# Determining and Monitoring Sea Level in the Caribbean using Satellite Altimetry

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**Key words**: Mean Sea Level; Sea Level Change; Satellite Altimetry; Caribbean

## SUMMARY

Precise monitoring of changes in the mean sea level of the oceans is critical for understanding not just the climate but also the socioeconomic consequences of any rise in sea level. Though the impacts of sea level change are of international concern, they are especially significant for small island states, such as those in the Caribbean. Small Island States are especially at risk from the effects of climate change and sea level rise largely because of their environmental and economic dependence on coastal zones. Exacerbating this vulnerability is the fact that the Caribbean region is plagued by a lack of dependable in-situ tide gauges and spatially effective systems for monitoring sea level.

This paper aims to fill the gap in available mean sea level data in the Caribbean region using satellite altimetry. Satellite altimetry provides a method that resolves the sparse, unreliable sea level monitoring system in the Caribbean. The technique of satellite altimetry is examined in its use to effectively monitor and compute mean sea level (MSL) and subsequently derive sea level rise (SLR) rates for the Caribbean.

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## 1. INTRODUCTION

Over half of the world's population lives within 60 km of the shoreline, and coastal populations in many countries are growing at double the national rate (Turner et al, 1996). Small Island Developing States (SIDS) have characteristics that make them particularly vulnerable to the effects of climate change, sea level rise and extreme events, including: relative isolation, small land masses, concentration of population and infrastructure in coastal areas, a limited economic base and dependency on natural resources, combined with limited financial, technical and institutional capacity for adaptation (IPCC, 2007b). These countries are expected to be among the earliest and most impacted by climate change in the coming decades. Climate change is expected to jeopardize tourism revenues, fisheries, commercial and agricultural enterprises and human life in SIDS (Turner et al., 1996). This places exigent importance on coastal cities and SIDS to continue to ensure sustainable development and to decrease or eliminate any threat which may be pervasively detrimental to their socioeconomic prosperity.

Sea level change has been an imperative issue throughout the course of time. The steric and eustatic sea level variations are direct effects of climate change, affecting both society and the environment. This is a main product of the warming of the climate system, which is now evident from observation of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level (IPCC, 2007a).

Sea level monitoring, if it is based upon accurate and reliable measurements collected over long periods, is an excellent tool for determining and predicting changes and trends in the sea level. Unfortunately, long term consistent sea level monitoring has been lacking in the Caribbean. As suggested by Church et al (2001), the best estimate of sea level change over the last century is based mainly on tide gauge observations. However, throughout the Caribbean, only forty four of these tide stations are operational, most of which are plagued by problems of sporadic distribution, faulty equipment, data gaps and discontinuous results and coverage over time periods too short to account for climatic variations - this creates data gaps in Mean Sea Level (MSL) data (Sutherland, Miller and Dare, 2008). Using data solely from this method of measurement, without taking into account its drawbacks, would produce models with credibility too frivolous to be used for any successful future predictions. As an example of this shortcoming, Figure 1 shows a digital elevation model of the island of Bequia, St. Vincent and the Grenadines, which includes a predictive sea level of 0.4 metres above the mean – a potentially valuable tool to assist in developing appropriate adaptation and mitigation strategies. The lack of consistent long term tide gauge measurement, however, detracts much from the models predictive capabilities.

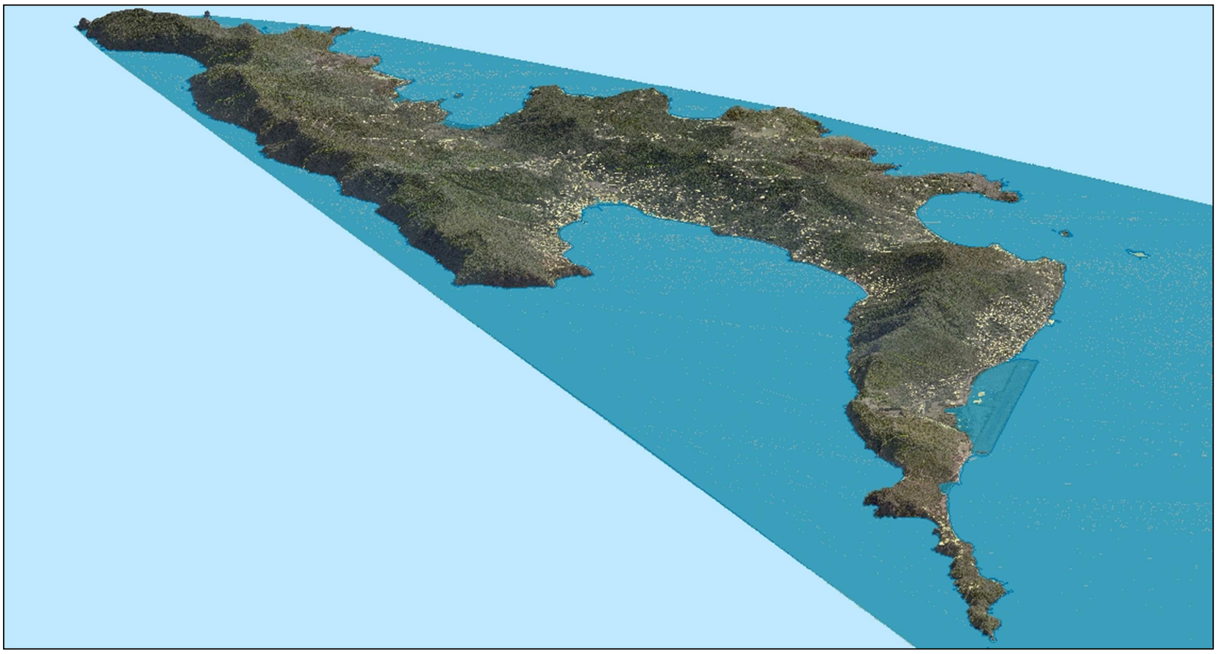

Figure 1 – Digital Elevation Model of the Island of Bequia

Bequia is not unique in its experience in the Caribbean with regard to establishing or maintaining its vertical datum. The lack of tide gauges and long term tidal data in most of the means that mean sea level is currently undefined, as in the specific case of Bequia, or benchmarks can no longer be verified or updated. This paper presents a modernistic approach to sea level monitoring and Mean Sea Level determination in the Caribbean, through satellite altimetry. Presented with the challenges of maintaining an effective tide gauge infrastructure, the potential of satellite altimetry is examined to perform these two key functions of tide gauges in the region.

## 2. SEA LEVEL AND SATELLITE ALTIMETRY

Satellite altimetry has developed into an established technology for measuring sea level, and in contrast to the sparse network of coastal tide gauges, measurements of sea level from space by satellite altimetry provide near global and homogenous coverage of the world's oceans. Altimetry, as shown in Figure 2, uses pulse-limited radar to measure the altitude of the satellite above the closest point of the sea surface, *H* and global precise tracking coupled with orbit dynamic calculations to determine the height of the satellite above the ellipsoid, *R*. The difference between these two measurements results in the height of the sea surface, *h* given as;

$$h = H - R$$

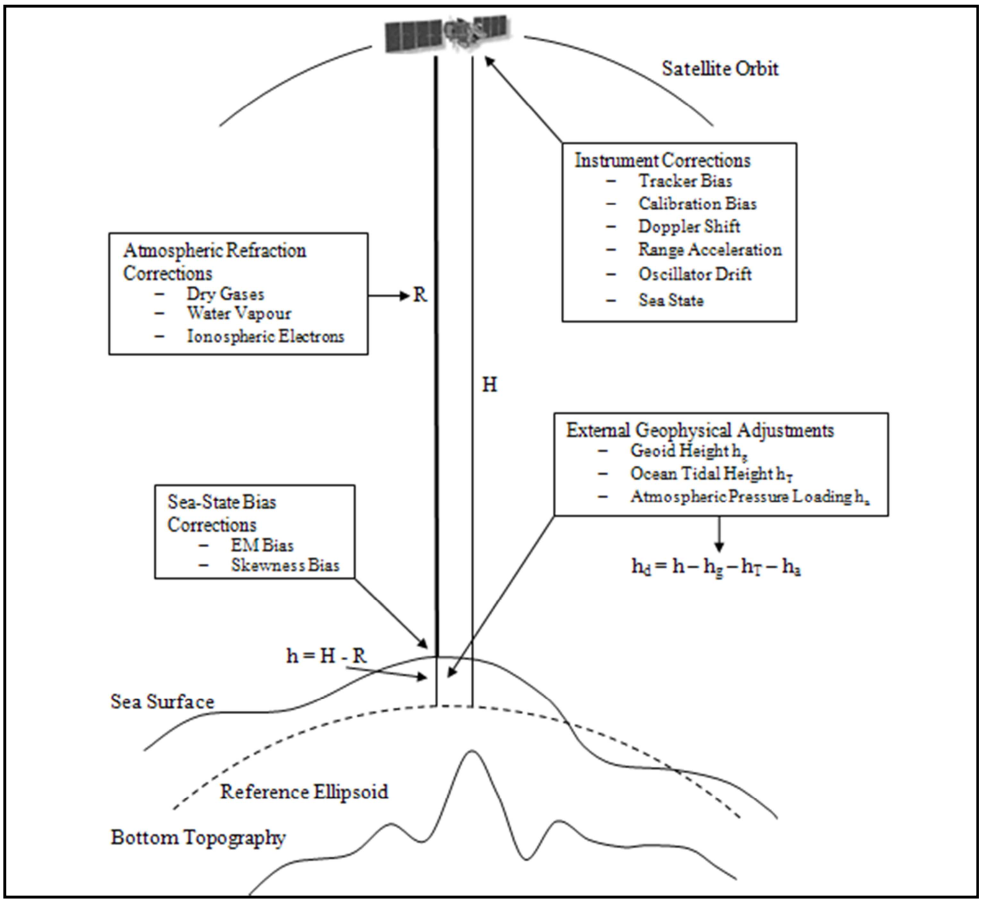

Figure 2 – Principle of Satellite Altimetry

However, accurate estimates of *R* and *H* are not sufficient for oceanographic applications of altimeter range measurements. The sea surface height, $h$ relative to the reference ellipsoid is the superposition of a number of geophysical effects. In addition to the dynamic effects of geostrophic ocean currents that are of primary interest for oceanographic applications, $h$ is affected by undulations of the geoid, $h_g$ about the ellipsoidal approximation, tidal height variations, $h_r$ and the ocean surface response to atmospheric pressure loading, $h_a$. These effects on the sea-surface height must be modelled and removed from $h$ in order to investigate the effects of geostrophic currents on the sea surface height field (Chelton et al., 2001). Thus the sea level is given as

$$h = H - \acute{R} + \sum_j \Delta R_j - h_g - h_r - h_a$$

Attaining the required sub-millimetre accuracy for sea level rise monitoring, is challenging and requires satellite orbit information, geophysical and environmental corrections and altimeter range measurements of the highest accuracy. It also requires continuous satellite operations over many years and careful control of biases (Church and Gregory, 2001).

Over the past 20 years satellite altimetry has provided a global, high resolution, consistent monitoring of sea level and ocean circulation. The launch of Topex/Poseidon mission in 1992 was the advent of accurate altimetric based sea level data. With a repeat period of ten days, satellite measurements provided more details than in-situ tide gauge based observations over the last hundred years. Later in 1995, the European based ERS-2 satellite was launched followed by the Jason-1 in 2001, Envisat in 2002 and more recently Jason-2 in 2008. This multi-mission satellite period brought increasing data quality with the reprocessing of measurements, along with the continuity and homogeneity of data. At present the Envisat satellite with a 35 day cycle, Jason-1 and Jason-2 satellites with a 10 day cycle are in orbit providing very precise sea level data.

## 3. SEA LEVEL MONITORING

The spatial and temporal distribution of satellite altimetric data, combined with the fact that it is a space-based measurement system means that it has the potential to address many of the problems that plague tide gauge installation, distribution and maintenance. It is therefore a particularly advantageous alternative to tide gauge measurements in regions like the Caribbean where these problems are characteristic to the challenge of effective sea level monitoring and consequently coastal zone management.

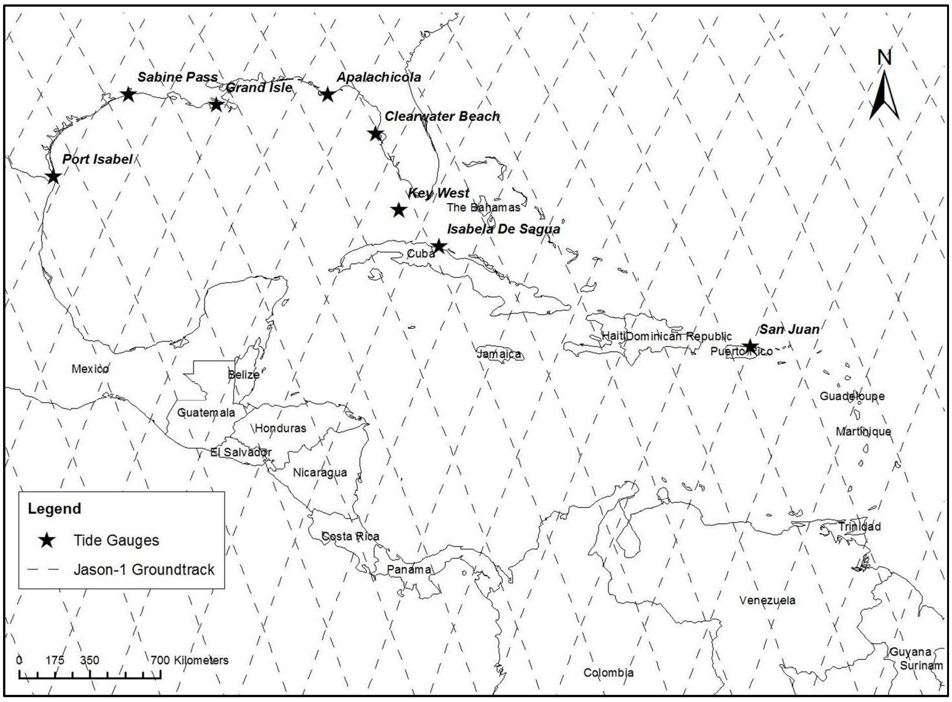

Figure 3 - Jason satellite groundtrack in relation to the selected tide gauges (Jaggan and Davis, 2012)

Several studies have been undertaken to show the applicability of the use of altimetric data as an alternative to tide gauge measurements (Madsen et al., 2007; Ginzburg, 2010 and Robinson, 2010). Jaggan and Davis (2012) describe a comparison of sea levels within the Caribbean between altimetric and tide gauge data. In the study, eight tide gauge sites in distributed in Puerto Rico and the Gulf of Mexico, as shown in Figure 3, were compared to interpolated satellite altimetry measurements for the period 2001 to 2010.

The results displayed an encouraging agreement between the tide gauge and altimetric data as shown in Figures 4 (a), (b) and (c), which depict the differences from three of the eight selected sites. Overall, the variations were generally of the order of 2cm in the mean and 5cm in the RMS between the tide gauge and satellite altimetry measurements.

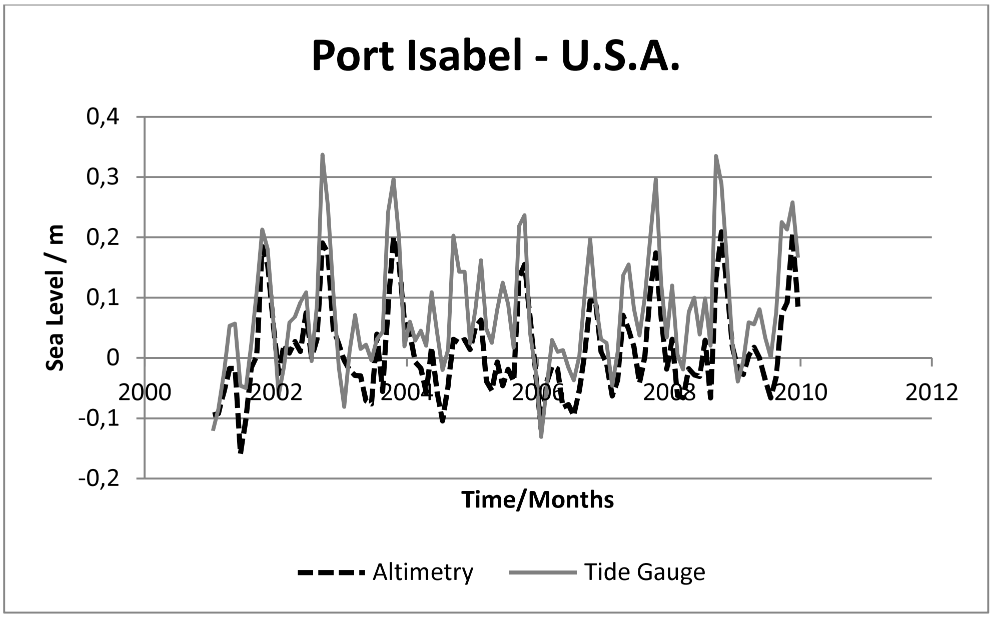


Figure 4 (a)- Sea level anomalies averaged over a month for Port Isabel 2001 – 2010 (Jaggan and Davis, 2012)

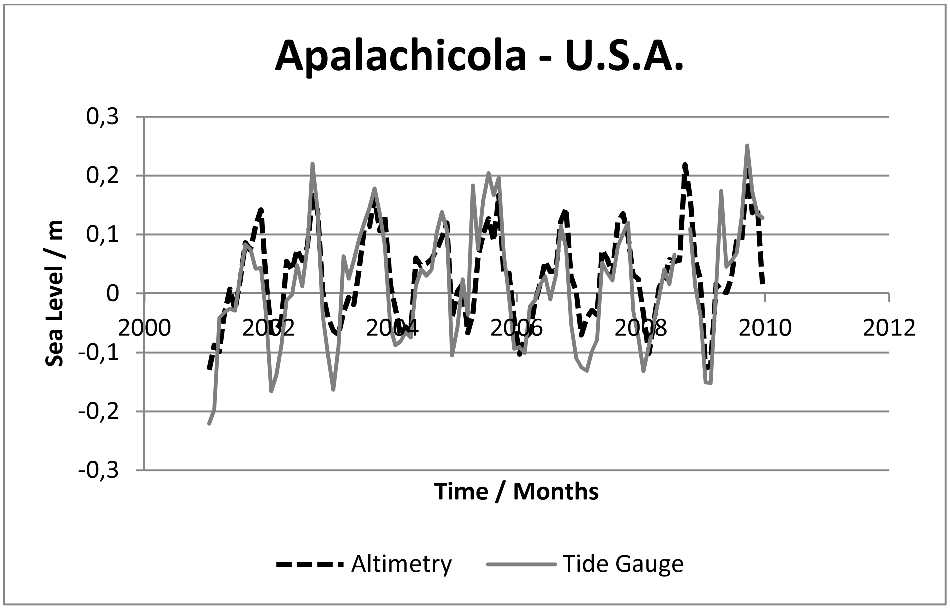


Figure 4 (b) - Sea level anomalies averaged over a month for Apalachicola 2001 – 2010 (Jaggan and Davis, 2012)

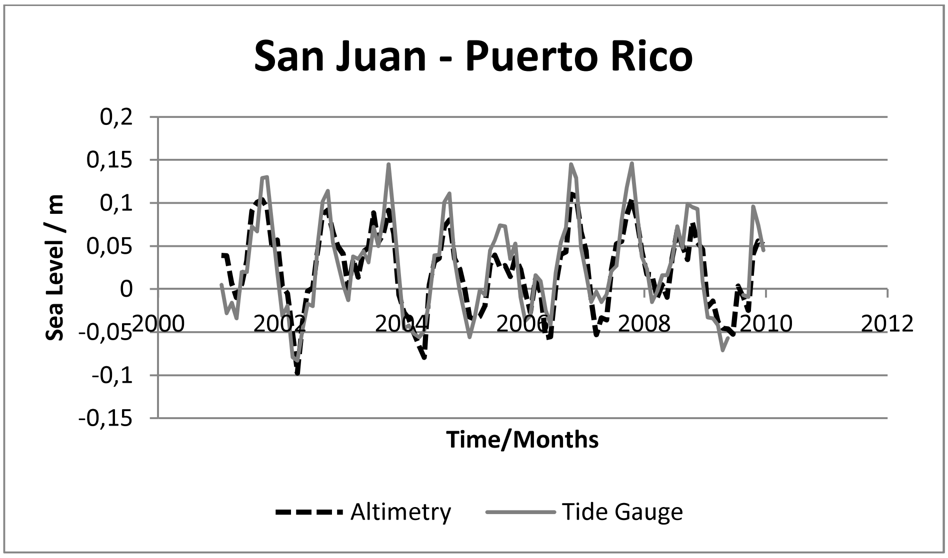


Figure 4 (c) - Sea level anomalies averaged over a month for San Juan 2001 – 2010 (Jaggan and Davis, 2012)

In the determination of sea level rise rates, a linear regression analysis was performed on the altimetric data with a summary of the results presented in Table 1. Taking into account the temporal and spatial differences between the measurement parameters; the altimetry being a 10-day discrete, open water measurement system vs. continuous coastal measurements for the tide gauges, the sub millimeter agreement for the sea level change demonstrates the applicability of the technology for sea level monitoring in the region.

Table 1 – Comparison of sea level change rates for tide gauge and altimetry (Jaggan and Davis, 2012)

| **Station Location** | **Sea Level Change Rates (mm yr$^{-1}$)** | | **Differences (mm yr$^{-1}$)** |
|---|---|---|---|
| | **Tide Gauge** | **Satellite Altimetry** | |
| Sabine Pass, Texas | 4.58 | 3.87 | 0.71 |
| Port Isabel, Texas | 7.14 | 7.80 | 0.66 |
| Apalachicola, Florida | 3.55 | 4.45 | 0.90 |
| Clearwater Beach, Florida | 7.88 | 7.86 | 0.02 |
| Key West, Florida | 6.09 | 6.34 | 0.25 |
| Grand Isle, Louisiana | 3.27 | 3.18 | 0.09 |
| Isabela De Sagua, Cuba | 0.97 | 0.85 | 0.12 |
| San Juan, Puerto Rico | -1.92 | -1.07 | 0.85 |

## 4. DETERMINING MEAN SEA LEVEL

Currently many Caribbean states lack an accurate and definitive reference of mean sea level due to the absence of long term functioning tide gauges. As a result, islands such as St. Vincent do not have a vertical reference system that can be easily maintained or verified. Although the geoidal model, CARIB97, exists as a reference surface, the geoid does not equate to mean sea level as the latter is not an equipotential surface.

Sideris and Fotopoulos (2006) highlight a few approaches to determine a vertical reference system (MSL).

- Using a network of tide gauges, a free-network adjustment is done by holding one station fixed. A correction factor is applied to the adjusted heights so that the mean height of all tide gauges equals zero. However, this method relies heavily on measurements from a single tide gauge and ignores mean sea level (MSL) observations made at other stations.

- MSL can be measured by a network of reference tide gauges situated along the coastlines and fixing the datum to zero at these stations. This can result in distorted heights since it ignores land motions and subsequent movements of tide gauges.
- Using the best model for the Sea Surface Topography (SST) at a network of tide gauge stations and then adjusting the network by holding MSL to zero for all tide gauges. SST models are not accurate near the coasts and can result in distortions for MSL.
- Using estimates of orthometric heights derived from ellipsoidal heights and precise gravimetric geoidal heights along a network of tide gauges. This relates the regional vertical datum to a global vertical reference surface (ellipsoid) and supports the realization of a World Height System.

Satellite altimetry has provided two decades of near global, continuous sea level data. However, while consistent and reliable data is available, altimetric data is based on the open ocean and its weakness lies in coastal measurements and monitoring. A vertical reference system must be localized as local factors influence its determination. Hence, satellite altimetry derived data alone is not sufficient to effectively and accurately determine mean sea level.

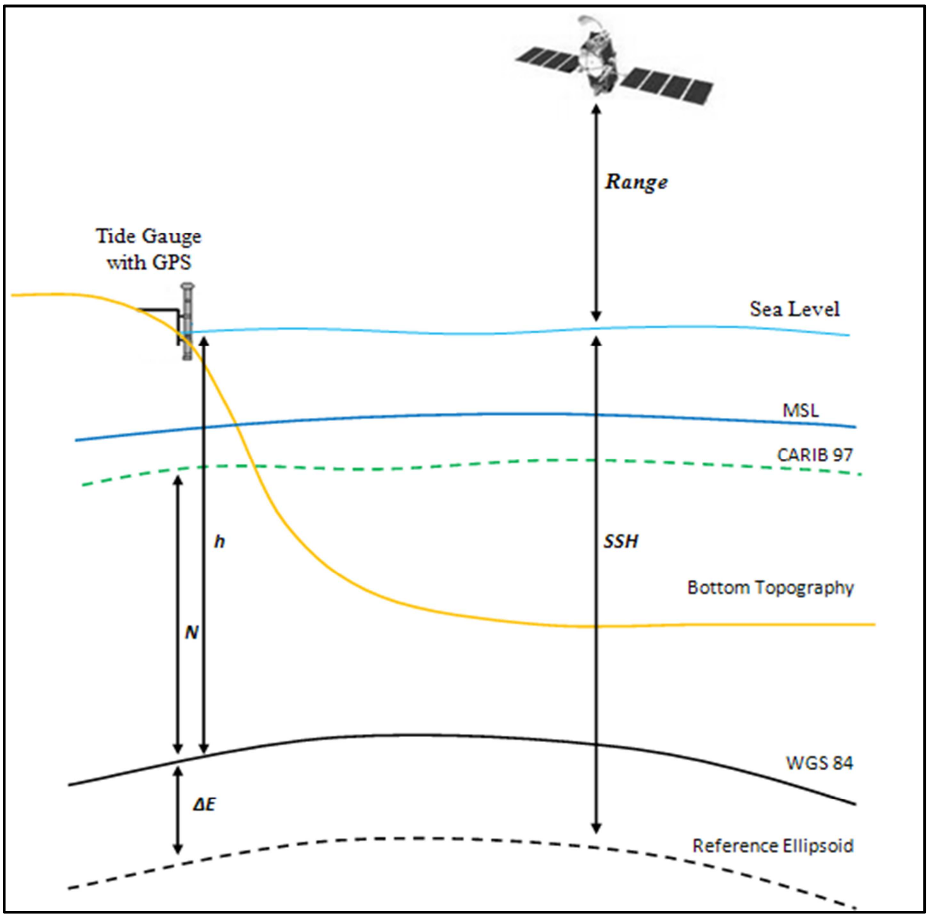


Figure 5 – Concept of MSL determination using Satellite Altimetry and Tide Gauges

To compensate for the weaknesses of the altimetric measurements closer to land, a method using a combination of satellite altimetry and short term tide gauge sea level monitoring, is proposed in an attempt to address this problem in Bequia, St Vincent and the Grenadines. The realization of a vertical datum would necessitate the installation of a network of tide gauges collocated with GNSS receivers at strategic points along the coast of Bequia to record short term sea level data. The GNSS measurements will monitor and allow corrections for any vertical land movement taking place. Since tide gauges measure sea level relative to land, satellite altimetric based data will be used to tie the tide gauge data in an absolute reference frame. Studies by Dong et al. (2002) and Mitchum (1998 and 2000) have been successful in verifying and integrating satellite altimetry data with tide gauges. These studies provide the basis and methodology that will be used to integrate the different measurement techniques in order to determine a MSL reference datum.

With MSL established, appropriate scenario analysis can now take place applying the sea level rise rates determined through the satellite altimetry. Applying the sea level rise parameters to an incorrect vertical datum will clearly overestimate or underestimate any potential impacts and consequently affect any coastal zone planning policy mitigation strategies adopted.

## 5. CONCLUSIONS

The situation regarding the vertical datum establishment and monitoring in Bequia, St Vincent and the Grenadines is a representative of many of the states in the Caribbean. Considering the vulnerability of the region to changes in sea level, the definition of the vertical datum is a major concern. This critical issue however has largely been overlooked because of the difficulty in establishing and maintaining adequate tide gauges as well as tide gauge records.

Satellite altimetry provides consistent accuracy, coverage, and independent space-based measurements in a geocentric reference frame, which are all necessary for the practical realization of a vertical datum. From the same altimetric datasets, there is the potential not only to obtain data to establish MSL, but also to monitor changes in sea levels. Currently, there is 20 years worth of altimetric data available, which would represent a long term data set for tide gauge records, adequate to establish MSL. Satellite altimetry gives an even spatial distribution free from issues of vandalism, theft or lack of proper maintenance that can account for the lack of tide gauges in the region. It therefore has the potential, once calibrated with tide gauge and GNSS data, to fulfil two of the major functions of the missing tide gauges in the region; establishing MSL and monitoring sea levels

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Dr. Dexter Davis holds a B.Sc. in Land Surveying from the University of the West Indies and a Ph.D. in Surveying Science from the University of Newcastle upon Tyne. He is currently a lecturer in the field of geodesy GNSS and geodetic surveying and is also Programme Coordinator of the B.Sc. of the Geomatics Engineering Programme in the Department of Geomatics Engineering and Land Management, University of the West Indies. He is a member of the Institute of Surveyors of Trinidad and Tobago as well as the ASPRS. His current research interests include geomatic techniques for hazard monitoring and mapping, including sea level rise and earthquake monitoring.

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Sandesh Jaggan holds a B.Sc. in Geomatics Engineering and Land Management from the University of the West Indies, Trinidad and Tobago. He is a researcher in the fields of geodesy and geodetic surveying within the Department of Geomatics Engineering and Land Management. He is currently an M.Phil. candidate and his thesis is based on investigating the applications of Satellite Altimetry for Sea Level Rise monitoring in the Caribbean region.

Demi Singh attained a Bachelor of Science Degree in Geomatics at the University of the West Indies, Trinidad and Tobago in the year 2010. She is currently pursuing a Master of Science Degree in Geoinformatics at the same university. She previously worked on an International Community-University Research Alliance (ICURA) project dealing with the effects of climate change on coastal communities in Canada and the Caribbean. Ms. Singh has also worked on a marine cadastre project at the Land Management Division, Ministry of Agriculture, Land and Marine Affairs, Government of the Republic of Trinidad and Tobag

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