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TIDE GAUGE AND SATELLITE ALTIMETRY DATA FOR POSSIBLE VERTICAL LAND MOTION DETECTION IN SOUTH EAST BOHOL TRENCH AND FAULT

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KEY WORDS: Vertical land motion; sea surface height; satellite altimetry; coastal retracking; tide gauge sea level

ABSTRACT:

Coupled with the occurrence of regional/local sea level rise on urbanized coastal cities is the possibility of land subsidence that contaminates the measurement by the tide gauge (TG) sensors. Another technology that could possibly check the in-situ data from tide gauge is satellite altimetry. The sea surface height (SSH) measured from satellite altimeter is compared with the observed tide gauge sea level (TGSL) to detect vertical land motion (VLM). This study used satellite altimeter retracked products near the TG Stations in Tagbilaran, Bohol; Dumaguete, Negros Oriental; and Mambajao, Camiguin located in the vicinity of the South East Bohol Trench and Fault (SEBTF).

Based on the results, the TG site in Tagbilaran is undergoing land subsidence. The rate of VLM is around 5 mm/year from 2009 to 2017. The same trend was manifested in the GNSS observed data in the PHIVOLCS monitoring station in Tagbilaran and the geodetic levelling done in the area. After the October 15, 2013 earthquake in Bohol, downward trends of around 27 mm/year and 17 mm/year were observed from GNSS measurements and SSH-TGSL difference respectively. These different rates may be due to the distance between the two sensors. The comparison between SSH and TGSL in Dumaguete showed small difference with a VLM rate of 1.8 mm/year. The difference in SSH-TGSL in Mambajao is quite large with a downward rate of 9.4 mm/year. This result needs to be further investigated for TG or TGBM instability or monitored for a possibility of land uplift.

1. INTRODUCTION

According to the submitted report of the Working Group I to the Intergovernmental Panel on Climate Change (IPCC), the global mean sea level (GMSL) rate is 3.2 mm/year. This is computed by the different altimetry data processing groups over 1993 to 2012 (Church, et al. 2013). However, regional MSL rates vary from the GMSL due to influencing factors such as vertical land motion, tide influence, storms, climatic variability, etc., (ibid).

Recent advances in space technology, made it possible to quantify sea surface height based on a global reference surface i.e. the surface of a geocentric ellipsoid such as WGS84. This can be considered an absolute reference surface. Satellite altimetry had been for more than 25 years measuring sea level globally equivalent to nearly half a million tide gauges (Weeman and Lynch 2018). The data collected from the several satellite missions were the basis for estimating the GMSL. In the open ocean, satellite altimetry is very reliable but in the coastal areas the signal is degraded due to the contamination of altimeter reflected signals linked to the presence of land within the instrument footprint (Deng, et al. 2002). Until recently, due to the development of new processing algorithms called retracking, altimeter data near the coasts can now be used (Cipollini, et al. 2015). Archived altimeter data are now being re-processed/retracked including current data acquisitions for coastal and inland waters applications.

This study explores the possibility of using satellite altimeter data near the coasts of the Islands of Bohol, Camiguin and Negros where the SEBTF (Bandibas 2016) is located (Figure 1). The assumption that VLM may have affected the measured sea level values of the TGs is due to the strong earthquake occurrences in this area. Reports of land emerging from the bottom after the earthquake were reported by locals and officially confirmed by the Department of Environment and Natural Resources (DENR) declaring the strip of land as “geological monument” (Udtohan 2015). Some TGs in the Philippines have just been recently co-located with GNSS receivers, hence no historical data to validate land subsidence/uplift in the sites. In Bohol area, the nearest GNSS monitoring station is around 5 km away from TG. It was established by Philippine Institute of Volcanology and Seismology (PHIVOLCS), but data collection was done through scheduled survey campaign.

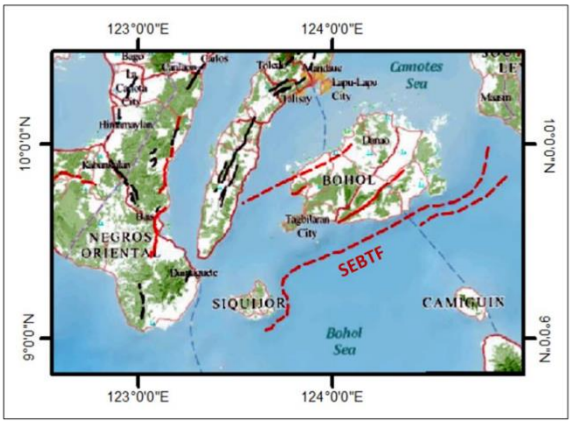


Figure 1. The South East Bohol Trench and Fault (SEBTF)

The potential of satellite altimetry, tide gauge and GNSS data for VLM determination were demonstrated in several studies (Fenoglio-Marc et al. 2004, 2011, 2012; Avsar, et al. 2017; Kleinherenbrink et al. 2018; Wöppelmann and Marcos 2015; Ray et al. 2010; Nerem and Mitchum 2002; Kuo et al. 2008; Zulkifli et al. 2018; Yildiz et al. 2013) with encouraging results. VLM detection is based on the difference of the SSH from different satellite altimetry missions and TGSL that are time co-located.

Importantly, since sea level from TGs are referred from Zero Tide Staff (0TS) that is arbitrarily located, it is necessary that this should be reduced to the reference level of satellite altimetry i.e. from the surface of the WGS 84 ellipsoid. The few satellite altimeter reliable data are one of the limitations of this research. Also, no GNSS receivers are collocated near the TGs. The TG data gaps also limits altimeter data matching.

2. THE TIDE GAUGE AND SATELLITE ALTIMETRY

2.1 Tide gauge sea level

In this study, only tide gauge data from 2009 to 2017 was considered to correspond to the period with available satellite altimeter data. The comparison was done through time co-location of TGSL to SSH during the period of acquisition. The tide gauge data provided by NAMRIA were hourly observations. To correlate the data observed by the tide gauge with the satellite altimeter time of acquisition, interpolation was performed on the tide gauge data. Linear interpolation is not ideal for predicting tides due to the non-linear nature of tides. The Pytides module in Python Programming was used in interpolating the tide gauge data. Pytides is a module that analyses and predicts the tide using harmonic constituents (Cox 2014).

2.2 The Tagbilaran, Dumaguete and Mambajao sea level

The Tagbilaran TG station in Bohol is located at approximately 9º38'56" N, 123º50'47" E. The tide gauge benchmark (TGBM) established in 2009 is located just about 4 m from the TG station. It is 5.971 m above OTS and 69.523 m above the WGS 84 as determined from GNSS observation on the benchmark on November 2018. The TG station is equipped with Leupold and Stevens float gauge (POD NAMRIA 2018). Figure 2 shows the hourly observed sea level referenced from the WGS84 ellipsoid. There are already some data gaps that started in May 2013 prior to occurrence of the MW 7.2 earthquake on October 15, 2013 From September 2015 up to August 2016 there is another data gap. Observation re-started on 27 August 2016 and looking at the data sea level trend is increasing.

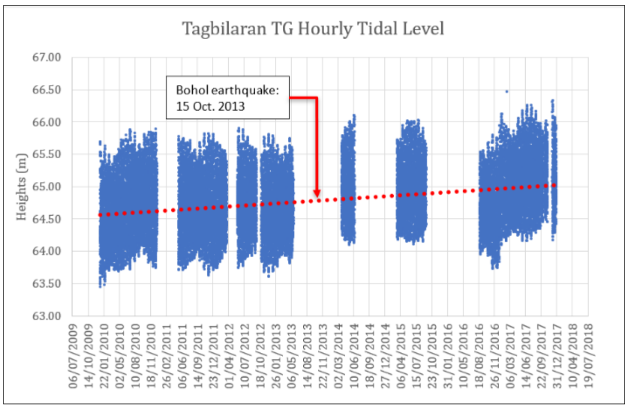


Figure 2. Tagbilaran TG hourly tidal level

The TG in Dumaguete is inside the port at approximately 9º18' 51" N, 123º18'42" E. The station is equipped with Leupold and Stevens float gauge. The TGBM is located just about 8 m from the TG station. It was levelled at 3.943 m above 0TS and with ellipsoidal height of 67.087 m. The hourly tidal level is shown in Figure 3. There is a data gap of 11 months from October 2012 to September 2015 (POD NAMRIA 2018). The sea level trend observed by the Dumaguete TG is showing an increasing trend but very minimal.

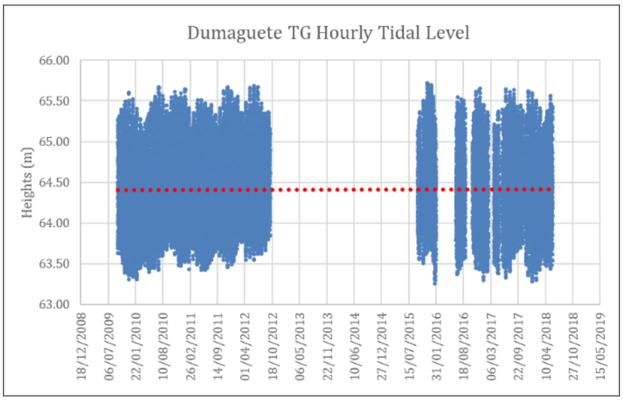
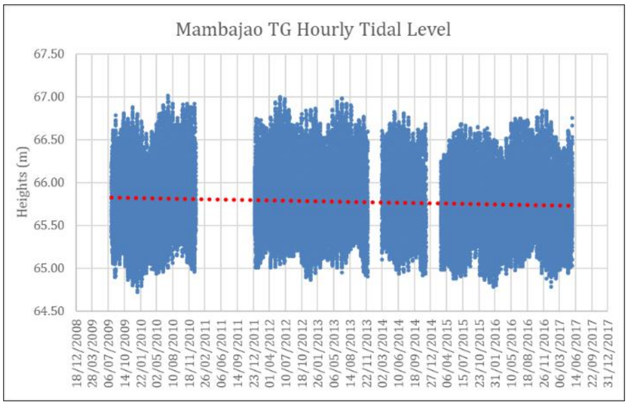


Figure 3. Dumaguete TG hourly tidal level

The Mambajao TG Station with Station ID 2174 in the PSMSL data catalogue is located inside the port of Balbagon at approximately 9º 14' 37" N, 124º 44'16" E. The station is equipped with Leupold and Stevens float tide gauge. The TGBM is located inside the port and 11.412 m above 0TS. Ellipsoidal height in the said TGBM was measured at 76.813 m during the GNSS observation in 2018. Figure 4 is the hourly tidal level referred from the WGS 84 ellipsoid. A data gap of 12 months occurred from January to December 2011 (POD NAMRIA 2018). A decreasing sea level trend is observed in this area.

Figure 4. Mambajao TG hourly tidal level



2.3 Satellite altimetry

Satellite altimetry can compute SSH using the time travelled by a radar pulse from the satellite to the surface together with precise positioning and corrections (Cipollini and Snaith 2013). Originally, satellite radar altimetry is primarily used for monitoring open ocean and ice-sheets. For the past years, development of new retracking algorithms for coastal application is increasing due to the strategic importance of coastal zones. The current goal is to fully exploit the voluminous data from satellite altimeter missions (Vignudelli, Snaith, et al. 2007).

Satellite altimeter is like a tide gauge in the sky. It is a more complicated RADAR tide gauge mounted on a satellite. Unlike tide gauge stations, satellites are not affected by land subsidence or any ground movements since they are in space. The distance between the satellite and the sea surface, as well as the precise location of the satellite is taken using RADAR techniques (CNES 2015). This distance is called range where it is corrected for the effects of propagation through the atmosphere and surface reflection (Rosmorduc, et al. 2011). The SSH is obtained by getting the difference of the altitude of the satellite and the corrected range (Figure 5). The reference level of SSH is the ellipsoid, however, oceanographers prefer using the geoid whenever possible (Vignudelli, Kostianoy, et al. 2011). The accuracy of the SSH obtained depends on the accuracy of the reference ellipsoid or the geoid (Shum, Ries and Tapley 1995).

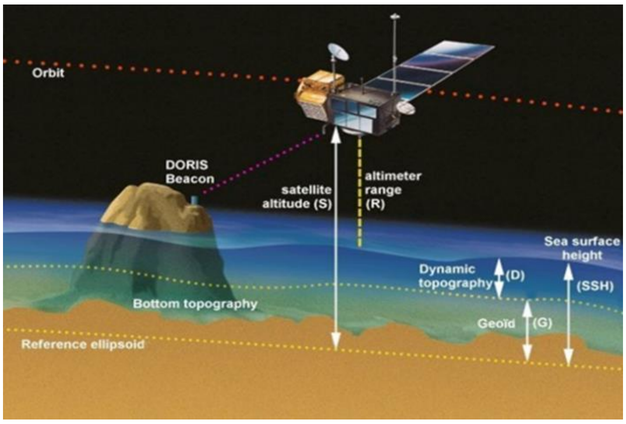


Figure 5. SSH determination from satellite altimetry

2.4 Coastal waveform retracking

A large portion of the data from satellite altimetry is not suitable for coastal applications due to contamination with land and calm water interferences as shown in Figure 6 (Passaro, 2014). New retrackers dedicated for coastal observations were developed such as ALES, OCOG, COASTALT, X-TRACK, etc., produced promising results on sea level observations on coastal areas.

Passaro, Cipollini, et al. (2014) developed ALES, the Adaptive Leading Edge Subwaveform retracker. This is a new retracking algorithm for determining the sea level for both coastal and open ocean products. The ALES retracker uses part of the returned echo and fits it with the Brown model then convergences through the Nelder-Mead nonlinear optimization technique using least-square estimation (Passaro, Cipollini, et al. 2014). The Brown Model is based on the combined computation of the instrument point target response, flat surface response and probability density function of the specular points (Brown 1977). It assumes that beam from the satellite is reflected directly back only at specular points (Cipollini and Snaith 2013).

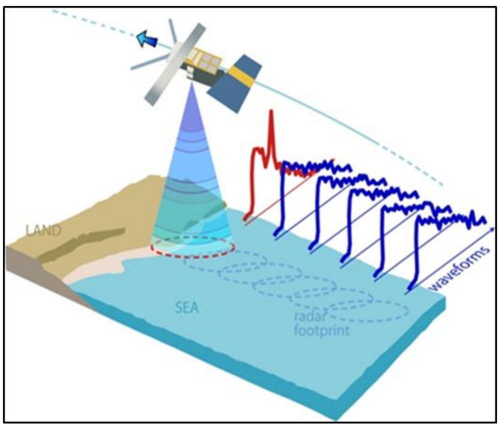


Figure 6: Satellite altimetry waveform in the open ocean (blue) and near coast (red). (https://sentinels.copernicus.eu/)

The ALES algorithm can retrieve more coastal waveform compared to standard processing algorithm. Based on the validation from Envisat, Jason-1 and Jason-2 with in-situ data, ALES produced more reliable 20-Hz data. A root-mean-square difference (RMSD) of up to 14 cm was also produced between the data of tide gauge and satellite altimeter (Passaro, Samreena, et al. 2018). Using data from Envisat and AltiKa, a root-mean-square error (RMSE) of 12/14 cm was observed by Gómez-Enri, et al. (2016). Additionally, data from ALES produced higher accuracy compared to SGDR and CTOH products.

Multiple coastal retrackers (i.e. Oce3, Red3, Ice1 and Ice3) to generate the PISTACH (Prototype Innovant de Système de Traitement pour les Applications Côtières et l'Hydrologie, or Innovative Processing System Prototype for Coastal and Hydrology Applications) (Mercier, et al. 2010). PISTACH is a project funded by CNES that aims to improve satellite radar altimetry data over coastal areas and continental waters. It is an experimental evolved version of the official Jason-2 IGDR (Interim Geophysical Data Record) products that includes new retracking solutions, better geophysical corrections and higher resolution global/local models. PEACHI is another experimental product for coastal areas processed by CLS and CNES. According to Valladeau and Ablain (2011), the PEACHI project aims to analyse and improve the Ka band of SARAL/AltiKa mission and develop new algorithms and parameters for processing on coastal areas, surface hydrology, ice, etc. Using Red-3 and BAGP retrackers an improvement on standard variation on coastal areas was observed on higher frequency of Ka band of AltiKa and smaller waveform footprint (Valladeau and Ablain 2011). A threshold of 5.7 km from the coast is set by Poisson, Thibaut and Valladeau (2013) due to the land contamination as the satellite gets near to the coast.

The X-TRACK coastal products are from different satellite missions (TOPEX/Poseidon, Jason-1, Jason-2 interleaved, TOPEX/Poseidon interleaved, Jason-2, Jason-3, GEOSAT Follow-On, SARAL/AltiKa and Envisat) which was developed by LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) (AVISO+ 2018) . This product is a combination of geophysical data record (GDR), corrections from CTOH database and 1Hz SLA with a spatial interval of about 6-7 km. Roblou, et al. (2007) produced a centimeter error level using the X-TRACK processor on both Mediterranean Sea and Karguelen Archipelago. Birol, et al. (2017) present the improvements of the 2016 X-TRACK relative to in-situ TG measurements in the Bay of Biscal in Western Africa.

2.5 Satellite altimeter data validation by comparison with tide gauge data

The handbook for validation of altimeter data by comparison with tide gauge measurement by Service Altimetrie & Localisation Precise (SALP), Collecte Localisation Satellite (CLS) and Centre National D'Etudes Spatiales (CNES) set criteria for determining if the sea level observed by the satellite altimeter and the tide gauge is valid for comparison. Two of these criteria are: 1) the standard deviation of the differences between altimetry and tide gauge data should not exceed 30 cm; and 2) the difference between altimetry and tide gauge data should not exceed the 12 cm threshold (Valladeau and Ablain 2011). Also, satellite altimeter should have a minimum of 2 years observations. Passing these criteria means that the 2 datasets are correlated and therefore in agreement.

3. MATERIALS AND METHODS

3.1 Study area

The study focused on coastal areas where tide gauge stations are located along the SEBTF. Specifically, these are the Tagbilaran in Bohol, Dumaguete in Negros Oriental and Mambajao in Camiguin. The selection of the area for this research was based on previous results of Reyes and Forsberg (2017) showing the large discrepancies of the MSLs from the Philippine Geoid Model (PGM) of 2014 (Forsberg, et al. 2014). The results showed clustering of large offsets in the vicinity of the SEBTF as shown in Figure 7. This prompted the researchers to conduct further investigation if vertical land motion is contributing to these large offsets. The Manila Bay also showed large offset and was the subject of an undergraduate research by Noveloso, Rediang and Reyes (2018). Several locations have also indicated large offsets but some of these were investigated by the POD NAMRIA.

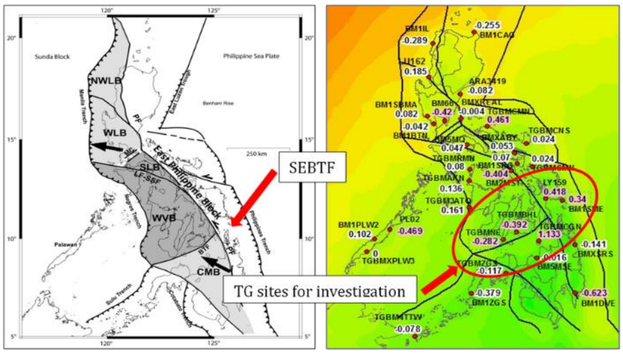


Figure 7. Clustering of large MSL offsets from PGM 2014 near SEBTF

The data observed by the three tide gauge stations and the data observed by satellite altimetry within 50-km radius from each tide gauge were used for this study. The 50-km radius was adopted from PISTACH Users' Handbook (Mercier, et al. 2010), where data from satellite altimetry can still be effectively compared. However, the radius of data consideration was extended to about 55 km for the Tagbilaran TG case to capture the data from PISTACH. Figure 8 shows the location of these sites and the SEBTF. The satellite passes are also indicated in the same figure: Red lines for Topex Poseidon (T/P), Jason-1 (J1), Jason-2 (J2), Jason-3 (J3); Pink lines the interlaced orbit of J1, J2 and T/P; and Yellow lines for Envisat, Saral, ERS-1 and ERS-2 orbit (AVISO⁺ n.d.).

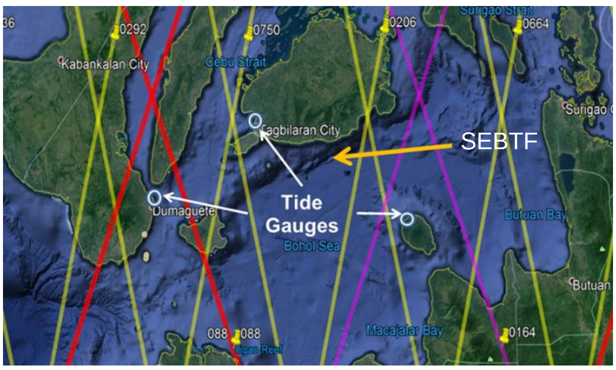


Figure 8: Location of tide gauges and satellite altimeter passes plotted on Google Earth

3.2 Data acquisition and description

Satellite altimetry data acquired from different sources are listed in Table 1, while tidal data acquired from POD, NAMRIA are listed in Table 2. A total of seven product-satellite pair were used. Jason-2 satellite data were retracked using ALES by Dr. Marcello Passaro and provided to the researchers. PISTACH and PEACHI were sourced from AVISO. SARAL/AltiKa was also obtained from AVISO which is a PEACHI product. Jason-1 and EnviSat were also retracked using ALES which were obtained from OpenADB and PODAAC, respectively. X-TRACK products from various satellite missions were downloaded from AVISO/CTOH.

Product	Satellite	From	Frequency	Location	Years Available
ALES	Jason-1	OpenADB	1Hz	Bohol	2002-2008, 2012-2013
				Camiguin	2009-2013
				Dumaguete	2002-2008, 2012-2013
ALES	Jason-2	Dr. Passaro	20Hz	Bohol	2008-2015
				Camiguin	no pass within 50 km
				Dumaguete	2008-2015
ALES	EnviSat	PODAAC	18Hz	Bohol	2002-2010
				Camiguin	2002-2010
				Dumaguete	2002-2010
PISTACH	Jason-2	AVISO	20Hz	Bohol	2010-2016
				Camiguin	no pass within 50 km
				Dumaguete	2010-2016
PEACHI	Jason-2	AVISO	20Hz	Bohol	2008-2016
				Camiguin	no pass within 50 km
				Dumaguete	2008-2016
PEACHI	SARAL/ AltiKa	AVISO	40Hz	Bohol	2014-2015
				Camiguin	2014-2016
				Dumaguete	no pass within 50 km
X-TRACK	GFO	AVISO/CT OH	1Hz	Bohol	2000-2007
	RA2				2003-2010
	SRL				2013-2016
	GFO			Camiguin	2000-2007
	RA2				2003-2010
	SRL				2013-2016
	TPN + J1N				2002-2005, 2009-2012
	GFO			Dumaguete	2000-2007
	RA2				2003-2010
	SRL				2013-2016
	TP+J1+J2 +J3				1993-2017

Table 1. Satellite altimeter data used

3.3 Tide gauge data pre-processing

Hourly readings of each tide gauge station are referred to the 0TS that are arbitrarily located. GNSS observations on the TGBMs were conducted by POD to compute the ellipsoidal heights (*h*). Subtracting the height of TGBM above 0TS from its' ellipsoidal height converts the 0TS level to ellipsoidal height (h_{0TS}). Thus:

$$h_{0TS} = h_{TGBM} - H_{TGBM/0TS} \quad (1)$$

After obtaining h_{0TS}, all tide gauge readings are added to convert them to ellipsoidal heights to conform with altimeter data

Location	Data Availability
Bohol	Jan 1-Dec 31 2010
	May 18, 2011- May 23, 2013
	Mar 27, 2014 - Jun 17, 2014
	Mar 17, 2015 - Sept 18, 2015
	Aug 27, 2016 - Dec 31, 2017
Camiguin	Jul 1, 2009 - Dec 31, 2010
	Jan 1, 2012 - Dec 3, 2013
	Mar 1-Nov 29, 2014 8am
	Mar 2015 - May 26, 2017
Dumaguete	Sept 15, 2009 - Oct 2, 2012
	Sept 19, 2015 - May 31, 2018

Table 2. Tide gauge data used

3.4 Data Processing

3.4.1 Programming. A faster and easier way to manipulate satellite altimeter data was done by the researchers through coding. Each product and satellite altimeter data contain different variables and methods for computing the necessary data i.e. SSH thus, different programs were coded. The flow of each program was based on the handbook of each product and satellite missions. A main program was created to incorporate each program for user-friendly interaction. The output of the program is a CSV file containing the extracted data from each satellite altimeter product and its location.

3.4.2 Tide Gauge Data Processing. Data acquired from NAMRIA were processed hourly heights in text file format. These were then arranged in MS Excel with the time converted to the number of seconds elapsed since January 1, 2000. Except for X-TRACK product, in which the time in seconds is recorded from January 1, 1950. This is to coincide with the acquisition time by the satellite altimeter.

3.4.3 Satellite altimetry data processing. Different processing was done on each product based on guidelines from product handbooks. The SSHs used were limited by the buffer-zone created from the shoreline up to 50 km (but extended to 55 km for Tagbilaran TG case) from the tide gauge stations. ALES retracked data were filtered out from the coastline up to 3 km seaward. PISTACH and PEACHI data were filtered out from the coastline up to 10 km seaward. X-TRACK data were used from the shoreline up to 50 km radius. Those data that fell within the buffer zone were used.

The J1, J2, SARAL retracked products and X-TRACK data were referred to the T/P ellipsoid while the SL readings from tide gauges were referred from the WGS-84 ellipsoid. To ensure compatibility of reference level, both data must be on the same datum. The SSH given in T/P ellipsoid was converted to WGS-84 ellipsoid using the equation below (Haran 2004), 2004):

$$\Delta h = h_2 - h_1 = -\left((a_2 - a_1)(\cos\varphi)^2\right) + (b_2 - b_1)(\sin\varphi)^2 \quad (2)$$

where:
φ is latitude,
h_1 and h_2 are elevations for ellipsoids 1 and 2, respectively,
a_1 and a_2 are equatorial radii of ellipsoids 1 and 2, respectively,
b_1 and b_2 are polar radii of ellipsoids 1 and 2, respectively,
Δh is the difference in height between the ellipsoids.

The SSH data from EnviSat were already provided in WGS-84 ellipsoid, thus no transformation was done. As discussed, SSH is obtained by getting the difference of the altitude of the satellite and the *corrected range*. This concept was used in obtaining the SSH for the PEACHI and PISTACH products, as well as, ALES' EnviSat. To get the corrected range, some of the corrections applied are atmospheric corrections, tidal corrections and sea state bias.

For X-TRACK product, the SSH was computed from adding the sea level anomaly (SLA) and the mean sea surface (MSS) height. ALES' J1 and J2 data were already provided with corrected SSH. All ALES retracked data were filtered based on the threshold recommended by OpenADB and Dr. Passaro. The following criteria for filtering were used: (1) Distance to coast: More than 3 km; (2) Sea level anomaly: Less than 2.5 m; (3) Significant wave height (SWH): Less than 11 m; and (4) Standard deviation of altimeter: Less than 20 cm. The outliers and spikes in the SSH data were filtered by means of the 1.5 * Interquartile Range (IQR) Rule.

3.4.4 Tide gauge and satellite altimeter data time co-location. The acquisition time for the satellite altimetry data differs from the tide gauge station. A python program called Pytides (Cox 2014) was used to interpolate the tide gauge data to match with the time observed from the satellite altimeter. The tide gauge data were also incomplete as shown in Table 2, so it was necessary to exclude the dates with incomplete data and only interpolate between given dates.

3.4.5 Computation of differences and filtering. The SL-SSH differences computed for each tide gauge-satellite altimetry pair were plotted in MS Excel. The linear regression function was used to determine the trendline as well as the VLM. The derived VLMs were analysed. The average of the SSH, average of SL of tide gauge and their difference was also computed after filtering.

4. RESULTS AND DISCUSSION

4.1 TGSL and SSH differences

The results of SSH from different satellite missions and retrackings and TGSL comparisons are listed in Table 3. The TGSL shows different average values because the TG data is being matched with the measurements from satellite altimeters, but they do not vary much. The average SSH from EnviSat retracked using ALES have the lowest values and inconsistent with the others. The root mean square deviations (RMSD) are also large. In general, TGSLs are higher than the SSHs determined by satellite altimeter.

Product	Satellite	From	Freq	TG Location	RMSD	Ave Sat Alt SSH	Ave TGSL	Diff
ALES	Jason-1	OpenADB	1Hz	Tagbilaran	0.5672	64.1236	64.6003	0.4768
				Mambajao	1.9952	63.8747	65.7659	1.8912
				Dumaguete	0.3429	64.1036	64.3324	0.2288
ALES	Jason-2	DGFI-TUM	20Hz	Tagbilaran	0.7313	64.1802	64.7721	0.5918
				Mambajao	No data			
				Dumaguete	0.4731	64.1366	64.3589	0.2223
ALES	EnviSat	PODAAC	18Hz	Tagbilaran	3.1258	61.8007	64.9073	3.1065
				Mambajao	4.2121	61.8214	65.9537	4.1323
				Dumaguete	2.9999	61.6374	64.6086	2.9712
PISTACH	Jason-2	AVISO	20Hz	Tagbilaran	0.5751	64.3677	64.7726	0.4049
				Mambajao	No data			
				Dumaguete	0.4227	64.2888	64.3762	0.0874
PEACHI	Jason-2	AVISO	20Hz	Tagbilaran	0.6252	64.2970	64.7639	0.4668
				Mambajao	No data			
				Dumaguete	0.4359	64.2445	64.3667	0.1222
PEACHI	SARAL /AltiKa	AVISO	40Hz	Tagbilaran	0.9350	63.8678	64.7960	0.9283
				Mambajao	2.4239	63.5642	65.9079	2.3438
				Dumaguete	No data			
X-TRACK	GFO RA-2 Jason 1	AVISO/ CTOH	1Hz	Tagbilaran	0.6138	64.3986	64.8589	0.4603
				Mambajao	1.8230	64.0889	65.8294	1.7405
				Dumaguete	0.5264	64.1228	64.4261	0.3033

Table 3: Results of sea level comparisons between satellite altimeter and tide gauge data (in m)

https://doi.org/10.5194/isprs-archives-XLII-4-W19-369-2019

The SSHs near Mambajao TG are very inconsistent as shown in ALES-Jason 1, ALES-EnviSat, PEACHI-SARAL and X-TRACK with large RMSDs. Nevertheless, the difference between the averages of SSH-TGSL at Mambajao TG (excepting ALES-EnviSat result) of around 1.99 m conforms with the more than 1 m difference of TGSL from the PGM 2014 (Reyes, Forsberg, 2017) as shown in Figure 7. This needs further checking.

The average SSH near Dumaguete TG from different products showed consistency except for ALES/EnviSat and X-TRACK. The RMSDs for the rest of the product-satellite pairings exceeded the 30 cm standard deviation criteria for SSH-TGSL differences. Taking the average of the SSH disregarding values from ALES/EnviSat and X-TRACK the result is 64.1934 m. The average of the TGSL is computed at 64.3586 m. The SSH-TGSL difference in average is -16.52 cm which is just 4 cm more than the 12 cm criteria.

In the Tagbilaran area, the product-satellite pairing results that were excluded are ALES/Jason-2, ALES/EnviSat and PEACHI/SARAL due to the large residuals. The average of the SSH for the rest of the product-satellite pairings is 64.2967 m and for TGSL is 64.7489 m. There is an average difference of -45.22 cm that is way above the 12 cm allowable. The RMSD average is 59.53 cm, which also exceeded the 30 cm standard deviation allowed. Therefore, the SSH and TGSL are not correlated.

4.2 Vertical land motion

The TGSL in Mambajao, Camiguin is exhibiting a downward trend at a rate of 9.4 mm/year that could mean land uplifting. This needs further investigation as it is unusual, as global SL trend is on the rise. The SSH-TGSL difference is quite large, which is also manifested in the TGSL and PGM 2014 difference (Reyes and Forsberg 2017). The research of De Castro, et al. (2018) also showed large offset of the TGSL from the initial processing of Earth Gravity Model by National Geospatial-Intelligence Agency (NGA) in 2017 (Barnes 2017). This model incorporates gravity from airborne measurements near Philippine coasts. It is possible that the TG or the TGBM level was disturbed but this needs to be checked. In Dumaguete area the difference in average of SSH-TGSL as previously mentioned is -16.62 cm. The computed downward VLM rate is around 1.8 mm/year. The Dumaguete TGSL trend as shown in Figure 3 is increasing but very minimal.

The average difference between SSH and TGSL in Tagbilaran is -45.22 cm, which is high. The VLM rate computed is around 5 mm/year from 2009 to 2017. The big SSH-TGSL difference may suggest that land subsidence is occurring. The research of Flores, Madjus and Reyes (2018), analysed the geodetic levelling done in Bohol using auto-level and GNSS receiver. By comparing the levelling in 2012 prior to earthquake occurrence with the after-earthquake levelling in 2016 and 2017 conducted by NAMRIA, the results showed that near the TG there is downward land movement as indicated by the blue dots (Figure 9a). Another study by Kobayashi (2014) using RADARSAT confirmed land uplift on red-colored areas and land subsidence in cyan-colored areas (Figure 9b). The GNSS survey campaign conducted by PHIVOLCS showed land subsiding from 2006 to 2011 (Figure 10) that corresponds to TGSL increasing as shown in Figure 2.

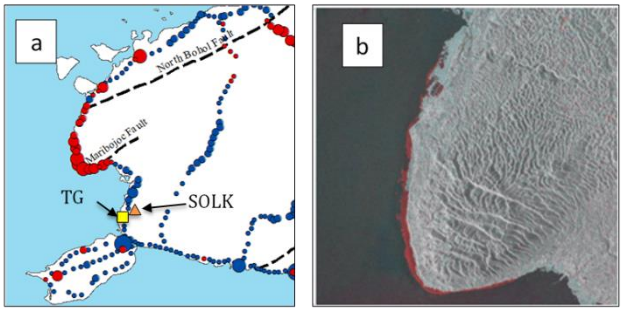


Figure 9. Land uplift (red) and land subsidence (Blue/Cyan) from geodetic levelling and RADARSAT SAR interferometry

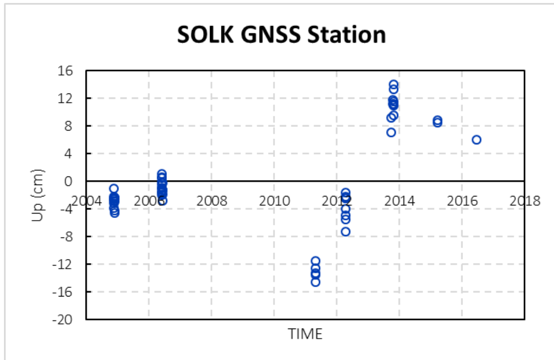


Figure 10. GNSS measurements from PHIVOLCS survey campaigns

A GNSS observation was made after the October 2013 earthquake and the result showed a sudden vertical increase from 2012. This increase was also recorded by the TG as the SL moved up after observation was resumed in early 2014. The GNSS measurements trend starts to go down at 27 mm/year after the October 2013 observation. The rate of SSH-TGSL difference after the earthquake is 17 mm/year. The difference between these rates is probably due to the distance between the sensors. This downtrend corresponds to an increase in the TGSL for the same period as shown in Figure 2. Thus, the findings from GNSS survey and geodetic levelling validate also the result of this study.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the results, the TGSLs determined from in-situ observations are higher than the SSH. Previous study by Reyes and Forsberg (2017) showed that the TGSLs are also higher than the geoid in the area. This could mean that at the coasts there are other factors that contribute to the departure of the TGSL from the geoid that could include VLM. In ideal condition where only the force of gravity is acting, the mean SSH, mean SL and geoid will coincide. This study showed great potential for TG measurements for checking coastal altimetry products and vice versa. The differences of SSH, TGSL and geoid height from each other provide data quality check. The data from many satellite altimeter missions serve also as quality check based on consistency of results.

Based on the TG data in Mambajao, Camiguin the rate of SL decrease that could correspond to land uplift is around 9.38 mm/year. Large offsets between TGSL and SSHs derived from retracked data from EnviSat RA-2, Geosat Follow-on, Jason 1 and SARAL/Altika were observed. This large offset was also observed from the difference of TGSL and the geoid. In the case

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of Mambajao the TG and TGBM levels should be checked as coastal altimetry and geoid differences from TGSL both showed large discrepancies.

The Dumaguete, Negros Oriental data showed minimal difference between the average of SSH-TGSL. The rate is around 1.8 mm/year. The hourly TGSLs from 2009 to 2017 showed only very small increase. The SSHs from PISTACH and PEACHI products from Jason-2 have 8.74 cm and 12.22 cm difference from TGSL. These showed correlation between the two datasets. Considering all the other satellite altimeter products that provide consistent results the average SSH-TGSL difference is -16.62 cm that is only 4 cm over the 12 cm criteria set for comparison.

The Tagbilaran TG site is undergoing land subsidence at 5mm/year as evidenced by the results of SSH-TGSL comparisons. Although, the GNSS data was from survey campaigns, this also validated the findings of this research. The geodetic levelling conducted in Bohol showed that in the vicinity of the TG, the land is subsiding. Notably, after the October 2013 earthquake, land subsidence rates of 17 mm/year and 27 mm/year were observed from SSH-TGSL difference and GNSS measurements, respectively. The difference in the results may be due to the distance between the TG and GNSS station.

This study demonstrated that with coastal retrackers the unusable data near the coasts can now be exploited in the Philippine area. Several studies as mentioned earlier have already proven the feasibility of using satellite altimetry and tide gauge for VLM detection. Importantly, differences between SSH, TGSL and geoid height can be used to check for data consistency. The TGSL trend can also show VLM especially when the rate of local sea level rise is more than the global mean sea level rise. GNSS co-located receivers will provide the best quantification for VLM in conjunction with TGSL.

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