Solid Earth Discuss., 4, C534–C549, 2012
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Solid Earth
Discussions

Interactive comment on "Reprocessed height time series of GPS stations at tide gauges" *by* S. Rudenko et al.

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The authors would like to thank the Referee A. Santamaría-Gómez for the thorough review of our manuscript and for the valuable comments and suggestions that contributed significantly to improve the quality of our paper. Our answers to the detailed remarks are given below. The Referee remarks start with symbols "> *" followed by the authors comments.

> * General comments

> * This is a paper on an important topic such as the estimation of vertical land motion of tide gauges for sea level research. The data processing and analysis presented constitute a great effort by the authors to provide an independent GPS solution within the

framework of the IGS reprocessing and the IGS TIGA project. The authors also provide discussion on some specific case studies of co-located GPS and tide gauge stations. However, the paper is generally not well written and some parts of the methodology and discussion must be clarified. Also, verify that all the figures are referred in the right order and that are provided with appropriate captions describing (not discussing) the content of the figure.

The methodology and discussion will be written in a more clear way in the revised paper after making the changes described below. The figure numbers will be given according to the order, as they are mentioned in the text. The discussion will be moved from the figure captions to the paper text.

> * Specific comments

> * P1026

> * L7: provide some numerical values on the quality of the estimated velocities (e.g., error bars, comparison).

The following sentence will be added in the abstract in the line 7 at page 1026 after the words “and other GPS solutions”: “The formal errors of the estimated vertical velocities are 0.01-0.80 mm/yr. The vertical velocities of our solution agree within 1 mm/yr with those of the recent solutions (ULR5 and ULR3) of the Universite de La Rochelle for about 67-75 per cent of common stations.”

> * L10: provide the number of tide gauges for which the vertical land motion was estimated by GPS.

The words “69 of them are GPS stations located at or near (less than 25 km) tide gauges.” will be added after the words “tracking history longer than 2.5 yr are computed” in line 6 at page 1026. It should be clear now.

> * L23: the authors should specify who requires the stated accuracies.

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The sentence starting with “The required accuracies” in line 23 at page 1026 will read “The accuracies required by oceanographic community for sea level studies are about 5-10 mm for station positions and less than 1 mm/yr for vertical motions (Schöne et al., 2009).”

> * P1027

> * L17: add here origin rate errors too

The words “and origin rate” will be added after the words “reference frame scale rate” in line 17 at page 1027, as correctly pointed out by the reviewer.

> * L21: define what is meant by “near”. Did the authors apply a distance threshold?

It has been clarified in the abstract - less than 25 km. The sentence “187 stations are located at or near tide gauges” will be erased here, since the number of GPS stations located near tide gauges will be given in the abstract.

> * L24: how many velocities with >2.5 yr of data were estimated? How many near a TG?

The number “266” will be added before the words “GPS stations with time series” in line 24 at page 1027. The sentence starting with words “Vertical velocities of GPS stations” in line 6 at page 1026 will read “Vertical velocities of 266 GPS stations having tracking history longer than 2.5 yr are computed, 69 of them are GPS stations located at tide gauges (TIGA observing stations). The vertical velocities calculated are compared with the estimates from the colocated tide gauges and other GPS solutions”.

> * P1028

> * L8: there are only 107 GPS stations officially committed to TIGA. Please clarify.

We have densified the network of TIGA stations by including, as mentioned in Section 5, some new stations located at or near tide gauges that are not yet included in the list of 107 GPS stations officially committed to TIGA. The second and third sentences of Section 2 (lines 7-9 at page 1028) will be written in more clear way: “The global network of GPS stations was split in two subnetworks. The first subnetwork includes 216 IGS stations, the second subnetwork includes 187 continuous GPS at tide gauges (TIGA): 107 TIGA observing stations and some other new stations”.

> * L10: the authors should clarify how the sub-networks solutions were combined. Was each sub-network aligned to the ITRF2005 by fixing the coordinates of the reference stations of were the sub-networks aligned to each other? What was the minimum number of reference stations used? Was their global distribution considered? Furthermore, it is not clear which set of reference coordinates was used (IGS05/ITRF2005). If it was ITRF2005, the authors should comment on the impact of the PCV inconsistency, especially on the vertical component (station coordinates in ITRF2005 were estimated using a relative PCV).

The words “using the procedure described in (Zhang et al., 2007) and taking into account the global distribution of the reference stations. All available reference stations were used which were available over time span.” will be added after the words “(cluster connectors)” in line 11 at page 1028. In fact, we used IGS05 (being an IGS realization of ITRF2005 for GPS stations) with an appropriate file igs05.atx for absolute PCV corrections. So, there was no inconsistency. This will be written in the paper in a more clear way.

The following reference will be added: Zhang, F. P., Gendt, G., and Ge, M.: GPS Data Processing at GFZ for Monitoring the Vertical Motion of Global Tide Gauge Benchmarks, GeoForschungsZentrum Potsdam Scientific Technical Report STR07/02, 28 pp., 2007.

> * L18-21: the authors should clarify how the terrestrial frame of the solution was realised. Only information on the a priori station coordinates and velocities are provided. How was the terrestrial frame aligned? Where and how the constraints were applied?

The sentence “Coordinates of reference stations were estimated with tight constraints to their initial values and loose constraints were used for all other stations." will be added after the words "estimated for remaining stations." in line 19 at page 1028.

> * L22: "few hundred" is too vague.

The words "few hundred stations" will be replaced by the words "up to three hundred stations per week", as shown in Figure 2.

> * P1029

> * L25: any reference to support this statement?

It is known from the analysis of GPS data performed within the IGS community, that the quality of the equipment used at GPS stations increased in the past 10-12 years. The words "are also linked" will be replaced by the words "can be also linked".

> * L26-27: only the station coordinate residuals are assessed, not the absolute station coordinate differences, nor the accuracy, nor the realisation of the reference frame. The transformation parameters must be shown. Additionally, if the authors want to show the level of agreement of the estimated coordinates with respect to the IGS repro1, a direct comparison of the stations coordinates at a common epoch would be helpful. Only IGS reference frame station coordinates should be used since the GT1 solution have less weight than for other stations. Vertical velocities should also be compared to IGS repro1.

We have computed weekly Helmert transformation parameters of GT1 solution with respect to the combined solution of the first IGS reprocessing campaign (IG1), as suggested by the Referee. The following phrase will be added after the words "with respect to the IGS combined solution of Repro1 (Dow et al., 2009)" in line 27 at page 1029 in Section 3: "The time series of weekly Helmert transformation parameters (X-, Y-, Z-rotations, X-, Y-, Z-translations and scale) of GT1 solution with respect to IG1 solution are shown in Fig. X. The average values and standard deviations of the transformation parameters are: -0.004$\pm$0.041, 0.007$\pm$0.042 and -0.007$\pm$0.045 mas for X-, Y-, Z-rotations, 0.298±1.074, -0.045±1.069 and 1.403±1.056 mm for X-, Y-, Z-translations and -0.501±0.166 ppb for scale indicating a good agreement of our solution with IG1 solution for the common stations." A figure showing the time series of X-, Y-, Z-rotations, X-, Y-, Z-translations and scale will be included in Section 3 of the revised paper. The results of the comparison of vertical velocities of our solution with other external solutions will be added in Section 5.

> * P1030

> * L13-15: this sentence needs explanation. How can be transformed the vertical coordinates only into longitude, latitude and height?

This misprint will be corrected. The words "by extracting the vertical coordinates" will be replaced by the words "by extracting the Cartesian coordinates".

> * L17-19: this sentence needs explanation. Did the authors apply any constraint between the estimated trends of the same time series (between breakpoints) to obtain a unique station velocity?

The elaboration on the determination of breakpoints was added when replying to the comments of the first Referee (J. Ray). We hope, that it is clear now.

> * L24: please clarify to which trend signal refers this statement.

The words "of the trend signal" will be replaced by the words "of the land movement trend signal".

> * P1031

> * L6: does the 2.5 yr threshold include breackpoints or does it represent breackpoint-free 2.5 yr data?

The 2.5 year threshold was defined independent of the presence of breakpoints. It serves as a means to identify any annual cycles present in the data. The phrase "stations with time series shorter than 2.5 yr" will be written as "stations with the total

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length of time series less than 2.5 yr". It should be clear now.

> * L16-20: vertical land motion estimated with GPS is consistent with that derived from TG data at Neah Bay assuming an absolute sea level change of 2 mm/yr (assumed by the cited Verdonck paper). This absolute sea level rise is completely in disagreement with the estimated altimetry sea level trend of 4 mm/yr (or it is -4.3 mm/yr ?). In addition, it is not clear what the altimetry value has to do here (the relative sea level trend is missing). An explanation is needed here.

Trends at tide gauges discussed in Section 4.2 were unfortunately affected by a script error. This section has been revised. We would like to thank the reviewer for alerting us to this problem. We have also excluded some discussion leading to misunderstanding. The remainder of the Section 4.2.1 starting with the words "This is in accordance with the results" will be replaced by "This agrees well with the results of Verdonck (2006), who arrives at an estimated rate of land movement of 4.0 $\pm$0.1 mm/yr. In his estimate, he subtracts a mean eustatic sea level rise 2.0 mm/yr from the trend calculated from the tide gauge data (-2.0 mm/yr)."

> * L21-23: this sentence is wrong or it needs rewording. Do the authors state that since the NA plate is subject to uplift so does geocentric sea level on a TOPEX grid point?

This sentence will be excluded, as an unnecessary comment, that leads to misunderstanding.

> * P1032

> * L9: does this trend refer to the relative sea level or to the absolute vertical land motion? Note that the relative sea level trend provided by the PSMSL is about -8 mm/yr. The authors must explain how this value was estimated and provide the data period. Also the source of the tide gauge data should be included.

The following sentence will be added in the second paragraph of Section 4.1 after the words “to separate the origin of the trend signal, where possible”: “All tide gauge data was retrieved from the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003). Linear trends at tide gauges were determined using a standard linear model with ordinary least square adjustment.” The following reference will be added: Woodworth, P. L. and R. Player, R.: The Permanent Service for Mean Sea Level: an update to the 21st century. J. Coastal Res., 19, 287-295, 2003.

The remainder of the second paragraph of Section 4.2.2 starting from the words “The tide gauge trend yields” will be replaced by the words “The tide gauge trend computed by us is -8.1 $\pm$0.2 mm/yr. So, the residual sea level rise from the sum of tide gauge and land movement signals is 2.7 $\pm$ 0.3 mm/yr.”

> * L10: the tide gauge trend changes by 64% when the annual signal is not removed. Can the authors explain this discrepancy?

This value was affected by the error in the tide gauge trend computation, as mentioned above. The value of the Skelleftea tide gauge trend for the case, when the annual signal is removed, is the same as the trend for the full data. This will be corrected in the revised version of the paper.

> * L11-13: This is wrong. Adding the GPS-derived vertical land motion and the relative sea level trend up, it should lead to the absolute sea level trend from satellite altimetry. See for instance equation in Santamaría-Gómez et al., 2012, Global and Planetary Change.

The reviewer is right. We were talking about the inverse GPS trend without making it clear, but it followed from the text that we were talking about the GPS land movement trend. This part of the text will be corrected.

> * L13: sea level change from geoid variations is also sensed by the tide gauge. Can the authors really explain the trend differences by local geoid changes?

These are no more such trend differences after recomputing the correct values of the tide gauge trends. This explanation will be excluded in the revised version of the paper.

> * L18: Nedre Gavle relative sea level trend is estimated by the PSMSL in -5.6 mm/yr for the same period. The authors should explain how this value was estimated.

The word "tide gauge" will be added after the words "Nedre Gavle" in line 17. The remainder of the third paragraph of Section 4.2.2 starting with the words "However, the accordance with the land movement trend" will be replaced by the words "The comparison with the land movement trend at Ma°rtsbo (7.62 $\pm$ 0.01mm/yr) shows that a large part of the tide gauge signal can be explained by the land movement through GIA. Assuming that the GIA trend was constant over the last 100 years, the residual sea level trend from the sum of tide gauge relative sea level trend and land movement signals is +1.62 $\pm$ 0.2 mm/yr."

> * L19-22: This sentence needs be revisited since the GPS-derived vertical land motion of 7.6 mm/yr does not seem to be in satisfactory accordance with the tide gauge trend (6 mm/yr) and the absolute altimetry trend of 4 mm/yr (see my comment on L11-13 above).

This sentence has been revised, as written in our answer to the previous comment.

> * P1033

> * L21: the Churchill relative sea level trend provided by the PSMSL for the 1940-2009 period is about -9.5 mm/yr. The authors should again explain what this trend represents and how it was estimated.

The remainder of Section 4.2.3 starting from the words "The tide gauge at Churchill yields a trend" will be replaced by the words "For 1940-2009, the Churchill tide gauge yields a trend of -9.7 $\pm$ 0.1 mm/yr (-9.54 $\pm$ 0.2 mm/yr with a seasonal component removed). It is clear even from visual inspection of the Churchill tide gauge that the overall negative regional sea level trend has flattened considerably from the beginning of the 1990s. For the 1998-2007, the trend at Churchill yields -2.8 $\pm$ 3.5 mm/yr. Re-

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moving the seasonal signal reduces the standard error and results in a substantially larger trend estimate of -5.18 $\pm$ 0.97 mm/yr. This means that, for 1998-2007, the full data trend is around two thirds smaller than for the whole period of coverage, and about half when the seasonal signal is removed. An explanation for this behaviour can be found in (Déry et al., 2010), who mentions that there is a notable positive trend in river discharge into Hudson bay, starting around the 1990s and continuing until 2008, the end of their time series. At the same time, there is a shift in the seasonality of river discharge into the Bay. With a positive trend in winter and negative trend in summer streamflow, the variance of the time series is expected to increase. This explains the large impact of the seasonal signal on the trend for the 1998-2007 time series. The tide gauge signal, which has long been dominated by GIA, is apparently now influenced much more strongly by the changing hydrological processes in Hudson Bay."

The following reference will be added for the used citation: Déry, S. J., Mlynowski, T. J., Hernández-Henríquez, M. A., Straneo, F.: Interannual variability and interdecadal trends in Hudson Bay streamflow, J. Marine Syst., 88, 341-351, 2011, ISSN 0924-7963, 10.1016/j.jmarsys.2010.12.002.

> * L26: the authors should include some reference for such construction fault or remove it. For instance, the cited Kaniuth et al. paper assumes it is due to sediment subsidence.

The section 4.2.4 will be rewritten in a more clear way: "This station located near the IGAC building in Bogota and has been continuously subsiding during the past years is a peculiar example. The station was treated in (Kaniuth et al., 2001) together with another station, BOGA, which is positioned on the top of the building. In their treatment, the authors suggest that construction work may have worsened the subsidence processes caused by sedimentation in the area. The vertical trend at BOGT has almost doubled since it was first estimated in their 2001 paper, now reaching the alarming rate of -44.21 ± 0.19 mm/yr (Fig. 13). Obviously, the station cannot be used for any purposes within the TIGA framework."

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> * P1034

> * L1-3: from the vertical time series of fig. 13 it is not clear if the vertical trend has more than doubled since 2001. Do you have an estimate for this period or it is a comparison with Kaniuth et al results which were estimated with only 48 days?

It is indeed a comparison with the (Kaniuth et al., 2001) values (-25.2±1.4 mm/yr) which were estimated with 366+48 = 414 days. It has been clarified in our answer to the previous comment.

> * L22-24: the authors should explain how the vertical land motion was estimated from the relative tide gauge sea level record. Following my comment on L11-13 (page 1032), in order to extract land motion from a tide gauge we need a hypothesis/observation/model for the absolute sea level signal recorded by the tide gauge.

The sentence "The land movement trend from the tide gauge before the earthquake is a moderate -0.6 ± 0.2 mm/yr, increasing by more than 800% to -6.5 ± 0.2 mm/yr after the earthquake." will be replaced by "The relative sea level trend from the tide gauge before the earthquake is a moderate $+0.6 \pm 0.2$ mm/yr, increasing by almost ten times to 6.5 ± 0.2 mm/yr after the earthquake."

> * P1037

> * L12: the authors should specify the percentage of stations with discrepancies below 1 mm/yr with respect to ULR solution.

This will be specified, as described in our answer to the next comment.

> * L13: the ULR solution from Bouin and Wöppelmann 2010 is rather obsolete (the data processing described by Wöppelmann et al., 2009 was performed in 2007). Note that since 2007, two improved ULR solutions have been published by Santamaría-Gómez et al., 2011 and 2012, respectively. These solutions have significantly increased the GPS-near-TG network. A comparison of the vertical velocities with the last ULR solution would be far more interesting since this has never been done yet

(even within the TIGA project).

We are grateful to the Referee for pointing our attention to the latest ULR4 (2011) and ULR5 (2012) solutions. We have performed comparison of the vertical velocities with the last ULR solution and will add the results of this comparison in the revised version of our paper, in particular in Table 3 and in Section 5. The new version of the second paragraph of Section 5 will read as follows. “We have compared the vertical velocities of our solution with the previous GFZ solution (Zhang et al., 2008) obtained by processing GPS data from a global network of 370 GPS stations from January 1994 till December 2006 and containing the vertical velocities of 335 stations aligned to ITRF2000 and two solutions of Universite de La Rochelle: ULR3 solution (Bouin and Woeppelmann, 2010) derived using GPS data from a global network of 227 stations from January 1997 to November 2006 and containing the vertical velocities of 180 stations expressed in ITRF2005 and ULR5 solution (Santamaria-Gomez et al., 2012) obtained by processing GPS data from a global network of 420 stations from January 1995 to December 2010 and providing the vertical velocities for 326 stations given in ITRF2008. Both ULR solutions use IGS absolute phase centre corrections for both tracking and transmitting antennas, as our (GT1) solution does, whereas the previous GFZ solution was computed using relative phase centre corrections and some older models. The comparison shows, that the discrepancies in the vertical velocities are below 1 mm/yr for 106 of 142 common stations, i.e. about 75 per cent, for GT1 and ULR3 solutions, for 120 of 179 common stations, i.e. about 67 per cent, for GT1 and ULR5 solutions, whereas only for 101 of 224 common stations, i.e. about 45 per cent, for GT1 and (Zhang et al., 2008) solution due to the use of some obsolete models, in particular, relative phase centre corrections in the previous GFZ solution.”

The following reference will be added: Santamaria-Gomez, A., Gravelle, M., Collilieux, X., Guichard, M., Martin Miguez, B., Tiphaneau, P., Wöppelmann, G.: Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field, Global Planet, 98-99, 6-17, doi:10.1016/j.gloplacha.2012.07.007, 2012.

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Additionally references for ITRF2000 and ITRF2008 mentioned in the text above will be provided.

The title of Table 3 will be changed to “Comparison of the vertical velocities (mm/yr) of GPS stations common in our and three recent solutions.” A column with the vertical velocities from ULR5 solution will be added in Table 3. An entry for station NANO that was missing will be added in Table 3.

> * Technical corrections

> * P1026

> * L10: add “correcting the vertical land motion in tide gauge records”. Remove “regional and global”.

The end of this sentence will be written as “can be used for correcting the vertical land motion in tide gauge records of sea level changes”.

> * L12: methods -> techniques

The word “methods” will be replaced by the word “techniques”, as suggested by the reviewer.

> * L13: The former one -> Satellite altimetry

The words “The former one” will be replaced by the words “Satellite radar altimetry” for better understanding.

> * L17: totally -> some

Here is meant, that time series of tide gauge measurements are available totally for a time span longer than 120 years. The word “totally” has been already replace by the word “totaling” for better understanding.

> * L21: remove GPS. Pilot Proyect -> Working Group

According to the web page http://adsc.gfz-potsdam.de/tiga/index_TIGA.html, the former “GPS Tide Gauge Benchmark Monitoring Pilot Project” has been recently transformed into “GPS Tide Gauge Benchmark Monitoring Working Group”. So, the words “the GPS Tide Gauge Benchmark Monitoring Pilot Project (TIGA)” will be replaced by the words “the GPS Tide Gauge Benchmark Monitoring (TIGA) Working Group, former Pilot Project (http://adsc.gfz-potsdam.de/tiga/index_TIGA.html)”.

> * L24: reserch -> research

This has been already corrected.

> * L26: older -> obsolete

The word “older” will be replaced by the word “obsolete”.

> * P1027

> * L3: remove “and made possible”

In fact, a reprocessing within the TIGA project wouldn’t be possible without new processing models or would have little sense. That is stressed by the words “and make possible”, that, from our opinion, should be kept in the paper.

> * L9: GPS -> IGS

The paper (Collilieux et al., 2011), as follows also from its title, discusses really GPS realization of the terrestrial reference frame and compares it with the SLR one, as is written in this sentence. So, no change is required from our point of view.

> * L13: estimates -> observations

The word “estimates” will be replaced by the word “measurements”, that seems to be more suitable in this context.

> * P1028

> * L5: the global -> a global

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The words “the global” will be replaced by the words “a global”.

> * L8: GPS near tide gauges

We use here widely used term “continuous GPS at tide gauges stations”. So, no change is necessary, from our point of view.

> * L17: remove reference

The reference (Altamimi et al., 2007) for ITRF2005 will be removed here, since it is already given above.

> * L24: remove X, Y, Z. Remove “of all stations”

The letters “X, Y, Z” will be replaced by “Cartesian”. The words “of all stations” will be removed.

> * P1029

> * L26: remove absolute

The words “absolute” will be removed.

> * P1030

> * L2: accuracy -> precision

The use of term “accuracy” is, from our point of view, correct here, since we provide the results of the comparison of our solution with another (IGS combined) solution.

> * L4: accuracies are-> accuracy is

The words “accuracies are” will be replaced by the words “accuracy is”, as pointed out by the reviewer.

> * L22: at -> near

The word “at” will be replaced by the word “near”.

> * P1031

> * L14: add a comma after Washington

A comma will be added after the word “Washington”.

> * P1032

> * L8: CGPS -> GPS

The word “CGPS” will be replaced by “GPS”.

> * P1036

> * L15: hit this region

The words “hit region” will be replaced by the words “hit this region”.

> * P1037

> * L13: the recent -> a

The words “the recent” will be replaced by the words “a recent”.

> * L19: the global -> a global.

The words “the global” will be replaced by the words “a global”.

> * P1038

> * L1: the recent -> a

The words “the recent” will be replaced by the words “a recent”.

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