Sea Level Records from Geodetic GPS Receivers: a New Coastal Sea Level Dataset

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INTRODUCTION

- Global sea level rise and local sea level variations due to climate change are a threat to coastal societies. Thus, it is important to monitor and understand how the sea level is changing.
- Measurements with traditional tide gauges are relative to the land where they are established. Thus, they do not give absolute sea level information and have the disadvantage of being affected by land surface motion, e.g. tectonics.
- Coastal Global Positioning System (GPS) stations are used to measure land surface motion. However, they are also affected by multipath signals that reflect off the sea surface, which is especially visible in the recorded Signal-to-Noise Ratio (SNR) data. Analysis of the multipath effects allow to determine relative sea level and its variations. Thus, coastal GPS stations can be used as GPS tide gauges.
- The advantage of a GPS tide gauge is that it provides both, the relative sea level and the position with respect to the International Terrestrial Reference Frame, using a single geodetic instrument. This is particularly valuable in areas with land motion where the usefulness of traditional tide gauges is restricted.
- We present how to derive a new sea level dataset from existing coastal GPS stations. We describe the GPS tide gauge concept, show examples of sea level records derived from 5 existing GPS stations in different parts of the world (Sweden, USA, France, Australia, and Antarctica), and compare the results to those from co-located traditional tide gauges.

HOW TO DERIVE SEA LEVEL FROM GPS DATA

We analyze SNR data from standard geodetic-type GPS receivers at the coast.

The receiver records a combination of the direct satellite signals and the satellite signals that are reflected off the sea surface. The latter is known as multipath, see **Figure 1**, and causes oscillations in the SNR data, see **Figure 2A**.

From the SNR oscillations it is possible to determine the vertical distance between the antenna phase center and the reflecting sea surface.

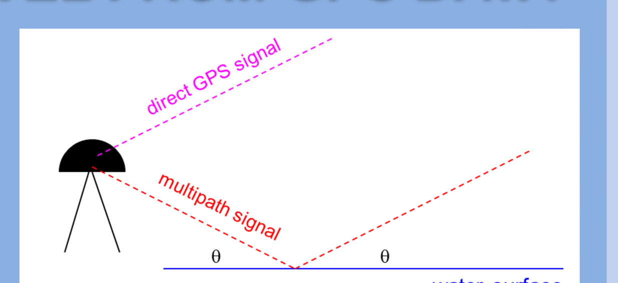


Figure 1 *– The satellite signal reflected off the sea surface, i.e., multipath, interferes with the direct satellite signal and the combination is recorded with a standard geodetic-type GPS receiver.*

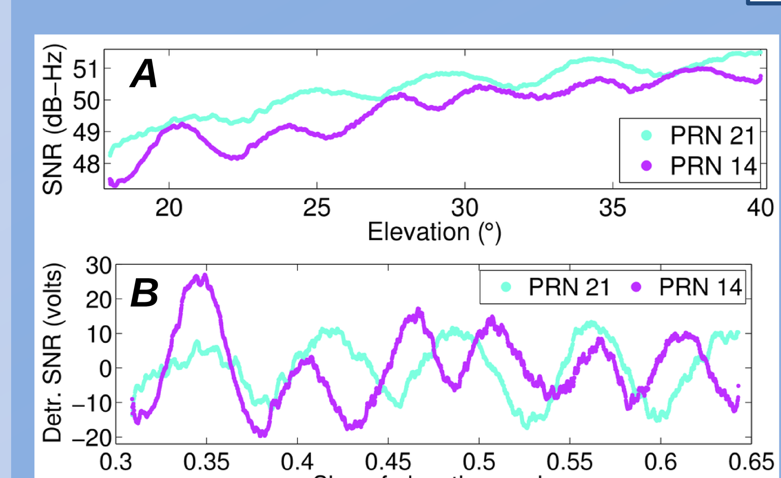


Figure 2 *– Original (**A**) and detrended SNR data (**B**) for two satellite arcs. The observations from satellites with Pseudo Random Noise (PRN) number 21 (cyan) and 14 (magenta) correspond to high and low sea level, respectively.*

For each satellite arc the original SNR data, **Figure 2A**, are converted to natural units and detrended by fitting and removing 3:rd order polynomials (see **Figure 2B**).

Assuming that the sea level does not change for a satellite arc, the oscillation frequency of the detrended SNR data (dSNR) is constant as a function of sine of the satellite elevation angle, see **Figure 2B**.

In order to estimate a local sea level height from each arc of dSNR data, the Lomb Scargle Periodogram (LSP) is used.

The peak frequency of each LSP (see **Figure 3**) is converted to reflector height (by scaling with ½ times the carrier wavelength).

A large reflector height value corresponds to a low sea level and vice versa.

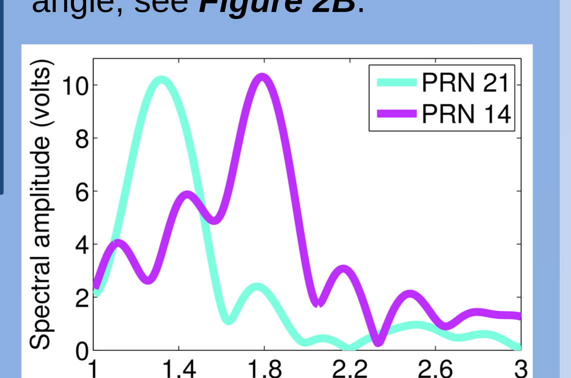
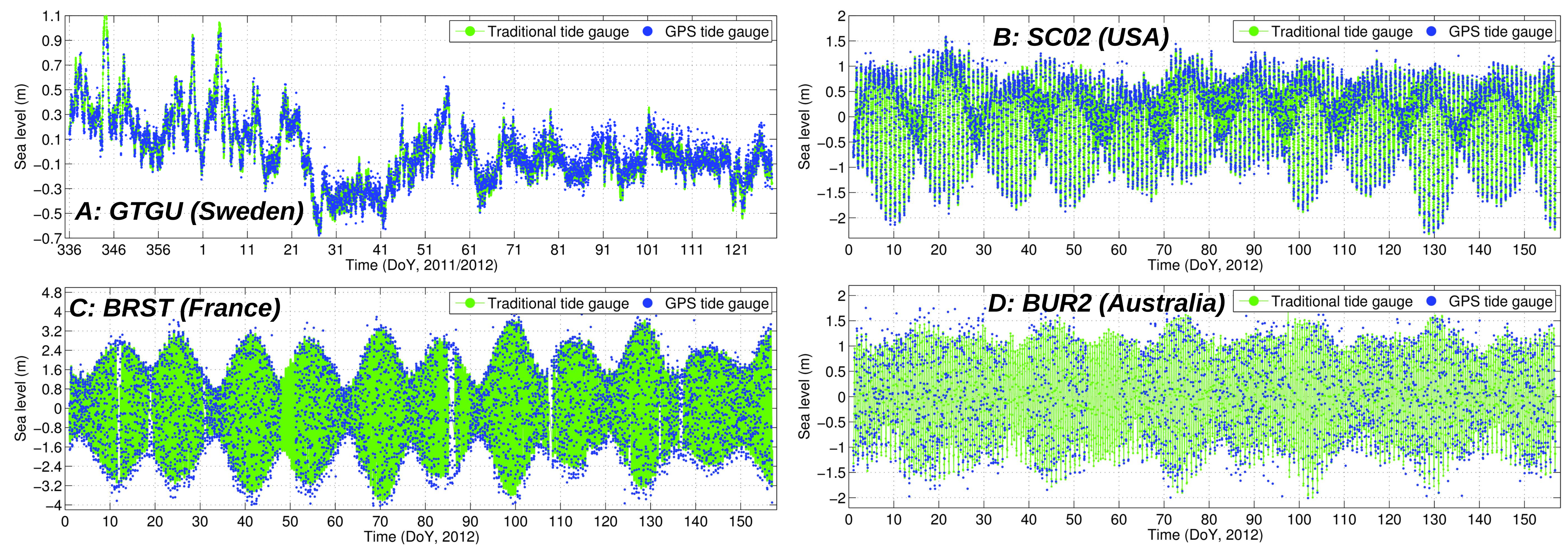


Figure 3 *– LSP for the two arcs of detrended SNR data presented in Figure 2B, showing their corresponding reflector heights.*



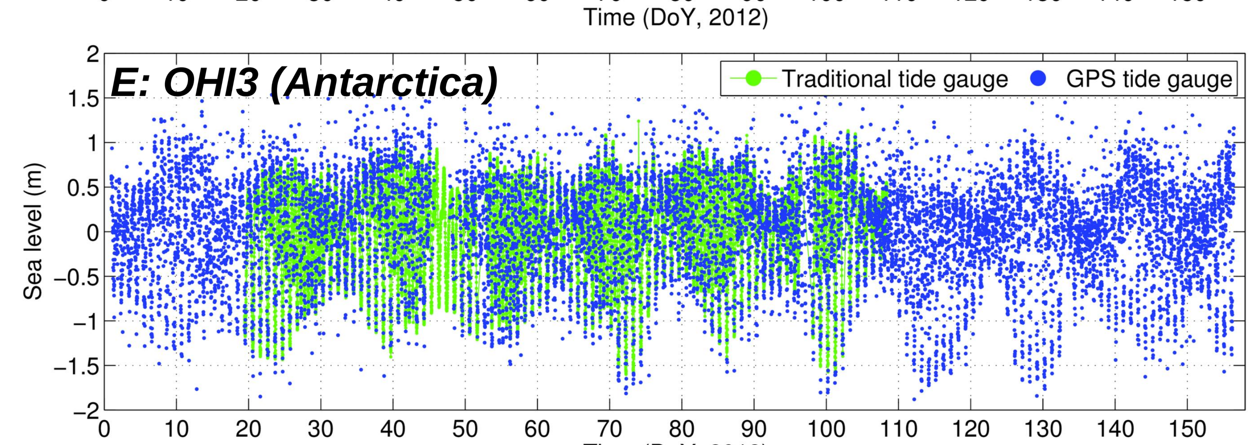


Figure 5 *– Time series of local sea level in m from the GPS stations GTGU (**A**), SC02 (**B**), BRST (**C**), BUR2 (**D**), and OHI3 (**E**) and traditional tide gauges for more than 5 months. The GPS sea level results from the SNR analysis are shown in **blue** and the sea level from the co-located traditional tide gauges are shown in **green**. All time series are centered around zero.*

Table 1 – Statistics for the comparison between the GPS tide gauges and the traditional tide gauges. See also Figure 7.

	GTGU	SC02	BRST	BUR2	OHI3
Sea level range (m), 5 months	1.6	4.5	8.2	3.9	3.5
Mean abs. difference (cm)	5.2	9.5	50.8	20.2	19.5
Stand. dev. of the difference (cm)	6.8	12.2	65.4	27.7	26.2
Correlation coefficient	0.97	0.99	0.93	0.95	0.89
Rate of linear regression	1.01	1.01	0.87	0.93	0.84
Total number of data points	7693	8776	6781	3135	10795

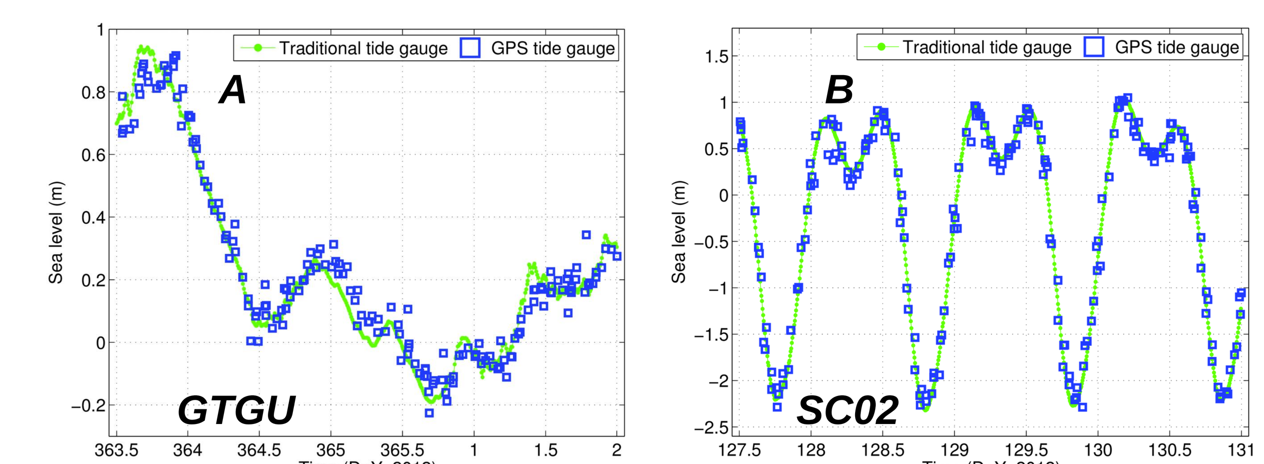


Figure 6 *– Details of Figure 5A and 5B showing sea level for GTGU (**A**) and SC02 (**B**). The GPS sea level results are displayed as **blue** squares and the traditional tide gauge sea level is displayed as **green** circles.*

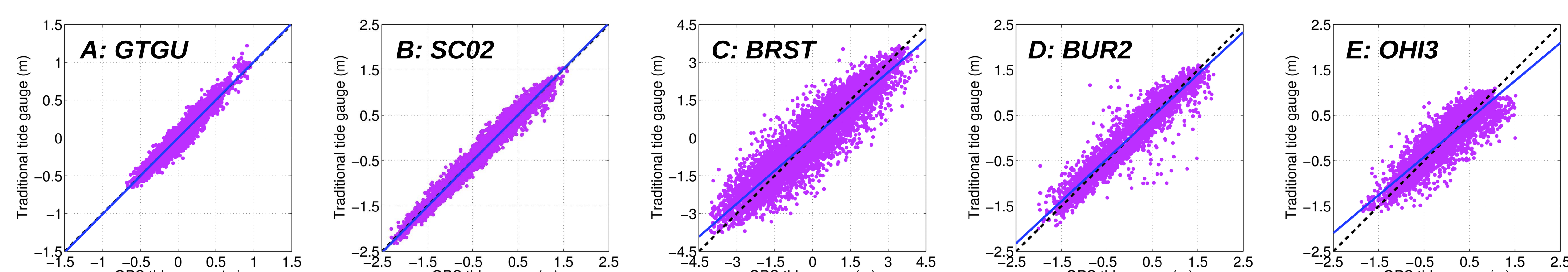


Figure 7 *– Scatter plots of sea level from the GPS tide gauges **A**, **B**, **C**, **D**, and **E**, and the co-located traditional tide gauges. The dashed **black** lines are x=y and the solid **blue** lines represent the linear regression.*

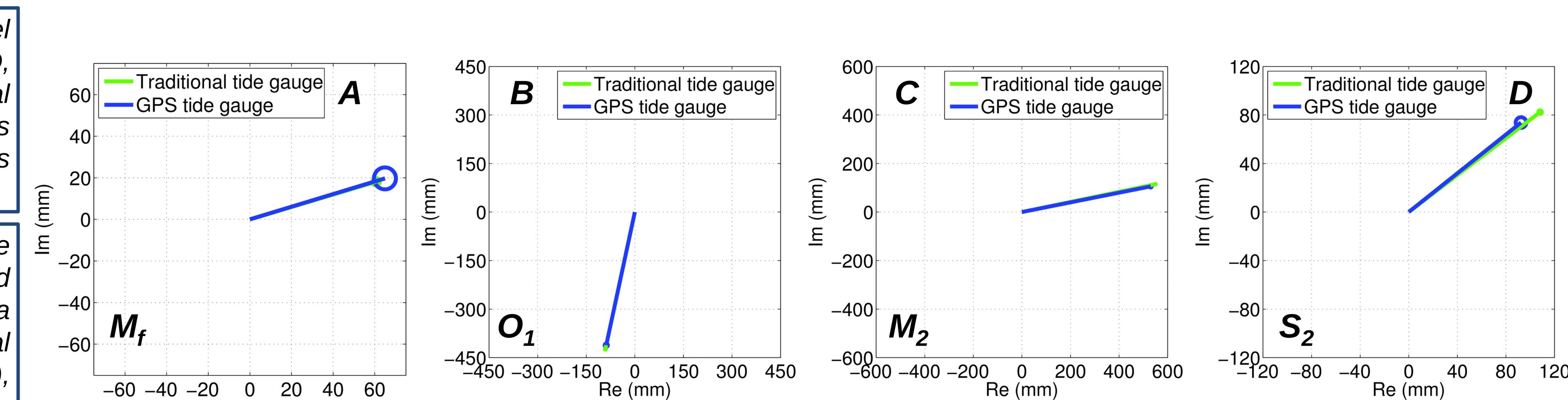


Figure 8 *– Results from ocean tide analysis of the GPS (**blue**) and traditional tide gauge (**green**) sea level for the site SC02 showing tidal components M_f (**A**), O_1 (**B**), M_2 (**C**), and S_2 (**D**).*

GPS AND TIDE GAUGE DATA

The dataset consists of more than 5 months of GPS SNR data from 5 coastal GPS stations (see ***Figure 4***):

- ***GTGU*** (Sweden), Onsala Space Observatory (OSO)
- ***SC02*** (USA), University NAVSTAR Consortium (UNAVCO)
- ***BRST*** (France), Institut Geographique National (IGN)
- ***BUR2*** (Australia), Geoscience Australia (GA)
- ***OHI3*** (Antarctica), Bundesamt für Kartographie und Geodäsie (BKG)

The traditional tide gauges are co-located with the GPS stations (except for GTGU, which is 33 km south of the tide gauge) and the data are provided by the ***Swedish Meteorological and Hydrological Institute***, the ***National Oceanic and Atmospheric Administration***, ***Réseaux de référence des observations marégraphiques***, the ***Bureau of Meteorology***, and **BKG**.

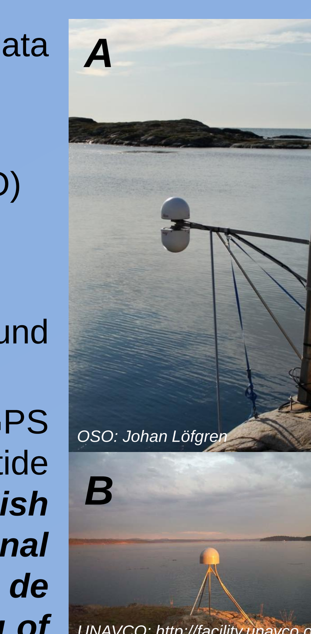


Figure 4 *– GPS tide gauges located in different parts of the world: GTGU (**A**), SC02 (**B**), BRST (**C**), BUR2 (**D**), and OHI3 (**E**).*

OCEAN TIDE ANALYSIS

The ocean tide analysis was done using the Tamura potential and solving for tidal wavegroups such that they are spectrally non-overlapping. This implies that waves like K_1 and P_1, closer than one beat cycle per time series duration, share the same wavegroup.

A difficulty was found in uncertain timing of the GPS derived sea level results, i.e. the effective temporal centerpoint of the GPS satellite arcs. There appears a clear difference between results based on ascending and descending satellite arcs, see ***Figure 9***.

Assuming that the residual errors of the tidal analysis are uncorrelated and normally distributed, standard deviations of around 5 mm and 1.6 mm are determined for the tidal amplitudes derived from the GPS and traditional tide gauge, respectively.

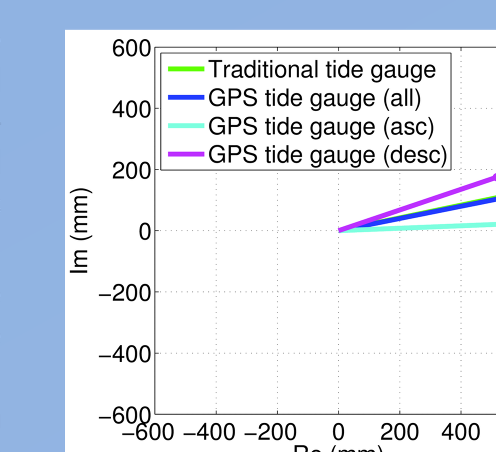


Figure 9 *- M_2 tide results for GPS site SC02 for ascending (cyan), descending (magenta), and complete arc segments (**blue**), and as reference the corresponding result from the traditional tide gauge (**green**).*

RESULTS AND CONCLUSIONS

- Coastal GPS stations that are affected by multipath, due to signals reflected off the sea surface, can be used as GPS tide gauges.
- GPS tide gauges provide both local and absolute sea level and work well for sites worldwide with low or high tidal variation.
- When comparing sea level derived from GPS tide gauges with sea level from co-located traditional tide gauges we find:
  - *Correlation coefficients between 0.89 and 0.99.*
  - *Mean absolute differences between of 5 and 51 cm.*
  - *Standard deviation of the differences between 7 and 66 cm.*
- There appears a difference between results based on ascending and descending satellite arcs, in particular for sites with high tidal range. An improved analysis technique is under development.
- Tidal components can be derived from harmonic tidal analysis and show good agreement between GPS tide gauges and traditional tide gauges.
- Data from coastal GPS sites worldwide could be exploited systematically to derive a sea level data set that complements existing traditional tide gauges.