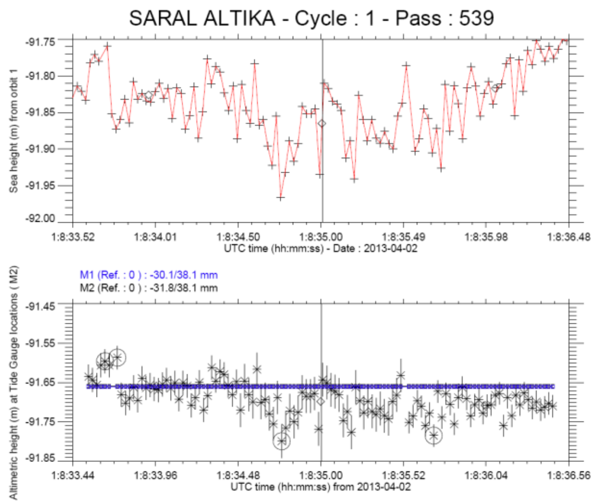
Calibration of Ka-band Altimeter (AltiKa) onboard SARAL satellite: Project completion report



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9. Abstract	The very first calibration site in tropical region for Ka-band Altimeter (AltiKa) onboard SARAL satellite located in open ocean near Kavaratti island has its own advantages to carry out absolute calibration of altimeters. The absolute calibration of SARAL/AltiKa sea surface height with Radar tide gauge has been carried out for its 17 cycles (till October 2014) at this site. The determined absolute bias is -38.3mm which is within the mission requirement (46 mm). In this initial calibration exercise, local high resolution tide models, effects of atmospheric wind pressure and vertical land motion for the precise local geoid estimation have been ignored in determining the absolute SSH bias. The initial results show that the location is very robust and encourages us to continue observations to carryout the absolute calibration of altimetric SSH.
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Participating agencies

National Institute of Oceanography, Goa	Dr. P. Mehra
Department of Science and Technology, Kavaratti	Dr. Iddrish Babu Dr. Poo Koya Mr. Abdul Riyas Mr. Thaiyyob Mr. Mushakunni

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Calibration of Ka-band Altimeter (AltiKa) onboard SARAL satellite: Initial Results

Abstract

The very first calibration site in tropical region for Ka-band Altimeter (AltiKa) onboard SARAL satellite located in open ocean near Kavaratti island has its own advantages to carry out absolute calibration of altimeters. The absolute calibration of SARAL/AltiKa sea surface height with Radar tide gauge has been carried out for its 17 cycles (till October 2014) at this site. The determined absolute bias is -38.3mm which is within the mission requirement (46 mm). Relative validation with JASON-2 SSH observations has also been performed. In this initial calibration exercise, local high resolution tide models, effects of atmospheric wind pressure and vertical land motion for the precise local geoid estimation have been ignored in determining the absolute SSH bias. The initial results show that the location is very robust and encourages us to continue observations to carryout the absolute calibration of altimetric SSH.

1.0 Objectives

The calibration and validation of SARAL/AltiKa is considered as one of the mission requirement of joint ISRO/CNES program. Under this activity, we need to identify potential calibration site/s over Indian peninsular region which can suitably be developed as a reference standard for absolute calibration of altimeters through its derived product like “Sea Surface Height” (SSH). The validation element considered consists of a direct validation of Geophysical Data Record (GDR) using in-situ observations like radar tide gauge and a relative validation of GDR with contemporary satellite altimeter ‘Jason-2’. The relative SSH calibration and the validation is performed over global regions.

2.0 Introduction

Satellite radar altimetry is a technique used in oceanography to measure sea level over a larger scale. This large scale data is vital to understand ocean circulation and its variations. Successful satellite altimetry for past 17 years (TOPEX/Poseidon, ERS-1/2, GFO, JASON-1/2, Envisat) has provided immense data. Therefore, global consensus has emerged that there is a strong necessity for maintaining satellite ocean altimetry observations (recommendation from WMO, GODAE, GOOS, and IGOS-P). High accuracy information from the radar altimeter missions are needed to continuously observe the global oceans and to understand short-to-long-term changes to ocean circulation. The ISRO-CNES joint SARAL (Satellite with ARGOS and AltiKa) mission is expected to play complementary role to Jason-2 and as a partner to a global constellation of ocean topography missions. The aim of AltiKa mission is to provide altimetric measurements matching those from ENVISAT mission and playing a key role for insuring the continuity of a multi-satellite altimetry. Additionally, the high-frequency, wideband Ka-band altimeter (37.75GHz, 500MHz) is expected to provide higher performance both in terms of spatial and vertical resolution. Thus AltiKa, Ka-band radar altimetry, will provide improved ocean features both from open- and coastal-oceans.

The calibration and validation of altimetric missions is “the process of quantitatively defining and assessing the altimetric system’s response to known and controlled signal inputs, determined by independent means”. This can be achieved by using dedicated research infrastructures together with distributed tide gauges to consistently and reliably determine (1) the absolute biases for each of these various satellite altimeters and (2) the relative biases among missions. Another approach for calibration is to use a tide gauge network, equipped with GPS receiver, in order to simultaneously measure Sea Surface Height (SSH). Globally there are only five permanent sites for providing calibration of satellite altimeters, three of which are located in Europe (Gavdos in Greece, Corsica in France operated by CNES, Ibiza in Spain), one in USA (Harvest oil platform, California operated by JPL) and one in Australia (Bass Strait, Tasmania). These sites, some of which have been operational since early 1992, produce absolute biases and drifts for overflying satellite altimeter measurements. Nonetheless, calibration results depend on the local conditions, standards and specifications applied, duration of measurements and geographical location of the calibration sites.

The calibration and validation activities for Ka-band altimeter (AltiKa) onboard SARAL satellite were initiated with analysis on tide gauge observations procured from Survey of India. The initial object was to find possible, minimum, well qualified, long term observational tide gauge stations over Indian region of global ocean. As the altimeter calibration was not performed till date over this part of the ocean by any agencies. In order to select few potential stations we adopted two screening condition namely: minimum radial distance to altimeter track (most preferable crossovers) and negligible geoid gradient along the radial distance. This selection criterion and data analysis effectively eliminated many geo-locations and finally we concluded with four stations. Though four stations are ambitious for doing the absolute sea surface height calibration of altimeter, we are interested to fix a permanent station for many altimeter missions: both present and future. National Institute of Oceanography has actively collaborated in setting up these four stations with down looking radar tide gauge (Port Blair, Kanyakumari, Machilipatnam and Kavaratti Island). The Kavaratti Island site is commissioned with two tide gauges.

Under a joint ISRO-CNES program of SARAL/AltiKa mission, we could get a standard calibration package with five days training at SAC, Ahmedabad by Dr. Pascal (Observatoire de La Côte d`Azur – Géoazur, Grasse, France). This calibration module is very well tested by various agencies and the calibration methodology adopted in this report is similar to the other dedicated sites in coherent with Jason-2 standards which is followed by Harvest, Corsica and Bass Strait sites. Further, the Kavaratti calibration site is standardized by conducting a GPS-buoy experiment in October 2012 in collaboration with CNES. This joint experiment was successful in quantifying the geoid gradient along the radial distance. Part of this experiment's outcome a permanent GPS receiver is installed by SAC in February 2014.

This report presents the results of calibration activities carried out by us for SARAL/AltiKa satellite altimeter over Indian region. The absolute calibration of SARAL/AltiKa is done over Kavaratti calibration site, and the relative calibration is performed with Jason-2 altimeter over global oceanic region.

3.0 SARAL specifications

Satellite with ARGOS and AltiKa (SARAL) is a ISRO-CNES joint effort carrying a Ka-band altimeter was launched on February 25, 2012 and since then playing a complementary role to Jason-2 as a partner to global constellation of ocean topography missions. This mission is dedicated to realize precise, repetitive global measurements of SSH, Significant Wave Height (SWH) and Wind Speed (WS) for developing operational oceanography and understanding of climate studies. As part of global ocean surface topography mission, AltiKa mission is considered as "Altimetric gap filler" between ENVISAT and SENTINEL-3. Therefore it is necessary that it repeats the ground track of ENVISAT. The accurate measurements using Ka-band radar altimetry will allow the recovery of the improved ocean short wavelength features both for open and coastal ocean. SARAL/AltiKa's mission specifications is given in **Table 1**.

Table 1: SARAL/AltiKa's specifications

Sr. No.	Parameter	Specification
1	Apogee altitude	814km
2	Orbit inclination	98.55^{o}
3	Repeat period	35day
4	No. of orbits in a cycle	501
5	Orbit type	Sun-synchronous
6	Local time of ascending node	06:00hr
7	Nodal period	100.59min
8	No. of orbits/day	14+11/345
9	Path to path distance	75km
10	Consecutive track	2800km
11	Pointing accuracy	0.1^{o}
12	Attitude sensors	Star, magnetometer, DTG (3nos.), 4 pi sensors (4 heads)
13	Life time	~5years

The AltiKa payload consists:

- A Ka-band altimeter (35.5-36GHz)
- A dual-frequency radiometer (23.8/36.8GHz)
- A Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) receiver
- A Laser Retro-reflector Array (LRA)

The main instrument of this payload is a Ka-band radar, the basic idea is derived from the TOPEX/Poseidon altimeter which operates at 35.75GHz.

4.0 SARAL/AltiKa data products

SARAL/AltiKa provides three types of data sets: Operational Geophysical Data Record (OGRD), Interim Geophysical Data Record (IGDR), and Geophysical Data Record (GDR). Different levels of data products are:

Level 0 – Data as acquired by the satellite.

Level 1 – It consists of extraction of raw measurements from telemetry packets, decoding and conversion of all parameters for further instruments and geo-physical processing. The altimeter echoes/waveforms are time tagged and the radial component of the orbit is generated and associated with measurements. In case of radiometer data, antenna temperatures for each channel are generated.

Level 1b – At this level, processing is done by computing all instrumental corrections and applying them to instrument measurements. Now data is in the altimeter parameters and the radiometer brightness temperatures with instrumental and internal calibration corrections applied.

Level 2 – Geo-physical processing is done at this level. Altimeter waveforms are processed (on ground re-tracking) to estimate relevant physical parameters such as altimeter range, backscattering coefficient (σ^0), SWH, thermal noise and square of the off-nadir angle. All environmental and geo-physical correction are applied on the data in this step and data in interpreted in terms of SSH, WS etc.

Level 3 – Objectively analysed gridded products of sea level anomaly, wind and SWH.

The level-2 products of this mission will be calibrated and validated using controlled Cal-Val site over Indian region by us. The level-2 product specifications are given in **Table 2** for reference (taken from SARAL/AltiKa products Handbook).

Table 2: Level-2 SARAL/AltiKa products for Cal-Val exercise

	OGDR family	IGDR family	GDR family	Goals
Sea surface height (cm)	30.5cm	5.3cm	4.6cm	2.8cm
Significant wave height (m)	10% (0.5m)	10% (0.4m)	10% (0.4m)	5% (0.25m)
Wind speed	2m/s	1.7m/s	1.7m/s	1m/s
Latency period	3-5 Hour	< 1.5 Day	~40 Day	

5.0 Site selection for altimeter calibration

The primary requirements/conditions for the site selection are:

1. The current satellite altimeter should have a overhead pass over the selected site.
2. The site should be located sufficiently far offshore so that the area illuminated by the altimeter's radar pulses is covered entirely by ocean when the satellite is directly overhead. Measurements from such sites will avoid land perturbations on the radar echoes that imply a rapid decreasing of the track precision.
3. Island sites are better, since they are away from the effects of shallow water.
4. The data collection platform should be small enough so that it does not influence the reflected radar signal.
5. Ultimately the site at open ocean environment is the best for these missions to monitor the spacecraft measurement systems under which they are designed to best operate. It must be remembered that the in-situ SSH refer to a "pinpoint" location underneath the platform, while the satellite altimeter measures SSH over a footprint with typical diameter of 3-5km. The spatial variability of the SSH within the footprint is probably the least understood of the error-budget components. Christensen et al. (1994) assumed a variable error of 2cm (RMS) to account for the effects of local SSH variability on reconciling the tide-gauge and altimeter measurements at Harvest site.

Initial survey was done to identify a suitable location and infrastructure for calibrating altimeters using SSH measurements over Indian peninsular region. For this purpose, the geo-locations of all tide gauge stations by various Indian institutions were collected, which were reported working during that time (Year 2011). Along with these locations, ENVISAT tracks were over laid to pickup overhead geo-locations. Through this approach many geo-locations were screened out for the site finalization. Further, condition of geoid undulation was over imposed (Earth Geoid Model 2008 solution was used for the geoid gradient determination). In an ideal case, geoid should be uniform between the crossover point and the tide gauge location. It means that gradient should not vary much between crossover point and tide gauge location.

The model computed geoid variation over Indian region is shown in **Figure 1**.

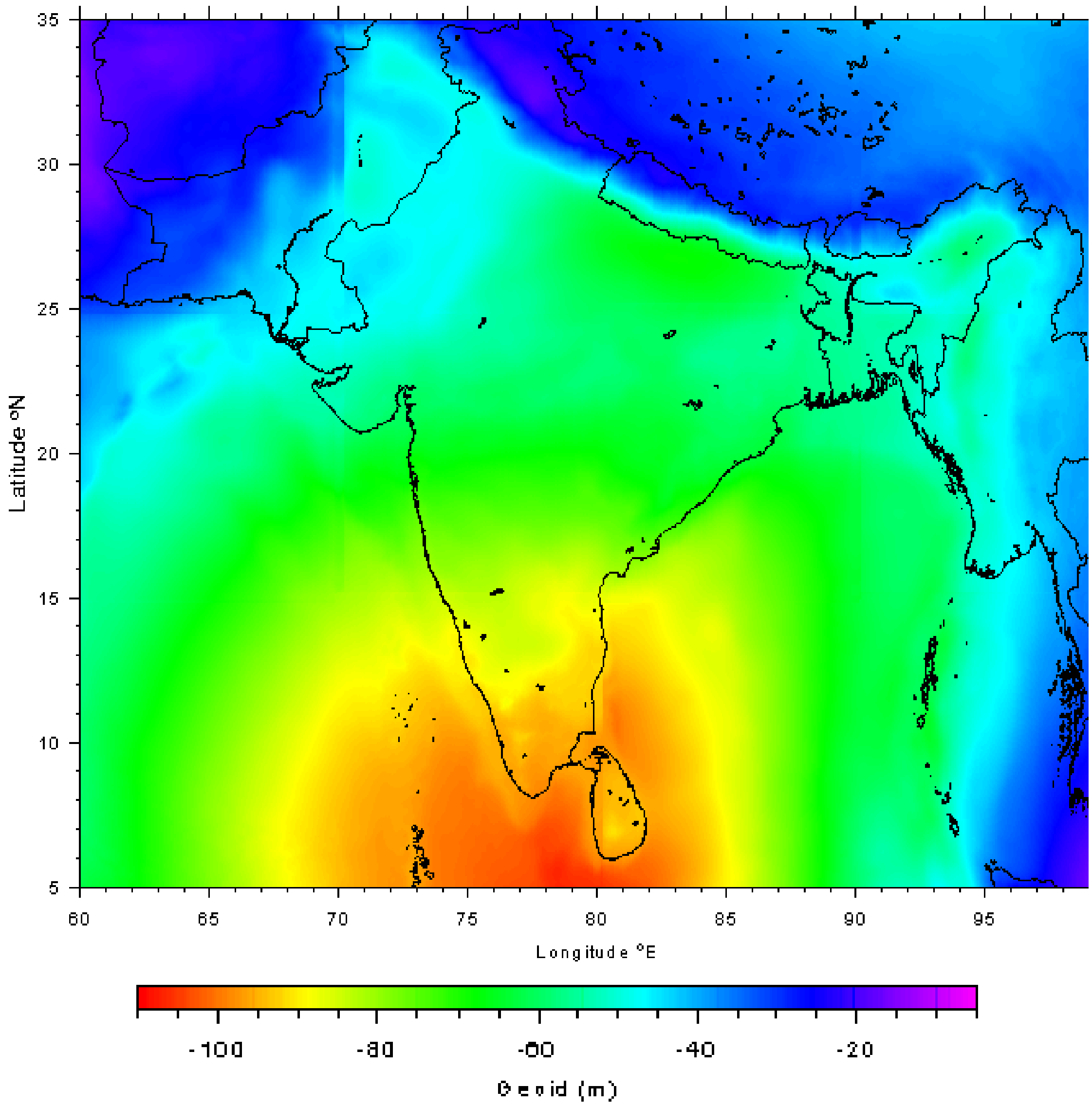

Figure 1: Geoid variation over Indian region (EGM2008).

Earth Geoid Model 2008 is used which has 5km X 5km resolution with few centimeters accuracy. This model contains fully-normalized, unit-less, spherical harmonic coefficients of the Earth's gravitational potential and their associated (calibrated) error (standard deviation). The scaling parameters (GM, a) associated with this mode have the following numerical values:

$GM = 3986004.415 \times 10^8 m^3 s^{-2}$

a=6378136.3m

Initial sites are finalized by considering different conditions e.g. geoid gradient and the distance between cross over point and tide gauge. If the distance between tide gauge to crossover point is less, then the site is considered as good calibration site, because for absolute calibration wind and pressure corrections should be similar at both places so that these corrections can be avoided. Also the geoid gradient at crossover point should be minimum. If it is zero, then the geoid gradient corrections are not required for the absolute calibration purpose.

The detailed analysis on selection of calibration sites and analysis of SOI tide gauge data for absolute calibration of satellite altimeter is reported in 'SAC/EPSA/MPSG/CVD/CAL-VAL/02/12'. In this work total seven sites of tide gauge observations were procured from SOI for a limited period and they have accuracy upto 0.5cm. With this data analysis we confined to four locations for exploring the possibility to develop them for altimeter calibration site. **Table 3** gives the location details with respect to SARAL/AltiKa pass.

Table 3: Site name with distance from SARAL/AltiKa pass

Sr. No.	Name	Distance in km (AltiKa pass)
1	Bangaram	2 (single pass)
2	Kanyakumari	5 (crossover pass)
3	Machilipatnam	9 (crossover pass)
4	Portblair	4 (single pass)

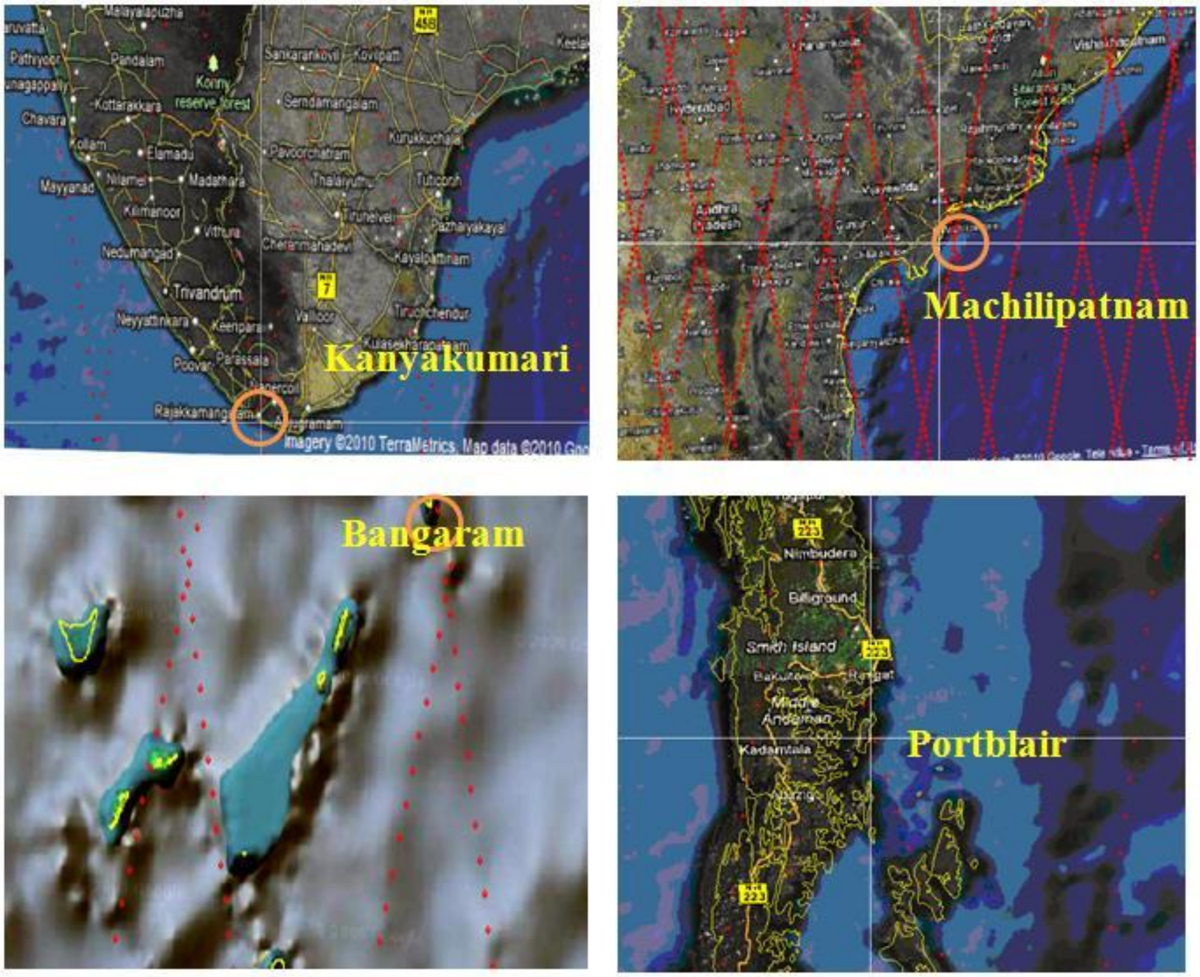

Figure 2: The four sites location along with SARAL/AltiKa ground track.

The selected four locations along with SARAL/AltiKa ground tracks, dotted lines, are shown in **Figure 2**. We used down-looking aerial microwave radar gauge for sea level measurements. The radar tide gauge possesses the following specification **(Table 4)**:

Table 4: The technical specifications of down-looking radar tide gauge.

Sea level sensor	**Down-looking microwave radar**
Transmission frequency	24GHz (wavelength 1.25cm)
Accuracy	Better than □1cm
Averaging time	30 seconds (filters out ripples and wind waves)
Data acquisition interval	5 minutes
Data storage medium/capacity	SD card / 1GB
Data uploading interval	5 minutes (to internet)
Time stamp	Internet synchronized time

Typical installation scheme of radar gauge with 12volts battery and solar panel is shown in **Figure 3**.

Figure3: Typical installed radar gauge at Kavaratti site

5.1. Tide gauge time series measurements on sea level

One advantage of using tide gauge data as the in-situ measurements is that the capability of SSH monitoring in a continuous sense. It provides a continuous and long-term time series to be compared with the measurements from the altimeter. This is favorable for the determination of bias drift becaues with longer time series it is more likely that a pricese drift estimation will be obtained. The primary limitations include that tide gauge calibration of altimeter does not have absolute bias information unless the true datum is known. In addition, the estimated drift from tide gauges represents the total drift, including drifts from instrument and individual media and geophysical corrections. The other technical issues are: (1) height conversion, (2) datum transformation, (3) geoid gradient.

A tide gauge measures the water level changes with respect to a local vertical benchmark. The relation from tide gauge to benchmark is often maintained by spirit leveling exercise and the sea level changes measured by the tide gauge consequently refers to the same vertical datum to which the benckmark refers. The other disadvantage of using tide gauges in altimeter calibration is that the gauges might not be on, or within 1-2 km of the altimeter sub-satellite points. Although data from some of the tide gauges can be tracked back to several decades or longer, their original purpose was not for altimeter calibration and they are not likely to be near the altimeter sub-satellite points either. Also, the water vapor measurements from the on-board radiometer are often corrupted by land contamination in the coastal regions, and altimeter SSH measurements can be problematic near the coastal region. As a result, the tide gauge SSH measurements are required to be extrapolated to where the good altimeter SSH measurements are.

The sea level measurements from the four stations as mentioned in **Table 3** are shown below. These measurements are with respect to local datum (lowest low water level). The time series observations of sea level at Port Blair tide gauge station is shown in **Figure 4,** and **Figure 4a** shows one day observation. The diurnal and semi-diurnal cycles are well depicted in the measurements. The other stations tide gauge observations are shown in **Figures 5, 6, 7** and **8**.

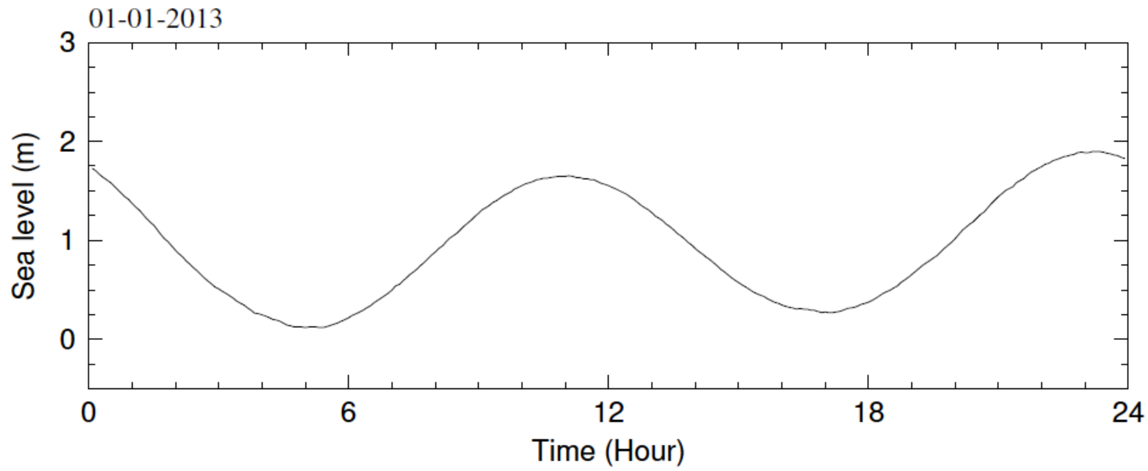

Figure 4a: One day tidal observation from Port Blair tide gauge station.

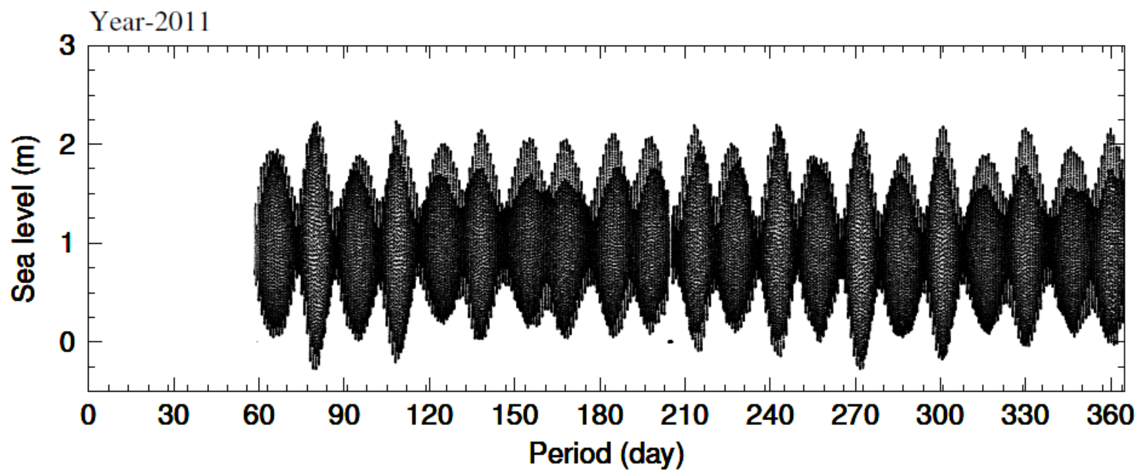

Figure 4b: Time series tidal observations from Port Blair tide gauge for the year 2011

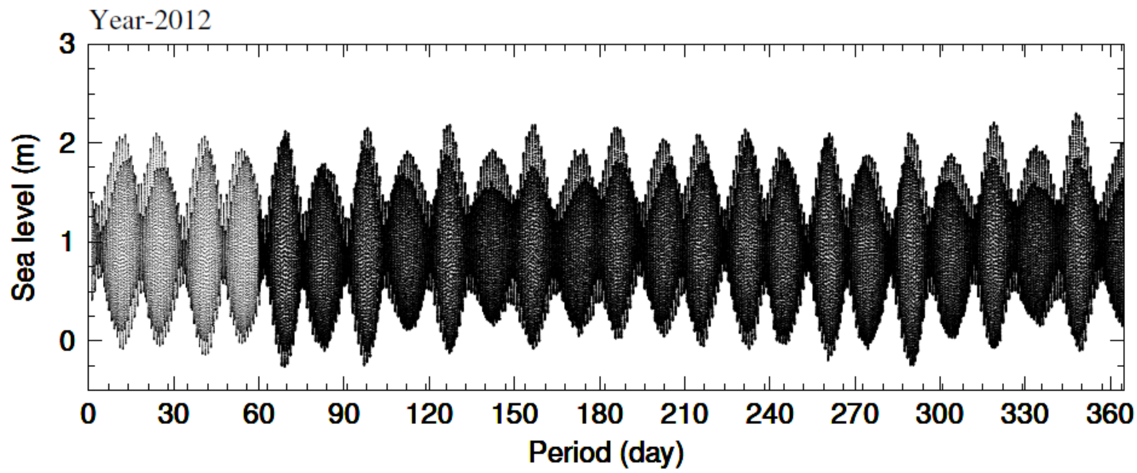

Figure 4c: Time series tidal observations from Port Blair tide gauge for the year 2012

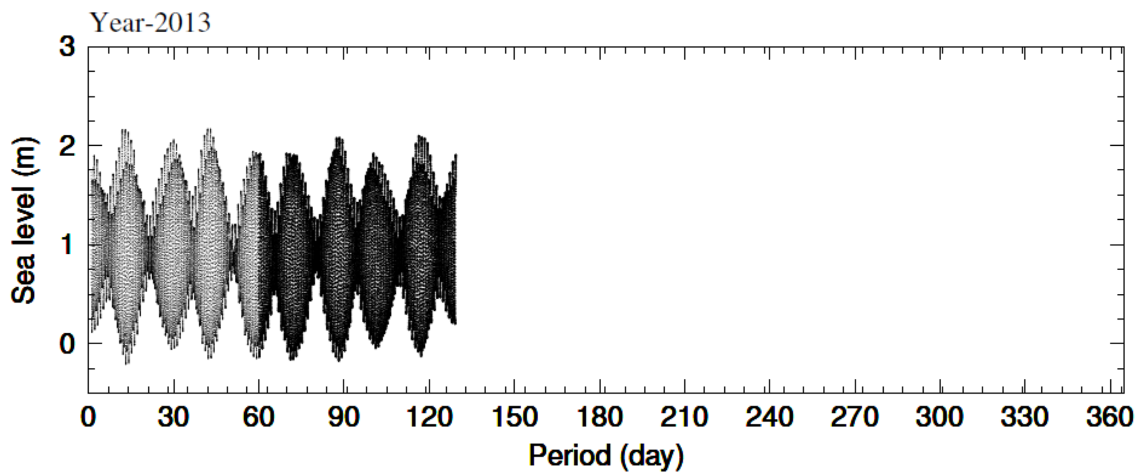

Figure 4d: Time series tidal observations from Port Blair tide gauge for the year 2013

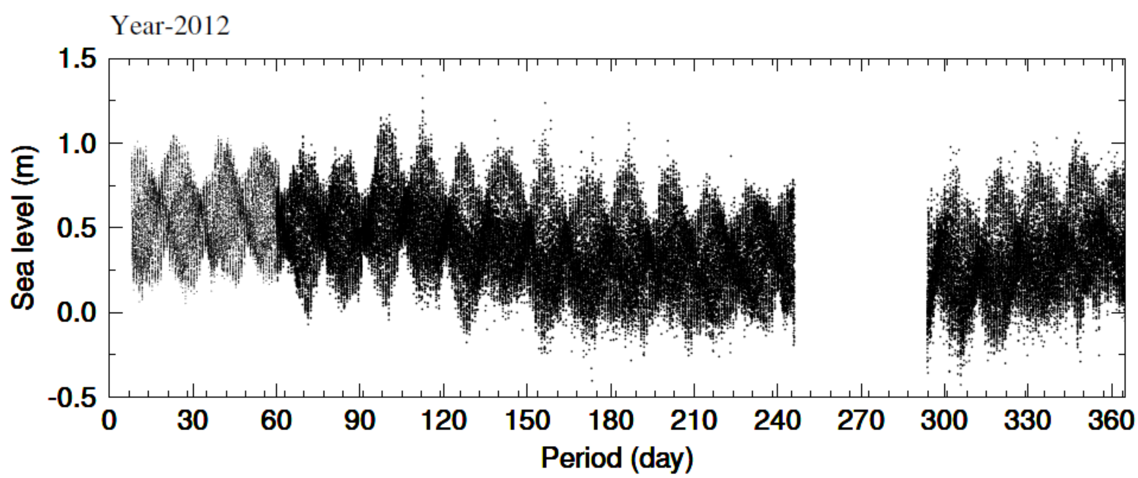

Figure 5a: Time series tidal observations from Kanyakumari tide gauge station for the year 2012.

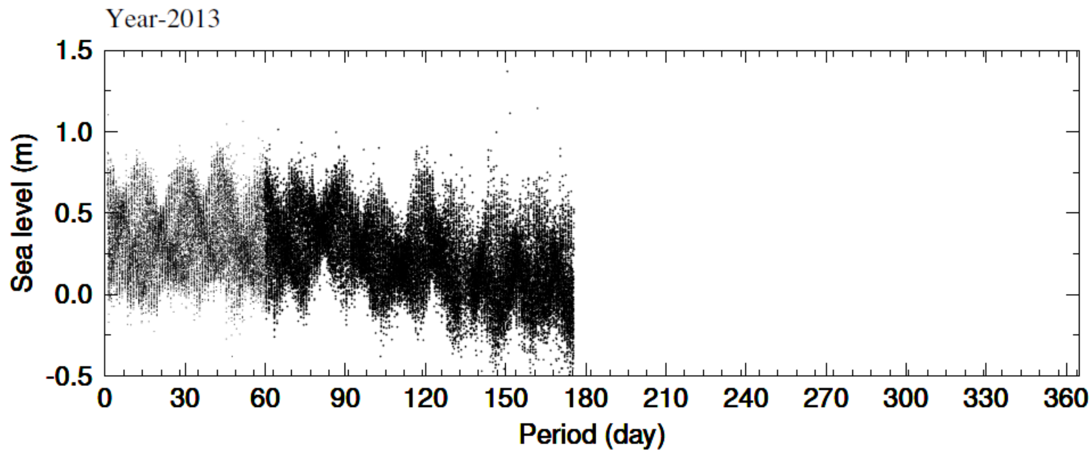

Figure 5b: Time series tidal observations from KanyaKumari tide gauge station for the year 2013.

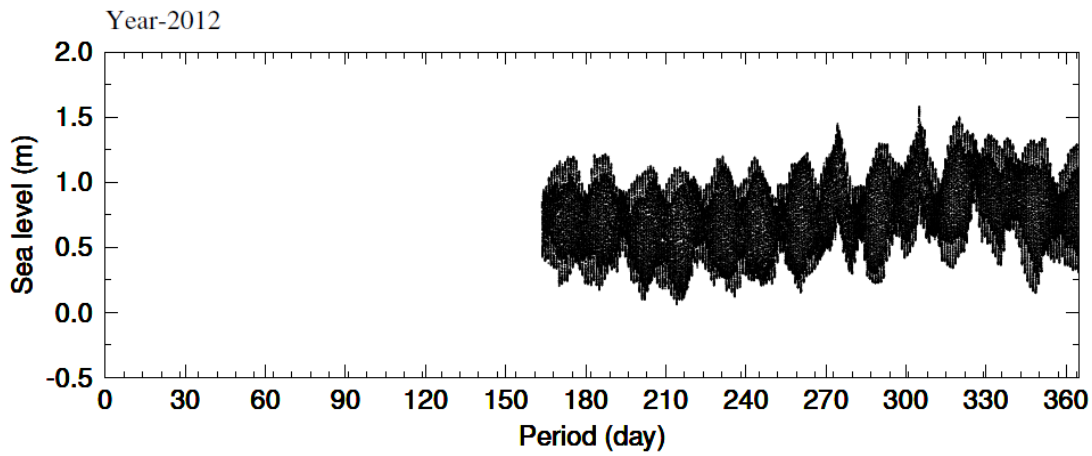

Figure 6a: Time series tidal observations from Machlipatnam tide gauge station for the year 2012.

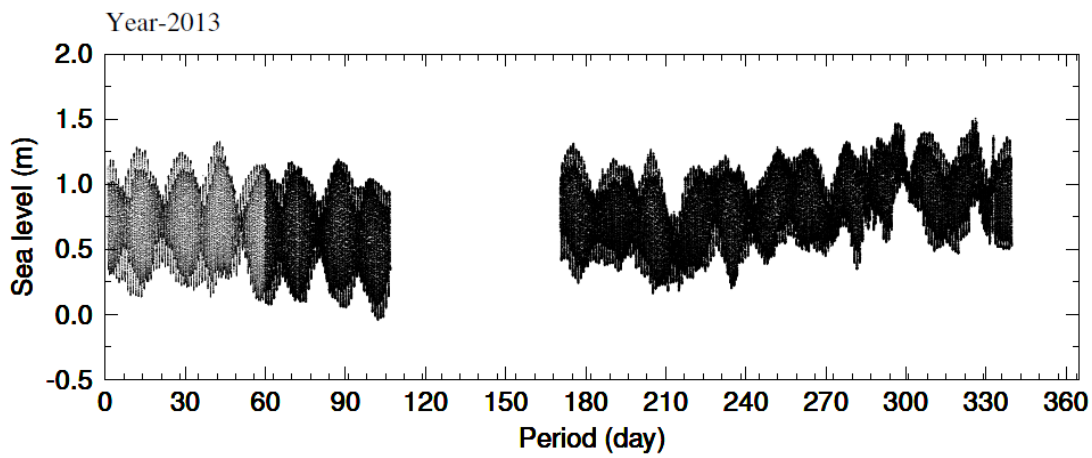

Figure 6b: Time series tidal observations from Machlipatnam tide gauge station for the year 2013.

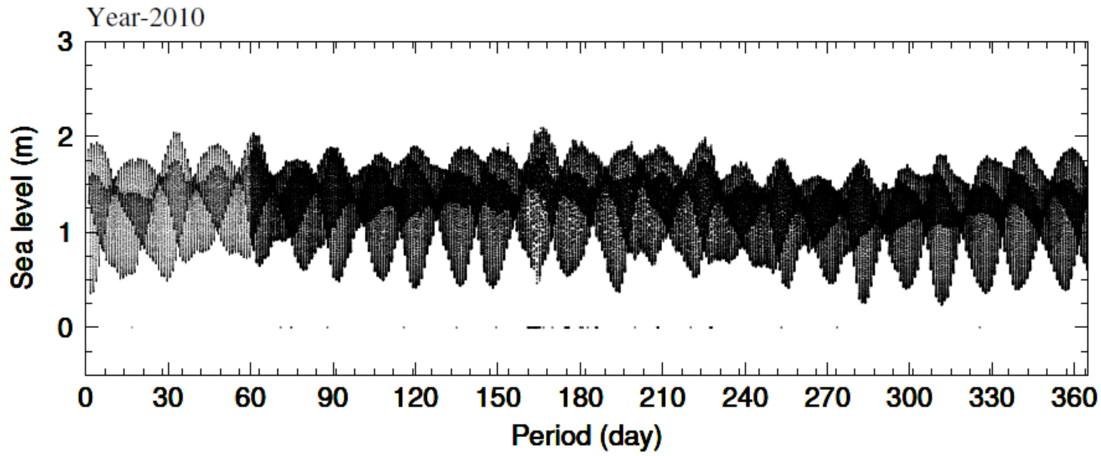

Figure 7a: Time series tidal observations from Kavaratti main jetty (TG1) tide gauge station for the year 2010.

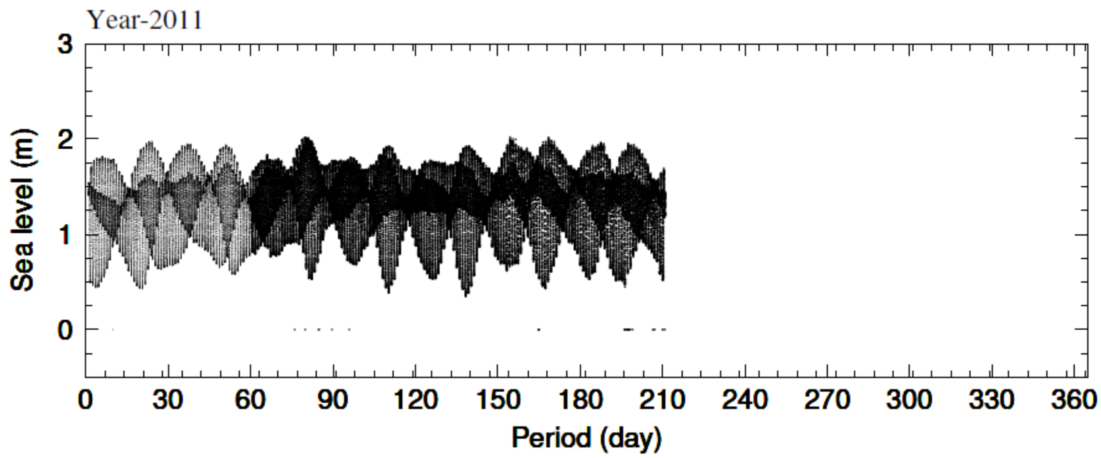

Figure 7b: Time series tidal observations from Kavaratti main jetty (TG1) tide gauge station for the year 2011.

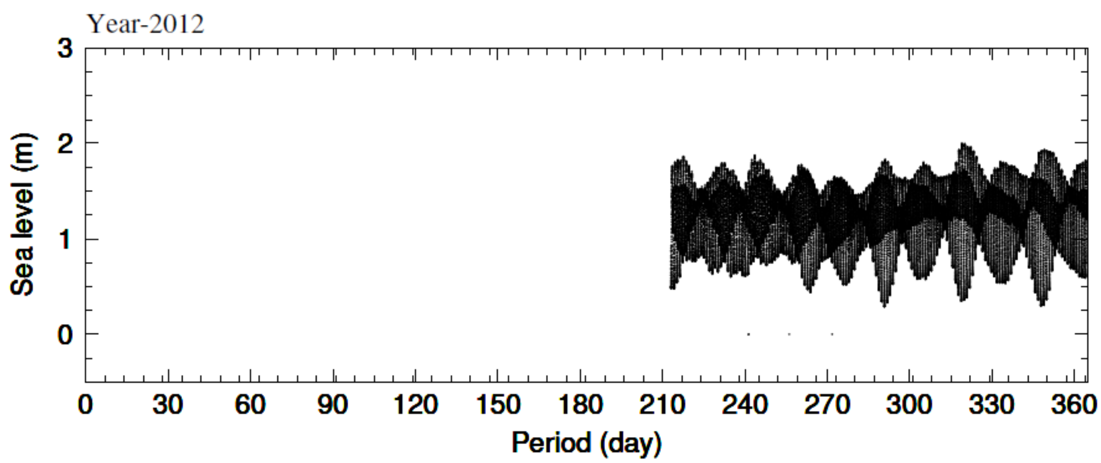

Figure 7c: Time series tidal observations from Kavaratti main jetty (TG1) tide gauge station for the year 2012.

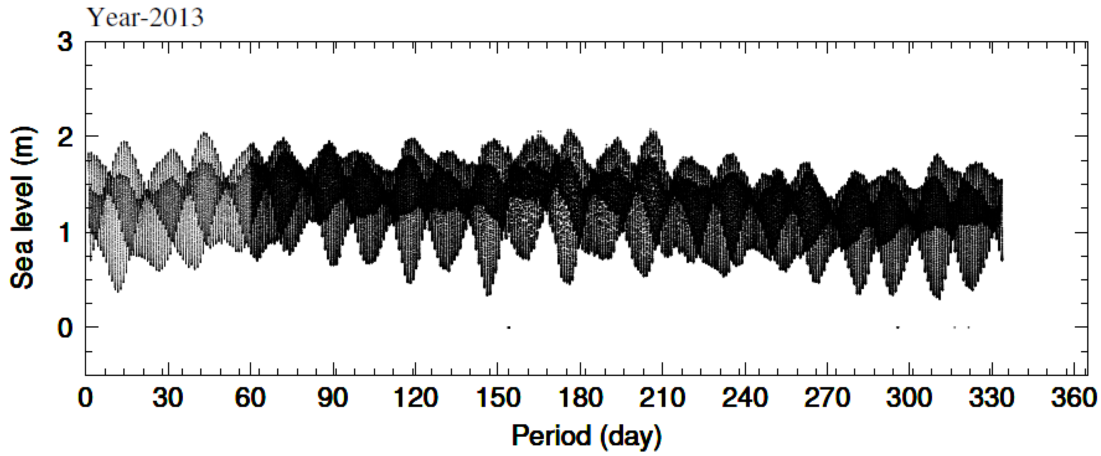

Figure 7d: Time series tidal observations from Kavaratti main jetty (TG1) tide gauge station for the year 2013.

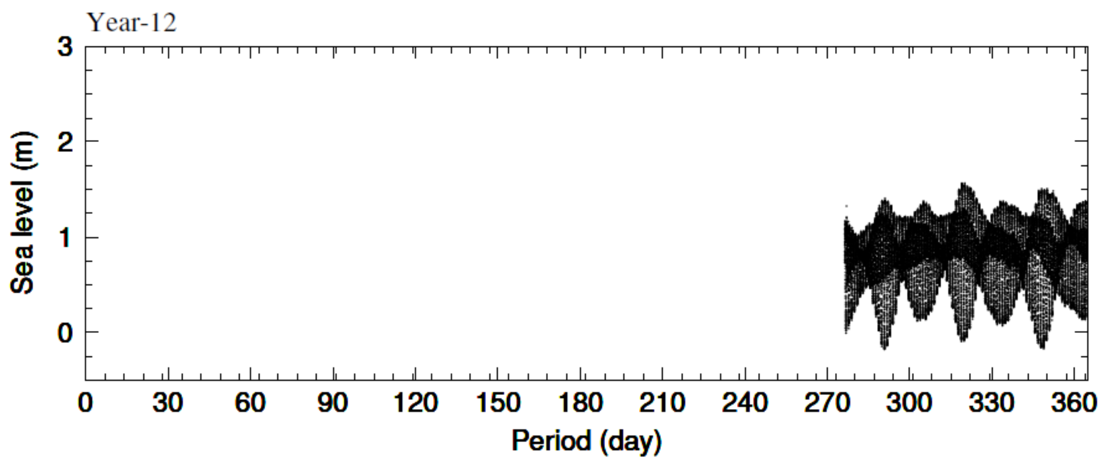

Figure 8a: Time series tidal observations from Kavaratti NIOT jetty (TG2) tide gauge station for the year 2012.

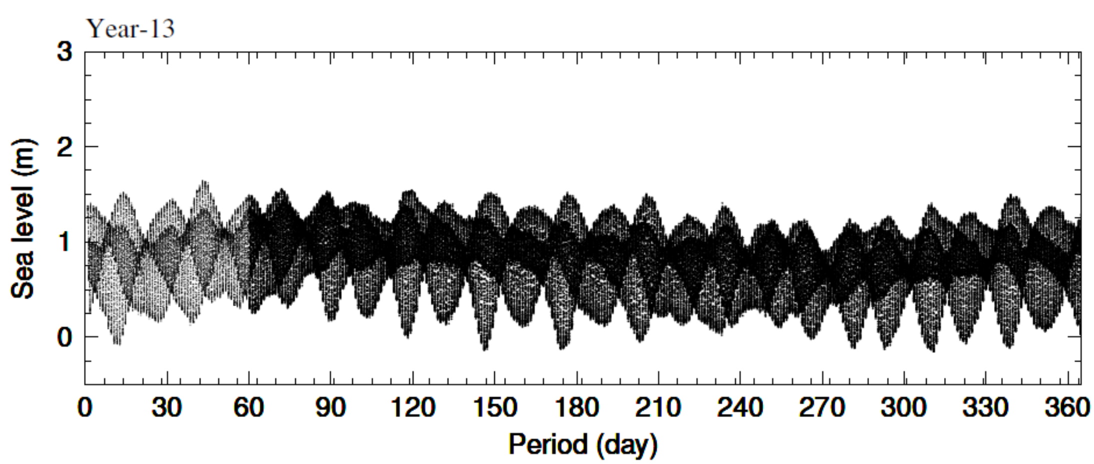

Figure 8b: Time series tidal observations from Kavaratti NIOT jetty (TG2) tide gauge station for the year 2013.

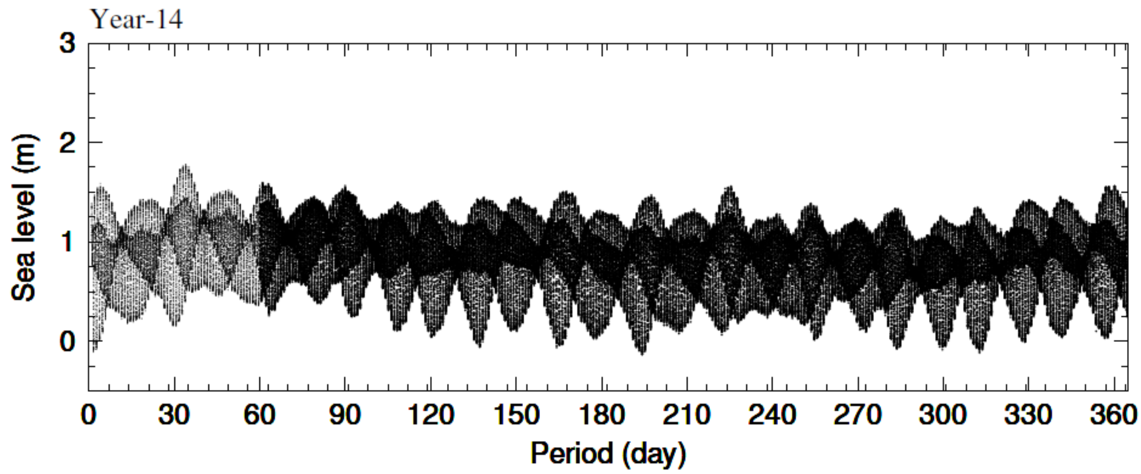

Figure 8c: Time series tidal observations from Kavaratti NIOT jetty (TG2) tide gauge station for the year 2014.

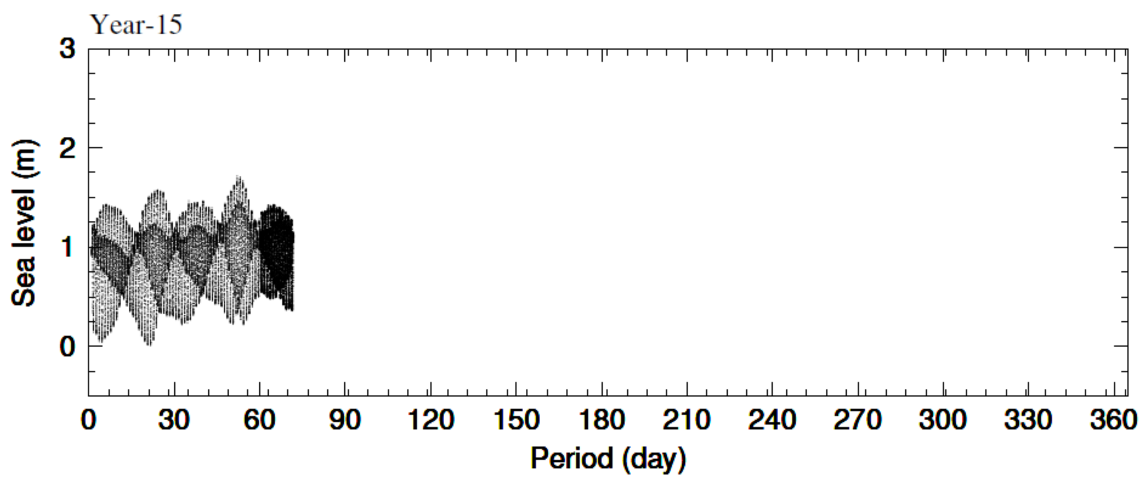

Figure 8d: Time series tidal observations from Kavaratti NIOT jetty (TG2) tide gauge station for the year 2015.

The common period of observations from TG1 and TG2 are analysed (3rd October 2012 – 28th September 2013) in order to see the consistency of tidal measurements and also make use of TG1 as redundant tidal station at Kavaratti. The mean range value of TG1 is 2.778 m and TG2 is 4.511 m during the period. Daily mean for each tide gauges are calculated for the same period and differences of the daily mean are used to estimate the mean range bias (1.701 m) and standard deviation (σ = 29.6 mm). For some of the days, the range value from both the tide gauges are removed (which are doubtful during our visual inspection) using 3σ criteria on the range bias (i.e., 1.701±0.089 m). These results confirm consistency of TG1 and TG2 stations. We used TG2 station observations for further analysis to calculate the absolute SSH bias of altimeter since the TG1 station is within the lagoon region which needs to be investigated further for lagoon effect on tidal observations.

5.2. Qualifying Kavaratti site for calibration

The part of Kavaratti Island in Lakshadweep Sea is shown in **Figure 9**. This figure is generated using Google Earth software, the details of this image and its related activities are explained in later section. This site has two radar tide gauges separated by ~1.5km apart, later on one permanent GPS receiver is installed. The tide gauge stations are marked by TG1 (which is main jetty tide gauge), TG2 (NIOT jetty tide gauge), bottom pressure recorder (BPR), GPS1 (main jetty GPS receiver) and GPS2 (NIOT jetty GPS receiver). The close look of radar tide gauge and BPR in installed conditions is shown in **Figure 10**.

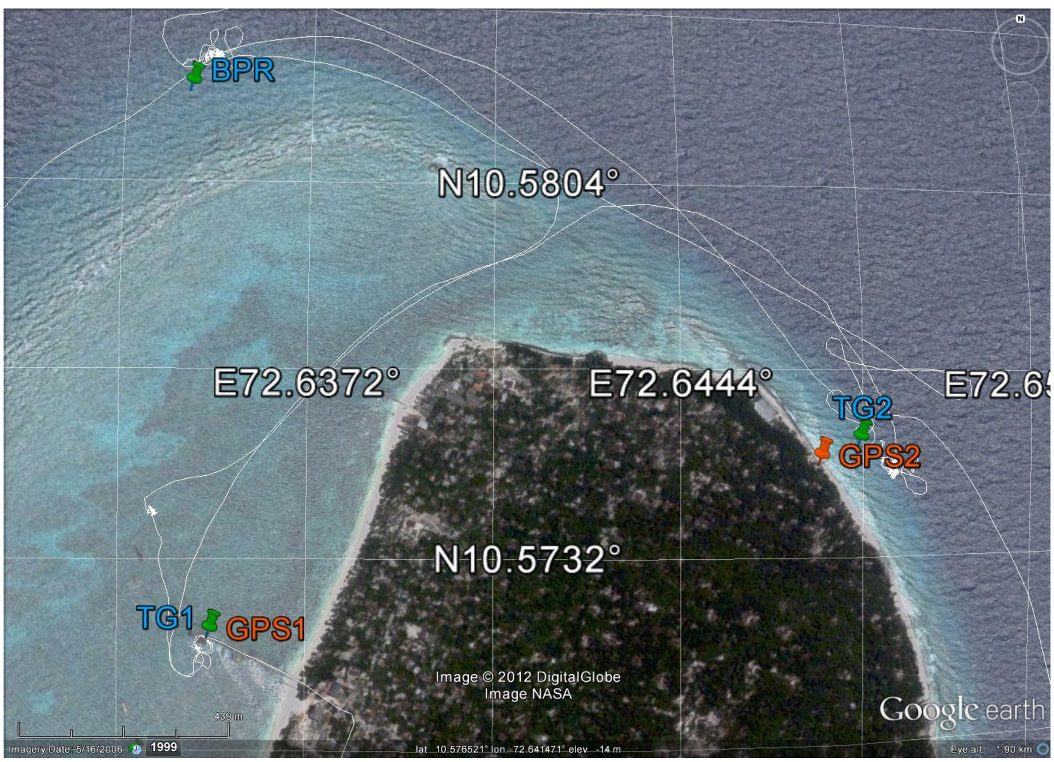

Figure 9: Positions of the instruments at main Jetty (GPS1 and TG1), at NIOT Jetty (GPS2 and TG2) and at offshore BPR mooring. The white track displays the temporal positions of the GPS buoy.

Figure 10: Downlooking aerial microwave radar gauge at NIOT jetty (right panel), the bottom pressure recorder at deployed condition at off lagoon Kavaratti (left panel).

The AltiKa waveforms are analysed to see the impact of Island and coast on radar echos over Kavaratti site. In order to assure the normal ocean waveform nature in its received radar ground signals, the reflected waveforms from the sea surface over Kavaratti region is shown in **Figure 11**. The panels (D) and (E) are the waveforms which are received from the closest approach of SARAL/AltiKa to the Island. We have analyzed 11 cycles of the waveforms for the pass #539 and found a similar nature (the leading edge of the waveform starts at gate number 52; the waveform index for most of the time exceeds 100; very smooth trailing edge of the waveform) in all the cycles. This figure confirms that the waveforms are free from Island contamination and thus should lead to accurate SSH estimation. The result of Bonnefond et al. (2013) also confirms significant improvement in inferring waveforms up to ~3 km from the coast, whereas, Envisat could not exploit any information within 7km off the coast.

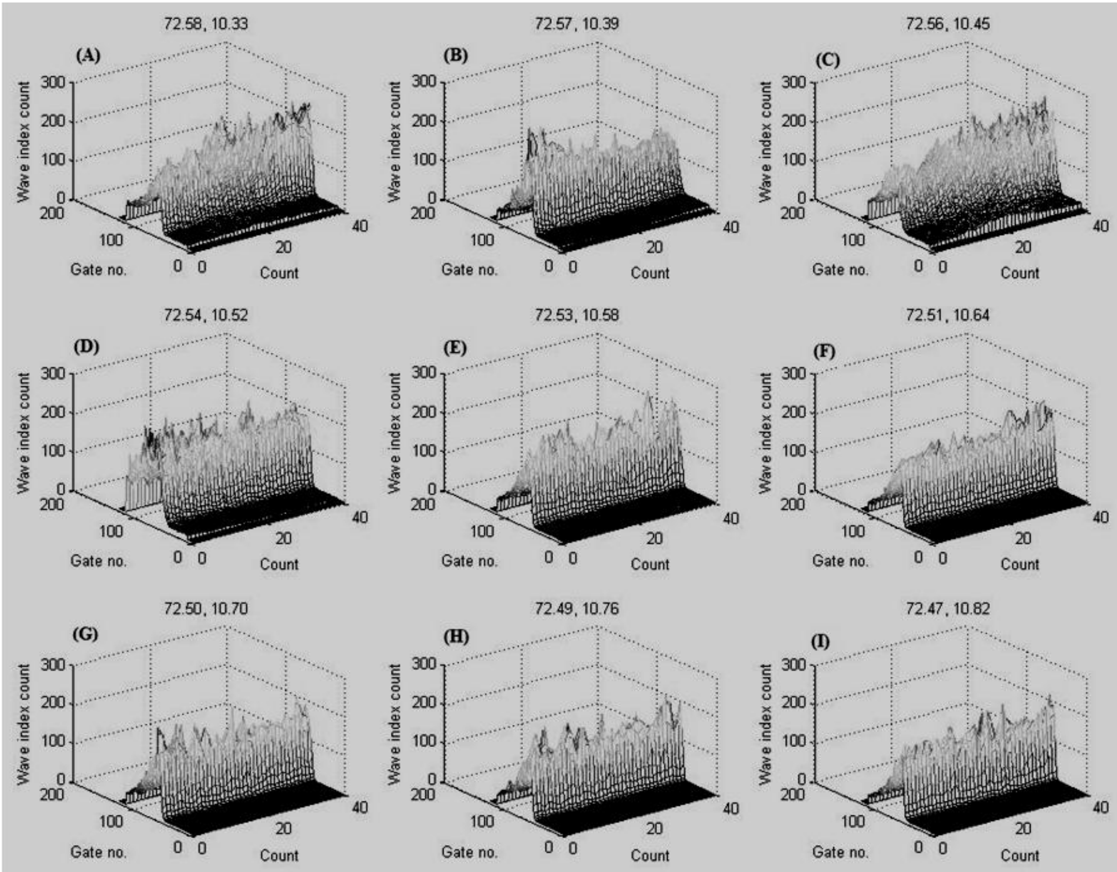

Figure 11: The 40Hz waveforms received by AltiKa from sea surface in and around Kavaratti tide gauge station.

The differential tidal signal was analyzed from the results of set of global and regional tide models over Kavaratti (FES2004, FES2012, GOT4.7 and TPXO7.2) and found no significant difference both in magnitude and in phase (~2 mm and ~1^{o}) for a distance of 12 km (results are not shown here) or the differences are within the model inaccuracy. We plan to setup a dedicated local high resolution model in order to resolve some possible tidal differences due to higher harmonics and estimate sea level differences due to wind and atmospheric pressure. The CNES-CLS09 mean dynamic topography (v1.1 release, Rio et al., 2009) having 1/4^{o} spatial resolution was used to find its impact on SSH. This data set was interpolated to 1km grid interval using 2D spline technique. The difference in interpolated mean dynamic topography between the tide gauge locations (TG1/TG2) and crossover point is found to be 1.4 mm/1.1 mm.

5.3. Kavaratti experiment for geodetic reference

Sea surface height is defined as the "**height of sea surface from Earth's reference ellipsoid**". Hence the basic measurements are to be referenced with respect to the common reference ellipsoid for a specific altimeter mission. An intensive experiment was carried out to address the derivation of SSH from the installed radar gauges at site during first half of October 2012. In this experiment two Trimble 5700 GPS receivers, one bottom pressure recorder and one GPS buoy is used. **Figure 9** shows part of Kavaratti Island with tagging of tide gauges (TG1, TG2), bottom pressure recorder (BPR) and the white lines represent the track of GPS buoy on 3rd October 2012. The TG1 is located inside the lagoon region of Kavaratti where water depth typically of 3 to 4m, the TG2 is located relatively in open ocean where water depth is quite deep. Since the NIOT jetty has discontinued concrete platform, we installed the GPS reference station on main land location. The details and duration of experiment is listed in **Table 5**. In order to estabilish commanality of referencing, GPS monuments are created at TG1 station and TG2 station (during this experiment, a metal screw on concrete base is fixed). Through sprit leveling and calibrated scale, the height levels are measured between the antenna phase centre and GPS manument. Further, the height level between GPS manument and radar tide gauge is measured. This leveling procedure, using spirit level and calibrated scale, has 1mm uncertainty. Three such measurements are made by three individuals (inorder to reduce the manual error of measurement) and average value is taken as standard. This leveling exercise gets repeated during Kavaratti site visit for other project assignments. Incidently the TG2 tide gauge is installed during this experimental time frame. The BPR is installed at off lagoon area which has an accuracy of ±0.03% of true water depth (the average water depth at the point of deployment is ~7m and hence the BPR measurement accuracy during this campaign is ±0.21cm). The BPR is operated at 1minute sampling interval. **Figure 10** shows the actual field photo of TG1 and BPR at Kavaratti site. Both the radar tide gauges are programmed for sampling at 5min interval and its measurement has an accuracy of ±1cm. **Table 6** gives the details of sampling interval of observations programmed during this experiment.

Table 5: List of events with time on Kavaratti experiment.

Time (UT)	Event
02/10/2012	
5h16-5h35 : Start of the GPSB on the ground of the Jetty (9 GPS / 5 GLONASS) 5h35-5h49 : GPSB deployed at sea and readings of the lateral rules 5h49-5h56: GPSB pulled to the NIO radar location 5h56-6h20: GPSB under NIO radar (perturbation of GPS1 due to drilling of the screw 6h02 to 6h11) 6h20-7h10: GPSB is pulled to a dead weights (10°34.448N/72°38.046E) inside lagoon. 7h10-21h52: GPSB stayed anchored inside the lagoon 21h57-23h32 : Transit of GPS Buoy to cross-over point	
03/10/2012	
23h35-02h23 : Session under the J2 X-Over point 2h26-4h00: Transit back to Kavaratti 4h00-8h26: GPSB above BPR 8h48-23h59: GPSB at NIOT Jetty	
04/10/2012	
0h0 – 9h20 : GPSB at NIOT Jetty	
08/10/2012	
-8h30 : BPR removed from deployed locations -10h30: GPS reference stations are removed from main and NIOT jetty	

Table 6: List of equipments and sampling interval

Equipment	Sampling interval
Radar tide gauge	5 minutes
Bottom pressure recorder	1 minute
GPS reference station	1 seconds
GPS buoy	1 seconds

We occupied the two tide gauge stations with Trimble 5700 GPS receiver so that the tide gauges can be levelled with respect to a benchmark, which is placed below the GPS antenna. The setup of GPS receiver is given in **Figure 12** with geometrical details. The reference station GPS receivers were operated at 1Hz sampling interval continuously for 6 days. The GPS data sets were processed with GAMIT software for deriving the geo-coordinates of benchmark. The individual day GPS solutions from both the stations are given below. The average value is taken for referencing the tide gauge inorder to estimation SSH using tide gauge observations. The summary of the levelling exercise is shown in **Figure 13**.

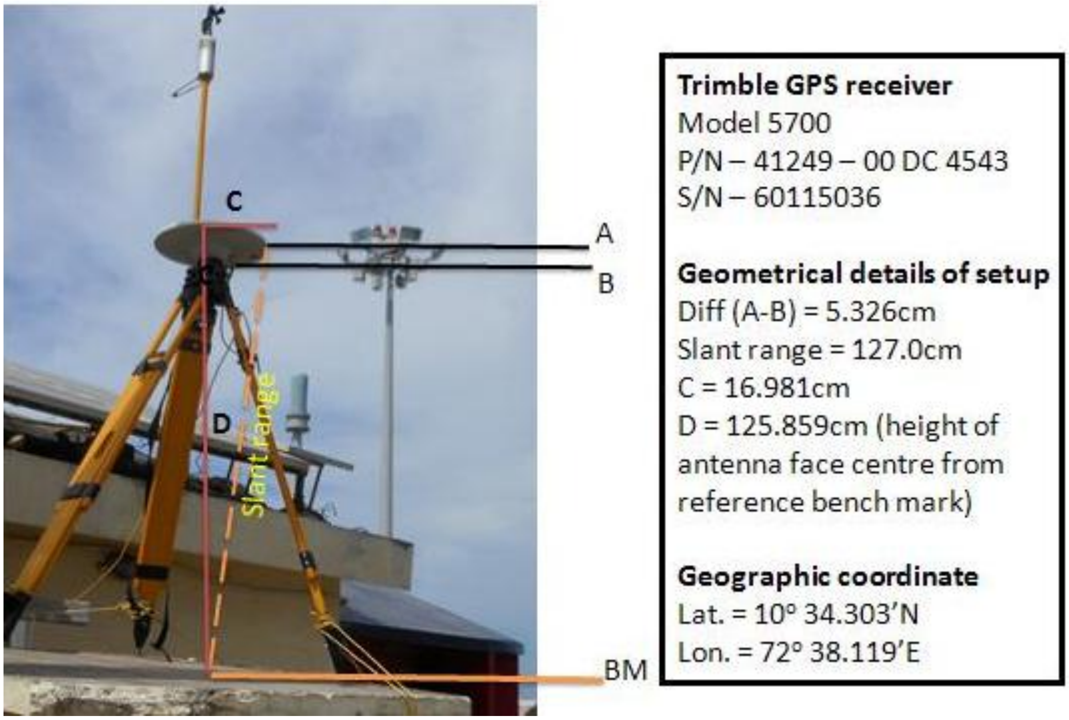

Figure 12a: GPS reference station at TG1 during levelling experiment

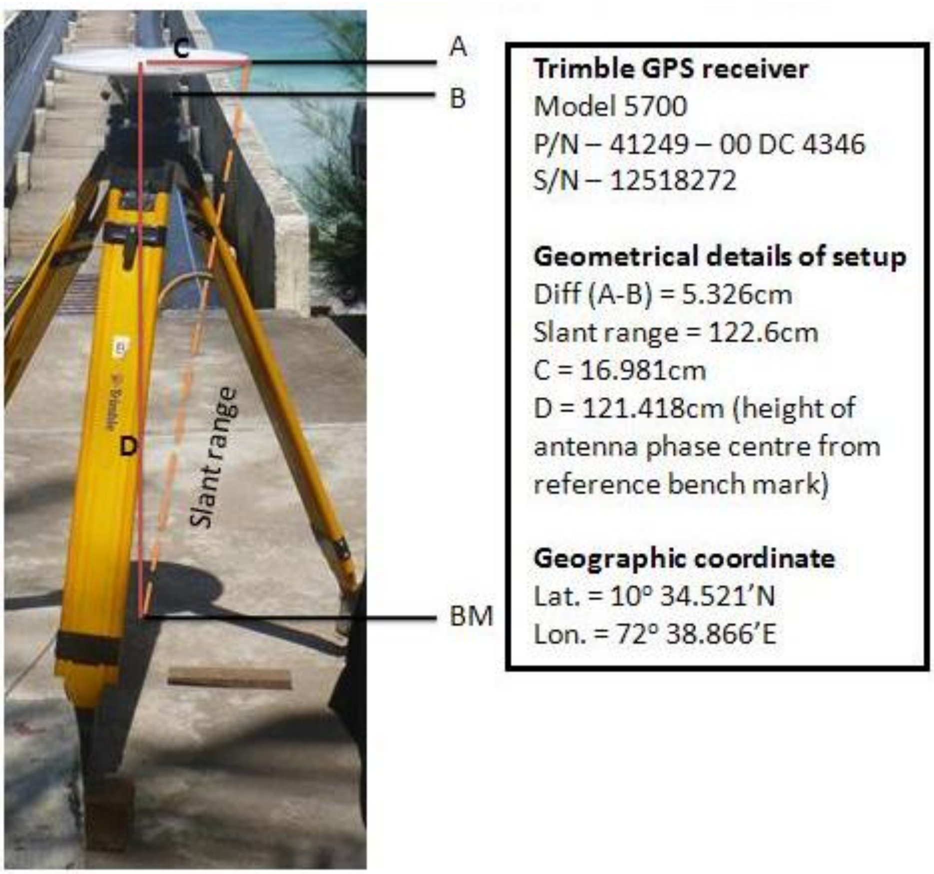

Figure 12b: GPS reference station at TG2 during levelling experiment

GPS1-BM at TG1 solution

http://www.geod.nrcan.gc.ca/products-produits/ppp_f.php

ARP ⌖ BM = 1.197m

02/10/2012 : gps1276d ~~~~~~
Latitude (ITRF08): 10 34 18.1498 (dms) / 0.003 (m)
Longitude (ITRF08): 72 38 07.3128 (dms) / 0.012 (m)
Hauteur ellipsoïdale (ITRF08): -88.216 (m) / 0.018 (m)
03/10/2012 : gps1277d ~~~~~~
Latitude (ITRF08): 10 34 18.1498 (dms) / 0.002 (m)
Longitude (ITRF08): 72 38 07.3130 (dms) / 0.009 (m)
Hauteur ellipsoïdale (ITRF08): -88.230 (m) / 0.015 (m)
04/10/2012 : gps1278d ~~~~~~
Latitude (ITRF08): 10 34 18.1497 (dms) / 0.002 (m)
Longitude (ITRF08): 72 38 07.3129 (dms) / 0.008 (m)
Hauteur ellipsoïdale (ITRF08): -88.211 (m) / 0.015 (m)
05/10/2012 : gps1279d ~~~~~~
Latitude (ITRF08): 10 34 18.1497 (dms) / 0.002 (m)
Longitude (ITRF08): 72 38 07.3130 (dms) / 0.008 (m)
Hauteur ellipsoïdale (ITRF08): -88.228 (m) / 0.014 (m)
06/10/2012 : gps1280d ~~~~~~
Latitude (ITRF08): 10 34 18.1497 (dms) / 0.002 (m)
Longitude (ITRF08): 72 38 07.3129 (dms) / 0.007 (m)
Hauteur ellipsoïdale (ITRF08): -88.227 (m) / 0.014 (m)
07/10/2012 : gps1281d ~~~~~~
Latitude (ITRF08): 10 34 18.1498 (dms) / 0.002 (m)
Longitude (ITRF08): 72 38 07.3128 (dms) / 0.007 (m)
Hauteur ellipsoïdale (ITRF08): -88.227 (m) / 0.014 (m)
08/10/2012 : gps1282d ~~~~~~
Latitude (ITRF08): 10 34 18.1499 (dms) / 0.005 (m)
Longitude (ITRF08): 72 38 07.3128 (dms) / 0.015 (m)
Hauteur ellipsoïdale (ITRF08): -88.231 (m) / 0.033 (m)

02/10/2012	**-88.216**
03/10/2012	**-88.230**
04/10/2012	**-88.211**
05/10/2012	**-88.228**
06/10/2012	**-88.227**
07/10/2012	**-88.227**
~~08/10/2012~~	~~**-88.231**~~
MEAN	**-88.2232 +/- 0.008 m**

GPS2-BM at TG2 solution

ARP → BM = 1.152m

02/10/2012 : gps2276d ~~~~~~
Latitude (ITRF08): 10 34 29.7661 (dms) / 0.006 (m)
Longitude (ITRF08): 72 38 49.3870 (dms) / 0.026 (m)
Hauteur ellipsoïdale (ITRF08): -88.104 (m) / 0.041 (m)
03/10/2012 : gps2277d ~~~~~~
Latitude (ITRF08): 10 34 29.7660 (dms) / 0.004 (m)
Longitude (ITRF08): 72 38 49.3875 (dms) / 0.019 (m)
Hauteur ellipsoïdale (ITRF08): -88.136 (m) / 0.026 (m)
04/10/2012 : gps2278d ~~~~~~
Latitude (ITRF08): 10 34 29.7660 (dms) / 0.004 (m)
Longitude (ITRF08): 72 38 49.3872 (dms) / 0.018 (m)
Hauteur ellipsoïdale (ITRF08): -88.128 (m) / 0.027 (m)
05/10/2012 : gps2279d ~~~~~~
Latitude (ITRF08): 10 34 29.7660 (dms) / 0.004 (m)
Longitude (ITRF08): 72 38 49.3877 (dms) / 0.017 (m)
Hauteur ellipsoïdale (ITRF08): -88.136 (m) / 0.026 (m)
06/10/2012 : gps2280d ~~~~~~
Latitude (ITRF08): 10 34 29.7659 (dms) / 0.004 (m)
Longitude (ITRF08): 72 38 49.3876 (dms) / 0.018 (m)
Hauteur ellipsoïdale (ITRF08): -88.129 (m) / 0.026 (m)
07/10/2012 : gps2281d ~~~~~~
Latitude (ITRF08): 10 34 29.7660 (dms) / 0.004 (m)
Longitude (ITRF08): 72 38 49.3873 (dms) / 0.016 (m)
Hauteur ellipsoïdale (ITRF08): -88.125 (m) / 0.026 (m)
08/10/2012 : gps2282d ~~~~~~
Latitude (ITRF08): 10 34 29.7662 (dms) / 0.007 (m)
Longitude (ITRF08): 72 38 49.3873 (dms) / 0.028 (m)
Hauteur ellipsoïdale (ITRF08): -88.128 (m) / 0.055 (m)

~~02/10/2012~~	~~**-88,104**~~
03/10/2012	**-88,136**
04/10/2012	**-88,128**
05/10/2012	**-88,136**
06/10/2012	**-88,129**
07/10/2012	**-88,125**
~~08/10/2012~~	**-88,128**
MEAN	**-88.1303 +/- 0.005 m**

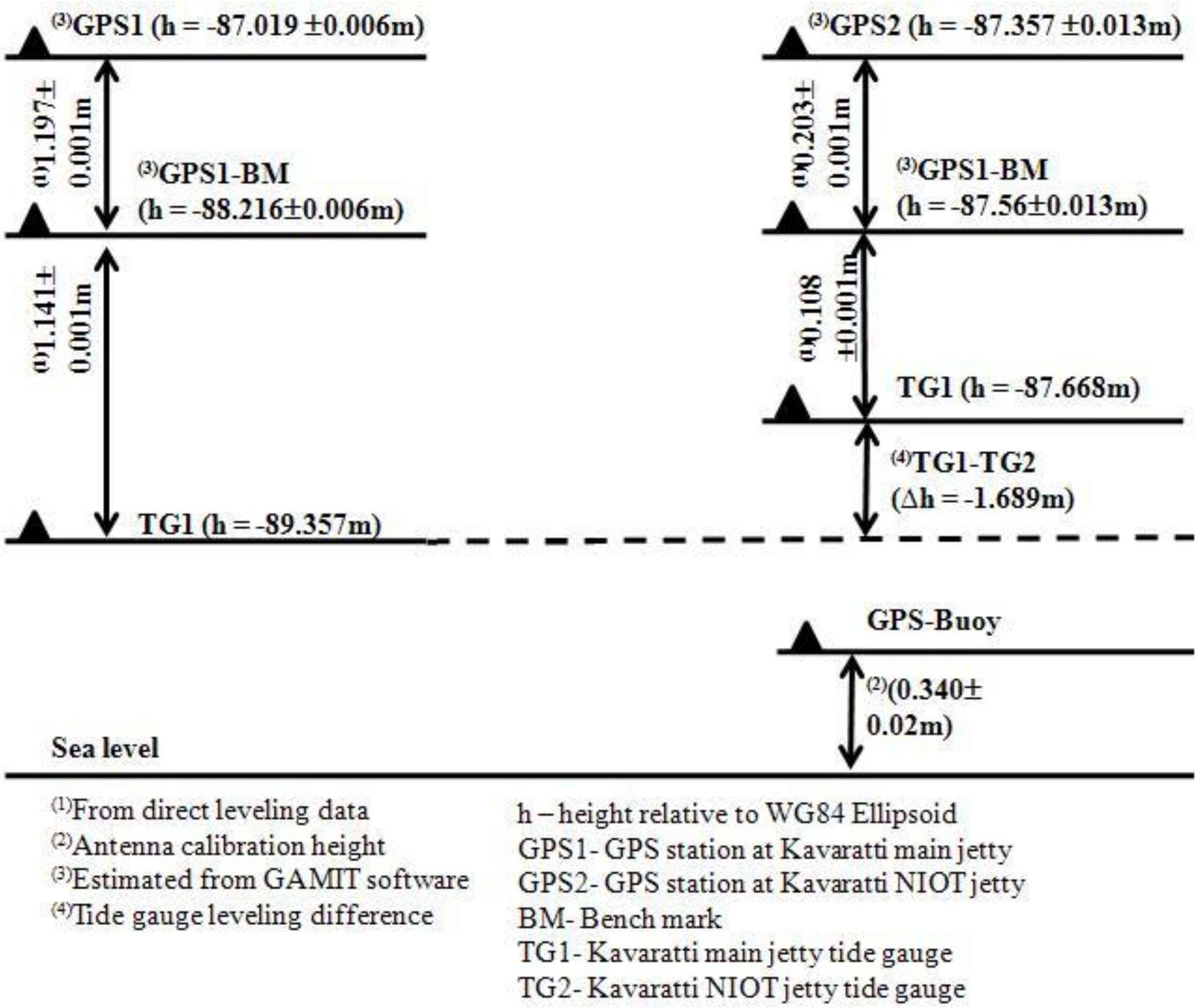

Figure 13: The summary of leveling experiment conducted in October 2012 at Kavaratti calibration site (This part of the world has negative geoid values).

Table 2: GPS marker heights and the offset correction for radar tide gauge through leveling experiment

Solution	GPS1 height (WGS84)	GPS2 height (WGS84)
GAMIT	-88.216±0.006 m	-87.560±0.013 m
	Offset correction	
TG1 tide gauge	TG2 tide gauge	GPS buoy
1.141±0.001[(1)]-0.02[(2)]+4.094[(3)] m	-0,108±0.001[(1)]-0.02[(2)]+5.360[(3)] m	0.304±0.02 m

[1]Through spirit leveling
[2]Correction for radar gauge reference estimated
[3]Sensor height with respect to chart datum for TG1 (4.094 m) and TG2 (5.360 m), estimated using tide table values available from SOI for this location
[4]GPS antenna calibration height

5.4. In-situ sea surface height and cross-verifications

5.4.1. From GPS buoy

The raw Topcon GPS buoy data sets along with Trimble GPS reference data sets are pre-processed using “GAMIT/TRACK” software and smoothed data sets are processed for “Kinematic solutions”. The GPS buoy is considered as rover and the main jetty GPS reference station as the master station. **Figure 14** shows the flow diagram of SSH derivation using GPS buoy. **Figure 15** shows the derived SSH along with tide gauge observations.

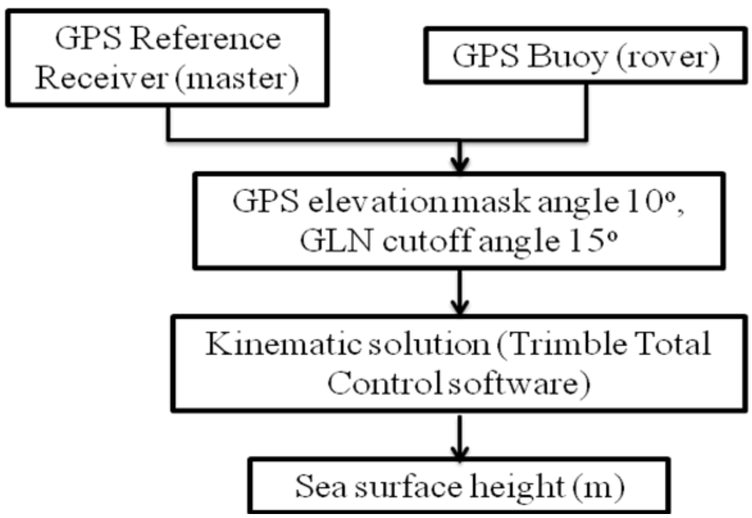

Figure 14: Flow diagram on derivation of SSH from GPS buoy.

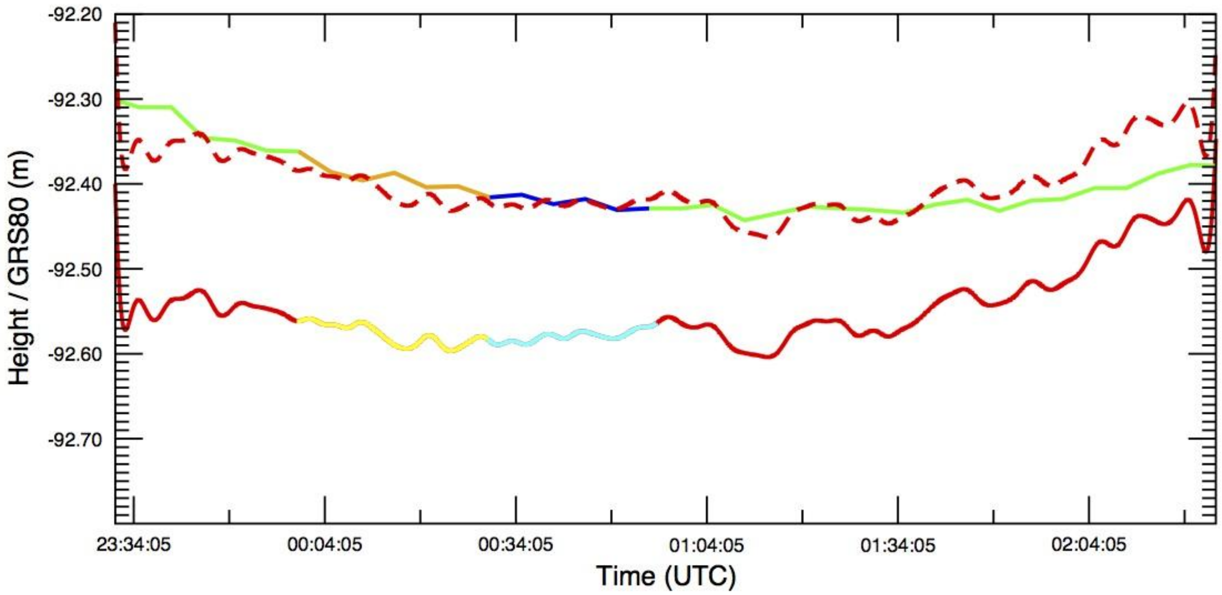

Figure 15a: Top for December 2012 and bottom for September 2013 experiments: GPS buoy solution from GPS (red at offshore location, TG1 tide gauge (light green) and TG2 (dark green). Orange and yellow lines correspond to tide gauges and GPS buoy data respectively selected from Table 4 criteria (for Jason-2 tracks). Dark blue and light blue lines correspond to tide gauge and GPS buoy data respectively selected from Table 4 criteria for (SARAL/AltiKa track). The dash red lines correspond to the GPS buoy solution corrected from EGM08 height differences between the GPS buoy location and the tide gauge location.

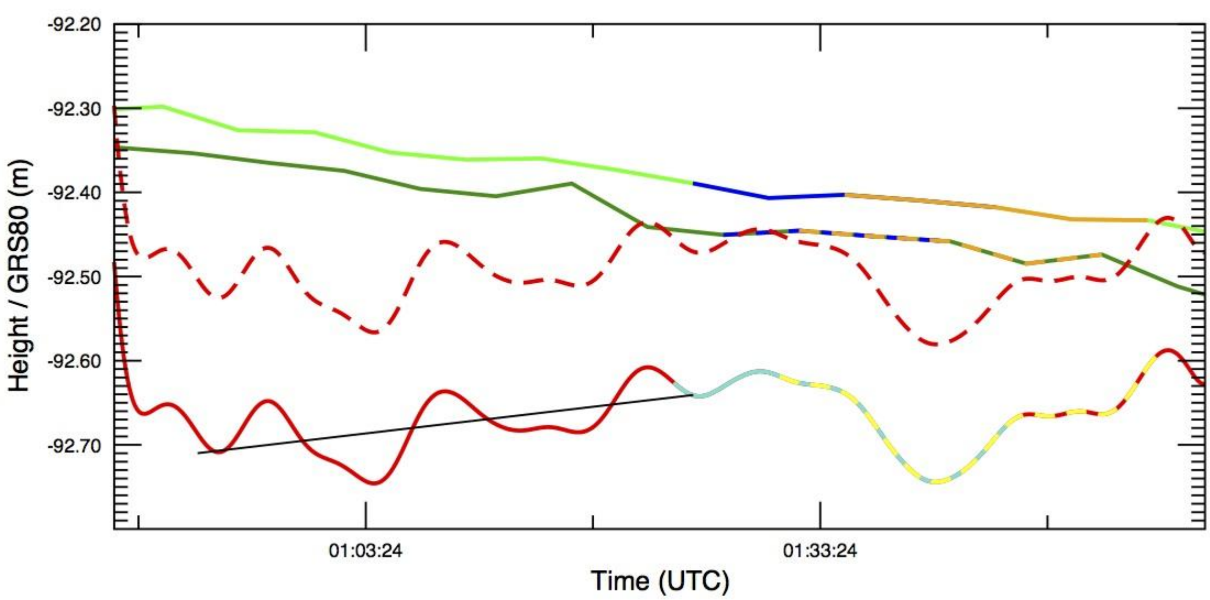

Figure 15b: Continuation …

5.4.2 From BPR

The very basic measurement of BPR is overhead pressure caused due to sea water at a given installed condition. The water level above BPR, R_{BPR} can be expressed as:

$$R_{BPR} = \frac{(P_{BPR} - P_{Atm})}{\rho_{mean} * g} \qquad (2)$$

Where, R_{BPR} is the derived sea level above the BPR, P_{BPR} is the pressure at BPR sensor level, P_{Atm} is the atmospheric pressure, ρ_{mean} is the mean density, and g is acceleration due to gravity. The accurate sea level is derived by using the above equation. The ECMWF atmospheric pressure fields (three hourly interval) were downloaded and they are linearly interpolated to 1minute interval. The mean sea water density was considered to 1025kg/m^3 for the computation.

Height of the BPR from the reference ellipsoid or the datum offset of BPR has been obtained by taking long term (~3days) time series records of BPR and TG2 SSH. The BPR records are convolved for 5minutes resampling before deriving the calibration function. **Figure 16** shows the scatter plot for the calibration exercise. These results are verified with GPS buoy derived SSH. The BPR calibration information is given in **Table 7**.

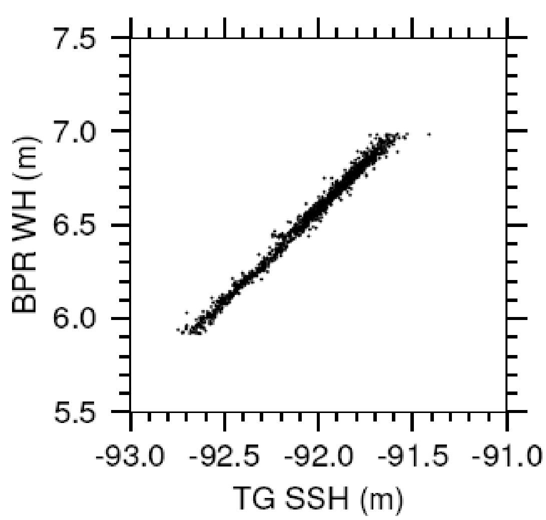

Figure 16: Scatter plot of BPR and tide gauge derived sea surface height

Table 7: BPR calibration table

SSH_{BPR} = 1.01*SL – 98.65
Where, ***SL*** is sea level in meter as measured by BPR
R^2 = 0.99
RMSE = 0.95cm

5.4.3 Verification with GPS buoy at main jetty, NIOT jetty and BPR locations

The GPS buoy derived SSH and BPR derived SSH are convolved through a moving average filter with 5minutes window. This filter reduces the random noise while retaining sharp step response. As the name implies, the moving average filter operates by averaging a number of points from the input signal to produce each point in the output signal. In equation form, this can be written as:

$$Y\left[i\right]=\frac{1}{M}\sum_{j=-5}^{j=5}X\left[i+j\right] \qquad (3)$$

Where X[ ] is the input signal, Y[ ] is the output signal, and M is the number of points in the averaging. A moving average filter is a convolution using a very simple filter Kernal. That is, the moving average filter is a convolution of the input signal with a rectangular pulse having an area of one. The one second GPS buoy kinematic solutions (red dots) are converged into 5 minute samples synchronous with radar tide gauge measurements. **Figure 17** shows the comparison plot between the GPS buoy solutions (solid blue line) and TG1, TG2 observations (soild black line) on 2nd October 2012.

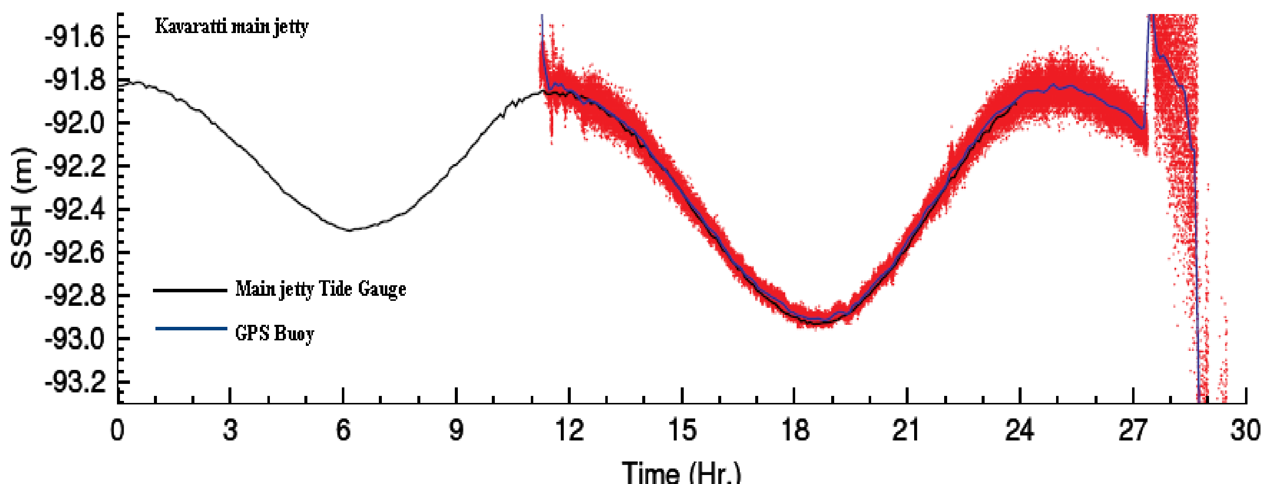

Figure 17a: Comparison of GPS buoy kinematic solution and TG1 observations on 2nd October 2012.

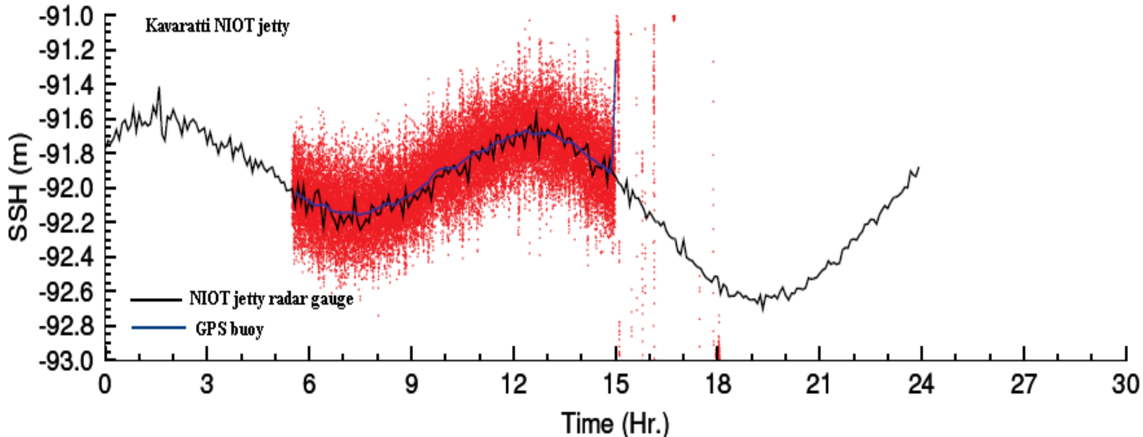

Figure 17b: Comparison of GPS buoy kinematic solution and TG2 observations on 4th October 2012.

GPS buoy was anchored on 2nd/ 3rd October 2012 at BPR location and at TG2 locations respectively. **Figure 17c** represents the results on 3rd and 4th October 2013 at Kavaratti lagoon regions. The red solid line represents the BPR derived calibrated SSH at 1 minute sampling interval and black dots represents the TG2 SSH at 5 minutes interval and the solid blue line corresponds to GPS buoy derived solutions on SSH at 1 minute resampled interval. Comparison of TG2 and TG1 are shown in **Figure 17d**.

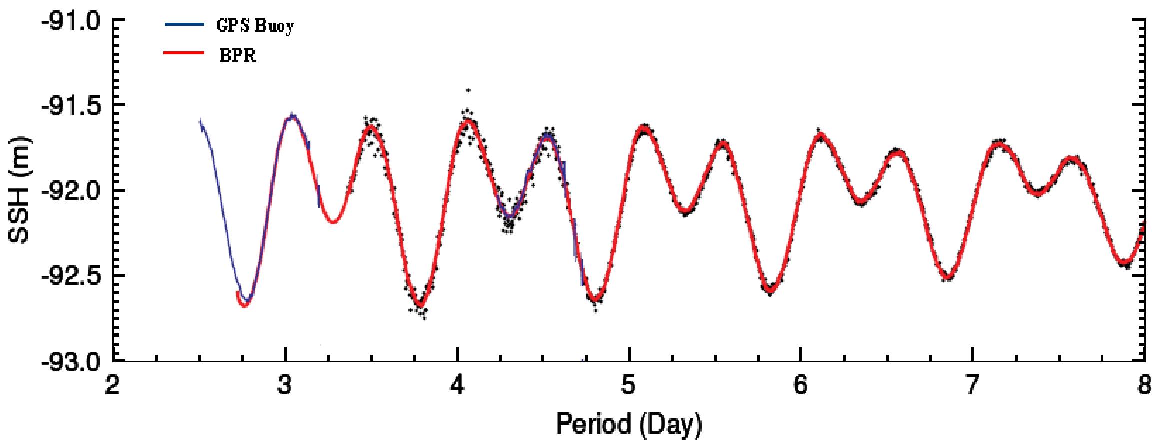

Figure 17c: Comparison of GPS buoy kinematic solutions, BPR and NIOT jetty radar gauge observations.

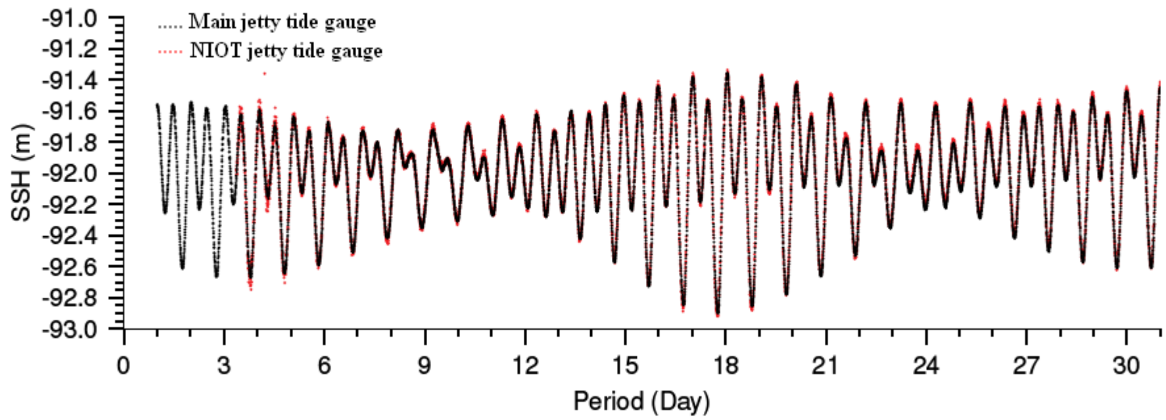

Figure 17d: Comparison of TG1 and TG2 observations.

6.0. Sea surface height calculation from Altimeter

The sea surface is not smooth and flat but, it is a surface that is in constant movement. This moving surface is what we call dynamic topography. If we want to measure SSH, we must measure it relative to a defined, constant surface. This theoretical surface is called the ***reference ellipsoid***. It is a rough approximation of Earth's surface, a sphere flattened at the poles. Since the sea depth is not known accurately everywhere, this reference is the best way to provide accurate, homogeneous measurements.

The satellite flies in an orbit at a certain altitude ***S*** (orbit) from the theoretical *reference ellipsoid*. The altimeter on board the satellite emits a radar wave and analyses the return signal that bounces off the surface. The time it takes for the signal to make the trip from the satellite to the surface and back again, defines the satellite-to-surface range ***R***. In other words, the range is the actual distance between the satellite and the moving sea surface. The SSH at any location or point in time is a deviation from the stable reference ellipsoid. The SSH is thus defined as the difference between the satellite's position with respect to the *reference ellipsoid*, and the satellite-to-surface range, That is, ***SSH = S – R***.

The corrected SSH is computed, namely (orbit – range – path delays – geo-physical corrections). Here range delay comprises of sea state bias range correction, ionosphere range delay, wet troposphere range delay, dry troposphere range delay. The geo-physical correction refers to inverted barometer correction. The SSH estimation in SARAL/AltiKa mission is given below and the global estimated SSH is shown in **Figure 18**.

SSH = Altitude – (atimeter range + wet tropospheric correction – dry tropospheric correction + ionospheric correction + sea state bias + mean sea surface + solid earth tide + ocean tide + inverse barometer) ……….(4)

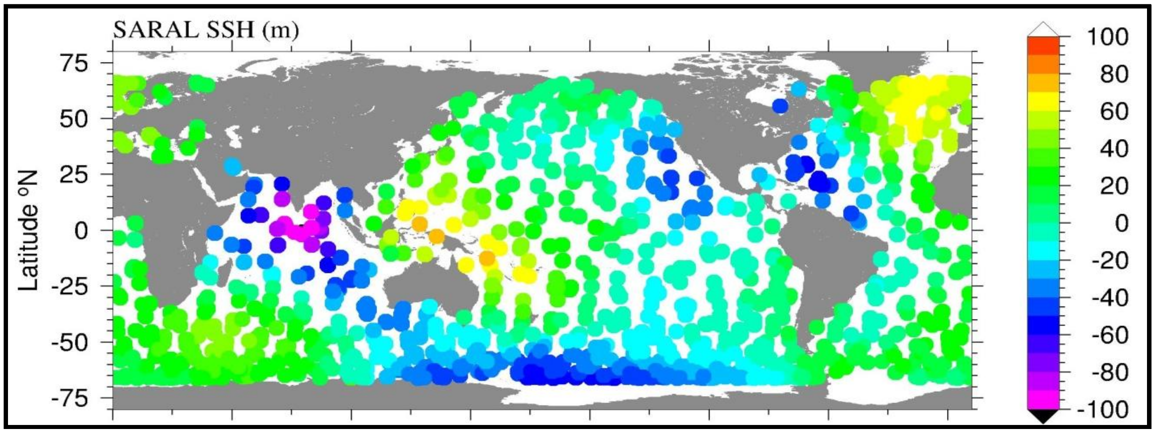

Figure 18: The coverage of sea surface height (m) measurements, as measured by SARAL/AltiKa.

7.0. GPS buoy experiment for geoid correction

The geoid correction is one of the major components to translate the altimetric measurements to the tide gauges locations. At present, no local geoid has been performed to correct for this at the Kavaratti calibration site and hence we used EGM08 model results. However, geoid models are generally less accurate when approaching the coast and hence the geoid height at the tide gauge locations can be erroneous which may directly affect the absolute value of the SSH bias. Geoid gradient is a measure of the change of the SSH because of measurements collected at different locations. The *in-situ* SSH measurement is expected to be exactly at the altimetric sub-satellite point when the satellite overflies. If we were to compare the altimeter-measured SSH with GPS data or tide gauge data that were taken elsewhere, we need to account for the geoid gradient. Applying this correction, the altimeter-measured SSH will be "translocated" to where the *in-situ* measurements were taken (or vice versa). In other words, the geoid gradient should be applied to either SSH_{Alt} or SSH_{TG}. Its magnitude depends upon the displacement between the points and may change in different area. In general, farther the extrapolation, larger is the error. It could dominate over other errors if the distance is extremely large.

A GPS buoy experiment was conducted on 24th September 2013 for SARAL/AltiKa's cycle #6 and pass #539 and another one was also performed about one year before in preparation of SARAL/AltiKa launch (3rd October 2012). The GPS receiver data of NIO and NIOT (GPS1 and GPS2 receiver data for October 2012 experiment) and the GPS buoy receiver data were processed using TRACK solution at 1Hz frequency (TRACK is part of GAMIT package to compute kinematic GPS solutions): The processing is based on differential GPS computations and TRACK parameters have been tuned to account for the distance between the fixed receiver and the GPS buoy (this mode is called "short mode" using L1+L2). The formal error on height given by TRACK is typically of the order of 1-2cm. In order to remove high frequency signal in the GPS solution a low-pass filter of 300 sec has been applied. The **Figure 17** corresponds to the GPS buoy filtered SSH at the offshore locations (crossing of Jason-2 and SARAL/AltiKa satellite tracks), as well as the TG1 and TG2 tide gauge derived SSH respectively. The September 2013 GPS solution is not very good in comparison with the October 2012 one, mainly because the buoy was deployed for about one hour while it was deployed for about 3 hours in October 2012. For such a short period ambiguities are difficult to solve. There's lot of drops and jumps of up to 10cm in amplitude and the tidal signal is clearly different to the tide gauge one (see bottom plot of **Figure 17**).

At the tide gauge locations (separated by ~1.4 km), the EGM08 geoid height is -92.852 m and will serve as reference to compute the geoid height differences at the different offshore locations. These differences are presented in the first and second column of **Table 8**. The third and fourth columns correspond to the SSH differences computed from the data selected at ±500 m from the crossing of the GPS buoy paths and the satellites ground tracks. The last column summarizes the differences between EGM08 height differences and SSH differences, and then corresponds to the value that should be added to the tide gauges geoid heights to correct from EGM08 errors. However, tide gauges and GPS buoy SSH can have their own errors and to estimate this, the GPS buoy was deployed very close to the tide gauges (few meters) to derive any bias in their respective SSH. These comparisons were performed at the beginning and at the end of each experiment and are summarized in **Table 9**. Clear bias up to 5cm and with high standard deviation (~4 cm) have been found for TG1 and TG2 during September 2013 experiment and we suspect that the whole GPS solution was not at the level of accuracy required for such exercise: we have tried different parameterizations of TRACK software that do not lead to substantial improvements and then suspects that it could come from the GPS data themselves.

Then, we decided to determine the SSH differences from offshore locations (close to the satellite ground track) to the tide gauge locations by conducting GPS buoy experiments. The main part of these SSH differences are close to the geoid height differences but may have additional differential tidal signal and other ocean dynamic differences (mean dynamic topography and high frequency signal due to pressure and wind differences). The last column of **Table 9** summarizes the correction that should be applied to the tide gauges geoid heights when accounting for the biases detected from GPS and tide gauges SSH differences. From September 2013, 2.3 cm differences are found between the two determinations (TG1 and TG2), and the averaged value (10.9 cm) is greater by 3.7 cm than the one determined with October 2012 experiment (7.2 cm). This can be explained by the strong drop around 1:40UTC (see bottom plot of **Figure 17**). We have then decided to only keep the value obtained from October 2012 experiment from which we have better level of confidence: tidal signal coherent between GPS buoy at the offshore locations and tide gauges (see top plot of **Figure 17**), small jumps and drops (less than 3 cm), and a very small bias between GPS buoy and tide gauges SSH at the same location (0.9 cm, see **Table 9**). The geoid height at tide gauges location is then set to - 92.780 m: -92.852 m (from EGM08) to which is added the +0.072 m geoid correction (**Table 9** for October 2012 experiment). Other GPS buoy experiments should be performed to confirm and consolidated this datum.

Table 8: Geoid height differences from offshore locations to tide gauges

Location (1)	From EGM08 geoid height differences (2) (m)	From GPS buoy minus TG1 tide gauge SSH(3) (m)	From GPS buoy minus TG2 tide gauge SSH(3) (m)	Differences between EGM08 height differences and SSH differences from GPS buoy and tide gauges(4) (m) (TG1 / TG2)
October 2012				
1	-0.097	-0.185	NA	+0.088 / NA

2	-0.084	-0.158	NA	+0.074 / NA
Average	**-0.091**	**-0.172**	**NA**	**+0.081 / NA**
September 2013				
3	-0.084	-0.261	-0.215	+0.177 / +0.131
4	-0.084	-0.252	-0.208	+0.168 / +0.124
Average	**-0.084**	**-0.256**	**-0.211**	**+0.172 / +0.127**

[1]See **Figure 9** for the numbered locations
[2]The EGM08 height (-92.852m) is the same for TG1 and TG2 tide gauges because they are only separated by ~1.4 km.
[3]The differences are computed from data selected ±500 m from the crossing of the GPS buoy paths and the satellites ground tracks (see Figure 9)
[4]Columns 2 minus 3 for TG1 and columns 2 minus 4 for TG2 (no data from TG2 for October 2012 experiment due to tide gauge malfunction)

Table 9: GPS – Tide gauges differences for TG1 and TG2 tide gauges when the GPS buoy was close (few meters) to the tide gauge and the adjusted geoid correction

Location	Mean (m)	Standard Deviation (m)	Adjusted geoid correction1 (m)
October 2012			
M1	-0.009	0.015	+0.081 + (-0.009) = +0.072
M2	NA	NA	NA
September 2013			
M1	-0.052	0.039	+0.172 + (-0.052) = +0.120
M2	-0.030	0.039	+0.127 + (-0.030) = +0.097

[1]Correction from averaged values of last column in **Table 8** + column “Mean” of this Table: this permit to correct the biases detected from GPS and tide gauges SSH differences.

8.0 SARAL absolute SSH calibration results

The conventional “overhead” concept of *in-situ* altimeter calibration involves the direct satellite overflight of an instrumented experimental site. It is essential that such experimental site has some means of observing sea level and subsequently linking the sea level measurements to a terrestrial reference frame comparable to the satellite altimeter. In an ideal condition, the calibration site should be located on a repeating ground track (or better still a cross-over of an ascending and descending altimeter pass), sufficiently out in the open-ocean to avoid contamination of either the altimeter or radiometer footprints by the land. The schematic diagram of altimeter calibration geometry is shown in **Figure 18**.

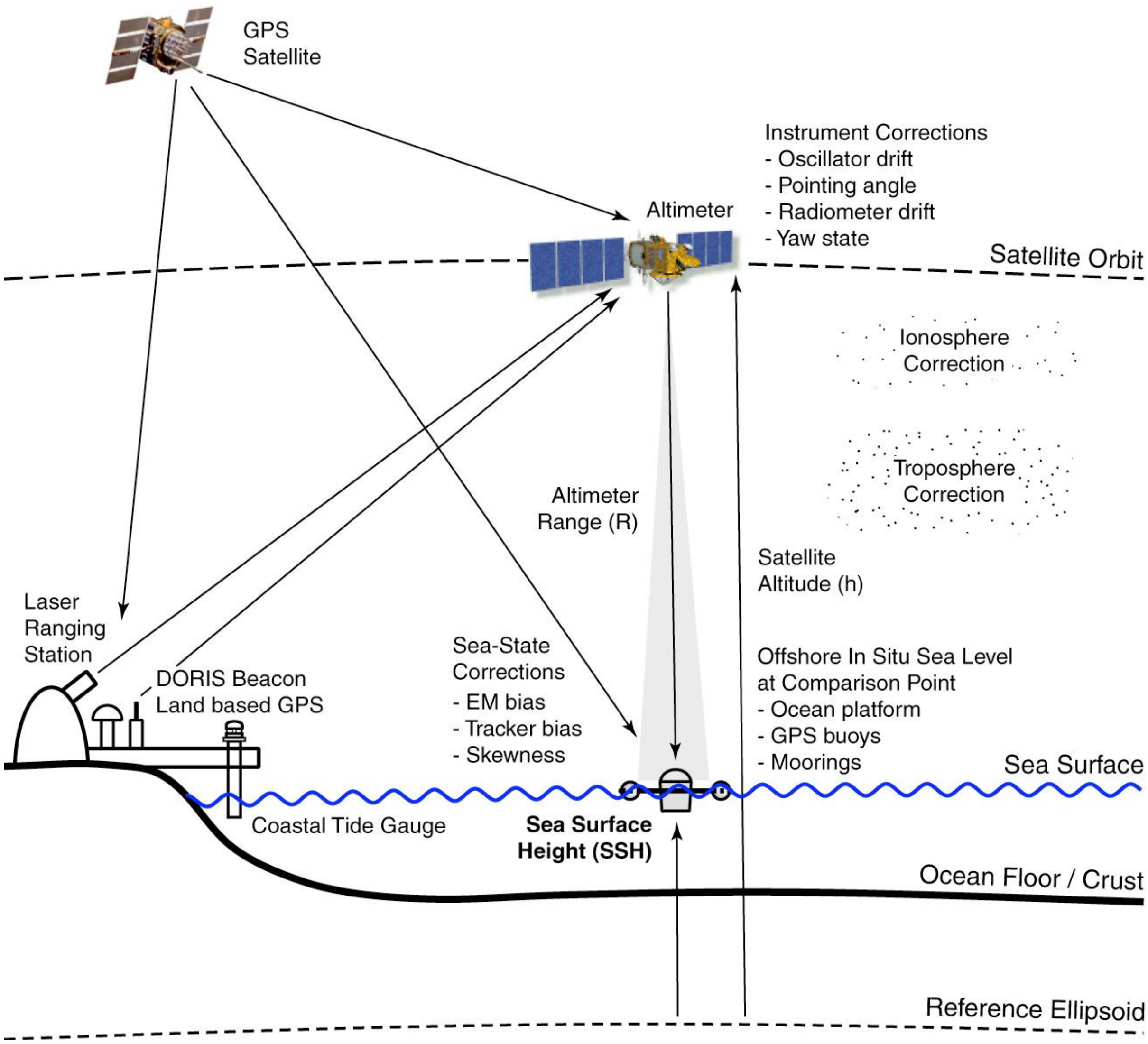

Figure 18: The schematic diagram shows altimeter point calibration geometry.

The principle of this method is to estimate the bias by means of comparison of altimetric SSH information to an adjacent tide gauge derived SSH located within the same geodetic reference frame. The method depends upon the distance between tide gauge and altimeter measurement point not being large (a few 10s of kilometers being ideal), so that the sea level changes and in particular the nontidal changes observed by the two systems are almost the same and the existence of a geoid model can provide the required geodedic connection between tide gauge and altimeter measurement points. The schematically the altimeter calibration is explained in **Figure 19**.

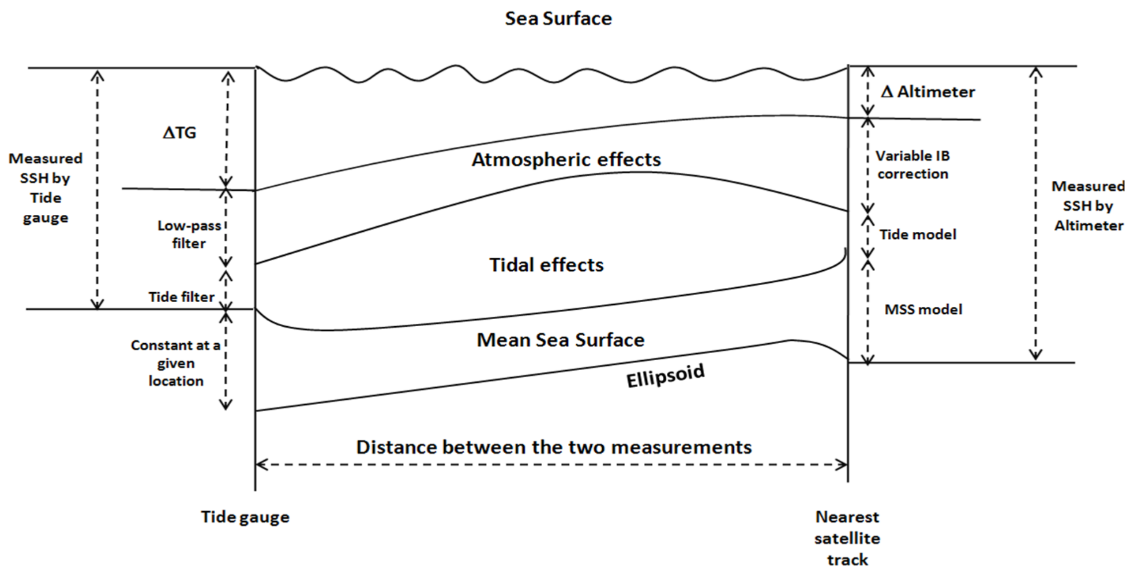

Figure 19: Schematic diagram of performing altimeter absolute calibration

The determination of absolute altimeter bias requires *in-situ* measurement of SSH in a comparable terrestrial reference frame at some chosen comparison point ($SSH_{ComparisonPoint}$). The absolute bias of the altimeter ($Bias_{Alt}$) may be determined using the simple relationship:

$$Bias_{Alt} = SSH_{Alt} - SSH_{TG} \qquad \ldots\ldots\ldots(5)$$

Where SSH_{Alt} is the altimeter derived SSH estimate. A negative bias is therefore indicative of SSH being measured too low by the altimeter (i.e., the altimeter range is too long of the orbit biased downwards). Two distinct methodologies exist for the measurement of *in-situ* SSH at the comparison point (i.e., $SSH_{ComparisonPoint}$) namely: direct measurement and indirect measurement.

Direct measurement: In this case, SSH is observed at the comparison point by physically occupying the overhead location at open ocean during the time of altimeter pass. In case of the NASA calibration site at Harvest (Hains et al. 2003), the platform itself (with associated geodetic and sea level instrument) is located at the comparison point, allowing the direct measurement of SSH for each overflight. Studies utilizing solely GPS equipped buoys are other examples of direct calibration methodology.

Indirect measurement: In this case, the SSH measurement involves the observation of sea level away from the comparison point, typically using a tide gauge at nearby (coastal) location. The remote SSH is then “transferred” or “extrapolated” offshore through the use of precise regional geoid models, and in many cases, numerical tide models. Examples include the CNES calibration site (Bonnefond et al. 2003), the United Kingdom project, and the Greek GAVDOS project (Pavlis et al. 2004). The indirect method offers logistical advantages whilst maintaining the ability to determine cycle-to-cycle estimates of absolute bias. The accuracy of indirect technique is the limiting factor for this methodology. One must also take into account differential effects of tides and atmospheric pressure in the error budget. The magnitude of these effects depends not only on local conditions (e.g., shape of the coast, bathymetry), but also the distance between the location of the *in-situ* sea-level observation and the comparison point. Outside of the intensive calibration phase of the respective missions, a coastal tide gauge is used “indirectly”, combining it with an observed tidal difference (that may be predicted at any time using standard tidal prediction routines) to extrapolate the SSH to the comparison point.

The absolute SSH bias of altimeter in an indirect method can be expressed as:

$$Bias_{Alt} = SSH_{Alt} - SSH_{ComparisonPoint} - [Geoid_{Alt} - Geoid_{Tg}] - Higher\ order\ terms \quad \ldots\ldots\ldots(6)$$

Where the SSH information for both the data sets recorded at the time of altimeter overpass within the same refence frame. The flowchart of the method adopted here is given in **Figure 20**.

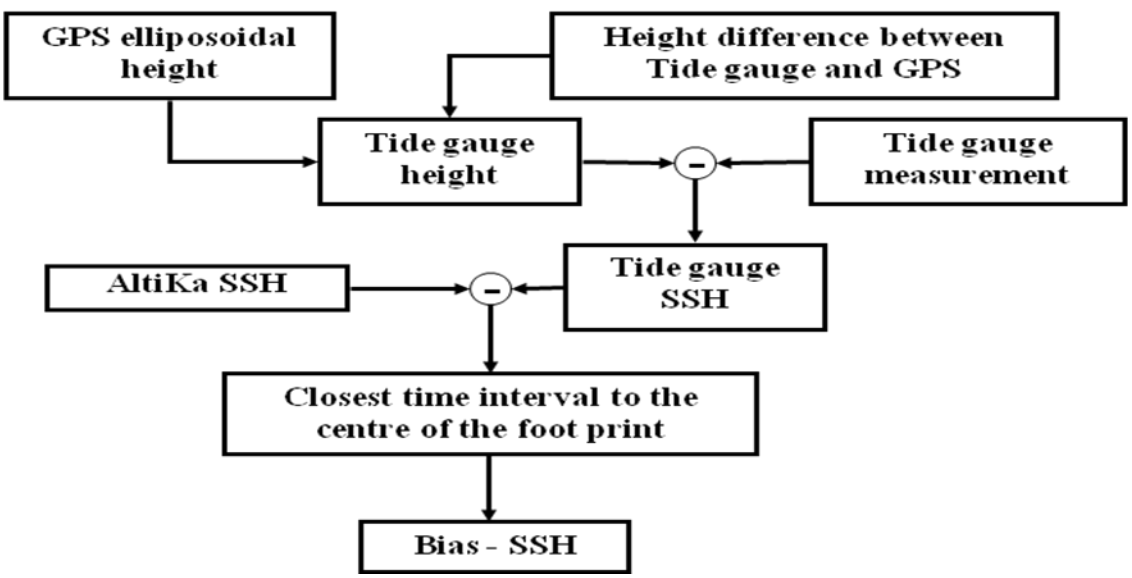

Figure 20: Flowchart of absolute SSH calibration of altimeter user tide gauge observations.

<u>Note: Tide gauge based absolute calibration</u>

The use of tide gauge located away from the altimeter comparison point complicates the determination of the absolute bias. The SSH measured by the tide gauge will differ from sea level at comparison point due to a range of influences including oceanographic conditions (tidal difference, along and cross shore currents), meteorological differences (winds, atmospheric pressure difference), geophysical differences (differential tidal and non-tidal loading) and geometric differences (geoid slope). In addition to these effects, tidal displaments and loading from atmosphere plays a major role.

The calibration methodology adopted in this report is similar to the other dedicated sites in coherent with Jason-2 standards which is followed by Harvest, Corsica and Bass Strait sites that are described by Bonnefond et al. (2011). It is centered on the determination of absolute bias between the SSH derived from the radar altimeter (SSH_{Alt}) and the tide gauge (SSH_{TG}) at the comparison point located in the same coordinate reference frame as that of the altimeter. The tide gauge measured SSH could differ from sea level at the comparison point (Watson et al. 2004) if the observations are apart from each other. In order to overcome this difference, the altimetric observations are trans-located to tide gauge location through correcting the geoid difference between the points of observations.

Similar to Gavdos and Corsica calibration sites, the concept of point of closest approach (PCA) and the relative time of closest approach (TCA) with respect to the geo-location and time that the altimeter is close to the measurement location, is adopted. At Kavaratti site, the calibration exercise takes input of linearly interpolated parameters of ionospheric, dry troposphere, wet troposphere correction values as provided along in the respective products covering a time frame as given in Table 10. All these time series are referenced with respect to the time of closest approach (t=0 sec). Based on these model fittings, we have calculated the SSH at any point of satellite measurement.

The final absolute altimeter bias of altimeter in this work is defined as:

$$Bias_{(Alt)} = SSH_{(Alt)} - SSH_{(TG)} + geoid\ correction \qquad \ldots\ldots(7)$$

Table 10: Interpolation schemes in the calibration exercise (adapted from Bonnefond et al. 2011)

Specifications of correction representation	
Ionospheric	Mean over -11 sec to 11 sec around the TCA
Dry tropospheric	Linear fit over -2 sec to 2 sec around the TCA interpolated at the TCA
Wet tropospheric	Linear fit over -5 sec to 5 sec around the TCA
Sea state bias	Cubic polynomial fit over -4 sec to 4 sec around the TCA
Tide gauge	Linear fit over 30 min centered on TCA (5 min sampling)

EGM08 is used to compute the geiod height at the location of each altimetric data to translate it to the tide gauge locations using the previously computed reference geoid height (-92.780 m). However, even offshore EGM08 can contain some errors and then we have performed a study to choose the best area to compute the SSH bias. Two cases are illustrated in **Figure 21**: [-10 km, +10 km] and [-3 km, +17 km] with respect to time of closest approach. **Figure 21** shows that EGM08 do not correct well the geoid gradient from -10 to -3 km from PCA. The remaining slop is about 1.4cm/km and at the location of the Jason-2/SARAL crossover, the geoid difference is about 50mm. With [-3 km, +17 km] parameter, the SSH bias is much more stable as a function of distance (blue line) with a mean bias of -48 mm (σ = 32 mm): there is a remaining slope but only of about 1 mm/km the absolute value of the SSH bias changes by about -17 mm as compared to the [-10,+10] parameter (-31 mm). We then decided to set the area for absolute calibration to [-3 km, +17 km] and the time series of SARAL/AltiKa absolute SSH bias is illustrated in Figure 8 GDRT products from cycle 1 to 11).

The Table 11 gives individual errors in computation of the absolute bias of SARAL/AltiKa. The geodetic error of ±13mm refers to 1σ value of GPS2 benchmark height solution derived from 6days GPS observations using GAMIT software, ±1 mm error in spirit leveling arises from the least count of scale used in leveling experiment. The daily mean range bias of TG1 and TG2 is ±29.6 mm, which may be the relative error in tide gauge observation (however future GPS buoy experiments are planned for precise estimation). **Figure 22** shows the absolute bias in SSH for the cycles 001-017 with mean value of -38.3mm & standard deviation as 23.8mm.

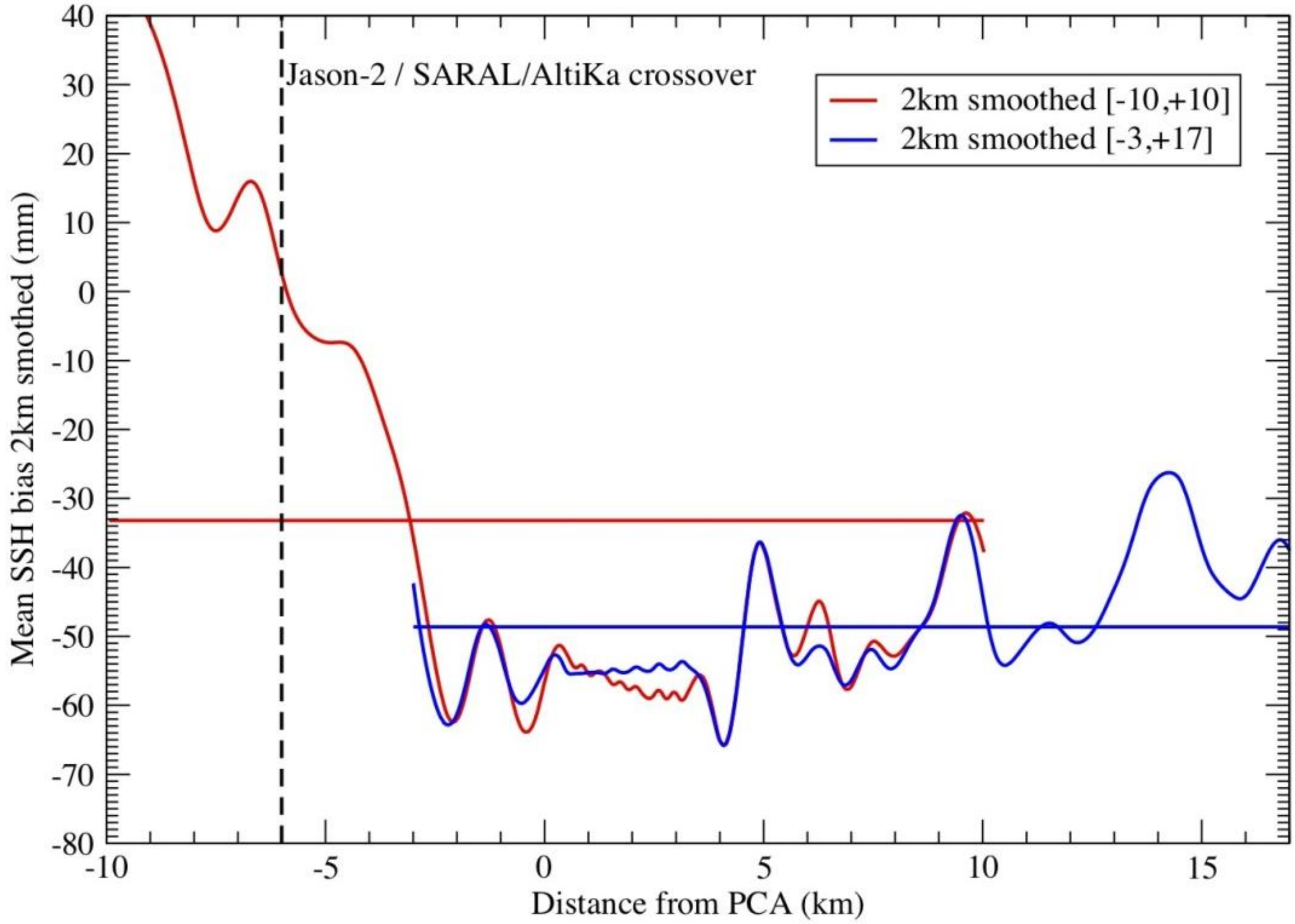

Figure 21: SARAL/ALtiKa SSH bias as a function of distance from the PCA

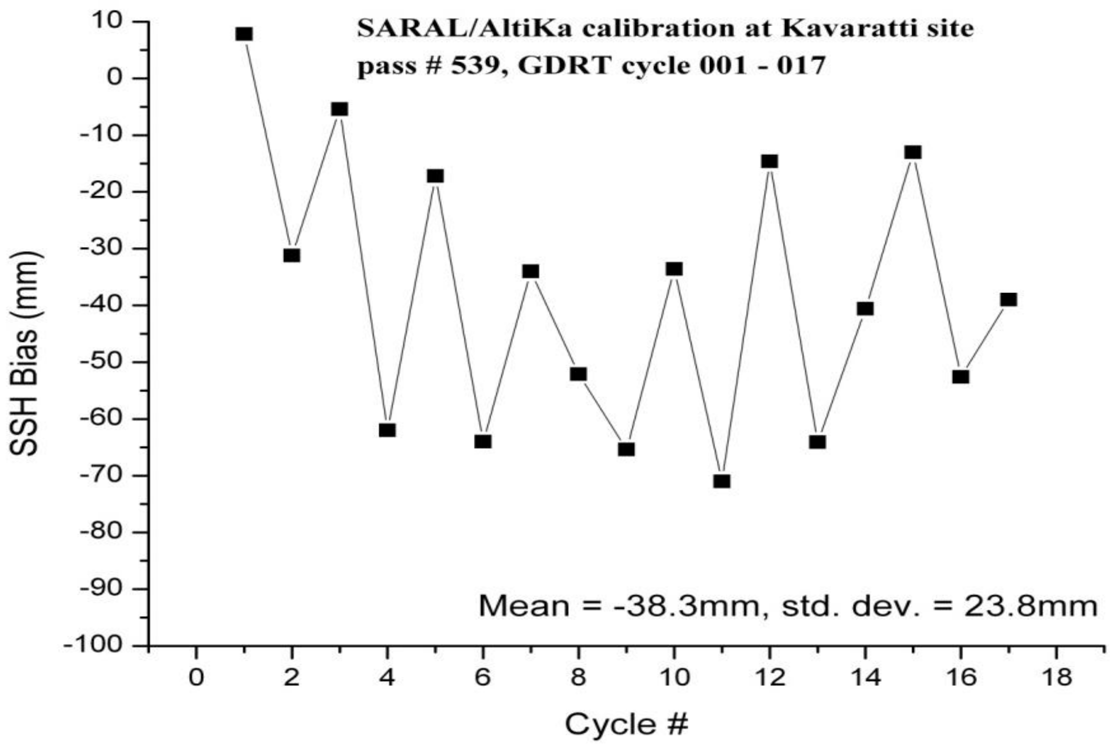

Figure 22 : SARAL/ALtiKa SSH bias from cycle 1 to 17 using GDR-T products.

Table 11: Errors in estimation of the absolute bias of SARAL/AltiKa

Parameter	Error
Geodetic reference	±13 mm
Optical leveling	±1 mm
Tide gauge	29.6 mm
Absolute bias	-38.3±23.8 mm

9.0 Conclusions

The Kavaratti site gives an opportunity to do absolute calibration of Ka-band altimeter AltiKa over the tropical region. This very first tropical calibration site that shows very less contamination due to Island and being at the open ocean, it is an added advantage. This paper explains with GPS solutions about the stability of tide gauge observations along with bench mark leveling. However, repeated crosschecks are needed to be carried out at regular interval like other international permanent sites. The absolute calibration of SARAL/AtiKa is carried out for its 17 cycles at this site. The determined absolute bias is -38.3mm in its initial 17 cycles of observations. In this initial calibration exercise of SARAL/AltiKa we have not used any local high resolution tide models, also the effects of wind atmospheric presses, and vertical land motion for the precise local geoid estimation are ignored in determining the absolute SSH bias. The initial results show that the location is very robust and encourages us to continue observations to carryout the absolute calibration of altimetric SSH. The errors in estimation of absolute SARAL/AltiKa bias over this site will be improved through future field experiments.

List of publications:

1) "SARAL/AltiKa CAL-VAL Project Execution Document". *SAC/RESA/MESG/SARAL/CAL-VAL/1/2010*.

2) "Initial Calibration and Validation results of SARAL/AltiKa". K. N. Babu, Suchandra A. Bhowmick, S. V. V. Arun Kumar, N. M. Suthar, R. P. Prajapati and A. K. Shukla. *SAC/EPSA/MPSG/CVD/CAL-VAL/07/13*.

3) SARAL CAL-VAL work plan and readiness report. K. N. Babu, Suchandra A. Bhowmick, S. V. V. Arun Kumar, R. P. Prajapati and A. K. Shukla. *SAC/EPSA/MPSG/CVD/CAL-VAL/01/13*.

4) "Relative performance of SARAL/AltiKa with Jason-2 and Cal-Val over Kavaratti and Global seas". K. N. Babu, Sharad Chander, Suchandra A. Bhowmick, S. V. V. Arun Kumar, A. K. Shukla and Prakash Chauhan. *SAC/EPSA/MPSG/CVD/CAL-VAL/09/13*.

5) "Calibration of SARAL-AltiKa altimeter using tide gauge and GPS buoy over Oceans of Indian peninsula – A plan". K. N. Babu, Kaushal B. Mehta, Abhineet Shyam, & A. K. Shukla. *SAC/RESA/MESG/SARAL/CAL-VAL/2/2010*.

6) "Validation of SARAL-AltiKa Geo-physical products – A plan". Suchandra A. Bhowmick, Rishi Kumar Gangwar, K. N. Babu, & A. K. Shukla. *SAC/RESA/MESG/SARAL/CAL-VAL/3/2010*.

7) "Tide gauges for sea level measurement over Indian region – A study". Abhineet Shyam, Rishi Kumar Gangwar, K. N. Babu, & A. K. Shukla. *SAC/RESA/MESG/SARAL/CAL-VAL/4/2010*.
8) "Selection of calibration sites and analysis of SOI tide gauge data for absolute calibration of satellite altimeter". Kaushal B. Mehta, K. N. Babu, Suchandra A. Bhowmick, A. K. Shukla. *SAC/EPSA/MPSG/CVD/CAL-VAL/02/12*.

9) "Comparison of SOI tide gauge with Jason-1 & ENVISAT for sea level bias determination". *Kaushal B. Mehta, Suchandra A. Bhowmick, K. N. Babu, A. K. Shukla. SAC/EPSA/MPSG/CVD/CAL-VAL/03/12*.

10) "Absolute calibration of SARAL/AltiKa using Bottom Pressure Recorders in Coastal waters - A science Plan". S. V. V. Arun, K. N. Babu, and A. K. Shukla. *SAC/EPSA/MPSG/CVD/CAL-VAL/05/12*.

11) "Initial calibration and validation results of SARAL/AltiKa". K. N. Babu, Suchandra A. Bhowmick, S. V. V. Arun Kumar, N. M. Suthar, R. P. Prajapati and A. K. Shukla. *SAC/EPSA/MPSG/CVD/CAL-VAL/07/13*.

12) SARAL CAL-VAL preparedness over Indian Sub-continent. K. N. Babu, Kaushal B. Mehta, Suchandra A. Bhowmick, and A. K. Shukla. *PORSEC, Cochin, India*.

13) Inter-comparison of EnviSAT Wind Wave and SLA with Jason-1 and Jason-2 Altimeters. Suchandra A. Bhowmick, K.N. Babu, A.K. Shukla, Raj Kumar. *PORSEC, Cochin, India*.

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Bonnefond, P. B. Haines and C. Watson. 2011. In site Calibration and Validation: A link from Coastal to Open-ocean altimetry, chapter 11 in Coastal Altimetry, PP 259-296, edited by S. Vignudelli, A.Kostianoy, P. Cipollini, J. Benveniste, Springer, ISBN: 978-3-642-12795-3.