The King Edward Point Geodetic Observatory

Technical Report

Felix Norman Teferle
University of Luxembourg
Faculty of Science, Technology and Communication
http://wwwen.uni.lu

The cover image shows the newly installed GNSS antenna and monument on Brown Mountain. In the background Grytviken, the historical whaling station, and King Edward Point Research Station are visible (Photo: S. White).

With contributions from the following organizations:

UNAVCO

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

Summary

During the period from 7th until 14th February 2013 Norman Teferle (University of Luxembourg) and Seth White (Unavco Inc.) visited King Edward Point (KEP) research station, South Georgia, to establish the KEP Geodetic Observatory (KEPGO). The observatory consists of an autonomous, continuous Global Navigation Satellite System (GNSS) station with auxiliary equipment on Brown Mountain, as well as, benchmarks on Brown Mountain and at KEP research station. The primary objective of the observatory is to measure vertical land movements in order to study sea level changes using the KEP tide gauge record or satellite altimeter data. Therefore, the existing tide gauge was connected to the observatory through precise levelling and campaign GNSS observations. The levelling was carried out over the tide gauge itself, two existing United Kingdom Hydrographic Office (UKHO) and four newly established KEPGO tide gauge benchmarks (TGBMs). The GNSS observations were carried out on two benchmarks and their coordinates were computed with respect to the continuous GNSS station on Brown Mountain. Taking the UKHO height information together with the levelling and GNSS results it is suggested that the UKHO TGBM on the jetty may have settled by a few centimetres over the period from 2003 to 2013 and that the UKHO height datum requires a shift of by about -1 m in order to bring it closer to a globally consistent vertical reference system. This technical report details the installation work and analysis carried out during and after the visit.

Acknowledgments

Financial support for this work was obtained throught the University of Luxembourg research project “New Geodetic Infrastructure and Reprocessed GPS Solutions for Sea Level, Climate Change and Geodynamics (GSCG)”. The project has also received in-kind contributions from the British Antarctic Survey, the Royal Navy and One Ocean Expeditions. The helicopter squadron of the HMS Edinburgh is acknowledged here for air-lifting all equipment to the installation site on Brown Mountain and One Ocean Expeditions for making available two berths on their cruise vessel Akademik Ioffe, providing transport for Mr Teferle and Mr White from Stanley to South Georgia. Thanks also go to colleagues from the National Oceanography Centre, Liverpool, for their continued support and advice on various aspects of the project, as well as, to colleagues from the University of Luxembourg and the British Antarctic Survey. The Government of South Georgia and the South Sandwich Islands is acknowledged for their support prior to and during the installation of the observatory and for providing the opportunity to work in this magnificent location. The final thank you goes to Mr Seth White, for his help and attitude as without whom this installation would have not been possible.

Contents

List of Figures

List of Tables

1 Introduction

During the period from 7th until 14th February 2013 Norman Teferle (University of Luxembourg) and Seth White (Unavco Inc.) established the King Edward Point (KEP) Geodetic Observatory (KEPGO) in South Georgia, South Atlantic Ocean (Figure 1). With its remote location, South Georgia is one of few remaining islands in the ocean-dominated Southern Hemisphere which can be employed to densify the global geodetic infrastructure and to counteract the hemisphere imbalance in its observations.

The KEPGO is fully funded by the University of Luxembourg under the project "New Geodetic Infrastructure and Reprocessed GPS Solutions for Sea Level, Climate Change and Geodynamics (GSCG)". Its installation was much supported by personnel from the United Kingdom National Oceanography Centre, Liverpool, and the British Antarctic Survey. Furthermore, the Government of South Georgia and the South Sandwich Islands (GSGSSI) has granted permission to run the observatory for an initial ten years.

The observatory consists of an autonomous, continuous Global Navigation Satellite System (GNSS) station with auxiliary equipment on Brown Mountain, as well as, benchmarks on Brown Mountain and at KEP research station. As the primary objective of the observatory is to measure vertical land movements in order to study sea level changes using the KEP tide gauge record, the tide gauge and two United Kingdom Hydrographic Office (UKHO) tide gauge benchmarks (TGBM) were connected to the observatory through precise levelling and campaign GNSS observations. In view of the visible settlements of the jetty, which houses the tide gauge, four additional TGBMs were established and linked to the two UKHO TGBMs and the tide gauge itself.

Besides the application to sea level research the GNSS observations from the KEPGO have the potential to make important contributions to a number of other geoscience applications. During the operation of the observatory it will enable the determination of land movements at the site at the millimetre level, as well as, establish an important record of atmospheric conditions, both of the ionosphere and troposphere.

This report will introduce the KEP research station followed by a description of the observatory. As part of the latter the installation and equipment of the continuous GNSS station are detailed. This is followed by information on the TGBMs at KEP research station and the survey work carried out during the visit in February.

2 KEP Research Station

KEP research station, approximately 54°17'S and 36°30'W, lies at the entrance to King Edward Cove, a small bay within Cumberland East Bay, which is located on the northern side and midway along South Georgia (Figure 2). It is approximately 1400 km (860 miles) from the Falkland Islands, 1470 km (920 miles) from the northern-most reach of the Antarctic Peninsula and 4800 km (2950 miles) from the southern-most tip of Africa. Access to KEP and the rest of South Georgia is by boat or ship based helicopter only. Figure 3 shows details of the research station. Of importance are the locations of the pier and adjacent slipway (1), satellite tower (7) and the James Cook Laboratory (8), which houses the communincation room. More information can be obtained from BAS website at `www.antarctica.ac.uk`.

3 KEP Geodetic Observatory

The KEPGO currently consists of the continuous GNSS station on Brown Mountain and a network of TGBMs around the KEP tide gauge and research station.

3.1 Continuous GNSS Station

The continuous GNSS station, 4-char ID KEPA and registered with the International Earth Rotation and Reference Frame Service (IERS) DOMES number 42701M001, is the first GNSS station in the territory of South Georgia and the South Sandwich Islands. In order to enable as many high-precision applications as possible, it was important to select a site favourable to GNSS observations. This is why the station was not established at the KEP research station directly next to the tide gauge. There, a GNSS station would have had a large portion of the sky obstructed by Mount Duse which can lead to a degradation of the positioning results. Mount Duse rises to 507 m above sea level [Survey, 2004] just north of the research station (Figure 2) and lies in the area of the sky from which most GNSS signals would have been observed.

Therefore, the installation site was chosen to be on the top of Brown Mountain at an altitude of about 332 m above sea level [Survey, 2004]. Prior to the visit, this location had been identified as one with few obstructions above 10° elevation angle, a recommendation of the International GNSS Service (IGS) for the installation of continuous GNSS stations. The only significant intrusion beyond this elevation angle lies in the southerly direction of Mount Paget, which is with 2934 m above sea level, the highest point in South Georgia. Figure 7 shows the 360° elevation angles of the horizon with a panoramic photograph in the background used during the planning of the installation.

As Brown Mountain is situated to the south of KEP research station across King Edward Cove (Figures 2 and 4), the proximity of the GNSS station to the research station means that it can be easily reached for servicing by foot (within 1.5 hours) and allows the use of an Ethernet radio bridge for transmitting the data to the research station (Figure 5).

The installation of the continuous GNSS station KEPA on Brown Mountain and its connection to the communication system at KEP research stations is described in Section 4.

3.2 Benchmark Network

The second component of the KEPGO is the local network of TGBMs. Prior to establishing the observatory the height datum was realized by four TGBMs located in Grytviken and KEP research station. These were last inspected by the Hydrographic Department of the UK Ministry of Defence during a visit of the HMS Herald in 1987 and the HMS Endurance in 2003. See Table 1 for the TGBM information extracted from the United Kingdom Hydrographic Office (UKHO) database in March 2013. These four TGBMs realize the chart datum and are only accurate to centimetre level. Two of these benchmarks are located in the vicinity of KEP research station and are shown in Figure 6: one near the jetty, marked Hydrographic Department 1997/98 Triangulation (UKHO-HD-9798), and the other near Discovery House, marked International Satellite Triangulation Station Number 061 (UKHO-ISTS-061). Table 2 gives details of these two UKHO TGBMs. As the two other benchmarks are located in Grytviken, approximately 800 m from KEP research station, these were not considered for the levelling work (Section 5.2) nor has their existence been confirmed during this visit.

As part of the KEPGO four additional TGBM were established and their locations are shown on Figure 6. These are located (1) on the concrete jetty directly above the tide gauge (KEPGO-KEP-001), (2) on the north-western concrete foundations (next to the boatshed) of the western mast of the HF dipole fan array antenna (KEPGO-KEP-002), (3) on the eastern concrete foundations of the eastern mast of the HF dipole fan array antenna (KEPGO-KEP-003), and (4) on the concrete foundations of the satellite tower (KEPGO-KEP-004). Table 3 gives details of the four new TGBMs. The approximate geodetic coordinates of all six TGBM are listed in Table 9 and Figures 18 to 21 show the TGBMs and their surroundings.

KEPGO-KEP-003 and UKHO-ISTS-061 were used during the GNSS survey, hence more accurate coordinates for these two TGBM follow in Section 5.1.

4 KEPGO Installations

The KEPGO installations comprise all the work in relation to establishing the continuous GNSS station KEPA on top of Brown Mountain and its connection to the communication system in place at the KEP research station.

4.1 Logistics

All equipment for KEPA was procured and configured by Unavco Inc., Boulder, USA. The hardware largely follows Unavco's design for GNSS stations operating in polar regions. However, a key difference in the specific hardware for KEPA is that no wind turbines were included, as these can be high in maintenance, while the number of batteries was increased from 10 to 20. This is possible due to the mid-latitude region of South Georgia. Although KEPA is not in the direct path of the gale-force katabatic winds coming from nearby glaciers, wind speeds of 30 to 40 m/s are not uncommon.

Unavco Inc. shipped all equipment via the UK and Falkland Islands to South Georgia in November 2012. Chiltern Air Freight Ltd handled the cargo between London and Stanley, Sulivan Shipping Ltd handled temporary storage and delivery to the port in Stanley, and the GSGSSI fisheries vessel MV Pharos SG carried the cargo to KEP research station. See Table 4 for their contact information.

In December 2012 BAS personnel at KEP research station repacked the roughly 900 kg of cargo upon which it was air-lifted to the top of Brown Mountain by the helicopter flight squadron of the HMS Edinburgh of the UK Royal Navy. Once on site, BAS personnel secured the equipment against wind and weather. With all equipment already on Brown Mountain KEPA was fully installed and commissioned within three days by Norman Teferle and Seth White. A detailed list of activities is given in Table 5.

All waste, tools and spare parts have been removed from the Brown Mountain. A list of tools and spare parts kept for storage at KEP research station can be found in Table 6.

4.2 GNSS Monument and Antenna

The GNSS antenna is bolted directly to bedrock via a 1-metre tall mast at a rock outcrop at the highest point of Brown Mountain (Figure 8). The primary reference point (KEPGO-BMT-001) is the centre of the mast at the surface, which touches the bottom of the antenna, i.e. at the antenna reference point (ARP). The secondary reference point (KEPGO-BMT-002), a BM in the rock, is located roughly 60 cm southeast of the mast. The height difference between KEPGO-BMT-001 and KEPGO-BMT-002 was levelled to be 1.0629 ± 0.0002 m (KEPGO-BMT-002 below KEPGO-BMT-001) directly after installation. The KEPA levelling observations can be found in Table 7. The 3D components of the vector between the two BMs were not determined at this stage and is foreseen for a future maintenance visit.

A standard 30 m antenna cable (LMR-400 specification) protected by conduit and placed in a small trench covered with rocks and stones (see Figure 9) runs from the antenna to a small system nearby, where the GNSS receiver and all other auxillary equipment are housed.

4.3 Equipment Frame

The aluminium equipment frame (Figure 10) houses the electronics, radio antenna, weather station and the solar power system. It sits away from the mountain edge in order to prevent it from being seen from below. Of importance to the GSGSSI was that the equipment would not be seen from King Edward Cove, i.e. preserving the pristine views of the natural environment of South Georgia.

Prior to placing the frame the area was cleared of large rocks and approximately levelled. The size of the frame is roughly 2.0 x 1.2 x 2.0 m (length x width x height) with the upward poles being at a slight angle. The weather station and radio antenna are fixed to these.

After installation of both enclosures and equipment, the frame was chained down and weighted with rocks. The upper enclosure is strapped to the lower one and the frame.

In case of repairs or unforeseen modifications, spare parts and tools (Table 6) have been left in the store at KEP research station. In particular, these contain extension poles in order to raise the weather station or radio antenna should the site be prone to snow accumulation during winter periods.

4.4 Electronics

The GNSS station equipment of the KEP geodetic observatory is designed to run continuously all year from solar power. The GNSS receiver, power system electronics, and remote radio are located in the upper enclosure, along with 10 12 V Deka Solar photovoltaic batteries with an Ampere hour capacity of 98.4 Ah. All components are mounted onto a PVC board and placed in an anti-static bag (Figure 11). Another 10 batteries are located in the lower enclosure. The power system is a 12 V DC system, powered by two 80-watt solar panels. The GNSS receiver is a Trimble NetR9, which telemeters to KEP research station via an Intuicom EB-1 900 MHz Ethernet radio bridge. To save power, this radio is turned off 50% of the time (5 hours on / 5 hours off). The timer is a basic on/off unit and is the standard timer used by Unavco, Inc for remote GNSS stations. Table 8 gives details of the equipment installed.

The timer switch can not be set accurately for hourly downloads necessary for near real-time GNSS applications. An upgrade to a better timer is possible but an hourly download of data would create an increased load on the already limited VSat communication link.

A short Yagi antenna for the radio (Figure 12) and a Vaisala WXT-520 weather station (Figure 13) are attached to the top of the frame. Temperature, pressure and wind speed from the weather station are fed into the GNSS receiver and are stored together with the GNSS observations.

All electronics installed at KEPA use together on average 5.2 W of power. This includes the receiver (recording GPS+GLONASS+Galileo), the choke ring antenna and the USB-stick together with 4.15 W, the solar regulator with 0.1 W, the weather station with 0.1 W, the timer switch with 0.1 W and the radio with 0.75 W. The power consumption of the weather station is kept to a minimum by not using a heating device for the rain and hail sensor, which could add 13 W to the power requirements during cold periods. Furthermore, the rain and hail measurements have been switched off. Similarly, the radio requires between 0.8 W (sleep) and 6 W (transmission) of power and by switching it off for half the time, power can be saved.

Without detailed information on cloudiness for South Georgia Island it was difficult to plan the power budget for the GNSS installation. According to Unavco's power analysis table a system using approximately 5 W and two 80 W solar panels would require about 9 batteries with a capacity of 100 Ah. Having available twice the number of batteries needed has added a good level of redundancy, which should improve the lifespan of each individual battery.

4.5 KEP Communication System

Another Intuicom EB-1 radio is installed in the KEP communications room in the James Cook Laboratory (Figure 3). It uses another Yagi antenna (Figure 17) attached to the top corner of the satellite tower (Figure 15) opposite the KEP communications room, connected by a long coaxial cable. This cable was already in place from a disused antenna and only required to be terminated with N-Type connectors on both ends. The base radio (Figure 16) is connected to the network switch with a Cat5 cable, and is powered by 12 VDC from an AC/DC converter plug from a 240 V power outlet. When the remote radio is on, the CD LED on the base radio will be green; otherwise it is red. A hole in the KEP network firewall has been established which allows Unavco Inc. to connect to the GNSS receiver to retrieve the data files in Trimble binary format about 1MB per day.

5 KEPGO Survey Work

The aim of the survey work at KEP research station was to establish an accurate, long-term maintainable height reference for the tide gauge in order to fulfill the primary objective of the KEPGO. This height reference will allow the tide gauge to be used for satellite altimeter calibration and long-term sea level change studies once a long enough record has been established.

5.1 GNSS Survey

A GNSS survey was carried out in order to determine the heights of the existing and newly established TGBMs at KEP research station in a terrestrial reference system, such as the ITRF2008 [Altamimi et al., 2011]. For this purpose the coordinates of KEPGO-KEP-003 and UKHO-ISTS-061 were computed with respect to KEPA. A Leica SR530 GPS receiver with a Leica choke ring antenna LEIAT504, their details are given in Table 10, were used to occupy both benchmarks. Information on the occupation is listed in Table 11. Due to time constraints it was not possible to observe both TGBMs for a full 24-hour period. For observation periods different from this, some effects, e.g. multipath, may not average out and can affect the solution.

Prior to the computation of the baselines the coordinates of KEPA were determined as the mean coordinates over a 14-day period from Precise Point Positioning [Zumberge et al., 1997] using the Bernese GNSS Software v5.2 (see Dach et al. [2007]). This resulted in the coordinates being in the IGb08 refererence frame, a GNSS-only realization of ITRF2008 [Rebischung et al., 2012] used by the IGS in all their products. New coordinates for KEPA will be determined using a double-difference approach in future. The baselines were then computed in Leica Geo Office 8.0 while fixing the coordinates of KEPA.

At the time of the analysis no individual absolute antenna phase centre variation calibrations were available for the antennas at KEPA and the one used on the benchmarks. Although KEPA's antenna was calibrated by the US National Geodetic Survey prior to installation, at the time of this report the calibration had not been released. The Leica antenna used at KEPGO-KEP-003 and UKHO-ISTS-061 has been sent for calibration after its was returned from South Georgia. For the computations as part of this report, the type-mean antenna calibration from the IGS were applied as given in the official ANTEX-file `igs1735.atx`. The effect of the small differences in the antenna phase centre models on positioning can reach centimetre level over sub-daily observation periods. Hence the accuracy of the height difference between KEPA and both TGBMs may currently only be at the centimetre level. Table 12 lists the cartesian and geodetic coordinate results in IGb08.

5.2 Levelling

As the TG was fixed to the side of the jetty it was difficult to find an adequate point on it usable as a reference, for which the height of the tide gauge can be derived prior to the next maintenance. Although two possible points were identified (Figure 22), only the edge of the top right side was accessible with the tide gauge in place and using a modified levelling staff (Figure 23). This reference point is denoted as *TG-right*.

The modification of the levelling staff included a small block of wood tightly attached to form an "L" shape in order to reach below the overhang of the concrete pier and allow placing the staff on TG-right. A proper tool will be engineered at the University of Luxembourg in order to allow repeated surveys with the TG in place. It can be easily shown that through carefully placing the staff and holding it vertically, to within $\pm 2.5°$, the error on the staff readings can be kept to below 1 mm.

It was not possible to level between TG-right and KEPGO-KEP-001 from in-between with equal back and fore sight lengths in order to cancel the effect of small instrument errors. Hence the staff readings for TG-right, KEPGO-KEP-001 and UKHO-HD-9798 were taken from across the slipway (next to the jetty). From this follows that the calculations for this part were not performed as for a levelling loop which allows the calculation of a misclosure between a forward and backward run. The levelling observations and calculations are shown in Table 13. The height differences were observed four times and then averaged. In these calculations the height of UKHO-HD-9798 was set to be 1.34 m according to the UKHO database value. For TG-right and KEPGO-KEP-001, their heights and standard deviations can then be computed to be $0.6496 \pm 0.0005\,m$ and $1.3165 \pm 0.0007\,m$, respectively.

All other height differences were levelled scrictly from in-between with equal back and fore sight lengths on the levelling line shown in Figure 6. This line starts at UKHO-HD-9798 and passes over KEPGO-KEP-002, KEPGO-KEP-003 and UKHO-ISTS-061 to KEPGO-KEP-004. The levelling was carried out in forward and backward runs forming a levelling loop with a total length of 446 m. Sections for which the height differences between the forward and backward runs did not agree to less than 1 mm were re-plevelled. The levelling observations and computations of the TGBM heights are provided in Table 14. The overall misclosure in the loop was computed to be -0.0009 m. The misclosure was then used to calculate a correction for each height difference by scaling it proportionally according to the levelling distance. These corrections were then applied to the height differences upon which corrected heights, specific to each run, were computed. In the next step the corrected heights of the forward and backward runs were averaged to form the adjusted heights for which the standard deviations were computed as an estimate of the height error. In these calculations the height of UKHO-HD-9798 was set to be 1.34 m according to the UKHO database value.

As it is not possible to provide an error estimate for the height of KEPGO-KEP-004 in this manner, i.e. no standard deviation can be computed, an estimate of the error could be based on the misclosure itself. It is suggested from Table 14 that this may give a pessimistic estimate of the height error if one considers that the biggest error might be associated with the height difference between UKHO-HD-9798 and WP1. With 0.0013 m WP1 shows the biggest difference in its height estimates between the forward and backward lines.

Finally, using the formula for the standard deviation of a 1 km long levelling loop computed from the misclosure m, i.e.

$$\sigma_{l/km} = \frac{m}{\sqrt{d_{km}}}$$

it can be shown with $m = 0.0009$ and $d = 0.4462\,km$ that $\sigma_{l/km} = 0.0013\,m$. This is the theoretical error made if the levelling loop was 1 km long.

In summary, Table 15 shows the collected adjusted heights for TG-right and all TGBMs with respect to UKHO chart datum as defined by the heights of UKHO-HD-9798 and UKHO-ISTS-061. By introducing both official UKHO TGBM height values the adjusted heights differ by -0.0403 m, which may be reflected by the accuracy of the official benchmarks information. However, if it can be assumed that official TGBM heights are correct to the given centimetre, then the levelling observations here would indicate some instability in these benchmarks. The settlement of sections of the jetty, which is clearly visible, leads to the assumption that instabilities are more likely to occur at UKHO-HD-9798 than at UKHO-ISTS-061, which is in a more protected location. In fact, the levelling observations support the assumption of subsidence of UKHO-HD-9798 by about 4 cm since 2003.

It is possible to carry out a consistency check of the height differences between KEPGO-KEP-003 and UKHO-ISTS-061 derived from the GNSS survey (Section 5.1) and from the levelling. It can be shown that the ellipsoidal and levelled height differences (from UKHO-ISTS-061 to KEPGO-KEP-003) are -0.3045 m and -0.3053 m, respectively. With the Geoid height difference between the two TGBMs of 4.5 mm, see next section, the agreement of 0.8 mm suggests good precisions of GNSS-derived heights for the two TGBMs although using relatively short observation time spans and the current use of type-mean antenna calibrations.

5.3 KEPGO Height Datum

In Section 5.1 highly accurate coordinates where determined for the TGBMs KEPGO-KEP-003 and UKHO-ISTS-061. Using the ellipsoidal heights of these two TGBM together with Geoid heights from the Earth Gravitational Model 2008 (EGM2008) [?] an alternative height datum for KEP and South Georgia can be defined. Figure 24 shows the EGM2008 Geoid heights for the region around South Georgia Island. It can be seen that for the area around KEP research station a steep gradient in the gravity is visible.

Table 16 lists the ellipsoidal heights from the GNSS survey, the Geoid heights (undulation) and the derived orthometric heights for KEPGO-BMT-001(KEPA), KEPGO-

BMT-002, KEPGO-KEP-003 and UKHO-ISTS-061. The EGM2008 Geoid heights indicate that over the 1.8 km distance from KEPA on Brown Mountain to the TGBMs at KEP research station the Geoid changes by roughly -23.8 cm, and that between KEPGO-KEP-003 and UKHO-ISTS-061, which are only 40 m apart, a further Geoid change of -4.5 mm occurs.

Using the orthometric heights of 2.0151 m for UKHO-ISTS-061 and 1.7061 m for KEPGO-KEP-003 as references for two alternative datum definitions, new heights for the TG and other TGBMs can be derived. Table 17 shows the heights of the TG and TGBMs with respect to the two possible height datums. The difference in the heights between the two sets is 4 mm. As the GPS observations at UKHO-ISTS-061 were taken over a longer period than on KEPGO-KEP-003 preference could be given to the datum defined by this UKHO TGBM.

In a further analysis datum shifts based on either datum can be computed. Using the heights derived from the UKHO-HD-9798 height of 1.34 m (column 2 in Table 15) together with the new datum definitions based on UKHO-ISTS-061 and KEPGO-KEP-003, shifts of -1.0552 and -1.0592 m, respectively, can be computed. Similarly, using the heights derived from the UKHO-ISTS-061 height of 3.03 m (column 3 in Table 15) together with the new datum definitions based on UKHO-ISTS-061 and KEPGO-KEP-003, shifts of -1.0149 and -1.0189 m, respectively, can be computed. Assuming that UKHO-HD-9798 has indeed undergone some settlement during the period from 2003 to 2013, then using the values based on UKHO-ISTS-061 the datum shift could be reported to be -1.02 m. Irrespective of the differences in these and assumptions, the recent observations suggest that a datum shift of about -1 m would be needed in order to bring the current UKHO height datum closer to a globally consistent vertical reference system.

6 Conclusions

This reports gives details of the establishment of the Kind Edward Point Geodetic Observatory (KEPGO) in South Georgia during February 2013. The observatory consists of the continuous GNSS station KEPA, located on Brown Mountain, and a network of benchmarks connecting the KEP tide gauge to the observatory while establishing a new height reference. This datum will allow the tide gauge to be used for satellite altimeter calibrations and long-term sea level change research. The survey work carried out as part of KEPGO suggests a settlement of the United Kingdom Hydrographic Office (UKHO) tide gauge benchmark (TGBM) on the jetty by several centimetres with respect to the second UKHO TGBM at KEP research station, if the latter is assumed to be stable. At the same time the newly established KEPGO height datum suggests that a datum shift of about -1 m would be needed in order to bring the current UKHO height datum closer to a globally consistent vertical reference system.

References

Z. Altamimi, X. Collilieux, and L. Métivier. ITRF2008: An improved solution of the international terrestrial reference frame. *Journal of Geodesy*, 85(8):457–473, 2011.

R. Dach, U. Hugentobler, P. Fridez, and M. Meindl. *Bernese GPS Software Version 5.0*. Atronomical Institute, University of Bern, Bern, 2007.

P. Rebischung, J. Griffiths, J. Ray, R. Schmid, X. Collilieux, and B. Garayt. IGS08: the IGS realization of ITRF2008. *GPS Solutions*, 16(4):483–494, 2012.

British Antarctic Survey. *South Georgia 1:200 000 Scale Map, Sheets BAS (Misc) 12A and 12B*. British Antarctic Survey, Cambridge, 2004.

J. F. Zumberge, M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research*, 102(B3):5005–5017, 1997.

Table 1: Tide gauge benchmark information for Grytviken and KEP as obtained from the United Kingdom Hydrographic Office in March 2013.

```
SOUTH GEORGIA KING EDWARD COVE
54 17'·000 S; 36 30'·000 W

HMS HERALD 1987
Chart Datum is 2.09m below BM cut into highest part of rim of hollow
round iron bollard, 0.4m diameter and set in concrete base 2.5m x 2.7m,
bearing 285' (M) 2 10m from root of N arm of Grytviken Wharf.

or 2.12m below top of ringbolt, set into concrete with BM cut into it,
about 1.0m x 0.7m, bearing 334'(M) 20m from NE root of central arm
of Grytviken Wharf and 5.9m from steel girder, 2.1m high,
set vertically in ground.

HMS ENDURANCE 2003
or 3.03m below brass triangulation plate in position 54 17'.02S;
36 29'.68W located at rear of new Post Office building, the first white
building adjacent to jetty, and at base of aerial mast anchor wire.

or 1.34m below brass triangulation plate in position 54 16'.99S;
36 29'.79W located on S corner of new concrete jetty nearest to green
maintenance shed.
```

Table 2: Tide gauge benchmarks observed by HMS Endurance in 2003.

Marker	Description	Name
	TGBM of the Hydrographic Department, M.O.D. Navy, Taunton TA12DN, 1997/98 Triangulation	UKHO-HD-9798
	TGBM of the International Satellite Triangulation Station N061, 1967	UKHO-ISTS-061

Table 3: New tide gauge benchmarks established and observed during February 2013.

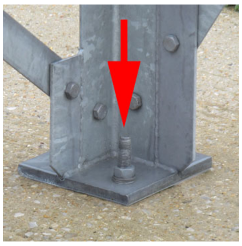
Marker	Description	Name
	TGBM directly at the tide gauge	KEPGO-KEP-001
	TGBM on north-western concrete foundations of the eastern HF dipole mast	KEPGO-KEP-002
	TGBM on eastern concrete foundations of the eastern HF dipole mast	KEPGO-KEP-003
	TGBM on top of bolt inside north-eastern corner of satellite tower	KEPGO-KEP-004

Table 4: Contact Information

Rod Strachan Base Commander King Edward Point Research Station South Georgia South Atlantic (via Falkland Islands) SIQQ 1ZZ Email: kpbc@bas.ac.uk VoIP: +44 (0) 1223 1782 Fax: + 870 382359032 Inmarsat C telex: 580 492 348018	Leslie B. Whittamore British Antarctic Survey High Cross, Madingley Road Cambridge CB3 0ET United Kingdom Email: lpw@bas.ac.uk Tel:+44 (0)1223 221492 Fax:+44 (0)1223 362616
Mark Hughes Chiltern Air Freight Limited Wraysbury House Poyle Road Colnbrook Berkshire SL3 0AY United Kingdom Email: mark@chilternairfreight.co.uk Tel: +44 (0)1753 680535 Fax: +44 (0)1753 682501 Mob: +44 (0)7976631711 Website: www.chilternairfreight.co.uk	Russell Morrison Sulivan Shipping Services Stanley Services Ltd Airport Road P.O Box 117 Stanley FIQQ 1ZZ Falkland Islands Tel: +500 22626 Fax: +500 22625 Mob: +500 51856 Website: www.sulivanshipping.com

Table 5: Work log for the period 7 to 14 February 2013.

Date	Activity
7 Feb	Arrived at KEP research station on cruise vessel Akademik Ioffe at 1500, inductions by Base Commander to KEP facilities and GSGSSI official to working in South Georgia
8 Feb	First visit to site on Brown Mountain, installed monument and mounted antenna, prepared secondary reference point benchmark, assembled the aluminium frame
9 Feb	Installed GPS antenna cable, positioned and leveled frame, installed aux and main enclosures, batteries and electronics board, solar panels, radio and weather station
10 Feb	Went to Brown MT to fetch items. Levelled antenna (KEPGO-BMT-001) to KEPGO-BMT-002. Searched for old survey mark on Brown Mountain. Anchored the frame. Started work on radio link at KEP.
11 Feb	Terminated antenna cable on comms mast. Tested radio link and Ethernet connection to Unavco Inc. Went up Brown MT to fetch remaining items. Completed radio installation on KEP satellite tower. Established additional TGBM at KEP and levelled between KEPGO-KEP-001, UKHO-HD-9798 and KEPGO-KEP-002. Started GPS occupation at KEPGO-KEP-003.
12 Feb	Levelled between KEPGO-KEP-004, UKHO-ISTS-061, KEPGO-KEP-003 and KEPGO-KEP-002. Taken photographs and collected information for report.
14 Feb	After being on stand-by from 0900 due to high swells departed from KEP research station on fishing vessel SIL at 1400.

Table 6: Tools and spare parts left at KEP research station.

Number	Item
1	Intuicom EB-1 ethernet radio #953-1542 (configured as master for the comms room, must be reconfigured to be a spare for the remote radio at KEPA).
1	Intuicom radio programming cable
1	Intuicom software CD
1	Intuicom 120/240 VAC to 12 VDC radio power supply
1	7-element Yagi antenna, Blue Wave, with short coax cable attaches (terminates in N female)
1	solar regulator, Flexcharge NC30L12
1	radio timer switch, ABB ESDR125A5P
1	Trimble 120/240 VAC to 18 VDC power supply
1	Trimble NetR9 power/download cable (LEMO - serial - coax power)
1	Trimble NetR9 DC power cable (LEMO - red/black leads)
2	coaxial cable, LMR400, 30 meter, N-N90 connectors
1	coaxial cable, LMR400, 4 meter, N-TNC connectors
1	coaxial cable, LMR400, 7 meter, N-TNC connectors
1	coaxial cable, RG58 x 1 meter, N-TNC connectors
1	TNCM-NF adapter
1	TNCF-NM adapter
1	N bulkhead fitting
2	TNC bulkhead fitting
1	drill jig kit for 1-meter monument (no drill guides for 2-meter monument)
1	set of frame leveling feet (small aluminum pipes)
2	saddle clamps with washers and locknuts
2	aluminum pipes, 1 meter, for extending radio antenna if necessary (one pipe has wall flange pipe fitting attached to it)
1	small roll of Velcro
4	red flag quick-disconnect terminals
4	blue flag quick-disconnect terminals
1	weatherpack connector contact removal tool
2	short ethernet cables (1x 10cm and 1x 1m)
2	battery jumper pairs
4	rolls of vinyl electrical tape
1	roll of amalgamating tape
1	roll of duct tape
2	18 inch metal cable ties (for monument)
8	12 inch metal cable ties
1	lot of plastic zip ties, small and large
2	16mm rock drill bits x 70cm long

Continued on next page

Table 6 – *Continued from previous page*

Number	Item
2	1/2 inch rock drill bits x 24 inch long (one new, one used)
3	brass survey nails, split-drive
1	steel survey nail, larger
1	steel survey nail, smaller
1	small wood block (for attaching to height stick for tide gauge leveling)
4	1/2 inch stainless monument nuts
4	1/2 inch stainless monument washers
1	allen wrench for monument cap screws
4	1/2 inch x 24 inch monument rock anchor bolts
1	straight cable gland fitting
1	90 degree cable gland fitting
4	mil connector o-rings
3	terminal blocks with jumpers
2	terminal block separator plates
3	set screws for frame fittings
5	1/2 inch x 6 inch rock anchor bolts, with nuts, locknuts, and bolt hangers attached
1	bag of 5/16 inch bolts (3 inch and 1 inch) with locknuts and washers
4	3/8 inch bolts with locknuts, 3 and 4 inch lengths
4	hose clamps
2	hacksaws
1	24 inch bubble level
1	Hilti box with epoxy gun, dust blower, wire brush, and 3 tubes Hilti 500 epoxy
1	crimp kit for LMR400 cable, complete set in Husky bag, w/some N/N90/TNC/TNC90 connectors
1	sledge hammer w/unbreakable handle
1	anti-static bag for GPS board
1	orange tool bucket, complete UNAVCO GPS hand tool kit

Table 7: Levelling observations at KEPA continuous GNSS station.

BM	backsight [m]	foresight [m]	height difference [m]
KEPGO-BMT-001	0.2890		
KEPGO-BMT-002		-0.7740	1.0630
KEPGO-BMT-002	-0.6084		
KEPGO-BMT-001		0.4545	-1.0629
KEPGO-BMT-001	0.4012		
KEPGO-BMT-002		-0.6615	1.0627

Table 8: Equipment information for KEPA continuous GNSS station.

Item	Serial Number	Description
Trimble NetR9 GNSS receiver	5218K84772 (Unavco 50517)	Firmware 4.61; Ext IP: 192.171.138.233; Int IP: 10.105.2.233;
Trimble GNSS choke-ring antenna Type TRM59800-00	5225354542 (Unavco 50518)	No individual absolute antenna phase centre calibration at time of installation; will be available from NGS
SCIS radome Type 0010	1272	
Vaisala WTX-520		
Intuicom Inc., Ethernet radio bridge EB-1, FIP1-900C2B-RE	953-1561	Slave at Brown Mountain
Yagi antenna (short)		Brown Mountain
Intuicom Inc., Ethernet radio bridge EB-1, FIP1-900C2B-RE	953-1564	Master at KEP
Yagi antenna (long)		KEP satellite tower
Flexcharge USA Charge/Load controller, Type NC 30 L12		
Solar panels		
Timer		
Deka Solar Photovoltaic battery		20 pieces, Type 8G31, 12 VDC, Ampere hour capacity 98.4 Ah, non-spillable, 3/8-16 stainless steel threaded post

Table 9: Approximate geodetic coordinates for locating the TGBM at KEP research station.

Name	Latitude [$^\circ\,'\,''$]	Longitude [$^\circ\,'\,''$]
UKHO-HD-9798	-54 17 00.05	-36 29 47.28
UKHO-ISTS-061	-54 17 01.02	-36 29 40.80
KEPGO-KEP-001	-54 16 59.61	-36 29 48.29
KEPGO-KEP-002	-54 17 01.16	-36 29 45.35
KEPGO-KEP-003	-54 17 01.38	-36 29 43.35
KEPGO-KEP-004	-54 16 59.64	-36 29 38.62

Table 10: Equipment information for KEP survey work.

Item	Serial Number	Description
Leica SR530 GPS receiver (Type 667122) and controller (Type 667127)	Firmware X	Firmware X
Leica AT504 GPS choke-ring antenna (Type 667132)	103425	No individual absolute antenna phase centre calibration available at time of survey.
Wild N3 (high precision level)	B22-62	. . .

Table 11: Details of TGBM occupation during KEP GNSS survey.

Name	Date [dd-mm-yyyy]	Start Time [hh:mm]	Duration [hh:mm]	Antenna Height [m]
KEPGO-KEP-003	11-02-2013	17:52	15:30	1.2605
UKHO-ISTS-061	12-02-2013	11:35	27:30	1.3170

Table 12: Coordinate Results in IGb08.

Point	X [m]	Y [m]	Z [m]
KEPGO-BMT-001(KEPA)	2998460.1295	-2219901.2724	-5156272.7836
KEPGO-KEP-003	2999878.2695	-2219418.4467	-5155260.4711
UKHO-ISTS-061	2999916.0423	-2219392.8195	-5155249.9719
Point	**Latitude [°]**	**Longitude [°]**	**ell. Height [m]**
KEPGO-BMT-001(KEPA)	-54.295244764	-36.514289581	346.2091
KEPGO-KEP-003	-54.283716661	-36.495375242	21.9376
UKHO-ISTS-061	-54.283551281	-36.494713983	22.2421

Table 13: Levelling observations for TG-right, KEPGO-KEP-001 and UKHO-HD-9798. Heights are with respect to height of UKHO-HD-9798.

Name	Backsight	Foresight	ΔHeight	Height
TG-right	1.7017			0.6502
KEPGO-KEP-001	1.0275	1.0347	0.6670	1.3172
UKHO-HD-9798		1.0047	0.0228	1.34
UKHO-HD-9798	0.9970			1.34
KEPGO-KEP-001	1.0355	1.0215	−0.0245	1.3155
TG-right		1.7020	−0.6665	0.6490
TG-right	1.6948			0.6498
KEPGO-KEP-001	1.0204	1.0279	0.6669	1.3167
UKHO-HD-9798		0.9971	0.0233	1.34
UKHO-HD-9798	0.8410			1.34
KEPGO-KEP-001	1.0214	0.8645	−0.0235	1.3165
TG-right		1.6885	−0.6671	0.6494

Table 14: Levelling observations and caluclation table of the levelling loop using the "rise and fall" method. ΔHeight is the difference backsight minus forsight, Height (run) are the initially computed heights, the Corrections to ΔHeight are computed in the form of $c = d_i/\Sigma d_i * m$, which lead to the corrected Heights of the forward and backward runs within the loop. The adjusted Heights are the mean heights of the forward and backward runs, and the Error is the associated standard deviation. All values are in m.

BM Name	Distance d	Back-sight b	Fore-sight f	ΔHeight Δh	Height (run)	Correction[a] c	Height (corr.)	Height (adjst.)	Error
				forward run					
UKHO-HD-9798		1.8640			1.34		1.34	1.34	n/a
WP1	39.3	1.7560	1.5465	0.3175	1.6575	−0.0001	1.6574	1.6568	0.0009
KEPGO-KEP-002	41.2	1.7960	0.6035	1.1525	2.8100	−0.0001	2.8098	2.8095	0.0005
KEPGO-KEP-003	30.9	1.5800	1.8405	−0.0445	2.7655	−0.0001	2.7653	2.7653	< 0.0000
UKHO-ISTS-061	40.5	1.6640	1.2750	0.3050	3.0705	−0.0001	3.0702	3.0703	0.0001
WP2	28.2	1.5180	1.4215	0.2425	3.3130	−0.0001	3.3126	3.3128	0.0002
KEPGO-KEP-004	43.0	1.0239	1.0760	0.4420	3.7550	−0.0001	3.7546	3.7546	n/a
				backward run					
WP2	43.0	1.4395	1.4655	−0.4416	3.3134	−0.0001	3.3129		
UKHO-ISTS-061	28.2	1.7515	1.6820	−0.2425	3.0709	−0.0001	3.0703		
KEPGO-KEP-003	40.5	1.8260	2.0565	−0.3050	2.7659	−0.0001	2.7652		
KEPGO-KEP-002	30.9	0.6160	1.7820	0.0440	2.8099	−0.0001	2.8092		
WP1	41.2	1.5740	1.7690	−1.1530	1.6569	−0.0001	1.6561		
UKHO-HD-9798	39.3		1.8900	−0.3160	1.3409	−0.0001	1.3400		
	$\Sigma d_i =$ 446.2	$\Sigma b_i =$ 18.4089	$\Sigma f_i =$ 18.4080	$\Sigma \Delta h_i =$ 0.0009					

[a]Misclosure: $m = -\Delta h = -\Sigma h_i = -(\Sigma b_i - \Sigma f_i) = -0.0009\,\text{m}$

Table 15: Adjusted heights for TG-right and TGBMs with respect to UKHO chart datum, i.e. UKHO-HD-9798 with a height of 1.34 m and UKHO-ISTS-061 with a height of 3.03 m. All values are in m.

Benchmark	Height (UKHO-HD-9798)	Height (UKHO-ISTS-061)
UKHO-HD-9798	1.34	1.2997
UKHO-ISTS-061	3.0703	3.03
TG-right	0.6496	0.6093
KEPGO-KEP-001	1.3165	1.2762
KEPGO-KEP-002	2.8095	2.7692
KEPGO-KEP-003	2.7653	2.7250
KEPGO-KEP-004	3.7546	3.7143

Table 16: Geoid, ellipsoidal and orthometric heights for KEPGO and UKHO TGBM.

Benchmark	Height (ellipsoidal) [m]	Height (Geoid) [m]	Height (orthometric) [m]
KEPGO-BMT-001(KEPA)	346.2091	20.4679	325.7412
KEPGO-BMT-002	345.1462	20.4679	324.6783
KEPGO-KEP-003	21.9376	20.2315	1.7061
UKHO-ISTS-061	22.2421	20.2270	2.0151

Table 17: TG-right and TGBM heights with respect to KEPGO height datum, i.e. UKHO-ISTS-061 with a height of 2.0151 m and KEPGO-KEP-003 with a height of 1.7061 m. All values are in m.

Benchmark	Height (UKHO-ISTS-061)	Height (KEPGO-KEP-003)
UKHO-HD-9798	0.2848	0.2808
UKHO-ISTS-061	2.0151	2.0111
TG-right	−0.4056	−0.4096
KEGGO-KEP-001	0.2613	0.2573
KEPGO-KEP-002	1.7543	1.7503
KEPGO-KEP-003	1.7101	1.7061
KEPGO-KEP-004	2.6994	2.6954

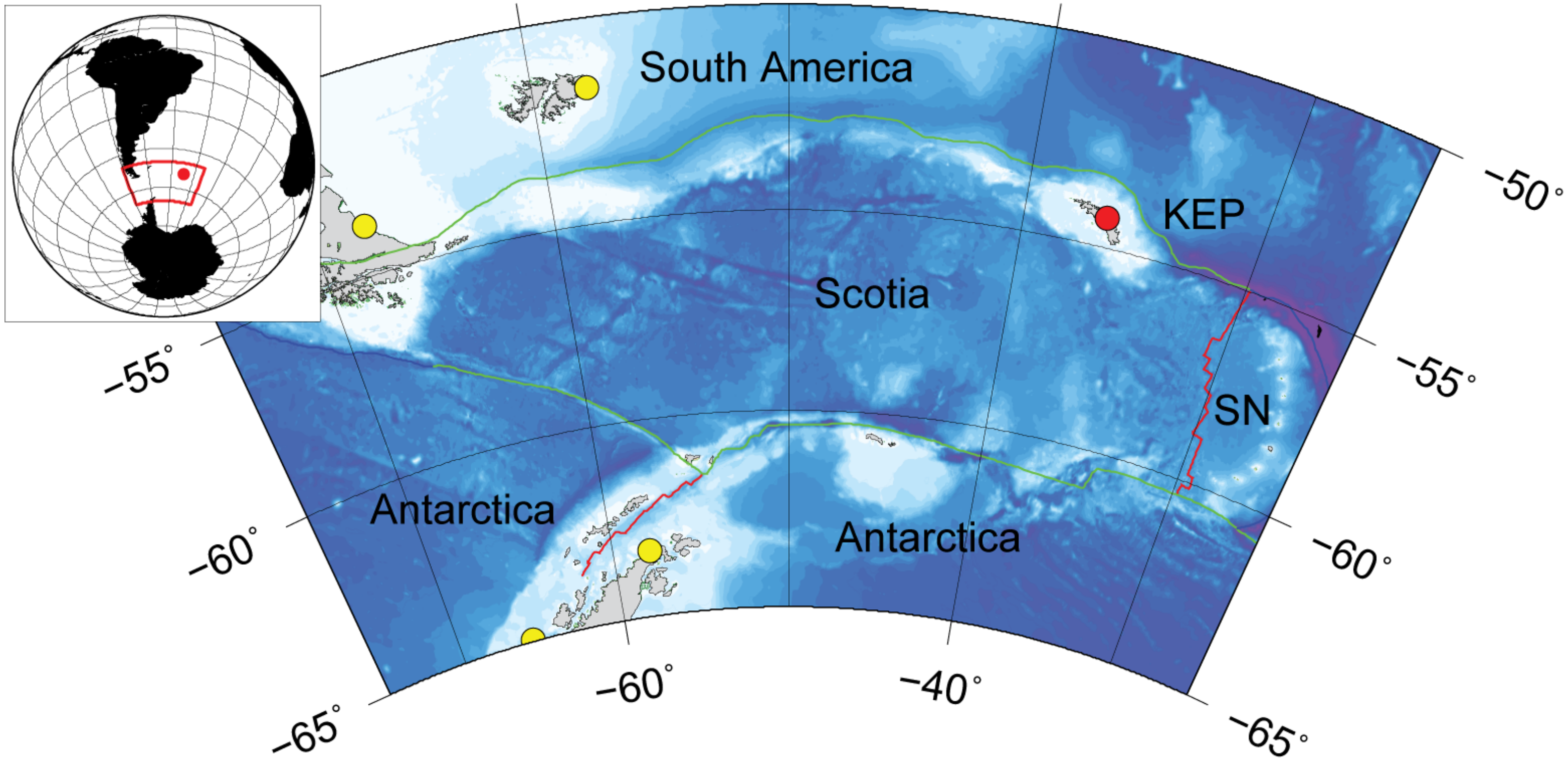


Figure 1: Location of South Georgia and King Edward Point(KEP) Research Station in the South Atlantic Ocean with its tectonic plates (Plate Project, Institute of Geophysics, University of Texas at Austin): transforms/fracture zones (green), ridges (red) and trenches (blue); existing continuous GNSS stations (yellow circles) and KEP geodetic observatory (red circle); SN: the South Sandwich plate.

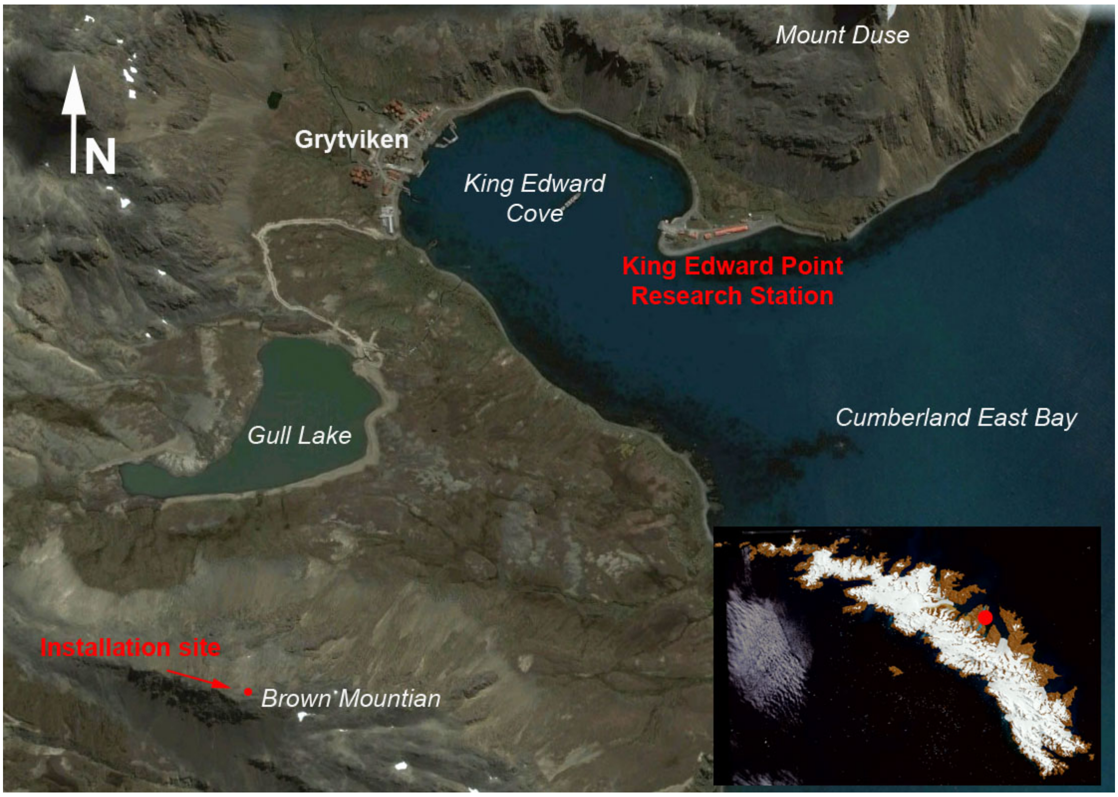


Figure 2: KEP research station surroundings with installation site on Brown Mountain. Inset shows South Georgia with the location of King Edward Cove.

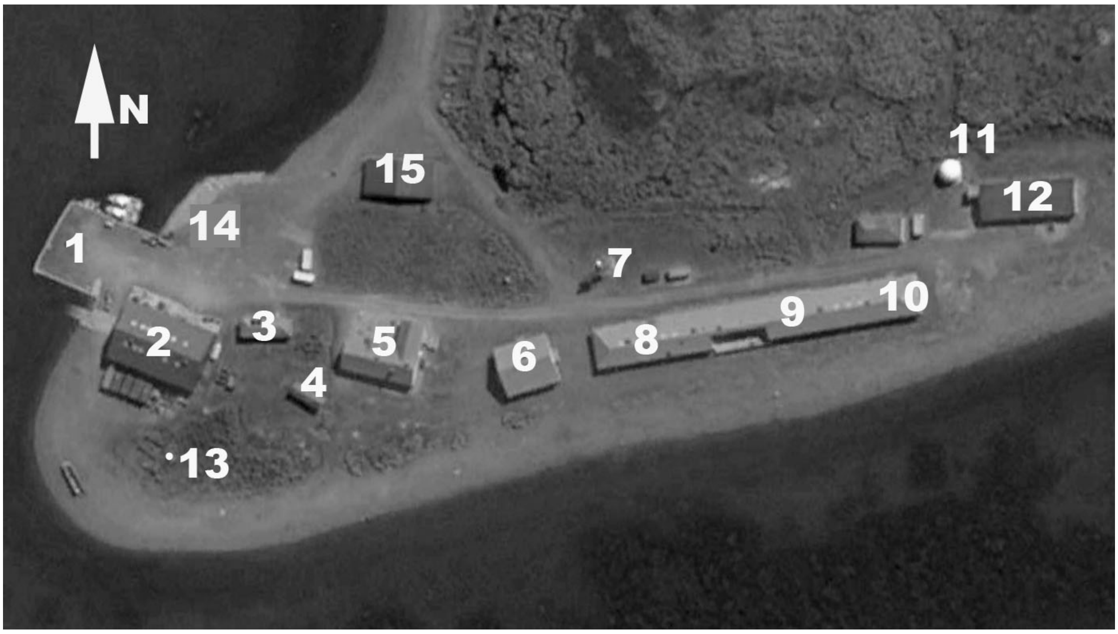


Figure 3: Schematic map of KEP research station: jetty with slipway next to the south (1), boatshed, workshop and garage (2), main food store (3), Discovery House coal store (4), Discovery House (5), Carse House (6), satellite tower (7), James Cook Laboratory (8), Everson House (9), Shackleton Villa (10), VSat dome (11), Larsen House with medical centre (12), automatic weather station (13), biosecurity building (14), and the fuel farm (15).

Figure 4: Brown Mountain as seen from KEP research station with the location of the installation site for the continuous GNSS station KEPA.

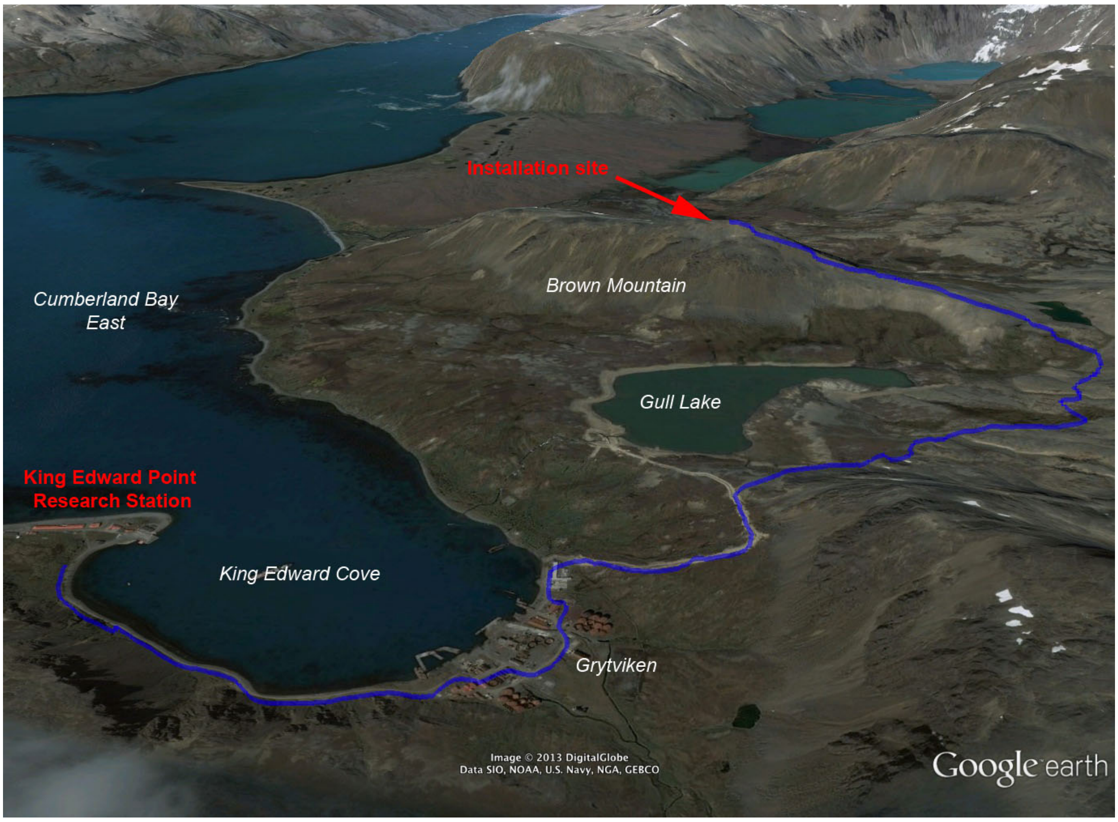


Figure 5: View of the path to KEPA continuous GNSS station installation site on Brown Mountain, looking in a south-easterly direction. The path follows the track from KEP through the historical whaling station Grytviken and up to the plateau with Gull Lake. This first ascent is approximately 100 m. The path carries on to the west of the lake across the morane deposits and boggy sections to the back of Brown Mountain mostly ascending slightly. The final ascent follows the back/ridge up onto Brown Mountain.

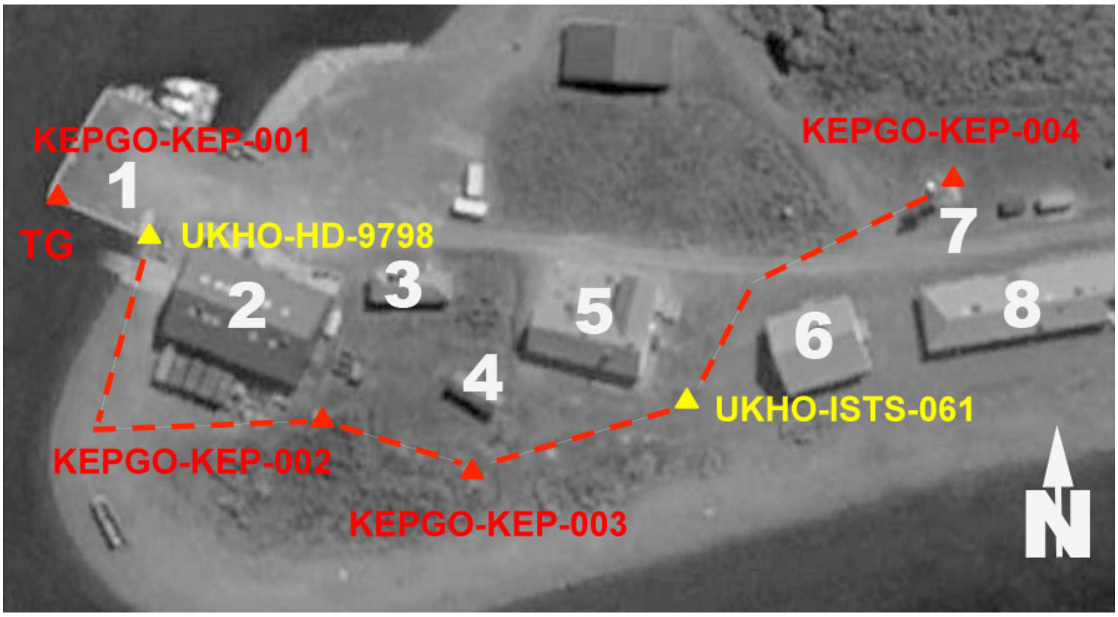


Figure 6: Network of TGBM at KEP research station. Existing TGBM (UKHO-HD-9798 and UKHO-ISTS-061) are in yellow and new TGBM (KEPGO-KEP-001 to KEPGO-KEP-004) in red. Dashed line shows the path of levelling work carried out during February 2013: from the tide gauge on the jetty (1) past the boatshed (2), over the grass area south to the food (3) and coal (4) stores, between Discovery House (5) and Carse House (6) and to the satellite tower (7).

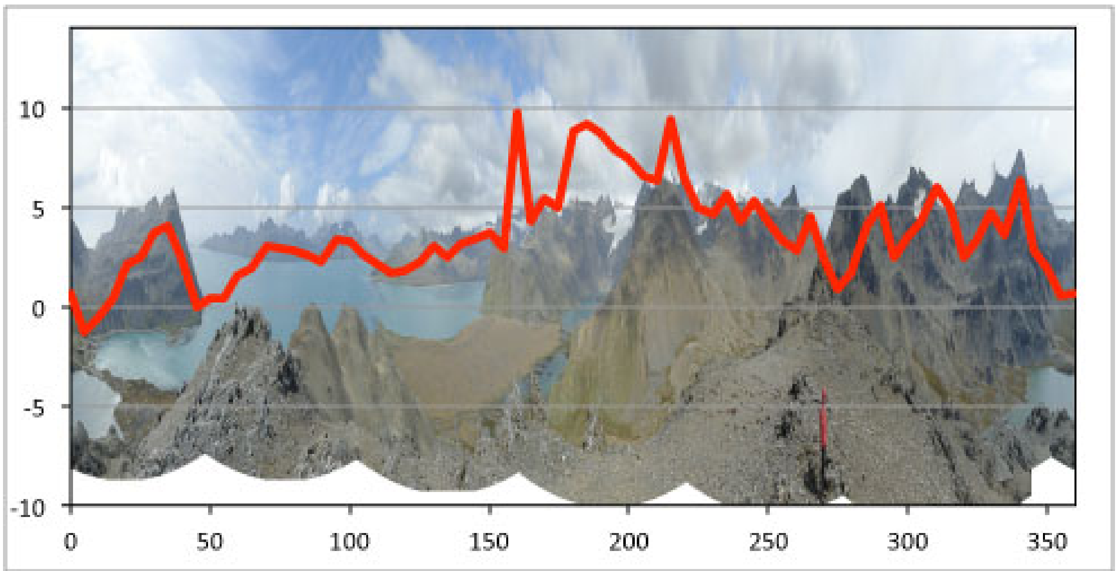


Figure 7: Elevation angles versus azimuth of proposed installation site prior to visit.

Figure 8: KEPA GNSS antenna and mast.

Figure 9: KEPA antenna cable run from equipment frame to monument (as seen from equipment frame).

Figure 10: Aluminium pipe frame with auxiliary equipment.

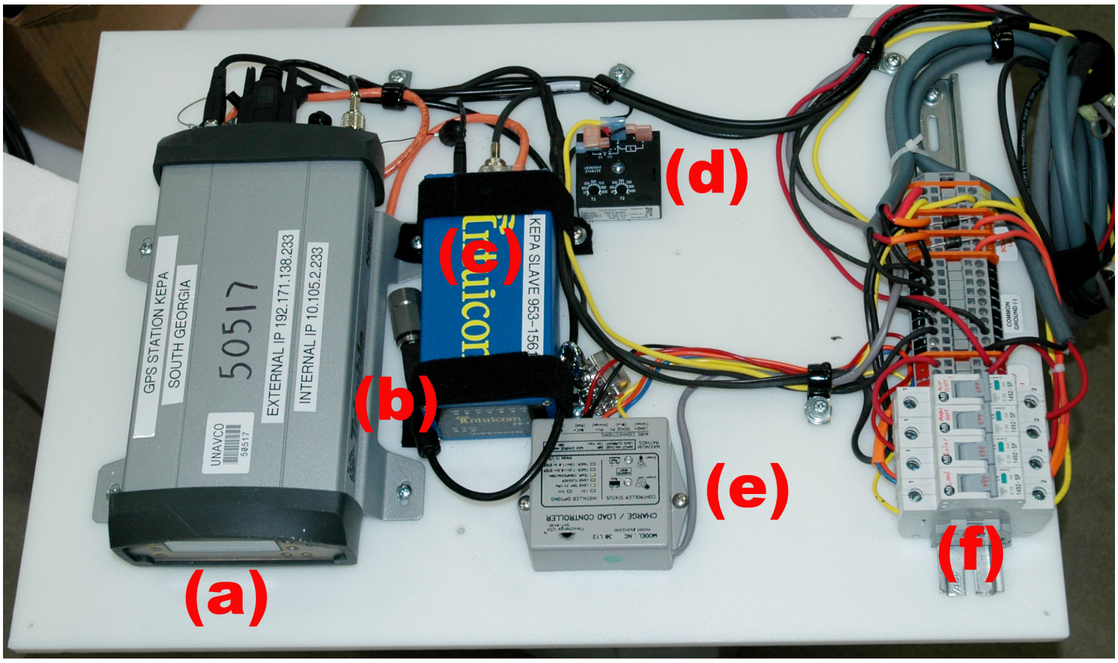


Figure 11: Electronics board at KEPA with: (a) GNSS receiver, (b) 8Gb industrial USB stick, (c) radio Ethernet bridge, (d) timing switch, (e) power system and (f) power distribution with On/Off switches and fuses.

Figure 12: KEPA radio antenna.

Figure 13: KEPA weather station.

Figure 14: View of complete KEPA continuous GNSS station installation.

Figure 15: View of communication tower from communication room with receiving radio antenna and tide gauge benchmark KEPGO-KEP-004.

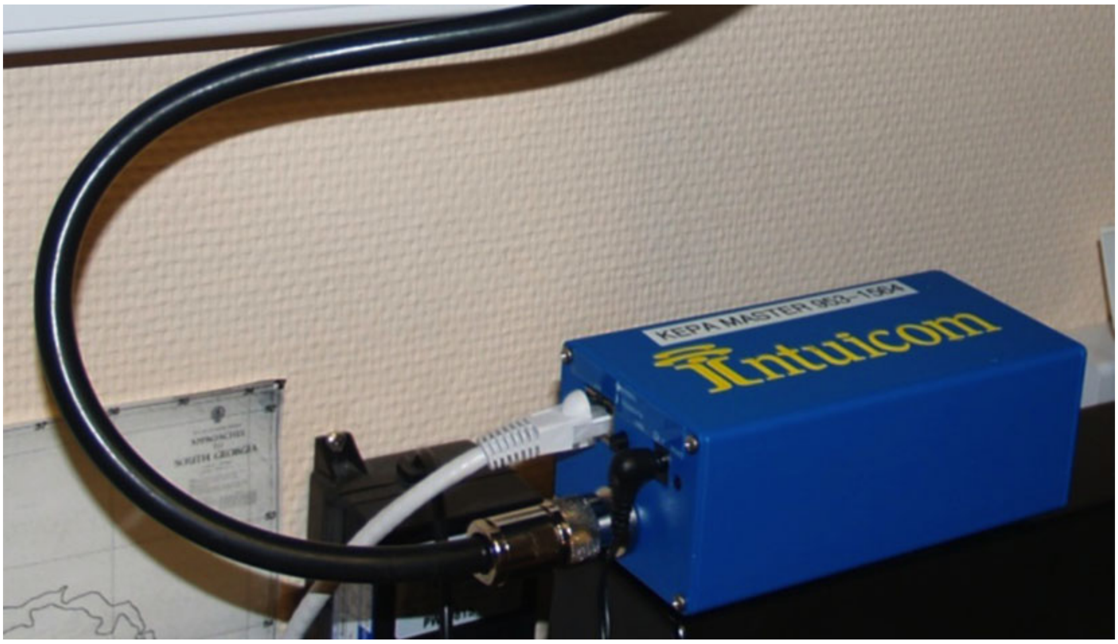


Figure 16: Intuicom Ethernet bridge in KEP communications room.

Figure 17: Yagi radio antenna on satellite tower opposite KEP communications room in the James Cook Laboratory.

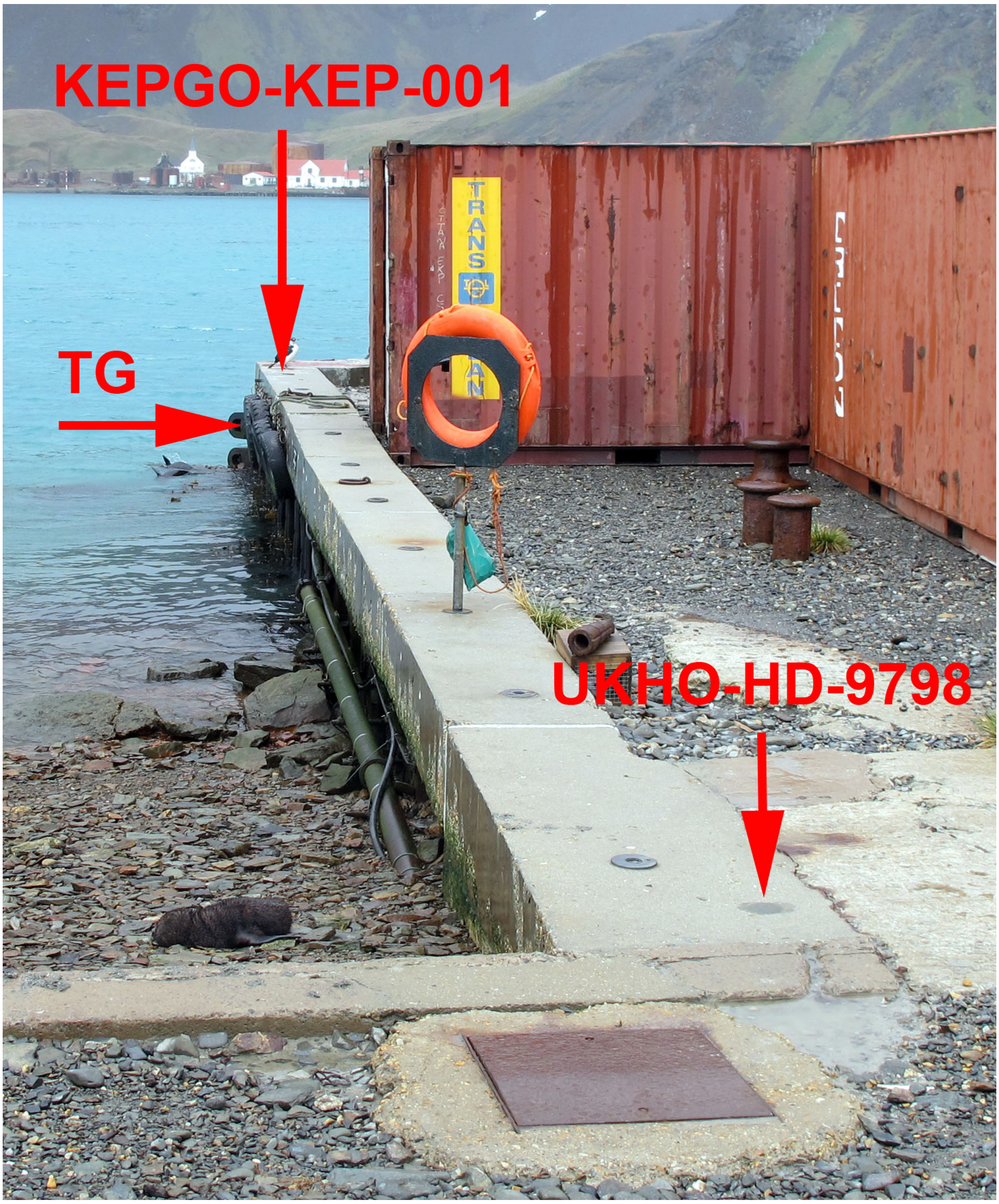


Figure 18: View of the jetty from boat shed with tide gauge and TGBMs KEPGO-KEP-001 and UKHO-HD-9798. Grytviken is situated in the background.

Figure 19: View of the jetty from slipway with tide gauge and TGBM KEPGO-KEP-001.

Figure 20: View of the TGBM KEPGO-KEP-002 located on the north-western concrete foundations of the western HF dipole fan array mast towards Cumberland East Bay. The HF dipole fan array mast is visible in the background.

Figure 21: View of the TGBM KEPGO-KEP-004 inside of the north-eastern corner of the satellite tower.

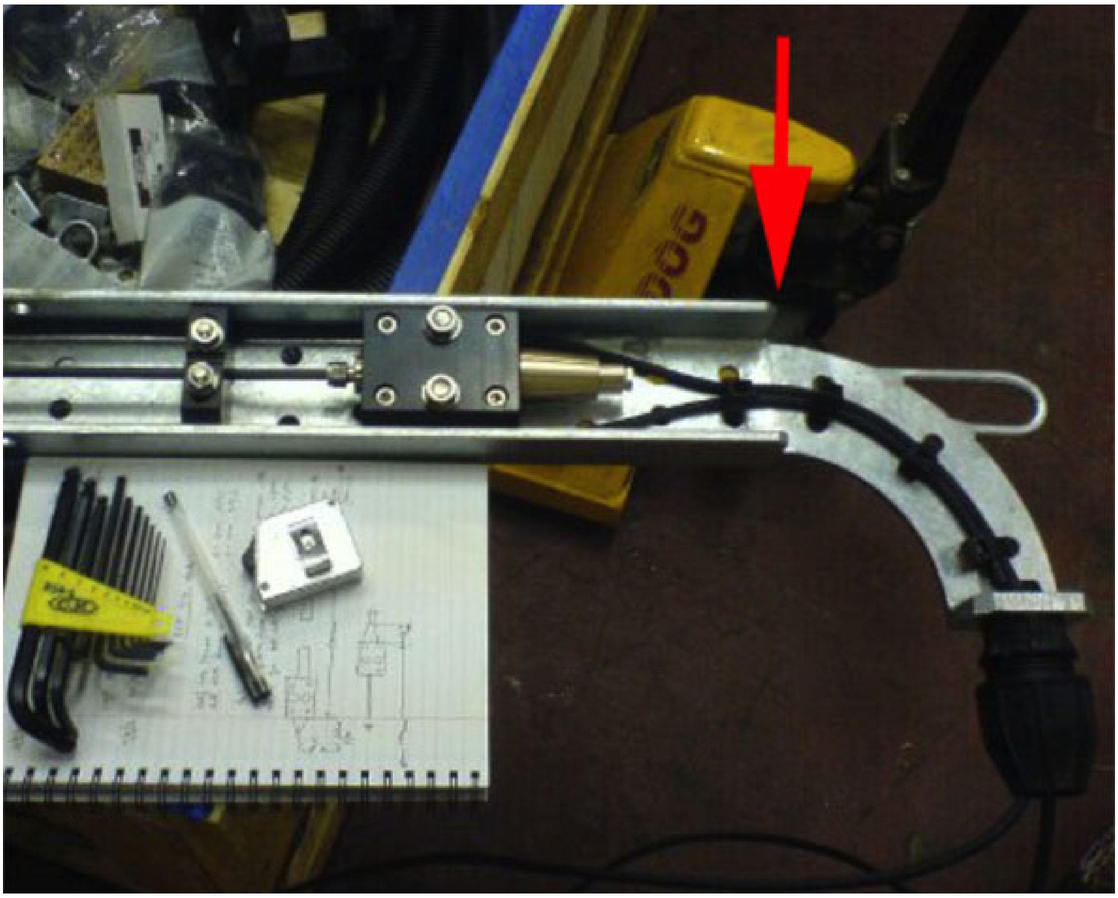


Figure 22: View of the tide gauge as in picture provided by Peter Foden, National Oceanography Centre; the reference point *TG-right* is indicated by the arrow.

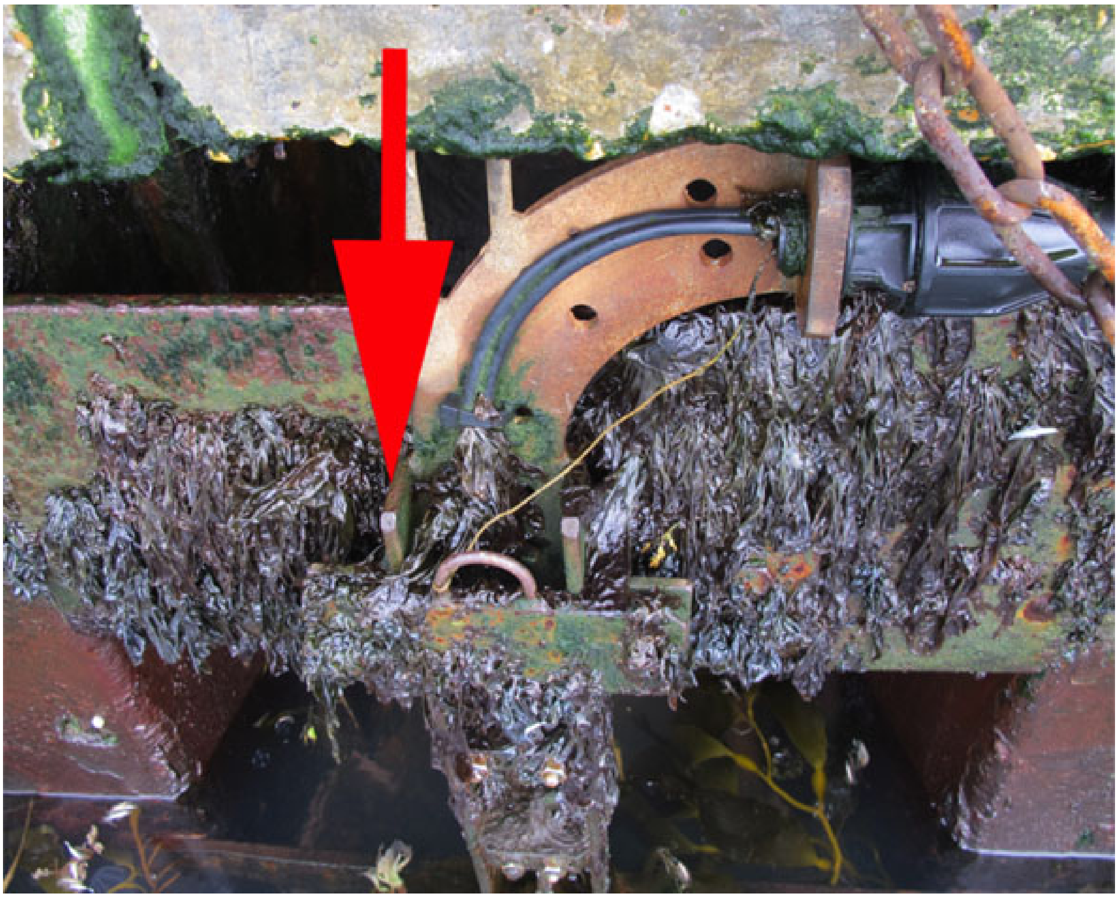


Figure 23: View from top of the jetty with tide gauge in place during survey; the reference point *TG-right* is indicated by the arrow.

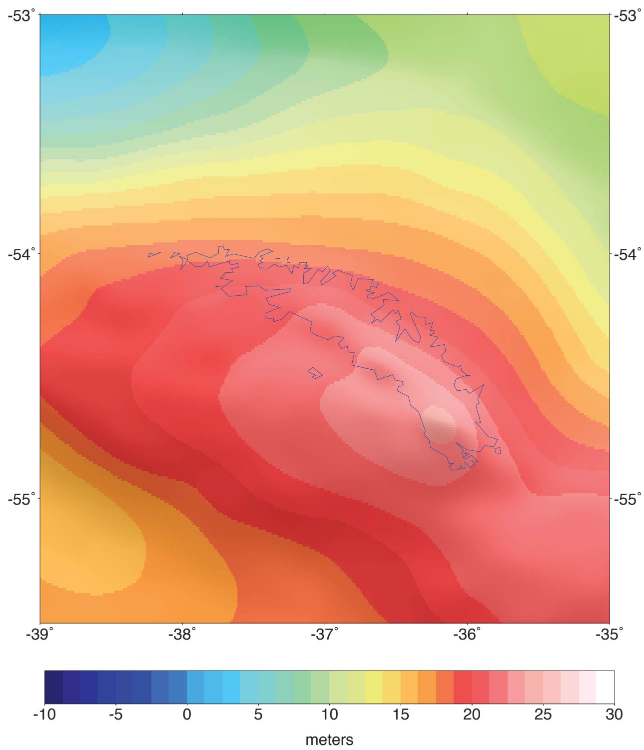


Figure 24: EGM2008 Geoid heights for the region around South Georgia Island.