First Six Months of Superconducting Gravimetry in Argentina

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Abstract

On December 16th, 2015, the superconducting gravimeter SG038 started to measure again after it was moved from the previous station in Concepcion, Chile to the Argentine-Germany Geodetic Observatory (AGGO) near the city of La Plata in Argentina.

The temporal gravity variations recorded with superconducting gravimeters (SG) enables research in several geodetic and geophysical studies that involve Earth's changes in the surface gravity field. In particular, it allows computing local models of earth tide parameters. The superconducting gravimeter SG038 at station AGGO was used to monitor gravity for the first 6 months after its installation.

The gravity time series was preprocessed after removing the principal constituents of the largest influences of the gravity signal that can be modeled sufficiently accurate like atmospheric effects, theoretical tides of the solid Earth, ocean loading effects and pole tides. In the remaining residual signal spikes were fixed, earthquake perturbations were reduced. Finally, the theoretical tides of the solid Earth and ocean loading effects previously removed were restored to obtain the corrected gravity signal.

The transfer function of the SG038 was determined by analyzing the step response of the whole system. Empirical amplitude and phase response functions are presented. The group delay at zero frequency was used in the tidal analysis.

By harmonic analysis of the preprocessed hourly data, amplitude factors and phases for tidal wave groups were estimated.

Keywords

Argentine-Germany Geodetic Observatory • Earth tide parameters • Superconducting gravimeter • Transfer function

1 Introduction

On 16th December 2015, the superconducting gravimeter SG038 was installed at the Argentine-German Geodetic Observatory (AGGO) and it has been measuring continu-

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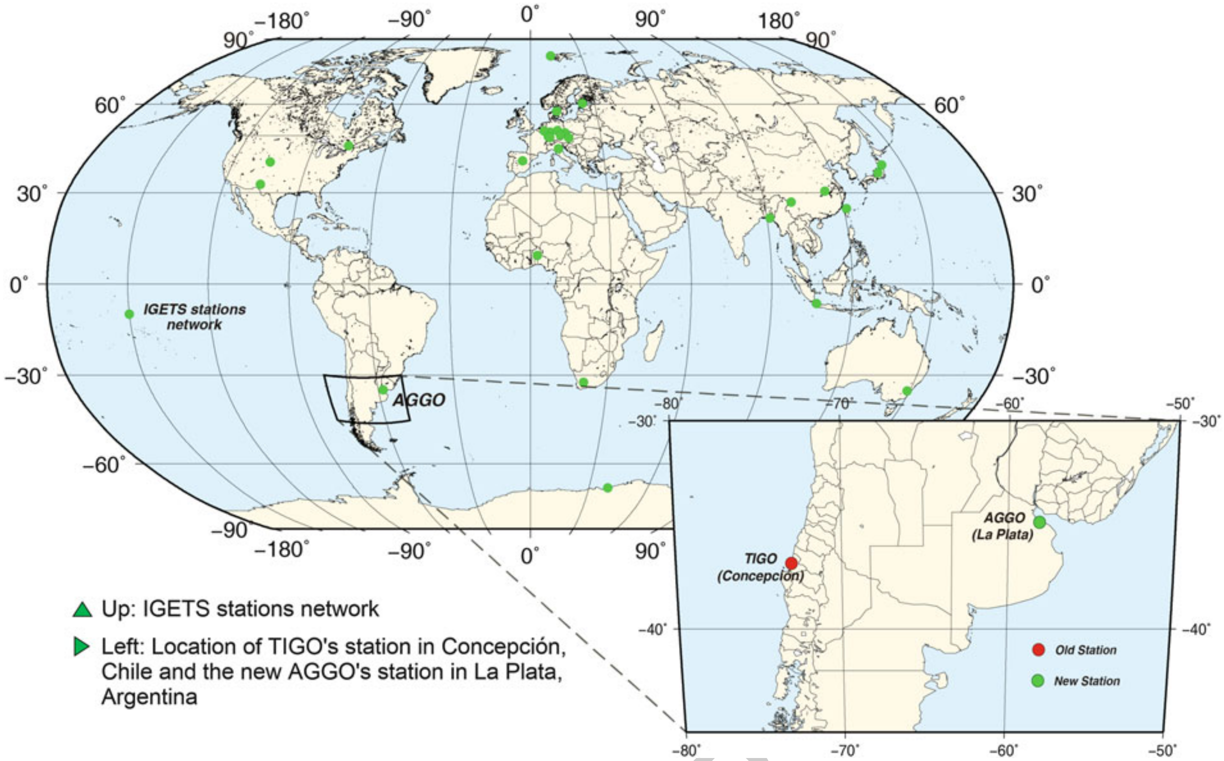

Fig. 1 Map of the global network of superconducting gravimeters grouped within the IGETS. Location of superconducting gravimeter SG038 at station AGGO

ously since then. AGGO is a fundamental geodetic observatory project of the Argentinean CONICET and the German Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie – BKG), located near the city of La Plata. This station is unique in South America and the Caribbean and one of five in the southern hemisphere (Fig. 1). AGGO contributes with the gravity time series to the International Geodynamics and Earth Tide Service (IGETS) of International Association of Geodesy (IAG), the worldwide network of superconducting gravimeters.

A superconducting gravimeter is a relative gravimeter and with highest sensitivity and temporal stability. The measuring principle is based on a superconducting sphere levitated in the magnetic field generated by two superconducting coils. Observed is the voltage fed into a feedback coil in order to keep the sphere in its position (Hinderer et al. 2015). The changes in gravity are proportional to these voltage changes, which are low pass filtered with the analogue 'GGP1' filter by GWR and recorded with 1 s sample rate. The sensor of SG038 was the first where the magnetic gradient is fixed at the factory by carefully adjusting the turns-ratio of the upper and lower coils, which are connected in series. Therefore, only one current is used to levitate the sphere. Upon centering the sphere, the magnetic gradient is correctly adjusted. This is achieved by a separate small centering coil that operates independently from the series coil (Warburton et al. 2000). Due to this concept, only minor modifications of the magnetic field were necessary to re-levitate the sphere after more than 3,800 km overland transportation from Chile to Argentina.

The SG data enable research in several geodetic and geophysical studies that involve temporal changes in the Earth's surface gravity field. In particular, it allows to compute local models for the Earth's tides. In this study, the gravity signal recorded during the first 6 months after its installation was analyzed. As a precondition, the transfer function of SG038 has been experimentally determined.

2 The Station

AGGO is a fundamental geodetic observatory located in the east-central part of Argentina close to the city of La Plata. The transportable design of the observatory was chosen to allow for an operation at different locations to improve the global coverage and to stabilize the terrestrial reference

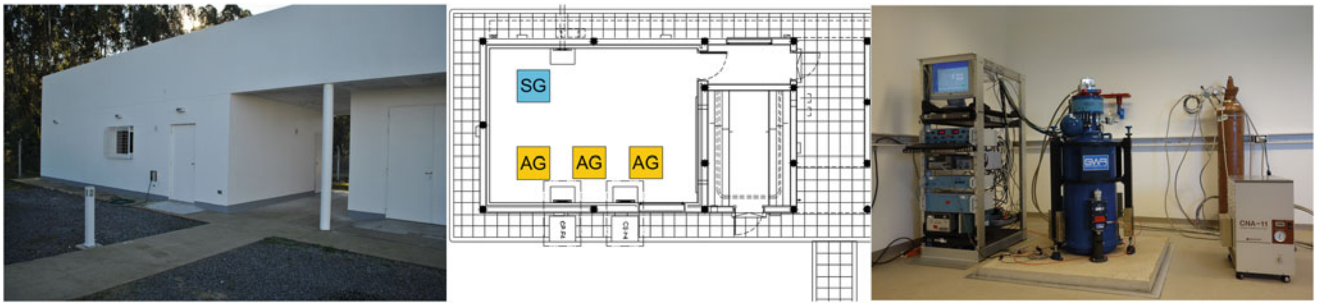

Fig. 2 Gravity laboratory (*left*), floor plan of the gravity laboratory (*middle*) and SG038 (*right*)

frame. All main space geodetic techniques are established, from very long baseline interferometry (VLBI), satellite laser ranging (SLR) to global navigation systems (GNSS). As a complementary technique, a superconducting gravimeter is part of the observatory. As precise time keeping is essential, different atomic clocks are operated, too.

In order to acquire environmental parameters, a weather station (precipitation, air temperature, air humidity, wind speed, wind direction, solar radiation, net radiation), soil moisture sensors (about 40 sensors in soil depths of 10–380 cm below surface) in two pits and two vertical profiles were installed in cooperation with the GFZ German Research Centre for Geosciences, Potsdam, Germany.

The complete instrumentation of the transportable integrated observatory (TIGO) was moved in April 2015 from the previous location close to the city of Concepcion, Chile, to the actual place. AGGO is the only station in South America and the Caribbean where all these different techniques are collocated.

The SG038 was the first instrument to start measuring on the 16th December 2015. The signal is recorded with 1 s sample rate by a digital voltmeter with 7 ½ digit resolution. The instrument can be accessed and controlled remotely via internet. It is installed in a dedicated gravity laboratory which has four stable monuments made of concrete, about $1\ \mathrm{m}^2$ in size and founded 4 m deep, large enough to setup all types of FG5 absolute gravimeters. All monuments are separated from the floor of the building to minimize disturbances on the gravimeter. AGGO fulfils the requirements for a regional comparison site for absolute gravimeters and is a candidate for the future Global Absolute Gravity Reference System (Wilmes et al. 2016). Figure 2 shows the gravity lab, a floor plan and SG038.

3 Determination of the Frequency Transfer Function of SG038

Following the procedure of Van Camp et al. (2000), a step function with a pulse length of 10 min is added to the current of the feedback coil. The extra signal in the feedback loop induces an extra force, which causes the sphere to move out of its position. The displacement is detected immediately by the three plate capacitor surrounding the sphere, causing an additional signal at the input of the control loop. This signal, overlying the gravity signal, is transformed into an extra current in the feedback coil, forcing the sphere back to its center position. It is recorded and low pass filtered in the same way as the normal signal by the registration system.

With this experiment, the response of whole system can be identified, including (but not limiting to) the characteristics of the low pass filters. However, in normal operation, gravity changes do not cause the sphere to move, as the feedback loop is fast enough to compensate these forces. So this experiment characterizes the system under different conditions.

The experiment was performed at two times:

1. At the beginning of the operation at station TIGO/Concepcion (Chile) in December 2002,
2. After moving the SG to station AGGO/La Plata (Argentina) in May 2016.

First, tidal and atmospheric effects were removed by models. Then the all valid response segments were cut to 3 min to avoid the impact of other signals. All segments were stacked and low pass filtered by a short finite impulse response (FIR) filter. Next it was transformed into the impulse response by numerical differentiation. In the frequency domain, the impulse response is identical to the transfer function of a linear time invariant system. To enhance the resolution at lower frequencies, the signal was transformed into the frequency domain using the chirp-z-transformation (Rabiner et al. 1969).

The characteristics of the frequency response is similar in both cases, the difference in the amplitude response is less than −20 dB (Fig. 3). A strong overshot is visible in the time domain (Fig. 4a), corresponding to an amplification of 2 dB (Fig. 4b, c), and a phase distortion in the range of 10 mHz (Fig. 4d, e). It is not clear, whether this represents a different characteristic of the system under the conditions of the experiment or if the system shows a non-linear behavior in a limited range. However, in the range of typical gravity

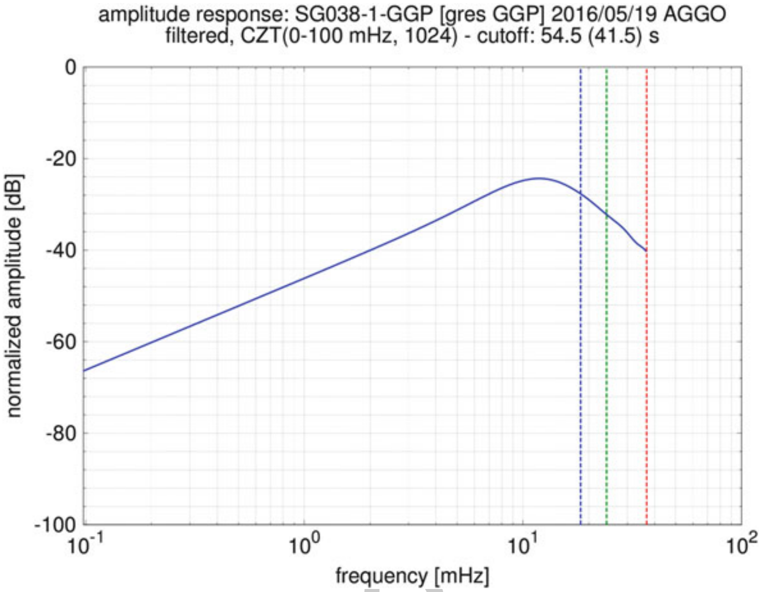

Fig. 3 Differences of amplitude responses between the two periods of time considered

signals below 1 mHz, the system is stable and responds linearly. The most important information for analysis of gravity time series is the time delay at zero frequency as can be seen in Fig. 4d, e. It is assumed, that the delay below the lowest determined frequency at about 3 h remains constant and is representative for the whole tidal range, starting from zero frequency. The difference of 0.8 s between both experiments may be due to changes in the electronics during an upgrade of the SG038 in 2008 (Table 1).

4 First Tidal Analysis

For the first tidal analysis, 6 months of data from SG038 (from January to June 2016) were used. The TSOFT software (Van Camp and Vauterin 2005) was used for the following processing steps depicted in Fig. 5:

1. The registration in voltage was transformed to gravity units using the scale factor -736.5 nm/s^2/V as obtained from numerous parallel recordings mainly with the Absolute Gravimeter FG5-227 during the period 2006–2012 at station TIGO/Concepción.
2. To obtain preliminary residuals, the principal effects were modeled (atmosphere, theoretical tides, ocean loading and polar motion effect) and subtracted from the signal. Atmospheric effects were modeled with a simple air pressure admittance using a constant value of -3.0 nm/s^2/hPa (Torge 1989). Theoretical tides were computed using Tamura's catalogue of 1,200 waves (Tamura 1987) and synthetic Earth tide parameters (Dehant et al. 1999). The ocean loading effect on gravity was computed using the EOT11a model (Savcenko et al. 2012) with parameters provided by the ocean tide loading provider of M.S. Bos and H.-G. Scherneck (http://holt.oso.chalmers.se/loading/). The polar motion effect is based on the EOP C04 pole coordinate series of the International Earth Rotation and Reference Systems Service (IERS) using an amplitude factor of 1.16 (Wahr 1985).
3. Spikes were eliminated manually by linear interpolation in order to have a smooth signal without disturbances. No steps or gaps were recognized in the signal.
4. The signal was filtered with the purpose of eliminating the frequencies that do not contribute to the tidal model or generate noise. A low pass least squares filter was applied with a cut-off frequency of 50 cpd (cycles per day) and a window size of 200.
5. Finally, the theoretical Earth tide model and the ocean loading effect removed previously in step 2. were restored. In contrast, atmospheric and polar motion effects were not restored to the preprocessed residual signal. Then, the signal was decimated to 1 h sample rate.
6. The Earth tide parameters were then computed using the ETERNA 3.4 software package (Wenzel 1996) and tidal wave groups for 1 month. The time delay was taken into account. No air pressure admittance factor was estimated. The final results are included in Table 2.

Analyzing the standard deviation (Std. Dev.) of the results, the main diurnal and semidiurnal waves are well determined while this is not the case for longer period waves such as MM or SSA, which were omitted completely from the analysis, because the time series is not long enough to resolve these waves, due to the low amplitude at the latitude of the station (lower than 5 nm/s^2). As the time series of the SG grows, the longer period waves will be determined with better approximation.

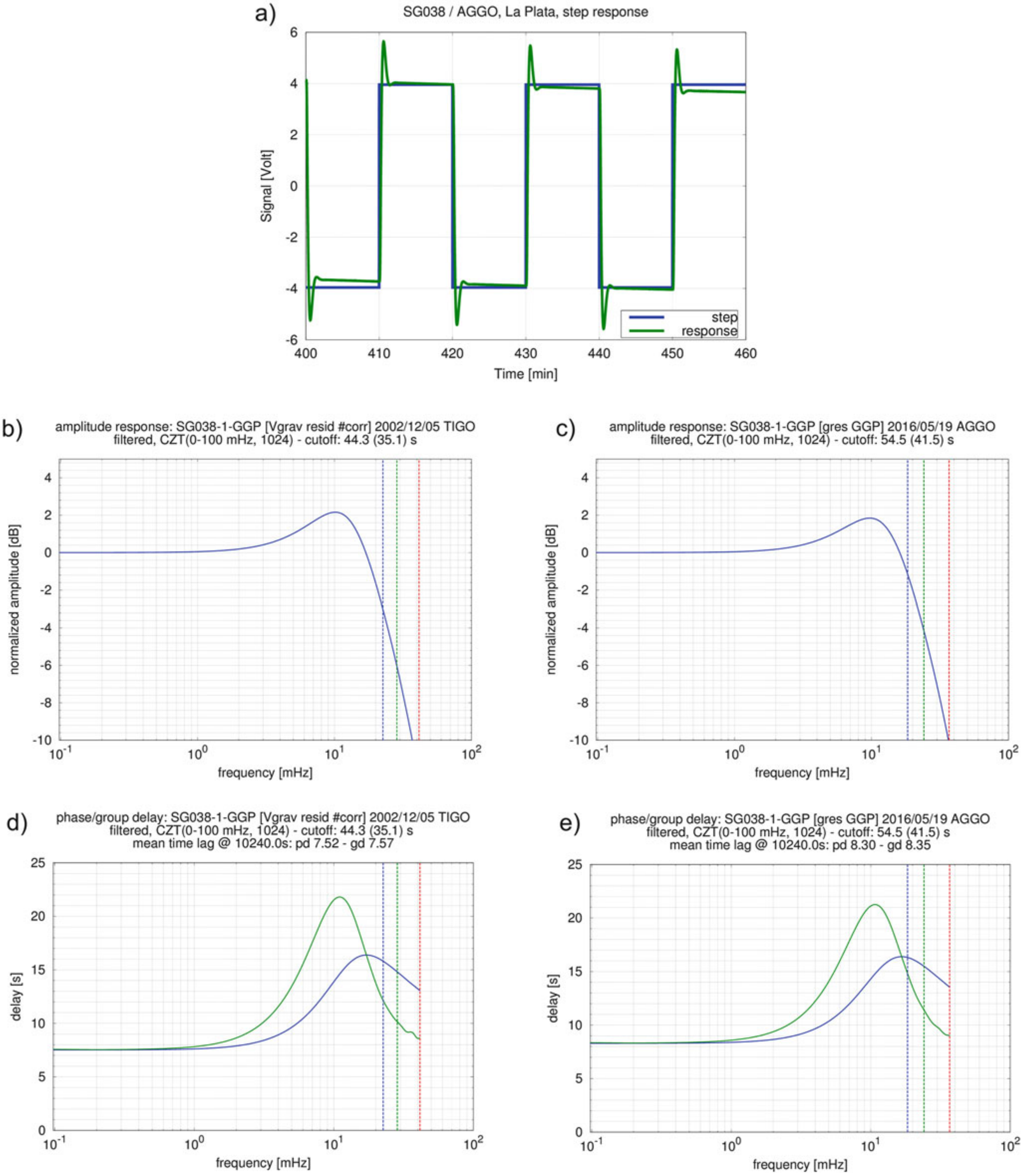

Fig. 4 Selected step response in time domain. The overshot after the step is clearly visible. The response is overlaid by tidal changes (**a**). (**b**, **c**) Shows the amplitude responses at stations TIGO and AGGO, respectively. (**d**, **e**) Shows the phase/group delay at stations TIGO and AGGO, respectively

After the tidal analysis, the spectrum of the final residuals (Fig. 6) shows a clear improvement over the residuals obtained from theoretical tides (WD model) and ocean tide loading (EOT11a model). Only small peaks at S1 and S2 remain as atmospheric tides could not be resolved independently due to the coarse wave grouping. Deviations in amplitude and phase at these particular frequencies from the elastic response of the solid Earth can currently not be modelled sufficiently well. A more efficient atmospheric correction, e.g. based on operational weather models, will certainly reduce the spectral energy further.

Table 1 Results of the transfer function for the two experiments (the first when the SG038 was at station TIGO and the second when it was moved to station AGGO)

Date	Phase delay (s) GGP1 low pass filter	Group delay (s) GGP1 low pass filter	Cutoff periods (s) (−3/−6/−12 dB)
1) December 2002	7.51	7.57	44.33/35.07/24.15
2) May 2016	8.30	8.35	54.47/41.46/27.16

Currently, no reliable estimate about the instrumental drift can be given as no absolute gravity measurements are available yet. This didn't affect the tidal analysis, as the signal was high pass filtered. An overall trend of approximately 250 nm/s^2/year provides a limit, overlaid by seasonal environmental effects. Estimates of local and global water storages changes are currently under investigation. As the instrument was moved cold and the currents were not purged in the coils, the sphere only needed to be centered. Therefore no major change in the magnetic field occurred and only a small run-in effect of less than 40 nm/s^2 was observed during the first week. It is therefore assumed that the major characteristics of the sensor was preserved, which is partially

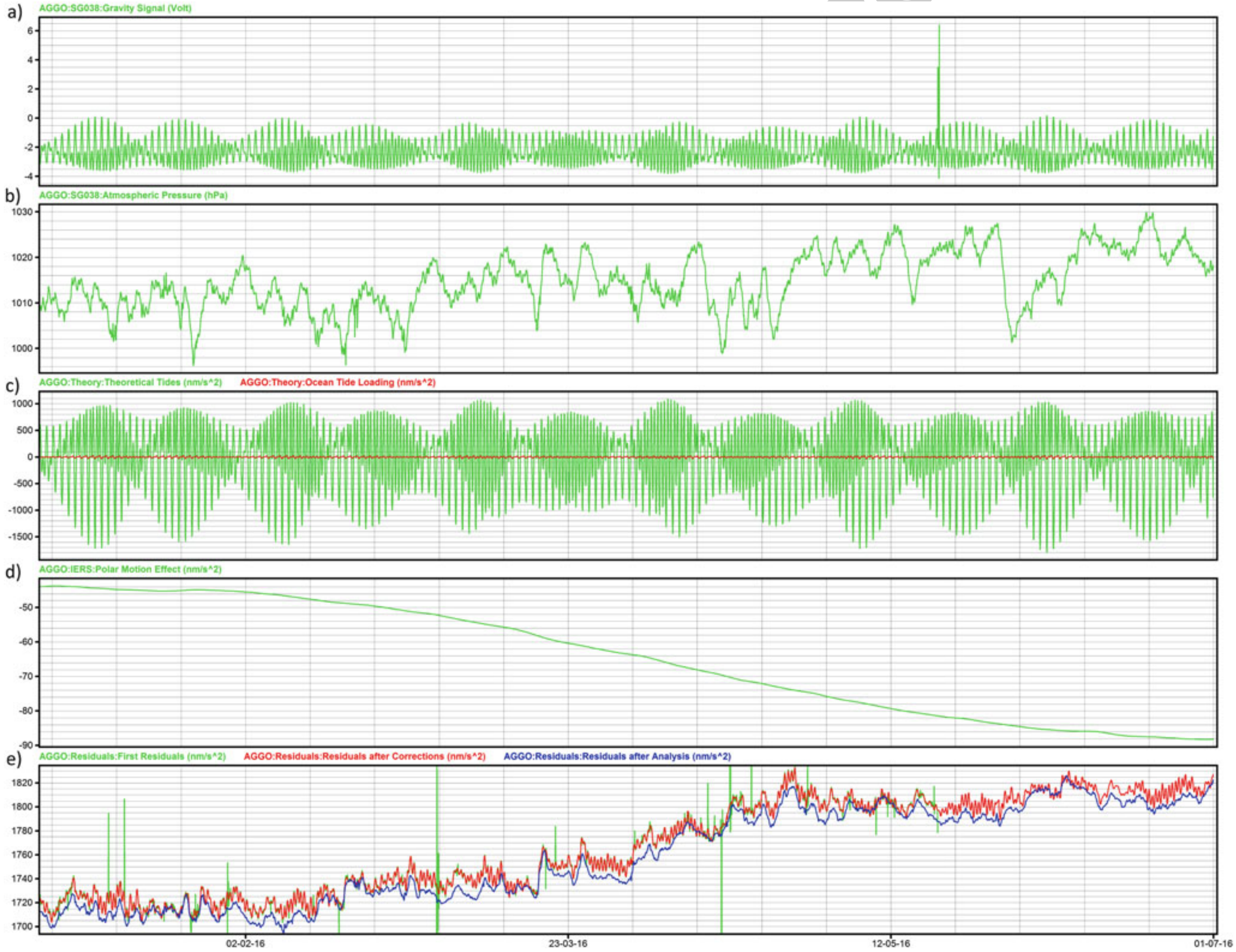

Fig. 5 (**a**) Gravity signal from the superconducting gravimeter SG038 at station AGGO from January to June, 2016; (**b**) Atmospheric pressure; (**c**) Tides based on theoretical elastic response and Tamura's potential catalogue (*green*); Ocean loading from model EOT11a (*red*); (**d**) Polar motion effect on gravity; (**e**) First residuals after removing the effects shown above (*green*); Residuals after removing spikes and disturbances and low pass filtering (*red*); Residuals after tidal analysis (*blue*)

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Table 2 Earth tide parameters at station AGGO estimated using the 6 first months of observations taken with the SG038

Wave	Initial frequency (cpd)	Final frequency (cpd)	Observed amplitude factor (nm/s^2)	Std. dev. of amplitude factor (nm/s^2)	Observed phase (deg)	Std. dev. of phase (deg)
SGQ1	0.72	0.83	1.2810	0.0429	−0.2540	1.9224
SGM1	0.85	0.87	1.2068	0.0086	3.1025	0.4091
Q1	0.89	0.91	1.2029	0.0020	0.0753	0.0941
O1	0.92	0.94	1.1895	0.0004	−0.2227	0.0200
NO1	0.96	0.97	1.1828	0.0035	−0.0505	0.1672
PSK1	0.99	1.01	1.1563	0.0003	−0.3370	0.0147
J1	1.03	1.04	1.1819	0.0047	0.0227	0.2268
OO1	1.06	1.08	1.1761	0.0105	0.9708	0.5108
NU1	1.10	1.22	1.1485	0.0558	1.3217	2.7840
EPS2	1.72	1.84	1.1739	0.0074	1.8938	0.3603
2 N2	1.85	1.87	1.1931	0.0015	1.7293	0.0715
N2	1.89	1.91	1.1963	0.0003	0.9238	0.0165
M2	1.92	1.94	1.1825	0.0001	0.4918	0.0035
L2	1.96	1.98	1.1812	0.0021	0.2124	0.0999
S2 K2	1.99	2.01	1.1660	0.0002	0.0330	0.0077
ETA2	2.03	2.05	1.1864	0.0155	0.0195	0.7476
2 K2	2.07	2.18	1.1894	0.0487	−1.9669	2.3470
M3	2.75	3.08	1.0947	0.0027	0.7911	0.1433

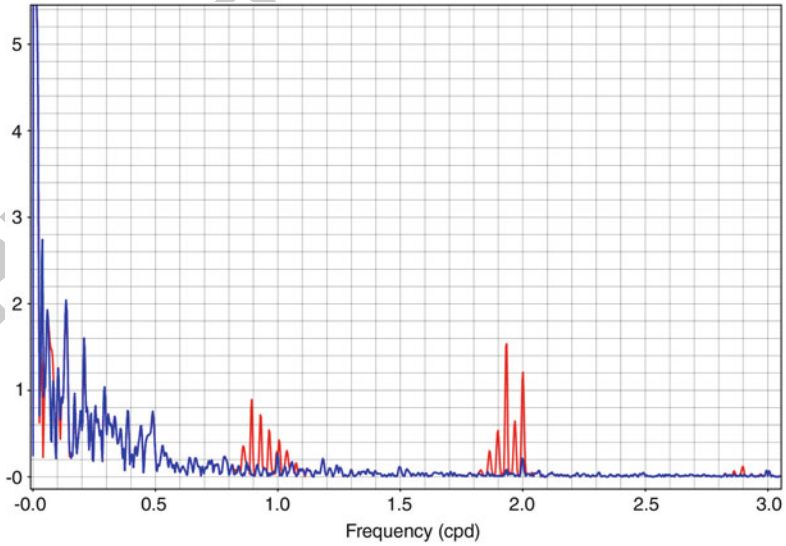

Fig. 6 Spectrum of the residuals, based on theoretical tides (WD) and ocean loading (EOT11a) (*red*) and after the tidal analysis (*blue*). Small peaks remain at S1/S2 as atmospheric tides could not be resolved independently

demonstrated by the similar behavior of the transfer function. However, the overland transportation may have affected the instrumental drift, which was only about 60 nm/s^2/year at the previous location.

5 Conclusions

The first 6 months of data of the superconducting gravimeter SG038 were analyzed after setup at the new station AGGO. The time delay of the instrument was calculated from transfer functions for two periods of time. The difference in the time delay between both periods is probably caused by upgrades of the electronics of the instrument in 2008.

Parameters for the main diurnal and semidiurnal tidal waves were well determined. Longer period waves, e.g. fortnightly waves could not be resolved due to the fact that the time series considered for the analysis was too short and the amplitude of these constituents is low at the latitude of the station. The wave group separation will be further enhanced when a longer time series becomes available.

A correlation between residuals from the tidal analysis and the atmospheric effect exists and will be studied in the future.

The influence of local water storage changes was not considered so far, but the extensive hydrological instrumentation will enable a detailed investigation in the future. As it can be seen from Fig. 5e, the residuals show a clear positive trend. This effect will partially contain seasonal variations of local, regional and global water storage changes. Furthermore, strong rain fall events as typical for the La Plata region will need to be separated from corresponding loading effects due to wind effects in the La Plata estuary.

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