11. Listening to the Earth — The Schiltach Observatory BFO

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1 A brief history of BFO

The Joint Geoscientific Observatory Schiltach, also known as Black Forest Observatory [BFO] is an interdisciplinary institution which is operated by the Geodetic and Geophysical Institutes of the Karlsruhe Institute of Technology (earlier: University of Karlsruhe) and the University of Stuttgart. The observatory (latitude 48.33°N, longitude 8.33°E, altitude 589 m a.m.s.l.) is located in a seismically rather quiet region about 5 km from anthropogenic noise sources like industry and heavy traffic.

The observatory was established in the years 1971-72 in parts of the abandoned ore mine ”Anton” near the small town of Schiltach in the Black Forest (SW-Germany). The mine was dug into granite and is about 170 m below the surface. Between 1770 and 1850 cobalt minerals and silver were excavated in the mine. In the years 1834 - 1850 more than 732 kg of pure silver and more than 189 t of cobalt ore were retrieved from the so-called ”Reiche Firste” in this mine. Mining activities stopped in the late 1870s and the mine was left open afterwards.

The initiative to establish a broadband geoscientific observing station was taken by Stephan Müller in the mid 1960s shortly after he was appointed to the geophysics chair at Karlsruhe [GPI]. Geodesists Lichte and Mälzer of the Geodetic Institute in Karlsruhe [GIK] joined him in his efforts and an extensive search for a feasible mine in the Black Forest took place right afterwards and soon a decision was made in favor of the “Anton”. The search was strongly supported by mineralogist Rudolf Metz, professor at Karlsruhe University and Black Forest expert. In the summer of 1967 work in the mine started and in December of that year the first instruments (a pair of BLUM-pendulums for tidal measurements) were installed for a test phase. Klaus Strobach was appointed as director of the Institute of Geophysics [IGS] at the University of Stuttgart in 1969 and immediately agreed to the cooperation in the observatory to be constructed. In December of that year a proposal was submitted to the Volkswagenwerk-Foundation which was granted somewhat later. Hermann Mälzer and Jörg Ansorge [GPI] accepted the main responsibility for the next stages. On November 2, 1970 excavation and construction work in the mine began. In September 1971 the construction work of the laboratory and the amagnetic hut started. Most of the construction work, including electric and phone installation was finished in December 1971 and observatory work could begin. In the meantime Karl Fuchs had replaced Stephan Mueller as director of GPI and fully supported BFO.

In the early years the staff of the observatory consisted of two scientists (Dieter Emter and Walter Zürn [WZ], hired August 1, 1972 and January 1, 1974, respectively), two technicians (Heinz Otto and Walter Grossmann, hired July 1, 1971 and October 1, 1974, respectively), a cleaning lady and neighbour (Magdalena Hauer, hired December 2, 1971), and a housekeeper (Alois Hauer, husband of the former, hired on an hourly basis in 1971). The formal director of the BFO, representative for all institutes, Hermann Mälzer, his secretaries, Otto and the Hauers belonged to the GIK. Hermann Mälzer visited the observatory during his directorship on a weekly basis and from the beginning created a friendly atmosphere for discussions and decisions. GPI had hired Walter Grossmann and WZ, while Dieter Emter belonged to the IGS. The director position was remaining in the GIK with Hans-Georg Wenzel following Hermann Mälzer in 1988 and Bernhard Heck following H.-G. Wenzel in 1999.

In 1996 the Hauer family retired and their positions at BFO and GIK were given to the son Alois Hauer Junior and his spouse Martina. They live in their house directly below the observatory, a very favorable situation. Incidentally, this house burned down on February 16, 2004 and was reconstructed completely. Walter Grossmann retired in 1999 and unfortunately the GPI could not support the position at BFO due to restrictions in Karlsruhe, therefore he could not be replaced. Dieter Emter retired 2 years early in the fall of 2000 and his position at IGS and BFO could be filled by hiring Rudolf Widmer- Schnidrig. Thomas Forbriger replaced WZ at BFO and GPI in 2003. Heinz Otto had to retire in 2005 and to replace him was not easy because of the general negative trend for permanent positions at the universities, but after negotiations with Stuttgart fortunately Peter Duffner could be hired in February 2006 as his and Grossmann's successor.

When Erik Grafarend was appointed as director of the Institute of Geodesy in Stuttgart around 1980 this institution also became one of the parent houses of BFO. On several occasions Grafarend played a decisive role in the appointment of new positions of importance for BFO. His successor Nico Sneeuw (since 2004) is a strong supporter of BFO as well. The successor of Strobach at IGS in 1988, Erhard Wielandt, was a great step forward for BFO and its staff. As an instrumental genius, great physicist, and very good friend of BFO from the beginning his contributions are too numerous to be appreciated here in full. He hired Ruedi Widmer-Schnidrig for the BFO position in 2002. He was replaced in 2005 as director of IGS by Manfred Joswig, who participated also as a supporter. After Hans-Georg Wenzel left BFO and GIK in 1998 for a director position at Institute for Earth Measurements [IfE] Hannover, Bernhard Heck as the new director of BFO decided to hire a geophysicist for the staff position at GIK responsible for BFO and Malte Westerhaus was hired in 2000.

At the GPI besides Karl Fuchs, strong advisers and supporters of BFO were Gerhard Müller and since 1979 his successor Helmut Wilhelm. Gerhard Müller had accepted a position in Frankfurt but continued to cooperate and consult WZ. Helmut Wilhelm is a strong theoretician in the field of earth tides and also cooperated and consulted WZ on many issues. He was the first to detect an extension to the tidal potential due to the Earth's ellipticity (Wilhelm 1983). Ten years later Tony Dahlen published a paper on this effect without being aware of Wilhelm's paper. WZ pointed this out to Dahlen who wrote a nice letter of apology to Helmut Wilhelm. The terms first derived by Helmut Wilhelm are included in the modern catalogs of the tidal potential (e. g. Wenzel 1997a).

Helmut Wilhelm also analyzed theoretically the reponse of seismological Earth models to shear forces on the surface (Wilhelm 1986). He especially was a very important and critical correspondent for all the student theses at GPI supervised by WZ. Karl Fuchs instigated especially the participation of BFO (WZ) in the SFB 108, and supported the work over all the years when he was director of GPI and speaker of the SFB. When Thomas Bohlen was appointed to the chair for applied geophysics at GPI in 2009 the BFO again gained a strong supporter.

2 General

The task of the observatory is the measurement, storage and analysis of variables pertaining to deformations of the Earth and temporal variations of the Earth's gravity and magnetic fields in a wide range of frequencies and using a variety of sensors. The major signals provided by the Earth are body waves, surface waves, and free oscillations excited by earthquakes, volcanic eruptions and any other disturbances of the system; the tides of the solid Earth driven by the differential gravitational forces exerted by sun, moon, and to a lesser extent the other planets, including the disturbing effects caused by the motion of huge water masses in the oceans; the gravitational and deformation effects by local, regional, and global atmo- and hydrosphere; and finally the magnetic variations caused by processes in the Earth's core and the sun. Of course, the data are always searched for new or undetected phenomena. One of the prime goals at such an observatory is, of course, also to improve the sensitivity of the sensors and to develop methods for noise reduction.

BFO also functions as a small but efficient research institution. The research carried out by the staff of the observatory and their students at the universities is documented in about 200 publications and goes beyond BFO topics. More than 50 Diploma theses and more than 10 dissertations were produced using data, problems and ideas stemming from the observatory. Dissertations at the Universities at Strasbourg, France, and Louvain-la-Neuve, Belgium (d'Oreye and Zürn 2005, 2006), were also supervised by BFO scientists. Editors of high impact international journals (Nature, Science, AGU journals, Geophysical Journal International among others) rather often approach the scientists at BFO for peer reviews (between only 2000 and 2005 a total of 80 reviews were written). One BFO scientist (WZ) was cited by Journal of geophysical Research for excellence in reviewing. Incidentally, WZ was foreign examiner in Ph.D. and Habilitation examinations at several foreign universities (Cambridge (UK), IPG Paris (twice), Utrecht, Strasbourg, Chambéry (Haute Savoie), Louvain-la-Neuve (Belgium), and Helsinki), while he was not allowed to participate actively in such examinations at Karlsruhe since he was not a member of the ”Lehrkörper”.

BFO presents a unique opportunity for students at both universities to gain knowledge and skills on leading-edge seismological observation techniques. Consequently BFO plays a role in the bachelor and masters programs at KIT. Thomas Forbriger offers a compulsory lecture with exercises on the physics of seismic instruments in the geophysics masters program. Malte Westerhaus teaches BFO research topics in a course on recent geodynamics in the geodetics masters program. In 2012 the first BFO-Winterschool took place. During three days students work with research quality broad-band seismometers on installation and calibration in an observatory environment under the supervision of Thomas Forbriger and graduate students. Ellen Gottschämmer organizes study trips for students in the bachelor program to BFO on a regular basis. Joachim Ritter brings his graduate and undergraduate students to BFO once a year to discuss seismological research for a day with the BFO staff. WZ, Ruedi Widmer-Schnidrig and Thomas Forbriger were responsible for many years for the 4-5 day long field practice course in applied geophysics taking place in the Hegau volcanic region near the Lake of Constance (Thomas Forbriger still is). All this makes the observatory a place for education, too.

Besides the 24h/7d-routine operation the observatory also functions as an experimental station, where new instruments and methods developed by other institutions and colleagues may be compared in their performance with the ”gold standard data” (an expression coined by Prof. Jon Berger, UCSD La Jolla 2009) obtained routinely at BFO. This possibility was used very often during the lifetime of BFO, a few selected examples are listed below.

The observatory consists of an approximately 700 m long almost horizontal mine shaft with side tunnels and vaults, at the end about 170 m below the surface, a second tunnel about 40 m higher up (”Upper Anton”), the laboratory building, and a garage housing an uninterruptable power supply in front of the mine adit, and a small amagnetic hut at about the altitude of the upper mine shaft. The tunnel system is dug into granite, while starting 60 m higher triassic ”Buntsandstein” makes up the country rock. The innermost parts of the main tunnel, between about 400 and 700 m from the entrance, where the observatory sensors are installed is blocked off from the outside atmosphere by two airlocks. The first one was installed in 1974, the second one in 2009. Each of those consists of two very nearly airtight doors about 8 m apart. These locks can be described as simple low-pass filters for atmospheric pressure variations with time constants between 4 and 60 h, thus heavily reducing direct influences of ambient pressure variations on the sensors in the long-period seismic band. They also prevent air currents from the outside and serve to stabilize the temperature near the sensors to a few mK near 10°C. Of course, the sensor positions and azimuths were estimated carefully by the colleagues from the GIK under supervision by Hermann Mälzer.

The laboratory building houses offices and workshops for the staff. Nowadays the observatory is operated by two scientists and only one technician, although the number of sensors and computers has increased steadily. Sensors and data acquisition electronics are operated from uninterruptable power supplies since power outages occur several times per year in this rural environment.

After several tests with horizontal pendulums and short period seismographs the first continuously recording instrument, a short period seismometer, was installed in January 1972. Since then the number of sensors has much increased and at present the following instruments are providing data continuously (24h/7d, unless disturbed):

- Double-sphere superconducting gravimeter GWR OSG-056 with on-line refrigeration of liquid Helium and without running the tilt-feedback (possible because of the stability of the underground).
- LaCoste-Romberg Earth Tide gravimeter ET-19 with electrostatic feedback (LCR ET-19)
- 3-components of Streckeisen STS-1 broadband seismometers
- several Streckeisen STS-2 three-component broadband seismometers
- ASKANIA 2-component borehole-tiltmeter with modernized electronics
- Three 10 m - Invar wire strainmeters (improved Type Cambridge) in azimuths N2°E, N60°E, and N300°E
- 111 m long-baseline fluid-presssure tiltmeter (Type Horsfall) in azimuth N331°E
- 3-components of Fluxgate magnetometers (Rasmussen)
- Overhauser-Proton magnetometer
- Continuously recording GPS-receiver with a special antenna monument near the amagnetic hut
- Pressure transducers in several environments (2 Paroscientific)
- Other meteorological sensors (precipitation, temperatures, wind etc.)

The data are published through international data centers IRIS, SZGRF, GFZ (GGP), BKG, and Intermagnet. In addition there is quite a number of instruments for experiments, reference, and education.

When the observatory started in the early seventies signals were either recorded on photographic film next to the instruments or on chart recorders in the laboratory. The latter were connected to the instrument outputs through copper cables with lengths of several hundred meters. Frequent damages of electronics at both ends of these cables by lightning strikes above the mine were a disastrous consequence of this setup. Films in the mine had to be changed once a week which resulted in severe disturbances of the tiltmeter records and since the two ASKANIA tiltmeters then recording in the same vault as the photographically recording BLUM and MELCHIOR-VERBAANDERT horizontal quartz pendulums had much better signal-to-noise ratio, the recording of the latter two types of instruments was stopped in favor of the ASKANIAS.

In 1979 the first digital recording system was introduced. This consisted of an antialiasing filterbank (25 s cutoff period, 8-pole) and a multiplexer for 16 channels driving a 16 bit A/D-converter (DATUS-PROCON) located in the electronics vault right in front of the first airlock, which in turn was connected (at first by copper cables and later by optical fibers) to a receiver plugged into the RAYTHEON 704 minicomputer in the laboratory about 400 m away. The clock of the computer was synchronized using self-made (Hans Stecker at GPI) electronics to a radio-clock driven by the DCF-time signal transmitter in Meinflingen. The data were recorded on half-inch magnetic tapes. Especially during the period when this system was operating the help by Werner Kaminski at GPI was invaluable with soft- and hardware problems. This system recorded until 1989 with sampling intervals of 2 and 5 s.

The PC-era arrived and after some testing a new system was developed and installed. The same filterbank was used, but now connected to a 20-channel HEWLETT-PACKARD multiplexer and digital voltmeter in the electronics vault. The resolution of the digitization was thus increased from 16 to about 22 bits. In the laboratory a PC was programmed to send information via optical fibers to the HP and to receive and save the data coming in packages of 1 minute. Time pulses all 5 s were selected by a special unit from the DCF-clock and sent to the HP to trigger the sampling sequence. The 5 s -blocks were accumulated in hourly files and recorded on magneto-optical discs and CDs. This system operated until August 2012.

The first A/D-conversion at BFO directly at the sensor was installed in 1990 with the first station of the German Regional Seismic Network [GRSN]. The outputs of the STS-2 broadband seismometer of that system were fed into a QUANTERRA 680 digitizer with a resolution of 24 bits and sampling rates 80, 20, 1, and 0.1 Hz. Data packages were sent to the lab through optical fibers and received at first by a dedicated UNIX-machine (ADEBAHR) and later by a PC running SEISCOMP. In 1996 IRIS/IDA (San Diego) decided to adopt BFO because of the high data quality as an ”affiliated” station of GSN and agreed to record continuously and in near-real time besides the three STS-1s also gravimeter, tilt-, strain- and barometers. However, the expensive recording equipment had to be purchased by BFO, because IRIS at this time was trying to expand into the ”white” areas of the global seismic station distribution and not into central Europe. Between 2002 and 2012 all remaining sensors were provided with QUANTERRA Q330HR digitizers whose internal clocks are synchronized by second pulses from GPS-disciplined clocks in the lab. The SG-signals are recorded on two systems, an AGILENT digital voltmeter (and PC) and a QUANTERRA Q330 in order to have redundancy. The connections between the computers in the lab and the QUANTERRAS consist also of optical fibers. This setup definitely has less sensitivity to close lightning strikes than the early setup using long multiwire copper cables.

In 1990 with the GRSN-station also the data transmission to data centers via the Internet started and again this was expanded to most data streams and occurs now in near-real time. Seismic data are transmitted to the GRSN data center at BGR Hannover and to the IRIS data centers in San Diego and Seattle, magnetic data to Intermagnet, and GPS data to BKG Frankfurt were they are routinely processed. On a monthly basis the data from the superconducting gravimeter are sent to the GGP data center at GFZ Potsdam.The data are also stored in LSDF@KIT.

3 Research

3.1 Earth tides

When the observatory started in 1972 to record Earth tide gravity, tilts and strains the paradigm in the field was to determine the amplitudes and phases of these signals as accurately as possible and then obtain results for the Love numbers h_2, k_2 from the so-called gravimetric and diminishing factors from gravity and tilt and finally strain observations could be used in addition to retrieve the Shida number l_2. These numbers could then be compared to theoretical results obtained from seismologically constrained models (e. g. Wilhelm 1978).

However, measurements told another story. In the late 1960s it had become clear that the tides in the oceans due to their gravitation and deformation of the earth (”loading”) significantly affect the body tide measurements (especially near the coasts but also in the interior of the continents) and methods had to be developed to correct the observations for these effects using models of the ocean tides and the response of the Earth (e. g. Farrell 1972). If these corrections would be good enough, Love and Shida numbers could be retrieved. However, since the ocean loading effects must vary smoothly in space away from the coast they could not explain the dispersion of tidal tilt measurements within one observatory at distances of only a few meters. In 1973 two papers appeared side by side in ”Nature” clearly identifying this problem (Baker and Lennon 1973) and providing a physical explanation for it (King and Bilham 1973): local distortions of the strain field due to cavities, topography and geological inhomogeneities.

3.1.1 Tidal tilts and strains

At BFO it was clear from the beginning of tilt and strain measurements due to close contact with the Cambridge group that these effects are important. Bilham and King came to BFO to install their invar-wire strainmeters (10 m long) at several locations in the mine in order to study the variations of the observed strain amplitudes and phases and their dispersion. Several tiltmeters were installed at about the same time within the pendulum vault: BLUM- and MELCHIOR- VERBAANDERT horizontal quartz pendulums, HUGHES level bubble tiltmeters, and two ASKANIA borehole-tiltmeters fixed to the wall. Originally meant to provide a comparison of their performance these turned out to be important for the validation of the local elastic distortions. Emter and Zürn (1985) summarize all the results together with some 2-D Finite Element [2D-FE] calculations in an invited contribution to a compilation by Harrison of the most important contributions to Earth tide research. The author of this book, J. C. Harrison (1985), refers to this work in his introduction to the chapter as ”an important series of tests ... with sobering conclusions”. Several key experiments were carried out to validate the conjecture of local distortions during the first two decades at BFO (Mälzer et al. 1979; Beavan et al. 1979, Emter et al. 1989).

When the first tidal results from the two ASKANIAs installed 50 cm apart at the N-wall of the vault were obtained there was about a factor of two between the amplitudes. After some effort and a hint by the late Wolfgang Grosse-Brauckmann an error in the calibration of one of them was detected with the help of BODENSEE-WERKE. Many years later it was revealed by Frank Wyatt and Duncan Agnew at La Jolla in 1993 and afterwards verified by Heinz Otto and WZ at BFO as well as by Gerhard Jentzsch at Clausthal that the ASKANIAS suffer from non-orthogonality of the two components by up to 7° varying from unit to unit. After the calibration error was fixed it became clear that both instruments showed much reduced amplitudes for the O_1 and M_2 NS-tilts, with the phase of the semidiurnals and diurnals near zero and 180°, respectively. The bulging of the N-wall due to tidal strains was out-of-phase with the body tide NS-tilts and since the NS-tilt for diurnal tides is rather small at 48° latitude the strain-induced tilt was larger than the body tide (+ocean load) tilt and thus the signal was flipped. Consequently one of the ASKANIAs was installed at the S-wall and indeed in this case we obtained enhancements (100 % for O_1 and 30 % for M_2) of all NS-tilts due to the bulging wall. Afterwards the prediction by Harrison (1976) with 2D-FE-models that the floor of a cavity remains flat while the walls bulge was verified by installing one ASKANIA in the center of the vault. At the same position a vertical 2.5 m Invar-wire strainmeter was installed and it was found that the ”strain” tides were enhanced by a factor of 2 approximately (Heil, 1985).

If the local anomalies of the tidal tilts are caused by the response of the local inhomogeneities to the tidal strains these disturbances should include the signature of the Nearly Diurnal Free Wobble (NDFW). Since diurnal tidal NS-tilts are small at the latitude of BFO we looked for the two experiments which showed the largest discrepancy in the diurnal EW-tilts in terms of the observed complex admittance (diminishing facor and phase). Also the records had to be long enough to separate the diurnal waves P_1, K_1, ψ_1, and Φ_1. The two records chosen are from the ASKANIA mounted in the middle of the N-wall and from a HUGHES-tiltmeter sitting in a niche in the W-wall of the pendulum vault. The complex differences of the resulting diurnal tidal admittances turned out to be in quadrature to the body tide signal and clearly showed the resonance due to the ellipticity of the core-mantle boundary. This is strong evidence for the anomalies to be due to the tides themselves and not e. g. due to calibration, orientation errors or noise (Zürn et al. 1988).

The next idea was to average out small local inhomogeneity effects and approach the global signal by installing an instrument with the longest baseline possible within the mine behind the air-lock. A differential fluid-pressure Horsfall tiltmeter was bought and installed with an azimuth of N25.23°E and a length of 170 m. The design of this instrument required certain properties of the liquid to be used and two different fluorocarbons with densities near twice that of water were used over the years. When the excellent tidal data had been analyzed the results for O_1 and M_2 were close to the predicted sum of body and ocean load tides, although we had expected a small topographic effect from 2D-FE-models (Zürn et al., 1986; Emter et al. 1989). In order to confirm this result in favor of the local elastic effect conjecture the instrument was reinstalled in a different azimuth of N331°E with a length of 111 m and the results were again within a few percent of the predictions with small phase differences. However, a small effect from the topography/geology cannot be ruled out (Otto et al. 1998). Anyway, after these measurements it was pretty clear that long-baseline tiltmeters are able to get closer to the global tidal response because of their averaging property. However, one can never claim that they are only affected to the level of 1 % by the local effects and therefore the Love numbers still can not be determined to the required accuracy.

A very convincing experiment was carried out with a 1 m Invar-rod strainmeter across the ”Heinrich”-cleft in the mine (Beavan et al. 1979; Emter and Zürn, 1985). It is clear that the ”strains” measured with this instrument cannot be related to stresses in the rock (there is no rock between the end mounts) but rather constitute relative displacements of the walls of this cleft. Tides enhanced by a factor of 50 with respect to the predicted body tide strains were observed. Two earthquakes were also recorded and again there were factors of 35 and 56 between these signals and the ones measured with a parallel 10 m Invar-wire unit mounted along the tunnel near the cleft. A factor of approximately 50 was also obtained with both a 2D-FD-model and an analytical model, an elliptical cavity with aspect ratios adjusted to the best of our knowledge to the real cleft.

Heinz Otto had the idea that a crack in one of the niches housing the VERBAANDERT tiltmeters possibly caused excessive drift of those instruments. Therefore two ultra-short strainmeters (less than 10 cm) were installed in that niche, one across the crack and one parallel to it. It turned out that the one parallel to the crack did not show tides within the noise, while the one across the crack measured about 6 times the predicted tides (Zürn et al., 1991).

In the late eighties two new low piers at the S-wall of the seismic vault were constructed side-by-side for the broadband seismometers STS-1 and STS-2 and these were installed on those. Looking at the tides recorded by these two sets of instruments we found a large cavity effect of about 75 and 85 % on the NS-components while the EW-components were only amplified by 20 and 26 %, respectively (Zürn and Emter, 1995). The idea arose that one could possibly be able to see the tides across the gap between the two piers and another ultra-short strainmeter was installed to attempt this. Indeed again a tidal signal could be detected which was enhanced with respect to the prediction (Zürn et al., 1991).

3.1.2 Theoretical considerations on local effects

King et al. (1976) pointed out that the local elastic distortions of regional and global signals do not only occur for tides but also for long period seismic signals like surface waves and free oscillations. This could be verified when the megaquakes off the NW-coast of Sumatra in 2004 and off the E-coast of Tohoku, Japan excited the free modes of the Earth to the largest amplitudes since BFO started recording. King et al. (1976) also suggested methods on how the disturbances could be corrected.

Paul Richards had conjectured that if many instruments at one station record tidal tilts and strains and if the local anomalies are caused by linear reaction to the tidal strains, then these disturbances cannot be independent (the "Richards constraint" coined by WZ), because only the three horizontal tidal strains are the cause (ε_{NN}, ε_{EE}, and ε_{NE}). The first attempt to verify the validity of this conjecture was performed by Zürn et al. (1979). Twelve residual O_1 and M_2 tilt tides from within the vault at BFO were tested against this hypothesis by casting the constraint into a matrix formalism which allows to form a set of 4x4 determinants which should be zero if the constraint holds. 495 determinants were obtained, however, the results were not encouraging probably because at the time ocean loading corrections caused systematic errors. Zürn and Young (1983) reported on a second study with a new method using 18 components of tilts and strains from BFO. A subset of 11 components including the cleft strainmeter looked like they satisfy the constraint.

3.1.3 Tidal stresses

Of course, the tidal strains in the Earth are caused by the tidal stresses, which in crustal rocks near the surface of the Earth are of the order of some tens of hPa. GLOETZL-stressmeters had been installed in shallow boreholes in the earthquake source region of the Swabian Jura in the framework of the SFB 108 by the Karlsruhe geologists. Dieter Emter and WZ could convincingly demonstrate that these instruments were not coupled to the rock because all they recorded was the (negative) air pressure and during the summer also the temperature. The first effect was caused by the fact that these devices normally measure the difference between rock stress and air pressure and since there was no rock stress acting on the meters the negative air pressure remained. Secondly the electronic equipment for recording the stresses was installed in small huts with controlled temperature. However, when the ambient temperature was higher than a threshold this control unit was saturated and the temperature in the hut followed the outside temperature. However, it had been shown in the lab that the GLOETZL-sondes were able to resolve pressure differences as small as the Earth tide stresses. Therefore it was decided to try to verify this in the BFO mine. Three shallow boreholes (≤2 m) were drilled in front of the airlock and several experiments were carried out in order to find the best expansive additive for the cement with which the sondes were coupled to the rock. In the final installation tidal stresses were clearly recorded and in addition the stresses caused by the seismic waves from the Shikotan earthquake in 1994 (Emter et al. 1996).

Starting when the RAYTHEON 704 was operating at BFO it was possible to run programs while the machine recorded data. During that time David Young from Cambridge University visited BFO for three months and an attempt was made to correlate the origin times of the earthquakes in the Swabian Jura with the Earth tide stresses. Several different statistical methods were used but no significant correlation could be detected (Young and Zürn 1979).

3.1.4 Tidal gravity

For the quality of gravity data the underground is by far not as important as for the horizontal components. However, the BFO mine definitely verifies a very good site for vertical accelerations too. In 1973 BFO was equipped with an ASKANIA GS-15 gravimeter, a little later an ASKANIA GS-12 modified by M. Bonatz and called BN-06 was installed and in 1976 the LCR ET-19 arrived. It turned out quickly that the least noisy of these devices was the ET-19. This instrument is equipped with electrostatic feedback and was modified for optimal performance at BFO by WZ. With the data recorded by this instrument it was possible to demonstrate the errors in the Cartwright-Tayler-Edden tidal potential catalog (Wenzel and Zürn 1990). In addition lower noise levels in the frequency band from 0.5 to 4 cycles/day (cpd) were obtained with this instrument than at other stations with the more sophisticated superconducting gravimeters at the time (Zürn et al. 1991). The absolute calibration of ET-19 (it became known in the 1980s that the factory calibration of the LCRs was slightly off) was improved by a simultaneous record at BFO with two carefully on the vertical calibration line in Hannover calibrated geodetic LCR gravimeters (Wenzel et al. 1991).

In 1994 the ”Bundesamt für Kartographie und Geodäsie” [BKG] loaned its superconducting gravimeter SG102 for half a year to BFO for a parallel registration with ET-19. The goal was to compare these two instruments under identical conditions in terms of their performance and noise levels and to clarify below which frequency the superiority of the SGs over (one of) the best spring gravimeters would show up. Except for the sensors themselves everything else in the data streams and the data processing was identical. The surprise was then that this crossover frequency occurred at a frequency as low as about 0.2 cycles per day (Richter et al. 1995). By chance the important deep 1994 earthquake struck in Bolivia during the period of this simultaneous recording, allowing to compare the signal-to-noise ratios (SNR) of the recorded free oscillations. Unfortunately a liquid helium refill was necessary three days after the quake necessitating to cut all the records into two parts. Nevertheless it could be clearly shown that in that frequency band the ET-19 and STS-1/Z seismometer provided better SNR for the low-degree modes than the SG102. The STS-2/Z had the lowest SNR in that case (Richter et al. 1995). For these reasons the STS-1/Z and ET-19 at BFO were used by Banka and Crossley (1999) in a study of the noise levels of a worldwide collection of superconducting gravimeters as a reference. In their collection then the two BFO instruments were clearly the best. This was in a way a trigger for the producer of the SGs, GWR in San Diego, to look for ways to improve their instruments which was partially successful (Widmer-Schnidrig, 2003).

Rydelek et al. (1991) investigated the M_2 gravity tides recorded by ET-19 at BFO and by eight other instruments of high quality in Central Europe. After subtraction of body tides and ocean load signals the residuals are basically all zero within their error bars (noise, calibration and ocean model bias). This means they cannot be correlated with station properties such as heat flow (which had been claimed by some researchers) and/or crustal structure (Rydelek et al. 1991).

In 1998 ET-19 (after more than 20 years of operation) developed leaks and hence became sensitive to ambient air pressure variations. After a complete overhaul (except for the seals) it was reinstalled in 2009 in the mine but now on a new pier in front of the seismic vault behind the second air-lock. It is now again one of the best long-period vertical seismometers worldwide since ambient pressure variations in that frequency band are heavily damped by the air-locks. However, in the tidal band this damping is not as strong as in the seismic band and therefore the signature of local air pressure in the records is higher there than before the seals became leaky. Nevertheless, Calvo et al. (2014) used the data from ET-19 to study the tides in comparison with other very long records in Europe.

In view of the intended aquisition of a superconducting gravimeter (SG) and the necessary monitoring of the (albeit small: 1000 times less than for good spring gravimeters) drift of such an instrument a series of absolute gravity measurements was started in January 2001. Colleagues from the following institutions owning FG-5 absolute gravimeter (MICRO-g SOLUTIONS) visited BFO irregularly for a few days and measured absolute gravity:

Strasbourg (EOST), Hannover (IfE), Frankfurt (BKG), and Brussels (ROB). First the measurements took place on a pier in the ”Heinrich”-cleft in front of the first air-lock, since 2009 on a new pier in front of the pendulum vault now containing the SG. These instruments observe repetitively the free fall of a test mass measuring its position with a laser interferometer as a function of time measured with a rubidium clock. These measurements serve the purpose of monitoring the drift of the SG. When the tide is large they can also be used for calibration of the SG.

After many years BFO received funding to acquire an SG from GWR in San Diego. After the instrument was ordered the pendulum vault and its immediate environment were secured against rock falls and a container was inserted into the vault the interior of which can be kept dry. In 2009 OSG-056 arrived and was installed by R. Warburton and R. Reineman from GWR and the staff at BFO introduced in its operation. A special feature of this instrument is that there are two gravity sensors inside the dewar in a vertical distance of about 20 cm. The two superconducting test bodies (2.54 cm niobium spheres) suspended in magnetic fields from superconducting coils have different masses, the lower one with 17.7 g and the upper one with the usual 4.34 g. The dewar is filled with liquid He and the sensor temperature is kept at a temperature of 4.5 K. The evaporating He is reliquified by a coldhead. This instrument, in contrast to many other SGs by the same company at the time, does not necessitate He refills, which constitute major disturbances. He gas can be injected slowly and the coldhead is able to liquefy it. Also in contrast to essentially all other SGs the possible tilt feedback by the thermal levelers is turned off and the supports are instead rigidly fixed to the frame because the underground at BFO is more stable than the tiltmeters in the SG are. This was verified long before on that pier by LIPPMANN-tiltmeters measuring excellent tidal signals.

3.1.5 Nearly Diurnal Free Wobble

The earth has four rotational free modes, most importantly: the Chandler wobble with a period of 435 sidereal days and the Nearly Diurnal Free Wobble (NDFW) with a period of nearly 1 sidereal day associated with the Free Core Nutation with a period of 430 sidereal days. Wobbles are observed by observers rotating with the Earth, the corresponding nutations by observers in space. Because the NDFW has its eigenfrequency between the diurnal tides K_1 and ψ_1 and because the tesseral pattern of diurnal tides tries to deform the mantle in such a way that the rotation axis of the mantle differs from the one of the core the Earth reacts resonantly to the tidal forcing, in other words the Love numbers as derived from the diurnal tides exhibit a resonant behaviour. It is like having the Earth on a shake table in a narrow range of frequencies.

In 1987 Jürgen Neuberg at GPI finished his dissertation under supervision of WZ (Neuberg 1987). He analyzed several data sets from BFO in order to retrieve parameters of the NDFW from the obtained tidal admittances in the diurnal tidal band. The data were from the ET-19 gravimeter, the EW-components each from an ASKANIA- and a HUGHES-tiltmeter, and the best of the strainmeters *N*2°E. In addition tidal gravity results from Strasbourg, Bad Homburg, Brussels, Berlin, and Potsdam were used. A nonlinear least squares and several stacking methods were developed to retrieve the eigenfrequency, quality factor, and complex admittance of the NDFW. Of course, the tidal admittances needed corrections for the contributions of ocean loading to the signal. The surprising result was that the eigenperiod of the associated FCN was near 432 instead of the 466 sidereal days predicted from seismologically constrained models. For a possible interpretation of this result were considered: viscomagnetic coupling, effect of the solid inner core, elasticity and anelasticity of the lowermost mantle, and finally an increased dynamic ellipticity of the core-mantle-boundary, the most likely explanation for the shift to higher frequencies. It turns out that the core-mantle-boundary flattening needs only to be increased by 300 to 600 m. Such a fine result could probably never be detected by seismological methods. The results of the stacked gravimeter data and possible interpretations of the anomaly were published by Neuberg et al. (1987, 1990). The BFO data used by Neuberg (1987) had been recorded with chart recorders, therefore part of the work was repeated by Polzer et al. (1996). Although the data were much less noisy it turned out that no improvement could be obtained for the precision of the NDFW parameters, which indicates, that the uncertainties in these results are caused by systematic effects (Zürn 1997). The frequency shift had been obtained independently very shortly before the work at GPI and BFO by the groups analyzing nutation data using results from Very Long Baseline Interferometry, so these results corroborate each other nicely. The methods developed by Neuberg et al. (1989) have become standards within the tidal community with only slight modifications. The data from the superconducting gravimeter at Bad Homburg were already included in the work by Neuberg et al. (1987) and especially for that instrument an analysis of the Chandler wobble and the NDFW was carried out (Richter and Zürn 1988) in addition.

3.1.6 Tidal potential and analysis

While being director of the BFO Hans-Georg Wenzel developed together with Torsten Hartmann (University of Tübingen) an extensive tidal potential catalog (Hartmann and Wenzel 1994, Wenzel 1997a) on the basis of the most precise ephemerides available. This catalog contains 12935 tidal constituents derived from the tidal potentials of Moon (degrees 2 to 6), Sun (2 to 4), Mercury, Venus, Mars, Jupiter, and Saturn (2 only for all planets).

Hans-Georg Wenzel during the same time also developed a program package for tidal analysis (ETERNA) which was widely distributed, accepted and still is extensively used for tidal research (Wenzel 1997b).

3.1.7 Core modes

Gravity signals with periods of some hours are predicted for the translational free oscillation of the Earth's inner core within the liquid outer core (the Slichter mode) and also for inertial waves in the liquid outer core. At all times the gravity data were searched for traces of such signals. Zürn (1974) showed that under certain conditions a persistent harmonic signal could be detected in digital data even when its amplitude would be smaller than the least significant bit . After a claim was made for the detection of core modes Zürn et al. (1987) showed that what had been observed was very likely not a signal from the core. Later on Zürn (1994) and Zürn and Rydelek (1994) demonstrated with the phasorwalk method that the spectral peak detected in the Brussels record was not caused by a harmonic oscillation but by a transient burst of noise. Up to now no realistic observation of such oscillations was reported.

3.2 Seismology

3.2.1 Local and regional seismology

Almost from the very beginning a 3-component set of short-period GEOTECH S-13 seismometers was recording the seismicity. In 1997 the S-13 horizontals were replaced by two KINEMETRICS SH-1s. The observatory staff, concentrating on long period signals, did not really work on local earthquakes. The routine analysis of the seismograms was carried out by Klaus Bonjer at GPI and his colleagues. The station BFO was, of course, incorporated in the network of the state (Württemberg) seismological service (Landes-Erdbeben-Dienst) in Stuttgart besides its being part of the Rheingraben network operated by GPI. In 1993 these routine tasks of monitoring and analyzing the seismicity in the state were handed over to the newly founded state seismological service of Baden-Württemberg in Freiburg (also named LED) and BFO belongs to that network now.

At first recording of the signals took place on wide ink-chart recorders manufactured at GPI (Volk). In 1986 additional recording on magnetic audio-tapes with high dynamic range (120 dB) by an event-triggered LENNARTZ PCM was introduced. Again the processing of the tapes was carried out at GPI. When the broadband instrumentation was introduced in the late 1980s the frequency range of the short-period seismometers was also covered by these instruments and in 2007 the short-period seismometers were given to the new LED and were deployed at other stations.

3.2.2 Surface waves and free oscillations

BFO is integrated into two more seismic networks besides the LED: the German Regional Seismic Network (GRSN) since 1990 and the Global Seismographic Network (GSN) of the Incorporated Research Institutions for Seismology (IRIS) since May 1996. This means that the broadband data from the STS-2 and STS-1 seismometers sampled with resolution of 24 bits and rates of 80, 20, and 1 Hz, respectively, are continuously delivered to the corresponding data centers and are made freely available to all interested scientists. IRIS also obtains and archives data from other sensors at BFO together with the STS-1 data: gravimeters, tiltmeters, strainmeters and barometers. Until early 1997 the most quiet stations of the GRSN including BFO (of course) were used in GSETT3 (Group of Scientific Experts Technical Test) to verify the possibility of discrimination between nuclear explosions and earthquakes.

Two citations from the independent literature testify to the high quality of the seismic data from BFO. Beauduin et al. (1996) write: ”... in a very good seismic vault such as BFO ...” and Freybourger et al. (1997) say: ”.. because of the well known low level of background noise at BFO ...”. Banka and Crossley (1999) found in their study that ET-19 and STS-1/Z at BFO had clearly the lowest noise levels in the normal mode band for vertical components. This is confirmed by Berger and et al. (2004) in a study of noise levels in the GSN: it turns out that the STS-1/EW seismometer at BFO defines their model of low horizontal noise for many low frequencies.

At BFO and in the working group of WZ at GPI the study of globe circling surface waves and free modes was a central issue from the start. In the early years until 1979 no digital data from BFO were available, as a matter of fact the great Sumbawa earthquake in 1977 could only be recorded on chart recorders at BFO. This event triggered a flurry of activity in the field of normal modes because the IDA network (International Deployment of Accelerometers) had started to operate just in time (Zürn et al. 1991). However, due to the continuing cooperation of WZ with the group of L. B. Slichter and Leon Knopoff at the Institute of Geophysics and Planetary Physics [IGPP] of the University of California at Los Angeles [UCLA] digital records from the ET-4 and ET-11 gravimeters at the South Pole and at UCLA (siblings of ET-19) could be analyzed. Thus the frequency and damping of the ”breathing mode” ${}_0S_0$ could be determined (Knopoff et al. 1979, Zürn et al. 1980) and for other spheroidal modes eigenfrequencies and Qs were also estimated by Xu et al. (1983) from these records.

When the first digital records from BFO became available and a few large earthquakes (Colombia, Dec 12, 1979) had struck, Michael Grünewald (Grünewald 1988) and Christine Fichler at GPI began vigorously analyzing these records for globe circling Rayleigh waves and free oscillations, respectively working towards their doctorates (e. g. Fichler-Fettig et al. 1986). Especially the coupling of toroidal and spheroidal modes was investigated. On the theoretical side Wolfgang Friederich developed a new approach for Gaussian beams and their application to globe-circling surface waves and demonstrated the effects of lateral heterogeneities on focussing and defocussing of surface waves (Friederich 1989) theoretically and with the records from BFO. In any case, the GPI working group on long period seismology, partially financed through the SFB 108 ”Stress and stress release in the lithosphere” by the DFG, was continuously analyzing data from BFO without realizing the quality of the data. Ruedi Widmer had visited BFO with Erhard Wielandt, who had equipped BFO with the prototypes of his broadband seismometers in the early 1980s (the STS-1 to be). When Ruedi Widmer was working on his PhD in La Jolla at the University of California at San Diego [UCSD], he was analyzing many seismograms from the IDA and GSN-networks. He realized that he possibly could also use the digital seismograms from all the BFO-sensors for his work. He came to BFO during the summer of 1988 and extracted the free oscillation records. During his PhD work he looked at many seismograms from all over the world and detected soon that the BFO records belonged to the best as far as SNR was concerned, especially for the horizontal components by the STS-1 prototypes and the ASKANIA tiltmeter, but also for the vertical component and the ET-19 gravimeter.

In 1989 a large quake struck near the Macquarie Islands and when analyzing the records from the BFO strainmeters WZ detected that the toroidal fundamental mode ${}_0T_2$ could clearly and unambiguously be seen in the resulting spectra together with next higher-degree toroidal modes. This had not really been expected. The observation was corroborated by the disappearance of these modes when the areal strain was computed from the three strainmeter signals (Widmer et al. 1992). This observation made it into the textbook by Dahlen and Tromp (1998). These authors write on p. 287: "The first unambiguous detection of this oscillation did not occur until after ... earthquake on the Macquarie Rise in 1989 (Widmer, Zürn & Masters 1992)". ${}_0T_2$ was observed with the BFO strainmeter array for four more large earthquakes: Shikotan 1994, Balleny Islands 1998, Wharton Basin 2000, and Peru 2001, before the disastrous megaquake off the W-coast of NW-Sumatra and Andaman Islands struck in 2004 and excited the free oscillations to unprecendented amplitudes since 1964 and all the modes were recorded with extremely good SNR by many instruments including of course the ones at BFO.

On June 15, 1991 Mount Pinatubo in the Philippines produced the secondmost energetic volcanic eruption in that century. During this eruption the ET-19 recorded a very strange signal for about 8 hours which was observed by WZ in real time. Computing a spectrum revealed that the signal was composed essentially of two spectral lines with frequencies of 3.68 and 4.44 mHz. Very quickly it became clear that this signal was observed globally and that it traveled around the globe with the group velocity of Rayleigh waves with these frequencies and that the source was located near Mount Pinatubo (Widmer and Zürn 1992, Zürn and Widmer 1996). Of course, the record archive was checked whether such a signal occurred before unnoticed and it was found that the eruption of El Chichón in Mexico in 1982 also had produced such signals, albeit only for one hour and the frequencies were 3.7 and 5.14 mHz in that case. These frequencies are now understood as eigenfrequencies of the atmosphere which get their energy from the volcano and then push on the surface to excite Rayleigh waves. An enigmatic and still unexplained observation was made a few days before the Mount Pinatubo eruption: on June 10, 1991, for about one hour an oscillation with a frequency of 3.7 mHz was observed at 4 stations with vertical accelerometers: BFO, 2 stations in eastern France and one in northernmost Italy. The frequency indicates that the atmosphere was probably involved in the excitation.

Since BFO provided excellent long-period horizontal seismograms Gabi Laske made an attempt in the early 1990s to retrieve information on the lateral heterogeneities in the mantle by studying the polarization of surface waves. Since Guy Masters at UCSD was also interested in this problem a cooperation was started and Gabi finished her dissertation in La Jolla (Laske et al. 1994). She could show that for the very long periods the polarization represents the large-scale heterogeneous structure of the mantle and corroborates the models obtained by surface wave dispersion and local eigenfrequency data.

When the 1998 great Balleny Islands earthquake had excited free oscillations again close inspection of spectra computed from the records of the ET-19 showed peaks at the periods of some low-degree toroidal modes. This observation was corroborated by spectra from a record of superconducting gravimeters in Membach, Belgium and Strasbourg, France. To explain it, local effects were ruled out and the coupling of toroidal modes to spheroidal modes remained as a possibility, which was corroborated by the synthetic seismograms computed by Gabi Laske. The responsible mechanism is with high probability the Coriolis coupling on a global scale (Zürn et al. 2000).

The small series of megaquakes starting December 26, 2004 made improved observations and measurements on free modes possible. Especially at the low-frequency end of the free mode spectrum the sparse network of SGs [GGP] provides excellent records. Häfner and Widmer-Schnidrig (2012) used the data from GGP to study the splitting of ${}_0S_2$ with improved resolution and thus determined new gross Earth data which can be used in inversions for the density structure of the Earth. Other long period instruments also provided excellent low-frequency mode data. Ferreira et al. (2006) modeled the free oscillation records obtained after the great 2004 Sumatra-Andaman Islands event from a water-tube tiltmeter in Walferdange (Luxembourg) and the Horsfall tiltmeter at BFO and compared these records to the ones from horizontal broadband seismometers. The strainmeters at BFO provided excellent SNRs for the low-degree free modes after the 2004 Sumatra-Andaman Islands (Fig. 1) and the 2011 Tohoku quakes. The complete set of singlets of ${}_0S_2$ could be resolved, ${}_0T_2$ was recorded nicely and even splitting of that mode could be seen for the first time in individual records, and ${}_0S_0$ was observed at good SNR with an amplitude of about 10^{-11}. Zürn et al. (2013) compare these data favorably with the records from the excellent STS-1 horizontal seismometers at BFO and with synthetics computed including the effects of rotation and ellipticity. Thomas Forbriger participated in seismological research in Romania in context with the SFB 461 ”Strong Earthquakes” (Sèbe et al. 2009).

3.2.3 Background free oscillations - the ”Hum”

Intrigued by the observation of the 3.7 mHz oscillations due to volcanoes WZ and Ruedi Widmer-Schnidrig decided in 1995 to send a proposal to DFG for obtaining money for a graduate student who should search the excellent data from BFO for small and unusual mode excitations due to silent earthquakes, volcanoes, or atmosphere. This was not granted due to a lack of promises of detections (phone call to J. Karte, DFG). However, in 1998 Japanese colleagues were the first to publish papers reporting the continuous excitation (called the ”hum of the Earth”) of fundamental spheroidal modes between 2 and 7 mHz and their observation in many good vertical accelerograms. Very quickly then this was confirmed with the data from the ET-19, STS-1/Z, and STS-2/Z at BFO (Zürn et al. 1999, Widmer-Schnidrig 2003). Actually, Benioff et al. (1959) had already searched records from two LCR tidal gravimeters and the quartz extensometer at Isabella, California for such oscillations and concluded that their amplitudes are below the sensitivity of the instruments then and intended to repeat the search when the instruments would be more sensitive.

At first the atmosphere was identified rather convincingly as the energy source of these oscillations with amplitudes less than 1 nGal. Later on the opinions of the involved researchers changed somewhat and infragravity waves in the oceans were made responsible. Since statistics are needed to bring the modes out of the noise it is rather difficult to locate the source. However, several studies succeeded to a certain extent, among them the work by Kurrle and Widmer-Schnidrig (2006) using the best stations of the GRSN as an array.

Dieter Kurrle was very ambitious and he and Ruedi Widmer-Schnidrig detected the ”hum” also in the EW-component seismograms from the STS-1 and STS-2 seismometers at BFO (Kurrle and Widmer-Schnidrig 2008). Two more stations were found in this work to show the ”hum” in horizontal components. However, more importantly, fundamental toroidal modes were also identified by these authors for the first time at about the same amplitude as their spheroidal counterparts. The latter fact raises serious questions on the mechanism of excitation which are still unresolved.

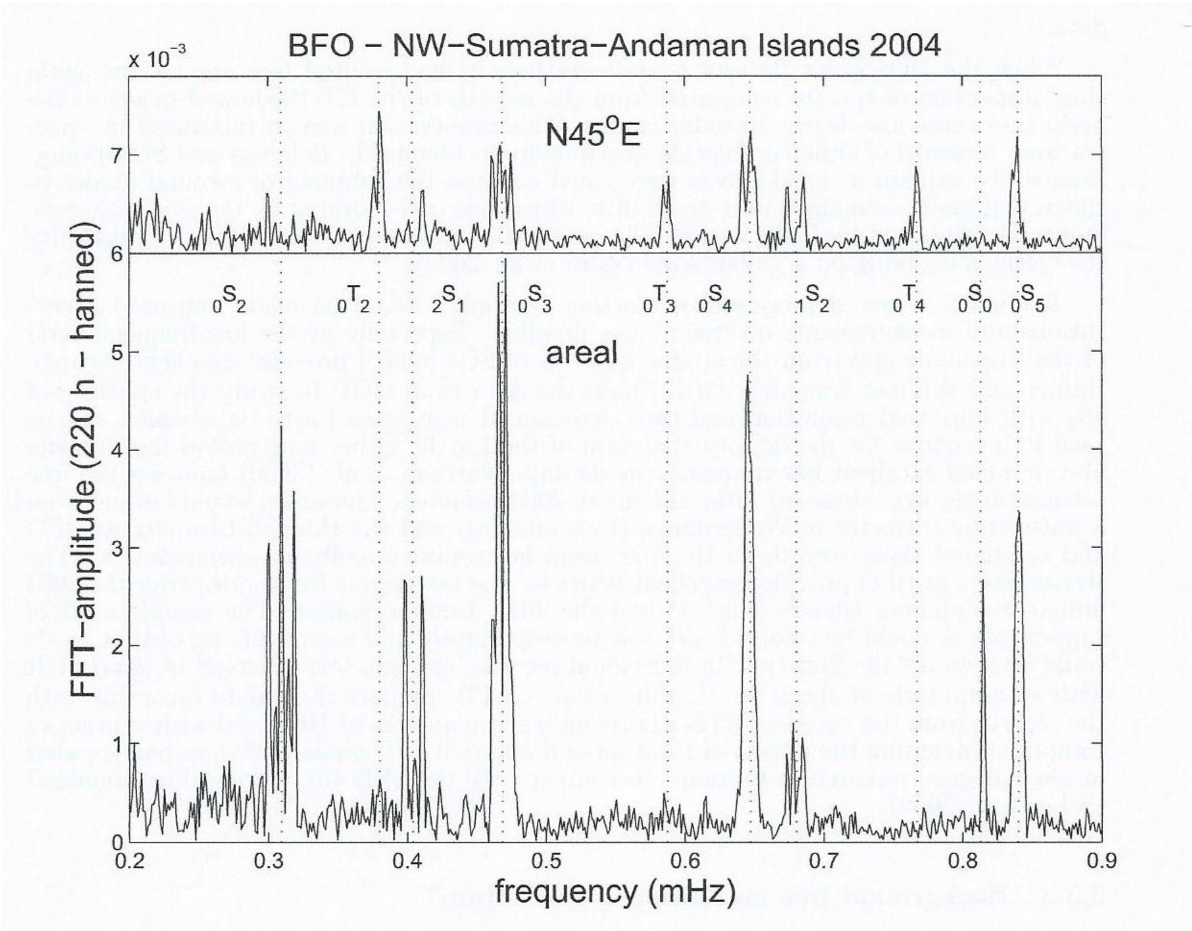

Figure 1: Spectra (FFTs) of two combinations of 220 hour records from the three 10 m invar-wire strainmeters at BFO representing shear strain on a vertical plane striking N45°E (top panel) and areal strain (bottom panel; the areal strain is basically the sum of the three records). Note especially: absence of toroidal modes in the areal strain and their relative enhancement in the shear strain; resolution of all five singlets of $_0S_2$; (partial) splitting of $_0T_2$; high SNR of $_0S_0$ and its absence in the shear strain. Data were calibrated, the tides were removed and a correction for atmospheric pressure loading was applied before combining them. As it should theoretically, the effectivity of the pressure correction for shear strain is much lower than the one for areal strain.

In the context of the work on the ”hum” Kurrle and Widmer-Schnidrig (2010) detected Rayleigh waves with periods larger than 50 s caused by large storms over North Atlantic Ocean. They used GRSN and other networks to locate these sources.

3.3 Magnetic field variations

In cooperation with the Geomagnetic Observatory Fürstenfeldbruck measurements of the magnetic variations were carried out in the amagnetic hut above the mine. Until 1987 this was done with a photographically recording ASKANIA-variograph. Then a digital system consisting of two LEHNER horizontal magnetometers and one vertical fluxgate magnetometer (FÖRSTER-sonde) were installed and operated until about 2000. Ruedi Widmer-Schnidrig then made efforts to join the international network Intermagnet by acquiring new equipment and move the station from the hut into the "Upper Anton"-tunnel about 40 m above the main tunnels where the temperature is much more stable than in the hut. This equipment consists of a three-component RASMUSSEN-fluxgate system and an Overhauser-Proton magnetometer. The required absolute measurements to verify the baselines are still carried out in the hut, only 150 m away. The observatory staff has not done research in geomagnetism, however, the magnetic records were very useful for studies of long-period seismic noise (see below).

3.4 Continuous GPS measurements

Since November 2006 a permanent GPS-station BFO1 is recording continuously with a sampling interval of 15 s. The antenna on a 3.6 m high tripod is located in front of the amagnetic hut and sitting on a massive concrete pier cemented directly onto the granite. Despite the unfavorable location on a slope in the forest the quality of the daily solutions is nearly as good as the ones from free standing antennas. The data are collected at BKG Frankfurt. These measurements have to be considered in the context of the series of absolute gravity measurements in the mine below (Mayer et al. 2008).

3.5 Noise reduction

To study noise and develop methods for its reduction where possible is an important task for researchers working at an observatory. Of course, there is a wide variety of causes of noise: instrumental sources, sensitivity to ambient variables, and sources at distance whose effects cannot be avoided. Heavy shielding is a requirement for all long-period sensors, especially against temperature variations. The two air-locks in the BFO mine help to reduce ambient pressure and temperature variations and also prevent fast exchange of air between inside and outside, for example. To run meteorological sensors and magnetic instruments side-by-side with the seismic sensors helped to identify external noise sources. The ET-19 gravimeter could be operated in the mine environment with the outer thermostat running continuously and with the power to the inner thermostat reduced from the a-priori level thus reducing the instrumentally produced noise. Another example for studies in that direction is the SG with the two different spheres. Together with the company GWR it was decided to have for the first time in such instruments one heavier sphere in order to reduce Brownian motion and to see whether this is the physical mechanism causing some excessive noise in the records of those devices in the seismic band.

3.5.1 Noise caused by atmospheric mass redistributions

Fairly early WZ noticed by looking at chart records of air pressure and band-passed gravity signals from the ET-19 that sometimes there were simultaneous large transients on both. These were quickly identified as produced by cold fronts passing the station at speeds of some tens of m/s and studied in detail by Torsten Müller (Müller and Zürn 1983). The changing Newtonian attraction of the sensor mass by the atmosphere above the station was modeled and could explain the observed signal. It was also found that similar signals only about 5 to 10 times larger occur in the records of horizontal broadband seismometers (STS-1 prototypes). Of course, gravitation cannot be shielded. Early attempts to model the effects to remove them from the vertical records were not very successful because the filter response was not known well enough.

However, at tidal and longer periods it became routine to remove signals correlated with local barometric pressure in gravity with the help of a linear regression. A simple number, about -3.5 nm/($s^2 \cdot hPa$), multiplied with the local barometric explains most of this unwanted but unavoidable signal in gravity. After the Shikotan earthquake 1994 this was used for the tidal data from ET-19 and unexpectedly the noise was so much reduced that the hard to observe mode ${}_0S_2$ emerged clearly from the noise (Zürn and Widmer 1995). It turned out that this could not be duplicated with the data from the STS-1/Z seismometer, so an attempt was made by Erhard Wielandt in 1996 to shift noise from one feedback channel of the STS-1/Z to another, but this was unsuccessful. This pressure correction only functions very nicely for the best gravimeters. Only for large pressure disturbances do the STS-1/Z seismometers clearly see these disturbances but the noise reduction only works down to the Low Noise Models based on such instruments, while the gravimeters are better with the help of this correction below about 1 to 2 mHz, i. e. for the lowest-frequency free modes.

From the horizontal records it was clear that the mass redistribution in the atmosphere deforms the crust continuously, more or less. That means that in the regression factor for the gravity records mentioned above there is a small contribution from the free air effect due to the vertical displacement. If there is vertical displacement at some frequency there is an inertial force on the sensor mass which is proportional to frequency squared and thus becomes more and more important as frequency rises. Since the free air and inertial effects have opposite sign compared to the gravitational effect there must be a strong frequency dependence of the admittance of local barometric pressure to gravity including a zero response with the sign changing. Zürn and Wielandt (2007) developed simple models incorporating the inertial effect and showed that for realistic parameters these models all explain the minimum of observed vertical acceleration noise near 3 mHz. Indeed, Bruno Meurers had made an intriguing observation with his SG in Vienna. Reducing the noise with the well-know admittance at long periods he detected a nice wavetrain whose amplitude was increased instead (Zürn and Meurers 2009) thus clearly validating the conjecture by Zürn and Wielandt (2007).

After the success with the vertical components an extensive attempt was made to improve the records from horizontal components using similar methods (Zürn et al. 2007). Similar models were used to try to improve the records with the help of local barometric pressure and its Hilbert transform. Variance reductions up to 80 % could be obtained for some time series, it was also possible to improve SNRs in some mode spectra. However, it must be expected that for traveling pressure waves the effects depend for example on the direction from which they pass over the station, so time-independent admittances for a given component cannot be expected. Nevertheless it appears that a regression with barometric pressure (after converting seismic signals to acceleration or tilt) is always worthwhile. But there are certainly improvements possible.

An important issue here is that the tilts caused by atmospheric loading are the major source of noise at long periods in the horizontal components. Inertial seismometers cannot by themselves distinguish between tilts and horizontal accelerations. Methods to measure tilt alone with some method in order to subtract it from the seismograms containing tilts and the translational accelerations will not work when inertial mass is involved in the tilt measurement (Ferreira et al. 2006).

3.5.2 Noise caused by magnetic field variations

Dieter Emter noticed in 1994 that a magnetic storm was visible in the 3 components of the STS-2 seismometer. This was then studied in more detail by WZ and reported by Klinge et al. (2002). Thomas Forbriger had observed at the TNS station that passing trucks caused signals unrelated to the total mass of those trucks, so the magnetic fields were suspected and this was verified in a detailed analysis of these disturbances. When he had started to work at BFO he followed up on these effects for the whole GRSN, other stations and a variety of instruments (Forbriger 2007). He found out that variations in the magnetic field translate directly into apparent acceleration of the sensor mass. The strength of the effect varies strongly with the instrument, however, for a given instrument it appears to be stable. Once one has determined the sensitivity for a sensor the noise caused by magnetic fields can be reduced with the help of the measured magnetic field variations. An interesting observation is that the noise recorded at MOX could be reduced with the magnetic field records obtained at BFO more than 300 km away, at least for the strong magnetic storm under investigation. In principle instruments could be made sufficiently insensitive against this kind of noise by improvements in design or shielding in contrast to the noise produced by atmospheric masses discussed in the previous section.

At first it was thought that only very strong magnetic storms would be a transient problem. However, Forbriger et al. (2010) found out that sensors with their magnetic sensitivity on the high side are not able to reach the low noise levels needed for good free oscillation recordings due to the always present background magnetic field variations. ET-19 and the strainmeters at BFO have ferromagnetic alloys in their spring and length standards, respectively, but their sensitivity to ambient magnetic fields is lower than that of the seismometers and thus too low to matter.

3.6 Examples of guest experiments

BFO is involved in some planetary exploration programs as a test site for broadband seismometers. The first was the Mars mission NETLANDER which was eventually cancelled because the partner NASA was short of money. The second Mars mission, called "InSight", is still in the preparation stage. The seismometer to be flown to Mars was tested at BFO in 2012 for several weeks. A short-period seismometer for the moon, built by the Japanese, was tested simultaneously.

Akito Araya from the Japanese TAMA collaboration for the detection of gravitational waves tested his newly constructed laser interferometric seismometer at BFO and compared his data with the STS-1/Z and ET-19 data for a few weeks in 2000/2001. At present and for more than two years now Mark Zumberge (UCSD La Jolla) is also testing STS-1 seismometers with laser interferometric displacement transducers (called iSTS-1) at BFO.

The ringlaser at the Fundamental Station in Wettzell (Bavarian Forest) can record subdaily fluctuations in the Earth's rotation rate with very high resolution. In order to achieve this quality the tilts of the platform with respect to the rotation vector have to be measured and used for correction. To that end six small tiltmeters designed and built by Erich Lippmann are set up on the zerodur block on which the laser is mounted. In 2000 these tiltmeters were carefully tested at BFO before they were installed on the ringlaser and proved to be very good and suited for the task (e. g. Widmer-Schnidrig and Zürn 2009). The same kind of tiltmeters were modified by Lippmann later for installation in boreholes and after tests at BFO installed by Carl Gerstenecker (Techn. Univ. Darmstadt) in the vicinity of Istanbul and the Marmara Sea to provide information on impending earthquakes.

The Geoforschungszentrum (GFZ) Potsdam had the intention to install a tiltmeter in the KTB-borehole at great depth where the temperature is above the threshold normal electronics can take without giving up. This instrument was tested in the 1990s in several phases of the development on different piers at BFO, however, it was never installed in KTB.

The Canadian company NANOMETRICS came to BFO also in 2007 to test their newly developed broadband seismometers (Trilliums) against the instruments at BFO. Strong sensitivity to magnetic field variations instigated Forbriger et al. (2010) to study those effects.

In the late seventies BODENSEE-WERKE (successor of ASKANIA), tested three borehole tiltmeters sold to Canadian colleagues before shipping them to Ottawa, where they were then installed at depths of 100 m in the Charlevoix earthquake zone. The three boreholes were located in what was thought to be one solid block. However, the tidal signals recorded were significantly different, demonstrating that boreholes are not free of local effects.

3.7 Additional activities

3.7.1 The 5th force and the Hornberg experiment

In the middle of the 1980s a lot of excitement was produced by the claim that there is a fifth type of fundamental interaction besides gravitation, electromagnetism and the weak and strong nuclear forces. The claim consisted of the gravitational constant (Big G) to be either dependent on distance or on materials. Since geophysicists and geodesists were involved in this claim by having measured with gravimeters down mine shafts in Australia or up 600 m high television antennas in USA, respectively, Gerhard Müller and WZ decided to check this by using large water masses in a hydroelectric lake, the Hornberg reservoir in the southern Black Forest. After a one-week pilot experiment in 1987 the gravity effect of the daily moved large water mass was measured with six LCR field gravimeters for 22 days in 1988. Many additional measurements were carried out to be used for the data analysis or to make sure to make no systematic errors with the help of geodesists Klaus Lindner (GIK) and Norbert Rösch (IfE Hannover) and also Heinz Otto and Walter Grossmann of BFO. Basically Big G was determined by measuring the integrated effect of the water masses and no difference to the laboratory value could be detected with uncertainties of the order of 0.3 %. The effective distances were 39 and 68 m for the two groups of three gravimeters above and below the water, respectively. The most important source of error was the calibration uncertainty of the gravimeters (Müller et al. 1989, Müller et al. 1990). The experiment made it into two books on the physics of the ”fifth force” (Franklin, 1993, Fishbach and Talmadge 1999). However, the results were not accurate enough to refute the claims for a fifth force with a strength of 3% and a range of 200 m.

The seiches of the lake could be observed clearly with the gravimeters also as a function of the water level (Zürn et al. 1991). For a while Helmut Wilhelm and WZ conjectured together with oceanographer Erich Bäuerle that historical observations of seiches in larger lakes could be used to infer the magnitudes of large earthquakes before the start of seismographic observations. However, the possibility of other physical mechanisms (e. g. landslides) for seiche excitation made them abandon this idea and research consequently was stopped.

3.7.2 The UCLA-connection and Antarctica

Karl Fuchs at GPI was very interested to continue the cooperation of WZ with the IGPP at UCLA. Therefore he fully supported the responsible participation of WZ in the move of the two LCR-gravimeters from the old to the new station at the geographic South Pole in the austral summer 1974/1975. WZ also was supported by Karl Fuchs for 6-week research visits to UCLA each year from 1976 to 1981, where WZ helped with the instrumentation and analysis of data obtained at the South Pole and elsewhere (Zürn et al. 1976, Slichter et al. 1979, Rydelek et al. 1982, Knopoff et al. 1989a,b, Zürn et al. 1995, Bos et al. 2000).

When the German government decided to obtain consultative status in the Antarctic Treaty Organization in the very early 1980s this necessitated to establish a research station which is occupied for the whole year. The decision was made to build ”Georg-von-Neumayer” station [GvN] on the Ekström ice shelf. BFO staff (WZ and Heinz Otto) were invited by the Alfred Wegener Institute [AWI] in Bremerhaven to participate in the planning of the geophysical observatory at that station. Heinz Otto went to GvN when it was constructed in the austral summer of 1981/82 to setup the seismic and the geomagnetic observatory together with Alfons Eckstaller (AWI). He also took the ASKANIA GS-15 gravimeter belonging to BFO and installed it in the seismic container on a heavy table whose legs were frozen into the ice. This instrument recorded for several years at GvN and also later at the new station called ”Neumayer”. Since the station was located on a floating ice shelf it recorded essentially the ocean tide under the ice. Tezkan and Yaramanci (1993) analyzed the record and estimated the rheology of the ice.

In the early years the geophysicists to winter-over at GvN were trained for a week or two at BFO. These men held close contact with BFO through telexes. In one case a FORTRAN program was telexed to GvN. It happened that in the single year 1983/84 there were three recent geophysicists from GPI wintering-over in Antarctica (Arno Brodscholl and Klaus Wallner at GvN and Hans-Albert Dahlheim at the South Pole). Very sadly, KlausWallner died in an accident at GvN after the winter. He had carried out his diploma work together with Jürgen Neuberg (”Locko”) doing field gravity work at BFO under the supervision of WZ. Therefore the director of AWI, Gottfried Hempel, asked WZ (and indirectly Locko) to accompany him in an immediate visit to Klaus Wallner’s parents in Rottenburg, a very sad duty. Over the years there were several more geophysicists (both male and female) with their diploma from GPI to winter-over at the German station.

3.7.3 Miscellaneous

In the early days of the BFO the staff (Walter Grossmann, Heinz Otto, WZ, but especially Dieter Emter) participated actively in refraction seismological experiments in Germany, the Alps, France, Britain, Norway and Sweden, Iceland and Namibia. The refraction seismic equipment earlier allocated to Stuttgart had been moved to BFO by Dieter Emter.

In 1983 Dr. Jürgen Schmitz from the Research Center Karlsruhe showed up at BFO. The state government had initiated a study of the mining related radioactivity in Baden-Württemberg and he was the one to carry it out. The baryte ($BaSO_4$) vein which contained the silver also carried small amounts of other very interesting minerals including UO_2 (”pitchblende”). Enhanced levels of radiation and Radon were detected and several long term studies were carried out until 1985 with the help of the observatory staff. It was found out then that radon gas is penetrating the laboratory building from the underground consisting of waste material from the mine. However, it was also found out that opening the windows for ten minutes helped to get rid of this excess amount. After Peter Duffner started working at BFO in 2006 he did a survey of the radioactivity in the mine and found a new hotspot in the main tunnel near the ”Reiche Firste”. He was a member of a voluntary firefighting team in Schramberg and responsible for radioactive issues there. By the way the minerals in ”Reiche Firste” were interesting enough to mineral collectors that break-ins occurred in the late 1990s, interrupting the work to some extent but fortunately not affecting the scientific data.

WZ, together with Klaus Lindner (GIK) participated in two international comparisons (1990 and 1994) of absolute gravimeters at the Bureau International des Poids et Mesures at Sèvres by measuring gravity differences between piers using the field gravimeters of GIK. When Ludger Timmen of IfE Hannover in 2008 carried out one of his absolute gravity campaigns in Fennoscandia for the measurement of the gravity changes due to post-glacial uplift he was accompanied by WZ for about 4 weeks. Two sites in Finland, three in Sweden were occupied with the FG-5 absolute gravimeter for 4 or 5 days each.

In cooperation with Rolf Schick (IGS) experiments were carried out at some volcanoes (Etna, Stromboli, Merapi) using seismometers and fluid-tube tiltmeters (Dreier et al. 1994). Dieter Emter and WZ also analyzed catalogs of volcanic events and looked for correlations with the Earth tide strains (e. g. Emter 1997).

Zaske et al. (2000) obtained borehole water pressure records from one of the boreholes at the Hot-Dry-Rock site at Soultz-sous-Forêts and analyzed the observed tides. The SNR was unexpectedly good and such that an analysis for the NDFW-parameters could be attempted. However, while the analysis gave stable results the period of the corresponding FCN was out of the range obtained by data from SGs and VLBI.

In the framework of the SFB 108 Hadiouche and Zürn (1992) analyzed surface wave data from (only few) stations around the Afro-Arabian Region using the two-station method. Anisotropy was needed and introduced to interpret the observed dispersion, however, this result is preliminary due to the poor coverage and method.

One of the ASKANIA borehole tiltmeters was shipped to Piñon Flat Observatory in California where it recorded for several years in boreholes with depths of 24 and 120 m together with a series of other instruments. The idea was to study crustal deformation in a sliver of crust between the San Andreas and San Jacinto faults. Unfortunately the instrument was damaged by lightning and recording stopped. However, several years of data were obtained and Johnson et al. (1993) analyzed those for the tidal signals. Again significant differences were detected between these data and those from other tiltmeters at the site.

3.7.4 Review articles

The researchers at BFO were over the years invited several times to write reviews in their fields, a very time-consuming kind of work: on surface waves and free oscillations (Müller and Zürn 1984, Masters and Widmer 1995, Zürn and Widmer-Schnidrig 2002, Widmer-Schnidrig and Laske 2007), on the tidal forcing field (Wilhelm and Zürn 1984), on solid Earth tides (Zürn and Wilhelm 1984, Zürn 1997), on the NDFW (Zürn 1997), on tidal triggering of earthquakes and volcanic eruptions (Emter 1997), on highly sensitive tiltmeters (Emter 1989), on deployment and shielding of seismometers (Forbriger 2012), and on strain-seismometers (Zürn 2001).

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