Consolidating Geodetic Observation of Land and Sea Level Changes around South Georgia Island

AGU FM2019 G51C-0603

Norman Teferle(1), Addisu Hunegnaw(1), Angela Hibbert(2), Simon Williams(2), Philip Woodworth(2),
Ian Dalziel(3), Robert Smalley(4) and Larry Lawver(3)

1) University of Luxembourg, Grand-Duchy of Luxembourg
2) National Oceanography Centre, United Kingdom
3) University of Texas at Austin, USA
4) University of Memphis, USA

Contact: Norman Teferle (email: norman.teferle@uni.lu)

Université du Luxembourg

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

The University of Memphis. Center for Earthquake Research and Information

Scan to download this Poster!

Abstract

With its mid-ocean location in the Southern Atlantic Ocean South Georgia Island is in a key position for the oceanic and geodetic global monitoring networks. Since 2013 the tide gauge at King Edward Point (KEP) with GLOSS ID 187 has been monitored using a GNSS station nearby on Brown Mountain. By accurately geo-referencing the tide gauge and monitoring any vertical land movements, a continuous record of its datum within the Permanent Service for Mean Sea Level (PSMSL) can be established, which in turn makes the recorded and averaged sea levels useful for long-term studies and satellite altimetry calibrations.

In 2014 another GNSS station was installed at KEP after local subsidence was suspected and later on, three additional GNSS stations came to service at the periphery of the main island, making it possible to monitor uplift/subsidence wider afield. 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, i.e. the stability of the jetty upon which the tide gauge is mounted.

In this study, we will present the results from the GNSS and precise levelling measurements, and will discuss their impact on the sea level record from the KEP tide gauge and nearby satellite altimetry sea surface heights. This study comes at a timely manner as during the Austral Summer 2019/2020 the jetty will be stabilized and enlarged, and consequently the current tide gauge will be replaced by a new one. Our measurements show that uplift is observed all over South Georgia Island while the area at the KEP jetty with tide gauge are subsiding relative to the rest of the island. In contrast, results for the tide gauge record show a lower magnitude of ob-served sea level rise than expected from nearby satellite altimetry. We will revisit all geodetic and oceanic observations in an attempt to improve the agreement between these measurements to summarize the status before the work at the jetty begins.

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 (SGM), which measures about 300 x 150 km and includes the shelf area around the island (see Smalley et al., 2019). 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 SGM 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 SGM and the associated shelf areas [Smalley et al., 2007; 2019]. 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 (Barlow et al., 2016). 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 with the latest sensor being installed in 2008. In 2014 a e visual tide staff was added, allowing regular cross checks of the sea level readings from the visual observations and the tide gauge records. Furthermore, the ground tracks of TOPEX/POSEIDON/Jason/Sentinel satellite altimetry missions reach within several 10s of km of the tide gauge, hence there is potential for the tide gauge data to be useful for altimeter calibration over the South Atlantic Ocean.

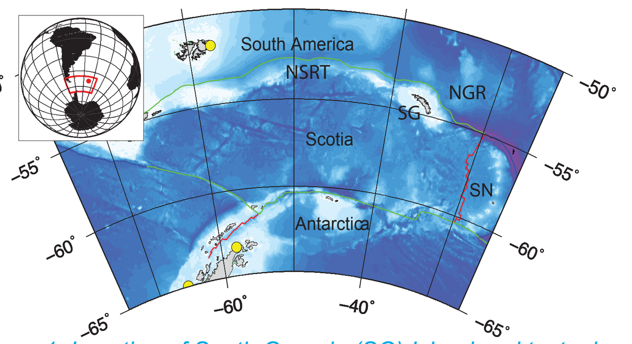

Figure 1: Location of South Georgia (SG) Island and tectonic plates in the South Atlantic Ocean (University of Texas at Austin): transforms/fracture zones (green), ridges (red) and trenches (blue); continuous GNSS stations (yellow circles); NSRT: North Scotia Ridge Transform, NGR: Northeast Georgia Rise,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

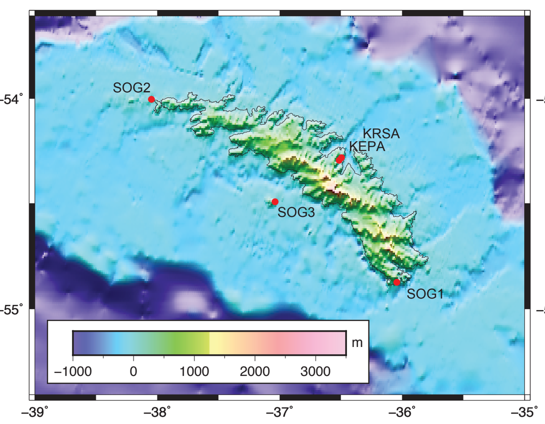

Figure 2: South Georgia Island with shelf area. Continuous GNSS stations (red circles). KEPA and KRSA are located at King Edward Point (KEP).

With the large potential for vertical movements at KEP, the tide gauge was equipped with a GNSS station to monitor any uplift or subsidence. This has led to the establishment of the King Edward Point Geodetic Observatory (KEPGO) [Teferle et al., 2014]. In 2014 a US-led project established three GNSS stations at the perimeter of South Georgia Island to investigate present-day tectonic processes [Smalley et al., 2019]. During the Austral Summer 2019/2020 the jetty, which holds the tide gauge, will be upgraded and a new one will be installed, which has triggered the authors to take stock of all results so far in this presentation.

GNSS Data Set and Processing

The full history of GPS data collected for the SGM stations was reanalyzed using the PRIDE software developed and maintained by The PRIDE Lab at the GNSS Research Center of Wuhan University, China. PRIDE is an open source Precise Point Positioning (PPP) software that allows for integer ambiguity resolution (AR – fixed PPP) using a special bias product and, thus, is highly computationally efficient while not showing the effects of previous float PPP solutions. This means our approach is different to the previously shown results for SGM using the Bernese GNSS Software version 5.2 [Dach et al, 2015] and a global network of stations. PRIDE is consistent with the International Earth Rotation and Reference Systems Service (IERS) 2010 conventions [Petit and Luzum, 2010] and due to the fact that the satellite orbit and clock products as well as the employed antenna phase centre models are consistent with IGS repro 2 and ITRF2008 [Altamimi et al., 2007], the PRIDE solutions here are also in this frame. 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. Further processing settings are listed in Table 1.

Processing Strategy	Estimated Parameters
Elevation angle cut off: 3 degrees	Station coordinates
Weighting: Elevation-dependent data weighting	Receiver clocks
A priori hydrostatic delay, VMF3	2-hour zenith tropospheric delay
CODE satellite orbit and clocks products	12-hour horizontal tropospheric gradients
Solid Earth tides, ocean tides, pole tides, relativistic effects (IERS Conventions 2003)	Integer phase ambiguities

Table 1: PRIDE software processing strategy and estimated parameters

GNSS Time Series and Vertical Rates

The daily height time series for the five GNSS stations on the SGM are presented in Figure 3. Currently the time series only reach to 2019. This means that currently the time series range from 4.3 to 6.0 years in length, which is still relatively short for interpretations of the small vertical motions. At KRSA and SOG2 the time series end before 2019 due to receiver problems. Despite the shortness of the time series and the still large uncertainties, these results indicate a general pattern of uplift at 1.1-3.4 mm/yr for the SGM. It is noted that some of the variation in the uplift is due to the different time series lengths, which was discussed in Teferle et al. [2017]. Also shown are the uplift estimates derived from geological information [Barlow et al., 2016], which are generally lower and less spatially variable.

A difference of 1.1 mm/yr is seen in the rates for KEPA and KRSA, two stations only 1.9 km apart, with KEPA on bedrock and KRSA on concrete foundations near the tide gauge. Using the Dual-CGPS analysis [Teferle et al., 2002] this difference is further investigated. The subtraction of one time series from the other reduces the day-to-day scatter of the difference time series due to the correlation in the daily GPS solutions and allows a better estimation of the relative rate between the two stations despite the shortness of the series. Figure 4 shows the difference time series of the daily height solutions for KEPA and KRSA. As can be seen the relative vertical rate is -0.4 ± 0.4 mm/yr, indicating a smaller difference and suggesting that despite its loctaion, KRSA might also be fairly stable. Moreover, the RMS/WRMS statistics in both figures indicate an improvement in the time series scatter of 47% for the difference time series. Nevertheless, as was indicated by Teferle et al. [2002], this could be somewhat better and this suggests some de-correlation in the position solutions of the two stations, most likely due to the larger signal obstructions at KRSA and the different multipath environments.

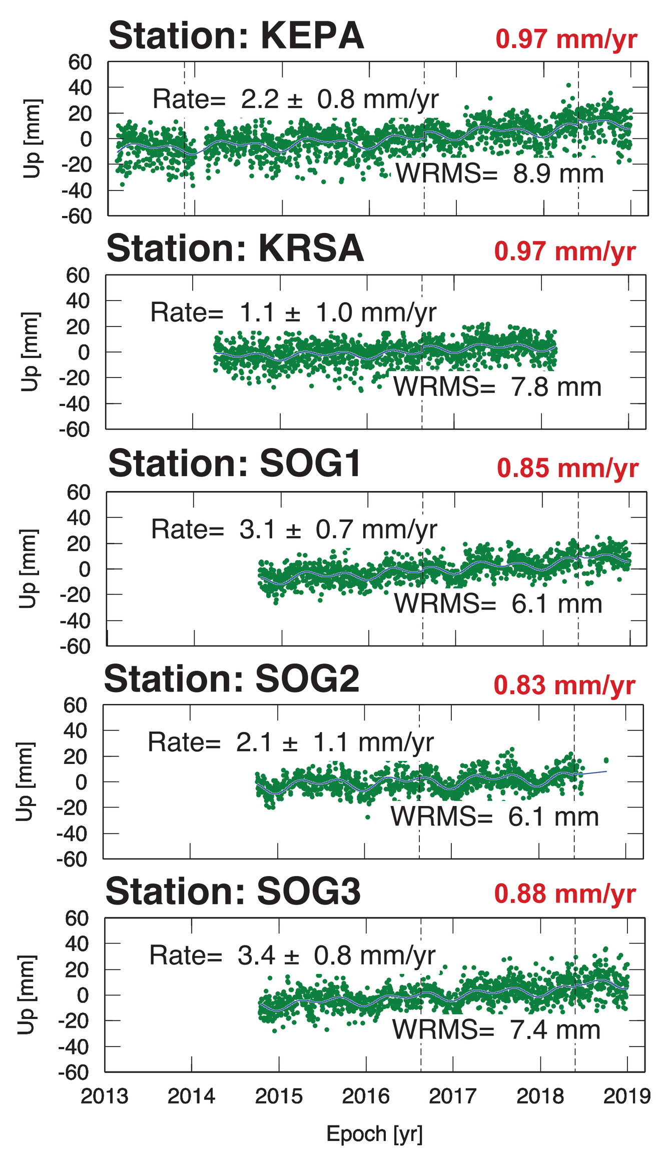

Figure 3: Height time series for the five GNSS stations on South Georgia Island. Vertical rates and uncertainties stem from the Hector Software [Bos et al., 2012], include annual and semi-annual periodic terms and assume a white plus power-law noise model. The uplift rates from geology [Barlow et al., 2016] are shown in red.

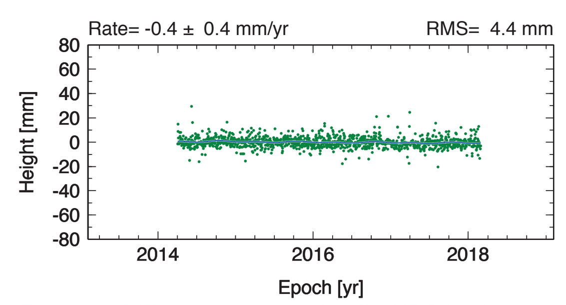

Figure 4: Difference time series for KRSA minus KEPA following the dual-CGPS station analysis [Teferle et al., 2002]. The difference rate and uncertainty stem from the Hector Software [Bos et al., 2012], include annual and semi-annual periodic terms and assume a white plus power-law noise model.

Table 2: Previous (BSW5.2 2017) and current (PRIDE 2019) vertical velocity estimates and uncertainties for the five GNSS stations.

	2017		2019	
Station	Time Span [years]	BSW5.2 [mm/yr]	Time Sapn [years]	PRIDE [mm/yr]
KEPA	4.0	3.3 ± 0.7	6.0	2.2 ± 0.8
KRSA	2.6	3.8 ± 0.9	4.6	1.1 ± 1.0
SOG1	2.3	2.3 ± 1.1	4.3	3.1 ± 0.7
SOG2	2.3	2.7 ± 1.9	4.3	2.1 ± 1.1
SOG3	2.3	4.3 ± 1.4	4.3	3.4 ± 0.8

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 5 shows this benchmark network which incorporates two benchmarks used by the United Kingdom Hydrographic Office (UKHO).

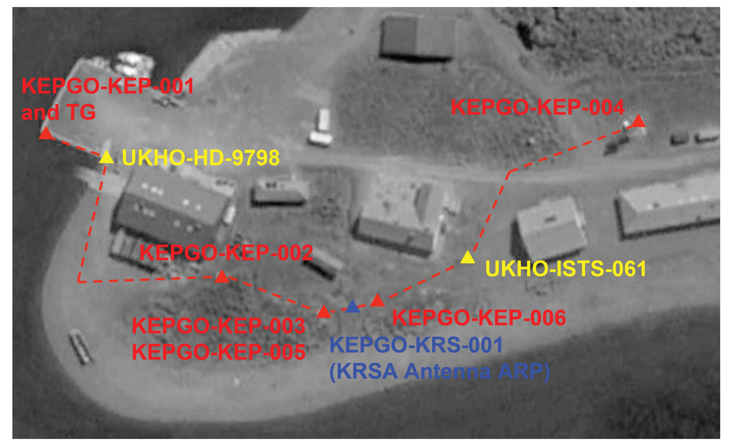

Figure 5: Benchmark network at KEP Research Station: tide gauge (TG) and KEP Geodetic Observatory (red), KRSA antenna and monument (blue) and UKHO (yellow). UKHO-ISTS-061 is the International Satellite Tracking Station Number 061 and was established in 1967/68.There are five benchmarks at the KRSA antenna 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, one in Febuary and one in March, were carried out using a high-precision digital level with Invar staff by two BAS personnel from KEP. The results of these were presented in Teferle et al. [2017] and are not shown here. Then, the levelling results suggested subsidence of the tide gauge with respect to the stable benchmarks (Figure 6) with a vertical rate for KEPGO-KEP-001 of -3,1 mm/yr for 2013,16-2017,25 (Figure 7) and for the visual tide staff of -2,1 mm/yr for 2014,25-2017,25, i.e. 2-3 mm/yr.

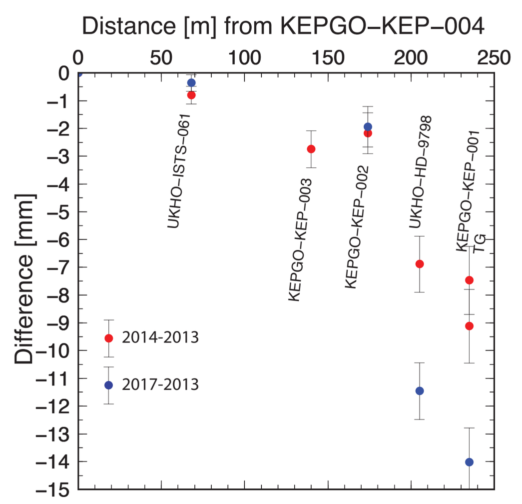

Figure 6: Height differences for benchmarks observed during the 2013, 2014 and 2017 levelling campaigns. Analysis assumes KEPGO-KEP-004 has been stable during the period. Uncertainties are 1-σ. It can be seen that KEPGO-KEP-001 subsided by 1,4 cm over the 4 year period.

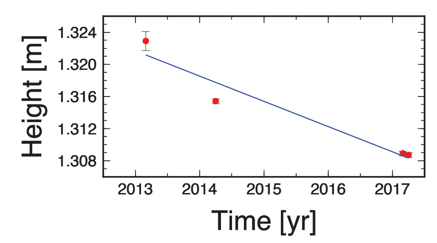

Figure 7: Height for benchmark KEPGO-KEP-001 for the four campaign epochs.with trend line.

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 8).

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 9 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).

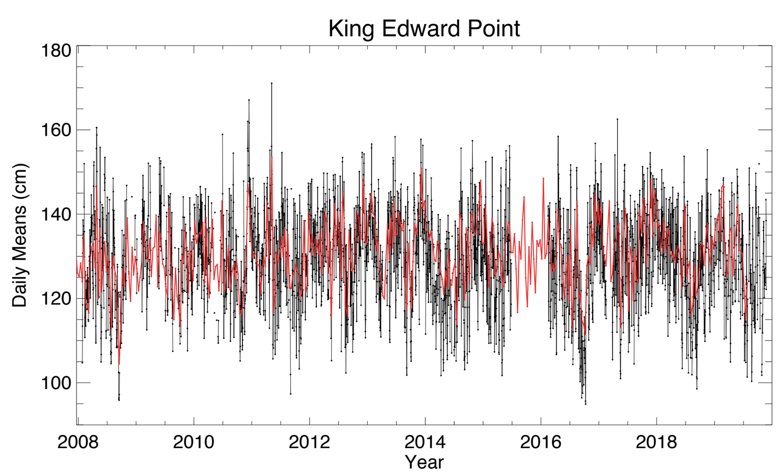

Figure 8: Sea level data for King Edward Point from daily mean tide gauge records (black line) and 10-day average satellite altimeter data (red line). Several data gaps in the tide gauge record are visible and need to be investigated.

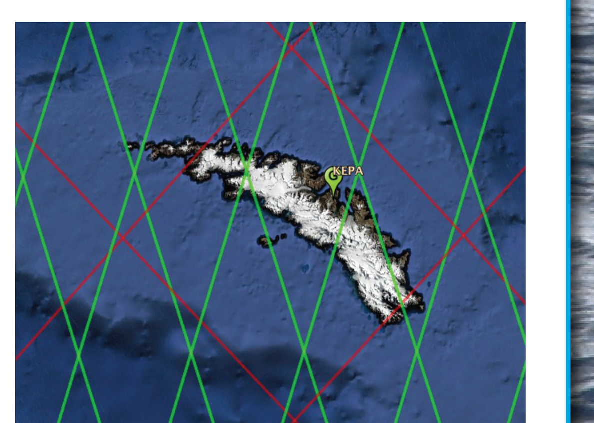

Figure 9: KEP tide gauge and satellite altimetry mission ground tracks for TOPEX/POSEIDON/-JASON (red lines) and Sentinel-3 (green lines - for future reference).

Tide Gauge Performance and Sea Level Comparison

Since the installation of the visual tide staff in 2014 monthly readings, each in the form of 10 x 3 min averages, have been taken, which allow the implementation of the tide gauge datum and a performance analysis of the instrumentation [GLOSS Manuals and Guides 14, 1985]. A comparison of the tide gauge with the visual tide staff readings link the tide gauge measurements to the benchmark network and consequently to the geocentre via the GNSS measurements. The comparison between these is shown in Figures 10 and 11.

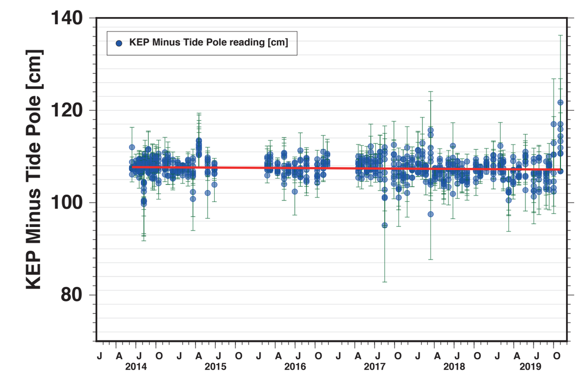

Figure 10: KEP tide gauge minus the visual tide staff reading for 2014-2019. There is high consistency over the complete time span with few outlying monthly comparisons. The trend, as indicated by the red line, is slightly negative, indicating little or no drift.

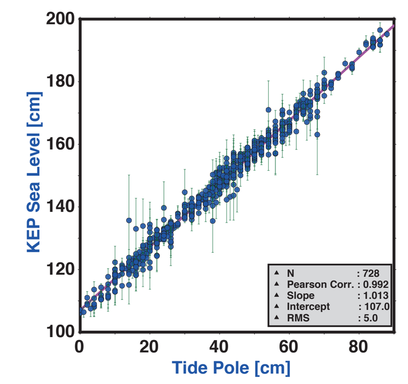

Figure 11: Correlogram between KEP tide gauge and visual tide staff readings. There is consistency over the range of tidal readings.

While Figures 10 and 11 demonstrate the good performance of the tide gauge, Figure 12 compares the 10-day altimetry means to the daily tide gauge means. Despite the fact that we do not list a rate estimate, the trendlines in Figure 12 clearly suggest different trends. Teferle et al. [2017] calculated the long term trends in sea level from the tide gauge and nearby satellite altimetry for 2008-2017.8 to be -1.5 ± 0.8 mm/yr and 4.3 ± 1.5 mm/yr, respectively. Adding the data for 2019 changes these to -0.2 and 4.0 mm/yr. While the estimate from satellite altimetry somewhat agrees with the overall rate for the South Atlantic of 2.7 ± 0.5 mm/yr (1993-2015) [Dangendorf et al., 2019], the estimate from the tide gauge does not. Hence, the original idea to reconcile the sea level information from satellite altimetry and the KEP tide gauge by use of the available vertical land movement estimates is currently not possible and further investigations are needed.

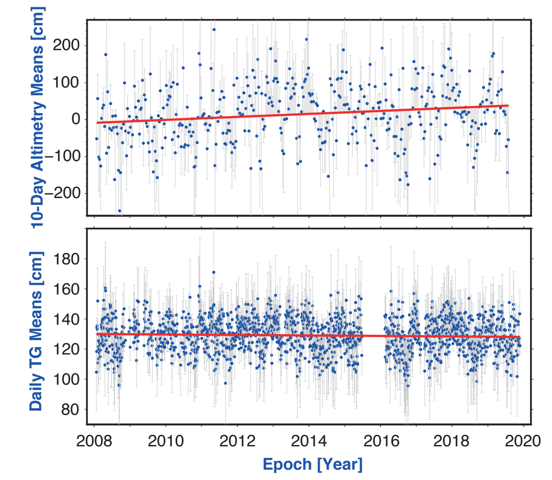

Figure 12: Sea level information from satellite altimetry (top panel) and KEP tide gauge (bottom panel) with trendline from least-squares.

Conclusions

We have presented vertical land movement estimates for five GNSS stations distributed across South Georgia Island and precise levelling results from KEP Research Station. Together, these allow for the tide gauge to be geo-referenced and for its sea level record to be used for climate studies and satellite altimeter calibrations.

The analysis of the GNSS height time series suggests general uplift of the island of 1.1 to 3.4 mm/yr, slightly lower than our previous estimates, likely due to the longer time series, and somewhat larger than the rates from geology (Barlow et al., 2016), which also show less spatial variation.

The levelling results suggest that the KEP benchmarks are stable except for those near the jetty, which are subsiding at a rate of approximately -3 mm/yr. From this it could be assumed that the general uplift of the island is counteracted by local subsidence, potentially leading to a no-net vertical land movements contribution to sea level measured by the tide gauge.

Using a visual tide staff good tide gauge performance has been demonstrated with no obvious drift and no clear scale issue at the different water levels observed. Hence the tide gauge record can be employed to measure geocentric sea level.

The sea level data from the KEP tide gauge 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 other factors that require further investigations to reconcile the sea level information.

Finally, with the upgrade of the jetty, the installations of a new tide gauge and visual tide staff become necessary. This requires the establishment of new benchmarks close to the tide gauge on the jetty and further high-precision levelling campaigns. Furthermore, sea level from the tide gauge and from satellite altimetry need to be regularly cross-evaluated.

Acknowledgements

This work is funded through the University of Luxembourg (UL) Research Projects GSCG and SGSL, and used the UL High Performance Computing (ULHPC) facility. Colleagues from the University of Memphis are funded through the NRF Grant (PLR-1245660). The authors would like to thank numerous colleagues from the University of Luxembourg, National Oceanography Centre, British Antarctic Survey and the Government of South Georgia and the South Sandwich Islands for their continued support of our work in South Georgia. Furthermore, data and products provided by the IGS and its ACs, and UNAVCO Inc. are highly appreciated [Johnston et al., 2017].

References

Altamimi, Z., et al. (2011). ITRF2008: an improved solution of the international terrestrial reference frame. Journal of Geodesy 85(8): 457-473.
Barker, P. F. (2001). Scotia Sea regional tectonic evolution: implications for mantle flow and palaeocirculation. Earth-Sci Rev 55: 1-39.
Barlow, N.L.M. et al. (2016) Testing models of ice cap extent, South Georgia, sub-Antarctic. Quaternary Science Reviews 154: 157-168.
Bentley, M. J., et al. (2007). Glacial geomorphology and chronology of deglaciation, South Georgia, sub-Antarctic. Quaternary Sci Rev 26(5–6): 644-677.
Gordon, J. E., et al. (2008).Recent glacier changes and climate trends on South Georgia. Global Planetary Ch 60(1-2): 72-84.
Bos MS, et al (2012) Fast error analysis of continuous GNSS observations with missing data. J Geodesy 87(4):351–360, DOI 10.1007/s00190-012-0605-0
Dach, R., et al. (2015). Bernese GNSS Software Version 5.2 Astronomical Institute, University of Bern: 884.
Dangendorf, S.,et al. (2019) Persistent acceleration in global sea-level rise since the 1960s. Nature Climate Change 9(9), 705-710.
Graham, A. G. C., et al. (2008). A new bathymetric compilation highlighting extensive paleo–ice sheet drainage on the continental shelf, South Georgia, sub-Antarctica. GGG 9(7): Q07011.
Holgate, S.J., et al. (2013) New Data Systems and Products at the Permanent Service for Mean Sea Level. J Coastal Res: 29(3), pp. 493 – 504.
Johnston, G., et al. (2017). The International GNSS Service. In Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967-982), Springer, DOI: 10.1007/978-3-319-42928-1.
Petit, G. and B. Luzum, Eds. (2010). IERS Conventions (2010). Frankfurt am Main, Bundesamt für Kartographie und Geodäsie.
Smalley, R., Jr., et al. (2007). Scotia arc kinematics from GPS geodesy. GRL 34(21): L21308.
Smalley, R., Jr., et al. (2019). The current tectonic setting of South Georgia Island based on GPS geodetic and marine seismic reflection data. AGU Fall Meeting 2019, Abstract Number G34A-01.
Teferle, F. N., et al. (2002). Application of the dual-CGPS concept to monitoring vertical land movements at tide gauges. Phys. Chem. Earth 27(32-34): 1401-1406.
Teferle, F. N., et al. (2014). The King Edward Point Geodetic Observatory, South Georgia, South Atlantic Ocean A First Evaluation and Potential Contributions to Geosciences. IAG Symposia. Download at: http://hdl.handle.net/10993/17029.
Teferle, F. N., et al. (2017). First Vertical Land Movement Estimates on South Georgia Island: An Impact Study on Sea Level Change from Tide Gauge and Altimetry Measurements. AGU Fall Meeting 2017. Download at: http://hdl.handle.net/10993/33530.
White, D. A., et al., (2017). Was South Georgia covered by an ice cap during the Last Glacial Maximum? in Exploration of subsurface Antarctica: Uncovering Past Changes and Modern Processes, Geological Society, London Special Publications, 461.

Presented at: *American Geophysical Union Fall Meeting 2019, San Francisco, California, USA, December 9-13, 2019*