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The role of errors and uncertainties, in strong ground motion parameters, in the achievements of the European Strong Motion database and databank.

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Abstract

A methodology is proposed in order to process reliable and important analog records in such a way to obtain physical displacements in the strong-phase time interval. To test the reliability of such a methodology, strong motion recordings of ground acceleration, obtained from a SMA-1 analog accelerograph, and the one obtained by a digital instrument installed in the same pillar, were analyzed in the time domain. Displacements were obtained by double integration of the acceleration and therefore analyzed. The second part of this paper underlines some possible improvements in collecting, selecting and analyzing statistical data based on strong motion recordings. As an application the original Sabetta and Pugliese database for the ground motion prediction of PGA is investigated. First a databank extension due to new digital measurement events, marked by a bigger accuracy, was implemented. Secondly a better statistical way of dealing such spatial data in ground prediction relations, making use of Geographically Weighted Regression (GWR), is illustrated. As a result a substantial reduction in epistemic uncertainty in relative hazard maps is evidenced.

Keywords: analog records, processing procedures, ground motion prediction, spatial data analysis, GWR

1. Introduction

It is reasonable to assert that ground motion prediction relationship is a field of knowledge in which the availability of new and improved acceleration recordings from destructive seismic events is crucial. New and technically more accurate registrations by means of new processing methodologies and availability of digital recordings could allow database enlargement an enrichment and a potential reduction in epistemic uncertainty. For the European records, results of this analysis were reported in the European research project: “Dissemination of European strong motion data” [1]. It was a result of several research programs financed by the European Commission in the years 1987-2000 and take advantage of a preliminary cooperation between the future partners. Paragraph 2, resume results of this cooperation for the processing methodologies and gives some highlights on recent progress of methodologies developed to baseline correction of digital recordings. Paragraphs 3 and 4, analyze a processing methodology that recover reliable displacements from analogic recordings. Many ground motion relationships are available for Europe (either for the PGA or for the SA) and the ones recorded on the European CD-ROM database seem to have a high level of reliability. Concerning Italy a prediction equation recovered from the ITACA database was developed [2]. However this study does not show satisfying results (see, Sabetta & al.[3]). The use of a huge amount of statistical variables within the so-called strong motion prediction relations could not be a good choice. Some Authors (e.g., Sigbjörnsson & Ambraseys [4]), after developing models based on simplified assumptions (such as Brune source model for shallow strike-slip earthquakes and PGA), found that an increase in variables number can turn into an unexpected increase in standard error of the estimate. A too complex model is likely to fail in predictive ability, as the statistical literature, in overfitting problem, shows. In order to estimate simpler models we collected a consistent database of 234 (99 classified A by EC8 [2]) observations relative to Italian earthquakes (see table 1). To test the stability of these models, the half-splitting method was adopted.

Table 1 Selected Database.

Sabetta & Pugliese [(1)]	Date Hour		M [(3)]	Number of records	Number of records (A on EC8 classification)	logPGA range	Epicentral distance range (Km)
yes	06 May 1976	08:00:00 PM	6.5	8	5	-1.721 ~ -0.48	24 ~ 179
yes	09 May 1976	12:53:00 AM	5.3	3	1	-1.440 ~ -1.090	21 ~ 33
yes	11 May 1976	10:44:00 PM	4.8	4	2	-1.569 ~ -0.520	7 ~ 15
yes	11 September 1976	04:31:00 PM	5.1	4	2	-1.350 ~ -0.640	6 ~ 19
yes	11 September 1976	04:35:00 PM	5.6	6	3	-2.150 ~ -0.635	13 ~ 180
yes	15 September 1976	03:15:00 AM	6	4	1	-1.540 ~ -0.580	14 ~ 38
yes	15 September 1976	04:38:00 AM	4.7	2	0	-1.460 ~ -1.240	13 ~ 17
yes	15 September 1976	09:21:00 AM	5.9	8	4	-1.720 ~ -0.469	10 ~ 101
yes	16 September 1977	11:48:00 PM	5.2	4	3	-0.996 ~ -0.620	4 ~ 13
yes	15 April 1978	11:33:00 PM	5.8	4	2	-1.420 ~ -0.800	14 ~ 37
yes	10 September 1979	09:35:00 PM	5.8	5	2	-1.444 ~ -0.706	5 ~ 45
yes	23 November 1980	06:34:00 PM	6.8	18	2	-1.660 ~ -0.492	21 ~ 145
yes	01 December 1980	07:04:00 PM	4.6	4	1	-1.120 ~ -0.720	5 ~ 7
yes	16 January 1981	12:37:00 AM	4.7	8	0	-1.155 ~ -0.820	5 ~ 9
yes	29 April 1984	05:02:00 AM	5.6	5	4	-1.460 ~ -0.740	16 ~ 50
yes	07 May 1984	05:49:00 PM	5.8	7	2	-1.360 ~ -0.830	15 ~ 53
yes	11 May 1984	10:41:00 AM	5.4	2	1	-1.420 ~ -0.650	2 ~ 27
no	26 September 1997	12:33:00 AM	5.5	8	2	-1.569 ~ -0.330	3 ~ 32
no	26 September 1997	09:40:00 AM	5.9	21	9	-2.155 ~ -0.481	5 ~ 128
no	06 April 2009	01:32:00 AM	6.3	44	24	-3.000 ~ 0	5 ~ 200
no	20 May 2012	02:03:00 AM	5.9	37	17	-2.460 ~ -0.577	17 ~ 111
no	29 May 2012	07:00:00 AM	5.8	28	12	-2.710 ~ -0.650	2 ~ 113

[(1)] *Record in Sabetta & Pugliese dataset*

Two different statistical technique were used, the classical ordinary least squares (OLS) and the Geographically Weighted Regression (GWR) [5], which is essentially an effort to put the emphasis on the spatial differences which occur when considering ground motion recordings. Results were analyzed in paragraphs 5 and 6.

Discussion and conclusions are presented in paragraph 7.

2. Strong motion processing methodologies: A/D conversion

In the early stage of earthquake prediction, a benchmark on records processing was held in Rome, Italy [7]. The idea was set up during a stage at Imperial College and it consists of the following steps: a) drawing a synthetic record (one component) on a film; b) Send a copy to several organizations everywhere in the world; c) compare digitized versions of the record in time and frequency domain; d) base-line corrected records, processed with organizations methodology were compared to evaluate uncertainties. Results were published in a plenary meeting in the ENEA research center of Casaccia (Rome) and in several meetings during seismological conferences [8,9,10,11]: as result of the above activities, digitized versions of analogue records show to be trustable in frequency interval, .1 to 10. Hz. In the automatic A/D conversion made by the ENEA-ENEL joint commission [12] spikes are introduced because of the processing of raw data. Figure 1a gives a pictorial view of the results achieved: the analogue trace of the acceleration component is converted, by the vector of photodiodes, in digital steps, as well as a spurious black dot. Then the operator may misinterpret the acceleration value, generating a spike. Normally, if the spikes are evident, they are eliminated by a processing routine. But sometimes differences are not so large and only comparisons with the original record will help to find the error.

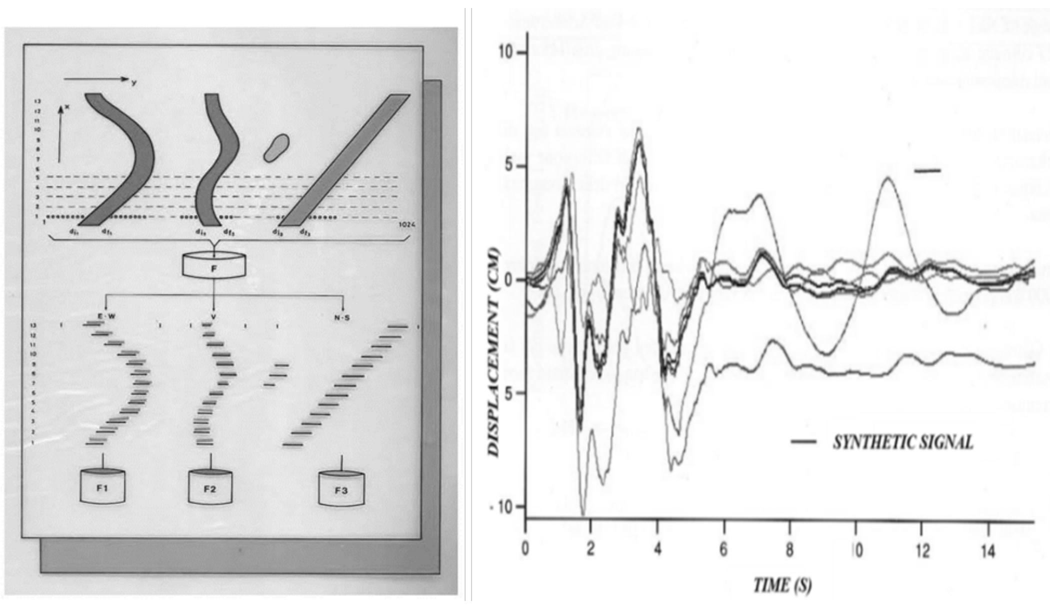

Fig. 1. a)ENEA-ENEL Joint Commission: automatic A/D conversion of accelerometric traces (see Sabetta 1985), b) Displacement obtained by processing the digitized version of the synthetic signal 2 (see Rinaldis, 1985, Rinaldis & al. 1987, Rinaldis & al., 1992, Goula & al., 1994) with methodologies adopted by the participants at the benchmark.

3. Strong motion processing methodologies: A/D conversion

Strong-motion records processing, should be subdivided in methodologies to process analog acceleration records and digital recordings processing methodologies. Results of the above mentioned benchmark were dealing with the uncertainties associated to analog records processing. As reported in a paper analyzing results of processing the synthetic signals [11] all the displacements obtained as result of the methods to correct the digitized versions of the signals, show the efficiency of the treatments to eliminate the spurious low frequency content in the uncorrected signals (if exception is made for unrealistic selection of the high-pass filter). It was concluded that, in real cases, where the real displacement is not known a priori, it is very difficult to reconstruct it reliably (see fig. 1b). More recently the conditions to recover a permanent displacement, from a strong-motion accelerometric record, using the above mentioned methodology were defined [13] : "…, (2) the interval [0,T1] is such that T1 occurs before the P-wave arrival (this obviously cannot be done for analog strong motion accelerographs which do not have pre-event memory) and (3) the interval [T2, T] is long compared to the long period surface and coda waves." The pre-event memory is a buffer where recorded acceleration (analog signals) after A/D conversion are stored, in such a way that N (T/dt=sampling time) samples only, are retained. As stated, one of the main advantages is that, if the record is triggered by the S-waves, a good selection of the buffer size will allow the recovering of the P-waves content, missed. The analog recordings may be processed in a similar way. The third condition needs a reliable post-event. The authors, after estimating the contribution of rotational acceleration, produced a figure (see fig. 6 in [13]) where the spectra, for event of different magnitude, were compared to the contribution of the rotational acceleration and the noise level for several digital instrument and analog accelerograph with associated A/D conversion method. The authors stated that the figure seems to indicate that even for the most accurate digitization the level of noise in analog traces render impossible the recovering of a correct permanent displacement. These arguments were used as well in another paper [14] where several analog time-histories of the acceleration recorded during different seismic events were analyzed. As stated by the authors, all displacement obtained by double integration of the acceleration look unphysical. As shown in the following paragraph, is possible to recover reliable displacements, from analogic recordings, if a correct processing is applied.

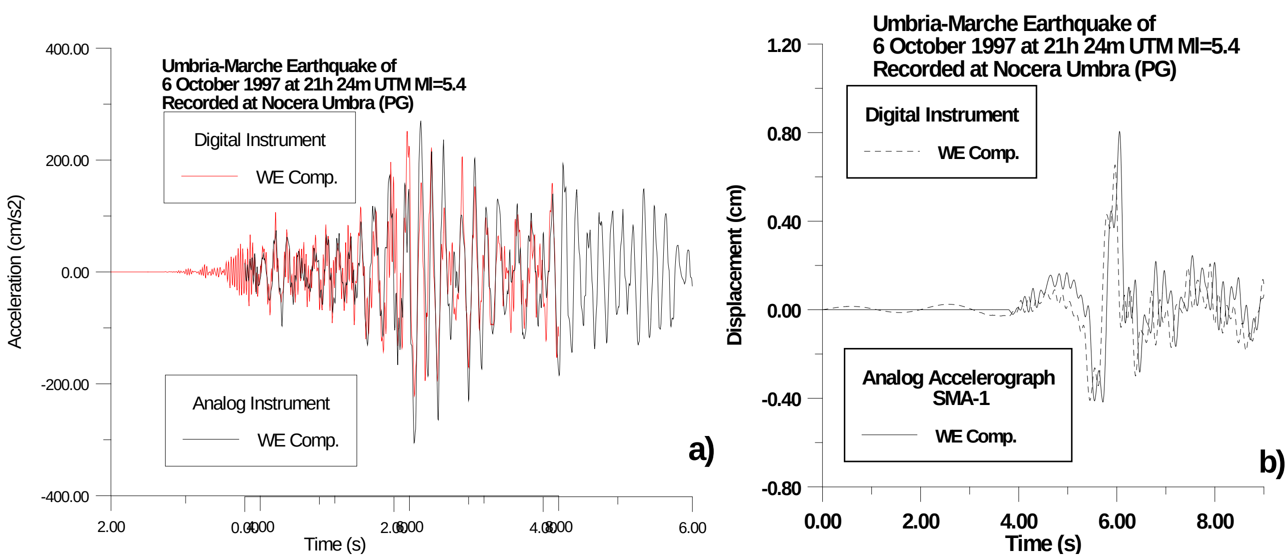

Fig. 2 a)Umbria-Marche Earthquake event of 6th October 1997 at 21:24 UTM, Recorded at Nocera Umbra: zoom of the NS components of acceleration in the time interval between 2 and 8 seconds and between 0 and 6 seconds respectively; b) WE component of displacements at Nocera Umbra after RMS straight line removal.

4. Strong motion processing methodologies: the example of Nocera Umbra analog and digital recordings.

During the Umbria-Marche sequence of 1997, at the station of Nocera Umbra was installed, in the same pillar of an analog accelerograph SMA-1, a digital strong-motion recorder. The instrument recorded several aftershocks the 3rd, 6th, 12th, 14th of October 1997. Those records were processed and integrated twice to obtain the displacement. Figure 2a) shows a comparison between the time-history recovered from the digital instrument and the one obtained from an SMA-1 for the event of the 6th of October 1997: the zoom between 3 and 8 seconds render possible to note very small differences in large part of the strong phase.

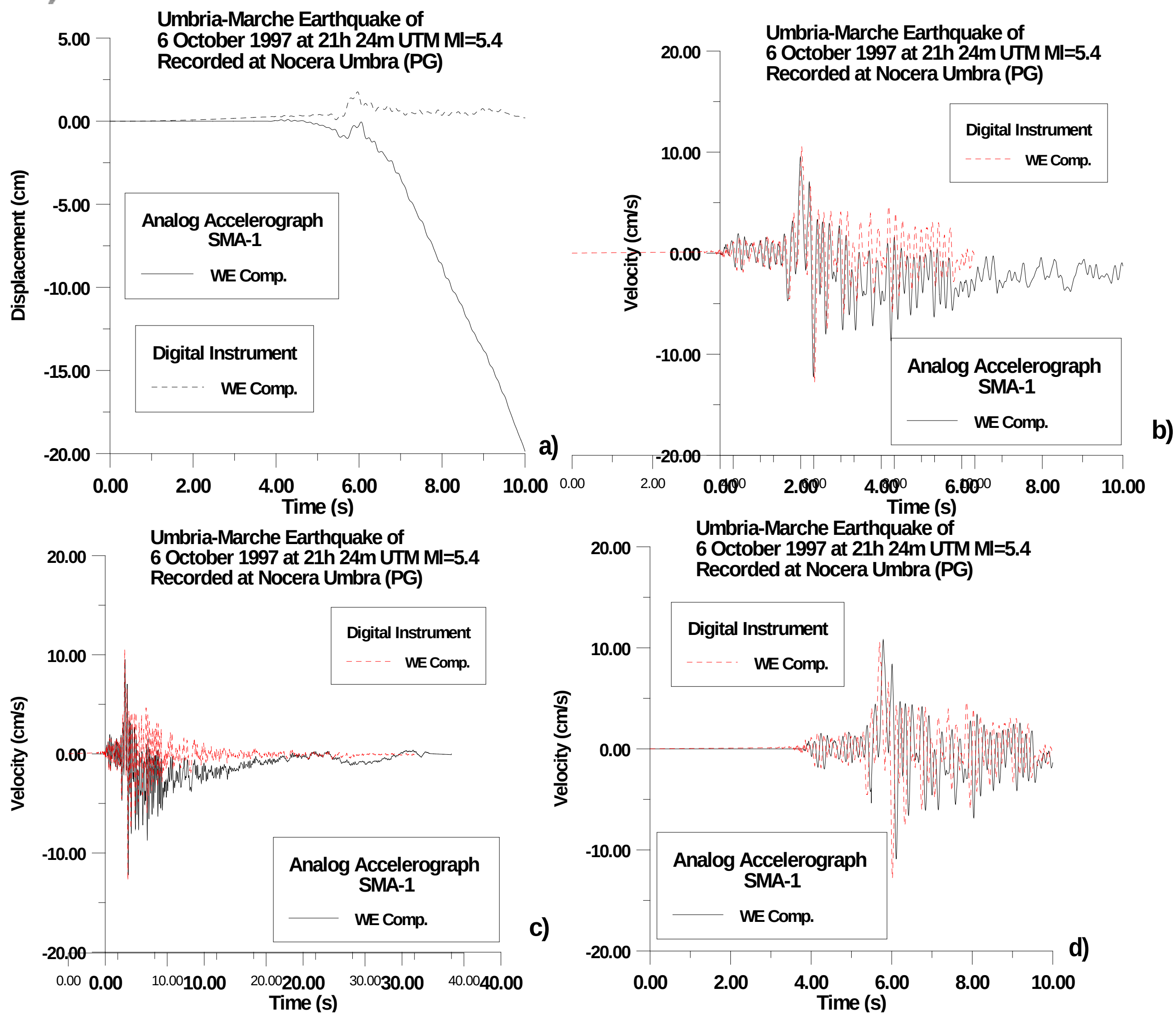

Fig. 3. Comparison between the WE component of the event recorded by a digital instrument and a SMA-1 at the station of Nocera Umbra during the seismic event of 6th October 1997. a) WE component of displacement in the time interval between 0 and 10 seconds; b) velocities between 0 - 10 seconds time interval; c) velocities between 0 - 30 seconds time interval; d) velocities between 0 – 10 seconds after removal of a straight line to minimize the trace RMS.

The record was obtained at 13 Km from the epicenter and, because the event was of Ml=5.4, may be classified as near-field record. The analog record was processed by subtracting the fixed trace, positioned between the WE components and the time-mark and shifted in time in such a way to be synchronized with the one generated by the digital instrument. Then both records were treated in a same way subtracting the mean value and integrated twice to obtain the ground displacement. Figure 3 a) shows both displacement records for the WE component at Nocera Umbra in the time interval between 0 and 10 seconds. The displacement from the analog instrument seems to follow at the beginning the digital one but after 6 seconds grow very fast reaching at the end more than 20 cm. Figure 3 b) show the velocities for the same time-interval in which is clear the discontinuity in the base-line at 2.5 seconds. Further, analyzing the total duration of velocity record it is clear the departure(see figure 3 c). We decided to process the record both by a standard methodology, by means of band-pass filtering the acceleration time-history, and applying the following method: A RMS straight line is fitted to the part of the velocity trace with uncorrected base-line; in effect the fitted straight lines were 3: the first between 2 and 4 seconds; the second between 4 and 12 seconds; the third between 12 and 30 seconds. Segments were selected by visual inspection of the trace. The operation was completed by subtracting the mean value in each segment to be connected. Then the straight line will be removed from the trace and connected with the previous part. Figure 3 d) shows the resulting velocity time-history, for the WE component of the acceleration, compared to the one obtained from the digital instrument, when figure 2 b) shows the corresponding displacement in the 0 to 9 seconds time interval.

5. The Ordinary Least Square as a ground motion prediction relationship.

Our estimate of OLS model is basically an adoption of the Sabetta & Pugliese one [6]. Sabetta & Pugliese model seems to reach requirements to reduction in uncertainty since the standard error of estimate of the logarithm of PGA is quite low (0.1914) and the adjusted R square is sufficiently high (0.709). For its parsimony and good performance this model is the starting point of the present study. The database enlargement since 1996 and the upgrading of the soil classification for some accelerometric stations makes it possible to point out some differences. The equation representing the model is the following:

$$Log\,PGA = a + b\,M + c\,log\left(R^2 + h^2\right)^{\frac{1}{2}} + d\,R \qquad (1)$$

where *a*, *b*, *c*, and *d* stand for intercept, magnitude, geometric attenuation and anelastic attenuation respectively. Nonlinear regression was used to estimate the model in a single step in which the geometric spreading parameter *h* is obtained too by means of an iterative process. A *-1* constraint was previously imposed on *c* parameter, in accordance with the theoretical assumptions. A new attempt to estimate a similar model is presented here. The database consists of 99 observations, relative to seismic events registered in Italy from 1976 to 1984. Only events relative to site named *A* in EC8 classification were taken into consideration. We did not consider in this work any explicit term related to site effect. Tab. 2 shows finally the outcome. The R^2 and the adjusted R^2 are good (respectively equal to 0.723 and 0.714). All of the parameter employed are sufficiently significant (all of them are significant at 0.01 level). The standard error (0.3478) is higher than in the original Sabetta and Pugliese (1987) model (0.1914). At first it could seem a worse adaptation of the equation 1 when extending the records but it is rather due to a much greater standard deviation in the dependent variable in the sample observed (0.653 with the extended databank against 0.355 of the sample with 95 observations). As it is known the impact of the standard deviation of dependent variable (σy) on the standard error of the estimate (*SER*), is direct and expressed as:

$$(SER):\ \sigma_{y,x} = \sigma_y \sqrt{1 - R^2}$$

It is possible to say that a larger SER is rather an aleatory uncertainty increase matter than an epistemic uncertainty one. Another question is related to the original theoretical formulation which includes in the model specification the anelastic term too. In spite of the theory the statistical fit should reject the introduction of both the terms related to distance due to multicollinearity. The only common solution is to ‘sacrifice’ the anelastic term. This practice seems quite unsatisfactory in the light of technological improvement in acquisition. The availability of highly sensitive digital instruments has made possible to possess accelerometric recording at a distance greater than 100 km. just a value which could make this term more valuable [3].

Tab. 2 - Results from OLS regression without epicentral distance term

	Regression coeff.	Std. error	Sig.
Intercept	-0.916505	0.529617	0.0819
Magnitude	0.304725	0.099556	0.0022
Geometric attenuation *	-1.504242	0.099725	0.0000

** Verticality parameter = 5.739*

$R^2 = 0.723$

Adj. $R^2 = 0.714$

Std. error: 0.3478

6. The spatialized approach: the Geographically Weighted Regression.

The Geographically Weighted Regression (GWR) technique [15, 16], implemented by means of the homonymous software 4.0 [5], has been used. The GWR does not aim to simply get an average parameter estimation all over the territory under observation but point-to-point estimates. The rationale behind it is that an explanatory variable can exert different effects in different environmental contexts. So it is possible to measure the sensitivity of one point of the geographical area to a certain ground motion parameter. This is known as *spatially varying variable*, as opposed to the *global* or *fixed* term in the traditional specification (e.g. the OLS regression). In other words instead of estimating one equation the GWR approach tries to estimate one equation each georeferenced point. In doing so an important issue of GWR is just the possibility to create a geographical map of parameters related to the spatially varying variable. Generally speaking GWR model makes it possible to bypass the usual spatial autocorrelation problem rather turning it into a strength point. This technique consists in applying different weights to each observation through an iterative method in order to achieve the maximization of the response of the dependent variable. The weights are bound to geographical location of the observations, so that each observation has bigger influence on the nearest one and less and less on the more distant one. The weighting scheme adopted is a function of the squared distances:

$$w_{ih} = e^{\left(\frac{1}{d_{ij}^2}h^2\right)}$$

where d_{ij} expresses the observed distance between i^{th} and j^{th} observations and h denotes the bandwidth. The bandwidth is a smoothing parameter or, in other words, a continuity parameter among observations. The higher the bandwith the more the GWR regression is similar to the traditional non-spatial one. The lower is the distance the higher is the weight that i observation puts on the j observation.

The general non spatialized OLS expression is the following one :

$$Y(x) = b_0 + \sum_k b_k x_{ij} + e_i$$

The GWR version is the following one:

$$Y(x) = \alpha\ (u_i, v_i) + \sum_k \beta_k (u_i, v_i) x_k + e_i$$

where u_i, v_i are the spatial coordinates of the point of the local term x, while z stands for the global term. Being sourced primarily from social sciences and geographical field of research, GWR technique has met a limited diffusion in earth science. We think that GWR technique is an interesting tool when studying complex phenomena such as those here dealt with. By modulating the effect of a certain variable all over the geographic space, and separating the pure random error from the spatial one, it has the ability to inform about *other* latent variables in addition to the explicitated ones. An important example of *other* variables is related to the previous discussion about the difficulty of inserting the anelastic term in an equation due to collinearity problem. By using GWR it is possible to insert only the geometric attenuation and to see *if* and *how* its regression coefficients describe some regional characteristics. Most of the spatial variation of the epicentral distance term could reflect a *regional geometric attenuation*. This could be a way of solving also the collinearity problem, since we have the chance of using just one term in the equation, related to the distance. Tab. 3 synthesizes the goodness of fit, performing OLS model. The general result is satisfying. The standard error is quite low (0.2895) and the adjusted R^2 value is sensibly higher than OLS model (0.8015 vs. 0.7140). Another important issue of GWR model tested here is its ability to produce residual estimates which are less spatially auto-correlated than the OLS ones (Moran's index = 0.03 vs 0.15). The strength point of GWR model tested here is however the above mentioned ability to *regionalize* the coefficient regression relative to the epicentral distance. A cartographic representation is helpful. Fig. 4 maps the spatially varying regression coefficients. The picture is related to points where, the recording stations collected data and does not represent all the Italian territory. The coefficients sign is negative in all of the observations, accordingly to theoretical assumptions, as reported in legend. The intensity is however different. In this map, from red to blue, warm colors stand for a higher impact and cold colors denote an impact lower than the average.

Tab. 3 - Results from GWR regression (median values)

	Regression coeff.	Std. error	Sig.
Intercept	-0.986551	0.3370	.0000
Magnitude	0.404734	0.0591	.0000
Geometric attenuation *	-1.360390	0.0558	.0028

** Verticality parameter = 5.739*

R^2 = 0.8309

Adj. R^2 = 0.8015

The geometrical attenuation seems to be more relevant in those stations that recorded the 2012 Emilia earthquake and in stations that have recorded seismic events from L'Aquila (2009). At north-west Friuli, which was interested by earthquake in May and September 1976, show a far less value. In other words this map captures five clusters of *regional sensitivity to the distance*. Following this evidence, fig. 5 reports the relationship between distance and PGA for these clusters, in the hypothesis that the other factors be constant. The difference between the extremes, clusters 5 and 1, are put on evidence. Under *coeteris paribus* hypothesis, the ratio of respective values is more than 10 (from 0.022 to 0.0023) when epicentral distance is 5 km. So far it is possible to say that from a statistical point of view the evidences are quite clear, because regional variations occur, but in order to think of these clusters such as five effective pattern of geometrical spread we need to identify and interpret them within a seismological domain. We have underlined the ability of GWR model to include some *other* variables than those explicitly stated. The detection of these other possible factors could help us to explain why spatial variation occur in the PGA estimate. It is a crucial matter but open to interpretation. We could see the spatial variations as spatial error both in the measurement and in the estimate of the original variables or as some spatial discrepancies that the GWR model tends to compensate for. Another class of intepretation is that related to the technical difficulty to obtain the "right" PGA value, expecially in the analogic recordings. A lack of homogeneity which is spatial dependent, for instance because older recordings come from the same geographical area, could be adjusted by GWR.

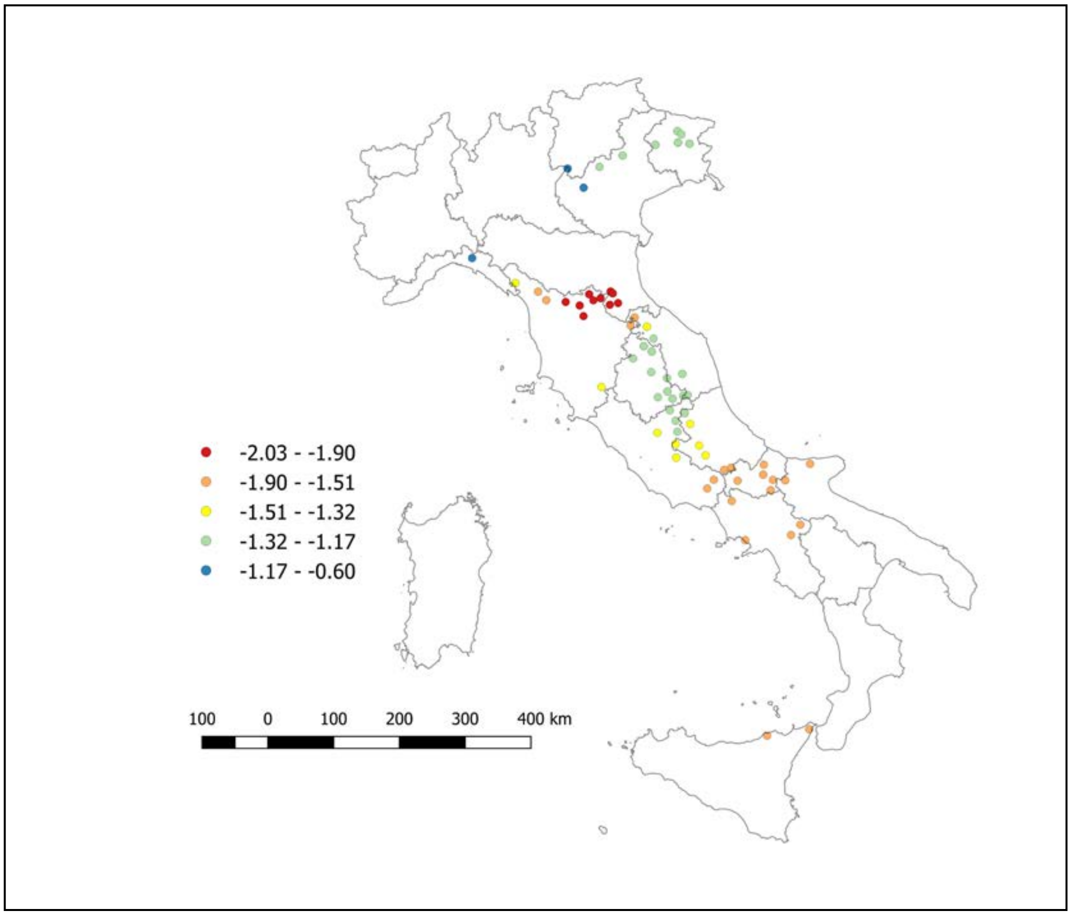

Fig.4 - Map of spatially varying regression coefficients relative to geometric attenuation from GWR model

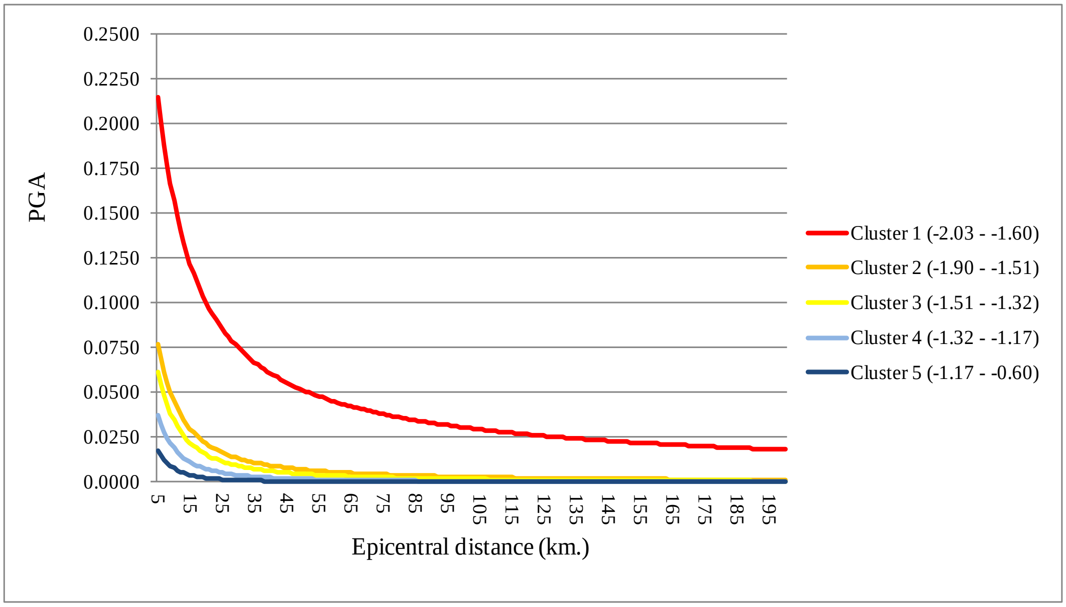

Fig. 5 - Five spatial cluster PGA attenuation curves when regional sensitivity to epicentral distance is considered. Each curve represents the net contribution to PGA logarithm being all of the other factors equal.

7. Discussion and conclusions

As stated the increasing in availability of database and databank do not give an unique answer about the effect on uncertainties on strong ground motion parameters. We analyzed the history in data acquisition and processing when database and databanks were built with analog accelerometric recordings. Results of a benchmark gave the frequency range where the so called uncorrected data may be used and a figure for the processing technique reliability. As consequence of availability of digital recordings, there has been an increasing distrust on data obtained from analog instruments. Displacement from double integration of the accelerometric records were defined unphysical and then all data recorded by analog instrumentation were discarded to this goal. The analysis of the records of Nocera Umbra seems to state that, in some way, very well acquired and processed analogic records may produce a reliable ground displacement. This is true, of course, if the records is processed in a similar way than digital recordings. Considering that 90% of the strong phase is concentrated in this period, the resulting displacement time-history may be considered physical. The analyzed ground prediction model confirm the goodness of fit is higher in GWR model, meaning that parameters significantly vary along the space. Finally a possible new statistical approach is presented such as Geographically Weighted Regression (GWR). As a result when applying to the augmented database the goodness of fit was high. One of the strenght points of this tecnique is the ability to capture the whole spatial variability of the regression coefficients, instead of determining a single one. The GWR model would work better with a homogeneous spatial distribution of events, while the accelerometric recording in our databank is related to a few and quite densely localized events and does not allow us to fully reach this goal. Furthermore not all the stations were activated when the threshold level was not reached. This turns into a certain degree of spatial heterogeneity and in theory could be a trouble. However the GWR model seems to lead to a good results not only by a goodness of fit level but in term of semantic exploration of each strong motion parameter too. In effect the spatially varying regression coefficients show the spatially varying importance of the single parameter, i.e. how PGA locally responds to the same value of distance and magnitude. For instance when a GWR regression coefficient related to epicentral distance is higher within a certain area, other factors being equal, it means that at shortest distances the effect on PGA is higher than other areas. A spatially varying coefficient related to epicentral distance reflects both the anelastic attenuation and the geometrical one. GWR application seems to suggest that the importance of a strong motion parameter can be very different on territory: e.g. the map of spatial parameters for the epicentral distance show high values for recording stations in two geographic areas (border Tuscany – Emilia; Campania – Molise. This means that seismic wave's propagation, in the earth deep layers, is the most important factor in these zones.

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