COBISS: 1.01

ILLUSTRATING THE SUPERPOSITION OF SIGNALS RECORDED BY THE GROTTA GIGANTE PENDULUMS WITH MUSICAL ANALOGUES

GLASBENA ANALOGIJA SUPERPOZICIJE SIGNALOV NIHAJNIH NAKLONOMETROV IZ JAME GROTTA GIGANTE (VELIKA JAMA V BRIŠČIKIH) Z GLASNEBO ANALOGIJO

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Abstract UDC 551.442(450.361)

Carla Braitenberg & Ildiko' Nagy: Illustrating the superposition of signals recorded by the Grotta Gigante pendulums with musical analogues

The Grotta Gigante houses a geodetic station since 1959, which has the goal to observe deformation of the cave. The instrumentation consists of two ultra-broad-band pendulum type tiltmeters, and two medium-to-longperiod tiltmeters, next to thermometer and pressure gauge. The exceptionally long and continuous time-series of the tiltmeters allows us to demonstrate the existence of several astonishing phenomena that cause the cave to change continuously in shape, also if only to a small amount and which can be recorded with sophisticated instruments, as the ones installed. The movements due to the different causes sum up to produce the complete observed signal, and our goal is to separate and identify the different phenomena. To illustrate the work we do in identifying the different agents, the analogy holds to a musician listening to a symphony- concert and identifying the melody of the first violin, flute, triangle, the violoncello and the double bass, and then identifying the corresponding musicians and instruments on stage. As the music has high and low tones, the deformation of the cave is composed of slow and fast movements, continuous movements, or abrupt, sudden events, that repeat very rarely. Here we show the observation sequence of tilt for the time interval 1966–2012, and discuss the deformation due to the following causes: temperature, underground water-level, sea level of the Adriatic sea, position of sun and moon and vibration of the Earth due some of the greatest mega-earthquakes ever recorded. To illustrate the analogues to music we use to explain the association of different frequency ranges to different causes of deformation signal to the general public of the cave. The results show an excellent example of scientifically sound and important instrumentation installed in a show-cave visited regularly by the public.

Keywords: Grotta Gigante (Northeastern Italy), horizontal pendulums, Earth music, Popular Geology, Ground water-movement.

Izvleček UDK 551.442(450.361)

Carla Braitenberg & Ildiko' Nagy: Glasbena analogija superpozicije signalov nihajnih naklonometrov iz jame Grotta Gigante (Velika jama v Briščikih) z glasnebo analogijo

V Veliki jami v Briščikih je že od leta 1959 geodetska postaja, ki je namenjena meritvam deformacij jame. Inštrument sestavljajo dva nihajna naklonomera z izjemno široko pasovno širino in dva naklonomera v območju srednjih in dolgih nihajnih časov. Izjemno dolga zvezna časovna vrsta meritev nosi zapis dogodkov, ki spreminjajo obliko jame. Čeprav gre za zelo majhne premike, občutljivi instrumenti to zaznajo. Premiki jame ustvarjajo signale, ki jih poskušamo ločiti in pripisati različnim vzrokom. To delo lahko primerjamo s poslušanjem koncerta, kjer različne zvoke pripisujemo različnim instrumentom in glasbenikom. Kot ima glasba visoke in nizke tone, so lahko tudi premiki počasni, hitri, zvezni, nenadni, pogosti ali redki. V članku obravnavamo časovno vrsto iz obdobja 1996–2012 in opisujemo deformacije zaradi sprememb temperature, nivoja podzemne vode, nivoja Jadranskega morja, položaja sonce in lune in nekaj najmočnejših do sedaj zabeleženih potresov. Različna frekvenčna območja signalov pripadajo različnim vzrokom, kar obiskovalcem jame ponazorimo z glasbeno analogijo. Opisana raziskava je lep primer izvajanja in predstavitve znanstvenih raziskav v turistični jami.

Ključne besede: Grotta Gigante (Velika jama v Briščikih), severovzhodna Italija, vodoravna nihala, glasba Zemlje, poljudna geologija, tok podzemne vode.

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Received/Prejeto: 05.07.2013

INTRODUCTION

The horizontal pendulums situated in the largest cave of the Italian Karst, in the Grotta Gigante, are very sophisticated instruments able to capture very small movements of the cave, as they detect cave rotation and horizontal cave shearing (Marussi 1960; Braitenberg 1999a; Braitenberg & Zadro 1999). Moreover they are sensitive to transient mass changes that induce changes in the inclination of the plumb line. The particular setup of these instruments is unique, as they are suspended from the top of the cave, making the cave the instrument casing. The Grotta Gigante station belongs to the world wide tiltmeter stations that have the scope to measure tilt either for the purpose of risk estimations in volcanic or seismic environments, or for the scientific purpose of better understanding the earth deformations (e.g. Zadro & Braitenberg 1999). Due to the different dynamic forces and atmospheric agents the superficial layers of the earth's crust deform continuously, a phenomenon that can be detected by surface measurements like the classical repeated leveling (e.g. Spampinato *et al.* 2013), satellite geodetic observations as GPS and Interferometric techniques like InSAR (Interferometric Synthetic Aperture Radar) and underground observations with tiltmeters and extensometers.

Due to their exceptional dimensions, made possible by the spectacular size of the cave (112 m height), the Grotta Gigante pendulums are extremely stable with a background noise which is several orders of magnitude less than traditional instruments of smaller size. This fact allows to detect extremely weak signals, that otherwise are masked by the noise. The different measurements made for observing deformation are illustrated in Fig. 1: two fixed GPS stations give us the horizontal and vertical movement of the benchmark in a global reference frame, the difference between the two GPS stations gives us either tilting if we take the difference between the two vertical movement rates, or horizontal extension rates, if we take the difference between the horizontal movement rates (Pinato Gabrieli *et al.* 2006). The horizontal extension can be observed also with a strainmeter installed underground, that consists in a device measuring the distance changes between two fixed points in a well or cave. The tilting underground is observed with a horizontal pendulum, or with water tube tiltmeters, bubble tiltmeters, or vertical pendulums (for a review on the instrumentation see Zadro & Braitenberg 1999).

A product of year-long study of the observations, is the identification of the many signals that compose the observed time variation of tilt (Braitenberg *et al.* 2001). We find different causes that make the earth deform, and which are captured by the pendulums. Our station being located in a touristic cave, we are confronted frequently with the problem of making our knowledge of the signals understandable to the general public and giving explanations of what the pendulums are observing. A typical feature of the observed deformation is, that the different causes that generate deformations, also have different characteristic periods, so we are able to separate them by filtering procedures. This concept is difficult to understand for many people and they cannot

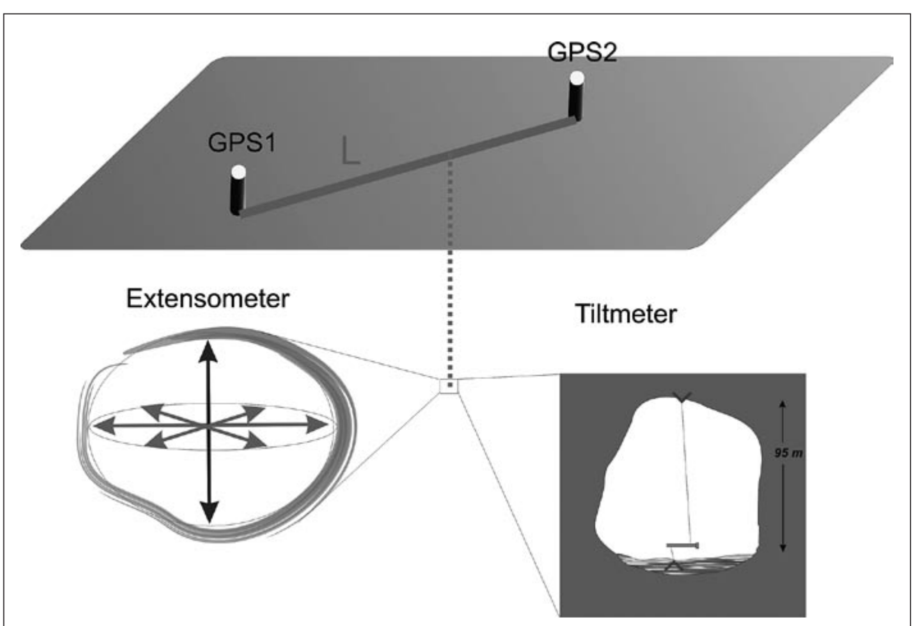

Fig. 1: Deformation measurement on and under the Earth surface. Cartoon illustrating the differential GPS measurements (tilt and extension), the extensometer and tilt measurements in caves.

imagine what we are talking about. The first obstacle in explaining the signals is the concept of superposition of signals at different frequencies, or equivalently different periods and their association to cause and effect. Here we show an easily accessible way of explanation, which uses analogies to the world of classical written music and which was possible due to the cooperation of an internationally known composer, Olga Neuwirth, and Peter Plessas from a specialized sound-studio, the IEM – Institute of Electronic Music and Acoustics, Graz. Here we publish an excerpt of the data record of the Sumatra-Andaman Island earthquake of 2004, transformed into a piece of music. It is Olga Neuwirth's composition "Kloing!" for computer-controlled piano, pianist and video. In this piece, the computer-controlled piano player reproduces a score deducted from the seismic data by the composer, while a human performer "competes" against the automatic piano in a spectacular duel. The full composition includes a video where simultaneously pictures are screened, showing famous pianists, the geodetic observation station in Trieste and a 1905 Welte-Mignon piano (http://www.festival-automne.com/olga-neuwirth-show1498.html).

DESCRIPTION OF INSTRUMENTS IN GROTTA GIGANTE

The ultra broad band horizontal geodetic pendulums of the Grotta Gigante are designed to measure the Earth crustal movement over a large range of periodicities, from quasi static changes, typical of secular tectonic movements to rapid seismic deformations. It measures the variation of the direction of two earth-fixed reference points with respect to the plumb line (vertical) (Zadro & Braitenberg 1999; Braitenberg 2011). The Fig. 2 shows two phenomena picked up by the pendulums, the rotation or shear of the cave through which the upper mounting of the pendulum is shifted horizontally relatively to the lower mounting (Fig. 2a), and the change in direction of the plumb line due to mass changes (Fig. 2b).

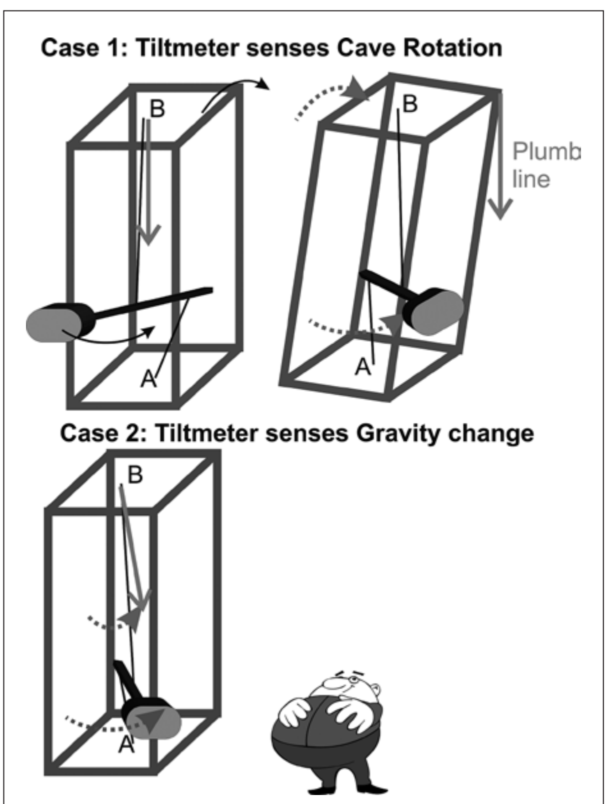

Fig. 2: Two aspects of the sensitivity of a tiltmeter. Case 1: Response of the tiltmeter to rotation or shear of the cave. Case 2: Response of the cave to the angular change of the plumb line.

The essential elements of the horizontal pendulums are shown in Fig. 3. Fig. 3a shows the suspension of the pendulum in the cave. The mechanical parts and the acquisition system are shown in Fig. 3b. The digital acquisition system (Braitenberg *et al.* 2004; 2006) consisting of a laser beam and a position device built by the colleagues Dr. Giovanni Romeo and Dr. Quintilio Taccetti from the Istituto Nazionale di Geofisica e Vulcanologia (INGV). It replaced the analog acquisition on photographic paper.

The vertical pendulum is made of a mass suspended by a rod or wire which can oscillate in the vertical plane about a horizontal axis. The horizontal pendulum is made of a mass attached to a rod which can oscillate in a subhorizontal plane about a near to vertical axis. This axis makes a small angle φ with respect to the vertical axis (Fig. 3b). Compared to the vertical pendulum of equal dimensions, the horizontal pendulum has an increased oscillation period. Supposing the upper fixed point of the near to vertical axis is shifted with respect to the lower fixed point along the Meridian, so that the line connecting the two fixed points makes an angle φ with the vertical, then the rod has its equilibrium position in the Meridian plane. If the direction of the vertical changes due to a mass change or the axis changes due to a deformation of the cave towards east by a small angle α, the rod will rotate towards east by the angle $\alpha/\sin\varphi$. Having two pendulums mounted at 90° to each other,

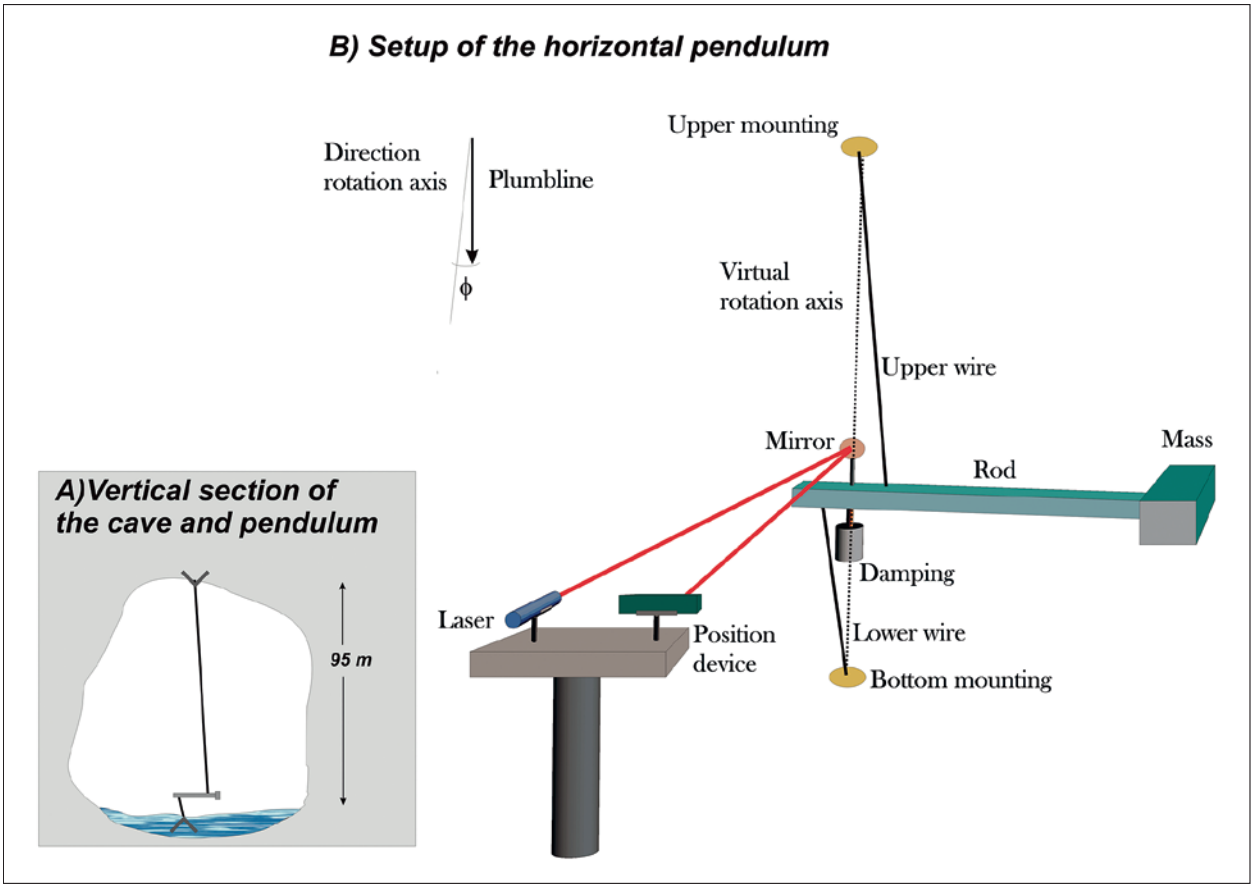

Fig. 3: Schematic drawing of the horizontal pendulum of Grotta Gigante. The rod with the mass rotates in the horizontal plane about the virtual rotation axis. The angle φ of the virtual rotation axis with the plumb line is essential for the amplification factor of the pendulum.

allows to have an instrument sensitive in both NS and EW directions. The movement of the rod is recorded by an optical device that records the light ray reflected by a mirror mounted on the rod (e.g. Braitenberg *et al.* 2006). The digital recording system is based on a solid-state acquisition system intercepting a laser light reflected from a mirror mounted on the horizontal pendulum beam. The sampling rate is 30 Hz, which makes this long-base instrument a ultra-broad- band tiltmeter, apt to record the tilt signal on a broad-band of frequencies, ranging from secular deformation rate through the earth tides to seismic waves. The smallest resolved tilt is 0.009 nrad (1 nrad = 10^{-9} radians). The digital data are transferred to the serial port of the PC, and the data are saved on hourly files of 109,600 samples by the acquisition software . The PC, running Linux, is accessible via ethernet, so the data are available in real time.

The first edition of the horizontal pendulums of the Grotta Gigante were built in 1959 by Antonio Marussi (Marussi 1959). The upper and lower wires of the horizontal pendulum-rod are fixed directly into the rock, at a vertical distance of 95 m. The oscillation period of the pendulum is near to 6 min. Next to tilt, the atmospheric pressure and temperature are measured at the station, as well as the tilting with a couple of traditional small scale tiltmeters.

THE DIFFERENT SIGNALS RECORDED BY THE GROTTA GIGANTE HORIZONTAL PENDULUMS

The complete time signal recorded by the pendulums is generated by many agents and when graphed, results in the superposition of oscillations of different frequencies, aperiodic variations and long term varia-

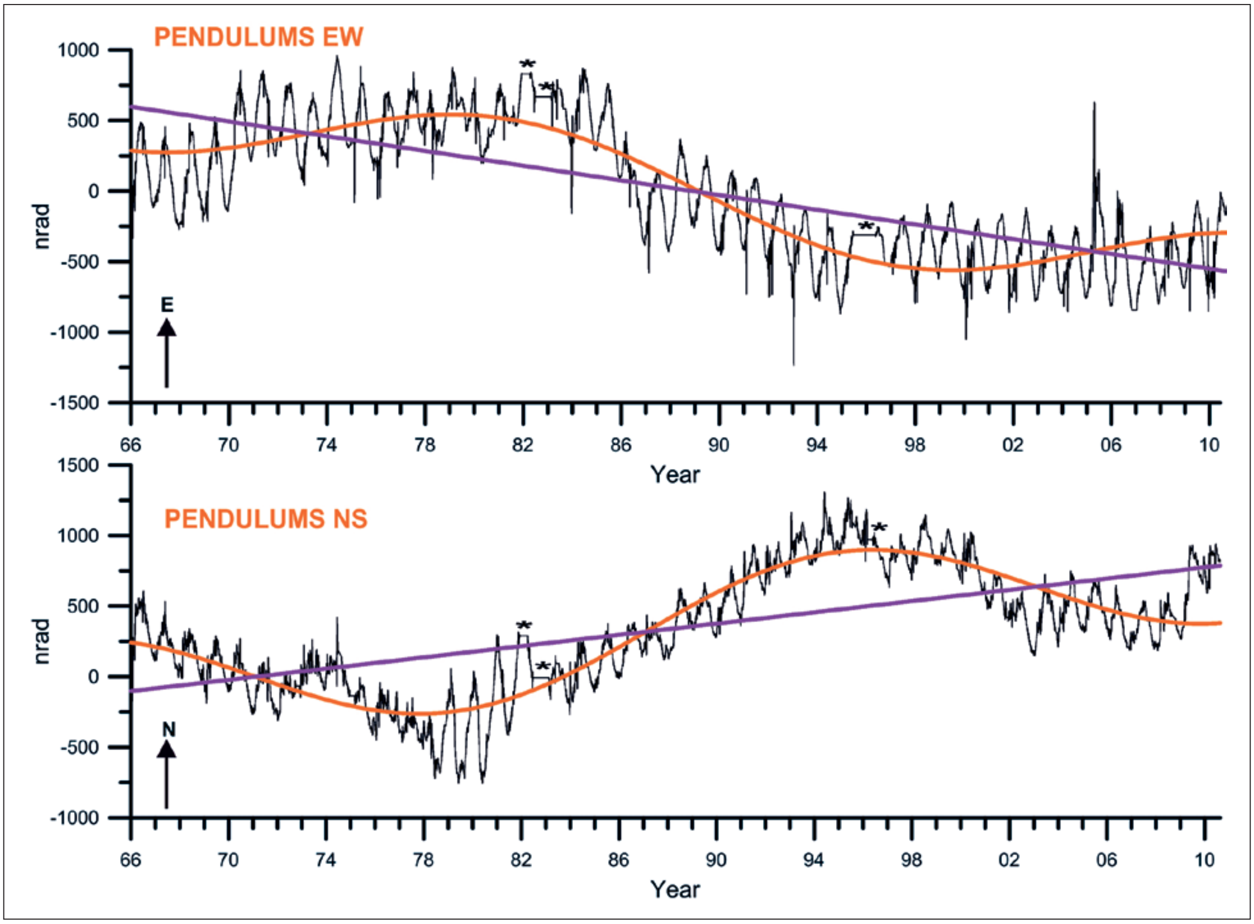

Fig. 4: Tilt observation(black) from 1966, secular variation (violet), secular variation and multi-decadal oscillation (orange).

tions. The main causes that make the Grotta Gigante deform are, from slow to fast movements: plate tectonic deformation, due to the fact that the station is on the north-eastern border of the Adria plate, which bends downwards and northwards below the sedimentary layers of North- Eastern Italy (Braitenberg *et al*. 2001). The movement generates the strong earthquakes of Friuli-Venetia and along the Dinarides mountain range. The pendulums record a steady north-westerly tilting of the cave over the last 48 years. The tidal movements are a perfectly regular oscillatory movement with the a package of diurnal and semi-diurnal periodicities of one day and half a day with a fortnightly modulation generated by the gravitational attraction of moon and sun. Near and far earthquakes are the expression of the rupture of a piece of rock, that gives way to the accumulation of deformation over decades of time. The fault can be in any place of the globe, and the seismic waves penetrate the globe as well as travelling along its surface before striking the cave. In the near field of the rupture a co-seismic deformation is observed, generated by the dislocation of the fault surface. The radius in which the co-seismic deformation is observed depends on the area of the fault plane and on the length of the dislocation. The amplitude of the deformation decays with the third power of distance and increases by a factor 31 for a unit increase in Magnitude (Wyatt 1988). Up to now the earthquakes were too distant to generate an observable coseismic permanent deformation at Grotta Gigante. The seismic waves generated by the breaking of the fault travel all over the globe. For very big earthquakes, greater magnitude 6, the pendulums measure the free oscillations of the earth, which are the series of well defined frequencies at which the earth oscillates. This signal is well defined due to the fact that the frequencies have been calculated with high precision (Dahlen & Sailor 1979). The lowest period is 54 minutes, and then the periods decrease up to fractions of a minute. The oscillations pursue for hours after the main shock and can be still recorded for days with decreasing amplitude (e.g. Braitenberg & Zadro 2007). Seismic waves caused by the rupture of the fault plane are propagating oscillations of the ground, that travel at a speed of 4–8 km/sec, and oscillate with frequencies between 1mHz and 50 Hz. A completely dif-

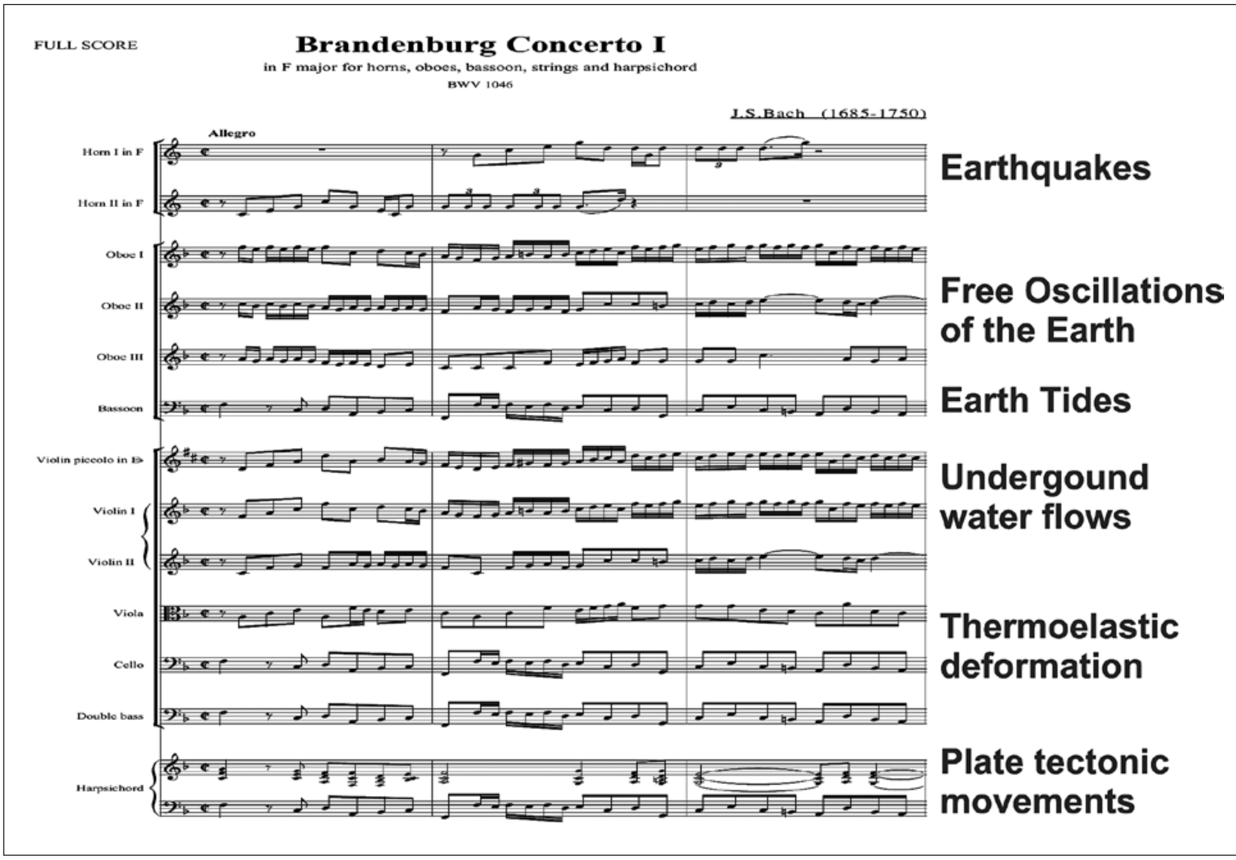

Fig. 5: The recorded movement is the sum of the effects of different agents, as in a score are acting different musical instruments for the final sound.

ferent type of tilting that is observed by the pendulums is due to the action of environmental effects, which are underground water flow (Grillo *et al.* 2011; Tenze *et al.* 2013; Braitenberg & Zadro 2001; Braitenberg 1999b), the ocean loading and the thermo-elastic deformation. The underground water flow is of general interest, as it could lead to trigger small earthquakes (Braitenberg 2000). The atmospheric pressure variations are hardly recorded in terms of deformation by the pendulums. All these deformations sum up and are the cause of the complete time varying tilting of the pendulums. In Fig. 4 the tilting from 1966 along the directions EW and NS can be seen as a graph. At the time scale of several decades only the slower movements can be appreciated, the faster movements as seismic waves and free oscillations having a much smaller amplitude.

In order to explain to the general public what the geophysical job is of interpreting the tilt signals, we choose the analogue to a piece of chamber music that has been written by the composer. The sheet music consists of the notes that the different instruments play at the same time (Fig. 5): The sheet scores give the deepest sounding at the bottom, and moving upward the higher-pitch instruments are found, grouped by type. In the example of Fig. 5 the score starts from the harpsichord, passing to the strings, and then to the wind instruments. Looking at an orchestra from right to left, we go from the double bass to the cellos and violins, and in second row from the flutes, trumpets back to the tuba on the right. The deep-sounding instruments usually play slowly, as the double bass, the higher instruments quickly. The deeper instruments are heard at great distance, the higher instruments only to close range. The sound that reaches the ear is the superposition of all the scores played by the single instruments. We could record it with a microphone and obtain a graph analogous to the one that we make for the tilt-observations. The musician will try to distinguish the scores played by the different instruments, and a skilled musician will even identify the size and type of instrument and qualities of the orchestral player. The job of the scientist in studying the records of the pendulum is analogous, in that from the complete record the goal is to define the different causes, their properties, the location, the evolution in time. It would correspond to writing down the sheet music by only listening to the orchestral piece.

We can also try to use our ear to understand the records of the pendulums better than representing it on a graph, by transforming it to the audible frequency range. A first audification of a 24h long sequence that covers the Earthquake of the Sumatra-Andaman islands of 2004 (Park *et al.* 2005) (Fig. 6) has been done by the composer Olga Neuwirth and Peter Plessas, IEM - Institut für Elektronische Musik und Akustik, Graz, Austria. Their experiments found that a direct transformation of 24^h observations to the 20Hz to 20 kHz audible frequency range of the human ear, resulting in a short piece of 10 sec, was not satisfactory for the ear, as the sound was too uniform, and only the main shock of the event gave an appreciable sound. Rather, the transformation was done mapping the amplitudes to frequencies of an instrument like the piano, in the sense that tilts to the East were mapped to low tones, tilts to West to high tones. The main shock of the event thus is transformed to a broad arpeggio that runs over the entire extent of the piano- keys. Smaller amplitude variations result in a twinkling sound of the piano. The final product was the composition "Kloing!" for computer-controlled piano, pianist and video, which was premiered in Weimar (Kunstfest 2008), with subsequent performances in Cologne (Philharmonie 2010), Paris (Festival d'Automne 2011) and Vienna (Wien Modern 2012) and gained lots of credits from the public. The aim of the experiment was to produce a piece that from the musical standpoint was valuable, so the scientific aspect of extracting the different geophysical signals was not pursued further. In the frame of the touristic caves it is a nice example of an innovative way to illustrate the different recorded signals to the general public and to illustrate the concept of a time series recorded by the geodetic pendulums. An example of the audification is given in an audio file (Audio 1), which is an excerpt from the composition Kloing! By Olga Neuwirth.

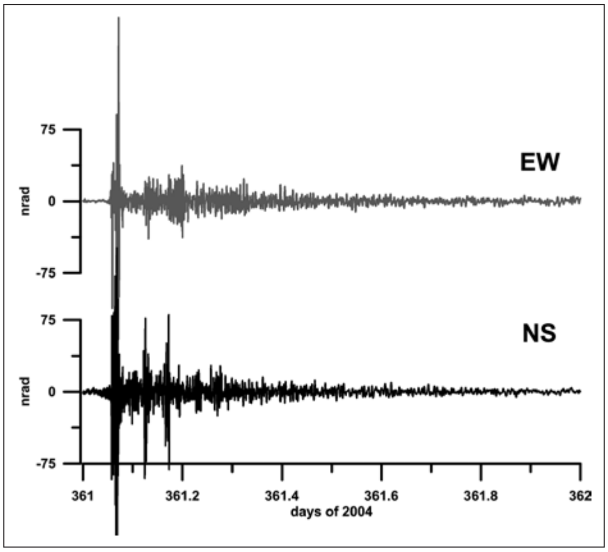

Fig. 6: Tilt records of the Earthquake Andaman-Sumatra Islands 2004, which was used for the sonification and transformed to music.

DISCUSSION AND CONCLUSIONS

The Grotta Gigante cave is a good example of a touristic unique cave being also the site of long lasting scientific measurements. Here we discuss the geodetic horizontal pendulums that measure deformation of the cave and mass changes. Next to these geodetic instruments, also seismometers and a Radon monitoring station are continuously producing data. The scientific measurements in the cave add value to the touristic attraction, because steadily new discoveries and results make multiple visits to the cave attractive. The scientists are then confronted with the problem of making the measurements understandable and fascinating to the general public of all ages and cultural background. It requires the illustration with hands on examples and intuitive transmission of information. An important concept in the geodetic measurements is the superposition of different signals each with characteristic frequencies, ranging from quasi-static movements to rapid aperiodic and periodic oscillations. The long history of scientific analysis has led us to be able to distinguish the different causes and associate them with their characteristic signals and frequencies. We find that this concept of associating a characteristic signal to its time variations, which can range from quasi-static to high frequencies, is not well understood by the public. It is for this reason that we find the analogue to a musical piece very useful. The concept of low and high tones, and the associated slow and fast movement is near to obvious to anyone. Musical groups have the slow and deep-sounding instruments and voices that complement the fast and high pitch soprano singer and instruments, and who listens to the music is well aware of being able to distinguish the different instruments and players. The other aspect of analogy of recorded sound to music, is to make the scientific records audible to the human ear, which in the case of the geodetic pendulums implies a mapping from the records to music. The experiments resulted in a piece of music for pianos that has been successfully performed on stage. Concerning other caves, it could be thought of making also the droplets hearable, temperature variations, water level of the river forming the cave. The transformation to sound allows results to be more effective than the visual graph of a wiggly curve, and adds a dimension in human perception of the tourist visiting the cave, who can use eyes, nose, ear and feeling, only missing taste to use all five senses during the visit to the cave.

ACKNOWLEDGEMENTS

Peter Plessas and Olga Neuwirth are thanked for granting permission to publish an excerpt from the composition "Kloing!" for computer-controlled piano, pianist and video, which was premiered in Weimar (Kunstfest 2008). Giovanni Romeo and Quintilio Taccetti from INGV are thanked for the development of the digital acquisition system of the Grotta Gigante pendulums and the INGV is thanked for the support of the Grotta Gigante geodetic station.

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Audio 1: Sonification of the record of the Sumatra Andaman islands 2004 earthquake of magnitude 9.2. Music by Olga Neuwirth in cooperation with Peter Plessas (IEM – Institut für Elektronische Musik und Akustik, Graz, Austria.). Excerpt from Kloing! The original record of the geodetic pendulums is shown in Fig. 6. Available at: http://www2.units.it/geodin/Neuwirth- Kloing!(Excerpt)_PromotionOnly.mp3