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Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field

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A B S T R A C T

This study aims to correct for long-term vertical land motions at tide gauges (TG) by estimating high-accurate GPS vertical velocities at co-located stations (GPS@TG), useful for long-term sea-level change studies and satellite altimeter drift monitoring. Global Positioning System (GPS) data reanalyses are mandatory when aiming at the highest consistency of the estimated products for the whole data period. The University of La Rochelle Consortium (ULR) has carried out several GPS data reanalysis campaigns with an increasing tracking network, an improving processing strategy and the best methodology. The geodetic results from the latest GPS velocity field estimated at ULR (named ULR5) are presented here. The velocity field includes 326 globally distributed GPS stations, from which 200 are GPS@TG (30% more than previous studies). The new GPS data processing strategy, the terrestrial frame definition and the velocity estimation procedures are described. The quality of the estimated vertical velocities is empirically assessed through internal and external velocity comparisons, including the analysis of the time-correlated noise content of the position time series, to be better than 0.6 mm/yr (2 sigma). The application of this velocity field is illustrated to appraise to what extent vertical land motions contaminate the estimates of satellite altimetry drifts. The impact on the altimeter-derived sea level trends was evaluated to be up to 0.6 mm/yr. Worldwide TGs were grouped into regions in order to explore long-term spatial sea level variability in the rates of sea level change. By taking into account the vertical land motion of the tide gauges, the dispersion of the observed sea level rates within each region was reduced by 60%. Long-term regional mean sea level variations up to 70% from the global mean were found.

1. Introduction

Long-term sea level changes are directly observed by tide gauges at some locations since the 18th century (Woodworth, 1999). Tide gauge records are however a relative and discrete measure of the sea level with respect to the tide gauge reference point or benchmark, i.e. they include any vertical land motion (VLM) of the benchmark to which the readings of the tide gauge are referred to.

Secular VLM contained in the tide gauge records is especially a hindrance to extracting the absolute sea level change signal (Wöppelmann and Marcos, 2012). This signal in the tide gauge records is useful to constrain the ocean warming budgets at global (Miller and Douglas, 2004) or regional scales (Ishii et al., 2006), and for detecting fingerprints of recent land-based ice melting (Douglas, 2008; Mitrovica et al., 2009).

Long-term VLM can be equal or larger than the local absolute sea level signal, thus masking the climatic-related information of the tide gauge record (Peltier and Tushingham, 1989; Baker, 1993). For instance, due to VLM, some parts of the world are experiencing extreme coastal flooding (e.g., Torres Islands; Ballu et al., 2011), while others are noticing a significant sea level fall (e.g., Fennoscandia; Johansson et al., 2002).

Typically, VLM at tide gauges are predicted using a GIA (Glacial Isostatic Adjustment) model (e.g., Church and White, 2011). This approach has however two main limitations: model errors due to poorly-constrained parameters (ice history, lithosphere thickness, mantle viscosity; Argus and Peltier, 2010), and the various local VLM processes that are not taken into account in the model (tectonic, sediment loading, fluid withdrawal, pier instability, monument displacement; Kolker et al., 2011). Rather than predicting all of these signals, an alternative approach is to estimate the long-term VLM at the tide

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gauges by means of co-located geodetic observations (Carter et al., 1989; Neilan et al., 1998). Since more than a decade, three geodetic techniques have been used to estimate the VLM at, or near to, tide gauges, namely DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) (e.g., Cazenave et al., 1999), absolute gravity (e.g., Williams et al., 2001), and GNSS (Global Navigation Satellite Systems) (e.g., Sanli and Blewitt, 2001). Among these three techniques, the GPS (Global Positioning System), being the first GNSS, has been the most used due to its relative low cost equipment and availability, its easy implementation and maintenance, and its continuous precision improvement over the past decades.

In this paper, GPS observations from permanent stations located at or near tide gauges are processed to compute a global velocity field. The velocity field is then used to assess the impact of VLM in estimating the stability of satellite altimetry drifts. It is also used to correct the sea level trends of a selected set of worldwide tide gauges, updating past results and exploring the spatial variability of the rates of sea level change. We finally discuss the current GNSS limitations and progress required to address the needs of the sea level community.

2. GPS and tide gauge data sets

The International GNSS Service (IGS) routinely collects and processes data from a global tracking network whose stations satisfy high-quality criteria (Dow et al., 2009). However, not all the co-located permanent GNSS at tide gauge stations (GPS@TG station hereinafter) satisfy the IGS criteria, and some of the stations satisfying these criteria are not included in the IGS network due to the high density of stations available in some regions (e.g., Europe, Japan, USA). To address the GPS requirements of the tide gauge community, the IGS created in 2001 the TIGA (Tide Gauge benchmark monitoring; Schöne et al., 2009) project.

The University of La Rochelle (ULR) Consortium created in 2001 as a TIGA Analysis Center was the first center correcting the VLM at tide gauges with a reprocessed GPS global vertical velocity field (Wöppelmann et al., 2007). Four ULR reprocessed solutions have been produced so far, each one being characterized by the improvement of the size and geometry of the tracking network, the data span period, the realized terrestrial frame, and the data processing (parameterization, models and corrections).

The latest reprocessed ULR solution (ULR5) is presented in this paper. It incorporates the latest advances in GPS processing strategies, in particular taking into account the lessons learned from the first international reprocessing campaign carried out between 2009 and 2010 within the IGS. It also extends the data set used in the previous solution by three additional years and by including about seventy additional stations at or near tide gauges.

The GPS@TG stations were selected to be located as close as possible to tide gauges (<15 km) with long-term records in the PSMSL (Permanent Service for Mean Sea Level; http://www.psmsl.org). A total of 282 GPS@TG stations were included in the GPS data reprocessing (Fig. 1). All corresponding tide gauges had time series of monthly sea level averages in the Revised Local Reference (RLR) data set of the PSMSL. The RLR is the most appropriate tide gauge data set for long-term trend sea level studies as its records have been previously checked and corrected for local datum continuity over time relative to benchmarks in the vicinity (Woodworth and Player, 2003). We thus used this tide gauge data set to compute the rates of relative sea level change (Section 4).

In addition, due to the inadequate spatial distribution of the GPS@TG stations, the stations of the IGS08 core network (Rebischung et al., 2011) were added to strengthen the terrestrial reference frame realization. The IGS core network consists of a well-distributed global set of stations extracted from the IGS contribution to the ITRF2008 (International Terrestrial Reference Frame 2008; Altamimi et al., 2011). Some of these core stations were already included in our GPS@TG network as they appear to be nearby a tide gauge.

In total, the tracking network of the ULR5 solution is composed of 420 permanent GPS stations. All the available data for these stations between January 1995 and December 2010 were included in the GPS reprocessing. It represents a substantial extension of the data set used with respect to the previous ULR4 solution (310 stations between 1996 and 2008; Santamaría-Gómez et al., 2011), especially for the GPS@TG component (from 216 to 282 stations).

3. Estimation of vertical land motion

We estimate the VLM as the linear rate of change of the GPS station height with respect to the Earth's center of mass (including solid Earth, atmosphere and oceans), as approximated by the Satellite Laser Ranging data used in ITRF2008 over the period 1993–2009. This estimation process is divided into two main steps: the estimation of the GPS station positions and the estimation of their position rate, i.e. their velocity, with respect to a well-established, conventional and Earth-centered reference frame. Although both the horizontal and vertical station positions and velocities are estimated, we will refer hereinafter only to the vertical component.

Daily station positions of the tracking network described in Section 2 were estimated using a state-of-the-art GPS data processing. Section 3.1

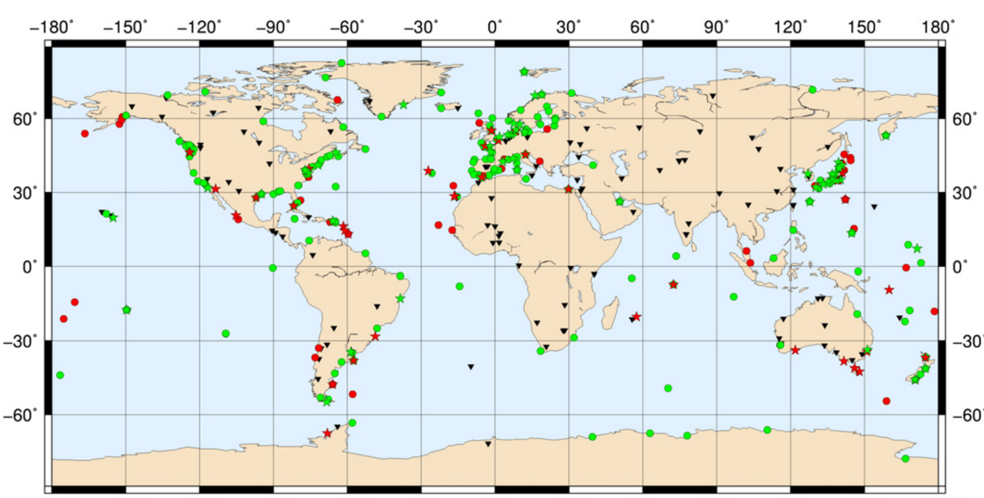

Fig. 1. The ULR5 GPS tracking network. Circles denote GPS stations included in previous solutions; stars are new in this respect. Green symbols highlight stations with a robust velocity estimate (Table S1); red stations failed our criteria. Black triangles are high-quality GPS stations not at or near a known TG, included mostly for the reference frame realization (see text).

describes the models and parameterizations applied to estimate precise station positions. In order to estimate the station velocities, the time series of the station positions were stacked into a long-term solution aligned to a terrestrial reference frame (Section 3.2). The geodetic quality of the VLM is then assessed (Section 3.3).

3.1. GPS data processing

Double-differenced ionosphere-free GPS data were processed using the GAMIT/GLOBK software version 10.4 (Herring et al., 2006). Observations below 10° were not included in order to minimize the effect of mismodelled low-elevation troposphere and antenna PCV (phase center variation) errors. Phase center offsets with azimuth-dependent and elevation-dependent absolute PCV corrections were applied. For those antennas without absolute calibration (11% of the antennas of the whole data set used in this study), converted relative-to-absolute phase corrections were applied. In such converted antenna calibrations, the azimuthal-dependent PCV is not included (assuming horizontal symmetrical phase centers), and the elevation-dependent PCV is only considered down to 10 degrees (Mader, 1999). For the satellites, satellite-specific antenna phase center offsets and block-specific nadir angle-dependent absolute PCV corrections were applied. The antenna phase center model, named igs08.atx (GPS week 1685) and recently released by the IGS (IGSMAIL-6354[1], 2011), is rigorously consistent with the a priori terrestrial reference frame used in the GPS data processing.

The phase observations were properly weighted in two iterations: by elevation angle first; and then by elevation angle and by station, accounting for the station-dependent scatter of the one-way phase residuals obtained from the first iteration.

Real-valued double-differenced phase cycle ambiguities were fixed to integers, where possible, using the Melbourne–Wübbena wide-lane to resolve the L1–L2 cycles first and then the L1 and L2 cycles. Satellite-dependent code bias corrections were applied for the whole period using monthly tables from the Astronomical Institute of the University of Bern (see IGSMAIL-2827[2], 2000).

A priori zenith tropospheric delay values were extracted for each station location at the ellipsoidal surface from the ECMWF meteorological model through the VMF1 grids (Boehm et al., 2006). These values were then corrected to the station heights using the GPT model (Global Pressure and Temperature; Boehm et al., 2007). Residual zenith tropospheric delays were adjusted for every station assuming they were dominated by the unmodelled wet component. The estimated zenith wet delay was parameterized by a 1 h piecewise linear continuous model. To relate the slant path delay with the zenith path delay, both the hydrostatic and wet VMF1 mapping functions were used. In addition to the tropospheric wet delay, to account for the effects of azimuthal asymmetry in the atmospheric delay, two atmospheric gradients were estimated for each day and station using the mapping function developed by Chen and Herring (1997).

The corresponding motions of the crust due to solid-Earth and pole tides were corrected following the International Earth Rotation and Reference Systems Service (IERS) Conventions (McCarthy and Petit, 2004). Crustal motion due to the ocean tide loading was corrected by interpolating the tidal constituents for each station from the global grid of the FES2004 model (Lyard et al., 2006). Loading due to heat-driven diurnal and semi-diurnal atmospheric tides was corrected using the ECMWF model (Ray and Ponte, 2003; Tregoning and Watson, 2010; 2011). Non-tidal loading corrections (atmospheric, oceanic, hydrology, ice, etc.) were not applied.

Earth orientation parameters (pole position, rate and UT1 rate) were estimated daily with a priori values from the IERS Bulletin B. Diurnal and semi-diurnal terms were added to the a priori UT1 and pole values. Since the UT1-UTC offset is correlated with the nodes of the satellite orbits, this parameter was tightly constrained to its a priori value.

Orbital parameters were adjusted using 24 h arcs and taking the IGS reprocessed orbits as a priori values. Non-gravitational constant and once-per-revolution accelerations on the satellites were adjusted using the Berne model (Beutler et al., 1994). Rotation of the satellite antenna away from the Earth-pointing position was also taken into account (Wu et al., 1993).

3.2. Estimation of vertical velocities

The number of stations available daily in the ULR5 tracking network ranges from 35 to 330. In order to overcome impractical GPS data processing time (roughly proportional to the square of the number of daily stations processed), we split the whole tracking network into several sub-networks depending on the number of daily available stations. A maximum of 50 daily-variable stations were included per sub-network by optimizing the global geometry of each sub-network. This daily-variable sub-network distribution improves the ambiguity integer fixing by up to 20% at the beginning of the data period with respect to the fixed sub-networks used in the past ULR solutions (Santamaría-Gómez et al., 2012).

To allow the combination of the estimated station positions from each sub-network into a daily frame solution, each sub-network included 6 daily-variable, and globally well-distributed, IGS08 core stations common to all daily sub-networks. The loosely-constrained estimates of the coordinates of these 6 common stations and of the orbital parameters were used to properly combine the sub-network frames using the GLOBK software.

In order to reduce the computation overload of the long-term terrestrial frame (station positions and velocities), the daily frame solutions were first stacked into weekly frame solutions (only station positions) using the GLOBK software. This is equivalent to filtering out high-frequency station position variations with periods smaller than 2 weeks. This is the current procedure used by the IGS for its GNSS-based products (station positions, satellite orbits and clocks) and by the IERS for the ITRF construction (Altamimi et al., 2011).

To estimate the station velocities, the weekly station position time series were stacked into a long-term frame solution using the CATREF software (Altamimi et al., 2007). Each weekly frame was aligned into the long-term frame by estimating the translation, rotation and scale transformation parameters. In order to minimize the aliasing of surface loading effects in the estimation of the transformation parameters, we estimated them using a global well-distributed sub-network of 30 stations spanning at least the 80% of the whole data period (Collilieux et al., 2012). The weekly transformation parameters estimated with this sub-network where then applied to the complete network of the weekly frame solutions. The long-term frame, in which the estimated velocities are expressed, was defined to be aligned to the ITRF2008. This alignment was realized by applying minimal constraints on all the transformation parameters (translation, rotation, and scale) with respect to the reference positions and velocities of a set of 40 high-quality and well-distributed IGS08 core stations. Indeed, the IGS08 station positions are consistent with the ground antenna model applied, whereas the ITRF2008 is consistent with the previous IGS absolute antenna model (Rebischung et al., 2011).

In order to properly estimate the station velocities, two requirements must be fulfilled: the station position discontinuities must be corrected; and enough data must be stacked to minimize the effects of periodic seasonal signals.

Regarding the first requirement, significant station position discontinuities (normalized position offset larger than 3 sigma) were mostly identified from the equipment changes recorded in the station logs (86% of the significant detected discontinuities were produced by an equipment change). The remaining significant discontinuities detected

[1] http://igscb.jpl.nasa.gov/pipermail/igsmail/2011/006346.html.
[2] http://igscb.jpl.nasa.gov/mail/igsmail/2000/msg00166.html.

on the station position time series were attributed to earthquakes (10%) or flagged as unknown (4%). The unknown origin was likely due to the lack of recorded information about equipment changes. When a position discontinuity was manually detected in a time series, the station position and velocity was estimated separately for the data before and after the discontinuity, together with the offset amplitude, and their formal uncertainties. We tightly constrained the estimated velocities to the same value before and after each position discontinuity unless a velocity discontinuity was detected (e.g. due to an earthquake). This way, short periods of data before/after a position discontinuity benefit from the estimated velocity of longer periods of data. In case of a velocity discontinuity, no constraint was applied and then a different velocity was estimated for each data period. Such stations are excluded from correcting long-term VLM at tide gauges in this study. Velocity discontinuities are however much more infrequent than position discontinuities. From the stations processed in this study, 6% of them showed a velocity discontinuity, from which 5% where likely due to earthquakes and the remaining 1% due to unknown sources.

Regarding the second requirement, the estimated station velocities can be significantly biased if the time series are too short, especially if seasonal signals are found in the time series (Blewitt and Lavallee, 2002). In addition, seasonal signals could also indirectly affect the station velocities in case of position discontinuities. Indeed, the presence of seasonal signals can bias the estimated offset amplitude, and thus, the estimated station velocity. For instance, we found velocity differences of up to 2 mm/yr for time series of 8 yr when seasonal signals were removed due to the presence of position discontinuities. Consequently, for those stations having at least 3 yr of data, annual signals were estimated before the velocity estimation and then removed from the time series.

Since the station velocities are estimated separately and constrained between position discontinuities, we therefore retained the station velocities for only those stations having more than 3 yr for, at least, one portion of data between two consecutive position discontinuities and with data gaps not exceeding 30%. These criteria also ensured that the estimated annual signals were reliable. The stations showing a velocity discontinuity were also rejected. These criteria resulted in 326 out of the initial 420 stations (Fig. 1) being included in the ULR5 velocity field (Fig. 2a and b), from which 201 are GPS@TG stations (81 GPS@TG failed to pass the criteria). Table S1 in the supplemental material provides this vertical velocity field.

3.3. GPS velocity uncertainties

The formal uncertainty of the vertical velocities (Fig. 2b) was estimated taking into account the time correlation of the residual position time series (trend, annual signal and offsets removed). The time correlation of the station positions was parameterized by a power law plus a variable white noise model. Both the white and colored noise amplitudes and the power law spectral index were adjusted using the MLE (Maximum Likelihood Estimator) method implemented by Williams (2008). Before the MLE adjustment, the remaining significant station-dependent periodic signals were removed from the residual position time series. A median spectral index of −0.85 was estimated. The median value of the resulting formal vertical velocity uncertainties (at 1 sigma) was 0.3 mm/yr, whereas a median uncertainty of

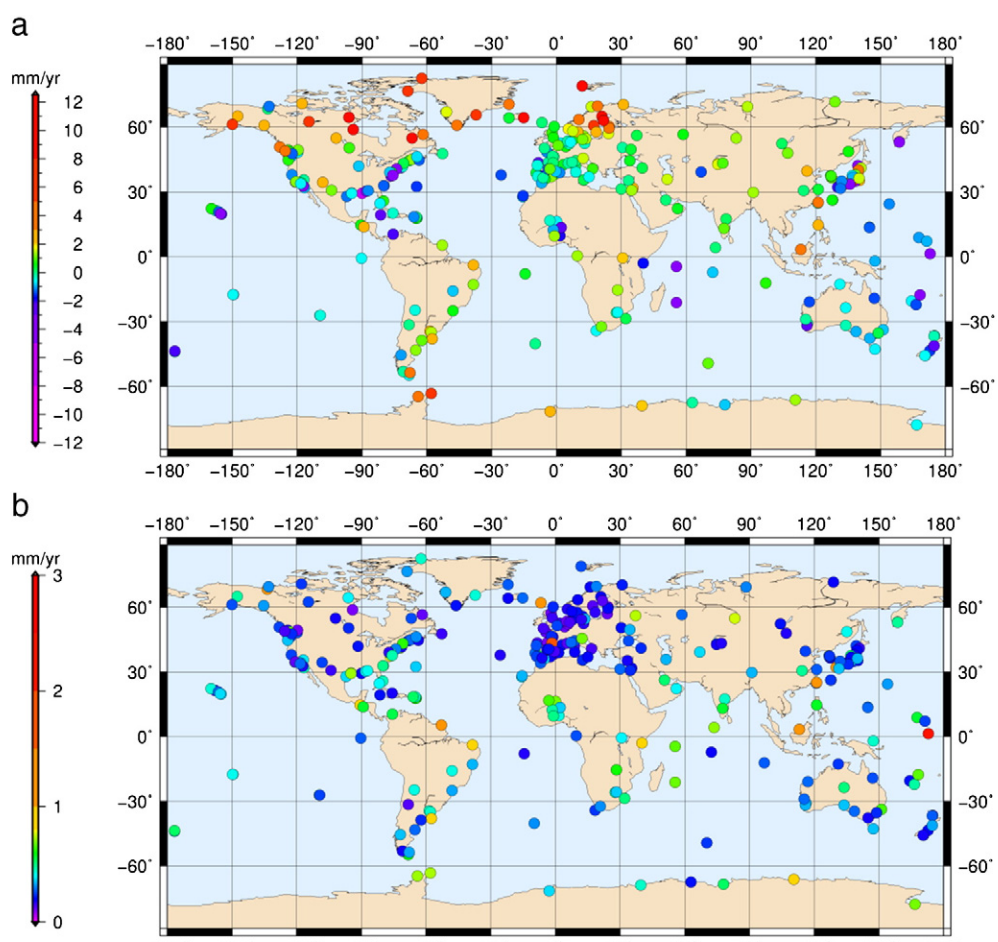

Fig. 2. ULR5 vertical velocity field (a) and associated formal uncertainties (1 sigma) (b).

0.12 mm/yr was obtained if time correlation is neglected. This represents a median uncertainty factor of 2–3 times larger. We compared the estimated correlated noise amplitudes with values given by Santamaría-Gómez et al. (2011) for the past ULR4 solution. For this noise comparison, a flicker noise model was adjusted using the common time series between both solutions trimmed to the ULR4 data period. The estimated flicker noise amplitudes of both solutions were consistent, being 2.2, 2.3, and 6.5 mm $yr^{-1/4}$, respectively for the North, East and Up components.

The station velocities were estimated by least-squares without taking into account the time correlation of the station positions (Section 3.2). In this section, the formal velocity uncertainties of such velocities were re-estimated in a station-by-station basis, but neglecting the spatial correlation of the estimated velocities. However, it has been demonstrated that the spatial correlation can be neglected when the velocity uncertainties are re-estimated by taking into account the temporal correlation in a station-by-station basis (Williams et al., 2004; Amiri-Simkooei, 2009).

In order to further assess the quality of the ULR5 vertical velocity field, we compared the vertical velocities of the ULR5 solution to the IGS reprocessed (repro1) solution. This IGS solution consists of a combination of several state-of-the-art solutions from the IGS Analysis Centers (Ferland and Piraszewski, 2009). The IGS station velocities used here were extracted from the ITRF2008 realization. To keep as much consistency as possible between both solutions for this comparison the ULR5 data period was reduced to match the IGS data period (i.e., 1997–2009.5; Altamimi et al., 2011), and the seasonal signals were not removed when the station velocities were estimated. Additionally, the IGS formal velocity uncertainties were scaled by a factor of 3 to empirically account for the time correlated position time series. Using 156 common IGS stations fulfilling the above-mentioned quality criterion (3 yr of data without discontinuities), the median absolute vertical velocity difference was 0.3 mm/yr with a WRMS (weighted root mean square) of 0.5 mm/yr. This level of agreement is consistent with the estimated formal uncertainties of the ULR5 solution. Less than 5% of the stations showed a velocity difference larger than 3 sigma. These atypical velocity differences between the IGS and ULR5 solutions are probably due to the use of a different position discontinuity set.

It should be noted that the assessment of the precision of the vertical velocity field, via the estimation of formal uncertainties or the comparison with IGS values, do not fully take into account possible global or station-dependent velocity biases. Although using a state-of-the-art data processing strategy, there may remain systematic errors that are not reflected in the estimated formal velocity precision and probably neither in comparison with the IGS solution. For instance, it is known that systematic errors are present especially in the GPS height time series and that these errors are one of the main source of the disagreement between GPS and GRACE time series (Tregoning et al., 2009; Tesmer et al., 2011). Sources of these errors include orbit mismodeling (Rodriguez-Solano et al., 2011; Sibthorpe et al., 2011), sub-daily mismodelled displacements (Penna et al., 2007), antenna multipath errors (King and Watson, 2010), and electromagnetic coupling of GPS antenna and monument (King et al., 2012). Some of them may generate spurious pseudo-periodic terms in the position time series (Ray et al., 2008) and apparent offsets (King and Watson, 2010). Moreover, the amplitude and phase of seasonal signals found in GPS position time series may be time-dependent, especially those with a geophysical origin (e.g., surface loading). The estimated velocities may thus be biased by the residual time-variable seasonal processes not accounted for by the sinusoid removed in the functional model (Davis et al., 2012). In addition to these error sources, we cannot rule out the possibility that station monuments actually contribute to the estimated ground motion (King and Williams, 2009), or that there may remain unnoticed position discontinuities in the time series contributing to the velocity biases (Williams, 2003).

Some of the systematic errors mentioned above are station-dependent and could have a significant impact on the estimated station velocities. They are thus of primary importance for the sea level application, especially at sparse sites, as in the Southern Hemisphere or island sites, where spatial data averaging/filtering approaches are not possible.

These station specific biases are not necessarily taken into account in the noise analysis we conducted, especially since the functional model applied might absorb the time-correlated content at the lowest frequency. We therefore compared the estimates from pairs of nearby stations of the ULR5 solution. Assuming that the VLM of nearby stations should be equal, the differences of vertical velocities of nearby stations are used here to infer the precision of the GPS vertical velocities. Indeed, conversely to past ULR solutions, in the present solution we did not apply at first velocity constraints between nearby GPS stations.

In our velocity field we found 23 pairs of stations separated by a maximum distance of 500 m. This set of stations includes 14 pairs of stations operating simultaneously. The other 9 pairs consist of station monuments that were replaced and hence do not overlap in time. All the 46 stations used in this comparison fulfilled the above-mentioned data requirements in order to estimate a reliable velocity (i.e. 3 yr of data without discontinuities and data gaps less than 30%). The median of the absolute values from the vertical velocity differences was 0.9 mm/yr with a WRMS of 1.3 mm/yr. However, taking into account the estimated formal uncertainties from the noise analysis (paired velocities assumed uncorrelated), the velocity differences were mostly insignificant (at 99% confidence level). This might indicate that the noise model used is adequate to describe the stochastic variability of nearby VLM estimates. Only 5 station pairs out of the 23 analyzed showed a significant velocity difference. The velocity difference for the BRAZ-FORT (Fortaleza, Brazil) pair (4.8 ± 1.2 mm/yr) might result from the effects of multipath and an uncalibrated antenna radome (Ray et al., 2007; King and Watson, 2010). The velocity difference for the NYAL–NYA1 (Ny-Alesund, Norway) pair (1.3 ± 0.3 mm/yr) might result from a non-linear very short-wavelength VLM process sampled over different time periods at each station (Kierulf et al., 2009). No explanation was found for the other 3 pairs of significant velocity differences (RIOG–RIO2 (Rio Grande, Argentina), SHK1–SHK5 (Sandy Hook, USA), and PLO3–PLO5 (Point Loma, USA)). These three station pairs do not overlap in time (station replaced) so their different vertical velocities may be related to geophysical non-linear VLM processes. It may also be related to underestimated formal uncertainties or station-dependent errors (including hidden discontinuities in the time series). Excluding these velocity outliers, the median and the WRMS of the velocity differences fell to 0.6 and 0.4 mm/yr, respectively, being much closer to the estimated median velocity formal uncertainty. The velocities of these 18 pairs of nearby stations were constrained as they showed insignificant differences.

The above comparison is limited to a small set of 46 stations (36 without the velocity outliers) compared to the 326 of the ULR5 velocity field, but it provides an independent assessment of the appropriateness of the estimated velocity uncertainties. Keeping in mind the quality assessment described in this section and the limitations in the estimated GPS velocities at some sites, especially regarding isolated stations, we explored the application of the ULR5 vertical velocity field (Table S1) to appraise the VLM contamination in estimating the stability of satellite altimeters (e.g., Mitchum, 1998), and to estimate VLM-corrected rates of sea level change from tide gauges.

4. Application

4.1. Satellite altimeter calibration

The ULR5 solution can provide valuable results for satellite altimetry sea level observations in two different ways. First, it provides precise positioning of dedicated GPS@TG stations used for calibrating the altimeter absolute sea level (ASL) bias, such as HARV in Harvest (Haines et al., 2003), AJAC in Corsica (Bonnefond et al., 2003), and BUR1/BUR2 in Bass Strait (Watson et al., 2004). It is worth remembering that there is a frame scale change of ~1 ppb (equivalent to ~6 mm at the Earth surface) between the ITRF2008 and the previous ITRF2005 (Altamimi et al., 2011). Second, a global tide gauge network provides the most reliable information about any drift in the satellite altimeters (Mitchum, 1998). However, the average VLM of the tide gauge set used, if not corrected, directly translates in a systematic bias of the estimated altimeter linear drift. The ULR5 velocity field provides thus VLM corrections for a global set of tide gauges that may be used to properly assess the stability of satellite altimeters.

Using a global network of 108 tide gauges, Mitchum (2000) estimated the linear drift for the TOPEX (Side A) altimeter with an uncertainty of 0.4 mm/yr. In an attempt to reduce the impact of the systematic VLM error, Mitchum (2000) applied VLM corrections from a combination of space geodetic (GPS and DORIS stations up to 1000 km) and tide gauge data (assuming a mean global ASL trend of 1.8 mm/yr). Even with these corrections, Mitchum (2000) stated that the main contribution to the uncertainty of the estimated linear drift came from the tide gauges for which no valid geodetic VLM estimates were available.

Following this previous study, we sought to assess the impact of the VLM correction on the altimeter linear drift estimation using our observations. For this purpose and since the 108 stations used by Mitchum (2000) were not explicitly given, we applied a Monte Carlo simulation to 100,000 random sets of 108 GPS@TG stations extracted from the ULR5 velocity field. We limited the ULR5 velocity field to the $\pm 66°$ latitude limits of the TOPEX/Poseidon mission, resulting in 178 available VLM estimates. For each set of 108 stations we estimated the median VLM. The resulting median VLM from the 100,000 sets ranged from -0.81 to $+0.25$ mm/yr with a mean value of -0.27 mm/yr and a standard deviation of 0.13 mm/yr. The estimated standard deviation was however optimistic due to the correlation of the median VLM estimates. The mean correlation of random sets of 108 values out of 178 is 0.61. To re-estimate a more realistic dispersion, the Monte Carlo simulation was run with six different sample sizes (from 10 to 108). The estimated standard deviation steadily increased as the used sample size was smaller, corresponding to a smaller correlation between the extracted sets. These standard deviations were used to tune a variance-covariance propagating function. This function was then re-evaluated in the case of a theoretical independent data set. The difference between both functions gave a variance scale factor of 1.5 for a set of 108 stations. Taking into account this variance factor and depending on the data set used, the unaccounted VLM of tide gauges may systematically affect the altimeter linear drift estimates between -0.66 and $+0.12$ mm/yr (at the two sigma level). Larger negative mean VLM effect would be obtained if, for instance, tide gauges affected by a large positive GIA signal are removed from the data set. These figures, derived from real observations, stress the need of using accurate estimates of the VLM at the tide gauges.

4.2. Sea level change from long tide gauge records

To estimate the absolute (geocentric) rates of sea level change, we focused on tide gauge records with a minimum length of 60 years. This criterion was adopted by Douglas (1991, 1997) in order to precisely determine long-term rates of relative sea level change by minimizing the impact of the interannual and decadal signals. Among the 1291 records available in the RLR data set (accessed January 2012), 243 covered more than 60 yr over the period starting in 1900. In this study, data prior to 1900 were discarded according to the coincident increase in the rate of sea level change found around the end of the 19th century in both hemispheres from different data types and samples (see Wöppelmann et al., 2008; and references herein). Consequently, the assumption that sea level is rising at a steady rate over periods including data prior and after that turning point around the end of the 19th century, cannot be supported. Over the 20th century, observational evidence for statistically significant acceleration terms was only detected in reconstructions of global sea level curves (e.g., Church and White, 2011). From individual tide gauge records, the issue has remained controversial and challenging (Fig. 3; see also Douglas, 2001). Fig. 3 shows a very small scatter of the acceleration term in the tide gauge records longer than 60 yr, suggesting that the rates of relative sea level change are essentially linear on the time span considered here (from 1900 to present), and governed by the noise of individual tide gauge records.

The 243 selected tide gauge records were further reduced to 223 when a minimum of 70% of valid data was required in the record. The latter 70% criterion was chosen as a tradeoff between rejecting records whose estimated linear trend could be affected by data gaps and/or sparse data and keeping the largest possible set of relevant tide gauges. Finally, crossing the selected tide gauges and the GPS stations of the ULR5 velocity field (Table S1) resulted in 62 long tide gauge records for which the VLM could be removed using state-of-the-art GPS estimates. It is worth noting that several tide gauges may be found near a single GPS station and, conversely, several GPS stations can be used to correct VLM at the same tide gauge. These case studies are discussed later on in Section 5. The final list was supplemented with the non-RLR tide gauge record from Alexandria, Egypt, which proved to show a reliable time series (Frihy, 2003).

The remaining GPS@TG data set that was not used may still be useful for other sea level studies such as detecting drifts in satellite altimeters (Mitchum, 1998; see also next section) or unifying vertical reference systems on land and at sea (Wöppelmann et al., 2006).

For each of the 62 selected tide gauge records, the relative sea level (RSL) trends were computed from the tide gauge series of monthly sea levels using a robust linear regression (Street et al., 1988). The ASL trends were then computed following the equation:

$$T_{ASL} = T_{RSL} + T_{VLM}$$

where T_{ASL} is the rate of absolute (geocentric) sea level change, T_{RSL} is the rate of relative sea level change estimated from the tide gauge record, and T_{VLM} is the estimated vertical velocity of the nearby GPS station.

The uncertainties of the ASL trends were obtained by propagating the formal errors of the tide gauge and GPS estimates assuming they

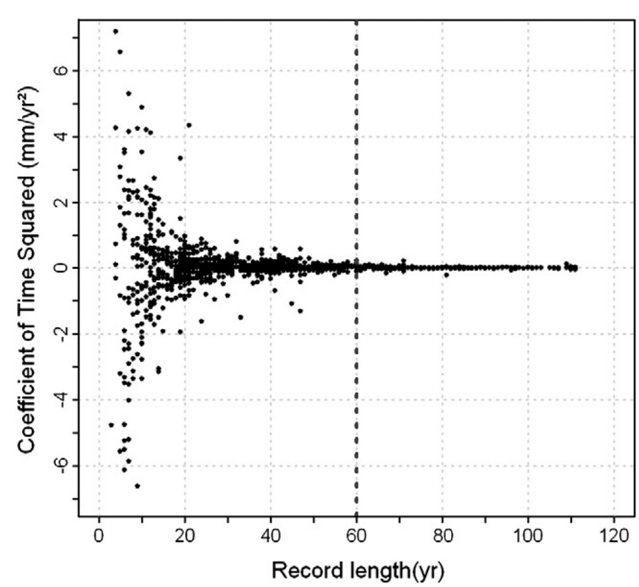

Fig. 3. Acceleration term of relative sea levels as observed by RLR tide gauges records available at the PSMSL.

were independent as they resulted from different data and methods. Both the estimated RSL and ASL rates are provided in Table S2 in the supplemental material. From this table a scatter (RMS) of 2.7 mm/yr in the rates of RSL could be derived. The Manila (Philippines) and Venezia (Italy) tide gauge records were not included in this computation due to serious concerns on the working hypotheses, which are discussed later on in Section 5. After applying the ULR5 velocities to correct the VLM at the selected tide gauge records, the scatter of the resulting ASL trends was reduced to 1.0 mm/yr (RMS). This represents a substantial reduction of 60% in the scatter of the individual rates of sea level change showing the impact of the VLM signal that is present in the selected tide gauge records.

5. Discussion

5.1. VLM and spatial variability of sea level trends

It is unlikely that the above (Section 4.2) observed dispersion of the individual rates of sea level change at our set of 61 stations distributed worldwide along a large variety of coastlines decreases by chance from 2.7 mm/yr to 1.0 mm/yr when correcting for VLM. Interestingly, Collilieux and Wöppelmann (2011) have shown that uncertainties (systematic errors) in the realization of the ITRF origin rate of around 1 mm/yr (a pessimistic scenario today) would translate into a maximum difference of the dispersion of the individual ASL rates of 0.3 mm/yr with respect to an ideal frame realization. In other words, it represents a factor of five with respect to the reduced dispersion observed here, suggesting that the observed RSL dispersion can mostly be attributed to the contribution of VLM affecting the long tide gauge records selected in this study. Moreover, Collilieux and Wöppelmann (2011) used only 27 CGPS@TG stations to infer the effect of the reference frame errors on the dispersion of the ASL trends. In this study (61 CGPS@TG), the propagation of reference frame errors on the dispersion of the ASL trends is reduced as the global geometry has improved.

To further investigate to what extent vertical land movements are affecting long-term tide gauge trends and are responsible for the observed spatial variability in the rates of relative sea level change, we considered the regional grouping of tide gauges proposed by Douglas (2001). The grouping is based on the correlation at low frequencies between neighboring tide gauge records, thus defining an oceanographic region. Douglas' rationale for the grouping was to avoid regions with a large number of tide gauges from having too much weight in its estimate of the rate of global sea level change, which implicitly assumes that sea level trends are not spatially uniform. Indeed, for more than a century, theoretical arguments have been proposed for the non-uniform distribution of sea level change from the melting of grounded ice due to gravitational effects (Woodward, 1888). More recently, observations from satellite altimetry have revealed considerable spatial variability in the rates of sea level change over the past two decades, with positive and negative values up to several times the global average of 3.3 mm/yr (e.g., Cazenave and Llovel, 2010). Although reduced in range, spatial variations in the rates of sea level change are also reported on longer timescales by a number of recent investigations using data from tide gauge records. For instance, the western tropical Pacific region is rising 2–3 times faster (Becker et al., 2012) than the global averaged rate of 1.7 mm/yr over 1900–2009 derived from the global sea-level reconstruction provided by Church and White (2011).

The grouping of our tide gauge records into regions is shown in Fig. 4 and follows that of Douglas (2001). Table 1 provides details on the regional trends (average and dispersion within each region), applying or not applying the VLM corrections from the ULR5 vertical velocity field. Since the spatial variability of the climate-driven long-term sea level signals is mostly long wavelength as it is also the case for GIA (Tamisiea and Mitrovica, 2011), the dispersion of relative sea level trends within a given region mostly reflects very local processes such as VLM. Consequently, the dispersion of the absolute sea level trends within the same oceanic basin should considerably decrease. This can be noticed in Table 1 (column 6) at the six regions with at least four GPS@TG stations, taking into account the estimated median uncertainty of the GPS velocities (Section 3) at a confidence level of 99%. The dispersion of the ASL trends in those regions with at least four GPS@TG stations is significantly reduced from 0.3–2.4 mm/yr to 0.3–0.7 mm/yr. This represents additional independent evidence supporting the quality of our GPS velocity field and, subsequently, its usefulness for sea level applications.

Special case studies are Brest (France) in the North Sea–English Channel region showing a large disagreement in the ASL trends of this region. Also disagreement was found in A Coruña (Spain). For these two stations, some concern is raised on the quality of the VLM correction applied. The 'outlier' trends of these two stations might result from an error on the estimated GPS velocity, but it might also result however from an inappropriate, although accurate, VLM correction (see discussion in Section 5.2). These two stations were identified due to the redundancy of the ASL trends of their respective regions. Therefore, particular care must be taken when using GPS-derived VLM corrections on isolated sites, especially at altimetry calibration sites. We have already discussed in Section 3 an alternative way to identify problems with the VLM corrections, that is, to compare VLM estimates from very nearby GPS stations (less than 500 m). We found significant differences in the VLM estimates for the stations SHK1-SHK5, and PLO3-PLO5. Since none of these GPS stations is installed directly on the tide gauge, their significantly different vertical velocity estimates makes the VLM correction unreliable and thus they were rejected in Table 1. These VLM estimates should not be used for altimeter calibration purposes either.

5.2. Working hypotheses

The usefulness of the GPS-derived VLM corrections to sea level trends from tide gauges depends on two requirements:

a) the estimated GPS velocities are essentially error-free VLM corrections;
b) the estimated GPS velocities are representative of the long-term VLM sensed by the tide gauge.

Despite the modeling improvements adopted here, vertical rates estimated from reprocessed GPS position time series may still be affected by systematic errors. The ULR Consortium regularly performs reprocessing campaigns in order to include all the available GPS@TG data and the most recent models and corrections which have significantly improved the homogeneity and reduced the noise content of the resulting GPS position time series (Santamaría-Gómez et al., 2011). Another issue concerning the accuracy of the estimated GPS velocities is the reference frame errors. The tracking network of the ULR solutions is a global network, thus minimizing the velocity biases arising from the terrestrial frame realization (Legrand et al., 2010). Additionally, recent work seeking to verify the accuracy of the global reference frame, which GPS rates rely on, have shown that significant progress has been made (Collilieux and Wöppelmann, 2011; Wu et al., 2011; Collilieux and Schmid, in press). However, probably the main limitation for estimating accurate GPS velocities is the remaining unnoticed discontinuities in the position time series. The equipment changes recorded in the GPS station logs have enabled us to detect small (unnoticed) but significant position discontinuities that if not accounted for would bias the estimated velocity up to ~2 mm/yr. This underscores to what extent a detailed and complete station log is crucial to estimate accurate velocities. For those stations lacking of such information, only the largest discontinuities could be identified and flagged as unknown origin. It is therefore likely that some discontinuities remain in our time series and could affect the VLM estimated at some stations.

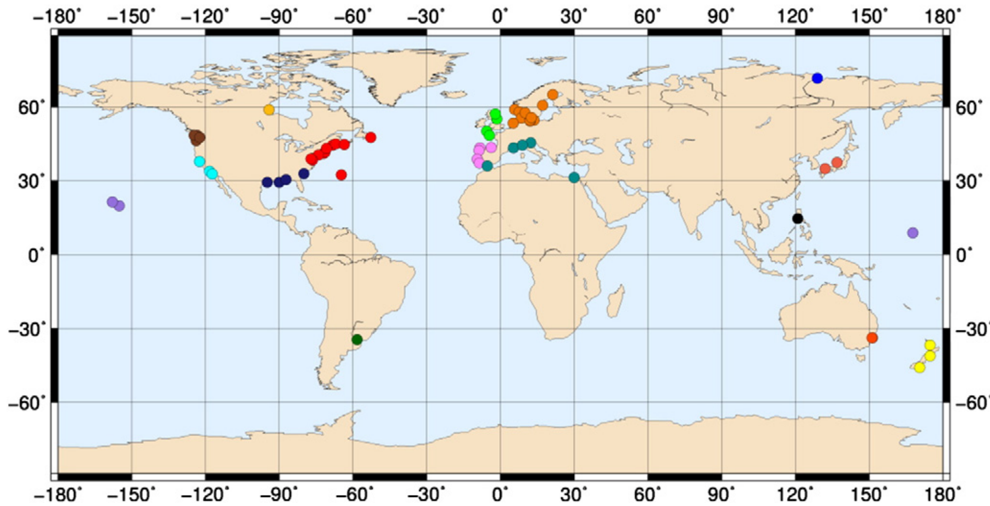

Fig. 4. Distribution of the 65 selected tide gauges used in this work. The *colors* highlight their morphological grouping based on spatial correlations of tide gauge series at low frequencies.

With respect to the second requirement, we have made use of two working hypothesis. In the first hypothesis, and only for the long-term sea level assessment (not for the altimeter calibration), we assumed that the VLM estimated from the GPS data (maximum of 16 yr in this study) is consistent over the tide gauge data period (minimum of 60 yr). Following this hypothesis the VLM would be perfectly captured by a linear trend that would be used then to correct the relative sea level trend. In the second hypothesis, we assumed that the vertical velocity estimated at the GPS station is representative of the VLM of the tide gauge benchmark, i.e. the vertical ground motion at both instruments is the same.

The first hypothesis is supported by the fact that for most of the longest tide gauge records, the VLM signal of interest is very low-frequency in character (e.g., GIA, sediment compaction and plate tectonics) and can be considered constant at most sites. Fig. 3 suggests that the acceleration terms in the relative tide gauge records longer than 60 yr of data can be neglected, whatever the origin of the signals from the land or the sea level. This is consistent with findings of several authors (Woodworth, 1990; Gornitz and Solow, 1991; Douglas, 2001). Therefore, vertical land movements, as recorded by long relative tide gauge records, are likely constant and can be absorbed by a linear trend.

There are, however, some particular cases where this hypothesis does obviously not apply. Non-linearity in the tide gauge records might be related to monument instability, changes in subsidence due to changes in the sediment supply, or gas/water pumping. As an example, Fig. 5 shows the annual mean sea level time series from the Manila (Philippines) tide gauge, where sea level rose at 1.5 ± 0.2 mm/yr from 1902 to 1963 and at 15.4 ± 2.8 mm/yr from 1963 to 2009. This sudden change of the rate of sea level rise corresponds to an increase in groundwater withdrawal over the second half of the past century (Siringan and Ringor, 1998), which appears to be very localized and can show significantly different rates of VLM at distances of a few kilometers. The GPS station is located 12.5 km northeast from the tide gauge. Its vertical velocity in ULR5 is showing uplift (2.7 ± 0.6 mm/yr) rather than subsidence. The GPS result is in agreement with the 3.2 mm/yr uplift sensed at the DORIS station, which is located 9.5 km southeast from the tide gauge (Willis et al., 2010; updated at http://ids-doris.org/plottool/stcdtool.php). Both the GPS and DORIS stations are thus testifying to

Table 1
Regionally-averaged sea level trends and dispersion within the regions from the relative and absolute individual rates of sea level change (see text for the grouping of the stations). Values are in mm/yr. Uncertainties are 1 sigma.

Groups of stations	Number of stations	Tide gauges (TG)		GPS+TG	
		Weighted mean (mm/yr)	*RMS (mm/yr)*	*Weighted mean (mm/yr)*	*RMS (mm/yr)*
Arctic Ocean	1	1.76 ± 0.35		2.90 ± 0.40	
Northern Europe	11	0.22 ± 0.04	2.04	1.88 ± 0.07	0.68
North Sea + English Channel	3	1.76 ± 0.05	0.34 (0.32)[a]	2.07 ± 0.10	0.44 (0. 91)[a]
Atlantic	4	1.61 ± 0.05	0.29 (0.50)[b]	1.67 ± 0.12	0.36 (0.53)[b]
Mediterranean Sea	4	1.09 ± 0.05	0.29 (0.58)[c]	1.14 ± 0.12	0.28 (0.53)[c]
Hudson Bay	1	-9.42 ± 0.22		0.94 ± 0.24	
NE North America	11	2.60 ± 0.03	0.57 (0.65)[d]	2.13 ± 0.09	0.66 (0.64)[d]
SE North America	4	4.42 ± 0.07	2.35	1.16 ± 0.20	0.27
Argentina	1	1.59 ± 0.15		4.08 ± 0.46	
NW North America	4	0.93 ± 0.05	1.09	0.74 ± 0.15	0.45
SW North America	2	1.47 ± 0.05	0.50 (0.47)[e]	0.46 ± 0.19	0.30 (0.87)[e]
Japan	2	0.04 ± 0.13	0.29	-0.80 ± 0.29	0.03
Pacific	3	1.82 ± 0.04	0.67	1.11 ± 0.15	0.08
Philippines	1	7.18 ± 0.16		9.97 ± 0.59	
New Zealand	3	1.44 ± 0.04	0.42	0.45 ± 0.14	0.38
Australia	2	0.82 ± 0.05	0.11	-0.07 ± 0.46	0.11

[a] With Brest.
[b] With La Coruña.
[c] With Venezia.
[d] With Sandy Hook.
[e] With San Diego.

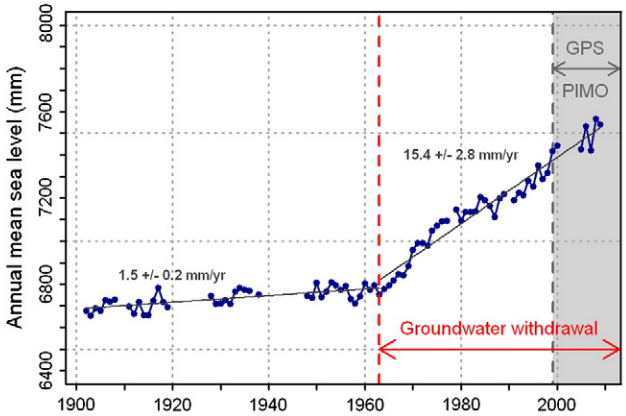

Fig. 5. Tide gauge record at Manila (Filipinas) station, from the PSMSL.

the presence of differential vertical displacements in the vicinity of the tide gauge, which prevents from using their velocities to correct for VLM at the tide gauge.

The second hypothesis, the relative stability of the co-located GPS and tide gauge stations, constitutes a major issue in the application of GPS velocities to correct VLM at tide gauges. Most of the studies found in the literature base the relative stability between a tide gauge and a GPS station (or whatever geodetic instrument) on the separation distance between them (e.g., Mitchum, 2000; Mazzotti et al., 2008; Teferle et al., 2009). The best situation is when the GPS station is installed directly on top of the tide gauge station, and some recent tide gauge designs start to account for this requirement (e.g., Löfgren et al., 2010). However, less than 14% of the GLOSS tide gauge stations are directly (on top of the tide gauge) equipped with a permanent GPS station (24% for all the co-located GPS@TG stations in SONEL). This is probably due to the fact that harbor environments are usually not the best place for installing a GPS station due to unclear horizon, reflecting surfaces and radio interference signals. In addition, coastal areas are likely unstable (Bevis et al., 2002), especially the ground in port facilities where stations are installed may not be as stable as the bedrock (e.g., Schenewerk et al., 1999). A decision based on indicators of the relative stability must be therefore taken to decide if a distant GPS station is suitable for correcting the VLM at a tide gauge. Leveling has proven for years to be the sole technique capable of providing information about the relative stability of nearby co-located stations at the required sub-mm/yr accuracy. However, due to its costs and limitations (short distances, experienced surveying team, high-end equipment, etc.), results from this technique are rarely available for most co-located sites. When the relative stability cannot be assessed, it is typical thinking that both stations should be as close as possible to avoid any bias in the VLM correction. The underlying hypothesis being that VLM at short distances is less affected by long wavelength processes. However, we may have to deal in fact with processes with different spatial scales and the VLM estimates at short distances may still be affected by station-dependent systematic errors. A distance threshold is therefore a very limited criterion to define a co-located site taking into account the large range of processes at local spatial resolutions that may affect the relative stability between two sites, for instance: sediment compaction, water extraction, volcanic deformation, tectonic deformation, or even monument motion. Such local differences in terms of VLM can be found in Venice (Italy), for instance. There, Tosi et al. (2002) and Strozzi et al. (2009) have shown high spatial and temporal VLM variations during the sea level record data time span from 1909 to 2000. Thus, correcting for the VLM in the sea level record at Venice with the estimated GPS vertical velocity is not reasonable. The GPS station VENE is 1.5 km distant from the tide gauge and the vertical velocity was estimated for the 1997–2007 period. In addition, it is well-known that Venice is subsiding as a result of natural long-term compaction of deltaic sediments exacerbated by anthropogenic pumping of water wells between about 1940 and 1975 (e.g., Pirazzoli, 1987; Pirazzoli and Tomasin, 2002); thus, resulting in a clear non-linear vertical land movement over the tide gauge record.

Emerging techniques such as InSAR (Interferometric Synthetic Aperture Radar) supplemented with GPS stations, will bring an invaluable means for measuring local stability between GPS stations and tide gauges in the next years (e.g. Brooks et al., 2007). Today, in the absence of supplemental and reliable information on the relative stability for most pairs of co-located instruments, the distance threshold is a limited but necessary working hypothesis. As an illustration of the limitation of selecting two co-located stations based on their distance, Fig. 6 shows the differences of vertical velocities estimated by GPS stations separated up to 30 km. This Figure shows that, up to ~5 km, the difference of the estimated vertical velocities for nearby GPS stations is not directly related to the separation distance. This is less clear for distances larger than 5 km, as more station pairs are involved. The vertical velocity differences for 49 station pairs separated up to 15 km (maximum distance used in this study for a co-located GPS and TG stations) have a WRMS of 1.4 mm/yr, a factor of 4–5 with respect to the estimated median velocity uncertainty (Section 3). On the other hand, the WRMS of the vertical velocity differences of 592 pairs of stations separated up to 500 km is 2.4 mm/yr, 58% larger. A Fisher test was performed to test the equality of the VLM dispersion from different clusters of station pairs according to their separation distance and assuming they are normally distributed. From this test, no significant variance difference (at the 95% confidence level) was found between station pairs separated by 500 m, 5 km, 15 km, and 500 km. The use of farther co-location distances and its impact on sea level studies may be interesting to explore in future work, especially in those regions identified in this study for which there are not many GPS@TG stations.

6. Concluding remarks

In this study, we explored the latest global reanalysis of GPS@TG data produced by the ULR Consortium (named ULR5). We have incorporated the latest advances in GPS processing strategies, in particular the lessons learned from the first international reprocessing campaign carried out within the IGS. It includes the largest ever published number of CGPS@TG stations globally distributed for which positions and velocities were estimated using the best up-to-date and state-of-the-art processing strategy. The precision of the vertical velocities was assessed from different approaches and is estimated to be of the order of 0.6 mm/yr (2 sigma), which is compatible with the most demanding applications of the sea level community.

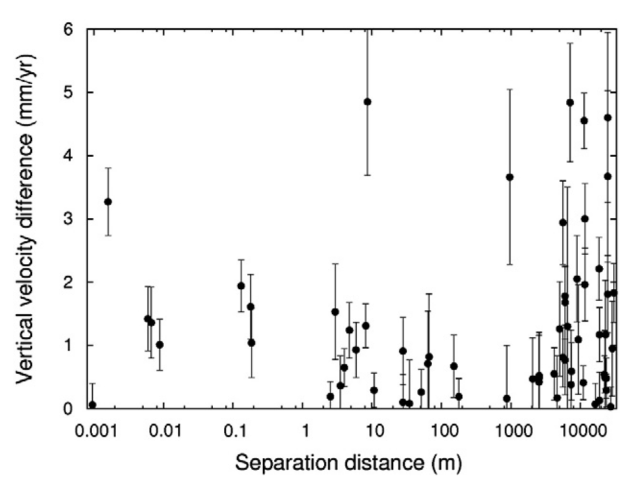

Fig. 6. Vertical velocity differences (mm/yr) of co-located permanent GPS stations separated from 0 to 30 km.

The vertical velocities and their associated uncertainties (Table S1), together with supplemental products (station positions, time series of position residuals, discontinuities), are provided open and freely to anyone through the SONEL web site (www.sonel.org). The SONEL infrastructure assembles, archives, and distributes GPS@TG observation data and metadata. It serves as the GLOSS (Global Sea Level Observing System; Merrifield et al., 2010) data assembly center for GNSS stations at or nearby tide gauges, and also as the IGS TIGA Working Group data center (Schöne et al., 2009). This way, any scientist can explore its usefulness for any sea level application; feedback will be welcomed for improving our future GPS reanalyses.

Here, we illustrated its application and performance by investigating to what extent vertical land motions are contaminating the estimates of satellite altimeter linear drifts (Section 4.1) or affecting the rates of sea level change derived from long tide gauge records (Section 4.2). Based on our results, a wide range of issues regarding measuring vertical displacements with GNSS at or near tide gauges are discussed, providing a comprehensive and updated overview to understand the current limitations and hypotheses with such work.

The dispersion of individual relative sea level trends decreased from 2.7 mm/yr to 1.0 mm/yr when correcting for VLM the set of 61 long tide gauge records distributed worldwide along a large variety of coastlines with the ULR5 velocities. It further confirmed the spatial grouping of stations suggested by Douglas (2001). The dispersion of the rates of absolute sea level change within each region (ranging between 0.3 and 0.8 mm/yr) are self-consistent within the associated GPS velocity error bars. Regarding the satellite altimetry application, we revisited the systematic VLM effect on the estimates of the satellite altimeter linear drift. Using observations taken from the ULR5 GSP@TG dataset, we have estimated a realistic upper bound of 0.6 mm/yr for this effect.

Although we used a threshold of 15 km for the co-location distance between the GPS and TG stations, our results indicate that larger co-location distances may be applied, provided VLM-corrected TG trends can be corroborated by means of redundant estimates of nearby stations. Last but not least, although considerable efforts are undertaken worldwide to upgrade tide gauge networks with co-located permanent GPS stations, their numbers are still limited. Installation of new permanent GPS stations with special focus on TG applications are definitely required (Merrifield et al., 2010).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2012.07.007.

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