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The King Edward Point Geodetic Observatory, South Georgia, South Atlantic Ocean

A First Evaluation and Potential Contributions to Geosciences

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Abstract During February 2013 the King Edward Point (KEP) Geodetic Observatory was established in South Georgia, South Atlantic Ocean, through a University of Luxembourg funded research project and in collaboration with the United Kingdom National Oceanography Centre, British Antarctic Survey, and Unavco, Inc. Due to its remote location in the South Atlantic Ocean, as well as being one of few subaerial exposures of the Scotia tectonic plate, South Georgia Island has been a key location for a number of global monitoring networks, e.g. seismic, geomagnetic and oceanic. However, no permanent geodetic monitoring station has been established previously, despite the lack of observations from this region. In this study we will present an evaluation of the GNSS and meteorological observations from the KEP Geodetic Observatory for the period from 14 February to 31 December 2013. We calculate multipath and positioning statistics and compare these to those from IGS stations using equipment of the same type. The on-site meteorological data are compared to those from the nearby KEP meteorological station and the NCEP/NCAR reanalysis model, and the impact of these data sets on integrated water vapour estimates is evaluated. We discuss the installation in terms of its potential contributions to sea level observations using tide gauges and satellite altimetry, studies of tectonics, glacio-isostatic adjustment and atmospheric processes.

Keywords Global Navigation Satellite Systems · King Edward Point Geodetic Observatory · South Georgia Island · South Atlantic Ocean

1 Introduction

During February 2013 the King Edward Point (KEP) Geodetic Observatory was established in South Georgia, South Atlantic Ocean, through a collaboration between the University of Luxembourg, National Oceanography Centre, and the British Antarctic Survey. Unavco, Inc supported the project by procuring and configuring the equipment. The primary objectives of the observatory are to measure crustal movements close to the tide gauge at KEP using a state-of-the-art autonomous, continuous Global Navigation Satellite System (GNSS) station and to establish a network of stable benchmarks to provide a long-term vertical datum at KEP research station.

With its remote location, South Georgia is one of few land areas in the ocean-dominated Southern Hemisphere, which can be employed to densify the global geodetic infrastructure and counteract the hemisphere imbalance in ground-based observations (Figure 1a). Although KEP research station hosts instruments for a number of global monitoring networks, e.g. the seismic (IRIS, 2011), geomagnetic (Harris et al., 2011) and oceanic (IOC, 2012) networks, no permanent geodetic monitoring station has been established previously despite the lack of observations from this region. It is noteworthy that the Scientific Commitee of Antarctic Research (SCAR) established the campaign Global Positioning System (GPS) station GRY1 near KEP research station (Figure 1b) and observed it for two days during 1998 (Dietrich et al., 2001). However, no re-

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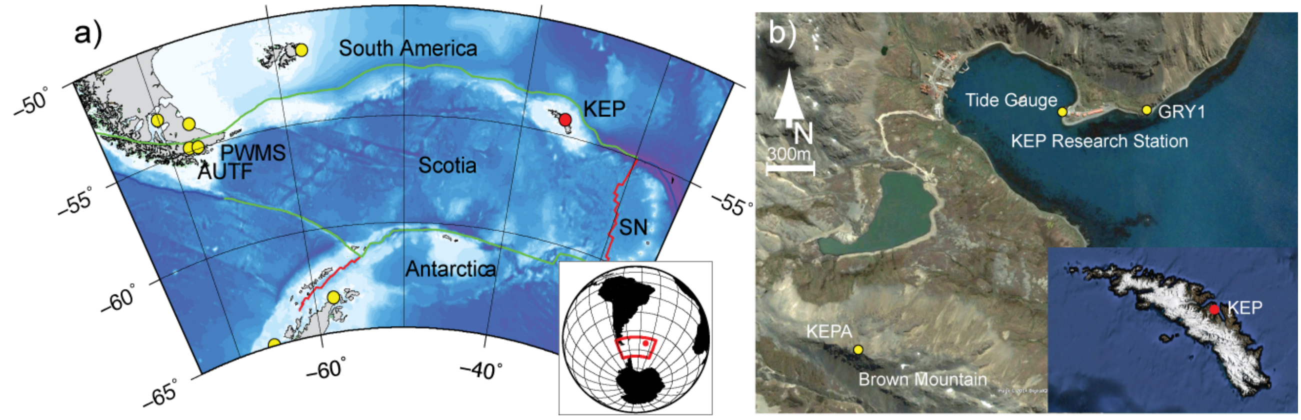

Fig. 1 a) Location of King Edward Point (KEP - red circle), South Georgia and tectonic plates in the South Atlantic Ocean (SN denotes the South Sandwich Plate). The plate boundaries include transforms/fracture zones (green), ridges (red), and trenches (blue) according to Smalley et al. (2007). Existing continuous GNSS stations are shown as yellow circles. b) Locations of KEPA continuous and GRY1 campaign GNSS stations, and of the tide gauge with respect to KEP research station. Imagery from Google Earth.

occupation has been carried out. Hence, with the large number of GNSS applications in the geosciences today, the importance of establishing and maintaining a continuous GNSS station on South Georgia Island, which follows the recommendations of the International GNSS Service (IGS) (Dow et al., 2009), cannot be underestimated.

Besides the application to sea level research the first crustal movement estimates from the KEP Geodetic Observatory (KEPGO) will provide valuable information on present-day geophysical processes. South Georgia Island is one of few subaerial exposures of the Scotia plate (Figure 1a). The only two other continuous GNSS stations on this largely oceanic plate are those in Ushuaia, Argentina (AUTF) and Puerto Williams, Chile (PWMS) (Smalley et al., 2003). Although information from geology, geophysics, seismology and satellite altimetry has led to a reasonable understanding of the Scotia Sea tectonic evolution (Barker, 2001), i.e. it is expected that the northern edge of the Scotia plate forms a left lateral transform with the South American plate, which has a transform rate of approximately 7 mm/yr (Thomas et al., 2003), there is still an incomplete understanding of the tectonic history of South Georgia and its associated shelf areas (Smalley et al., 2007). Furthermore, the recent study by Graham et al. (2008) revealed that the entire shelf area has been glaciated to the edges during the Cenozoic. Although it is believed that the glaciation and deglaciation cycles may have occurred several times, it is not clear if the shelf was covered during the Last Glacial Maximum (Bentley et al., 2007; Gordon et al., 2008). Hence, both regional and global glacial isostatic adjustment models may benefit from additional constraints from GNSS observations on South Georgia Island.

Besides the GNSS station the observatory also operates a weather station, which records a number of atmospheric variables in order to derive accurate integrated water vapour (IWV) estimates (Bevis et al., 1992). These meteorological observations together with the IWV products will contribute an important record of atmospheric conditions for South Georgia, potentially helping to improve local weather forecasts (Shanklin et al., 2009). Of particular interest will be the GNSS observations for monitoring of the ionosphere over this region, improving both spatial and temporal density of observations useful for ionospheric models, such as the SIRGAS (Sistema de Referencia Geocéntrico para Las Américas) Ionospheric Model (Brunini et al., 2013).

This paper introduces the KEP Geodetic Observatory and its continuous GNSS station. This is followed by an evaluation of the GNSS and meteorological measurements collected over the first ten months of its operation.

2 KEP Geodetic Observatory

The KEP Geodetic Observatory consists of an autonomous, continuous GNSS station (4-char ID: KEPA and DOMES number: 42701M001) with auxiliary equipment on Brown Mountain, as well as benchmarks on Brown Mountain and at KEP research station (Figure 1b). It employs a Trimble NetR9 GNSS receiver, a Trimble choke ring GNSS antenna with the Dorne Margolin element (TRM59800.00), and a SCIS radome. The receiver records GPS, GLONASS and Galileo observa-

Fig. 2 GNSS antenna and radome on 1-metre mast (left) and aluminium pipe frame with electronics and auxiliary equipment (right).

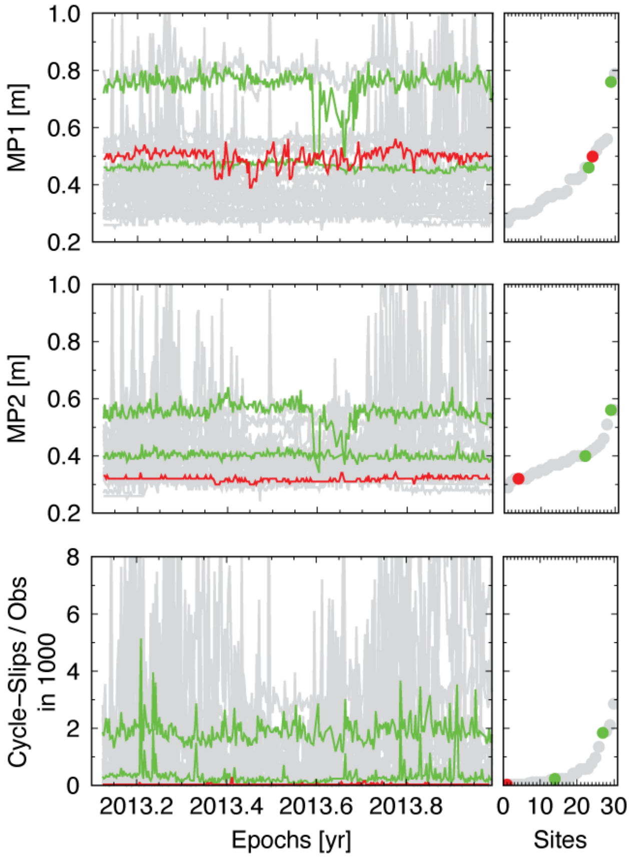

Fig. 3 Time series of quality control metrics MP1, MP2 and cycle-slips-per-observations in 1000 for 30 stations using a Trimble NetR9 receiver for 14 February to 31 December 2013. Shown are IGS stations (grey), CON2 (bottom green) and PHIG (top green) and KEPA (red). The panels on the right show the cumulative distribution of the medians for the quality control metrics for all stations.

tions in two sessions with recording intervals of 1 s and 15 s. The antenna and radome have been absolutely calibrated by the National Geodetic Survey (NGS) prior to installation (Bilich et al., 2012). KEPA is located on the highest point of Brown Mountain, which lies southwest of the research station. The GNSS antenna and monument are bolted onto a rock outcrop with an aluminium pipe frame housing the auxiliary equipment and enclosures approximately 30 m away (Figure 2). A Vaisala WXT-520 weather station is attached to the top of the frame and temperature, pressure, wind speed and wind direction are fed into the GNSS receiver. The GNSS receiver telemeters to KEP research station via an Intuicom EB-1 900 MHz Ethernet two-way radio bridge, which is connected to the existing VSAT communication link. Due to bandwidth limitations of this satellite link, the download of the GNSS data can, for the foreseeable future, only be performed on a daily basis. Further details on equipment and configuration can be found in the technical report of the installation (Teferle, 2013).

3 Results

This section presents the first results for data quality, position estimates and meteorological measurements for 14 February to 31 December 2013.

3.1 Data Quality

The standard tool within the IGS for the analysis of GNSS data quality is Teqc (Estey and Meertens, 1999). It allows the computation of a number of quality control metrics of which the most important ones include code-multipath on L1 and L2, denoted as MP1 and MP2, and the number of cycle slips per observations. The latter ratio can be expressed in terms of cycle-slips-per-observations in 1000, leading to a number close to zero for the optimal case. Estey and Meertens (1999) described the computation of the MP1 and MP2 metrics in detail and here we use the root-mean-square value after fitting a moving average to the absolute multipath values. The computed metrics only partly reflect the multipath environment at a particular site because they dependent on the receiver type and the receiver settings. Hence, for the KEPA data quality evaluation we compare the above metrics only for stations using receivers of the same type and assume that none of the observation data have been filtered. At the time of this study Trimble NetR9 receivers were operated at 27 stations within the global IGS tracking network. Furthermore, CON2 and PHIG, two sites installed and operated by Unavco Inc. in Antarctica, use the same receiver and the same 1-metre antenna mast as KEPA. For this evaluation only the Global Positioning System (GPS) data with a 30 s recording interval have been used.

Figure 3 depicts the time series of the quality control metrics MP1, MP2 and cycle-slips-per-observations for KEPA, CON2 and PHIG, and 27 IGS stations. It can be seen that the data quality of KEPA varies with the MP1 level being fairly high and the levels for the other two metrics being amongst the lowest. This is also shown by the medians for these metrics in the right panels, which have been sorted according to magnitude. Although at different levels, all three time series remain fairly constant over the first ten months of operation and show no spikes, which does not hold true for many of the IGS stations. The cycle-slips-per-observations metric remains consistently low, so that it is hardly visible in the figure and KEPA outperforms all other stations in this metric, which confirms its largely undisturbed environment on top of Brown Mountain.

The MP1 time series for KEPA shows clear variations from mid-May until mid-October. These are also visible in the MP2 time series but to a much smaller degree. As the onset of these variations, i.e. the 16 May, coincides with the first snow cover during the 2013 Austral winter, it is believed that KEPA's multipath levels are susceptible to the local snow conditions, a circumstance which is already being exploited at other stations (Larson & Nievinski, 2012). Unfortunately there are no official snow cover records for South Georgia to confirm this. In this study we inferred information on snow conditions from archived images taken by a webcam at KEP research station and as such, these only show the conditions at the research station and not on Brown Mountian.

Figure 3 also shows that KEPA's data quality metrics are nearly equivalent to CON2 and much better than PHIG. This suggests that not all of the apparent multipath effects at these stations are a consequence of the use of the 1-metre mast, but that there is also be a strong station-specific environmental component.

3.2 Position Estimates

Using 27 IGS stations, CON2 and PHIG, and KEPA daily position estimates were obtained using the Bernese GNSS Software version 5.2 (Dach et al., 2007) in precise point positioning (PPP) mode for 14 February to 31 December 2013. We applied only GPS observations with an elevation cut-off angle of 10° and used the final satellite orbit and clock, as well as the Earth rotation products from the IGS analysis centre CODE (Centre for Orbit Determination in Europe). For more details on the processing strategy the reader is referred to Hunegnaw et al. (2014).

Figure 4 depicts the position time series for KEPA. The figure also indicates outlying (red) and accepted solutions (green) as well as the weighted root mean square (WRMS) as computed from a linear trend fit. An outlier rejection criteria of three times the WRMS was applied and outlying solutions were removed in all three components. The WRMS statistics of 3.6 and 4.6 mm for the North and East components, respectively, are slightly larger than expected. However, the WRMS of the Up component is typical with a value of 6.8 mm. This is confirmed when comparing these to the mean WRMS and standard deviation computed for the other 29 stations: 2.1±0.5 mm (North); 3.2±0.9 mm (East); 6.1±1.5 mm (Up). Furthermore, it is suggested that most outlying solutions can be associated with the North and East components.

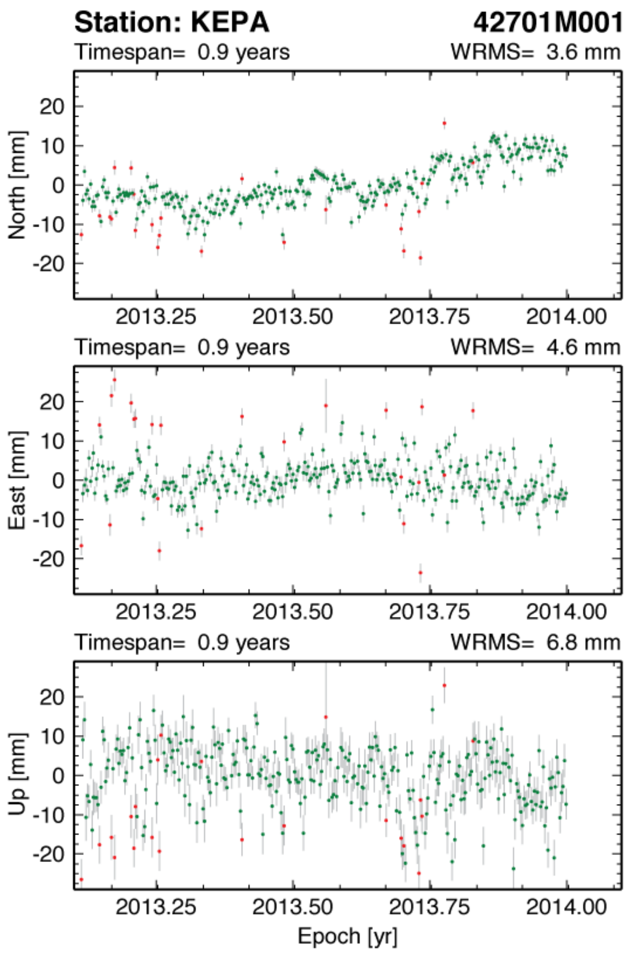

Fig. 4 Position time series for KEPA for 14 February to 31 December 2013. Position outliers are indicated by red circles and uncertainties are three times the daily standard error from the GPS processing.

Using azimuth and elevation information together with the MP1 metric, we found that the GNSS signals affected by multipath stem from satellites observed in an easterly to south-easterly direction with an elevation of less than 15°. Hence we identified the rocks shown in the right-hand foreground of Figure 2 (left panel) as the source and attribute the larger scatter in the horizontal components to the apparent multipath. Although a preliminary double-difference solution seems to be less affected by the multipath, we will investigate ways to improve the data quality of the station.

Figure 4 does not show any station velocities as the timespan is too short to give any reliable values separated from potential seasonal signals. However, there is an indication of a positive velocity for the North and a negative one for the Up component. The East component does not indicate any long-term motion at this point.

3.3 Troposphere Estimates

We use the observations of the weather sensor of the KEP Geodetic Observatory and the automatic weather station at KEP research station, denoted as BAS, together with NCEP/NCAR reanalysis (Kalnay et al., 1996) gridded data to verify the meteorological observations (for briefness only temperature and pressure) and to evaluate the impact of these data sets on integrated water vapour (IWV) estimates. In order to do so we applied the standard barometric height correction to the observations from BAS to account for the height difference between the KEP research station and KEPA. Figure 5 shows the time series of air temperature and pressure for 14 February to 31 December 2013. Clearly visible are the excellent agreements between the observations themselves and the model values. Table 1 shows the median and root-mean-square (RMS) agreements for the differences in these meteorological data and the gridded information. Given the lower specifications of the KEPA weather sensor when compared to BAS, it can be argued that it performed well with median and RMS pressure differences of -0.2 hPa and 0.9 hPa, respectively.

Accurate pressure information is critical for the conversion of GNSS-derived zenith tropospheric delay into IWV and an error in pressure of 1 hPa maps into an error in IWV of 0.36 kg/m^2. With the required accuracies for IWV estimates of 1-5 kg/m^2 and 0.25-2.5 kg/m^2 for forecasting and climate monitoring applications (Barlag et al, 2004), respectively, the RMS statistics indicate, if the relative accuracies between these data sets are taken as absolute, that observations and gridded data agree fairly well, and that a IWV product computed using pressure values from KEPA would be within the ranges for the above meteorological applications.

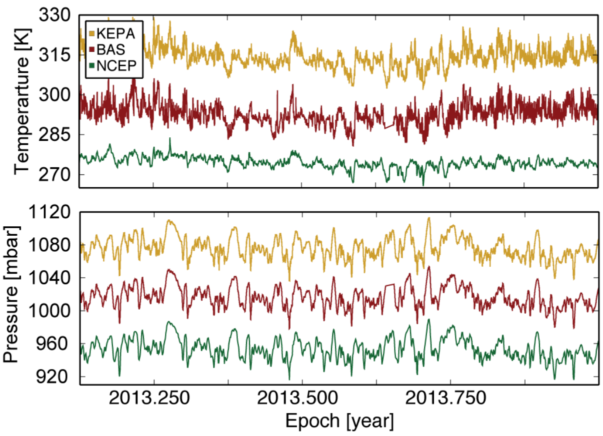

Fig. 5 Time series of temperature (top) and pressure (bottom) from KEPA and KEP research station (BAS) weather stations, and NCEP/NCAR reanalysis gridded data from 14 February to 31 December 2013. Time series are offset for clarity. The observations for KEPA are reported at 15 min and for BAS at hourly intervals. NCEP data are provided at 6-hour intervals.

Table 1 Median and RMS of differences in temperature and pressure computed for the meteorological observations from KEPA and KEP research station (BAS), and NCEP/NCAR reanalysis gridded data.

	Temperature [°K]		Pressure [hPa]	
	Median	RMS	Median	RMS
KEPA - BAS	-2.1	2.6	-0.2	0.9
KEPA - NCEP	-1.1	2.6	2.8	3.1
BAS - NCEP	0.6	3.4	3.0	3.3

4 Conclusions

The new King Edward Point (KEP) Geodetic Observatory and its KEPA GNSS station have been introduced and an initial evaluation has been performed. The data quality metrics for the first ten months have been fairly stable and indicate that multipath effects are present with some sensibility to snow covering the ground. The number of cycle slips per observations are extremely low. The initial position estimates from precise point positioning indicate a larger than average scatter in the daily solutions which has been attributed to the apparent multipath. Further tests will show to which extent more precise network solutions improve the position time series while ways to reduce the multipath are being investigated. The meteorological observations from the KEP Geodetic Observatory and KEP weather stations show excellent agreement, indicating that the former fulfills the GNSS meteorology requirements for forecasting and climate monitoring applications.

The KEP Geodetic Observatory is located in the geodetically under-sampled South Atlantic Ocean. Considering this and the general hemisphere imbalance in geodetic networks, the KEPA GNSS station has the potential to make an important contribution to a number of future studies besides its primary objectives of measuring crustal movements close to the KEP tide gauge and providing a long-term vertical datum for sea level studies.

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