THE WOOD ANDERSON MAGNITUDE OF THE TRIESTE STATION (TRI - NE ITALY): A NEW DATASET

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Introduction. The standard torsion Wood Anderson (WA) seismograph owes its fame to the fact that historically it has been used for the definition of the magnitude of an earthquake (Richter, 1935). With the progress of the technology, digital broadband (BB) seismographs replaced it. However, for historical consistency and homogeneity with the old seismic catalogues, it is still important continuing to compute the so called Wood Anderson magnitude. It has been proven that synthetic seismograms WA equivalent can be simulated convolving the waveforms recorded by a BB instrument with a suitable transfer function.

The seismological station of Trieste (TRI), belonging to the World-Wide Standardized Seismographic Station Network (WWSSN) and sited in Borgo Grotta Gigante, about 12 km out of town, and managed by the National Institute of Oceanography and Experimental Geophysics (OGS), was equipped on September 1971 with two horizontal WA seismometers Lehner-Griffith TS-220 for the computation of local magnitude (Finetti and Morelli, 1972).

However, the start of the WWSS Trieste (code TRI-117 of the global WWSS network) recordings dates back to July 29, 1963. The short-period seismograph comprised three Benioff seismometers, while Ewing-Press seismometers were employed for the teleseismic detection. The recording room was located at the surface (268 m above the sea level) while the seismometers were installed at the bottom (161 m above the sea level) of the Grotta Gigante: a giant cave of the Trieste Karst with its central cavern 107 m high, 65 m wide and 130 m long. The WA instrument was located at the surface in a darkroom. The daily development of the photographic paper required a lot of time, not to mention that the photo paper procedure itself was very expensive. This uncomfortable configuration, along with the progress of the technology, contributed over the time to the abandonment of the WA recording, which occurred in April 1992. In 1995 the station was enhanced by the installation of a very BB Streckeisen STS-1 seismometer at the bottom of the cave.

The WA seismograph, after a period of inactivity, was recovered and modernized by replacing the recording on photographic paper with an electronic device. From December 17, 2002 to the present, with a period of interruption due to the property renovation of the building where it is located (May 2005 - March 2010), the instrument is fully operational and has recorded 783 events till August 9, 2012. Since 2004, next to the WA (few decimeters apart), a Guralp 40-T BB seismometer was installed, with a proper period extended to 60 s. Since then, the following signals have been acquired at the same time: i) the data of the digitized original WA, ii) the data of WA simulated by the BB close to it, and iii) those of the broad band installed at the bottom of the cave.

From April 1992, the WA magnitude (*MAW*) estimates, regularly reported in the seismic station bulletins up to 1992, had no more official publication.

Aim of the present work is twofold: from one side to recover the whole data set of *MAW* values recorded until 2012, and from the other side to verify the WA static magnification *GS*, so that to apply it in the WA simulation from waveforms recorded by broadband (BB) seismometers.

The Wood-Anderson instrument. The WA torsion seismograph, with its natural period of 0.8 s, 0.8 damping and *GS* value equal to 2800, was the instrument with which Richter (1935) defined the local magnitude as:

$$M_L = \log A - \log A_0 + dM \qquad (1)$$

where A is the maximum excursion (mm) of the WA seismograph, A_0 is an empirical function that depends on the epicentral distance of the station, dM is the station-specific corrections factor. The magnitude of an earthquake is the average value of the magnitude calculated separately on each of the two horizontal components (Richter, 1958). Among the different types of magnitude developed afterwards, this magnitude is still a solid reference both for its simple definition and widespread usage worldwide.

The sensor is formed by a copper cylinder with a diameter of 0.2 cm, 3.5 cm long and 0.944 g of weight suspended from a tungsten wire with a diameter of 0.02 mm (Anderson *et al.*, 1925) and immersed in an adjustable magnetic field. A small moving mirror adherent to the cylinder (with an angle of 22.5° respect to the front wall of the frame) reflected incident light, generated by an external bulb lamp, on a fixed spherical mirror (100 cm focal length), fixed on the instrument frame. The light was reflected back by the spherical mirror to the moving one that sent it to sheet of photosensitive paper placed over a rotating drum at one-meter physical distance from the sensor. The optical distance, because the double reflection, was four times greater (4 m). The damping is obtained through the magnetic field in which the cylinder is immersed: when the system is energized, the cylinder moves and generates Foucault currents proportional to its velocity, the resulting magnetic field contrasts that of the permanent magnet and the system is damped. It is possible to set period and idle position of the instrument bending it by the regulation screws situated on the base (changing the gravity component acting on the mass). The construction mechanics of the TS-220 instrument make the assessment of its static magnification very difficult simply from its mechanical characteristics (Uhrhammer *et al.*, 1990). In 1957 Gutenberg obtained, using a vibrating table, a value of 2800 +/- 500 (Gutenberg, 1957; Uhrhammer *et al.*, 1990).

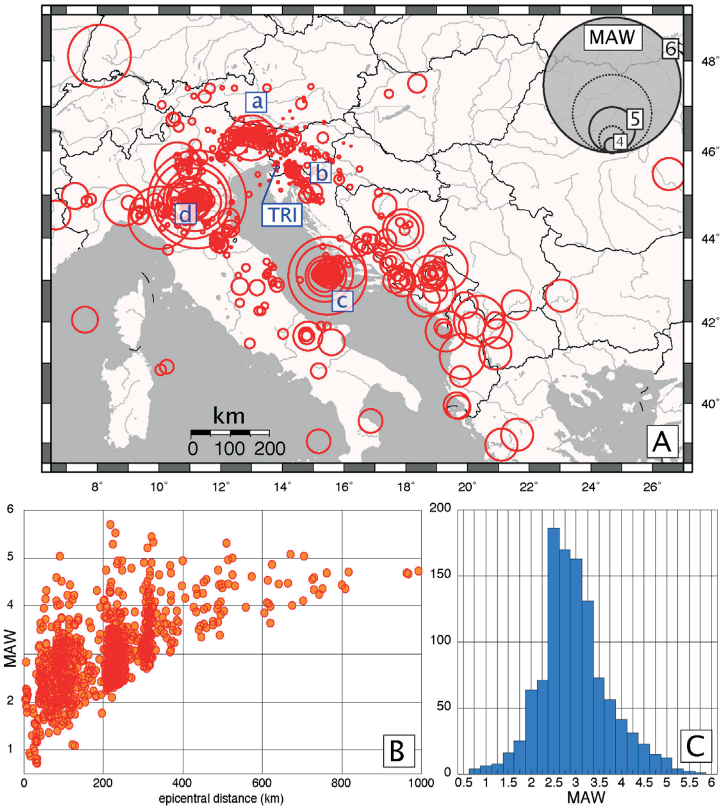


Fig. 1 – Overall data set of 1020 MAWs (circles proportional to the magnitude) recorded by the WA seismograph of the TRI station: A) (a) Friuli region, (b) Dinaric region, (c) Adriatic Sea, (d) Emilia region; B) distribution as function of epicentral distance; C) distribution as magnitude classes (bins equal to 0.25).

The Wood-Anderson instrument digitization and recalibration. The modernization of the instrument consisted in the removal of the fixed cylindrical mirror and its support creating a small side window; through this window a red laser visible beam (Flexpoint model FP-65/5 AE-AW-SD5-GL47, 650 nm wavelength, Power 5 mW) hits the moving mirror and then, once reflected, a Sitek 1L20 position-sensing detector (PSD) few centimeters far from the instrument. By removing the cylindrical mirror the ray undergoes a single reflection changing the optical leverage from 4 to 2 times. The PSD is a 1D semiconductor device sensitive to visible radiation. The sensor has two anodes (Y1 and Y2) and a cathode (bias) and provides an analogue output directly proportional to the position of the spotlight on its surface (20x3 mm of active area). It offers high resolution and linearity: it is enough to stay inside the 80% of his surface to preserve a 0.1% of linearity. The y centroid position measured from the center of the sensor surface is calculated by:

$$y = \frac{y_1 - y_2}{y_1 + y_2} \cdot \frac{L}{2} \qquad (2)$$

where L is the length of the PSD and y_1 and y_2 are the distances of the beam spot from Y_1 and Y_2 respectively. An ON-TRAK OT-301SL amplifier, that provides in output a voltage directly proportional to the beam spot centroid position, drives the PSD. Presently, after an antialiasing filtering, the traces are recorded by a 16 bit system at 100 sps.

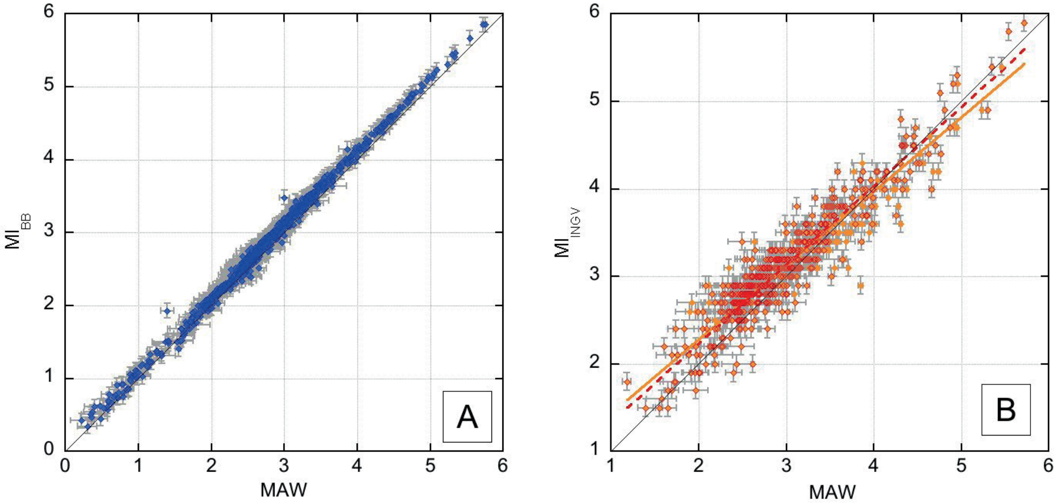
The two Lehner Griffith-TS-220 (N-S and E-W oriented respectively) were disassembled and cleaned, and then they were completely recalibrated. On the base of the two instruments there are two reference marks. Once the period and damping are correctly settled, moving the relative index over one of the two marks, a displacement of 50 mm over the photographic paper is produced. Dividing this value by the resulting number of counts, the sensitivity of the instruments is determined and has to be set in the data acquisition code. In this way we will have in output directly the width in mm of the tracks, equivalent to that we would have on the photographic paper. Tab. 1 reports the parameters for the first calibration operated. A few comments about it are reported in a devoted paragraph in the following.

Tab. 1 – The first calibration results after the new assemblage.

Component	Period (s)	Damping
N-S	0.792	0.787
E-W	0.796	0.818

Data available. First period: 1971-1992. During the period of operation of the original WA (1971-1992), the calculation of the local magnitude was performed following the Richter's formula (Richter, 1935), using the table of corrections factor unmodified from those calibrated for California and without station correction applied (Finetti, 1972). However the WA amplitudes were computed as vector sum (at the same instant of time) rather than as arithmetic average of the horizontal components, resulting in a systematic overestimation.

The TRI monthly paper bulletins reported only the phases recorded, the local magnitude and epicentral distance estimated by the time lag between P and S arrivals. On May 6, 1977 (exactly one year after the Friuli earthquake, whose TRI was the nearest station) OGS activated a stable network of 4 permanent stations that later expanded to cover a large part of Friuli first and north-eastern Italy later. Since 1977, then, OGS has been producing the seismological bulletin of its network. The bulletin locations have also undergone one major revision (Renner, 1995) and a number of minor revisions aimed at correcting the errors and maintaining, as possible, the homogeneity of the data over the years. At present, this bulletin is published in electronic format only, and it is accessible at the INTERNET address "http://www.crs.inogs.it/bollettino/RSFVG/" (complete access data from 1977 to the present).



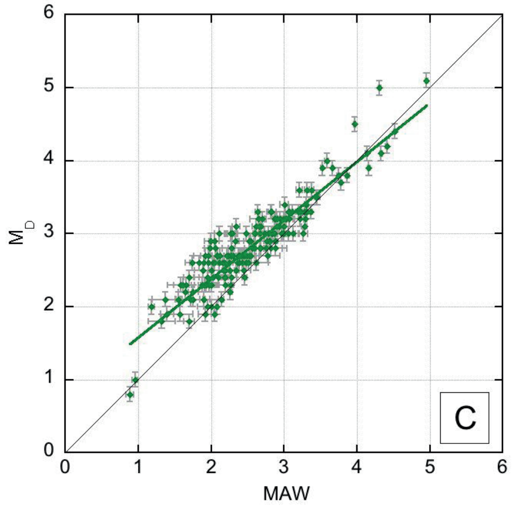


Fig. 2 – Orthogonal regression between *MAW*s and other quantities: a) the *MAW* simulated on the BB via the WA filter *MLBB*; b) M_L published by INGV (*MLINGV*). The earthquakes before April 16, 2005 are reported as red empty diamonds, the next as orange filled diamonds dots; c) M_D provided by OGS from October 31, 2004.

Crossing the TRI catalog with the localized events by the network, we retrieved a data set of 319 instrumentally located events with their *MAW*. As that the discrepancy between a vector length and the arithmetic mean of its projections strongly depends on azimuth, we have retrieved the E-W and N-S components of the original recordings. In fact, knowing the azimuth of the single event with respect to the Trieste station, the *MAW* vector has been resolved with respect to the horizontal (N-S and E-W) directions and then the correct *MAW* has been calculated, as the arithmetic mean of the two values estimated independently for the two horizontal components. The average overestimation of the *MAW* reported in the bulletins with respect to the actual *MAW* is equal to 0.25. The recovered earthquakes are mainly spatially concentrated in two regions: Friuli (a in Fig. 1a), with azimuth centered in the range 300°–330° N, and Dinarides (b in Fig. 1a), with a predominance of less clustered events with azimuth around 120° N. Overall, 56% of the data is placed in azimuthal bands where the two horizontal components have similar amplitude and, consequently, a minimal discrepancy (equal to 0.15) in magnitude computation (mean vs. vectorial composition) is theoretically expected.

To check the validity of the operation done, we selected 30 events of this data set, trying to cover the whole range of magnitudes, we recovered the original photographic sheets with the traces of the earthquakes, and we asked to three experts that were part of the seismological team from the 1970s to the 1990s to re-read the amplitudes of the WA waveforms. Apart from isolated cases, there was substantial agreement among the three specialists confirming a small but noticeable tendency to underestimate the obtained magnitude compared to the original one obtained wrongly by vectorial composition. This little exercise corroborated the opinion that the azimuthally operated recovery of the original WA amplitudes was satisfactory and that the past WA magnitude overestimation of the Trieste station was due to the incorrect method of its calculation (vectorial composition instead of arithmetic mean).

Second period: December 17, 2002 – August 09, 2004. December 17, 2002 marks the beginning of the recordings of the WA digitized seismograph. In this first stage 202 events has been recorded, however, only the magnitude and the epicentral distance have been catalogued. We have considered three location databases to associate to each event their hypocentral coordinates: that of OGS (www, preferred choice), that of the European-Mediterranean Seismological Centre (EMSC; www, second choice), and that of the National Institute of Geophysics and Volcanology [INGV; ISIDe Working Group (2010), last choice].

Moreover, we reported in the working data set the local magnitude provided by INGV, when available. If the difference in magnitude between the computed *MAW* and the *ML* provided by INGV was larger than 1, or the epicentral distances between the locations of the same event presented large discrepancies (greater than 50 km), the records were singularly double-checked, in order to avoid wrong earthquake associations. A total amount of 74 localized events has been retrieved for the time interval December 17, 2002 to August 9, 2004 and are largely clustered in the central Adriatic Sea (c in Fig. 1a).

Third period: October 22, 2004 to May 24, 2005 and March 6, 2010 to August 6, 2012. From October 22, 2004, the WA is placed side by side (at a distance of a few decimeters) to a Guralp 40-T BB seismometer with a period extended to 60 s. The *MAW* list was integrated with the hypocentral coordinates taken from the EMSC and INGV catalogues with the same approach adopted for the previous period. A total amount of 709 earthquakes have been recorded with an interruption in the recordings motivated by the renovation of the building where it is located. The instrument was temporarily moved from its historical site, and the recordings of this time period were discarded because the quality of the data in the temporary location was poor due to the high noise level.

The final catalogue. Putting together the events recorded in the three periods analyzed, a final catalogue of 1102 earthquakes, whose geographical distribution is shown in Fig. 1a, has been assembled. Three main clusters are clearly recognizable also in Fig. 1a and 1b, where the distribution of the earthquakes as a function of epicentral distance is plotted. The events of the first period and recovered from the historical paper bulletins are mostly local, with nearly half of the events in the range between 60 and 100 km, corresponding to the already mentioned area of Friuli (a in Fig. 1a). The cluster of events in central Adriatic Sea (c in Fig. 1a) refers to 80% of the localized events recorded in the second period (digitized WA). Most of the events recorded in the third period (50% in the range between 200 and 240 km) refer to the Emilia seismic sequence, started after the two strong earthquakes on May 20 and 29, 2012 (d in Fig. 1a). As regards the *MAW* distribution (Fig. 1c), the most represented bins are in the range 2.5 - 3.5. There are 14 events with magnitude greater than, or equal to 5, with the maximum value up to 5.7.

Comparative analysis of MAW values. As we have already stated, since 2004, the WA seismometer is placed side by side to a BB seismometer just with the intention to verify the goodness of the WA simulation on it. The WA magnification factor on the BB is set equal to 2800. Orthogonal regression has been performed on the data (Fig. 2a). This kind of approach, allows us taking into account the uncertainties of both magnitude values and achieving more reliable results (Castellaro *et al.*, 2006). The fitting equation is:

$$M_{LBB} = (1.016 \pm 0.004)\, MAW + (0.066 \pm 0.013) \quad R^2 = 0.9961 \qquad (3)$$

where M_{LBB} stands for the local magnitude simulated on the BB via the WA filter. The local magnitudes calculated by the BB seismometer are slightly higher than the actual *MAW*s. For the 833 events considered, on average, the M_{LBB} overestimation is equal to 0.11.

We compared the *MAW*s with the local magnitude provided by INGV M_{LINGV}, the institute that is responsible for the official magnitude publication in Italy (Fig. 2b). There were considered two different data sets and thus two corresponding fitting curves: the data until April 16, 2005 (red empty diamonds in Fig. 2b) are taken from Italian Seismic Bulletin (INGV, 2010), the following data (orange filled diamonds in Fig. 2a) are taken from the Italian Seismological Instrumental and parametric database ISIDe (INGV, 2010). Unfortunately the two data set of magnitudes are not entirely compatible because a mix of duration magnitude *MD* and local magnitude M_L is reported in the first data set while an *ML* simulated from BB recordings is available in the second data set. Considering only the earthquakes recorded after April 16, 2005 (538 events) the fit is:

$$M_{LINGV} = (0.930 \pm 0.007)\, MAW + (0.356 \pm 0.024) \quad R^2 = 0.8874 \qquad (4)$$

Taking into account also the events before April 16, 2005 (680 earthquakes), the fit is:

$$M_{LINGV} = (0.872 \pm 0.006)\, MAW + (0.511 \pm 0.021) \quad R^2 = 0.8743 \qquad (5)$$

The M_{LINGV} are on average higher compared to the MAW. In particular the overestimation (on average equal to 0.17) is more accentuated for events with a magnitude smaller than 3, while for higher magnitudes the difference is slightly reduced (on average it is equal to 0.13.)

As further analysis, we have compared *MAW*s and *MD*s provided by OGS in the time window October 22, 2004 to May 20, 2012, the day of the first strong event of the Emilia seismic sequence (Fig. 2c). The two catalogues have 187 events in common. A fixed uncertainty equal to 0.1 has been assumed on OGS *MD*s (Gentili *et al.*, 2011). The uncertainty on *MAW* was, however, obtained from the amplitude measurements as described in the next paragraph.

The equation of the fit is:

$$M_D = (0.84 \pm 0.01)\, MAW + (0.67 \pm 0.03) \qquad R^2 = 0.8874 \qquad (6)$$

It can be seen that *MD* overestimates *MAW* for low magnitudes, while it tends to underestimate it for high magnitudes. The result is qualitatively similar to that obtained in Gentili *et al.* (2011) comparing the local magnitude with that of duration comparing a set of local magnitude from Bragato and Tento (2005) and Garbin (2009) with the duration magnitude of the OGS bulletin.

Considerations on the WA magnification factor. The WA transfer function, determined empirically, is equivalent to an inertial pendulum with a free period of 0.8 s and damping of 0.8. Regarding the magnification, Anderson and Wood (1925) proposed a static magnification of 2800, which was commonly used since then. Uhrhammer and Collins (1990) and Uhrhammer *et al.* (1996) report a static magnification equal to 2080. According to Uhrhammer and Collins (2011), the difference derives from the wrong assumption by Anderson and Wood (1925) that the wire stretched in suspension used in the sensor WA does not deviate from a straight line. The deformation is actually sufficient to increase the moment of inertia and reduce the static magnification of about 30%. The difference in estimated magnification does not affect the measure of the amplitudes recorded by the original WA sensors, but it becomes crucial when synthetic seismograms are simulated. Using 2800 instead of 2080 in *MAW* estimation may cause an increase of magnitude of 0.129 (Uhrhammer *et al.*, 2011).

We tried to verify the static magnification factor of our WA with two different methods.

The first method involves a direct action on the instrument. According to Wood and Anderson (1925), *GS* is determined by:

$$G_S = A/a = L/l = \frac{A4\pi^2}{gbT_0^2} \qquad (7)$$

where *A* is the seismogram trace amplitude, *a* is the amplitude of the ground motion component normal to the equilibrium plane, *l* is the mass swinging center distance from the rotation axis, *L* is the optical lever length, *g* is the gravity acceleration (981 cm/s^2), acceleration, *b* is the instrument tilt angle (in radiants), and T_0 is its period of oscillation (0.8 s).

Tilting the instruments of a known angle *b* and measuring the output voltage from the PSD, which is proportional to *A*, and applying Eq. (7) we can calculate *GS* (Tab. 2).

Tab. 2 – Parameters used for the WA *GS* computation. *I* = WA seismograph component; *O* = PSD controller output (V); *A* = equivalent trace amplitude on paper (mm).

I	*O* (V)	*A* (mm)	*GS*
N-S	2.00±0.07	45.8 ± 1.6	2092 ± 73
E-W	2.31±0.07	52.9 ± 1.8	2339 ± 82

We must emphasize that the measure made on the N-S component of the instrument is more reliable than the E-W one because the latter was damaged. The moving mirror was partially detached and it was repaired at best with the tools and skills of the OGS technical staff. The total error associated to the estimate is evaluated as an amplifier error, equal to 1%, on the linearity of the response, plus the uncertainty on the voltmeter, equal to 0.05 V.

In order to assess the actual WA *GS*, the second method is based upon a comparative analysis of the data, in particular on the maximum amplitudes (peak to peak) of the seismograms traces, recorded by the two instruments placed side by side. On the BB seismometer we fixed *GS* equal to 2800.

Sliding a window of 50 WA samples on the values of the amplitudes recorded by the BB seismometer, the *GS* values have been calculated as the weighted average of the corresponding ratios (i.e. WA/BB×2800; see Fig. 3a). The uncertainty on the individual measurements was obtained by perturbing the error on the gain of the instrument. We simulated a series of test measurements moving the needle between two notches on the instrument from time to time, which correspond to one theoretical shift of 10 cm on the paper. We therefore measured the average number of counts of the test measures: the gain is the ratio between mm and counts. The standard deviation of the distribution of the test measurements is the error on the gain due to the imprecision in making the movement of the needle. To this, we added a further 1% error on the mean value of the measures of the test due to the amplifier.

The *GS* values decrease with increasing amplitude (Fig. 3a), reaching a value approximately constant in correspondence of 0.2 mm and close to that determined by Uhrhammer and Collins (1990) and equal to 2080. For amplitude values in the range 0.05-0.07 mm it is close to the original 2800 value. The asymptotic values in the two cases are very similar to those obtained with the first method (see Tab. 2). The magnitude estimation is slightly but clearly affected by adopting the theoretical magnification value equal to 2800 (Fig. 3b). If we simulate the WA through a BB seismometer fixing the magnification factor equal to 2800, instead of the real values of Fig. 3 A and B, we introduce an error that depends on the amplitude measured by the instrument, ranging between 0 and 0.13.

Conclusions. The Trieste Wood Anderson seismograph, officially discontinued in 1992, was recovered, modernized and after a decade of interruption, it continues presently to record earthquakes. We recovered the amplitudes of the two components of the past events (319 earthquakes retrieved from the TRI official paper bulletins) and re-computed *MAW* according to the original Richter (1935) formula obtaining a catalogue of 1102 events. The *MAW*s reported in the TRI paper bulletins are, on average, higher than the re-computed ones by 0.25. It has been asked to three experts to re-read the WA waveforms on the original photographic sheets, and we had the confirmation that the past WA magnitude overestimation was due to the wrong method of its calculation: the WA amplitudes were computed as vector sum rather than arithmetic average of the horizontal components.

For comparative purpose, we considered 833 common events recorded also by a Guralp 40-T BB seismometer installed close to the WA instrument. The WA transfer function, according to Anderson and Wood (1925) should have a *GS* value of 2800. As first result the *MAW*s calculated by the BB seismometer are higher than the WA *MAW*s on average 0.11. In order to check the actual WA *GS* value, we considered also a method involving a direct action on the instrument. The result suggests that the *GS* value depends on the waveform amplitude recorded: decreases with increasing amplitude, reaching a value approximately constant in

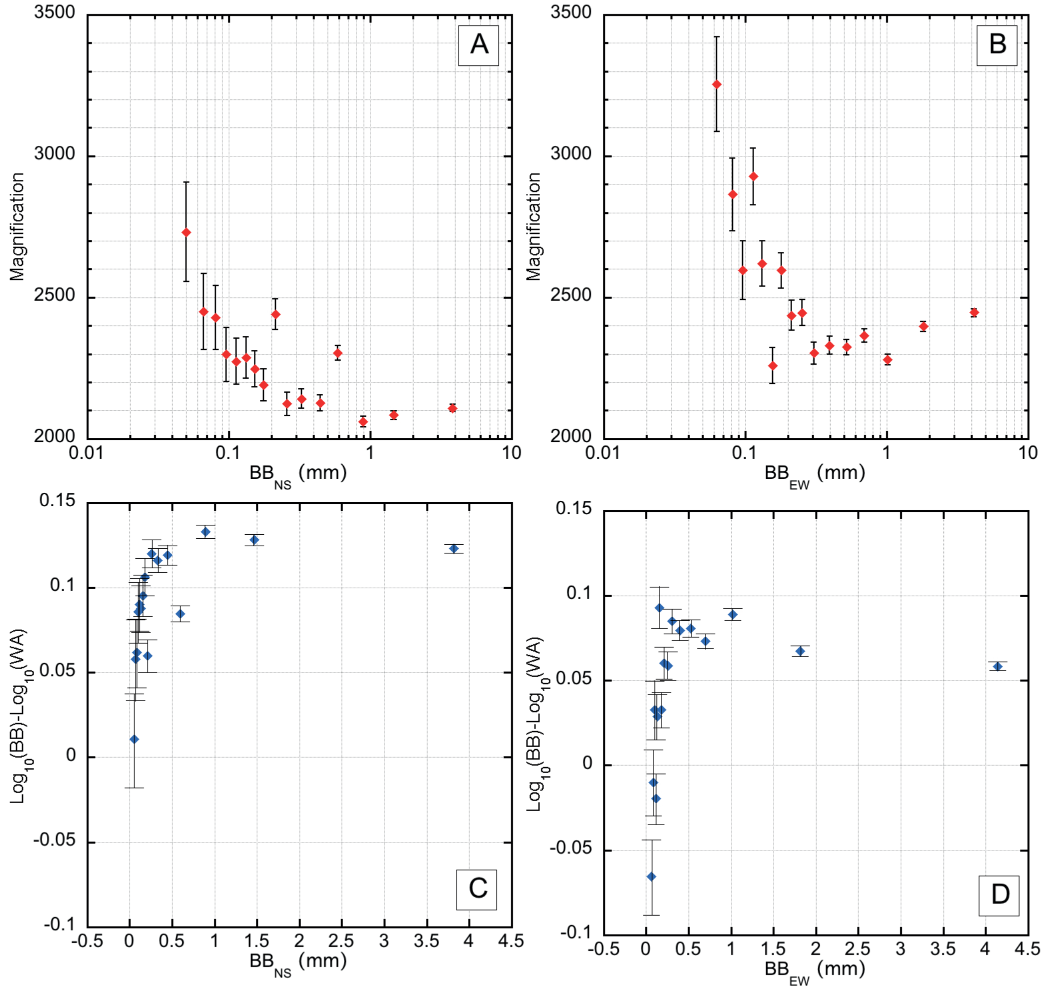


Fig. 3 – Actual WA *GS* as function of the amplitude of the seismograms recorded by the BB seismometer for: A) the N-S and B) the E-W components; uncertainty in the magnitude estimation applying a *GS* equal to 2800 as function of the amplitude of the waveform recorded on C) the N-S and D) the E-W component of the WA.

correspondence of 0.2 mm and close to 2080, i.e. the value determined by Uhrhammer and Collins (1990). For amplitude values in the range 0.05-0.07 mm the *GS* value is close to the original 2800 value proposed by Anderson and Wood (1925).

Our *MAW* values have been compared with the recent *ML* estimates provided by INGV and a good agreement has been obtained. Moreover, a comparison with the *MD* values provided by OGS for its regional network, that was originally calibrated on the TRI *MAW*, has shown an overestimation in agreement with previous a work (Gentili *et al.*, 2011), which reaches values up to 30% for magnitude less than 4.

Acknowledgements. All WA recordings are available at OGS. All the other magnitude and locations data used in this paper came from published sources listed in the references. Fig. 1a was made using the Generic Mapping Tools version 4.5.7 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998).

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