Land subsidence with tide gauge, radar altimetry and GNSS: a case study at subsiding coast in Texas

Xiaojun Qiao[1,2], Tianxing Chu[1,2], Philippe Tissot[1,3], and Jason Louis[1]
1 *Conrad Blucher Institute for Surveying and Science, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA*
2 *Department of Computing Sciences, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA*
3 *Department of Physical and Environmental Sciences, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA*

BIOGRAPHY

Xiaojun Qiao is a doctoral student in the Geospatial Computer Science program at Texas A&M University-Corpus Christi (TAMU-CC). He received a B.S. in survey and mapping in 2014 and an M.S. in photogrammetry and remote sensing in 2017, both from China University of Mining & Technology (Beijing). His research focuses on estimating vertical land motion as well as its contribution to sea-level rise along the U.S. Gulf Coast using continuous GNSS, satellite radar altimetry, and tide gauge data.

Tianxing Chu is an assistant professor at TAMU-CC. He received his Ph.D. in photogrammetry and remote sensing from Peking University, China. Prior to his faculty role, he worked at TAMU-CC as a post-doctoral research associate and assistant research scientist from January 2014 to August 2018. His current research interests include emergent remote sensing and geomatics techniques, ubiquitous navigation and positioning, indoor simultaneous localization and mapping, machine learning applied to geospatial applications.

Philippe Tissot is an associate research professor and the interim Director for the Conrad Blucher Institute at TAMU-CC. His research is focused on the development of artificial intelligence methods for the prediction and analysis of environmental systems and the analysis and prediction of coastal processes. Studies have included the modeling and impact of relative sea level rise, subsidence and storm surge at the regional scale, the development and implementation of predictive models supporting navigation and coastal management, tidal studies and local hydrodynamic models. Ongoing projects include studies of the spatial variability of relative sea level rise, the application of clustering algorithms to 3D point clouds of marsh environments and urban runoff water quality modeling.

Jason Louis is a research specialist at the Conrad Blucher Institute and a GIS instructor at TAMU-CC. His research focus has been on analytics of various types of real-world geospatial applications with GIS techniques with an emphasis on land subsidence along the U.S. Gulf Coast. He also actively conducts NOAA-funded filed work including installation and maintenance of continuous GPS stations and benchmarks in the Gulf Coast area.

ABSTRACT

Global sea-level is rising at an unprecedented rate in recent decades largely due to glacier/ice-sheet melting and ocean warming expansion, which is referred to as the absolute sea-level rise (ASLR). The combination of vertical land motion (VLM) and ASLR leads to a faster sea-level rise relative to the land, which is referred to as the relative sea-level rise (RSLR). The Texas Gulf Coast is one of the leading hotspots subject to VLM and/or RSLR issues in the United States. GNSS has long been used to monitor long-term and accurate VLM with a continuous GNSS (cGNSS) observation network. However, the observation network density offered by cGNSS stations is often limited. This study investigated the feasibility of estimating VLM using the sea-level change differences between the ASLR and RSLR data observed by tide gauges and satellite radar altimetry using 5-day, 15-day, and 30-day time windows. The results were validated by comparing against the GNSS measurements processed by GipsyX software. Independent time-series of VLM processed by using sea-level change differences and GNSS were obtained at Galveston and Rockport, two areas of the Gulf Coast experiencing substantial subsidence. The trends of the VLM time-series were estimated with Hector software. At Galveston, Texas, the VLM trend from GNSS (-3.9 ± 0.4 mm/yr) matched well with that from sea-level change difference estimated at the tide gauge (-3.8 ± 0.7 mm/yr with a 15-day mean window). At Rockport, Texas, an approximately 1.0 mm/yr VLM difference was observed between GNSS (-4.2 ± 0.3 mm/yr) and sea-level

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change difference (-5.2 ± 1.1 mm/yr with a 15-day mean window) within the confidence intervals of the two methods. This preliminary study demonstrated the feasibility of VLM estimates with sea-level change differences in coastal areas where long-term static cGNSS observations are absent. However, further investigation is needed to model error sources and improve noise mitigation for reliable VLM trend estimate.

INTRODUCTION

The Texas coast is one of leading subsidence hotspots relative to sea surface in the United States [1], potentially causing significant impacts to everyday life of coastal residents, the safety of near-shore infrastructures, and the resilience of the coastal ecosystem. Interferometric synthetic aperture radar (InSAR) and global navigation satellite system (GNSS) are two leading methods for monitoring land subsidence. InSAR provides large-scale land deformation results, but it usually requires high user cost and specialization in radar image processing and may cause delayed delivery of products with limited temporal and spatial resolutions. GNSS, on the contrary, can observe long-term and accurate vertical land motion (VLM) near the Earth's surface through continuous GNSS (cGNSS) observation network. However, VLM varies spatially and one obvious weakness of VLM monitoring with cGNSS network along coastlines is the limited observation density offered by cGNSS providers.

On the other hand, sea-level change studies commonly involve tide gauges (TGs) that usually measure sea-level rise relative to land-fixed benchmarks, referred to as relative sea-level rise (RSLR). RSLR combines the effects of both VLM and absolute sea-level rise (ASLR) in response to natural processes such as such as continuous glacier/ice-sheets melting to ocean, ocean thermal expansion, land water storage, and so forth [2]. Therefore, coastal subsidence and VLM can be estimated with TGs if ASLR component can be removed from the RSLR observation. Thanks to satellite radar altimetry (SRA) technique, changes in sea surface height can be measured in the ocean and ASLR relative to a geoid model can be obtained [3].

Prior studies have investigated the use of various types of SRA products coupled with TG measurements to estimate VLM. For example, Cazenave et al. found that the differences in sea level measurements between Topex/Poseido (T/P) radar altimetry and TG agreed well with VLM results estimated by Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) [4]. Kuo et al. estimated VLM using T/P SRA and TGs in Fennoscandia, and the results showed that trend difference was 0.2 ± 0.9 mm/yr compared with collocated GPS sites [5]. A recent study conducted at the Northeastern Adriatic Sea [6] showed that positioning results from three cGNSS stations agreed well with sea-level change differences for revealing the VLM trend. Oelsmann et. al. proposed the zone of influence to characterize sea-level variability and maximize the coherency between SRA and TG observations. They found that the difference between cGNSS and SRA/TG fusion was 1.28 mm/yr using 58 co-located cGNSS and TG stations globally [7]. The above studies documented the feasibility of using SRA data for VLM estimation. Over the U.S. Gulf Coast, some studies held the assumption that the amount of ASLR was homogeneous in the same oceanic basin [8, 9]. However, ASLR may vary in space over the ocean due to differences in natural processes such as weather, currents, salinity, tides, gravity field and so forth [10]. Fig. 1 shows the trend of ASLR over the Gulf of Mexico (GOM) region using the SRA sea surface height product provided by NASA's Jet Propulsion Laboratory (JPL), from which clear spatial pattern and variability can be observed over the GOM region.

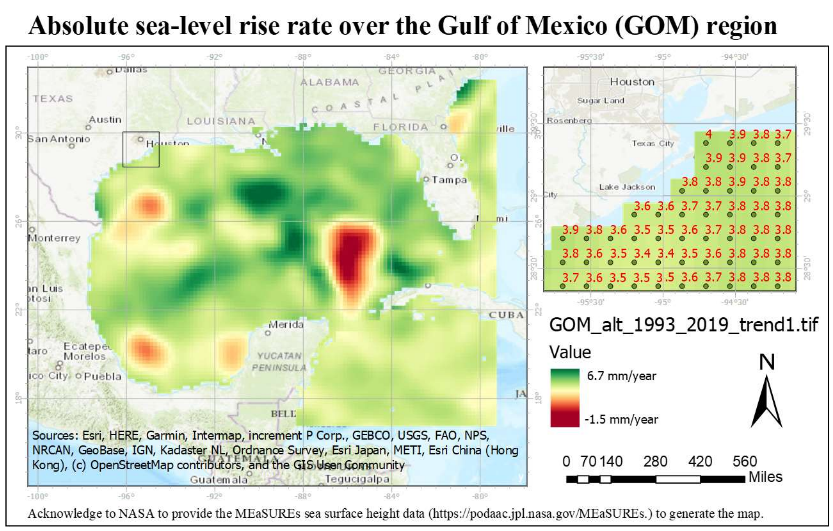


Fig. 1. ASLR estimate over the GOM region made by radar altimetry data from the Jet Propulsion Laboratory (JPL) sea surface height product

This study took ASLR spatial variability over the GOM region into account and combined the radar altimetry and TG measurements to estimate coastal subsidence rate for nearly 25 years at two Texas Coast city locations. The obtained results were compared against counterpart results obtained from collocated GNSS stations. The purpose of this study was to investigate the feasibility of estimating VLM with sea-level change observations, expecting to be an additional method for VLM estimation over the GOM region.

DATA AND METHOD

The data used in this study were composed of three components:

1) **SRA**: JPL's radar altimetry product, MEaSUREs, was used to extract the time-series of sea surface height anomalies for estimating the ASLR. This dataset provides sea surface height information at every 1/6-degree grid per each five days between 1992 and 2019 [11]. Grided time-series of sea surface height anomalies over the GOM region were extracted from the original global data.
2) **TG**: Galveston Pier 21 and Rockport TG stations in Texas were chosen due to relatively high subsidence rates in Galveston and Rockport [1]. Daily water level above the station datum for these two stations were averaged using 6-minute or hourly observations after 1992 from the NOAA's Center for Operational Oceanographic Products and Service (CO-OPS) Data application programming interface (API).
3) **GNSS:** At Galveston, Texas, a National Geodetic Survey (NGS) continuous operating reference station (CORS), TXGA was used, and its GNSS ephemeris and observation data were recorded in the receiver independent exchange format (RINEX). The distance between Galveston Pier 21 TG and TXGA is approximately 2.9 km. At Rockport, Texas, two different cGNSS stations were considered co-located to the TG station and therefore included, namely TXRP in the NGS CORS network and RKPT operated by Conrad Blucher Institute (CBI) at TAMU-CC. The TXRP station was damaged in August 2017 due to Hurricane Harvey, therefore its GNSS observation data was interrupted afterwards. However, the RKPT station remained unaffected by the storm and its observation data were continuously used in this study. TXRP and RKPT stations had 25 days of observation overlap in 2017, and their distances to the TS station are 4.5 km and 0.5 km, respectively.

For each of Galveston Pier 21 and Rockport TG stations, two different methods were used to acquire the VLM time-series: 1) VLM estimated with sea-level difference (SLD), and 2) VLM estimated with cGNSS.

1) **VLM estimated with SLD**: Since RSLR is a combined effect of ASLR and VLM as mentioned above, the following relationship holds:

$$VLM^{SLD} = ASLR - RSLR \tag{1}$$

where the left side of the equation means VLM estimated with SLD, and the right side was the difference between ASLR and RSLR values. The nearest grid to Galveston Pier 21 or Rockport TG station from the SRA dataset was selected to represent the local ASLR value. The ASLR data were observed per five days, and two more frequency windows (i.e., 15-day and 30-day) were also include in this study given the large temporal scale (i.e., nearly 25 years) of observations. It is worth noting that the TG data were offered in a per 6-minute or 1-hour basis, therefore the TG measurements needed to be averaged to line up with the SRA data before the subtraction operation as indicated in Equation (1). The resultant VLM values were offered with 5-day, 15-day, or 30-day windows.
2) **VLM estimated with cGNSS**: Daily RINEX files for the cGNSS stations of TXGA, TXRP, and RKPT were processed using JPL's GipsyX software [12]. GipsyX adopts precise point positioning (PPP) strategy to process GNSS data and provide millimeter-accuracy static positioning solution without needing to access nearby reference stations [13]. Based on the default tree provided by the software, various types of correction models were incorporated in the processing, including second-order ionospheric correction through IONEX map and the international reference ionospheric (IRI) model, tropospheric correction through the global pressure and temperature (GPT2) model, ocean-tide loading with the global ocean tide (GOT-4.8) model and so forth. PPP solutions were provided in the international terrestrial reference frame 2014 (ITRF2014) and were projected to the north (N), east (E), and up (U) directions by GipsyX utility. Time-series of daily position in the up direction were retained for VLM estimation. In this study, only GPS constellation was adopted.

For VLM time-series estimated with either SLD or GNSS, Hector software [14] was utilized for trend estimation. Hector can estimate linear trend by considering offsets, outliers, and season signals contained in the time-series. In addition, the software is able to tackle different noise models as well as their combinations based on Akaike Information Criterion (AIC) or Bayes Information Criterion (BIC) during trend estimation [15]. A total of six noise model combinations were examined and compared in the work as shown in Table 1 in order to select the optimal noise model that best estimated the VLM linear trend and uncertainty. Hector can return a series of parameters, among which AIC and BIC were leveraged to decide the optimal noise model.

Table 1. Noise model combinations used in this study through Hector software

	Name	Description
1	WN	White Noise
2	PLWN	Power-Law + White Noise
3	FNWN	Flicker Noise + White Noise
4	GGMWN	Generalized Gauss-Markov + White Noise
5	RWFNWN	Random Walk + FNWN
6	AR(1)	ARMA(0, 1) first-order autoregressive

RESULTS

GipsyX Processing

To ensure the accuracy and reliability of GipsyX processing, time series of X-Y-Z coordinates at TXGA cGNSS station processed by GipsyX were compared against the results obtained through NOAA's Online Positioning User Service (OPUS) interface (Fig. 2). OPUS computes coordinates using NOAA CORS network, and daily RINEX files were repeatedly uploaded to OPUS to acquire X-Y-Z coordinates on a per day basis. In general, results processed through GipsyX matched well with that through OPUS in terms of X, Y, and Z coordinates except for occasional outliers from GipsyX. It is also obvious that two abrupt shifts occurred along Y-coordinate, and the reason behind is the antenna change as suggested by the NGS station log file [16]. Both outliers and offsets contained in the time-series were successfully handled by Hector software for VLM trend estimation.

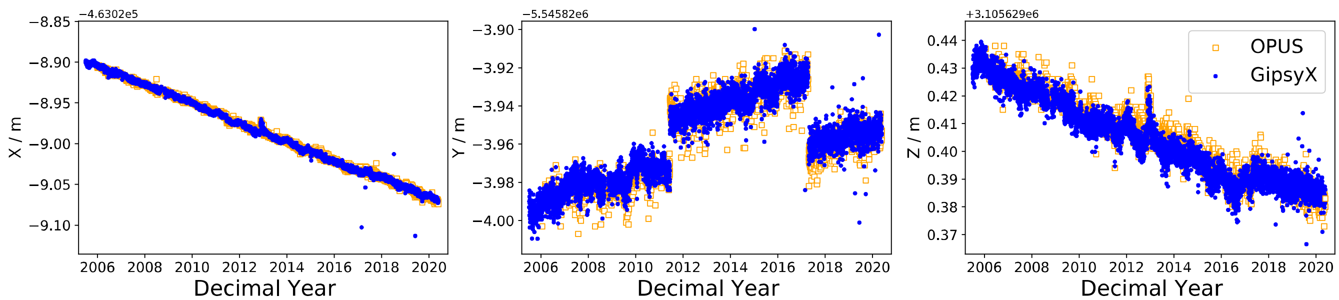
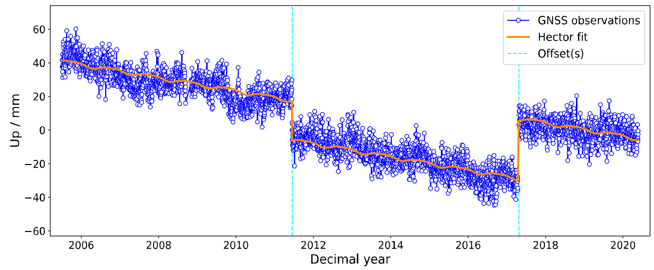


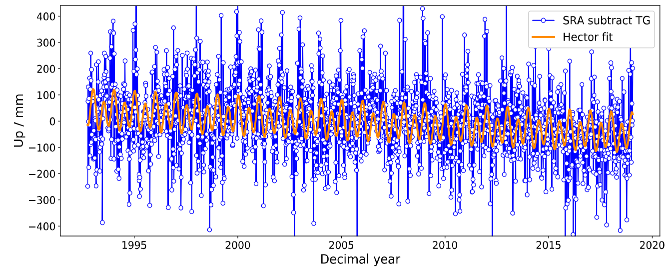
Fig. 2. X-Y-Z coordinates comparison between GipsyX and OPUS at TXGA cGNSS station

VLM Estimation at TXGA cGNSS Station and Galveston Pier 21 TG Station

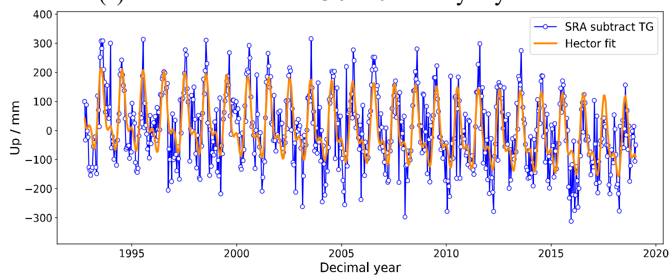
In close vicinity to the Galveston Pier 21 TG station (i.e., 2.9 km), the GNSS time-series at TXGA station in up direction is shown in Fig. 3 (a), where two abrupt shifts were identified, and outliers were removed by Hector. At Galveston, FNWN, GGMWN, and AR1 outperformed the other noise model combinations (Table 1) for VLM estimation with GNSS, 5-day and 15-day SLD, and 30-day SLD, respectively. The GNSS estimated VLM trend was -3.9 ± 0.4 mm/yr. The SLD estimated VLM trends were -3.9 ± 0.4 mm/yr, -3.8 ± 0.7 mm/yr, and -3.9 ± 0.7 mm/yr for 5-day, 15-day, and 30-day mean windows, respectively (Fig. 3). The results suggested that SLD estimated VLM trend agreed well with GNSS estimated trend, and the difference was 0.1 mm/yr by using the 15-day mean window.



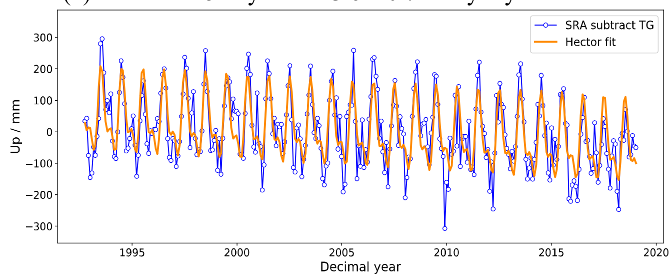
(a) VLM with GNSS: -3.9 ± 0.4 mm/yr by FNWN



(b) VLM with 5-day SLD: -3.6 ± 0.7 mm/yr by GGMWN



(c) VLM with 15-day SLD: -3.8 ± 0.7 mm/yr by GGMWN

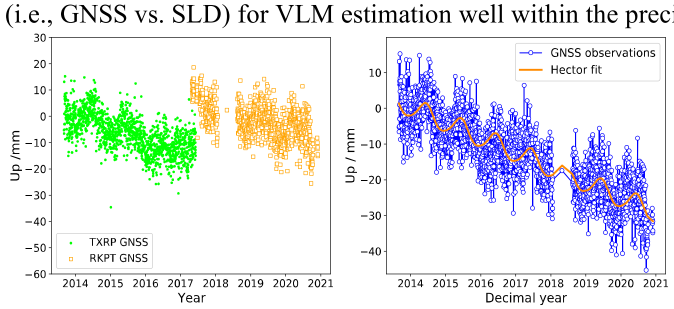


(d) VLM with 30-day SLD: -3.9 ± 0.7 mm/yr by AR1

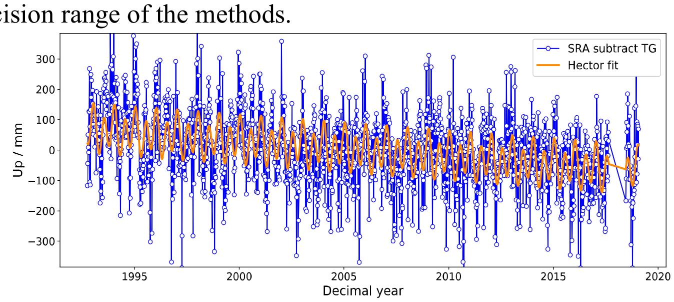
Fig. 3. VLM estimation with 1) TXGA station in CORS network and 2) differences in sea-level change at Galveston Pier 21 TG station

VLM Estimation at TXGA/RKPT cGNSS Stations and Rockport TG Station

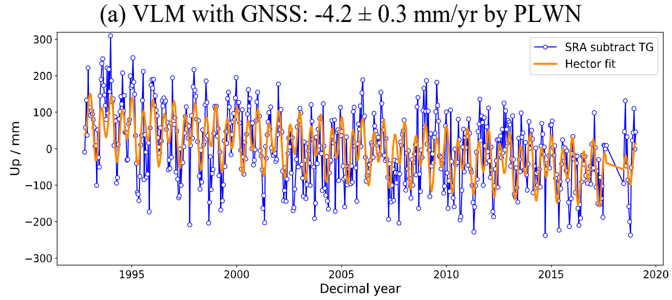
RINEX files of TXRP and RKPT stations were separately processed in GipsyX, and time-series in the up direction are shown in the upper left corner in Fig. 4. RKPT data were merged with TXRP by shifting RKPT with the mean of differences among 25 overlapping days of the two stations. This enlarged the entire GNSS data availability. However, it is worth noting that these two stations are 4.0 km apart. At Rockport, PLWN outperformed the other noise model combinations (Table 1) for VLM estimation with GNSS and SLD except 30-day mean window. The GNSS estimated VLM trend was -4.2 ± 0.3 mm/yr. The SLD estimated VLM trends were -5.3 ± 1.0 mm/yr, -5.2 ± 1.1 mm/yr, and -5.1 ± 0.6 mm/yr for 5-day, 15-day, and 30-day mean windows, respectively (Fig. 4). At Rockport, there was an approximately 1.0 mm/yr difference between the two methods (i.e., GNSS vs. SLD) for VLM estimation well within the precision range of the methods.



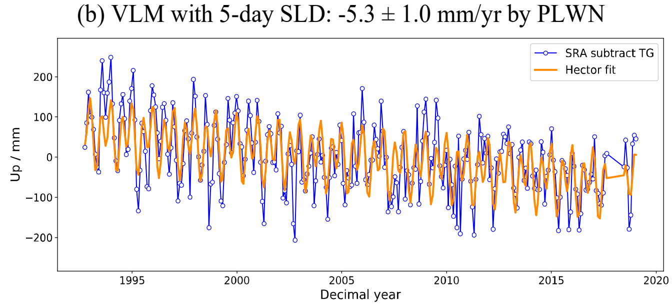
(a) VLM with GNSS: -4.2 ± 0.3 mm/yr by PLWN



(b) VLM with 5-day SLD: -5.3 ± 1.0 mm/yr by PLWN



(c) VLM with 15-day SLD: -5.2 ± 1.1 mm/yr by PLWN



(d) VLM with 30-day SLD: -5.1 ± 0.6 mm/yr by AR1

Fig. 4. VLM estimation with 1) TXRP (in CORS network) and RKPT stations and 2) differences in sea-level change at Rockport TG station

CONCLUSION AND DISCUSSION

GNSS can be generally considered as a common method in estimating VLM, however, a cGNSS network often fails to accurately map VLM along coastlines because VLM demonstrates high spatial variability while cGNSS stations are usually sparsely distributed. This study estimated coastal VLM at two tide gauge locations within general land subsiding environments (i.e., Galveston Pier 21 and Rockport) in Texas with GNSS and SLD. At Galveston Pier 21, the VLM trend obtained through GNSS (-3.9 ± 0.4 mm/yr) agreed well with that obtained through SLD (-3.8 ± 0.7 mm/yr in a 15-day mean window). At Rockport, VLM rate of GNSS was -4.2 ± 0.3 mm/yr while sea-level change difference yielded -5.2 ± 1.1 mm/yr (in a 15-day mean window), leading to an approximately 1.0 mm/yr difference between the two methods, within the combined confidence intervals of the methods. The preliminary results in this study suggested that fusing measurements recorded from SRA and TGs have great potential to complement long-term static GNSS observations in an effort to estimate VLM along coastlines.

Additional refinements would yield improved results. First, the differences in reference systems among GNSS, TG, and SRA have not been fully investigated nor compensated. Secondly, the impacts of the atmospheric pressure and wind on TGs have not been compensated before subtracting SRA measurements [6, 7]. Thirdly, outlier removal in GipsyX and noise mitigation in SRA and TG measurements by applying elaborate filtering or machine learning methods should yield a better VLM trend estimate. Some other factors may contribute to the VLM estimate discrepancy between using SLD and GNSS. For example, a pixel near the coastline may mix land and water in the SRA data and does not favorably reflect sea surface height. In addition, due to the nature of high spatial variability associated with VLM estimate, differences in the estimations from both methods may result from the distance between the TG and GNSS stations (e.g., the distance between Galveston Pier 21 TG and TXGA GNSS station is 2.9 km).

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REFERENCES

1. Boon, J. D., Mitchell, M., Loftis, J. D., and Malmquist, D. M. “Anthropocene Sea level change: A history of recent trends observed in the US East, Gulf, and West Coast Regions,” *Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE)*, No. 467, 2018, pp. IV-2.
2. Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S.Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
3. Wöppelmann, G. and Marcos, M. “Vertical land motion as a key to understanding sea level change and variability,” *REVIEWS OF* GEOPHYSICS, vol. 54(1), 2016, pp.64-92.
4. Cazenave, A., Dominh, K., Ponchaut, F., Soudarin, L., Cretaux, J. F. and Le Provost, C. “Sea level changes from Topex-Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS,” *GEOPHYSICAL RESEARCH LETTERS*, vol. 26(14), 1999, pp.2077-2080.
5. Kuo, C. Y., Shum, C. K., Braun, A. and Mitrovica, J. X. “Vertical crustal motion determined by satellite altimetry and tide gauge data in Fennoscandia,” *GEOPHYSICAL RESEARCH LETTERS*, vol. 31(1), 2004, pp.1-4.
6. De Biasio, F., Baldin, G. and Vignudelli, S. “Revisiting vertical land motion and sea level trends in the Northeastern Adriatic Sea using satellite altimetry and tide gauge data,” *JOURNAL OF MARINE SCIENCE AND ENGINEERING*, vol. 8(11), 2020, p.949.
7. Oelsmann, J., Passaro, M., Dettmering, D., Schwatke, C., Sánchez, L. and Seitz, F. “The zone of influence: matching sea level variability from coastal altimetry and tide gauges for vertical land motion estimation,” *OCEAN SCIENCE*, vol. 17(1), 2021, pp.35-57.
8. Wang, G., Zhou, X., Wang, K., Ke, X., Zhang, Y., Zhao, R. and Bao, Y. “GOM20: a stable geodetic reference frame for subsidence, faulting, and sea-level rise studies along the coast of the Gulf of Mexico,” *REMOTE SENSING*, vol. 12(3), p.350.

9. Liu, Y., Li, J., Fasullo, J. and Galloway, D. L. “Land subsidence contributions to relative sea level rise at tide gauge Galveston Pier 21, Texas,” *SCIENTIFIC REPORTS*, vol. 10(1), 2020, pp.1-11.
10. Tamisiea, M. E. and Mitrovica, J. X. “The moving boundaries of sea level change: Understanding the origins of geographic variability,” *OCEANOGRAPHY*, vol. 24(2), 2011, pp.24-39.
11. Zlotnicki V., Z. Qu, J. Willis. R. Ray and J. Hausman. “JPL MEASURES Gridded Sea Surface Height Anomalies Version 1812” PO.DAAC, CA, USA. Dataset accessed [2021-04-01] at https://doi.org/10.5067/SLREF-CDRV2.
12. Jet Propulsion Laboratory. [online] Available at: <https://gipsy-oasis.jpl.nasa.gov/> [Accessed 3 October 2021].
13. Bertiger, W., Bar-Sever, Y., Dorsey, A., Haines, B., Harvey, N., Hemberger, D., Heflin, M., Lu, W., Miller, M., Moore, A. W. and Murphy, D. “GipsyX/RTGx, a new tool set for space geodetic operations and research,” *ADVANCES IN SPACE RESEARCH*, vol. 66(3), 2020, pp.469-489.
14. Hector. [online] Available at: <http://segal.ubi.pt/hector/> [Accessed 3 October 2021].
15. He, Y., Zhang, S., Wang, Q., Liu, Q., Qu, W. and Hou, X. “HECTOR for analysis of GPS time series,” In Proceedings of the 2018 China Satellite Navigation Conference (CSNC), Springer, Singapore, May 2018, pp. 187-196.
16. Geodesy.noaa.gov. 2021. [online] Available at: <https://geodesy.noaa.gov/corsdata/station_log/txga.log.txt> [Accessed 3 October 2021].