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POSSIBLE EVIDENCE FOR DISTORTIONS IN THE AUSTRALIAN HEIGHT DATUM IN WESTERN AUSTRALIA

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ABSTRACT

The Western Australian STATEFIX GPS network, used in conjunction with the EGM96 global geopotential model, indicates the possible presence of distortions in the Australian Height Datum (AHD) over this state. The differences between 63 STATEFIX-EGM96 and AHD heights agree well with the differences between free- and fixed-network adjustments of the AHD, published by Roelse *et al*. (1971). The agreement between these two sources of height information *suggests* that the most likely source of these differences lies within the AHD due to its constraint to mean sea level at 30 tide gauges around the Australian coast.

INTRODUCTION

Sideris *et al*. (1992) published a paper in this journal entitled "*Geoid testing using GPS and levelling* (*or GPS testing using levelling and the geoid* ?)". In this paper, the remaining permutation of the relationship among Global Positioning System (GPS), optically levelled and geoid heights is considered. A homogeneous network of geodetic GPS measurements and a gravimetric geoid model are used to test the Australian Height Datum (AHD) in the state of Western Australia. International Terrestrial Reference Frame 1992 (epoch 94.0) ellipsoidal heights from the recently completed STATEFIX GPS network (Stewart *et al*., 1997) have been reduced by quasi-geoid heights generated by the EGM96 global geopotential model (Lemoine *et al*., 1997) to yield heights at 63 optically levelled AHD stations in Western Australia. A comparison between the STATEFIX–EGM96 heights and the AHD heights at these stations appears to indicate the presence of regional distortions in the AHD. Most interestingly, these distortions are largely coincident with the differences between the fixed- and free-network adjustments of the AHD, as published by Roelse *et al*. (1971). Based upon this observation and the deficiencies known to exist in the AHD (eg. Mitchell, 1990), a number of recommendations are made that should be considered in any future re-definition of the AHD.

THE STATEFIX GPS NETWORK

The Western Australian Department of Land Administration's (DOLA) geodetic GPS network, called STATEFIX, comprises 199 baseline vectors observed in 1996 between 80 geodetic monuments throughout Western Australia at a mean baseline length of approximately 200km (Stewart *et al*., 1997). The STATEFIX network used the existing Australian Fiducial Network (AFN) and Australian National Network (ANN) (Morgan *et al*., 1996) as a control framework. In turn, the AFN and ANN are geodetically connected to the International Terrestrial Reference Frame 1992 (ITRF92) epoch 1994.0. These nation- and state-wide GPS networks were observed as part of Australia's transition to a geocentric horizontal datum for surveying and mapping (eg. Featherstone, 1996). Sixty-three of the 82 STATEFIX stations have third-order, optically levelled heights on the AHD, and only these stations have been used in this analysis because of the increased uncertainty associated with trigonometric levelling. The accuracy (95% confidence) of the adjusted STATEFIX coordinates is approximately 30mm in plan and 50mm in height within the ANN (Stewart, 1998; Stewart *et al*., 1997).

THE EGM96 GLOBAL GEOPOTENTIAL MODEL

EGM96 (Lemoine *et al*., 1997) is the most recent estimate of the global gravity field and quasi-geoid, and includes data not previously used in earlier models. For instance, classified gravity data held by the US National Imagery and Mapping Agency or NIMA (formerly the Defense Mapping Agency or DMA) and five-arc-minute mean gravity anomalies from the former Soviet Union and China have been included in its computation. However, no significant amounts of new Australian gravity data have been included in EGM96, since the majority of the Australian gravity data-base has been available to those who compile global geopotential models for a number of years. Nevertheless, EGM96 is still considered the best global geopotential model currently available for Australia, and thus has been used in this analysis. It is considered to be the best model because of improved computational procedures and the use of geodetic satellites with different inclinations, which show improvements in the low frequencies especially in the low and mid latitudes.

Unlike a geodetic GPS network, the accuracy of EGM96 is more difficult to ascertain because of the limitations imposed by the accuracy of the data used, numerical procedures and approximations used in its computation. For instance, propagating the standard errors of the spherical harmonic coefficients yields an estimated precision of a few centimetres, whereas external accuracy estimates are more than an order of magnitude greater. However, the latter estimates are partly based on comparisons with GPS and levelling data (eg. Kirby *et al*., in press), which is the antithesis of this paper. Of importance, errors are known to exist in all wavelengths of any global geopotential model. Therefore, some systematic discrepancies can be expected to occur between the global geopotential model and GPS-levelling data. At present, however, it is impossible to accurately isolate these error sources, so a proportion of any observed differences will undoubtedly be due to errors in the geopotential model, hence the use of the qualifier ‘possible’ in the title of this paper.

DEFICIENCIES IN THE AUSTRALIAN HEIGHT DATUM

The appropriate definition and establishment of a vertical datum by optical levelling is outlined by, for example, Bomford (1971, §3). However, not all these ideal procedures were applied during the establishment of the AHD (Roelse *et al*., 1971). As such, the accuracy of the AHD has remained in question for a number of years. Probably the most contentious issue has resulted from the discrepancies observed between levelled and oceanographic estimates of height differences (eg. Hamon and Greig, 1972; Coleman *et al*., 1979; Macleod *et al*., 1988). Admittedly, the discrepancies observed along the north Queensland coast were subsequently identified as gross levelling errors (National Mapping Council, 1986). However, the discrepancies in other regions are also likely to stem from the fixing of 30 tide gauge estimates of mean sea-level to zero in the adopted adjustment of the AHD. Assuming that no errors exist in the levelling measurements and true orthometric corrections were applied, this approach is not ideal since the tide gauge estimates of mean sea level do not necessarily coincide with the same equipotential surface of the Earth’s gravity field (Mather *et al.*, 1976; Rapp, 1994; Featherstone, 1995). Moreover, several of the tide gauges used for the AHD were sheltered from the open oceans and are thus subject to localised oceanographic phenomena, such as fresh water outflow and coastal bathymetry. The clearest indication of this effect can be seen from the difference between the free- and fixed-network adjustments in Roelse *et al.* (1971). This is reproduced for Western Australia in Figure 1. Since, the levelling observations in each adjustment are subject to the same errors, the differences are predominantly due to the non-coincidence of the equipotential surfaces of the Earth’s gravity field and the 30 tide-gauge measurements of mean sea-level around the Australian continent.

Some question as to the accuracy of the AHD lies in the gross, random and systematic errors in the levelling observations used (eg. Roelse *et al.*, 1971; Morgan, 1992). However, the pressing need for an elevation datum to support national mapping programs in the 1960s and 1970s led to third-order standards being used over a relatively short period of time (Lines, 1992). This, in conjunction with the larger than ideal distance between junction points over most of the continent, will inevitably introduce some distortions in the vertical datum definition. For example, if the class C levelling tolerance of (12√km)mm (Inter-governmental Committee on Surveying and Mapping, 1996) is applied over ~300km, a typical distance between junction points in Western Australia (Fig. 1), a distortion of ~2.1m could conceivably occur. Admittedly, this is a worst-case scenario because it neglects the minimisation of such errors through survey practice and adjustment, but does serve to illustrate the potential problem. Nevertheless, the AHD can only be considered as a third-order vertical datum (Morgan, 1992).

Another defect in the AHD was the use of normal orthometric corrections to the levelling measurements (Holloway, 1988; Roelse *et al.*, 1971) that neglects the actual variations in the gravity field of Australia. The difference between true orthometric and normal orthometric corrections reaches approximately 150mm in Australia (eg. Zhang and Featherstone, 1997; Featherstone and Kirby, 1998).

Figure 1. *Contours of the differences between free- and fixed-network adjustments for the AHD in Western Australia from Roelse et al. (1971). The solid lines show the levelling loops used in the establishment of the AHD.*
(Conical projection. Contour interval 0.2m).

Figure 2. *Differences between optically levelled AHD heights and STATEFIX–EGM96 heights at the 63 STATEFIX stations in Western Australia (Conical projection. Contour interval 0.2m).*

DISCUSSION OF THE DIFFERENCES BETWEEN STATEFIX–EGM96 AND AHD HEIGHTS

The EGM96 quasi-geoid height at each of the 63 optically levelled AHD stations of the STATEFIX network was computed to spherical harmonic degree 360 using modified computer routines of Rapp (1982). Figure 2 shows a tensioned spline surface (Smith and Wessel, 1990) fitted to the differences between the STATEFIX–EGM96 heights and the optically levelled AHD heights at the same 63 stations. The zero-degree term, which is a constant bias resulting from the difference between the mass and potential of EGM96 and the GRS80 reference ellipsoid (Kirby and Featherstone, 1997), has not been considered since its omission happens to give a closer agreement with the AHD in an absolute sense. Nevertheless, this bias - although reduced - remains, so it is important to only consider the relative shape of the contours rather than their absolute values.

On comparison of Figure 2 with Figure 1, there is some regional similarity evident between the general shape of the contours, particularly east of Carnarvon (approx. 24°S, 114°E), north-west of Eucla (approx. 32°S, 129°E), west of Bunbury (approx. 33°S, 116°E), north of Kalgoorlie (approx. 30°S, 120°E) and between Broome and Port Hedland (approx. 22°S, 119°E). As the differences between the free- and fixed-network adjustments are only available to the authors as a map from Roelse *et al*. (1971), it is not possible to perform a numerical analysis of the differences through, for example, a correlation coefficient. Nevertheless, the agreements in the shape of the contours serve to illustrate the similarities between these height data. Importantly, the discrepancies shown in Figure 2 appear to be systematic, as evidenced by the general features being defined by more than one STATEFIX–EGM96 station. Kirby *et al*. (in press) point out similar differences, but the number of control points in their analysis caused them to raise question as to their authenticity. However, based on the additional STATEFIX data used here and the broad agreement among adjacent stations, it is reasonable to suspect that these features are indeed more likely to be due to systematic distortions in the AHD.

As well as pointing out the similarities, it is equally important to point out the differences between these height data. For instance, there is a large difference centred at (approx. 21°S, 123°E). However, this feature is only defined by a single STATEFIX–EGM96 point, which raises doubt to its significance, especially when bearing in mind that this study is concerned with regional distortions. Instead, it can be adequately explained as a gross error at this point. Moreover, the difference occurs in a region that is poorly covered with levelling traverses (cf. Figure 1), thus substantiating this hypothesis. Ideally, geodetic GPS measurements made at the junction points of the AHD may give a clearer indication of the validity of these differences.

Most importantly, the STATEFIX–EGM96 data gives a closer overall fit to the free-network adjustment of the AHD, because the differences between Figures 1 and 2 are similar. This illustrates that the fixing of the 30 tide gauges to zero during the final adjustemnt of the AHD is the most likely culprit for the distrotions in the AHD. However, these distortions are typically long wavelength in nature and have not been identified using localised analyses of the AHD (eg. Morgan, 1992), because they appear as a virtually undetectable bias at this scale. Therefore, for the practical use of the AHD over small areas, there is more user concern with gross errors.

It is acknowledged that there remains one major source of uncertainty in the comparison presented here: the assumed accuracy of the EGM96 geopotential model. The observed differences could equally be interpreted as low- and medium-frequency errors in EGM96. However, at present, it is impossible to distinguish between these and distortions in the AHD, notwithstanding the accuracy of the STATEFIX network. Nevertheless, based on the consistency among adjacent stations of the STATEFIX network and, moreover, the similarity between Figures 1 and 2, it is more likely that the differences can be better explained and accounted for by systematic distortions in the AHD due to the fixing of the 30 tide gauges.

Given the increasing body of evidence of deficiencies in the AHD, it would seem reasonable that a re-definition of the AHD should take place in order to resolve these issues, which, based on the findings of this paper, should include: situating tide gauge stations away from regions that may be subject to localised oceanographic effects; modelling any remaining sea surface topography at these tide gauges; applying constraints to the tide gauge heights, rather than simply fixing their heights to zero; utilising a longer time-series of tide-gauge data to estimate mean sea-level. Ideally, this time-series should be greater than >18.6 years so as to fully average away long-term tidal effects due to the precession of the Moon’s orbit. If these effects are modelled or considered, then the agreement between these data should be improved.

In addition to the above considerations, a re-definition of the AHD should also include: the addition of all two-way optical-levelling observations made since the 1971 adjustment; exclusion, or appropriate weighting, of lower than class C levelling data; true orthometric corrections using observed gravity data to the levelling measurements to define a genuine orthometric height datum that is physically related to the gravity field of Australia; and even the inclusion of high-precision GPS networks in conjunction with a precise gravimetric geoid, additionally constrained through GPS measurements at tide gauges.

CONCLUSION

This paper has compared 63 STATEFIX–EGM96 and optically levelled AHD heights over the state of Western Australia. There is a broad agreement of these differences with the differences between the free- and fixed-network adjustments of the AHD, where the closer agreement is with the free-network adjustment. This is most probably due to the tide-gauge measurements of mean sea-level not coinciding with the same equipotential surface. Therefore, any future re-adjustment of the AHD should either hold only one tide gauge fixed, as has been done in other continents (eg. North America), or use tide gauges in suitable locations in conjunction with the best available estimates of sea-surface topography.

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