A Global Vertical Land Movement Data Set from a Combination of Global Navigation Satellite System Solutions

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Abstract

Coastal sea-level measurements by tide gauges provide the longest instrumental records of sea-levels with some stretching from the 19th century to present. The derived mean sea-level (MSL) records provide sea-level relative to a nearby tide gauge benchmark (TGBM), which allows for the continuation of this record in time after, for example, equipment modifications. Any changes in the benchmark levels induced by vertical land movements (VLM) affect the MSL records and hence the computed sea-levels. In the past, MSL records affected by VLM were often excluded from further analyses or the VLM were modelled using numerical models of the glacial isostatic adjustment (GIA) process. Over the last two decades Global Navigation Satellite System (GNSS), in particular Global Positioning System (GPS), measurements at or close to tide gauges and the development of the associated processing strategies, have made it possible to obtain estimates of VLM in a geocentric reference system, such as the International Terrestrial Reference Frame release 2008 (ITRF2008) that approach the required accuracy for sea-level studies. Furthermore, the GPS-derived VLM estimates have been shown to improve estimates of sea-level change compared to those using the aforementioned GIA models as these models cannot predict local subsidence or uplift.

The International GNSS Service (IGS) Tide Gauge Benchmark Monitoring (TIGA) Working Group has recently re-processed the global GNSS data set from its archive (1000+ stations for 1995-2014) to provide VLM estimates tuned for the sea-level community. To achieve this, five TIGA Analysis Centers (TAC) contributed their reprocessed global GPS network solutions to the WG, all employing the latest bias models and processing strategies in accordance with the second re-processing compaign (repro2) of the IGS. These individual solutions were then combined by the TIGA Combination Center (TCC) to produce, for the first time, a TIGA combined solution (Release 0.99). This combined solution allows an evaluation of each individual TAC solution while also providing a means to gauge the quality and reliability of the combined solution, which is generally regarded as superior to the individual TAC solutions. Using time series analysis methods, estimates of VLM can then be derived from the daily position estimates, which are sub-sequentially employed to investigate coastal sea-levels. In this study, we show results from the evaluation of the relevant solutions, provide an evaluation of the TIGA VLM estimates and give examples of their impact on sea-level estimates for selected tide gauges from around the world. The TAC and TIGA combined solutions, as well as the derived VLM data sets are available from the IGS TIGA WG and will be accessible through SONEL (www.sonel.org) in the near future.

Introduction

After the two Carter Reports [1989; 1994] and the International GNSS Service (IGS) Workshop in 1997, the IGS established the Tide Gauge Benchmark Monitoring (TIGA) Pilot Project which later evolved to the IGS TIGA Working Group [Schöne et al., 2009]. The Pilot Project and WG would study the use of GNSS measurements at or close to tide gauges in support of the sea level community. The goals of the WG can be summarized as:

- To provide homogeneous sets of coordinates, velocities and robust uncertainties for continuous GNSS stations at or close to tide gauges (GNSS@TG) in a well defined terrestrial reference frame;
- To establish and expand the global GNSS@TG network for satellite altimeter calibration studies and other climate applications;
- To contribute to the IGS realization & densification of a global terrestrial reference frame;
- To promote the establishment of more continuous GNSS@TG stations, in particular in the Southern Hemisphere;
- To promote the establishment of local ties between GNSS antenna and tide gauge benchmarks (TGBMs).

With the IGS being a key service to the International Association of Geodesy, the WG holds strong links to the Global Geodetic Observing System (GGOS), the Global Climate Observing System (GCOS) and the Global Sea Level Observing System (GLOSS).

To achieve these goals, a number of TACs contributed re-processed global GPS network solutions to the TIGA WG, employing the latest bias models and processing strategies in accordance with the second re-processing campaign (repro2) of the IGS. By combination of the TAC solutions (SINEX files), i.e. following largely the example of the routine IGS combinations, a quality controlled solution can be provided, with improved precision and accuracy of the station coordinates and station velocities.

So far, only three of the five TAC solutions have complete time series. These include the solutions of the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle (Table 1). The solutions from the Deutsches Geodätisches Forschungsinstitut (DGFI) and Geoscience Australia (AUT) are soon to be completed and will be added in the future.

All five contributing TACs have analyzed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations, and added extra GNSS@TG stations to their networks (Figure 1).

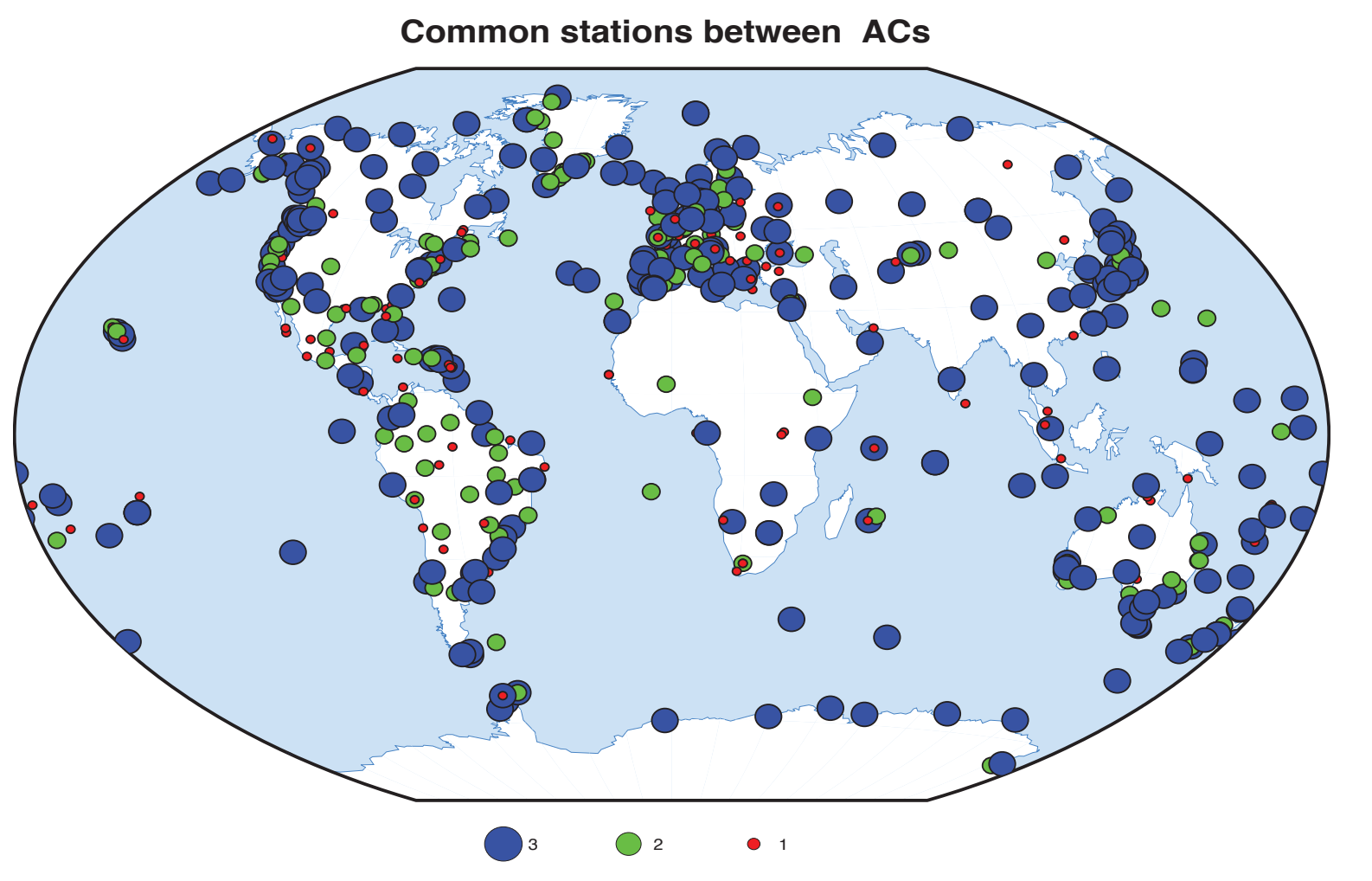

Figure 1: Map of GNSS stations processed by TACs BLT, GFZ and ULR. The colour-coded circles indicate how many TACs process a particular GNSS station.

Table 1: List of TIGA Analysis Centers: AUT, BLT, DGF, GFZ and ULR.

TAC	Host Institution	GNSS Software Package	Contributors
AUT	Geoscience Australia, Australia	Bernese GNSS Software V5.2	M. Moore, M. Jia
BLT	British Isles continuous GNSS Facility (BIGF) and University of Luxembourg TAC (BLT), UK and Luxembourg	Bernese GNSS Software V5.2	F.N. Teferle, A. Hunegnaw, R. M. Bingley, D. Hansen
DGF	Deutsches Feodätisches Forschungsinstitut-Technical University of Munich, Germany	Bernese GNSS Software V5.2	L. Sanchez
GFZ	GeoForschungsZentrum (GFZ) Potsdam, Germany	EPOS V8	T. Schöne, Z. Deng
ULR	Centre Littoral de Géophysique, University of La Rochelle (ULR), France	GAMIT/GLOBK V10.5	G. Wöppelmann, A. Santamaria-Gomez, M. Gravelle

Solution Combination

The main objective of the combination is to determine the best possible position estimates expressed in the IGS realization of ITRF2008 (IGb08) by combining the TAC solutions [Altamimi et al., 2011; Rebischung et al., 2012]. In doing so the combination provides an opportunity for inter-comparisons of the TAC solutions and on their effect on the combined solution, providing a better understanding of their weaknesses and strengths. As with the IGS combination, the TIGA combination can then be regarded as the primary product for scientists.

Prior to the combination, the TAC solutions are pre-processed and checked for inconsistencies. The pre-processing ensures that the contributions are unconstrained and corrected for discontinuities and various other inconsistencies between the solutions. For example, the combination software CATREF identifies stations by their DOMES number and it is critical that these are identical between TACs. After the pre-processing step, the best estimates are obtained through the weighted least squares adjustment using CATREF. As a final step, the long term combined stacked solution is aligned to core IGb08 stations so that the combined frame inherits its origin, scale and orientation from ITRF2008.

Figure 2 shows the residual height time series for the three TAC and the combined solutions for two example stations, Figure 3 the weighted RMS values of the daily height solutions extracted from the CATREF multi-year combination and Figure 4 the smoothed stacked power spectra of the residual height time series. All three figures are used for evaluation of the individual solutions with the combined solution to provide the best possible TIGA products.

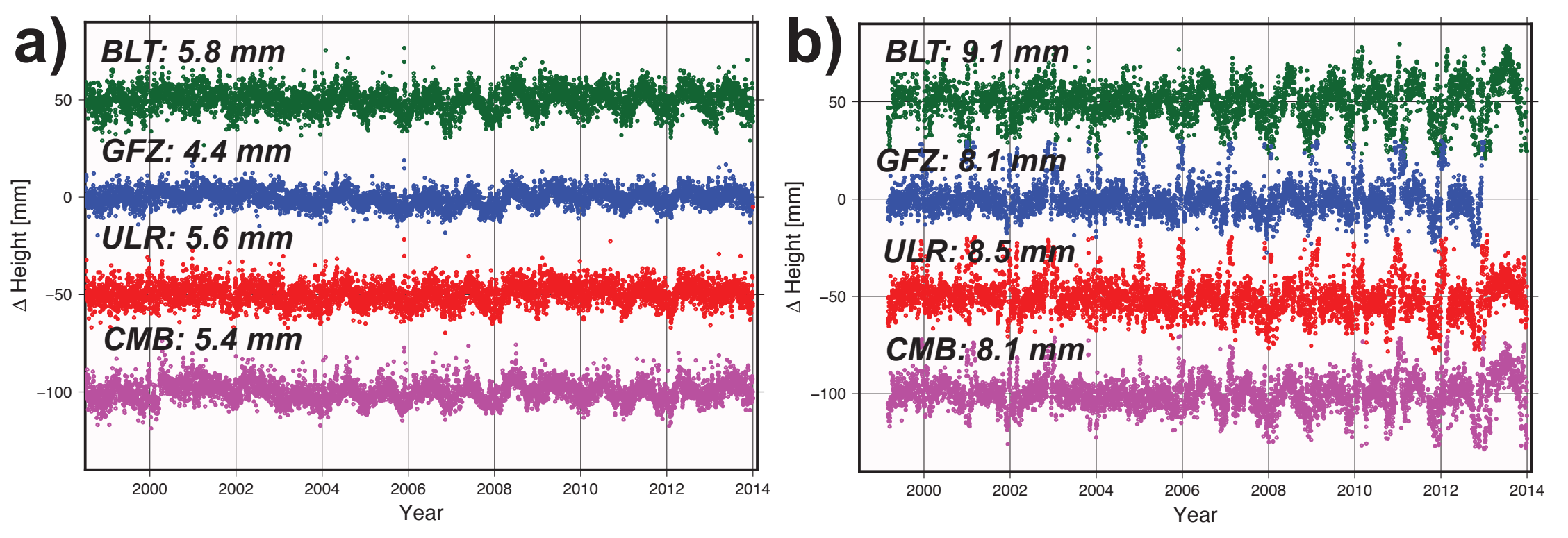

Figure 2: Residual (trend removed for display) height time series for three TAC and the combined solutions for two example stations: a) WSRT (Netherlands) and b) VAAS (Finland). Green depicts the BLT, blue the GFZ, red the ULR and magenta the combined solution. Clearly visible are the similarities between the TAC solutions showing of the high consistency in the GNSS processing strategies between the different software packages. Also visible is the reduced day-to-day scatter in the combined solution, demonstrating the higher precision from the combination.

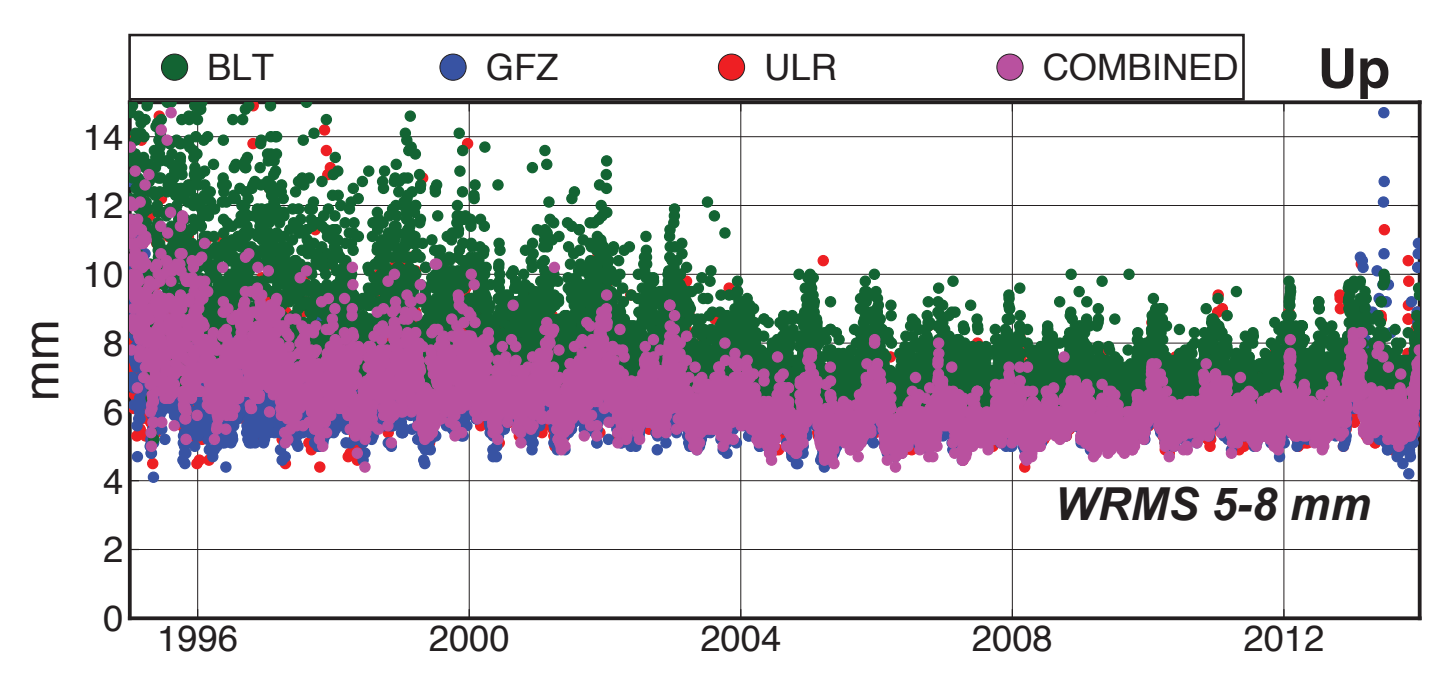

Figure 3: Weighted RMS values of the daily height solutions extracted from the CATREF multi-year combination. This plot is used for quality check, where a higher WRMS for the combined solution indicates the presence of outlier(s) in any of the individual TAC time series. Green depicts the BLT, blue the GFZ, red the ULR and magenta the combined solutions. Clearly visible is the reduced WRMS for the combined solution as compared to the individual contributors.

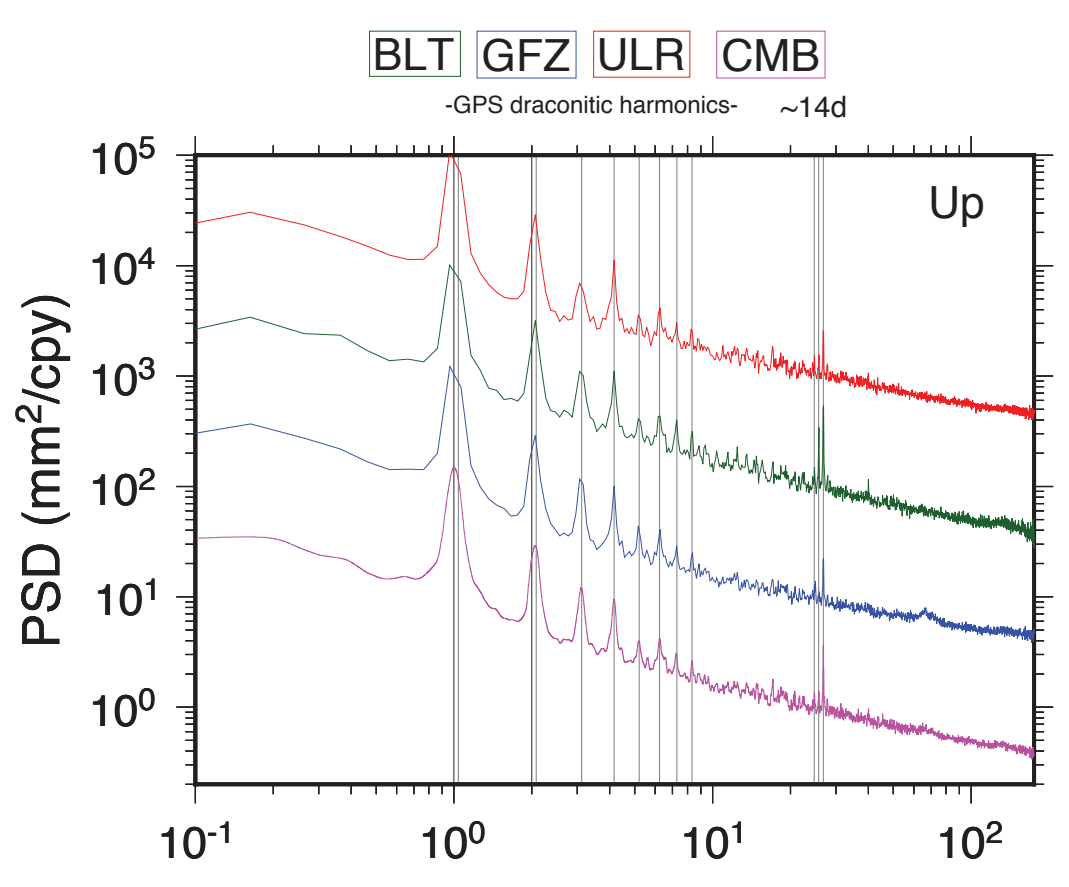

Figure 4: Smoothed stacked power spectra of the residual height time series. Green depicts the BLT, blue the GFZ, red the ULR and magenta the combined solutions. Clear seasonal peaks as well as harmonics of the GPS dracontic frequencies can be identified in all spectra. There are also sharp peaks in the fortnightly band. The vertical black lines indicate the annual, semi-annual and fortnightly periods. The grey lines indicate 10 of the harmonics of the GPS draconitic periods including the fortnightly period.

Acknowledgements

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Vertical Land Movement Estimates

Here we evaluate the vertical station velocity estimates which will be used as estimates of the vertical land movements. Figure 5 compares the VLM estimates from the TIGA combined solution to those from the recently released ITRF2014 [Altamimi et al., 2016]. The TIGA solution is still in ITRF2008, as only with the release of ITRF2014 the necessary products to bring the TIGA solutions into the latest realization become available. It is important to note that differences in the vertical velocities between ITRF2008 and ITRF2014 can occur, for example, at GNSS stations with missing antenna calibrations or due to different handling of discontinuities in individual station position time series. As the ITRF realizations are used for orbit computations of the satellite altimetry missions it is imperative to remain consistent with ITRF for the TIGA combination. Besides the comparison to ITRF2014 we have also carried out a comparison to two other global and independent solutions, namely those from the Jet Propulsion Laboratory (JPL) and the Nevada Geodetic Laboratory (NGL) at the University of Nevada Reno. The JPL and NGL solutions are individual solutions and similar to the TIGA combination, still in ITRF2008. Figure 6 and Table 2 show results from this comparison which was based on approximately 400 stations as not all three solutions include the same data set. The RMS values indicate the best agreement between the TIGA combination and ITRF2014, while the bias indicates a small difference as a consequence of the different reference frame realizations. It is noteworthy to mention that more than 57% have a velocity difference smaller than 0,5 mm/yr.

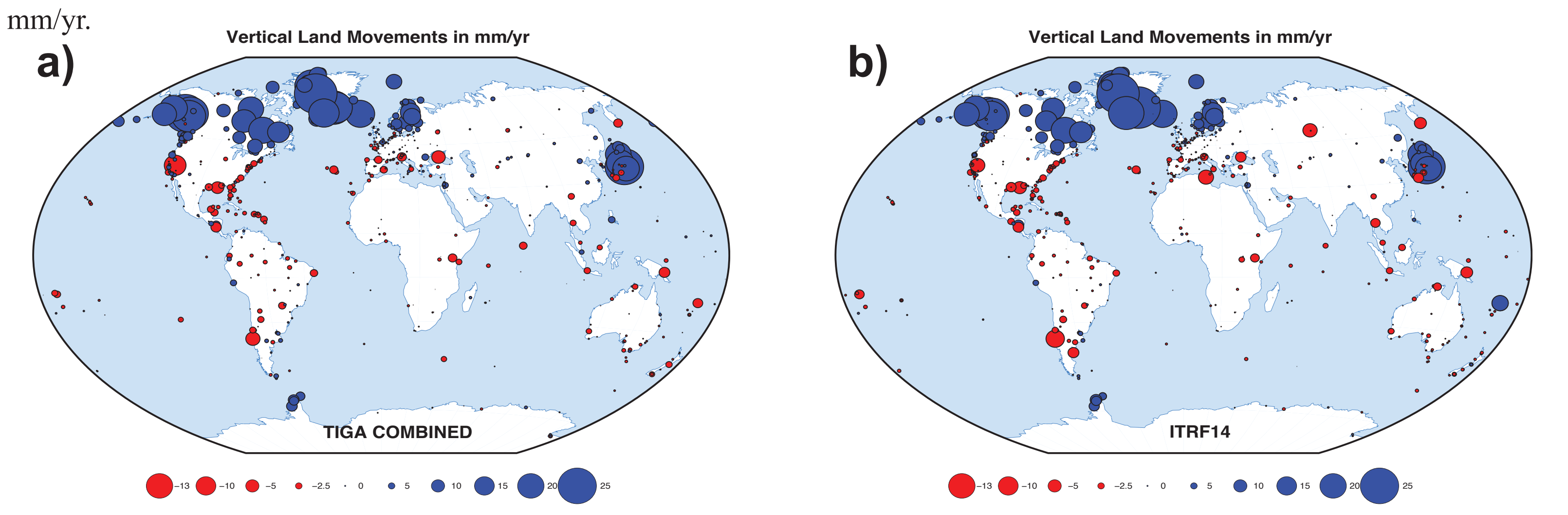

Figure 5: VLM estimates from a) the TIGA combined solution and b) ITRF2014. Clear VLM patterns with regional footprints emerge with similar magnitudes between both solutions. In regions such as Greenland, North America, and Fennoscandia, the VLM reflect uplift mainly caused by past and present ice load responses. The RMS difference between the two solutions is at 0.97 mm/yr with a bias of 0.2 mm/yr using more than 800 common stations. The differences between the two solutions do not exhibit any longitudinal or latitudinal dependencies.

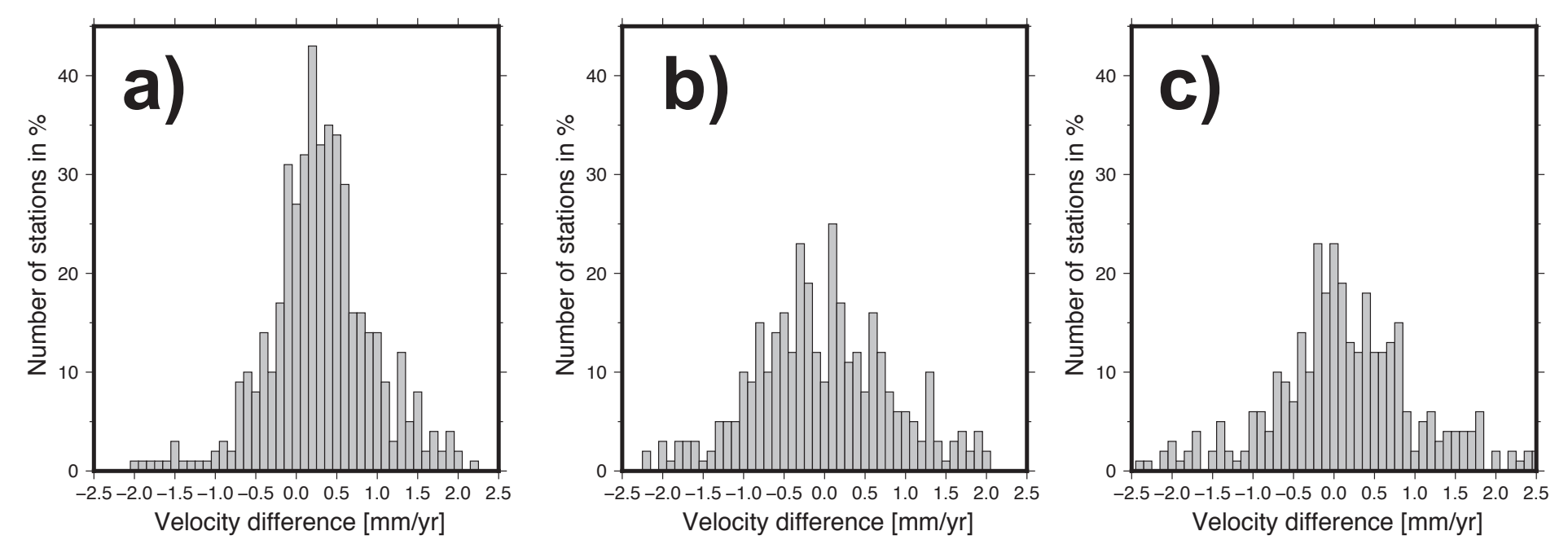

Figure 6: The distributions of velocity differences between the TIGA combination and solutions of a) ITRF2014, b) JPL and c) NGL.

Table 2. Statistics for the velocity differences between the TIGA combination and the solutions of ITRF2014, JPL and NGL.

Solution	Stn#	RMS [mm/yr]	Bias [mm/yr]	% <0,5 mm/yr
ITRF2014	465	0,65	0,29	57,0
JPL	326	0,95	0,12	48,6
NGL	460	1,10	0,05	45,8

Impact on MSL Trends

Here we investigate the impact of the TIGA combination VLM estimates and those from a model of the GIA process, in particular the ICE-6G (VM5a), on the sea level trend estimates for 27 tide gauges from the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference (RLR) data base. The 27 tide gauges are a selection of those from Douglas [2001] with particularly long and good MSL records. For consistency this investigation follows roughly that of Wöppelmann et al. [2009]. Table 3 provides the information relevant for this. In a second comparison, we show the impact on 10 tide gauges with different, but known, processes responsible for VLM at the site. Figure 7 provides a graphical presentation of this. Table 4 lists the standard deviations for the MSL trends when not corrected and when VLM-corrected using the different sets of corrections. A dramatic reduction in the statistics from 2,08 to 1,26 and 0,57 mm/yr can be observed when using no corrections, the VLM corrections from the ICE-6G (VM5a) GIA model [Peltier et al., 2015] and those from the TIGA combined solution.

Table 3: MSL Trends and VLM-corrected MSL Trends using the VLM estimates from the TIGA combination and the ICE-6G (VM5a) GIA model.

TG Name	Time Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend [mm/yr]	GIA Trend [mm/yr]	TIGA Trend [mm/yr]	TG+GIA Trend [mm/yr]	TG+TIGA Trend [mm/yr]
Northern Europe								
STAVANGER	63	16000	47	0.35 ± 0.18	0.59	1.91 ± 0.40	0.94	2.26
KOBENHAVN	101	7300	82	0.56 ± 0.12	0.06	1.30 ± 0.85	0.62	2.09
NEDRE GAVLE	90	11000	99	-6.04 ± 0.22	6.87	7.92 ± 0.88	0.83	1.88
North Sea and English Channel								
ABERDEEN I+II	103	2	361	0.97 ± 0.25	1.01	0.75 ± 0.21	1.98	1.72
NEWLYN	87	10	202	1.81 ± 0.12	-0.72	-0.31± 0.17	1.09	1.50
BREST	83	350	1	0.97 ± 0.12	-0.61	-0.10 ± 0.28	0.36	0.87
Eastern Atlantic								
CASCAIS	97	84	52	1.29 ± 0.18	-0.34	-0.07 ± 0.24	0.95	1.22
LAGOS	61	138	162	1.56 ± 0.25	-0.41	-0.34 ± 0.22	1.15	1.22
Mediterranean								
MARSEILLE	105	5	61	1.33 ± 0.12	-0.32	0.93 ± 0.30	1.01	2.26
GENOVA	78	1000	59	1.17 ± 0.08	-0.16	-0.34 ± 0.18	1.01	0.83
NE North America								
EASTPORT	63	800	332	2.21 ± 0.30	-1.34	-0.38 ± 0.37	0.87	1.83
NEWPORT	70	500	351	2.48 ± 0.14	-1.42	-0.27 ± 0.21	1.06	2.21
HALIFAX	77	3100	96	3.06 ± 0.19	-1.54	-0.91 ± 0.15	1.52	2.15
ANNAPOLIS	70	11577	311	3.50 ± 0.14	-1.84	-2.09 ± 0.11	1.66	1.41
SOLOMON ISL	62	200	412	3.69 ± 0.18	-1.71	-1.54 ± 0.33	1.98	2.15
NW North America								
VICTORIA	86	12000	166	0.74 ± 0.05	-0.53	1.01 ± 0.20	0.21	1.75
NEAH BAY	65	7800	385	-1.80 ± 0.09	-1.16	3.58 ± 0.28	-2.96	1.78
SEATTLE	104	5900	127	1.99 ± 0.14	-0.84	-1.00 ± 0.22	1.15	0.99
SE North America								
CHARLESTON I	82	8200	234	3.31 ± 0.28	-1.13	-1.65 ± 0.73	2.18	1.66
GALVESTON II	94	4200	161	6.33 ± 0.31	-1.06	-3.65 ± 0.55	5.27	2.68
MIAMI BEACH	45	4800	363	2.29 ± 0.26	-0.83	0.25 ± 0.72	1.46	2.54
KEY WEST	90	16000	188	2.40 ± 0.16	-0.82	-0.29 ± 0.37	1.58	2.11
SW North America								
LA JOLLA	72	700	256	2.21 ± 0.12	-0.72	-0.72 ± 0.58	1.49	1.49
LOS ANGELES	78	2200	245	0.94 ± 0.14	-0.74	-0.19 ± 0.28	0.20	0.75
New Zealand								
AUCKLAND II	85	5	150	1.32 ± 0.11	0.08	-0.43 ± 0.25	1.40	0.89
PORT LYTTELTON	101	2	247	2.18 ± 0.27	0.14	-0.69 ± 0.25	2.32	1.49
Pacific								
HONOLULU	99	5	155	1.43 ± 0.30	-0.23	-0.68 ± 0.19	1.20	0.75

Table 4: Standard deviations of individual sea level change estimates using no corrections for VLM (TG), and VLM corrections from ICE-6G (VM5a) (TG+GIA) and the TIGA combination (TG+TIGA).

	No Corrections	VLM Corrections	
	TG Trend [mm/yr]	TG+GIA Trend [mm/yr]	TG+TIGA Trend [mm/yr]
Scatter of MSL Trends	2,08	1,26	0,57

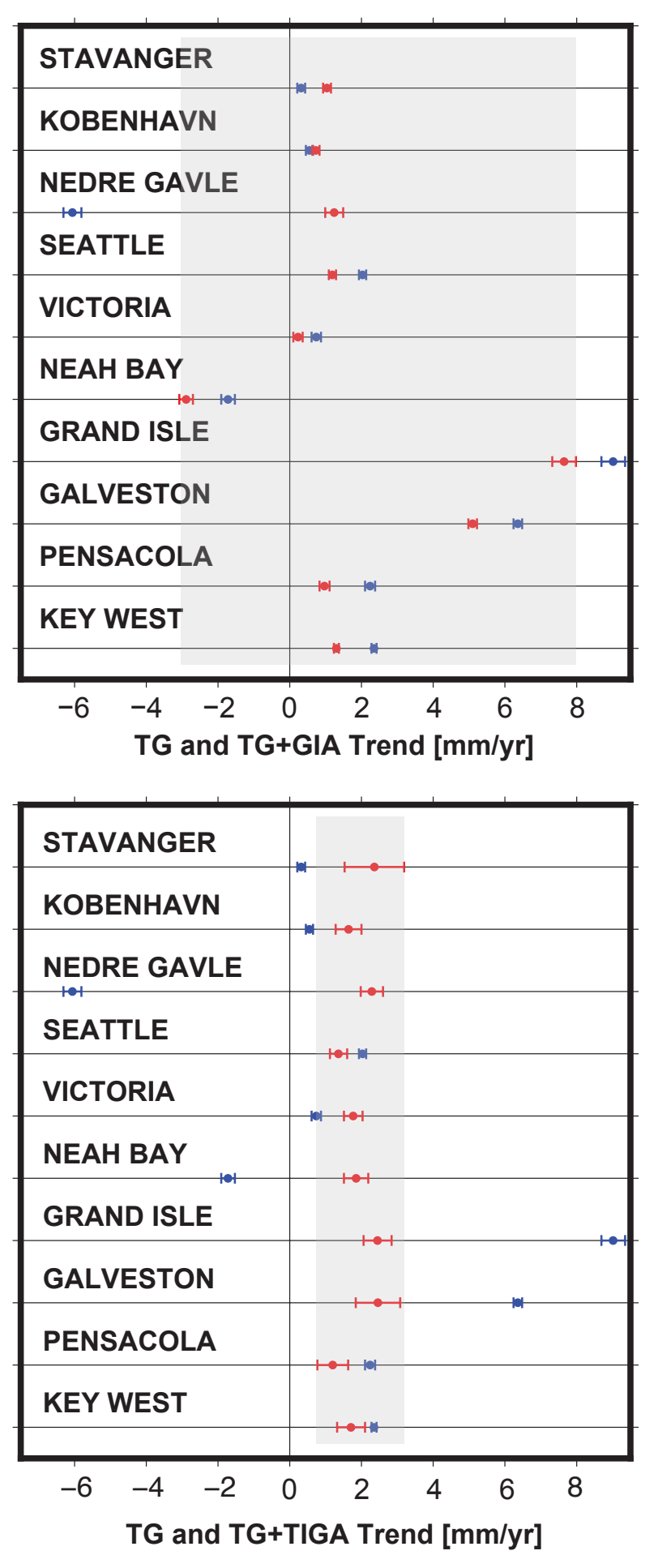

Figure 7: MSL trends (TG) and VLM-corrected MSL trends using a) the ICE-6G (VM5a) GIA model (TG+GIA) and b) the TIGA combination (TG+TIGA) for 10 tide gauges exposed to VLM due to different processes. The grey band indicates the spread of the sea level rise estimates after correction. Clearly visible is the improved agreement between the estimates after correction with the observed VLM from the TIGA combination.

Conclusions

We have presented the first TIGA combined solution termed Release 0.99. This solution is a combination of three individual TAC solutions from BLT, GFZ and ULR, as at the time of the combination the solutions from DGF and AUT were not ready. The missing contributions will be added for the next release. Nevertheless, the results already confirm the higher precision of the combined over the individual solutions.

The TIGA combined solution contains measurements from 1000+ GNSS stations over the period 1995 to 2014 with about 700 stations being active on a daily basis in the more recent years. This includes a large number of GNSS@TG stations which are not routinely processed by other IGS analysis centers.

Our evaluations show that the TAC solutions exhibit a high degree of agreement with each other and to the combined solution, with the latter showing the least day-to-day scatter. This solution has benefited from the implementation of various models, which improved the consistency of the TAC and the TIGA combined solutions. Moreover, the TIGA VLM estimates show very good agreement to the estimates from the recently released ITRF2014 solution and two other individual GNSS solutions.

Applying the observed TIGA VLM estimates to correct MSL trends results in superior performance than when using values from a GIA model, as is indicated by the reduction of the standard deviation of the VLM-corrected MSL trends from 1.26 to 0.57mm/yr.

Within the IGS and the GGOS community, the TIGA combined solution is envisaged as the primary product to provide VLM corrections to serve the sea level community.

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