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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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ABSTRACT

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

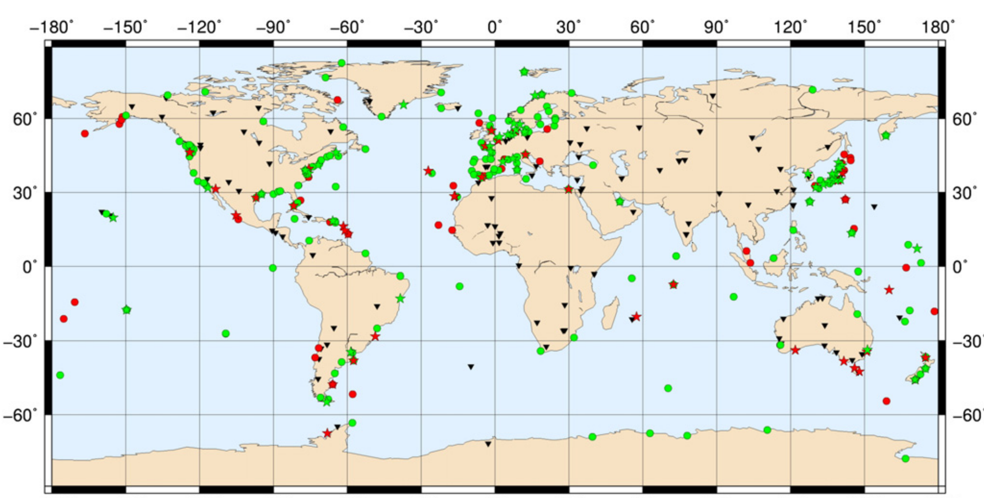

Fig. 1. The ULR5 GPS tracking network. Circles denote GPS stations included in previous solutions; stars are new in this respect. Green symbols highlight stations with a robust velocity estimate (Table S1); red stations failed our criteria. Black triangles are high-quality GPS stations not at or near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