# Observing Ocean Mass Variability with Spring Gravimeters – Storm Surge Induced Signals on the North Sea Island Helgoland

## Federgravimeter messen Massenverlagerungen im Ozean – Sturmflut-induzierte Signale auf der Nordseeinsel Helgoland

Adelheid Weise, Ludger Timmen, Zhiguo Deng, Gerald Gabriel, Christian Rothleitner, Manuel Schilling, Christian Voigt

Climate change is broadly discussed due to water level rise almost worldwide. Additionally, ocean-related risks driven by atmospheric dynamics are amplified, as tidal amplitudes in coastal areas and storm surges, which threaten coastal areas and the unique Wadden Sea in the German Bight. Investigations of the oceans in general and of the North Sea particularly are done by satellite technics as altimetry and the satellite mission GRACE-FO. Terrestrial geodetic measurements are needed for corrections and validation of the results. Several methods are in use in order to measure water level variations (tide gauges) and load related deformation (GNSS).

Our key question is: Are accurate continuous gravimetric observations sensitive to non-tidal oceanic loading of the sea floor? For the first time, three spring-type gravimeters were installed on the island Helgoland in the North Sea, predominantly in winter season, to observe surrounding maximal water mass variations during the winter period 2018/2019. In spite of the non-linear instrumental drift, gravity variations exceeding 100 nm/s$^2$* over periods of 1 – 3 days could significantly be separated. Partly they are assigned to water level variations due to storm events, e. g. Zeetje (1. 1. 2019) and Benjamin (8. 1. 2019), and wind directions, accordingly. A rough modelling of the estimated corresponding water mass load with maximum water level rise of 2 m in the German Bight agree with the observed attraction effects and with the vertical displacement observed in gravity and by GNSS.

We conclude that we succeeded on the island Helgoland to measure gravimetrically the non-tidal mass variations and the related crustal deformation in the North Sea. It should be further continued during winter seasons. Even more appropriate may be the installation of an iGrav superconducting gravimeter benefitting from its small, linear instrumental drift. Finally, this research will contribute to tidal and non-tidal ocean mass variability models and will support the monthly modelling of the geopotential field from the satellite mission GRACE-FO, where the so-called de-aliasing products for short-term variations in atmosphere and ocean are needed.

Keywords: Spring gravimeter, tidal and non-tidal gravity variations, mass variability in oceans, crustal deformation, wind-driven storm surge

* 100 nm/s² = 10 µGal

*Der Klimawandel wird mit Blick auf den weltweiten Meeresanstieg viel diskutiert. Zusätzlich werden Ozean-bezogene, durch die Atmosphärendynamik angetriebene Risiken verstärkt, das sind u.a. die Gezeitenamplituden in Küstenregionen und Sturmfluten, die die Küsten und das einzigartige Wattenmeer in der Deutschen Bucht bedrohen. Die geodätische Erforschung der Ozeane allgemein und der Nordsee im Besonderen wird mit Altimetrie und der Satellitenmission GRACE-FO realisiert. Terrestrische geodätische Messungen werden zur Bereitstellung von Korrektionen und zur Validierung der Resultate benötigt. Diverse Methoden finden Anwendung zur Messung von Wasserspiegelvariationen (Pegel) sowie auflastinduzierten Deformationen (GNSS).*

*Die Schlüsselfrage ist: Sind präzise kontinuierliche gravimetrische Beobachtungen sensitiv auf nicht gezeitenbedingte Auflasten des Ozeans auf den Meeresboden? Erstmalig wurden drei Federgravimeter in der Nordsee, auf der Insel Helgoland, installiert, um vorwiegend in den Wintermonaten 2018/2019 die Wirkung der umgebenden maximalen Wassermassenvariationen zu erfassen. Trotz der nichtlinearen instrumentellen Drift konnten Schwerevariationen von über 100 nm/s²* über Zeiträume von 1–3 Tagen signifikant separiert werden. Teilweise stehen sie im Zusammenhang mit windgetriebenen Wasserstandsänderungen, z.B. die Stürme Zeetje (1.1.2019) und Benjamin (8.1.2019), und den entsprechenden Windrichtungen. Ein einfaches, genähertes Modell der aus maximalem Wasserstandsanstieg von 2 m in der Deutschen Bucht geschätzten Wassermassenauflast stimmt bereits mit dem Attraktionseffekt und der vertikalen Bodenbewegung überein, wie sie in Schwere und mit GNSS beobachtet wurden.*

*Das Fazit ist, dass es auf Helgoland gelungen ist, die nicht gezeitenbedingte Massenvariationen in der Nordsee und die damit einhergehende Krustendeformation gravimetrisch zu messen. Die Fortsetzung der Registrierungen in den Sturmsaisons ist dringend zu empfehlen. Ein iGrav-Superconducting-Gravimeter, das eine lineare, kleine instrumentelle Drift gewährleistet, wird für diese Aufgabe noch geeigneter sein. Schließlich wird dieses Experiment zu Ozeanmodellen mit gezeiten- und nicht gezeitenbedingten Variationen sowie zu Reduktionsmodellen durch von der Atmosphäre bewirkte Effekte in Schwerefeldvariationen beitragen, welche aus der Satellitenmission GRACE-FO abgeleitet werden.*

*Schlüsselwörter:* *Federgravimeter, gezeiten- und nicht gezeitenbedingte Schwerevariationen, Massenverlagerungen in Ozeanen, Auflast der Nordsee, Krustendeformation, Windstau, Sturmflut*

## 1 INTRODUCTION AND MOTIVATION

The impact of ocean-related risks, such as extreme storm surges, is driven by atmospheric dynamics and therefore amplified by global climate change. This holds especially true for marginal seas like the North Sea where, with the expected sea level rise, storm events will lead to more frequent and stronger coastal surges.

Storm surges in the German Bight will become stronger in future with the ocean level rise, cf. /Weisse et al. 2012/, /DKK & KDM 2019/. They threaten coastal areas which are intensively used by society. Additionally, the height of the tidal range and the tidal flow have increased at the German North Sea coasts, since 1950 by up to 10 %. As a secondary effect, seasonal variations of the tidal range near the coastline have been observed /Müller et al. 2014/. As one of the consequences, the unique and vulnerable Wadden Sea in the German Bight is more and more at risk.

Satellite techniques help to investigate sea level variations. /Fenoglio-Marc et al. 2015/ impressively model the temporal development of the water level variations in the German Bight during cyclone Xaver (Dec. 5–6, 2013), using water level, GPS (Global Positioning System), and altimetry data. Vertical displacements of up to 30 mm near the coast were predicted. /Fratepietro et al. 2006/ present a model of deformation caused by loading of a typical storm surge of 2 m in the southern North Sea. Considerable magnitudes of vertical displacements (–20 to –30 mm, see also e.g. /Williams & Penna 2011/) and gravity increase of 60 to 80 nm/s² are calculated for coastal areas, and a wide area of northwest Europe can be affected.

Since 2002, the satellite missions GRACE (Gravity Recovery And Climate Experiment) and GRACE-FO are successfully observing indications of climate change like increasing global ocean level rise, seasonal variations, melting ice sheets, and changes in global hydrology (droughts and floods), cf. /Tapley and Reigber 2001/, /Kusche et al. 2013/. Geodetic ground-based methods are important for validating results of satellite missions, as reported by /Weise et al. 2012/ for continental hydrology. As GRACE-FO focuses the investigations on oceans worldwide, the correction for oceanic aliasing is strongly required in order to significantly improve the

* 100 nm/s² = 10 µGal

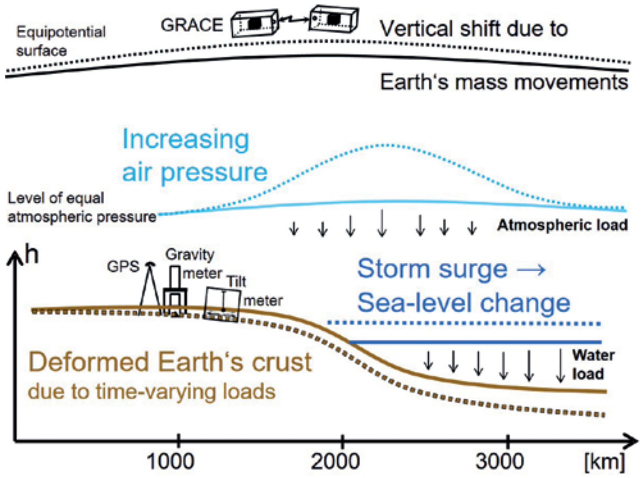



Fig. 1 | Highly accurate continuous observations of gravimetric tides on Helgoland are sensitive to oceanic loading of the sea floor as well as to atmospheric pressure forces. The sketch demonstrates the deforming Earth's crust caused by loading of temporal air mass (pressure) variations and sea mass changes (tides, storm surge) observable locally with terrestrial instruments as well as regionally with the satellite mission GRACE-FO.

accuracy of the gravity field models /Flechtner et al. 2016/. Tidal and also non-tidal background models of ocean mass variability are needed for de-aliasing the satellite gravity observations (e. g. AOD1B RL06 of /Dobslaw et al. 2017/) and for assessing the ability of the satellite mission GRACE-FO /Fenoglio-Marc et al. 2006/. Because non-tidal loading models (e. g. of storm surges) with high temporal resolution are required, terrestrial measurements near the coasts are valuable and requested. Furthermore, reduction models in terrestrial gravimetry as applied in near-coastal groundwater projects will be improved as well.

Our scientific key question is: Can highly accurate continuous observations of gravimetric tides reveal non-tidal oceanic loading on the sea floor? For the first time, we are conducting such experiments with spring gravimeters to prove temporal mass variations associated with non-tidal water level changes.

With respect to climate change, we observe gravimetric tidal and non-tidal variations on the island Helgoland situated in the North Sea in order to investigate the gravity and deformation (vertical surface shift of the solid Earth) effect caused by fluctuations of the mass distribution in the North Sea. In general, the gravitational effect (Newtonian attraction) of time-variable masses is associated with a second effect caused by the vertical shift of the surface of the elastic Earth's crust due to the varying mass load. In addition to the solid Earth's and ocean tides, a special focus is on identifying non-tidal gravity effects. The gravimetric analysis of non-tidal and tidal loading will provide time series of the vertical Earth's surface (sea floor) displacements (*Fig. 1*) with high temporal resolution. The deformation of the seafloor is largest during extreme highwater conditions (storm surges). Additional geometrical deformation measurements by GNSS (Global Navigation Satellite System) enable to distinguish between the contributions of the mass variations and the shift of the vertical position of the gravimeter.

## 2 ACQUISITION OF GRAVITY TIME SERIES IN HELGOLAND

The island Helgoland, about 50 km from the coasts with varying water masses all around, is chosen as a perfect location for continuous gravity recordings of tidal and non-tidal signals of the North Sea. But Helgoland is not a quiet location because of the natural noise caused by the sea, especially in winter seasons. Three spring-type relative gravimeters recorded at two stations on the island Helgoland (*Fig. 2*) during winter 2018/2019. In the cellar of James-Krüss-Schule (JKS) on Helgoland's upland (height ~ 38 m above mean sea surface), the gravimeters ZLS B64 /Jentzsch et al. 2015/ and Scintrex CG6-49 (*Fig. 3*) were part of a multi-parameter station, co-located with a seismometer, tiltmeter and a microbarometer. The recording of B64 started on 2018-08-30 for 280 days (until 2019-06-05, 10-seconds samples), while the CG6-49 was installed on 2018-11-28 for 127 days (until 2019-04-04, 1-minute samples). The parallel recording can give evidence about the reliability of the long-term signals recorded by spring gravimeters. The third gravimeter, Scintrex CG5-211, was installed at WSV (Wasserstraßen- und Schifffahrtsverwaltung) in the South Harbor (2-minutes samples, height ~ 2 m above mean sea water), almost on the level of sea

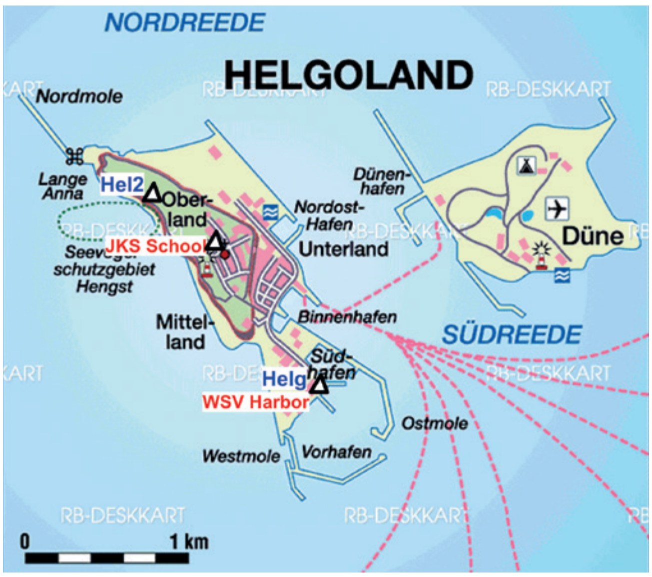



Fig. 2 | Map of island Helgoland in the North Sea. White triangles mark all three observation locations, as there are both gravity observation sites, JKS School in the upland (~ 38 m height above mean sea level) and WSV Harbor situated in the South Harbor (~ 2 m), and the GNSS stations Hel2 and Helg. /RB-DESKART: www.brennemann-deskart.de/

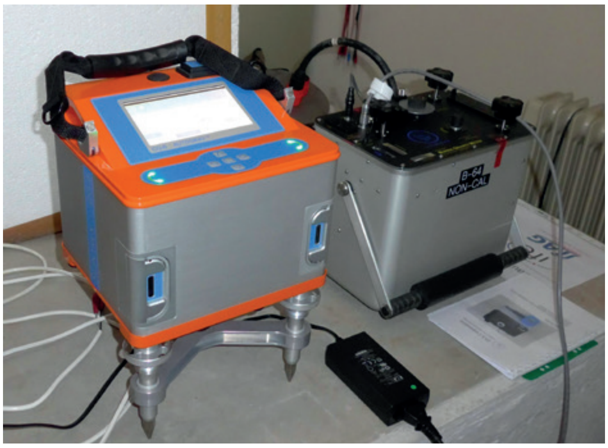


Fig. 3 | Installation of two gravimeters in the cellar of JKS school (James-Krüss-Schule) in Helgoland's upland, Scintrex CG6-49 (left) and ZLS B64 (right)

surface changes to achieve a minimum gravitational effect along the plumb line. The recorded samples of all three instruments are originally based on 1-second samples. The 10-seconds record of B64 is the result of numerical filtering (filter length 10 minutes, cut-off ~ 5 minutes). The samples of both Scintrex gravimeters are averages over one and two minutes, respectively, additionally outliers were eliminated. The gravimeters were calibrated in the Relative Gravimeter Calibration System Hannover with an accuracy in the order of $10^{-4}$ /Timmen et al. 2018/ ensuring that no calibration errors affect the expected small signals we are searching for. At both stations, air pressure is observed in parallel. Room temperature varied over the seasons by several degrees. Even if there is any related effect in a gravity record, it is considered during the data evaluation by the drift elimination. Hydrological effects caused e.g. by soil water variations will be widely minimized due to the building and ground sealing around, e.g. the schoolyard at JKS and asphalt covering at the harbor.

Continuously observed geometrical deformation is provided by two GNSS receivers on the upland (Hel2) and in the harbor (Helg, *Fig. 2*), operated by BKG (Bundesamt für Kartographie und Geodäsie), which enables to confirm the separation of attraction and deformation effect in gravity. Additionally, tide gauges record water level variations simultaneously at Helgoland's harbors, run by the Federal Maritime and Hydrographic Agency/Hamburg (BSH) who will additionally support the project by sea surface information in future.

## 3 DATA QUALITY

### 3.1 Noise Levels

Before investigating signals induced by mass changes due to water level changes, the data quality of the gravimeter recordings is evaluated shortly.

One criterion is the noise level, which also depends on the station environment. On Helgoland, we expect disturbances caused by the atmosphere (wind) and the ocean (North Sea), especially during winter seasons. The noise levels of a noisy day differ from those of a quiet day by a factor of 2 (*Fig. 4*). The deviating noise levels of the two gravimeter types is obvious: The considerable higher noise level of CG6-49 (20 – 50 nm/s$^2$) and the much lower noise level of B64 (3 – 8 nm/s$^2$). The recorded values of CG6-49 are averaged over one minute, with outliers eliminated, while the 10-second samples of B64 are filtered values (cut-off period ~ 5 minutes). The high noise level of CG6-49 (blue) in comparison with B64 (green) is predominant in the high frequencies down to 0.2 CHP (~ 5 hours) as shown in the Fourier spectrum (*Fig. 5a*). For comparison and to get an impression of the variability of gravimeters, a further spectrum is added from CG6-69 (red) which recorded for a few weeks in Hannover, HITec building, with a relative high noise level in view of the much quieter environment. An individual instrumental char-

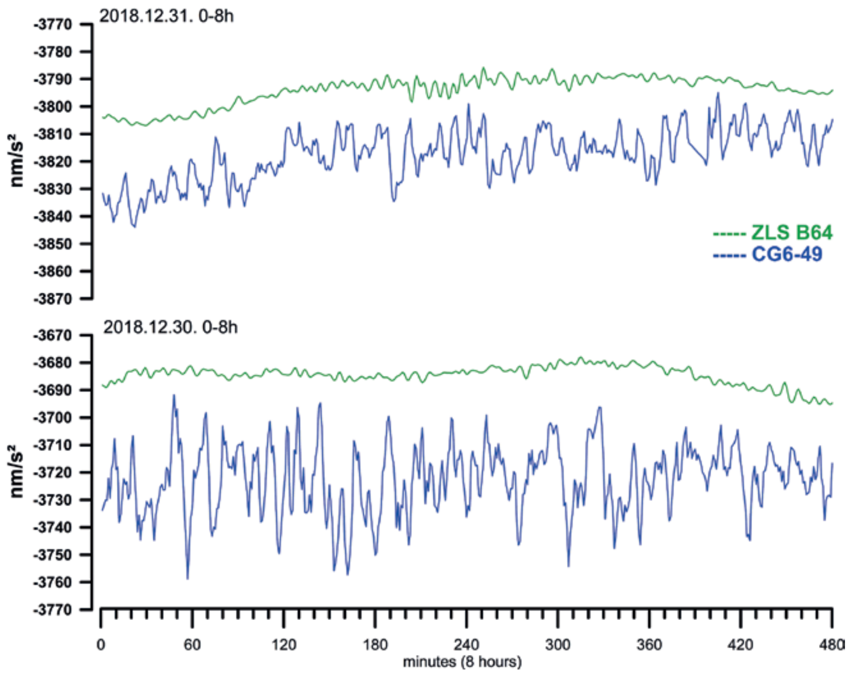



Fig. 4 | Noise level in the time domain (1-min. samples) of gravimeter records from Scintrex CG6-49 (average over 1 minute from 1 Hz samples) compared to ZLS B64 (filtered from 10-sec samples) over eight hours at two days of different environmental conditions

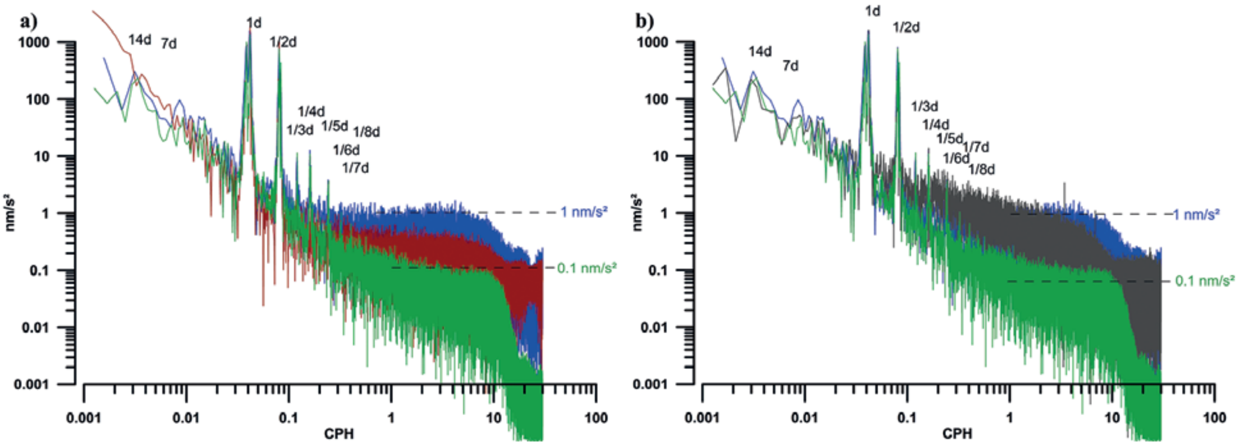



Fig. 5 | Noise levels in the frequency domain (Fourier spectra from 1-minute samples over 99 days) of the gravimeter records from Scintrex CG6-49 (blue, average over 1 minute) and ZLS B64 (green, filtered 10-second samples), both installed at JKS. a) A spectrum of a record of CG6-69 from Hannover under quiet conditions (HITec building) is added (red); b) A spectrum of gravimeter CG5-211 recording at WSV Harbor is added (grey). Note: higher harmonic signals above the ter-diurnal tidal bands.

acteristic is possible in this special case. The spectrum of gravimeter CG5-211 recording at WSV Harbor is added (grey, *Fig. 5b*). The higher noise level is reasonable because of the installation site at the harbor, adjacent to the water movements beating the quay wall of the harbor (20 m distance). Although the manufacturer of Scintrex states that the gravimeters are originally not meant for continuous recording we notice that they are usable for recording in the long-term period range.

## 3.2 Long-term Drift

Spring-type gravimeters are known for their non-linear drift. For short periods of a few days and up to two weeks /Zürn et al. 1991/, linearity may persist approximately and depends on the instrument and its environment. Small signals of longer duration than several days may not be or just are not interpretable. The drift can generally be affected by environmental parameters as temperature and humidity, seasonal temperature variations of some degree occured at JKS school. The drift behavior of the three gravimeters employed on Helgoland is rather different (*Fig. 6*). For the Scintrex instruments CG5-211 and CG6-49 the residual drift is displayed. An a-priori provided linear drift coefficient was already considered during the recording. Both gravimeters at JKS school show a quite normal drift (0.04 and 0.055 µm/s²/day, manufacturer specifications ZLS: 0.1 µm/s²/day) while the drift of CG5-211 at WSV Harbor station is considerably higher (0.11 µm/s²/day) and varies enormously. However, all drift rates are in a common range and are not higher than the

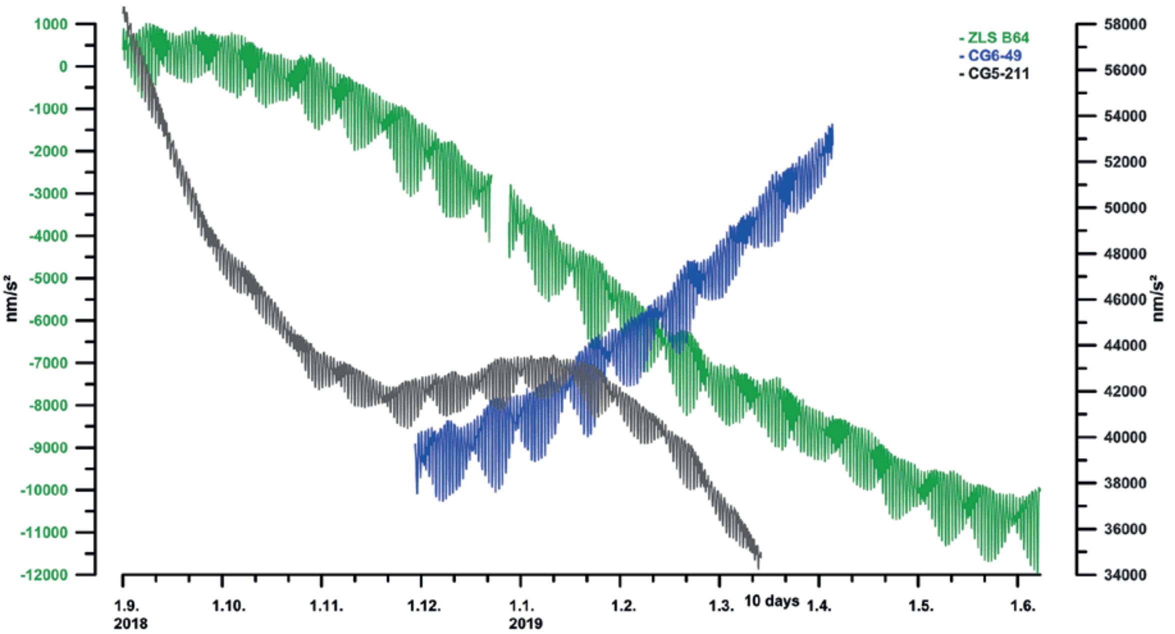



Fig. 6 | Long-term time series recorded at both sites in Helgoland showing the non-linear drift of spring gravimeters. Note: the left y-axis is valid for B64 (green) and CG6-49 (blue, both in JKS school), the right y-axis, with larger range, is valid for CG5-211 (black, WSV Harbor).

specifications of ZLS Corp. for Burris gravimeters. Only the residual drift of CG6-49 can be approximated by a polynomial function (quadratic) properly. Polynomials of higher degree do not fit the drifts of B64 and CG5-211 satisfactorily for the further investigations. A special high-pass filter has been constructed (cut-off ~10 days). After filtering or subtraction of the quadratic term, identification and investigation of high-frequent signals of a few days is possible.

## 4 GRAVITY SIGNALS

### 4.1 Tidal Results

The gravimetric time series contain the sum of the tides of the solid Earth and the oceans. After the tidal analysis (program package ETERNA 3.4, /Wenzel 1996/) of the three records, the deduced analytical tidal model has been used to calculate a pure tidal signal for each gravimeter. In the next step (Section 4.2) the predicted tidal signals from Eterna analysis and air pressure induced gravity effect (–4 $nm/s^2$/hPa) have been subtracted from the observed records. The result is the residual gravity time series.

We specify the results as follows:

- The observational tidal parameters (amplitude factor $\delta$, phase $\alpha$) of the semi-diurnal frequencies considerably deviate from the geophysical body tides of the inelastic Wahr-Dehant-Model (WD). The observed amplitude factors of M2 are $\delta = 0.9854$ (JKS, upland) and $\delta = 1.0332$ (harbor). The deviation from the model factor of $\delta_f = 1.1569$ is mainly caused by the tidal loading and gravitation effect of the ocean tides which is defined as difference between observed and body tidal vector $A_{th} \cdot \delta_{WD}$ (*Fig. 7*) and is exemplarily for M2 $L = 53$ $nm/s^2$ in the upland and $L = 35$ $nm/s^2$ at the harbor.
- Higher harmonics are not of astronomical origin, but they exist in the ocean tides in marginal estuaries, induced by resonance effects with the coast lines. Some main components estimated by BSH (personal communication, Dr. Boesch) from a 20-year time series of the tide gauge in the South Harbor of Helgoland were adjusted additionally to the main tidal waves of the gravity records, reducing the residual noise of the tidal analysis.
- Noise levels of main tidal wave groups (*Fig. 8a*) document the quality of the instruments and the station conditions: At continental stations, we expect the noise level diminishing with higher frequency from the diurnal to semi-, and ter-diurnal periods. The noise in the higher bands is similar to the white noise. We conclude: (1) At Helgoland, in the semi-diurnal band the noise levels of both instruments at JKS (B64 and CG6-49) are comparable, affected by the ocean tides while in the diurnal band the noise levels of both instruments differ significantly. The lower noise level of B64 may prove a higher quality of the B64 recording; (2) The noise levels of the record of gravimeter CG5-211, installed at the harbor, are significantly higher due to the impact of the unsteadily moving sea water very nearby; (3) Comparing with the results of gravimeter CG6-69, located in the rigid and vibration optimized HITec-building in Hannover, these noise levels of CG6-69 are substantially lower. It might be a matter of instrumental quality that the noise levels of CG6-69 are similar or even slightly lower than those from B64 on Helgoland. Note, that the record of CG6-69 is shorter (102 days) than the records from Helgoland, which could result in relatively higher noise levels.
- Signal-to-noise ratios (S/N) of some main wave groups (*Fig. 8b*) represent the significance of the results of the tidal analysis: (1) The time series of B64 is of higher quality than of CG6-49, both recorded side by side; (2) The lower S/N ratios of the recording at South Harbor (CG5-211) is caused by nearby water movements; (3) The recording of CG6-69 with higher S/N ratios at the quieter site in Hannover is of much higher quality; (4) Finally, the S/N ratios of M2 are unusual low showing that at Helgoland the semi-diurnal band is more disturbed by unstable ocean tides (higher harmonics).
- The quality of the recordings and the gravimeters in comparison can be assessed regarding the results of the tidal analyses of both gravimeters installed beside each other at JKS. The amplitudes of some main components are in high agreement, mostly within the noise levels from the Fourier spectra of the residuals (< 1 $nm/s^2$, *Tab. 1*).

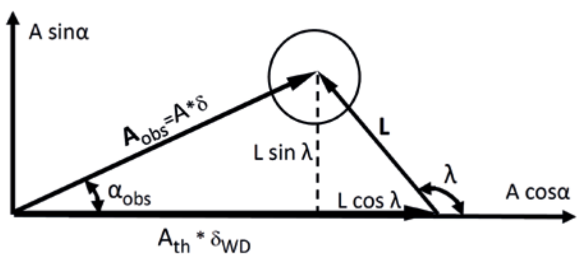



Fig. 7 | Oceanic tidal vector $L$, $\lambda$ (load) is the residual vector difference between the observed tidal vector $A_{obs} = A_{th} \cdot \delta_{obs}$ and a geophysical body tide vector according to the Wahr-Dehant-Model $A_{WD} = A_{th} \cdot \delta_{WD}$ (after /Ducarme & Kääriäinen 1980/)

| Wave group | ZLS B64 JKS school | Noise level B64 | CG6-49 JKS school | Noise level CG6-49 | Amplitude difference |
|---|---|---|---|---|---|
| O1 | 343.32 | 0.52 | 342.55 | 0.81 | –0.8 |
| P1 | 156.74 | 0.52 | 157.57 | 0.81 | 0.8 |
| K1 | 467.63 | 0.52 | 467.17 | 0.81 | –0.5 |
| M2 | 253.88 | 0.76 | 253.82 | 0.74 | –0.1 |
| S2 | 128.36 | 0.76 | 129.30 | 0.74 | 0.9 |
| K2 | 34.71 | 0.76 | 35.83 | 0.74 | –1.1 |

Tab. 1 | Amplitudes of main tidal constituents (diurnal and semi-diurnal, in $nm/s^2$) from tidal analysis of both records at JKS School, B64 and CG6-49, agree within 1 $nm/s^2$ which proves the reliability of the parallel recordings of the spring gravimeters and the calibration stabilities of their electronic measuring systems

### 4.2 Non-Tidal Gravity Signals

We subtract the time series of the observational tides, predicted by applying the adjusted tidal parameters analyzed with Eterna, from the observed gravity record including the air pressure effect (–4 $nm/s^2$/hPa) to obtain a residual time series nearly without tides.

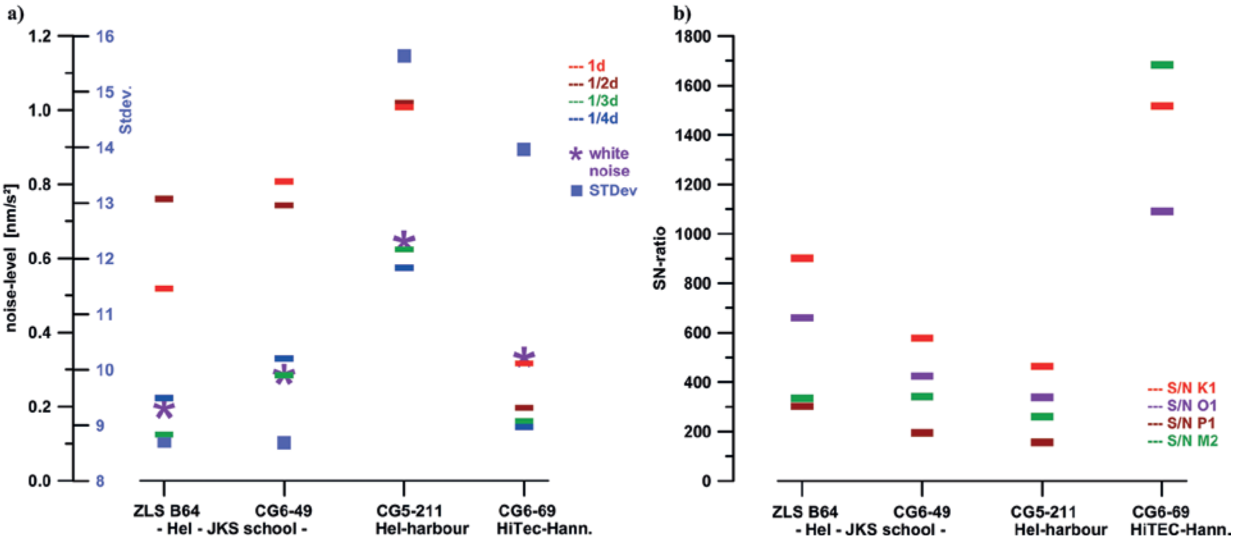



Fig. 8 | a) Noise levels from tidal analyses: the higher noise levels from CG5-211 are caused by the noisier environment at the harbor; the noise levels in the semi-diurnal bands could be caused by unstable higher harmonic tides; the noise levels of CG6-69 at Hannover are lower than from the CG6-49 record at Helgoland, but on the same levels as those of ZLS B64. b) Signal-to-noise ratios reveal higher quality of the ZLS B64 record versus CG6-49 at the same site; the S/N ratio of the CG6-69 at Hannover is clearly higher than S/N ratio of all records in Helgoland.

This residual signal contains the partly non-linear instrumental drift (see *Fig. 6*) and some anomalous signals. We investigate the winter period for gravity signals associated with water level rise during storm surges. Exemplarily, the residual series of both gravimeters, B64 and CG6-49 at JKS school, show in a period around the turn of the year 2018/2019 a linear drift and a few typical signals (*Fig. 9a*). After subtraction of the drift, the full signal content is more clearly visible (*Fig. 9b*, upper graphs). At least two anomalous signals of about 100 nm/s$^2$ are obvious on 1st and 8th of January. The residual series of CG5-211, at the harbor, reveal similar but smaller signals around 60 nm/s$^2$ (third graph) and higher noise. Very similar and highly correlated, the residual series of the water level at South Harbor (tide gauge) contains two concurrent events of 1.5 m and 1.7 m rise (*Fig. 9b*, lowest graph). This proves the physical source of the signals which occurred during the storms "Zeetje" (1.1.2019) and "Benjamin" (8.1.). One consequence of the last high water was the flooding of the place "Fischmarkt" in Hamburg.

In case of signals of longer duration functions of higher degree are required for modeling a non-linear drift behavior of a spring gravimeter. The time series of CG6-49 (*Fig. 6*, blue) of four months can be fitted successfully by a polynomial of degree three. For the varying drifts of B64 and CG5-211, a proper fit with a polynomial of

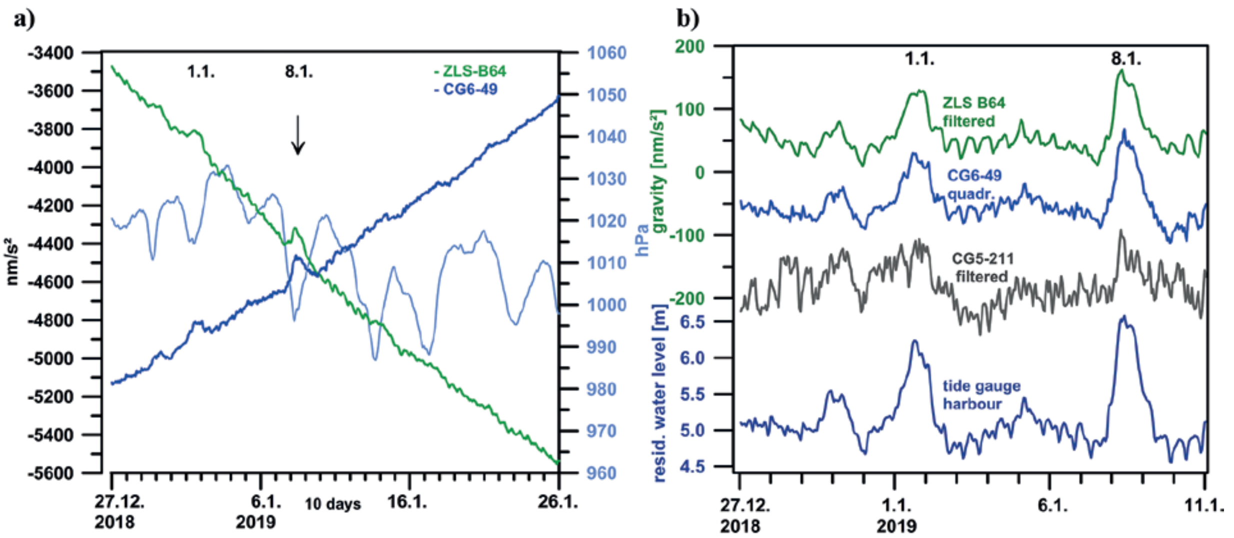



Fig. 9 | Residual time series of a period around the turn of the year 2018/2019 revealing signals in the order of up to 120 nm/s$^2$ on 1st and 8th of January (tides, air pressure effects with –4 nm/s$^2$/hPa subtracted). a) Both gravity time series from JKS School with instrumental drift over one month; b) Three gravity residual time series of period 2018-12-27 to 2019-01-10: Top, the two highly agreeing parallel records at JKS, the third record from WSV Harbor is characterized by higher noise level and minor signals. Drift reduction of B64 and CG5-211 is achieved by filtering, and a quadratic function for drift approximation is subtracted for CG6-49. Bottom, the residual water level record at the harbor exhibits consistent high tide of > 1 m indicating that the origin of the gravity signals are the storm surges "Zeetje" (1.1.2019) and "Benjamin" (8.1.) in the German Bight.

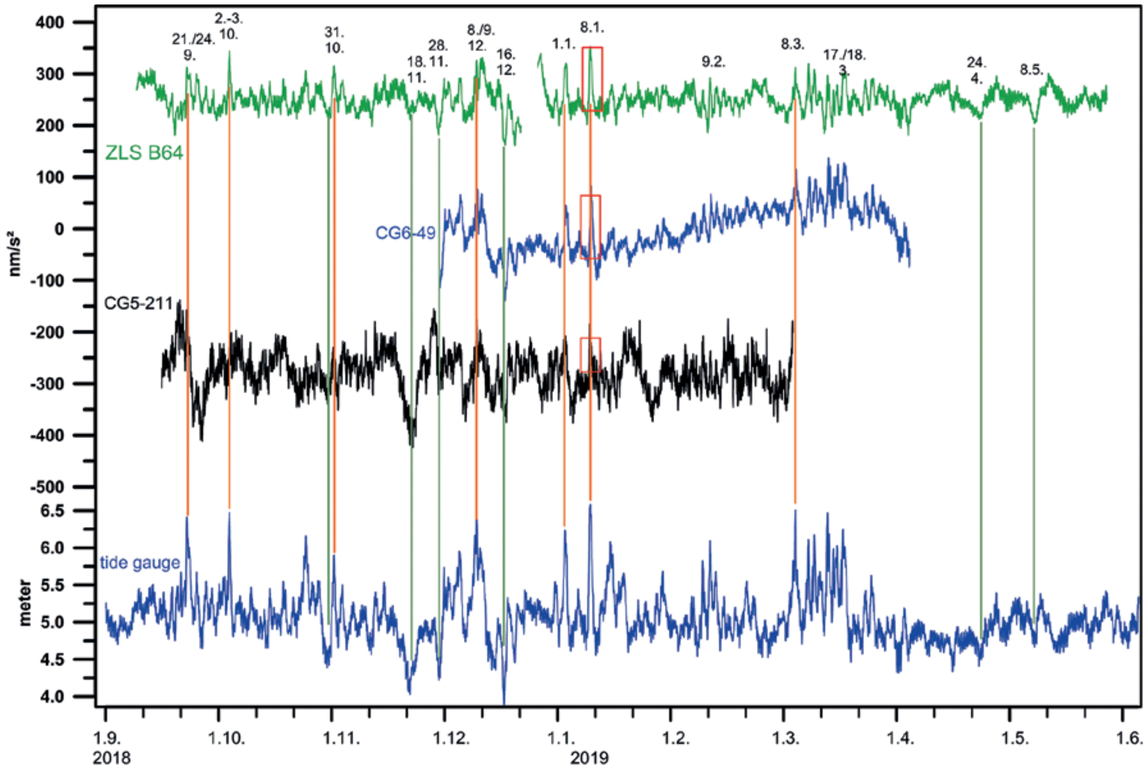



Fig. 10 | Three residual gravity time series 2018/2019 are revealing a high correlation with the residual tide gauge not only during pronounced storm surges. Orange vertical lines indicate some maximum signals, negative gravity signals correlate with low water level (green lines).

higher degree is not possible. Therefore, we constructed an adequate filter (length 50 days, cut-off ~ 20 days). The results after filtering or subtraction of a polynomial, respectively, reveal gravity signals in the order of 50 to 100 nm/s$^2$ in high agreement among each other at JKS (B64, CG6-49) and with the residual tide gauge (*Fig. 10*). The correlation with the gravity record at the harbor (CG5-211) seems lower because of partly higher (e.g. 18$^{th}$ of November) or smaller signals (e.g. 8$^{th}$ of January) and higher noise induced by very near water movement. The correlation is positive for signals of gravity increase (*Fig. 10*, indicated by vertical orange lines) and decrease as well (green lines). Thus, it is physically plausible that gravity increase is accompanied by water level rise and gravity decrease by dropping water level. Water level rise is usually driven by wind mainly from North-West, while a drop can be induced by wind from East to South-East. For several events of both cases we could verify this relationship with wind data of DWD (Deutscher Wetterdienst). Regarding storm surge Benjamin (8.1.2019, red rectangles in *Fig. 10*), the amount of the gravity variation is ~ 120 nm/s$^2$ at JKS on the upland and ~ 60 nm/s$^2$ at the harbor nearly on water level. The difference should be caused by Newtonian water mass attraction w.r.t. the vertical which depends on the gravimeter's elevation above and horizontal distance from the sea.

Overall, we conclude that

- The results from three relative spring-type gravimeters agree in terms of significant gravity changes with amplitudes of 50 to 100 nm/s$^2$ which testifies the measurement reproducibility of each instrument;
- The physical origin of these gravity changes can be verified as water level changes of the North Sea;
- To separate the deformation and the attraction part in the gravity signals, a first indication for the attraction effect during storm Benjamin is the difference of ~ 60 nm/s$^2$ between the upland and the harbor site.

## 5 VERTICAL DISPLACEMENTS

There are three possible ways to separate or estimate the vertical surface shift of the solid Earth from the observed total gravity signal induced by the storm surge:

- At WSV in the harbor, almost at height of the water level, the attraction effect w.r.t. the plumb line is supposed to be minimum, i.e. about zero. The difference between the observed amplitudes in the upland and at the harbor (~ 60 nm/s$^2$) is corresponding to the attraction affect related to elevation of the upper site. Thus, the deformation effect due to the position shift at both locations is ~ 60 nm/s$^2$.
- Geophysical modelling of the load of the North Sea on the Earth's crust during the storm surge.
- Measuring the vertical displacement by GNSS w.r.t. the Geocentre.

To model a vertical surface shift, a very first and rough attempt of a loading model of the North Sea during a storm surge has been drafted exemplarily for the storm Benjamin (8.1.2019). The used sea level data are from the tide gauges at Helgoland harbor (1.70 m height above mean high water) and at Cuxhaven (~ 2.0 m). Following the water distribution in /Fenoglio-Marc et al. 2015/ during the cyclone Xaver (5–6 Dec. 2013) our model was constructed with

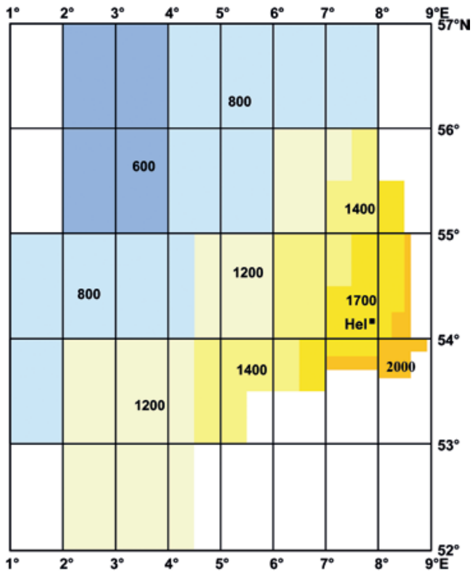



Fig. 11 | Sketch of the draft surge model for North Sea applied for loading calculation of a "modelled" gravity signal, according to the storm surge at 08.01.2019. Numbers indicate the load amplitudes in mm.

adapted amplitudes and patches of dimension 20" × 10" ($\Delta L \cdot \Delta B$, ~ 200 m × 200 m, *Fig. 11*). The software LOAD (author O. Francis) was applied using the Greens function basing on the Prem Earth Model. The resulting total load (attraction plus vertical displacement) is 119 nm/s$^2$ at JKS and 72 nm/s$^2$ at WSV Harbor. The effect of pure load induced vertical subsidence is calculated with 56 nm/s$^2$ or 25 mm, respectively, at both sites. These results agree with the observed gravity amplitudes and confirm the order of magnitude.

Geometrical position changes can be observed by GNSS. On the island Helgoland two GNSS stations, operated by BKG (Bundesamt für Kartographie und Geodäsie, Frankfurt a. M.), are recording displacements at the Earth's surface: the stations Hel2 in the upland and Helg in the harbor. Up to now, daily records of vertical deformation are available. Variations of up to 30 mm within a few days are mostly very consistent from both receivers (*Fig. 12*). Few deviations can occur, e.g. 22.–24.4.2019, due to missing data. Revised calculations with the aim to receive four values per day (six-hour time resolution) are aspired in future in order to reproduce realistic deformation events over the time period of one to two days, which is the usual duration of storm surges. Nevertheless, the anti-correlation of the daily samples with the hourly gravity variations and water level changes is obvious and remarkable high (*Fig. 12*). During the storms Zeetje (1.1.2019) and Benjamin (8.1.2019) subsidences of 15 and 25 mm, respectively, are observed as mean values of a 24-hour period. However, also smaller water level and gravity variations correlate with GNSS, e.g. in the periods 21.–24.9., 1.–3.10., 8.–9.12. in the year 2018 and in March 2019.

These first results are remarkable: The daily samples of GNSS vertical displacement match the draft load calculation mentioned above and the gravity observations on the upland and at the harbor, as well. We expect increased agreement between gravity data and vertical deformation when the resolution in time is enhanced to six-hour values.

## 6 CONCLUSIONS

The observed gravity time series in the winter season 2018–2019 are of high quality in the period range of 3 hours to several days although the location Helgoland is a noisy and challenging location. The Scintrex gravimeters, originally not constructed for continuous recording, deliver time series of sufficient quality and noise levels in

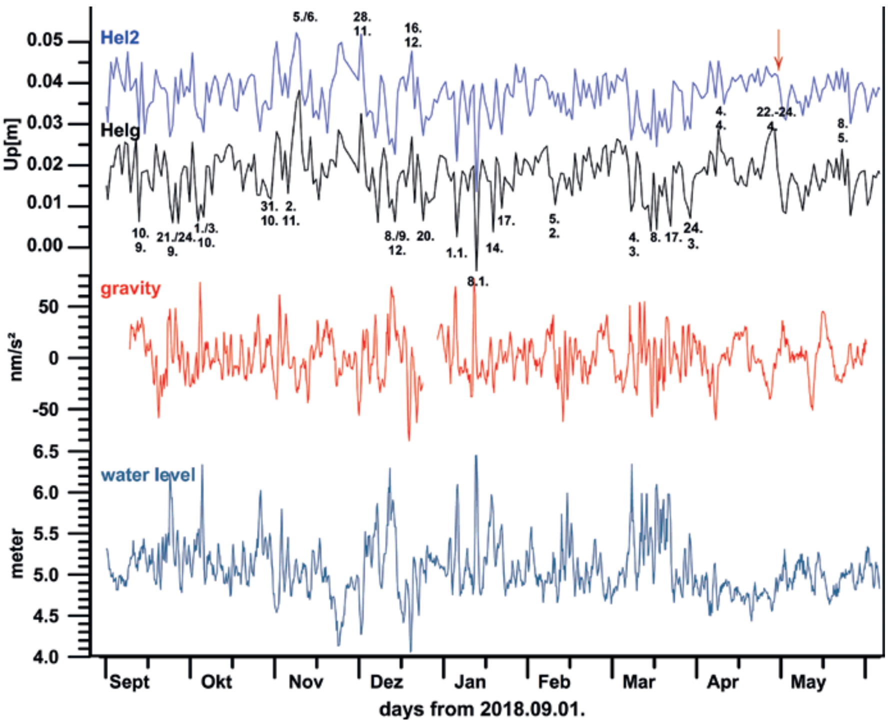



Fig. 12 | GNSS daily samples of vertical displacement recorded at Helgoland, at stations Hel2 on the upland and Helg in the harbor (see *Fig. 2*; corrections: Earth body and ocean tides) compared to the gravity residual record of B64 (filtered) and the residual tide gauge record. The high correlation with gravity and anti-correlation with the water level, respectively, are evident.

the long periodic range of some hours to a few days. However, the advantage of the ZLS instrument is the higher stability of the metal spring and the possibility of digital low-pass filtering which achieves lower noise levels.

In the high frequency band of microseism of 12-60 CPH (periods of 1–5 minutes) the noise level of the gravity recordings can reach 50 nm/s$^2$ and more (*Fig. 4*). Nevertheless, the tidal analysis of the filtered data yield noise levels only slightly higher than at a quiet station. The results of the ocean tides are with 53 and 35 nm/s$^2$ for the semi-diurnal partial tide M2 in a plausible order of magnitude.

Wind driven water level variations induce gravity changes in the order of 50–120 nm/s$^2$ over one to two days during storm surges in the North Sea which are repeatedly observed with three spring-type gravimeters. The according sea level rise above mean high water level at Helgoland is 1.0–1.7 m, up to ~ 2 m at the continental coast. In addition, smaller variations correlate well: Correlations of gravity with the water level of the North Sea at the harbor is highly significant and, likewise, gravity (and water level) increase and decrease correlate with wind directions in a plausible way. Additionally, the negative correlation with the vertical displacement from GNSS is remarkable. All these results are reproducible, plausible and highly significant.

We roughly separate vertical displacement of up to 60 nm/s$^2$ from the gravity signal induced by wind driven variation of water masses (storm Benjamin, 08. 01. 2018), equivalent to subsidence of about 20 mm or more, assuming a gradient of 3 nm/s$^2$/mm. A draft load modelling of the subsidence during the storm confirms the order of magnitude. GNSS observations of the vertical component confirm the subsidence with about 25 mm.

We conclude:

- The tidal results of ocean loading can be used for validating of tidal ocean models in the German Bight and as boundary conditions for model improvements.
- We prove for the first time that non-tidal mass variations associated with water level changes of the North Sea can successfully be observed with spring-type gravimeters.
- The order of magnitude of the observed gravity signals of 50–120 nm/s$^2$ is verified by load modelling with a very rough mass model for the German Bight for storm Benjamin (08. 01. 2019).
- The integrative gravity signals of mass changes, as observed on Helgoland, can become valuable constraints for benchmarking of oceanographic model simulations, as needed for correction and validation of the gravity field satellite mission GRACE-FO helping to avoid oceanic aliasing in the monthly GRACE products.
- Deformation data from GNSS measurements correlate with the gravity signal and are valuable for separating attraction and deformation component.

For future perspective, in March 2020, an iGrav superconducting gravimeter has been installed by GFZ Potsdam in the basement of the Alfred Wegener Institute in the South Harbor area of Helgoland. The advantages are its high resolution and the slight and linear drift behavior /Schäfer et al. 2020/ compared to spring-type gravimeters, cf. /Riccardi et al. 2011/ or /Hegewald et al. 2010/.

More realistic data of sea surface variations shall be provided by BSH for modeling. From loading models, we can deduce the varying deformation covering the whole North Sea area, even into the continent, which can be needed for GRACE-FO applications (de-aliasing issues) as well as for corrections of high precision terrestrial gravimetric data. Further, it could be promising to install gravimeters at the continental coast for receiving more information about the non-tidal redistribution of the North Sea's water mass.

An exciting discovery has been made by /Becker et al. 2020/. They have detected tidal frequencies in time series of microseisms in the North Sea. These seismic waves are generated by ocean waves and currents and consist of waves with periods of 5 to 30 s. The amplitudes of microseisms are varying continuously and are clearly correlated with ocean tides. In future, tidal recordings and their analyses may contribute to investigate the mechanisms which excite microseisms.

## ACKNOWLEDGEMENTS

We thank Andreas Güntner (Helmholtz-Zentrum Potsdam – Deutsches GeoForschungsZentrum, GFZ, Scintrex CG6-69) for permitting to use the data of their gravimeter. We thank an anonymous reviewer for valuable remarks and corrections.The investigations were funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC – 2123 QuantumFrontiers – 390837967 at Leibniz Universität Hannover.

## REFERENCES

Becker, D.; Cristiano, L.; Peikert, J.; Kruse, T.; Dethof, F.; Hadziioannou, C.; Meier, T. (2020): Temporal modulation of the local microseism in the North Sea. Submitted to Journal of Geophysical Research.

DKK & KDM (2019): Zukunft der Meeresspiegel – Fakten und Hintergründe aus der Forschung. Herausgegeben von Deutsches Klima-Konsortium e.V. (DKK, E. Weidinger) und Konsortium Deutsche Meeresforschung e.V. (KDM, S. Konitzer).

Dobslaw, H.; Bergmann-Wolf, I.; Dill, R.; Poropat, L.; Thomas, M.; Dahle, C.; Esselborn, S.; König, R.; Flechtner, F. (2017): A new high-resolution model of non-tidal atmosphere and ocean mass variability for de-aliasing of satellite gravity observations: AOD1B RL06. In: Geophysical Journal International 211(2017)1, 263–269. DOI: 10.1093/gji/ggx302.

Ducarme, B.; Kääriäinen, J. (1980): The Finnish Tidal Gravity Registrations in Fennoscandia. Publication of the Finnish Geodetic Institute, No. 90, 43 p.

Flechtner, F.; Neumayer, K.-H.; Dahle, C.; Dobslaw, H.; Fagiolini, E.; Raimondo, J.-C.; Güntner, A. (2016): What can be expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications? In: Surveys in Geophysics 37(2016), 453–470. DOI: 10.1007/s10712-015-9338-y.

Fenoglio-Marc, L.; Kusche, J.; Becker, M. (2006): Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrology fields. In: Geophysical Research Letters 33(2006).

Fenoglio-Marc, L.; Scharroo, R.; Annunziato, A.; Mendoza, L.; Becker, M.; Lillibridge, J. (2015): Cyclone Xaver seen by geodetic observations. In: Geophysical Research Letters 42(2015), 9925–9932. DOI: 10.1002/2015GL065989.

Fratepietro, F.; Baker, T. F.; Williams, S. D. P.; Van Camp, M. (2006): Ocean loading deformations caused by storm surges on the northwest European shelf. In: Geophysical Research Letters, 33(2006). DOI: 10.1029/2005GL025475.

Hegewald, A.; Jentzsch, G.; Jahr, T. (2010): Comparison of the LaCoste & Romberg gravimeter ET18 with the superconducting gravimeter CD-034 at the Geodynamic Observatory Moxa (Germany). In: Bulletin d'Informations Mareés Terrestres 146(2010), 11847 – 11855.

Jentzsch, G.; Schulz, R.; Weise, A. (2015): Ein bekanntes Prinzip in einem neuen Gravimeter: das automatisierte Burris-Gravimeter. In: allgemeine vermessungs-nachrichten (avn) 122(2015)5, 168 – 175.

Kusche, J.; Bosch, W.; Becker, M. (2013): Vermessung des globalen Wandels aus dem Weltraum: Meeresspiegel und Klima. In: Zeitschrift für Vermessungswesen 2013(1), 21 – 30.

Müller, M.; Cherniawsky, J. Y.; Foreman, M. G. G.; von Storch, J.-S. (2014): Seasonal variation of the M2 tide. In: Ocean Dynamics 64(2014), 159 – 177. DOI: 10.1007/s10236-013-0679-0.

Riccardi, U.; Rosat, S.; Hinderer, J. (2011): Comparison of the Micro-g LaCoste gPhone-054 spring gravimeter and the GWR-C026 superconducting gravimeter in Strasbourg (France) using a 300-day time series. In: Metrologia 48(2011), 28 – 39. DOI: 10.1088/0026-1394/48/1/003.

Schäfer, F.; Jousset, P.; Güntner, A.; Hinderer, J.; Rosat, S.; Voigt, C.; Schöne, T.; Warburton, R. (2020): Performance of three iGrav superconducting gravity meters before and after transport to remote monitoring sites. In: Geophysical Journal International (submitted).

Tapley, B. D.; Reigber, C. (2001): The GRACE mission: status and future plans. In: EOS, Transactions American Geophysical Union 82(2001)47, Fall Meeting Supplement, G41 C-02.

Timmen, L.; Falk, R.; Gabriel, G.; Lothhammer, A.; Schilling, M.; Vogel, D. (2018): Das Relativgravimeter-Kalibriersystem Hannover für $10^{-4}$-Maßstabsbestimmungen. In: allgemeine vermessungs-nachrichten (avn) 125(2018)5, 140 – 150.

Weise, A.; Kroner, C.; Abe, M.; Creutzfeldt, B.; Förste, C.; Güntner, A.; Ihde, J.; Jahr, T., Jentzsch, G.; Wilmes, H.; Wziontek, H.; Petrovic, S. (2012): Tackling mass redistribution phenomena by time-dependent GRACE- and terrestrial gravity observations. In: Journal of Geodynamics 59-60(2012), 82 – 91. DOI: 10.1016/j.jog.2011.11.003.

Weisse, R.; von Storch, H.; Niemayer, H. D.; Knaack, H. (2012): Changing North Sea storm surge climate: an increasing hazard? In: Ocean & Coastal Management 68(2012), 58 – 68.

Wenzel, H.-G. (1996): The nanogal software: Earth tide data processing package ETERNA 3.30. In: Bulletin d'Informations Marees Terrestres 124(1996), 9425 – 9439.

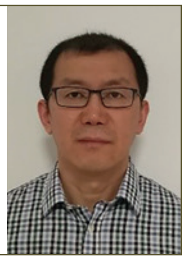
Williams, S. D. P.; Penna, N. T. (2011): Non-tidal ocean loading effects on geodetic GPS heights. In: Geophysical Research Letters 38(2011)9. DOI: 10.1029/2011GL046940.

Zürn, W.; Wenzel, H.-G.; Laske, G. (1991): High quality data from LaCoste-Romberg Gravimeters with Electrostatic Feedback: A challenge for superconducting Gravimeters. In: Bulletin d'Informations Marees Terrestres 110(1991), 7942 – 7952.

Dr. rer. nat. Adelheid Weise
LEIBNIZ UNIVERSITÄT HANNOVER
INSTITUT FÜR ERDMESSUNG
Schneiderberg 50 | 30167 Hannover
weise@ife.uni-hannover.de

Dr.-Ing. Ludger Timmen
LEIBNIZ UNIVERSITÄT HANNOVER
INSTITUT FÜR ERDMESSUNG
Schneiderberg 50 | 30167 Hannover
timmen@ife.uni-hannover.de

Dr.-Ing. Zhiguo Deng
HELMHOLTZ-ZENTRUM POTSDAM –
DEUTSCHES GEOFORSCHUNGSZENTRUM
GFZ – SPACE GEODETIC TECHNIQUES
Telegrafenberg Gebäude A17 | 14473 Potsdam
zhiguo.deng@gfz-potsdam.de



Prof. Dr. rer. nat. Gerald Gabriel
LEIBNIZ-INSTITUT FÜR ANGEWANDTE
GEOPHYSIK (LIAG) – SEKTION S1
SEISMIK & POTENZIALVERFAHREN
LEIBNIZ UNIVERSITÄT HANNOVER
INSTITUT FÜR GEOLOGIE
Stilleweg 2 | 30655 Hannover
gerald.gabriel@leibniz-liag.de

Dr. Christian Rothleitner
PHYSIKALISCH-TECHNISCHE BUNDESANSTALT
(PTB) – DEPARTMENT 1.1 –
MASS-DISSEMINATION OF THE UNIT
Bundesallee 100 | 38116 Braunschweig
christian.rothleitner@ptb.de

Dr.-Ing. Manuel Schilling
LEIBNIZ UNIVERSITÄT HANNOVER –
INSTITUT FÜR ERDMESSUNG
Schneiderberg 50 | 30167 Hannover
schilling@ife.uni-hannover.de

Dr.-Ing. Christian Voigt
HELMHOLTZ-ZENTRUM POTSDAM –
DEUTSCHES GEOFORSCHUNGSZENTRUM GFZ –
GLOBALES GEOMONITORING U. SCHWEREFELD
Telegrafenberg Gebäude A17 | 14473 Potsdam
christian.voigt@gfz-potsdam.de

Manuskript eingereicht: 14.05.2020 | Im Peer-Review-Verfahren begutachtet