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Detecting storm surge loading deformations around the southern North Sea using subdaily GPS

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SUMMARY

A large storm surge event occurred on 2007 November 2009 in the southern North Sea where strong winds caused the sea level to rise drastically by up to 3 m within several hours. Based on the Proudman Oceanographic Laboratory storm surge model, the predicted loading displacements at coastal stations can reach a few centimetres in the vertical and several millimetres in the horizontal directions. In this study, we used two-hourly global positioning system (GPS) positions at 26 stations around the southern North Sea to identify the loading displacements caused by this storm surge event. We find that the mean rms of the differences between the estimated and predicted displacements are 4.9, 1.3 and 1.4 mm, which are insignificant compared to the one-sigma GPS positioning errors of 5.1, 2.0 and 2.4 mm for the Up, East and North components, respectively. More interestingly, in both vertical and horizontal directions, the estimated displacements successfully tracked the temporal evolution of the storm surge loading effects. In addition, within the whole of 2007 November, we used the predicted displacements to correct the two-hourly GPS positions, and consequently reduced the rms of the estimated displacements on average from 9.3, 3.0 and 2.9 mm to 7.8, 2.8 and 2.8 mm for Up, East and North components, respectively. Therefore, subdaily loading effects due to storm surges should be paid attention to in the GPS positioning that contributes to crustal-motion studies around shallow seas such as the North Sea, the Baltic Sea and the Gulf of Mexico.

Key words: Satellite geodesy; Sea level change; Transient deformation; Europe.

1 INTRODUCTION

Position time-series derived from global positioning system (GPS) measurements have been essential in studies such as the estimation of secular rates for sea level rise, tectonic motions and post-glacial rebound (e.g. Blewitt *et al.* 2010; King *et al.* 2010). However, such GPS positions normally contain geophysical signals at intra-annual timescales caused by the mass loading of constantly redistributed atmosphere, continental and oceanic water (e.g. van Dam *et al.* 1994, 1997, 2001; Scherneck *et al.* 2002; Petrov & Boy 2004). These signals can account for about 40 per cent of the seasonal power in geodetic GPS height time-series (Dong *et al.* 2002; Ray *et al.* 2008), and consequently the uncertainties of secular rate estimates might be larger than expected (see Blewitt & Lavallée 2002; Collilieux *et al.* 2010). To date, the tidal component of ocean loading signals is routinely accounted for in most GPS data processing schemes (Penna *et al.* 2003). Nevertheless, for the non-tidal component, there is a lack of available models.

Non-tidal ocean loading (NTOL) is caused by seafloor pressure variations which relate directly to the oceanic response to atmospheric pressure and wind stress. Normally, an inverted barometer response to the atmospheric pressure is presumed for deep oceans (e.g. Munekane & Matsuzaka 2004; Zerbini *et al.* 2004), whereas a barotropic, or dynamic, response is presumed for shallow seas (e.g. Ponte 1994; Carrère & Lyard 2003). Using the Green's function approach proposed by Farrell (1972), surface deformations (or displacements) due to NTOL can be calculated by convolving the seafloor pressure or non-tidal sea level variations predicted from an ocean model such as the Estimating the Circulation and Climate of the Ocean (ECCO) model (see www.ecco-group.org). With an early version of the ECCO model, van Dam *et al.* (1997) showed that NTOL can typically cause a peak-to-peak surface displacement of about 5 mm in the vertical and two thirds less in the horizontal coordinate components of a coastal station.

Seasonal NTOL effects have been investigated for the vertical component of daily GPS position time-series spanning several years.

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Munekane & Matsuzaka (2004) and Zerbini *et al.* (2004) found a correlation of up to 0.4 between daily vertical GPS positions and NTOL effects over a period of 7 yr. When correcting daily GPS positions for the NTOL effects, Nordman *et al.* (2009) reduced the scatter of a 3-yr height time-series by 23 per cent for an island station in the Baltic Sea. Likewise, Williams & Penna (2011) reduced the scatter of a 4-yr height time-series by 27 per cent for an island station in the North Sea and by 14 per cent on average for 17 coastal stations around the southern North Sea. With a global network, van Dam *et al.* (2012) reported that the weekly vertical scatters for over 65 per cent of all stations were reduced by up to 0.7 mm over a period of about 10 yr after correcting for NTOL effects. We note that all results above were derived after atmospheric pressure loading effects were removed.

Although the seasonal NTOL effects are of prime concern to geophysical studies, subdaily NTOL effects are also of great interest, especially in the case of some extreme weather events, such as a storm surge in the North Sea (e.g. Fratepietro *et al.* 2006). During such an event, the sea level, forced by strong winds, can rise by several metres within a few hours. Fratepietro *et al.* (2006) showed that a sea level rise of over 2 m in the southern North Sea can produce loading displacements of up to 30 mm in the vertical and 10 mm in the horizontal directions at coastal stations. To date, subdaily NTOL or storm surge loading effects have only been identified with superconducting gravimeters and hydrostatic tiltmeters (e.g. Boy *et al.* 2009). In either case, only vertical loading signatures can be verified straightforwardly with observations (Fratepietro *et al.* 2006; Boy & Lyard 2008), in contrast to 3-D displacements measurable with GPS.

In this study, we investigate a large storm surge event, which occurred on 2007 November 9 in the southern North Sea when the sea level rose by up to 3 m, to demonstrate that subdaily GPS positions can track the temporal evolution of these effects in both vertical and horizontal directions. It should be noted that we study roughly the same region and GPS network as reported by Williams & Penna (2011), but who did not focus on storm surge events or carry out subdaily GPS data analysis. This paper is organized as follows: Section 2 presents the GPS data, models and processing strategies; Section 3 introduces the NTOL model used to predict the sea level variations in the North Sea; Section 4 addresses the GPS positioning errors and the storm surge loading displacements captured by subdaily GPS positions; Section 5 shows the scatter of two-hourly GPS position estimates after correcting for the NTOL effects; finally, Section 6 draws the conclusions of this study.

2 GPS DATA PROCESSING

For this study, we used an improved PANDA (positioning and navigation data analyst) software package (Liu & Ge 2003) to process all GPS data. GPS data from 2007 November were collected from 26 stations around the southern North Sea (Fig. 1 and Table S1 in the Supporting Information). Within these stations, 17 are in England and nine are on the European continent (note that we simply regard island stations HOE2, HELG, BORJ and TERS as continent stations throughout). Another group of 70 stations (not shown here) around these 26 stations was used to re-estimate satellite clock corrections and fractional-cycle biases in order to enable ambiguity fixing for precise point positioning (Geng *et al.* 2010a, 2012). We removed observation files covering less than 18 hr of measurements. Final satellite orbits and Earth rotation parameters from the Centre for Orbit Determination in Europe (CODE) were used. To reduce the

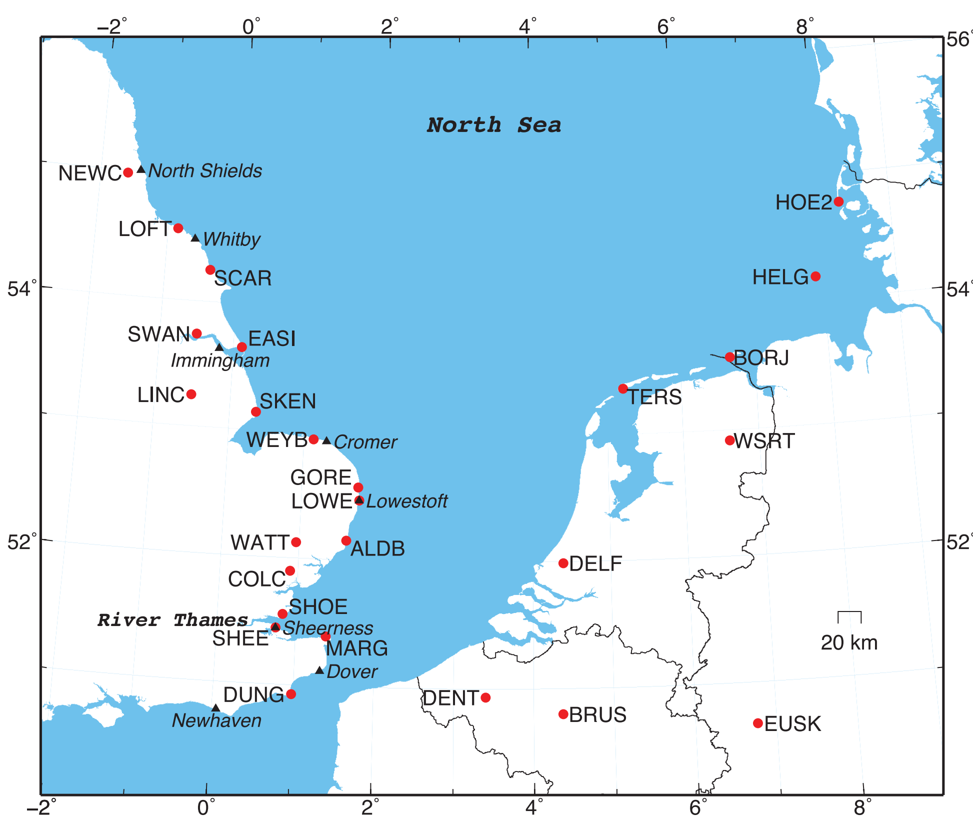

Figure 1. GPS stations around the southern North Sea. The red solid circles with names aside denote the 26 GPS stations used to capture the loading displacements caused by the 2007 November 9 storm surge. The black solid triangles with names in italic font denote the eight tide gauges listed in Table S2.

GPS data in a manner compatible with CODE's orbit generation, we applied absolute antenna phase centres (Schmid *et al.* 2007) and phase wind-up corrections; moreover, following McCarthy & Petit (2004), we also applied the displacements induced by solid Earth tide, pole tide and ocean tide loading based on the FES2004 model (Lyard *et al.* 2006) in the centre of the solid Earth's mass (CE) frame (Fu *et al.* 2012). We set a cut-off elevation angle of 7° for usable measurements. Residual zenith tropospheric delays (ZTDs) were estimated by applying the Vienna Mapping Function 1 and European Centre for Medium-Range Weather Forecasts derived *a priori* hydrostatic and wet zenith delays (Boehm *et al.* 2006; Tregoning & Herring 2006). Ambiguity fixing for each station was carried out successfully with a mean fixing rate of over 96 per cent on each day (Geng *et al.* 2009). In addition, the atmospheric pressure loading displacements estimated by Williams & Penna (2011) were applied to the 26 stations at the observation level (Tregoning & van Dam 2005).

Two-hourly GPS position estimates were generated for all 26 stations to identify the loading displacements due to the 2007 November 9 storm surge. In particular, position parameters were estimated every 2 hr as random walk parameters with 1 cm $\sqrt{\mathrm{hr}}^{-1}$ and 3 cm $\sqrt{\mathrm{hr}}^{-1}$ sigma for the horizontal and vertical components, respectively. Meanwhile, we estimated residual ZTDs every 1 hr and horizontal tropospheric gradients every 12 hr as random walk parameters with 2 cm $\sqrt{\mathrm{hr}}^{-1}$ and 2 mm $\sqrt{\mathrm{hr}}^{-1}$ sigma, respectively. We stress that it is 24-hr, rather than 2-hr, data arcs that were processed in each least squares estimation. In this manner, the ambiguity fixing rate and the precision of troposphere-related parameter estimates can be improved substantially, compared with those where subdaily data arcs were used instead (e.g. Geng *et al.* 2009, 2010b). In addition, since CODE's orbits were fixed in the GPS data processing, the resulting position estimates actually refer to IGS05, that is the International GNSS Service's (IGS) realization of International Terrestrial Reference Frame 2005 (Altamimi *et al.* 2007), whose origin is the centre of the Earth's surface figure (CF) on seasonal and short timescales (Dong *et al.* 2002).

Finally, we note that the horizontal and vertical displacements were derived directly from the least squares estimation above relative to *a priori* coordinates. These *a priori* coordinates were estimated with multiple days of GPS data prior to November. Then an intercept was estimated and removed for each displacement time-series, and outlier displacements were ruled out with a threshold of five times the standard deviation.

3 NON-TIDAL OCEAN LOADING MODEL

The North Sea, on the northwest European continental shelf, has a mean depth of 90 m, and therefore its dynamic response to atmospheric pressure dominates the non-tidal sea level variations. In this study, the Proudman Oceanographic Laboratory storm surge model (POLSSM) (Flather 2000) was used to calculate the hourly sea level distribution on a 12 km grid across the North Sea in order to predict NTOL displacements during the whole of 2007 November. The POLSSM is a barotropic model dedicated to the North Sea. Monthly rms of the differences between its predicted non-tidal sea levels and de-tided tide gauge measurements are around 10 cm irrespective of the time of year (Flather 2000). Particularly, the rms for 2007 November is around 11.9 cm (Table S2 and Fig. 1).

The predicted NTOL displacements were computed by convolving the predicted sea levels with the Green's functions proposed by Farrell (1972) in the CE frame (Blewitt 2003). We note that the origin of our GPS position estimates is actually the CF (Blewitt 2003; Dong *et al.* 2003), rather than the CE. Fortunately, the difference between the CF and CE frames is as minimal as 2 per cent of the observed geocentre motions (Dong *et al.* 1997). Compared to the magnitude of loading displacements, this difference is deemed negligible (Dong *et al.* 2002; Nordman *et al.* 2009) and hence ignored throughout this study. Furthermore, we point out that, although on subdaily timescales the centre of the entire Earth's mass (CM) frame is likely to be more appropriate than the CE frame, the differences between the predicted displacements in the two frames are negligible for a small scale and spatially limited load, such as derived from a regional model, since the only difference between the frames is the degree-one spherical harmonic.

We attempted to propagate the 10 cm sea level error into the predicted displacement error in the following way. Using 8 yr (2000–2008) of hourly sea level predictions, we picked the hours where the predicted peak-to-peak sea level variations across the North Sea were less than 0.26 m (i.e. the 5th percentile of all peak-to-peak variations). This threshold is also close to three times the

Table 1. Root mean square (mm) of the estimated and predicted displacements for the Up, East and North components of 26 stations from the 1st to 23rd June 2007. Each displacement time-series is smoothed by a Gaussian filter ($\sigma = 1$) with weights (0.0545, 0.2442, 0.4026, 0.2442, 0.0545), and the predicted displacements have been decimated into two-hourly time-series. The 26 stations are sorted by their geographic locations, that is roughly from northern to southern England, and then from Belgium, via the Netherlands to northern Germany.

Stations	Predicted with POLSSM			Estimated with GPS		
	Up	East	North	Up	East	North
NEWC	0.5	0.2	0.1	5.0	2.1	2.3
LOFT	0.5	0.2	0.1	5.8	2.0	2.7
SCAR	0.6	0.2	0.1	7.0	2.6	2.1
SWAN	0.5	0.1	0.1	5.8	2.4	2.3
EASI	0.6	0.2	0.1	6.5	1.5	2.2
LINC	0.4	0.1	0.1	5.6	2.1	2.2
SKEN	0.6	0.1	0.1	5.4	1.9	2.4
WEYB	0.7	0.1	0.1	4.9	1.6	2.1
GORE	0.7	0.1	0.1	4.6	1.9	2.2
LOWE	0.7	0.1	0.1	4.3	2.0	2.4
ALDB	0.7	0.1	0.1	4.4	2.2	2.3
WATT	0.5	0.1	0.1	4.7	1.6	2.4
COLC	0.5	0.1	0.1	4.3	1.8	2.2
SHOE	0.6	0.1	0.1	4.5	2.2	2.9
SHEE	0.5	0.1	0.1	4.8	2.1	2.2
MARG	0.7	0.1	0.1	4.0	2.0	2.3
DUNG	0.6	0.1	0.1	5.0	1.9	2.4
DENT	0.4	0.1	0.1	5.1	1.9	2.4
BRUS	0.3	0.1	0.1	4.6	1.9	2.2
EUSK	0.2	0.1	0.1	5.9	2.3	3.1
DELF	0.5	0.1	0.1	5.5	2.0	2.5
WSRT	0.5	0.1	0.1	5.8	2.3	2.5
TERS	0.8	0.1	0.1	5.5	1.9	2.6
BORJ	0.8	0.1	0.1	4.5	2.0	2.5
HELG	1.0	0.1	0.1	5.5	2.4	2.7
HOE2	1.0	0.1	0.1	5.1	2.0	2.3
Median	0.6	0.1	0.1	5.1	2.0	2.4

error of the sea level predictions. From this subset of hours, we calculated the rms of the predicted NTOL displacements for each station. Finally, the average rms for all 26 stations was found to be 0.5 mm in the vertical and 0.1 mm in the horizontal directions, which will be taken as the error of the predicted NTOL displacements in this study.

4 COMPARING THE ESTIMATED WITH THE PREDICTED NTOL DISPLACEMENTS

In this section, we quantify the positioning error of two-hourly GPS, and then test whether these two-hourly positions can capture

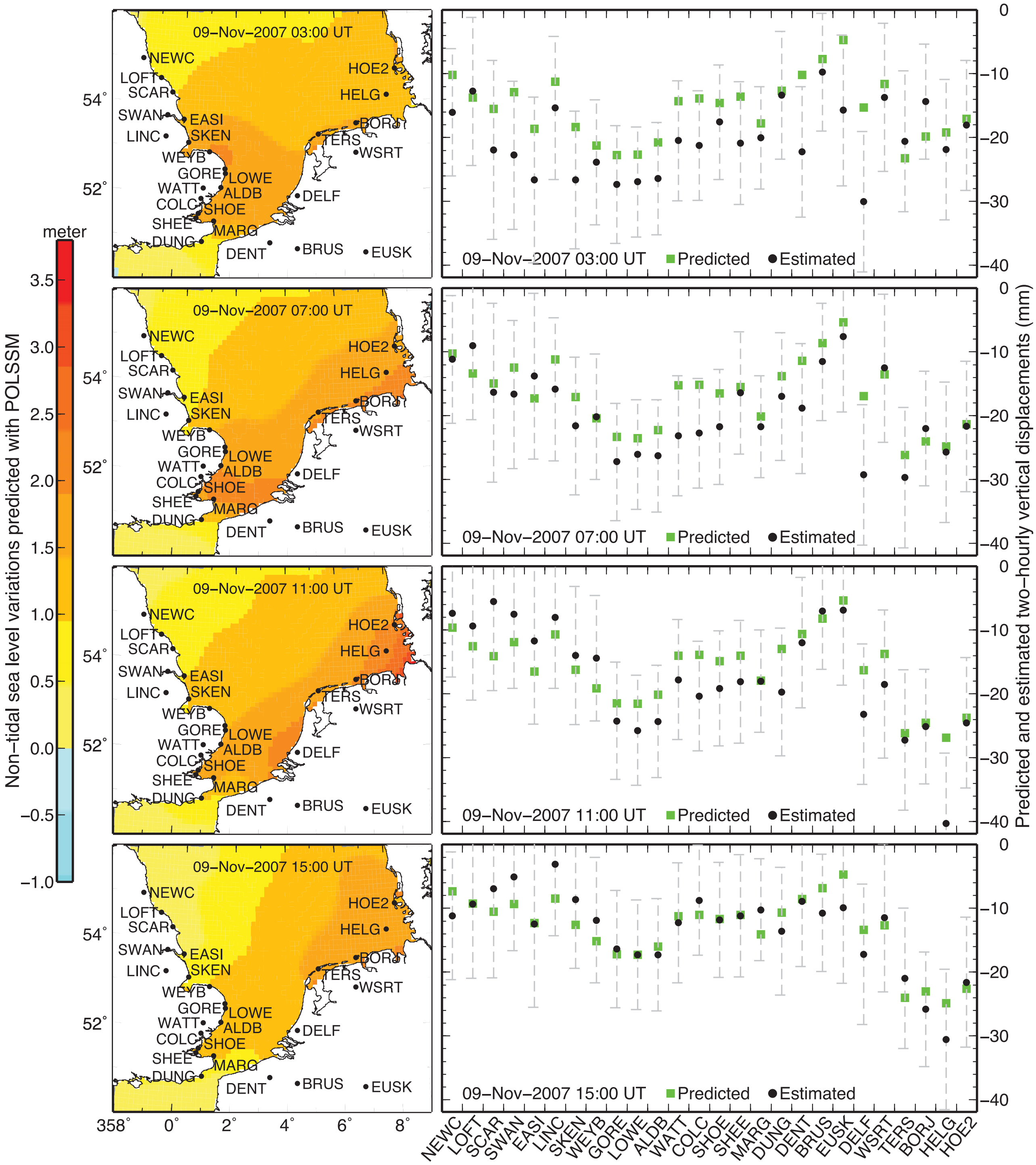

Figure 2. Non-tidal sea level variations and vertical loading displacements at 3:00, 7:00, 11:00 and 15:00 UT during the 2007 November 9 storm surge. The colour scale within the North Sea in the left panels denotes the magnitude of the predicted non-tidal sea level variations. Each displacement is a mean subsidence for a 2-hr period centred on one of the four times. Black solid circles denote displacements estimated with two-hourly GPS whereas green solid squares denote those predicted with the POLSSM. Each station has an error bar representing twice its GPS vertical positioning error. The 26 stations are sorted by their geographic locations, that is roughly from northern to southern England and then from Belgium, via the Netherlands to northern Germany.

both vertical and horizontal loading signatures caused by the 2007 November 9 storm surge. The displacements estimated using two-hourly GPS were compared with the hourly displacements predicted using the POLSSM. To mitigate high-frequency noise, all estimated and predicted displacement time series were smoothed by a Gaussian filter ($\sigma = 1$) with weights (0.0545, 0.2442, 0.4026, 0.2442, 0.0545). Note that the predicted displacements had been decimated into two-hourly time series by averaging every two hourly values to match the estimated displacements.

4.1 Positioning error of two-hourly GPS

In order to assess the error in the two-hourly GPS positions, we used GPS time series that were minimally affected by NTOL. We thus chose the period from the 1st to 23rd June 2007 when over 99 per cent of all predicted NTOL displacements were below 1.7, 0.4 and 0.3 mm, and the median rms of these displacements were 0.6, 0.1 and 0.1 mm for the Up, East and North components, respectively (see Table 1).

For the processing of the GPS data over this period, we used the same strategies as those described in Section 2. For each station, Table 1 shows the rms of the estimated displacements for its Up, East and North components from the 1st to 23rd June 2007. The rms for all stations range from 4.0 to 7.0 mm in the vertical, and from 1.5 to 3.1 mm in the horizontal directions. The median rms are 5.1, 2.0 and 2.4 mm for the Up, East and North components, respectively. Comparatively, these rms are around 10 times larger than those of the predicted displacements in Table 1. The noise of these estimated displacements can therefore be presumed irrelevant to NTOL effects. Throughout this study, we take the median rms of the estimated displacements as an overall measure of the two-hourly GPS positioning error, and the station-specific rms as individual positioning errors. For the remainder of the paper, we ignore the error in the predicted displacements because it is less than one tenth of the GPS positioning error. Finally, we note that the rms of the estimated displacements in Table 1 can only be presumed to be approximate estimates of the GPS positioning errors during the storm surge event, because we based these statistics on the GPS data from 2007 June, rather than 2007 November.

4.2 Vertical loading displacements captured by two-hourly GPS

The estimated and predicted vertical displacements at the 26 stations during the storm surge event are shown in Fig. 2. The temporal evolution of the storm surge is shown at four times, that is 3:00, 7:00, 11:00 and 15:00 UT on 2007 November 9. Note that each displacement is not an instantaneous snapshot, but a mean value over a 2-hr period centred on one of the four times. From the panels on the left of Fig. 2, we can see that the peak surge moved counterclockwise along the coasts of eastern England, Belgium, the Netherlands and northern Germany, before finally receding. We find that 81 per cent of all estimated displacements are statistically significant at the 95 per cent confidence level (i.e. twice the vertical positioning errors), and 96 per cent of all predicted displacements are within twice the errors of the estimated displacements. For all four times, the mean rms of the differences between the estimated and predicted displacements is 4.9 mm which is insignificant compared to the median GPS vertical positioning error. Over the 26 stations, the correlation coefficients between their estimated and predicted

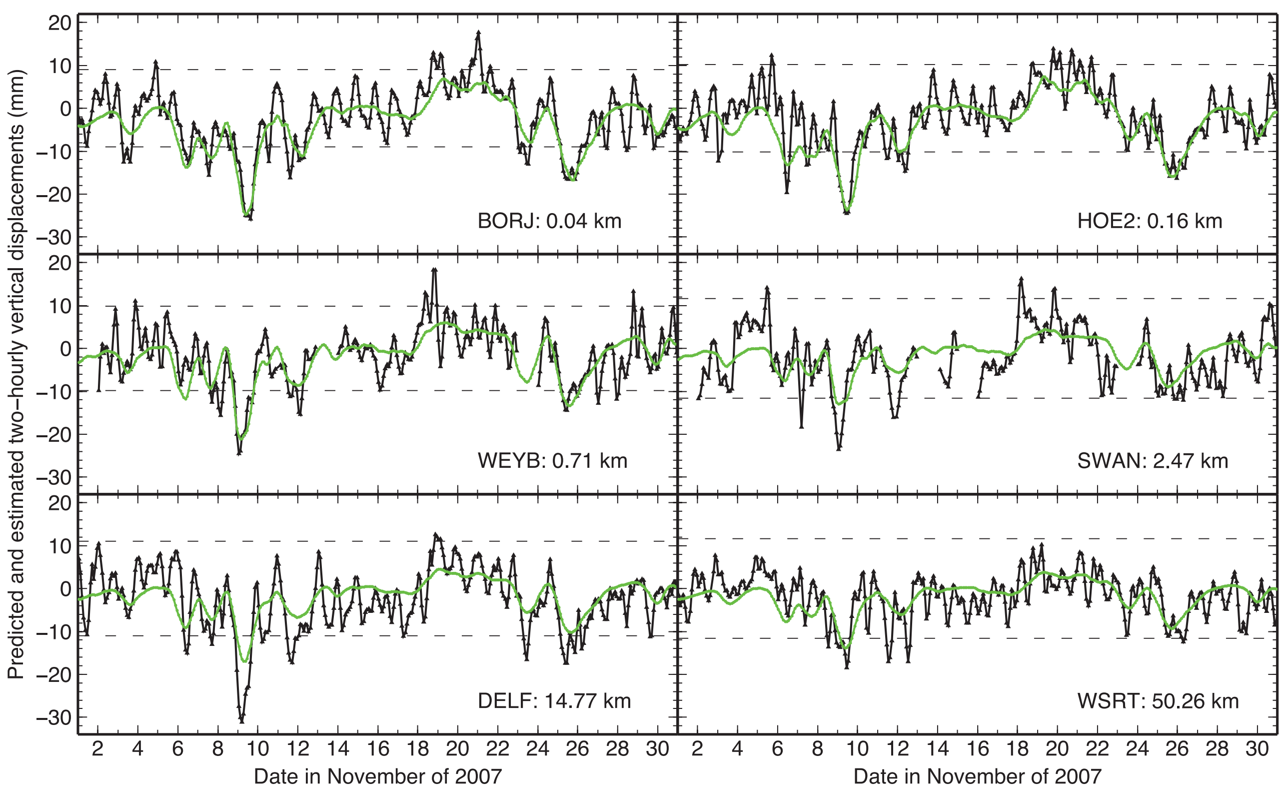

Figure 3. Vertical loading displacement time-series at six stations in 2007 November. Black curves denote the displacements estimated with two-hourly GPS whereas green curves denote those predicted with the POLSSM. Dashed lines denote the ranges of twice the GPS vertical positioning errors. The bottom-right corner of each panel shows the station name and the distance of each station to the nearest coastline. Note the data gaps for stations WEYB and SWAN.

displacements at the four times are 0.60, 0.80, 0.83 and 0.88 which are significant at greater than the 99.9 percentile. Hence, the estimated vertical displacements agree with the predicted ones during the storm surge event.

We then demonstrate the temporal evolution of the estimated displacements with respect to the movement of the peak surge. At 3:00 when the peak surge of over 2.5 m was adjacent to the eastern England, the estimated subsidence at the nearest five stations (i.e. SKEN, WEYB, GORE, LOWE and ALDB) ranged from 23 to 28 mm which were larger than those at most other stations. At 7:00 when the peak surge moved south towards the Thames Estuary, the five most northern England stations (i.e. NEWC, LOFT, SCAR, SWAN and EASI) were estimated to rebound substantially by 6.6 mm on average. Meanwhile, a two-metre surge formed in the Germany bight, and as a result, the nearby stations BORJ and TERS were found to subside further by 7.6 and 9.1 mm, respectively. At 11:00 when main surges of over 2.5 m had moved to the Netherlands and Germany coast, the estimated displacement for the island station HELG increased to a peak of 40.3 mm. Conversely, 14 England stations and two southern stations (i.e. DENT and DELF) were estimated to rebound by up to 6 mm. At 15:00 when the surges had started to recede, all southern England stations (i.e. from GORE to DUNG) as well as DELF, WSRT, TERS and HELG on the continent showed substantial rebound of around 7 mm on average. Therefore, the vertical GPS displacement time-series successfully tracked the temporal evolution of the storm surge loading effects.

In order to further verify the agreement between the estimated and predicted vertical displacements, we compare them over the whole of 2007 November for six representative stations BORJ, HOE2, WEYB, SWAN, DELF and WSRT in Fig. 3 (refer to Figs S1 and S2, Supporting Information, for other stations). At almost all six stations, we can find that the estimated displacement time-series coincide in general with the predicted ones at timescales of a few days at the 95 per cent confidence level, especially from the 9th to the 13th and from the 18th to the 25th. Overall, for all 26 stations, the rms of the differences between the estimated and predicted vertical displacements within the whole of November is 4.9 mm on average.

4.3 Horizontal loading displacements captured by two-hourly GPS

In Fig. 4, we present the estimated and predicted horizontal displacement vectors of the 26 stations during the storm surge event. Again, each displacement vector is not an instantaneous snapshot, but a mean over a 2-hr period centred on 3:00, 7:00, 11:00 or 15:00 UT. We can see that almost all vectors point uniformly towards the southern North Sea. Particularly, 87 per cent of all predicted vectors are within the one-sigma error ellipses of their corresponding estimated vectors. For all four times, the mean rms of the differences between the estimated and predicted displacements is 1.3 mm in East and 1.4 mm in North, which are insignificant compared to the median GPS horizontal positioning error. Hence, the estimated and

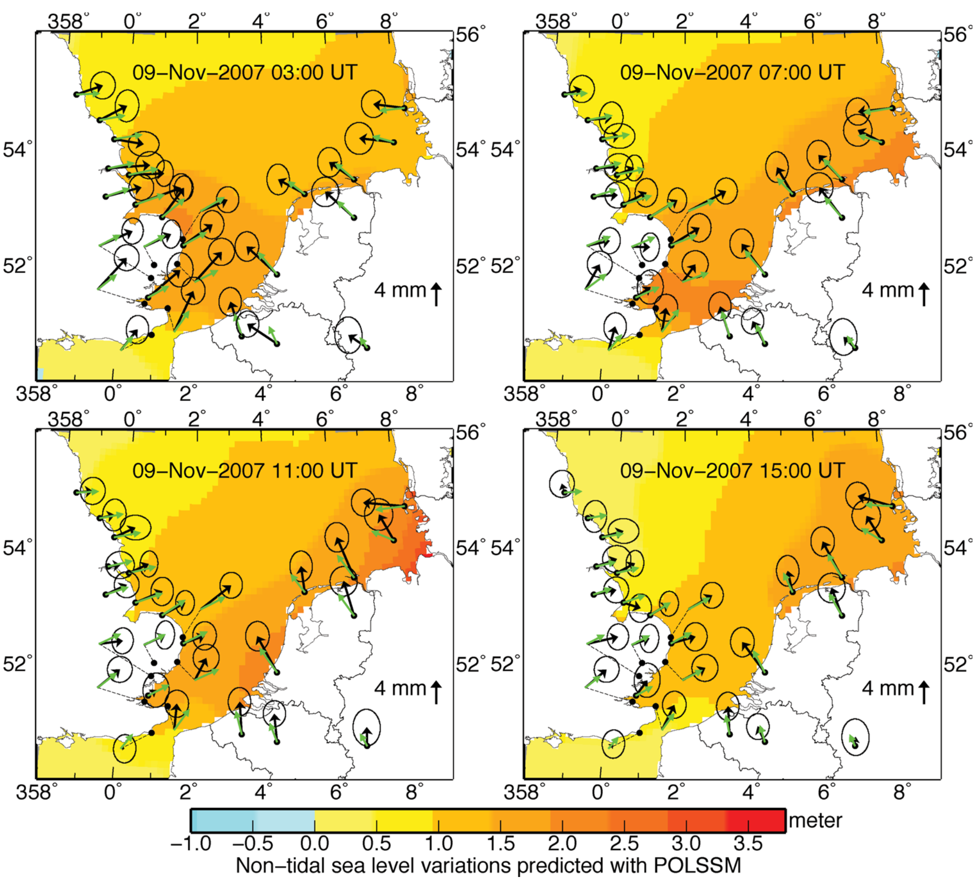

Figure 4. Horizontal loading displacement vectors at 3:00, 7:00, 11:00 and 15:00 UT during the 2007 November 9 storm surge. Each arrow is a vector denoting the direction and magnitude of a horizontal displacement. The black arrows are displacements estimated with two-hourly GPS whereas the green arrows are those predicted with the POLSSM. One-sigma error ellipses are plotted for all black arrows. For clarity, the arrows for southern England stations are shifted as shown by the dashed lines. The bottom-right corner of each panel shows an arrow representing a displacement of 4 mm.

predicted horizontal displacements agree during the storm surge event.

We then address the temporal evolution of the estimated vectors with respect to the migration of the peak surge. At 3:00 when the predicted peak surge was close to eastern England, 14 England stations were estimated to move eastwards substantially by 4.3 to 7.5 mm, while the Netherlands and northern Germany stations westwards by 4.0 to 5.7 mm. Meanwhile, the southern stations (i.e. ALDB, SHOE, SHEE, MARG and DENT) were found to move northwards by 4.9 to 6.9 mm. At 7:00 when the peak surge moved south to the Thames Estuary, the estimated displacements for northern England stations (i.e. from NEWC to SKEN) became insignificant as shown by their error ellipses. At 11:00 when the peak surge reached northern Germany, most stations on the continent were estimated to move northwards substantially by 4.8 to 6.9 mm. In England, however, 15 stations were estimated to have no significant displacements in either East or North. At 15:00 when major surges receded in the North Sea, almost all estimated displacements became insignificant at the 95 per cent confidence level. Therefore, the horizontal GPS displacements also successfully track the temporal evolution of the storm surge loading effects.

Similar to Fig. 3, Fig. 5 shows the estimated and predicted displacements spanning the whole of November for both East and North components of the six stations BORJ, HOE2, WEYB, SWAN, DELF and WSRT (refer to Figs S3 and S4 for other stations). We can see that the estimated displacements on the 9th November were statistically significant at the 95 per cent confidence level. By contrast, on the 25th November when another major surge was predicted, only BORJ, HOE2 and WEYB were estimated to be displaced significantly. Within other periods, nonetheless, the estimated and predicted displacement time-series do not resemble each other. Overall, for all 26 stations, the rms of the differences between the estimated and predicted displacements within the whole of November is on average 2.1 mm in East and 1.8 mm in North.

5 CORRECTING TWO-HOURLY GPS FOR THE PREDICTED NTOL DISPLACEMENTS

In the previous section, the agreement between the estimated and predicted displacements over the whole of 2007 November has been demonstrated in both vertical and horizontal directions. In this section, for all 26 stations, we correct the two-hourly GPS for the NTOL effects predicted using POLSSM. If the rms of the resultant estimated displacements is smaller than those derived without corrections, we can confirm that the two-hourly GPS positions sense the NTOL effects.

Table 2 presents the rms of the estimated displacements for the Up, East and North components of all 26 stations within the whole of November both before and after correcting for the NTOL effects. Note that, in contrast to Section 4, no Gaussian smoothing is applied before calculating the statistics in Table 2.

From Table 2, we can see that the vertical rms at all stations are reduced and that the reductions are in general a function of their distances to the nearest coastlines as demonstrated by van Dam *et al.* (2012). The vertical rms reductions range from 3.1 mm for the island station HELG, to 0.3 mm for the inland stations BRUS and EUSK. On average, the vertical rms is reduced from 9.3 to 7.8 mm which equates to an improvement of about 16 per cent. The rms reductions for stations SHEE, MARG and DUNG are only 1.1, 1.3 and 0.9 mm, respectively, although they are within 0.1 km of the nearest coastlines. Their inferior performance is evident when compared

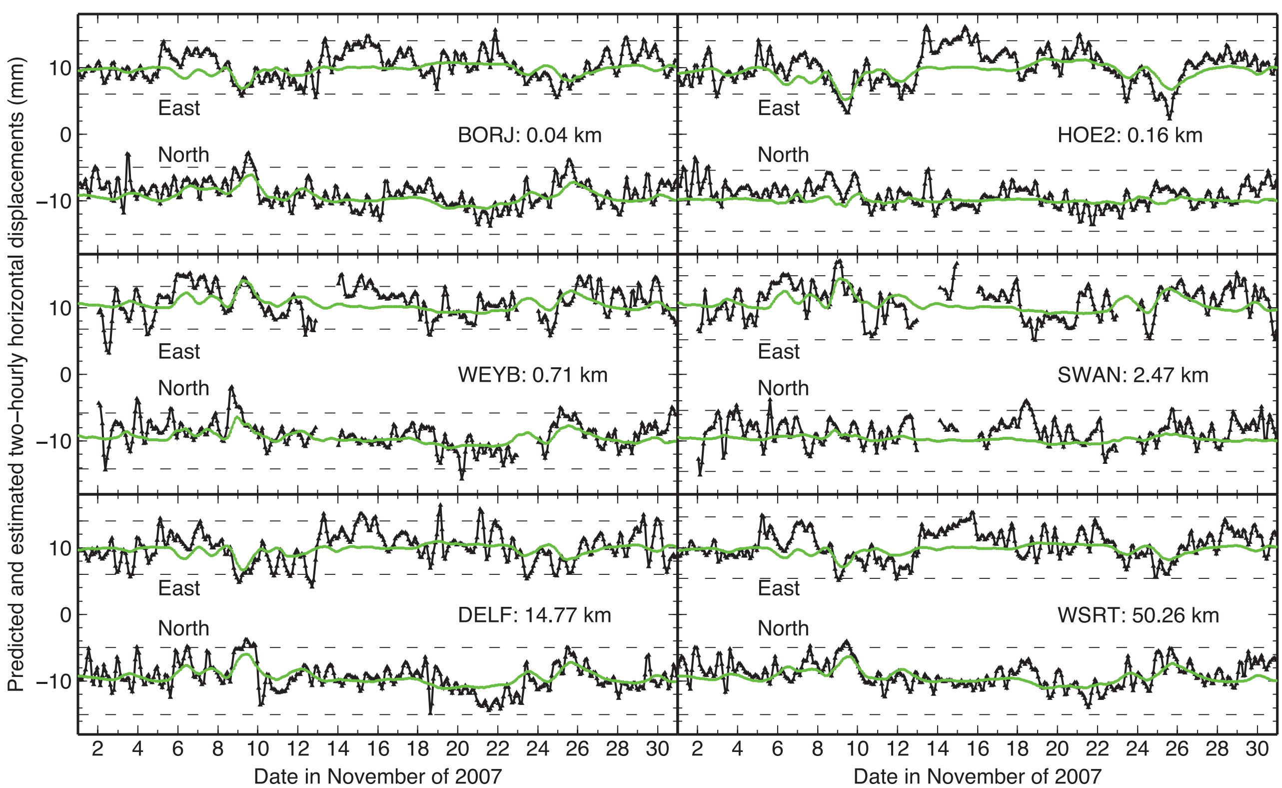

Figure 5. Horizontal loading displacement time-series at six stations in 2007 November. Meaning of curves refer to Fig. 3. Dashed lines denote the ranges of twice the GPS horizontal positioning errors. Note that the East component is offset by 10 mm whereas the North component by –10 mm for clarity.

Table 2. Root mean square (mm) of the estimated displacements for the Up, East and North components of 26 stations within the whole of 2007 November. The rms both before and after the mitigation of NTOL effects are exhibited. Numerals within parentheses are rms reductions. Column 2 shows the distance of each station to the nearest coastline, and all stations are sorted by these distances except four island stations BORJ, TERS, HELG and HOE2.

Stations	Distances from coastlines (km)	Before loading correction			After loading correction		
		Up	East	North	Up	East	North
BORJ	0.04	9.3	2.6	3.0	6.7 (2.6)	2.5 (0.1)	2.6 (0.4)
TERS	0.06	9.9	2.7	2.8	7.2 (2.7)	2.6 (0.1)	2.6 (0.2)
HELG	0.09	12.0	3.2	2.8	8.9 (3.1)	3.0 (0.2)	2.7 (0.1)
HOE2	0.16	9.2	3.0	2.4	7.1 (2.1)	2.6 (0.4)	2.4 (0.0)
SHEE	0.02	10.8	3.3	4.1	9.7 (1.1)	3.1 (0.2)	4.1 (0.0)
MARG	0.05	8.2	2.8	3.2	6.9 (1.3)	2.8 (0.0)	2.9 (0.3)
DUNG	0.07	8.9	2.9	2.7	8.0 (0.9)	2.9 (0.0)	2.6 (0.1)
LOWE	0.18	10.7	3.1	3.2	8.3 (2.4)	2.9 (0.2)	3.0 (0.2)
ALDB	0.20	9.5	3.1	2.7	7.0 (2.5)	3.0 (0.1)	2.5 (0.2)
GORE	0.36	10.1	3.3	2.7	7.6 (2.5)	3.0 (0.3)	2.6 (0.1)
SKEN	0.38	9.8	3.4	2.8	8.4 (1.4)	3.0 (0.4)	2.7 (0.1)
WEYB	0.71	9.1	3.1	2.9	7.5 (1.6)	2.8 (0.3)	2.6 (0.3)
SCAR	0.81	9.4	3.4	3.2	8.2 (1.2)	3.0 (0.4)	3.2 (0.0)
EASI	0.87	11.0	3.1	2.8	8.8 (2.2)	2.8 (0.3)	2.7 (0.1)
LOFT	0.89	10.3	3.1	3.2	9.2 (1.1)	2.9 (0.2)	3.2 (0.0)
SHOE	1.38	8.6	3.2	3.1	7.6 (1.0)	3.0 (0.2)	3.0 (0.1)
SWAN	2.47	9.1	3.2	3.2	7.8 (1.3)	3.0 (0.2)	3.1 (0.1)
COLC	7.11	11.0	3.3	2.6	9.2 (1.8)	3.1 (0.2)	2.5 (0.1)
NEWC	11.30	9.2	3.3	2.9	8.7 (0.5)	3.1 (0.2)	2.9 (0.0)
DELF	14.77	10.7	3.0	2.9	9.0 (1.7)	2.8 (0.2)	2.6 (0.3)
WATT	17.40	8.3	3.1	2.7	7.1 (1.2)	2.9 (0.2)	2.5 (0.2)
LINC	44.94	8.2	3.4	3.1	7.5 (0.7)	3.1 (0.3)	3.1 (0.0)
DENT	46.33	7.2	2.7	2.7	6.5 (0.7)	2.7 (0.0)	2.4 (0.3)
WSRT	50.26	7.8	2.6	2.7	7.1 (0.7)	2.5 (0.1)	2.4 (0.3)
BRUS	62.98	6.8	2.5	2.4	6.5 (0.3)	2.5 (0.0)	2.2 (0.2)
EUSK	187.42	7.7	2.3	2.7	7.4 (0.3)	2.3 (0.0)	2.7 (0.0)
Mean		9.3	3.0	2.9	7.8 (1.5)	2.8 (0.2)	2.8 (0.1)

to stations LOWE, ALDB and GORE despite being further from the coast. The most likely explanation is that SHEE, MARG and DUNG undergo relatively minor NTOL displacements because they have proportionally more land nearby than other stations such as LOWE, ALDB and GORE. This issue reminds us of the fact that the NTOL effects at a station are not only subject to its distance to the nearest coastline, but also to the shape of coastlines and the land-sea distribution around.

In addition, the rms reductions for both East and North components range from 0.0 to 0.4 mm. The mean rms is reduced, although slightly, from 3.0 to 2.8 mm for the East and from 2.9 to 2.8 mm for the North component. We note that the horizontal rms do not increase at any station after the mitigation of the NTOL effects, thereby reinforcing the idea that the GPS horizontal position time-series also sense the NTOL signals.

6 CONCLUSIONS

We use two-hourly GPS positions to successfully identify the loading effects caused by a storm surge event which occurred in the southern North Sea on 2007 November 9. During the storm surge, the estimated loading displacements at coastal stations were on the order of 40 mm in the vertical and over 5 mm in the horizontal directions. For the 26 stations around the southern North Sea (even stations over 50 km inland), their two-hourly GPS position time-series successfully tracked the temporal evolution of the storm surge loading effects in both vertical and horizontal directions. In particular, the estimated displacements agree with the predicted displacements within the uncertainties of the two-hourly GPS positions.

In order to further verify the agreement between the estimated and predicted displacements, we corrected two-hourly GPS positions for the NTOL effects for the whole of 2007 November. The rms of the estimated displacements is reduced on average by 1.5, 0.2 and 0.1 mm for the Up, East and North components, respectively. Therefore, for the North Sea and other shallow seas such as the Baltic Sea and the Gulf of Mexico, it can be beneficial if GPS data are corrected for the NTOL effects when precise models such as the POLSSM are available. Conversely, the prediction accuracy of such models may be improved if they are properly constrained using GPS measurements.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Vertical loading displacement time-series in 2007 November at 10 stations whose distances to the nearest coastlines range from 0.06 to 0.81 km. Black curves denote the displacements estimated with two-hourly GPS whereas green curves denote those predicted with the POLSSM.
Figure S2. Vertical loading displacement time series in 2007 November at 10 stations whose distances to the nearest coastlines range from 0.87 to 187.42 km.
Figure S3. Horizontal loading displacement time series in 2007 November at 10 stations whose distances to the nearest coastlines range from 0.06 to 0.81 km. Note that the east component is offset by 10 mm while the north component by 10 mm for clarity.
Figure S4. Horizontal loading displacement time series in 2007 November at 10 stations whose distances to the nearest coastlines range from 0.87 to 187.42 km.
Table S1. Geographic coordinates of the 26 stations around the southern North Sea.
Table S2. Root mean square of the differences between the de-tided tide gauge measurements and the predicted non-tidal sea levels with the POLSSM in 2007 November. Geographic coordinates of tide gauges are shown in column 2 and 3.

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