous Global Navigation Satellite System (GNSS) stations were installed within close proximity to the Fort Denison (<75 m) and Newcastle (<30 m) tide gauges providing a substantial investment in augmenting the scientific value of the tide gauge measurements for monitoring sea level rise into the future.

Importance of understanding landform movements at tide gauge sites

Long continuous tide gauge records are invaluable for sea level rise research because dynamic oceanographic and meteorological impacts can be increasingly averaged out (or isolated) over time to reveal the comparatively low underlying rise in mean sea level. The "relative" tide gauge measurements are, however, a combination of the actual rise in mean sea level and the vertical movement of the land upon which the tide gauge installation is located.

Woodworth (2006) noted that the vertical motion of land upon which a tide gauge is situated could be as great as the sea level change, thereby greatly complicating determination of sea-level trends. Vertical land motion may be due to tectonic activity, subsidence from sediment consolidation or groundfluid extraction, glacial isostatic adjustment (GIA), or other effects (Woodworth, 2006; Wöppelmann et al., 2007). Generally, sea-level trends obtained from tide-gauge records are only adjusted for GIA since other vertical land-motion components are not known (Houston and Dean, 2011).

Importantly, numerous researchers have highlighted the nature of various landform movements that can affect estimates of "eustatic" sea level rise derived from tide gauge measurements (in particular Lambeck, 2002; Church et al., 2004).

Critical site-specific issues in Australia have been highlighted previously. Belperio (1993) advised that the port of Adelaide in southern Australia provided a microcosm of geological factors that affect historic tide gauge data. Large tracts of inter-tidal wetlands peripheral to

the Port Adelaide estuary have been progressively reclaimed and masked by urban and industrial encroachment over the past 150 years. Belperio concluded that the major causes of land subsidence affecting the Port Adelaide estuary (including the site of the long tide gauge records at Port Adelaide and Outer Harbour) are surficial soil compaction associated with wetland reclamation and groundwater withdrawal from deeper tertiary aquifers. From measured observations, Belperio concluded that three-quarters of the secular rise in sea level recorded by the local tide gauges could be attributed to land subsidence.

From comparison of Fort Denison and Newcastle tide gauge records, Watson (2011) concluded the Newcastle record is likely contaminated by mine subsidence or other indeterminate factors. With insufficient survey records available to isolate the extent of possible subsidence, the difference between the respective records implied the Pilot Station gauge (Newcastle) may have subsided by approximately 60-70 mm over the period from 1940 to 2000 alone. One of the probable reasons for the clear disparity in the relative water level records is that the Pilot Station gauge at Newcastle is sited on a large area known to be affected by mine subsidence. Known coal mine workings exist for three separate seams (Borehole Seam, Yard Seam, and Dirty Seam) below the surface in the vicinity of the tide gauge. These workings possibly predate the 20th century and are at depths ranging from as shallow as 20 m to exceeding 70 m at this location.

The aforementioned examples highlight the necessity to understand landform movements so that they can be adequately considered in order to use local “relative” tide gauge data measurements to provide improved estimates of “eustatic” sea level rise.

Long tide gauge records in Australia

Long near-continuous Australian sea level records are extremely important in understanding southern hemisphere (or regional) trends in sea level rise. In particular, only 2 of some 123 records held by the Permanent Service for Mean Sea Level (PSMSL) that pre-date 1900 are located within the southern hemisphere, i.e. Fort Denison (1886) and Fremantle (1897).

The earliest self-recording tide gauge in Australia appears to have been installed at Williamstown, Victoria in 1858 (Matthäus, 1972; Hunter et al., 2003). Unfortunately there are extensive gaps in this record up until the mid 1940s.

Water level recording commenced at Fort Denison with the first entry in the Tide Register dated 11 May 1866. Until the installation of the Harrison automatic tide gauge recorder in 1914, the Tide Registers recorded daily high and low waters only. Notations in the Tide Registers indicate that prior to September 1885, the gauge did not accurately record low waters (Hamon, 1987). The near-continuous monthly average water level record for Fort Denison from January 1886 to present is the longest record of its type for the southern hemisphere.

The Port Adelaide (Inner) gauge record commenced in 1882, though similar to the Williamstown record, there are extensive gaps until the mid 1960s. In addition, this record is also known to be contaminated by significant factors contributing to measured land subsidence (Belperio, 1993).

The Fremantle record commenced in January 1897 with near-continuous monthly average data to present, representing the second longest record of its type for the southern hemisphere. Other long Australian tide gauge records exist for Port Headland, WA (≈

1913), Port Pirie, SA (\approx 1918) and Port Lincoln, SA (\approx 1920) though the early decades of these records contain extensive data gaps.

The Pilot Station record at Newcastle commences in the PSMSL in April 1925. As part of Watson's (2011) investigation, Newcastle Port Corporation provided all original Tide Registers available for the Pilot Station gauge. Notations inside the cover of the Tide Register commencing in April 1925 make mention of a record high water level on 14 July 1912, indicating formal records were collected that predated available records by more than a decade. Despite exhaustive searches, these valuable earlier tide records were unable to be located.

Using satellite technology to measure landform movements

GNSS CORS

Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) networks are being introduced across Australia and internationally to provide improved access to positioning infrastructure for a wide range of GNSS applications in areas such as surveying, mapping and asset management, precision agriculture, engineering and construction, airborne imaging and sensors, and utilities management. Benefits include datum definition, rationalisation of infrastructure, consistent and reliable connectivity to the national datum, and the ability to provide a degree of legal traceability for satellite-based positioning.

Real Time Kinematic (RTK) GNSS in particular, provides high-precision coordinates and allows instant "real-world digitising" with the ability to significantly enhance productivity. GNSS CORS networks also provide continuous data for numerous post-processing applications with higher accuracy requirements, mainly revolving around geodesy and geodynamics (e.g. datum realisation, tectonic plate motion, and the response of the Earth's crust to earthquakes and volcanic eruptions).

One of the first CORS networks was established in March 1988 on the Izu Peninsula in central Japan to support earthquake prediction research. Shimada et al. (1990) reported that "We have, for the first time, used GPS fixed-point measurements to follow the evolution with time of the crustal movements; such measurements provide a continuous uninterrupted record of deformation." This network has now grown to 1,200 CORS covering all of Japan and is known as GEONET. Numerous GNSS CORS networks have since been established for various applications, ranging in size from local scales to the global network administered by the International GNSS Service (IGS, 2012).

GNSS is increasingly being used for applications related to environmental monitoring (Awange, 2012). This includes GNSS-based radio telemetry (enhancing ecological and conservation monitoring by more accurately mapping animal movements, behaviours and their impact on the environment – e.g. Tomkiewicz et al., 2010), GNSS meteorology (contributing to weather and climate change studies – e.g. Choy et al., 2011), GNSS remote sensing (allowing rapid monitoring of changes in fresh water resources and the cryosphere – e.g. Jin and Komjathy, 2010), and epidemiology (improved efficiency in tracking and studying the spread of infectious diseases and climate change effects on vector-borne diseases – e.g. Carpenter, 2012).

In regard to climate change research, long-term changes in mean sea level relate to variations in ocean currents, changes in the volume of water in the oceans and thermal expansion of the ocean water mass. In order to understand "relative" sea level changes

properly from tide gauge data, it is crucial to decouple the different sea and land signals in the sea level records, i.e. is the sea level rising or the land falling?

Collocated GNSS CORS are the ideal candidate to provide accurate and continuous measurements of land movement at tide gauge locations (e.g. Tervo et al., 2007). While GNSS has long been used to determine highly accurate horizontal land movements, recent studies have shown that GNSS is also able to provide vertical land motion monitoring with an accuracy of better than 1 mm/yr, thereby improving the estimation of sea level rates both regionally (e.g. Bingley et al., 2001; Buble et al., 2010) and globally (e.g. Wöppelmann et al., 2009; Bouin and Wöppelmann, 2010).

In order to achieve the required vertical accuracy, GNSS processing is required to carefully take into account geophysical factors causing the Earth's crust to deform periodically (with periods ranging from several hours to several years) due to mass-redistributions in the atmosphere, continents and oceans. These factors include ocean tide loading (causing a periodic change in the mass loading of the Earth), atmospheric pressure loading (pressure-induced deformations of the Earth's crust and sea surface associated with the passage of weather systems) and solid earth tide displacements (periodic deformations due to the gravitational attractive forces of the planets in our solar system), all of which have to be considered within a stable reference frame over the time period considered (e.g. Sanchez and Bosch, 2009). Correcting GNSS observations for non-tidal ocean loading displacement in order to increase the quality of the results has also been recommended (Williams and Penna, 2011). Following analysis of an accurate time series of the land movement, relative tide gauge observations can be readily adjusted to measure the absolute (or "eustatic") changes in ocean water levels over time.

Compared to traditional monitoring methods based on terrestrial surveying techniques, the use of GNSS technology offers significant improvements in the measurement of landform movements at tide gauges. Table 1 provides a brief comparison of these two approaches, listed in priority order and highlighting the advantages of utilising GNSS CORS.

Table 1: Comparison of landform movement monitoring using traditional terrestrial survey methods and GNSS CORS.

Issue	Priority	Terrestrial Methods	GNSS CORS Techniques
Monitoring	1	episodic/sporadic	continuous
Reference Frame	2	local	global
Land Motion	3	relative	absolute
Data	4	internal, validated in-house	shared, validated by others
Precision	5(a)	generally fixed	improving with time/algorithms
Accuracy	5(b)	survey specific	homogeneous across all sites
Data Archiving	6	manual & centralised (lost)	electronic & distributed (not lost)
Labour	7	intensive	automated
Intent & Outcome	8	defined/limited	multi-user/infrastructure
Alarms	9	n/a	near-real time (variable thresholds)

CORSnet-NSW

CORSnet-NSW is a rapidly growing network of GNSS CORS providing fundamental positioning infrastructure for all of New South Wales that is accurate, reliable and easy to use (Janssen et al., 2011a; LPI, 2012a). It is built, owned and operated by Land and Property Information (LPI), a division of the NSW Department of Finance and Services. CORSnet-NSW currently (October 2012) consists of 111 CORS tracking multiple satellite

constellations, and efforts are underway to expand the network to over 150 stations by the end of 2013.

LPI's first CORS was installed in Bathurst to support internal survey and aerial photography operations (Kinlyside and Yan, 2005). In 2004, a network of seven CORS was installed in the Sydney metropolitan area and made available to the public one year later under the name SydNET (Roberts et al., 2007). A renewed effort of expansion to extend the coverage of CORS throughout NSW commenced in 2009 and corresponded with the rebranding of the network as CORSnet-NSW (Janssen et al., 2010).

Figure 1 illustrates the coverage of CORSnet-NSW, showing stations that are operational (indicated by small triangles) as well as some planned stations (indicated by small circles). A 50 km radius around active stations is shown to illustrate the maximum recommended coverage area for single-base RTK operation at the 2-cm level (horizontally), while Network RTK (NRTK) coverage at the 2-cm level (horizontally) is shown as a striped, pink polygon in areas that have sufficient station density to support this technique. Currently, 53% of the area of NSW (and 97% of the population) is covered by the single-base RTK service, while NRTK is available to 30% of the area of NSW (and 93% of the population).

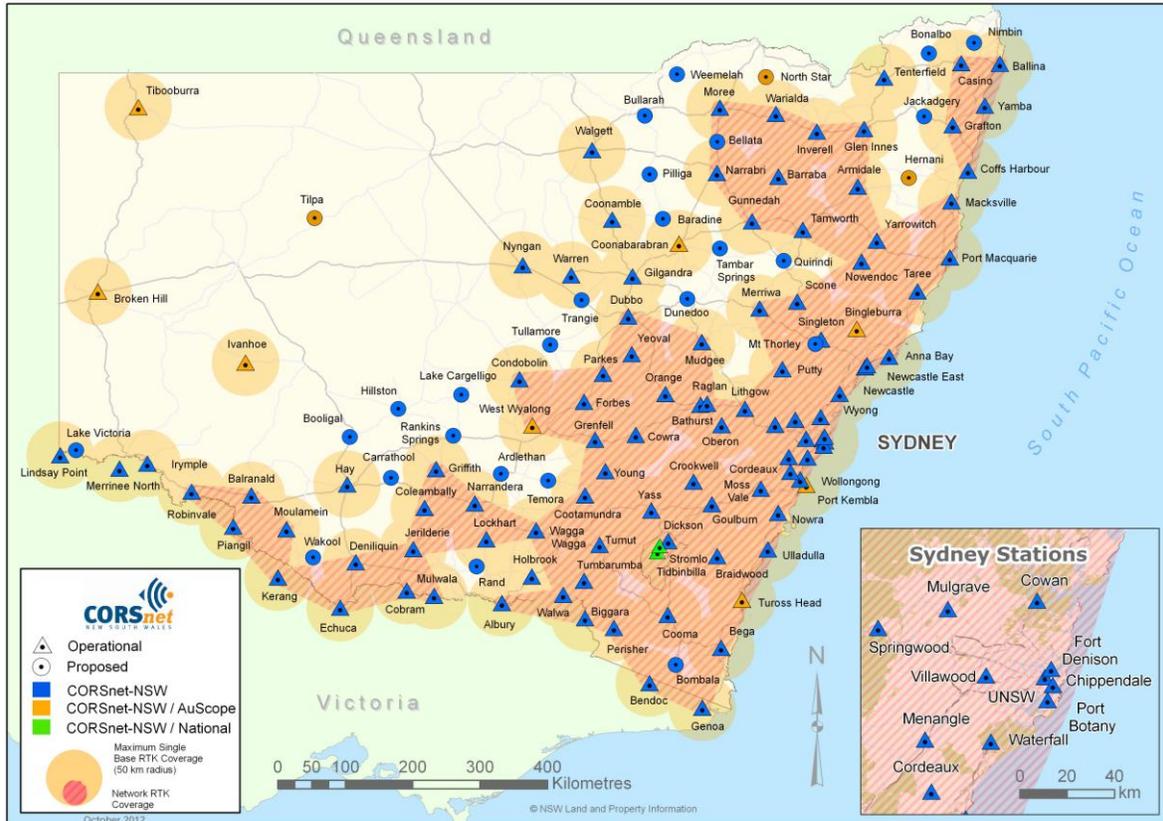


Figure 1: Current coverage of CORSnet-NSW (October 2012).

A dozen CORSnet-NSW stations are being built to international geodetic specifications with joint state/federal funding as part of the scientific, national AuScope CORS network (Janssen, 2009a). This includes Port Kembla CORS, installed in March 2010 and located within 260 metres of the Port Kembla high-precision tide gauge (managed by the National Tidal Centre as part of the Australian Baseline Sea Level Monitoring Project). The Fort Denison and Newcastle East (Pilot Station) CORS have been primarily funded by the

NSW Office of Environment and Heritage, specifically to augment the long-term tide gauges located at these sites. All CORSnet-NSW reference stations are equipped with the most recent dual or triple constellation GNSS hardware, purposely mixing GNSS equipment from different manufacturers. In order to provide a legally traceable survey monument that allows the GNSS antenna to be oriented to True North without the need to introduce an antenna height, the new CORSnet-NSW Adjustable Antenna Mount (CAAM) was developed and patented by LPI (Commins and Janssen, 2012).

Available CORSnet-NSW products include single-base RTK, NRTK, and real-time network-based DGPS services, as well as the provision of RINEX and Virtual RINEX data for a wide range of post-processing applications. Real-time data are provided via Radio Technical Commission for Maritime Services (RTCM) data streams (Heo et al., 2009) at 1-second intervals via the internet, accessed by users in the field via wireless cellular networks (Yan et al., 2009). NRTK data are provided according to both the Virtual Reference Station (VRS) approach and the Master-Auxiliary Concept (MAC) (Janssen, 2009b).

Compared to single-base RTK, the NRTK solution enables the distance dependent errors (i.e. atmospheric delays and satellite orbit errors) to be modelled more reliably across the network. It also allows the correction data provided to a user to be optimised based on their (changing) location within the network, thus effectively eliminating the degradation of RTK positioning accuracy with increasing distance from a single base station (Janssen and Haasdyk, 2011). Should a CORS go offline for any reason, an automatic switch is made to utilise an alternative reference station for the NRTK solution, without the need for the user to manually switch to another RTK reference station. NRTK operation thereby improves real-time service availability and reliability.

Installation of CORS at tide gauge locations

Building a GNSS CORS network is a challenging, expensive and time-consuming task (Janssen et al., 2011b; LPI, 2012b). The purpose of the network determines the required network density and station monumentation. The logistics involved in physically building the monument and installing the electronic equipment are some of the easiest issues requiring consideration. Collaboration with other organisations hosting a CORS, long-term tenure of the land and/or building to be used, site access, system redundancy and communications all play crucial roles. In addition, several operational aspects need to be addressed in order to provide (and achieve) reliable GNSS positioning of homogeneous and high accuracy across the network. These include the consistent connection to a high-quality datum, GNSS-based height transfer considerations, the use of absolute GNSS antenna models, stability and integrity monitoring, and the possible contribution to regional or global initiatives requiring GNSS CORS data.

When choosing a new CORS site, careful consideration should be given to the surrounding environment (e.g. access to bedrock, no radio interference, clear skyview and low multipath environment). However, in the case of a tide gauge, the conditions are usually far from ideal, particularly in a busy port. In addition, considerable difficulties may have to be overcome if the new CORS is to be installed in sensitive, heritage-listed, harsh marine environments.

Ideally, the GNSS CORS should be collocated with the tide gauge. However, in practice this is often not possible due to factors such as the physical location of the tide gauge (e.g. in a room at Fort Denison or on a pole in Newcastle), the marine environment being extremely challenging (e.g. negative effects of salt, wind and water), port land being prime

real estate (e.g. obstructions from nearby buildings, masts and vessels), jetties being subject to physical disturbances from vessels, and Work Health and Safety issues. CORS construction at any tide gauge is known to be the most challenging of all such constructions, requiring the use of special materials and techniques to protect the sensitive electronic equipment from the harsh environment (e.g. stainless steel mounts, dual air filters and sealed cabinets). For CORS placed in public view, security concerns (e.g. installation of security cameras and temper-proof antenna mounts, cabling and cabinets) and aesthetic considerations are generally also required. Understandably, these factors contribute to significantly higher installation costs.

Consequently, the planning, preparation, hardware requirements, associated approvals and installations for the Fort Denison and Newcastle East (Pilot Station) CORS were not straightforward exercises. Fort Denison is registered on the State Heritage Register and on the Register of the National Trust. Under NSW heritage legislation a Heritage Impact Statement (HIS) which addresses the management actions and principles of the Fort Denison Conservation Management Plan was required. Although development consent for a tide gauge CORS is not required under the State Environmental Planning Policy (SEPP) 2007 (Infrastructure SEPP), the prominent nature of the site required the preparation of a Review of Environmental Factors (REF) with the HIS. Due to the specific heritage nature of the Fort, the following constraints were imposed in addition to the standard selection criteria for CORS sites:

- Must have a negligible effect on the silhouette of the island (i.e. short mount with a low-profile antenna);
- Must not cause any damage/change to the original fabric of the Fort (classified as being of primary significance). Practically this meant that drilling sandstone was out of the question;
- Must involve minimal changes to any part of the Island (all areas, even recent additions, are classified as significant in the Conservation Management Plan);
- Must be compatible with the existing uses of the Fort;
- Must not involve any excavation;
- Should be constructed on bedrock for the maximum possible vertical stability; and
- Needs to be constructed entirely from materials that will not corrode in the marine environment.

Following attainment of all relevant approvals, facilitation of all necessary heritage considerations and rigorous, successful pre-testing of alternative hardware setups, the Fort Denison CORS was constructed and became operational on 18 May 2012 (see Figure 2).

Similarly, the Newcastle East (Pilot Station) site presented considerable heritage issues. The Newcastle Local Environmental Plan (LEP) identified almost the entire area as being within the Coal River Heritage precinct (listed in the NSW heritage register). The boat harbour was also specifically identified in the LEP as a heritage item which also fell within the Newcastle East Heritage Precinct.

Unlike Fort Denison, other considerations at Newcastle included the construction of a new port operations building at the eastern end of the Pilot Station property. Excavation for construction indicated that the boat harbour entrance and surrounds were almost certainly constructed from fill, primarily stone boulders and sand. This would make a stable monument almost impossible to build in that particular area (initially the preferred location).

A new pier for the antenna was considered but, in consultation with a wharf construction contractor, was discounted as the required stability could not be attained given the area's tide surge characteristics and relatively shallow bedrock (i.e. a pile could not be driven into unconsolidated material, nor could a concrete foundation be made on the surface).



Figure 2: Fort Denison CORS antenna mount (including CAAM).

During the reconnaissance phase, an old crane foundation was noticed but initially discounted due to possible heritage significance (and an accompanying council plaque). However, following further investigations it was discovered that:

- The crane base at the proposed antenna site was not listed on the State Heritage Register (unlike 14 others in the area), nor was it listed in schedule 5 of the Newcastle City Centre LEP 2008, schedule 6 of the Newcastle LEP 2003 or the revised Newcastle LEP 2012 (draft available at the time of consideration);
- It was outside the Coal River Heritage Precinct, and the Newcastle East Heritage Conservation Area. The crane base also falls outside the area described and shown as a general heritage item (Stone Boat Harbor) in the Newcastle City Centre LEP 2008 and its accompanying map (heritage map sheet HER-002). Due to the above, formal approval under the Heritage Act to construct the CORS at this location was not required (it should be stressed that nonetheless Council was formally consulted and had no objections); and
- Even though the above meant that heritage approval was not required, the crane foundation obviously held historical significance and great care was taken in preparing a design and installation method which would have minimal permanent impact on the structure.

Following attainment of all relevant approvals, facilitation of all necessary heritage considerations and rigorous, successful pre-testing of alternative hardware setups, the Newcastle East (Pilot Station) CORS was constructed and became operational on 26 June 2012 (see Figure 3).



Figure 3: Newcastle East CORS pillar (including CAAM).

Since the GNSS CORS could not be collocated with their respective tide gauges, it is crucial to provide a surveyed connection between these two continuously measuring instruments. This so-called “tie survey” continues to be performed episodically, thereby constituting a weak link that cannot be avoided at this stage. LPI will ensure that these ties are observed with the required precision (<1 mm) and temporal resolution (generally every two years).

Conclusions

The Fort Denison and Newcastle East (Pilot Station) CORS will provide valuable measurements on landform movements to augment the longest ocean water level measurements in NSW and the southern hemisphere. Considering Port Kembla CORS, NSW infrastructure now includes three GNSS CORS in close proximity to tide gauges.

It should be recognised that these CORS have only been operational for a very short period of time and that these measurements will become increasingly important as the record length increases (say greater than 10-15 years), providing significantly improved estimates of regional “eustatic” sea level rise into the future.

The utilisation of GNSS technology will substantially remove uncertainty over ground movement rates, particularly at the Pilot Station tide gauge site, that have been contained within the measured “relative” sea level measurements to date and improve the scientific value of the tide gauge data.

The installation of the Fort Denison and Newcastle East CORS to augment scientific endeavours to monitor sea level rise has been the result of considerable effort by a range of NSW Government agencies (OEH, LPI, Sydney Ports Corporation and Newcastle Ports Corporation) to meet challenging technical, environmental and heritage constraints.

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