The ups and downs of GPS Heighting in Britain – part 1: Ocean Tide Loading

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The promise of GPS heighting is millimetre-level accuracy over hundreds of kilometres. The reality is often more like centimetre-level accuracy over tens of kilometres. In this article – the first in a two-part series on the challenges and pitfalls of GPS heighting – the authors describe biases introduced by ocean tide loading and show that this may be a source of centimetre-level errors in GPS heights in the British Isles.

HAVE YOU felt seasick lately? It may sound like a strange question if your feet have not left terra firma recently, but despite not being able to feel it you are actually moving up and down with the ocean tides even on solid ground. If you live near the coast you will be more than familiar with the regular motion of the tides – cycles of low and high tide as enormous amounts of ocean water are shifted around by the gravitational attraction of the moon and sun. In some locations this happens twice per day, in others once per day, and in others a mix of once and twice per day. In the UK, we experience some of the largest tides in the world, up to 15m of water moving between high and low tides approximately twice per day. This enormous shift in mass results in compression of the Earth – the larger the tidal range, the larger the range of the compressions. Whilst it is true that the majority of this compression occurs at sea and away from typical relative GPS surveys, some of the magnitude 'leaks' on to the shore and sites more than 500 km away from the coast are still affected by what is known as "ocean tide loading" (OTL).

So how big is OTL? For most places in the world the range of this compression is no more than 5–20mm. However, in some regions such as Alaska, eastern Africa and the British Isles, OTL can exceed 100mm (200mm peak-to-peak). Figure 1 shows typical OTL magnitudes in the British Isles close to a spring tide, generated using a mathematical prediction of the ocean tides[1]. The south-west of the UK and Ireland are the most greatly affected while the east coast is much less so, although relative OTL here can still exceed 30mm over less than 100km. This pattern is generally repeated throughout the spring-neap tidal cycles, although the magnitudes of OTL are significantly reduced at neap tide when maximum OTL is only 30–40mm. Roughly six hours after the time shown in Figure 1 similar OTL magnitudes would occur but with an opposite sign, meaning that the total range in the south-west UK can exceed 140mm! Due to the different interactions of the lunar and solar gravitational forces, this range will at times (although rarely) be closer to 200mm and at other times closer to 60mm.

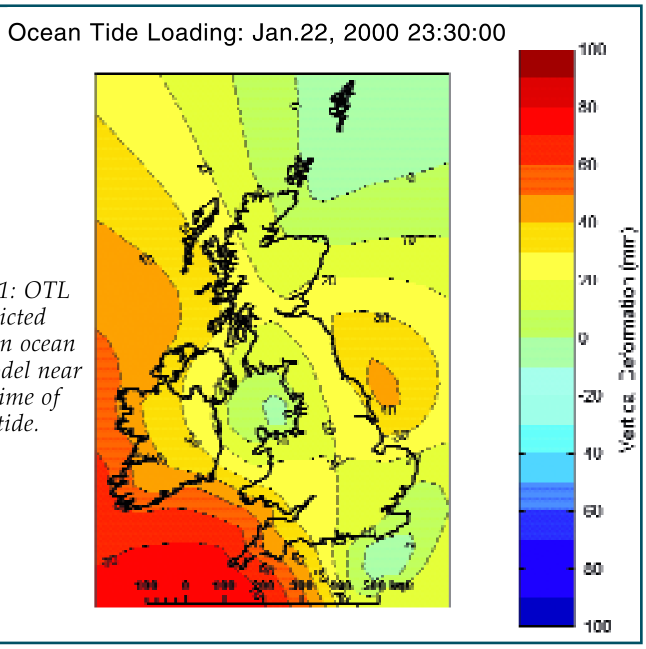

Figure 1: OTL as predicted using an ocean tide model near to the time of spring tide.

OTL's spatial variability

What is most important for relative GPS positioning is the spatial variability of the OTL. That is, as baseline lengths increase the relative OTL will generally have a greater impact. For most locations in the world, baselines need to be perhaps several hundred kilometres long before relative GPS heights are affected at the 10mm level, but in the British Isles relative OTL may exceed 10mm over baselines as short as 75km, and 50mm over baselines of 150–200km. With many parts of the UK and Ireland lying 50–75 km from the nearest national survey agency GPS reference site, this leaves surveyors with a real problem.

Figure 2 shows the effects of OTL on a 95km baseline in the south-west of the UK as measured using GPS data processed in 4-hour windows using one of the widely-available commercial software packages. The day was chosen randomly while the two Active Network stations (PLYM and LIZ1) were chosen based on where OTL was expected to be large. Plotted with the GPS measurements are estimates of OTL from a numerical tide model similar to the one used to estimate OTL in Figure 1.

Bias depends on time and place

There are several important conclusions that can be drawn from Figure 2. Firstly, if a surveyor measured a single 4-hour session along this baseline at this time, the height coordinates would almost always be biased. The magnitude of the bias will vary according to the tidal cycle and the geographical location, but on the day used to create Figure 2 the height bias along the PLYM-LIZ1 baseline is up to 20–50mm, although based on the model only 10–20mm is introduced by OTL. If at some later time the survey was repeated, a different bias would most likely be introduced and hence the two sets of measurements would disagree even if no other errors were present in the surveys. Importantly, these biases will not be reflected by the coordinate uncertainties reported in GPS processing software since the software does not 'know' that OTL is affecting the measurements over such a short observation period. The coordinate formal errors from the GPS software are shown in Figure 2, and they clearly do not reflect the true coordinate error. Secondly, observation session times need to be increased to approximately 12 or even 24 hours before relative OTL will average to zero. Thirdly, simply increasing the number of reference stations does not necessarily mean that the effect of OTL will tend toward zero. Rather, using reference stations further afield

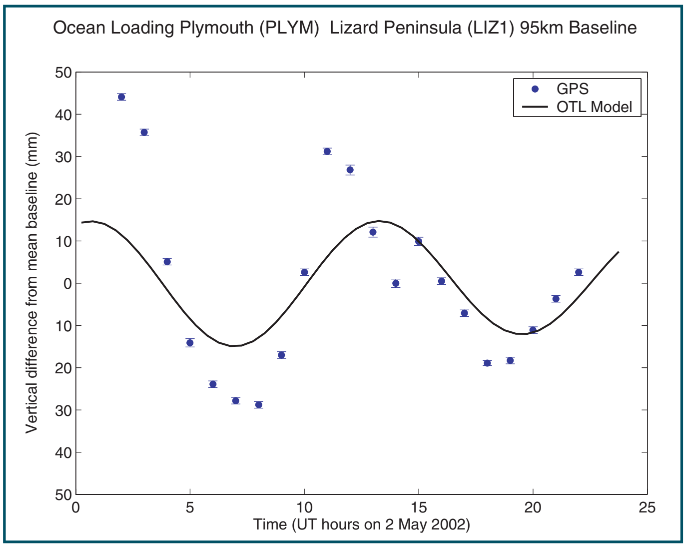

Figure 2: OTL as measured using GPS data from Ordnance Survey Active Network sites PLYM and LIZ1 processed in 4-hour windows using proprietary software. Both the OTL model and GPS measurements will have some error; formal errors (95% confidence interval, drastically underestimated!) from the GPS software are shown.

may result in sites with an even greater relative OTL being used. For example, the next nearest Active Nework site on this day was OSHQ, some 300km from LIZ1, and the relative OTL on this baseline would have introduced biases up to 60mm on this day. Finally, if the specification for such a survey required coordinates to be accurate to 20mm, then of the twenty-one baseline measurements shown in Figure 2, seven would exceed this specification without the knowledge of the surveyor.

While OTL has its largest effect on heights, there is also a horizontal deformation. Fortunately, this is generally no more than a few millimetres and at most approximately 10mm. The magnitudes of the horizontal OTL follow roughly the same spatial pattern as the vertical OTL and hence the south-west of the UK and Ireland will experience the largest horizontal OTL. Consequently, in most regions horizontal OTL can be ignored for all but the most precise surveys. Potentially more significant horizontal biases may be introduced by another less obvious means, however. We have recently shown[2] that if vertical OTL is not accounted for in the GPS software – which is the case for all current generations of commercial processing software – and at the same time the carrier phase ambiguities are not fixed to integers ('resolved'), then the horizontal coordinates may be biased by up to 40–50% of the amplitude of the vertical signal. For example, if an unmodelled relative vertical OTL of 20mm exists in a baseline for which ambiguities are not resolved, then the horizontal coordinates will be biased by up to 8–10mm! Therefore, if horizontal coordinate accuracy is important, users should take steps to ensure either:

(i) that ambiguities resolve
(ii) that vertical OTL is accounted for in the software, or
(iii) that long observation sessions are implemented.

Dealing with the effects

By now the question of how to overcome the effects of OTL may have sprung to mind. We suggest three possible approaches. Firstly, since relative OTL is only significant over baselines longer than 50km, minimising baseline lengths is an excellent method for reducing the impact of OTL. This is especially so in the south-west of the UK and Ireland. It must be remembered that errors can still accumulate over a series of short baselines. Secondly, if baseline length minimisation is undesirable or impossible then observation sessions must be close to 12 or 24 hours to allow OTL to average towards zero. Thirdly, you can model the OTL using a numerical ocean tide model in GPS processing software. If an accurate ocean tide model is available the effects of OTL can be removed at the processing stage and any baseline length and session duration will be unaffected by OTL (within the errors of the tide model). Unfortunately, such an option is not currently available in any proprietary GPS processing software, so 'scientific' GPS processing software (such as Bernese, GAMIT or GIPSY) must be used. Scientific software requires a higher level of user expertise than proprietary software and is usually only installed at academic or government institutions. This ability to account for OTL is one of the reasons why the Environment Agency has specified that all of their 'E1' station data must be processed using scientific software. Also contributing to the difficulty in modelling OTL is our present lack of understanding about which of the many ocean tide models predicts OTL most accurately for the British Isles. geomatics@newcastle is currently investigating this problem in conjunction with the Ordnance Survey and will deliver recommendations in late 2004.

Processing

Many surveyors presently process field data against as many as five reference stations. In view of OTL, how many should be used to position a single point? The answer is not as straightforward as we might like. A number of opposing factors are involved, but if the effects of OTL are to be minimised then there is a good argument for using as few reference stations as possible. For example, we recommend that when using proprietary software only the nearest one or two reference stations be used and a manual check be performed to ensure that the coordinates determined along each baseline are in good agreement. Part two of this series will discuss tropospheric effects which may also introduce errors of up to 50–100mm even over short baselines, and this provides further evidence that using as few reference stations as possible is the method that will, on average, provide the most accurate positioning results.

So far you may be thinking that this article should have been entitled "The downs and downs of GPS heighting"! But all is not negative. Firstly, it reminds the professional surveying community that GPS is not a black box and we cannot simply collect and process GPS data without thinking things through – right from the planning stage onwards. Secondly, being made aware of these issues may explain some of the disagreements that you have seen in your GPS processing. Thirdly, you should discuss with your GPS equipment provider what their future plans are to mitigate the effects of OTL, and the troposphere, on GPS heighting in their software. And fourthly, knowing that GPS is affected by OTL will hopefully result in its effects being minimised in future surveys, resulting in the delivery to clients of more accurate GPS positions. That, at the end of the day, will make our clients happier and reduce our feeling of sea sickness caused by ocean tide loading.

Acknowledgements

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Further Information

For further information, readers are referred to the slightly more technical review of OTL by Baker TF, Curtis DJ, Dodson AH (1995) Ocean tide loading and GPS. *GPS World* 6 (3): 54-59.

1 The GOT00.2 model produced by produced by Ray RD (1999) A global ocean tide model from TOPEX/POSEIDON altimetry: GOT99.2. NASA Technical Memorandum 209478.

2 King M, Coleman R, Nguyen LN (2003). Spurious periodic horizontal signals in sub-daily GPS position estimates. Journal of Geodesy, 77 (1-2), 15-21.