Vertical Land Movements and Sea Level Changes around South Georgia Island: Preliminary Results

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Abstract

South Georgia Island in the Southern Atlantic Ocean is a key location for the seismic, geomagnetic and oceanic global monitoring networks. In its sub-Antarctic location, the island is largely covered by mountain glaciers which have been reported to be retreating due to climatic change. Furthermore, during past glaciation periods the island and its shelf area have been ice covered as was revealed by scarring of the sub-oceanic topography. Together with ongoing tectonics along the North Scotia Ridge, these processes have the ability to produce significant uplift on local to regional scales, affecting the measurements of the tide gauge (GLOSS ID 187) at King Edward Point (KEP). Furthermore, with its mid-ocean location, the tide gauge is of particular interest to satellite altimetry calibrations over the Southern Atlantic and Southern Oceans. With the establishment of five GNSS stations on the islands during 2013 to 2015 and the scientific analysis of these data within the global network of stations of the International GNSS Service Tide Gauge Benchmark Monitoring (TIGA) working group, it has now become possible to study present-day vertical land movements of the region and their impacts on, for example, regional sea level. Furthermore, together with four precise levelling campaigns of the KEP benchmark network in 2013, 2014 and two in 2017, it has also been possible to investigate the very local character of the vertical motions near KEP, ie. the stability of the jetty upon which the tide gauge is mounted.

In this study, we will present the still preliminary results from the GNSS and levelling measurements and will discuss their impact on the sea level record from the KEP tide gauge. Our measurements show that while South Georgia Island and the area around KEP are rising, the jetty and tide gauge are subsiding, leading to a disagreement in the observed sea level change from the tide gauge and satellite altimetry. In order to improve the agreement between these sea level measurements both local and regional vertical land movements need to be monitored.

Introduction

South Georgia Island is located in the South Atlantic Ocean and is a relatively small island of about 170 x 50 km, bending towards the southeast about halfway along its length (Figures 1 and 2). It is the subaerial exposure of what is believed to be the South Georgia microcontinent, which measures about 300 x 150 km and includes the shelf area around the island. The island itself is very mountainous with peaks reaching over 2900 m a.s.l. and it is largely covered with glaciers, which predominately show rapid retreat. The microcontinent is the largest fragment within the North Scotia Ridge Transform and information from geology, geophysics, seismology and satellite altimetry has led to a reasonable understanding of the Scotia Sea tectonic evolution [Barker, 2001]. However, uncertainty remains as to the tectonics and potential glacio-isostatic adjustment (GIA) of South Georgia and the associated shelf areas [Smalley et al., 2007]. It is believed that the collision between South Georgia and the Northeast Georgia Rise, which lies opposite of the North Scotia Ridge Transform, is responsible for the orogeny of the island.

Graham et al. [2008] revealed that the entire shelf area has been glaciated to the edges during the Cenozoic. Since then, several glaciation and deglaciation cycles have occurred and while it was not clear if the entire shelf was covered during the Last Glacial Maximum [Bentley et al., 2007; Gordon et al., 2008], this has now been essentially confirmed [White et al., 2017]. This suggest that some vertical motion of the island due to the GIA process in addition to the tectonics cannot be ruled out and is fairly likely. Furthermore, present-day glacier retreat is likely to result in additional local vertical motions.

South Georgia Island is important for sea level measurements. The tide gauge at King Edward Point (KEP) (GLOSS 187) has been in operation on and off since 1957. It was upgraded several times and the current pressure sensor gauge was installed in 2011. In 2014 a tide board was added, allowing regular cross checks of the sea level readings from the visual observations and the tide gauge records. The ground tracks of TOPEX/POSEIDON/Jason/Sentinel satellite altimetry missions come close to the island.

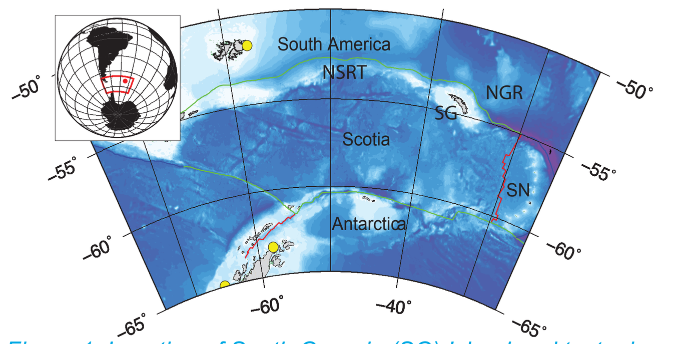

Figure 1: Location of South Georgia (SG) Island and tectonic plates in the South Atlantic Ocean (University of Texas at Austin): transforms/fracture zones (green), ridges (red) and trenches (blue); continuous GNSS stations (yellow circles); NSRT: North Scotia Ridge Transform, NGR: Northeast Georgia Rise, SN: the South Sandwich plate.

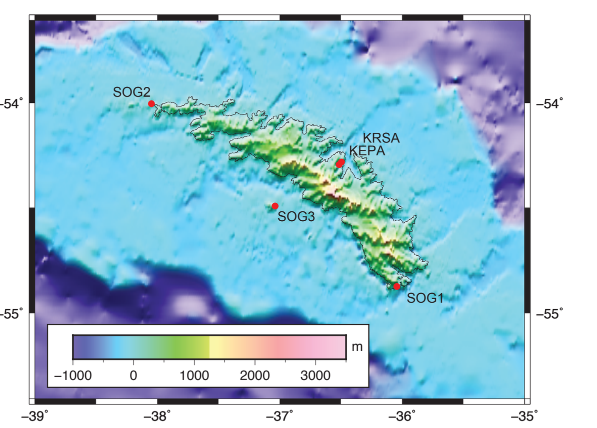

Figure 2: South Georgia Island with shelf area. Continuous GNSS stations (red circles). KEPA and KRSA are located at King Edward Point (KEP).

As these reach within several 10s of km of the tide gauge, there is potential for the tide gauge data to be useful for altimeter calibration over the South Atlantic Ocean. However, with the large potential for vertical movements at KEP it was decided to equip the tide gauge with a state-of-the-art GNSS station to investigate any uplift or subsidence. This has lead to the establishment of the King Edward Point Geodetic Observatory (KEPGO), which consists of two GNSS stations and local benchmark networks [Teferle et al., 2014]. At the same time a US-lead project established three GNSS stations at the perimeter of South Georgia Island to investigate present-day tectonic processes.

Acknowledgements

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GNSS Data Set and Processing

The full history of GPS data collected by a global tracking network from 1995 to 2017 was reanalyzed by the IGS TIGA Analysis Center at the University of Luxembourg (Figure 3). The solution uses up to 750 GPS stations besides the five stations on South Georgia Island and employs a network double-difference processing strategy using the Bernese GNSS Software version 5.2 [Dach et al, 2015]. Our GPS reprocessing strategy is detailed in [Hunegnaw et al, 2015] and incorporates recent model developments and the latest International Earth Rotation and Reference Systems Service (IERS) 2010 conventions [Petit and Luzum, 2010]. The GPS data was reprocessed using CODE precise final orbits and Earth orientation parameters, and was linked into ITRF2008 [Altamimi et al., 2007]. The daily coordinate time series were then analyzed using the Hector software [Bos et al., 2012] assuming a combination of power-law and white noise for the stochastic model.

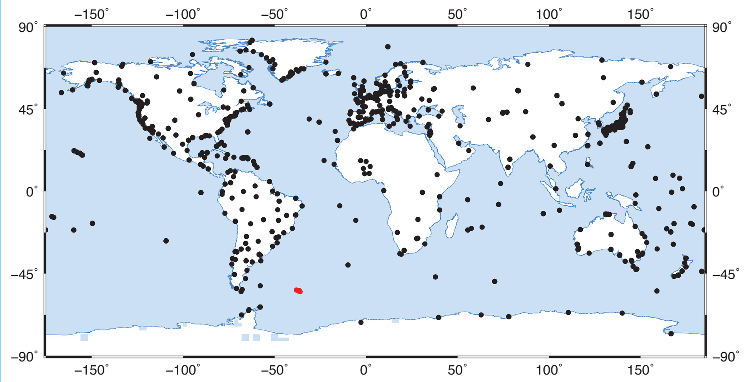

Figure 3: Global GPS network (black dots) and five South Georgia Island stations (red dots) reprocessed for this study. The global network consists of those stations from the IGb08 core network and from the Tide Gauge Benchmark Monitoring (TIGA) Working Group.

Benchmark Networks and Levelling Results

Two benchmark networks were installed: one at KEPA on Brown Mountain and a second one at KEP Research Station. The KEPA network provides a precise reference of the current GNSS antenna ARP in case the monument should get damaged or destroyed (not discussed further). The network at KEP Research Station provides the height connection of the KRSA antenna ARP to the tide gauge as well as allows stability monitoring of the KRSA monument and of the whole area. Figure 4 shows this benchmark network which incorporates two benchmarks used by the United Kingdom Hydrographic Office (UKHO).

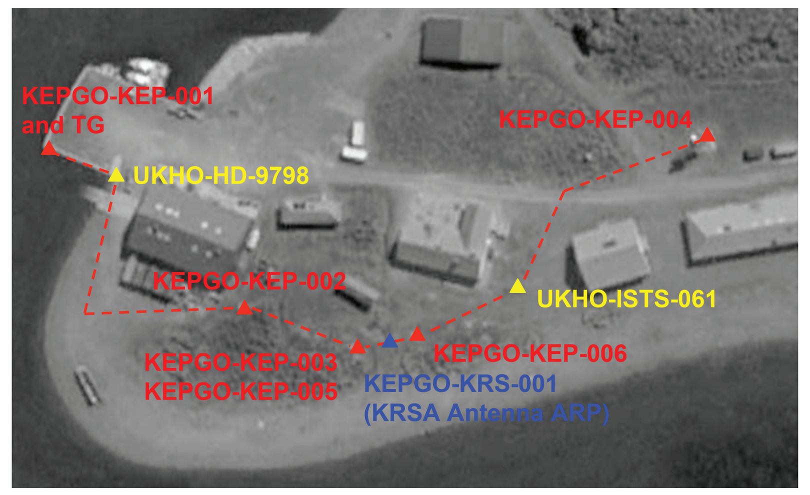

Figure 4: Benchmark network at KEP Research Station: tide gauge (TG) and KEP Geodetic Observatory (red), KRSA antenna and monument (blue) and UKHO (yellow). UKHO-ISTS-061 is the International Satellite Tracking Station Number 061 and was established in 1967/68.There are five benchmarks at the KRSA antenna and monument, only the one for the antenna ARP is shown. Imagery from Google Earth.

To date four levelling campaigns have been carried out: 2013, 2014 and two in 2017. The campaigns in 2013 and 2014 were performed using a high-precision analogue level with plan plate by a team from the University of Luxembourg. The two campaigns in 2017, (a) in Febuary and (b) in March, were carried out using a high-precision digital level with Invar staff by two BAS personnel from KEP. The tide gauge can only be levelled with a modified staff and requires experienced operators, hence it was not levelled in 2017. Instead, the level of the tide board, installed in 2014 next to the tide gauge, has been observed. This is more convenient as any standard staff, in this case the Invar staff, can be rested on top of the tide board. Table 1 shows the results from the levelling campaigns. All levelling lines were started at benchmark KEPGO-KEP-004, situated at the base of the satellite communications tower, ie. it is assumed to be stable, and heading towards the jetty with the tide gauge. The standard errors stem from the differences in the forward and backward measurements. It can be seen that up to benchmark KEPGO-KEP-002, the heights have not varied by more than 3 mm. Beyond that benchmark the ground starts to subside.

Table 1: Levelling results for benchmarks observed during the 2013, 2014 and 2017 campaigns. The height for KEPGO-KEP-004 was computed to be 3.76 m using KEPA and additional campaign GPS observations in 2013, 2013 levelling data and EGM2008 Geoid separations, and has been assumed to be stable over the period. The tide board was installed in 2014 and was used during the 2017 campaigns for convenience with the Invar staff. All uncertainties are 1-σ and are mostly sub-millimeter.

	Distance [m] from	Campaign 2013		Campaign 2014		Campaign 2017a		Campaign 2017b	
Benchmark	KEPGO-KEP-004	Height [m]	SD [m]	Height [m]	SD [m]	Height [m]	SD [m]	Height [m]	SD [m]
KEPGO-KEP-004	0	3,7600		3,7600		3,7600		3,7600	
UKHO-ISTS-061	68	3,0757	0,0003	3,0749	0,0001	3,0753	0,0001	3,0753	0,0001
KEPGO-KEP-003	140	2,7704	0,0006	2,7676	0,0002				
KEPGO-KEP-002	174	2,8145	0,0007	2,8124	0,0002	2,8126	0,0002	2,8128	0,0002
UKHO-HD-9798	205	1,3465	0,0010	1,3396	0,0003	1,3350	0,0003	1,3349	0,0003
KEPGO-KEP-001	235	1,3229	0,0012	1,3154	0,0003	1,3089	0,0003	1,3087	0,0003
Tide Board	235			1,1531	0,0003	1,1469	0,0003	1,1466	0,0003
TG	235	0,6560	0,0012	0,6469	0,0005				

GNSS Time Series and Vertical Rates

The daily height time series for the five GNSS stations on South Georgia Island are presented in Figure 5. Currently the time series only reach up to the end of 2016 but further processing runs are foreseen to bring the data time span up to the end of 2017 and beyond. This means that currently the time series range from 2,2 to 4,0 years in length, which is still too short for interpretations. Nevertheless, a preliminary analysis is attempted. Figure 5a (left panel) shows the full length of solutions for each station while in Figure 5b (right panel) shows the time series trimmed to be of equal length. One can see that the vertical rates for the full time series range from 2,3 to 4,3 mm/yr with uncertainties generally at the 1-2 mm/yr level and a mean rate of 3,3 mm/yr. The trimmed height time series show a similar range for the vertical rates with the largest change at KEPA of -0,7 mm/yr. Despite the shortness of the time series and the large uncertainties, these results indicate a general pattern of uplift at 2-4 mm/yr for South Georgia Island. Interestingly there is also agreement within the error bounds between KEPA and KRSA, suggesting that KRSA is on fairly stable ground, which is also being shown by the levelling results.

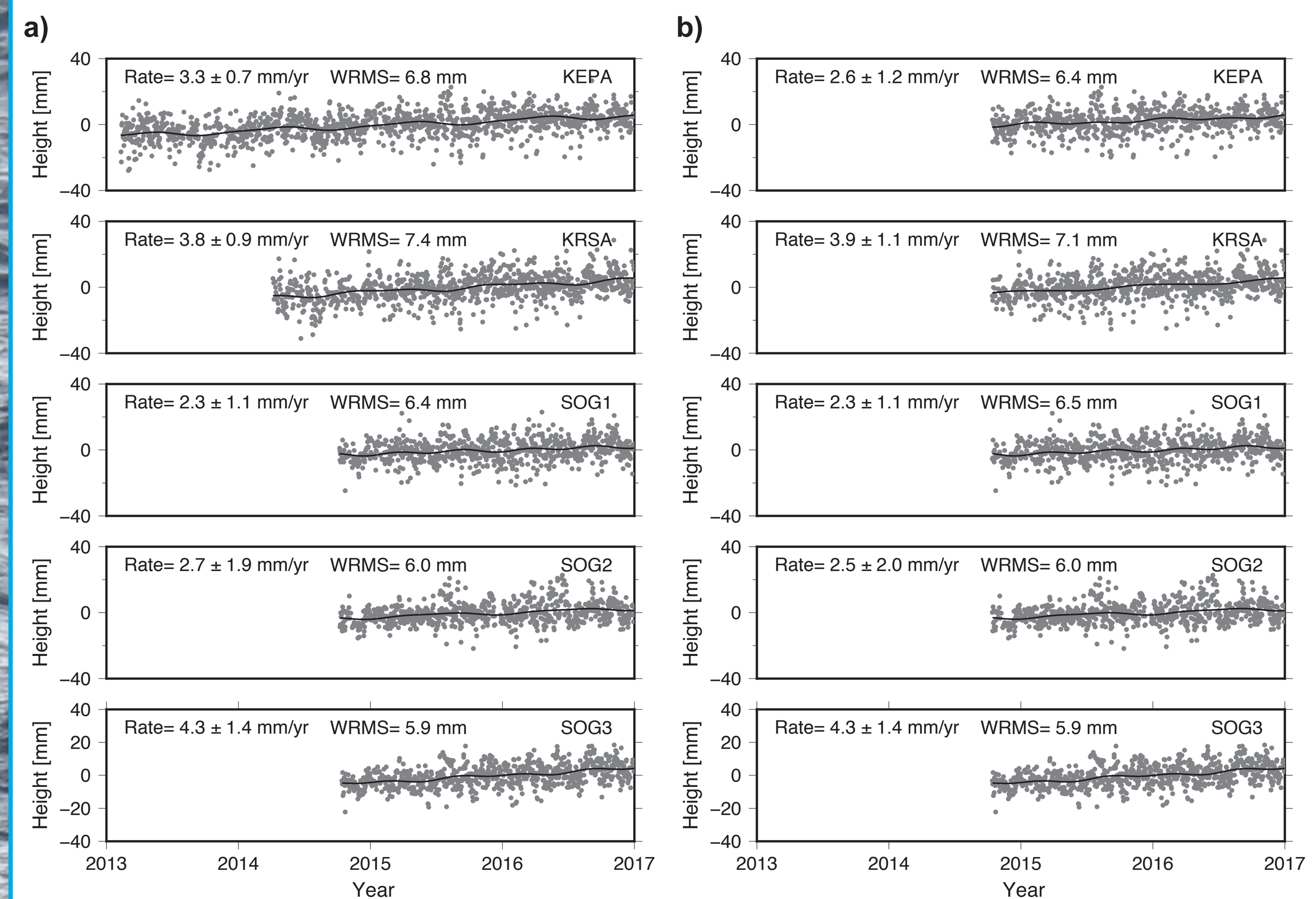

Figure 5: Height time series for the five GNSS stations on South Georgia Island. Left panels (a) show the full time series while the right panels show the trimmed time series. Vertical rates and uncertainties stem from the Hector Software [Bos et al., 2012] and assume a white plus power-law noise model.

Sea Level Information

Sea level information is available for the KEP tide gauge from the Permanent Service for Mean Sea Level (PSMSL) [Holgate et al., 2013] metric data base as monthly mean values and from the IOC Sea Level Station Monitoring Facility (www.ioc-sealevelmonitoring.org) as raw values. Here the daily mean values from 2008 to present have been used (Figure 6).

The satellite altimeter data was provided by Brian Beckley and Xu Yang of NASA and was derived from the NASA MEaSUREs v4.2 data set of merged TOPEX/JASON/OSTM altimetry. No inverted barometer (IB) and dynamic atmospheric correction (DAC) combined correction were applied to the data. The altimetry data are the 10-day averaged values. Figure 7 shows the ground tracks of the TOPEX/JASON/OSTM altimetry missions (tracks 059, 102, 176 and 237) and those of Sentinel-3 for completeness (not used yet).

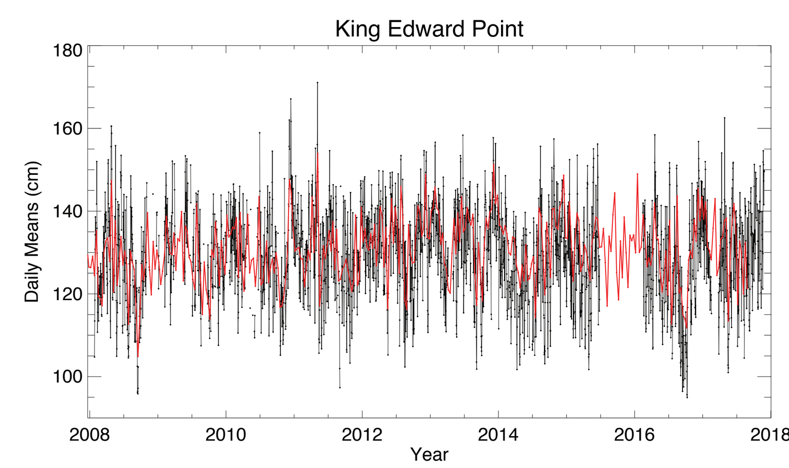

Figure 6: Sea level data for King Edward Point from daily mean tide gauge records (black line) and 10-day average satellite altimeter data (red line). Several data gaps in the tide gauge record are visible and need to be investigated.

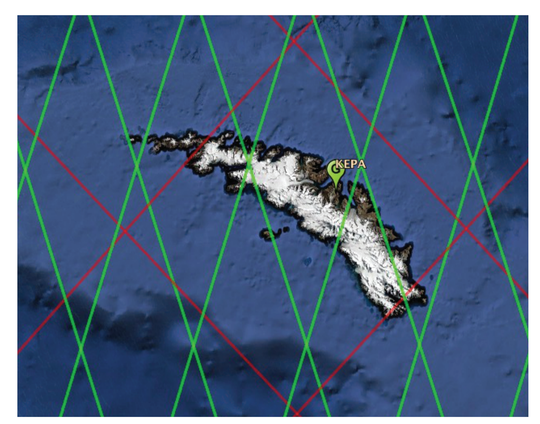

Figure 7: KEP tide gauge and satellite altimetry mission ground tracks for TOPEX/POSEIDON/JASON (red lines) and Sentinel-3 (green lines - for future reference).

Impact on Sea Level Estimates

As outlined above the vertical rates obtained for the GNSS height time series indicate uplift of South Georgia Island at the 2-4 mm/yr level. This is potentially due to a combination of ongoing tectonic processes, GIA associated with the unloading since the last Pleistocene glaciation period and on local scales also due to present-day ice mass loss. It is noteworthy that none of the five GNSS stations are close to any of the large glaciers, so this effect, if present, is most likely negligible. At this time the largest vertical uplift is suggested for SOG3, which is located on Annenkov Island to the south of the main island.

The vertical rates for KEPA and KRSA are similar although the one for KRSA seems slightly larger. At this stage this difference might be an effect of the time series length rather than real differential movement. Nevertheless, this indicates that KRSA is fairly stable, complementing the levelling results.

The levelling results suggest subsidence of the tide gauge with respect to the stable benchmarks and KRSA. Looking at the height differences between the campaigns in 2013, 2014 and 2017 (Figure 8) one can compute a vertical rate for KEPGO-KEP-001 of -3,1 mm/yr for 2013,16-2017,25 (Figure 9) and for the tide board of -2,1 mm/yr for 2014,25-2017,25) i.e. 2-3 mm/yr. This suggests that the local subsidence of the jetty is at a similar magnitude, although opposite in sign, as the overall uplift estimate for South Georgia Island. Clearly, this would reduce the impact of the vertical land movements on the sea level estimates.

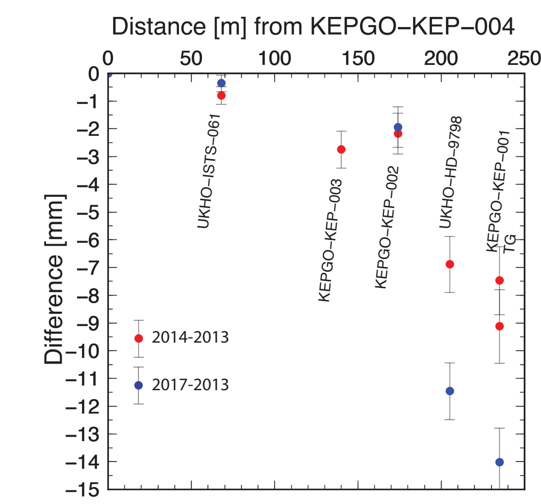

Figure 8: Height differences for benchmarks observed during the 2013, 2014 and 2017 levelling campaigns. Analysis assumes KEPGO-KEP-004 has been stable during the period. Uncertainties are 1-σ. It can be seen that KEPGO-KEP-001 subsided by 1,4 cm over the 4 year period.

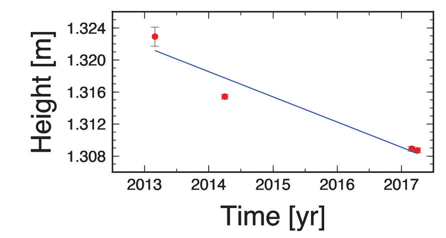

Figure 9: Height for benchmark KEPGO-KEP-001 for the four campaign epochs with trend line.

While the original idea for this study was to reconcile the sea level information from satellite altimetry and the KEP tide gauge by use of the available vertical land movement estimates, this was not possible due to the short-ness of the GNSS time series and the data period processed to date. Furthermore, it seems that the tide gauge record itself may need to be examined closely for discontinuities judging from the discrepancy in the sea level trends shown in Figure 10. With monitoring starting in 2013, there is no information on the regional uplift and local subsidence at the tide gauge before then. Needless to say that with current error bounds a szenario is emerging but no final conclusions can be drawn.

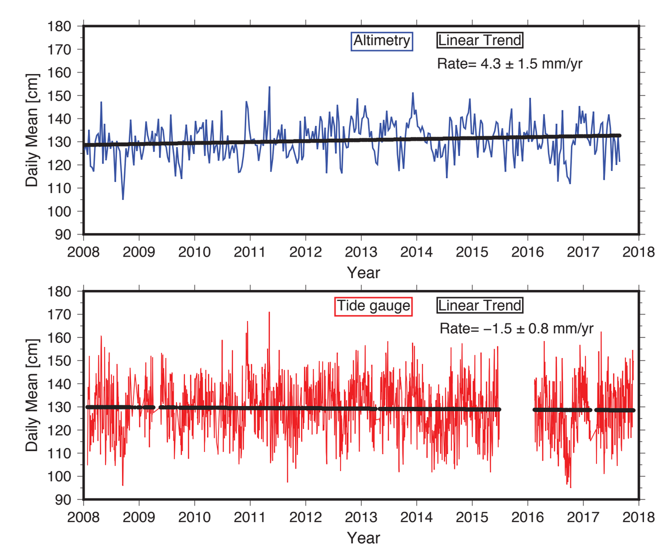

Figure 10: Sea level information from satellite altimetry (top panel) and KEP tide gauge (bottom panel) with trend estimates and trendline from least-squares.

Conclusions

We have presented a first and preliminary analysis of the present-day vertical land movements observed for South Georgia Island from a combination of GNSS and precise levelling results. The GNSS data stem from five stations covering the full extend of the island of which two stations are close to the tide gauge at King Edward Point. The analysis of the GNSS height time series suggests general uplift of the island of 2 to 4 mm/yr with the station on Annenkov Island to the south potentially showing a larger trend. Four levelling campaigns have been carried out since 2013. The results suggest that most benchmarks are stable except for those near the jetty, which are subsiding at a rate of -2 to -3 mm/yr. It can be argued that the general uplift is compensated for by local subsidence potentially leading to a no-net vertical land movements contribution to sea level measured by the tide gauge. The sea level data from the King Edward Point tide gauge and and a composite satellite altimetry record have been compared. In general the two time series agree well in their features but show a significant difference in the sea level rate. It seems that this difference cannot be explained by the observed vertical land movements and must be due to the shortness of the time series or inconsistencies in the sea level record of the tide gauge. To achieve the objectives and reconcile the sea level information, further analysis is necessary, employing besides the careful revision of the methodology, more GNSS, levelling and sea level data.

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