Exploring the feasibility of an early warning system in a moderate seismicity context: case study of Pyrenees

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SUMMARY
In the frame of the SISPyr project the feasibility of an Earthquake Early Warning system (EEW) covering Pyrenees is being studied. First of all, the analysis of the existing seismic stations shows that the SISPyr real-time network may be used as a base of a Pyrenean EEW despite that some difficulties exist to its implementation that should be solved. The exploration of an important Pyrenean waveforms database has also allowed to highlight that the main real-time magnitude assessment methodologies dedicated to EEW are fully adapted to the Pyrenean context even though the lack of strong-earthquakes' records limits the range of validity of our empirical relations. Finally, we considered the question of the opportunity to put in place an EEW in Pyrenees. As to do that, an analysis of theoretical performances of the system had been performed, completed by the carrying out of a survey, bound to Pyrenean potential end-users.
Keywords: Early-warning, real-time seismology, Pyrenees, France, Spain, SISPyr

1. INTRODUCTION

The massif of Pyrenees, consequence of compressive movement between Iberic and Eurasian tectonic plates and politic border between France and Spain, presents a moderate seismicity responsible of many destructive earthquakes over history, which maximum magnitude could probably reach 6.0-6.5. Thus Pyrenees constitute one of the Spanish and French areas where the seismic hazard is the most important, what have led to the progressive development of seismological forecasting networks around the massif. In this context, the SISPyr Interreg project (www.sispyr.eu) has as principal objective to allow the pooling of Pyrenean seismological data and to improve the massif coverage by the networks favouring the progressive transition to real-time data transfer technologies. In order to make profit of advantages offered by real-time seismology, the SISPyr project also aims at to assess the feasibility of a Pyrenean earthquake early warning system (EEW) (Auclair et al., 2012).

In a first time, we focused on "technical" feasibility aspects. Then, the SISPyr seismic network had been first examined in order to assess its adaptability to early warning purposes. In particular, redundancy issues, network coverage, data processing and time latency of the existing real-time system have been analysed. Then different rapid magnitude determination methodologies have been tested in order 1) to check their adaptability to the Pyrenean context and 2) to establish empirical relationships useful for Pyrenean region. To that end, a waveform catalogue had first been constituted, gathering more than 2.400 records from 193 Pyrenean seismic events.

In a second time, we considered the question of the opportunity to put in place an EEW in Pyrenees. As to do that, an analysis of theoretical performances of the system had been performed: this exercise allowed us to establish approximate levels, for different types of earthquakes, of expected warning delays in the Pyrenees, thus providing a basis to underlie a reflection on how appropriate such a system may be in the zone. Furthermore, this simplified approach can guide definition of potential uses of Pyrenean early-warnings, since they are closely dependant to the time separating warning arrival to the one of destructive seismic-waves. Finally, we carried through a survey, bound to Pyrenean potential end-users in order to evaluate their wishes in terms of EEW.

2. SEISMICITY OF PYRENEES

Pyrenees are a 400-km-long mountain range located in southwest Europe along the French–Spanish border. Pyrenees constitute one of the most earthquakes-prone regions of metropolitan France and Spain, with more than 400 M≥2.0 events per year, whose around ten are locally felt. In spite of their relatively moderate seismic activity compared to other European countries such as Romania and Italy, Pyrenees have historically experienced numerous large events (**Figure** 1.a), including events in 1428, 1660, 1750 and 1967 which reached intensity VIII (MSK) or more. Western part of the massif is characterized by a more marked seismicity activity concentrated along the North-Pyrenean Fault while eastern part area shows a more diffuse seismicity (Souriau et al., 2005). The existence of many events having caused intensity higher than VII (MSK) underlines the necessity to give attention to this area in terms of seismic hazard (Secanell et al., 2008).

3. THE SISPYR SEISMIC NETWORK

3.1. General overview

Pyrenean region disposes of several seismological networks on both sides of the Franco-Spanish border. Among others, four organisms involved in the SISPyr project manage seismic stations in the Massif: the Midi-Pyrénées Observatory and the French geological survey (BRGM) for the French part (with stations belonging to the Seismic Monitoring National Network – RéNaSS, and to the French Permanent Accelerometric network – RAP), and the Spanish and the Catalan seismological surveys (respectively IGN and IGC) for the Spanish part. It is also to notice the presence of a broad-band station in Andorra managed by Andorran Studies Institute (IEA). In all, Pyrenees is covered by around 60 seismic stations (broad-band, and strong-motion sensors taken together). The SISPyr project notably aims at pooling of Pyrenean seismological data monitored by these several networks and to improve the massif coverage. Thus, it is important to notice that the SISPyr has allowed installing a few new stations around the Pyrenean Massif.

In terms of geographic coverage of Pyrenees by stations disposing of a real-time data transmission, it is still relatively limited and heterogeneous. Thus, if Catalonia has ever numerous real-time stations, it is not the case of the remaining Pyrenean territory. In order to overcome this problem in France, numerous stations are progressively called to evolve to a real-time transmission. Moreover, in the frame of the SISPyr project, the real-time data transmission of an important number of additional stations has been done.

3.2. Adaptability of the SISPyr seismic network to early warning purposes

3.2.1 EEW SISPyr's seismic network description

Five different organizations (IGC, IGN, BRGM, OMP and IEA) are the owners of the seismic stations involved in the SISPyr project. At this section this network defined as result of cooperation between partners is described in order to assess its adaptability to early warning purposes.

From the complete station list a group of them can be rejected because they cannot be used to implement an EEW on SISPyr region. At this point we consider 3 reasons to reject a station: out of SISPyr area and far away from it, urban stations because they are too noisy and non real-time continuous streaming stations. Thus, the 29 remaining stations constitute the so-called "EEW SISPyr's seismic network". These stations are represented on **Figure** 1.a, where the SISPyr's area of interest is reported. A deep evaluation of this network is then performed.

3.2.2. Stations overview

In order to implement an EEW, we define 2 distinct categories of technical requirements (Table 3.1):

1. "Basic requirements" are minimum requirements that an EEW must accomplish.
2. "Recommended requirements" are all requirements and considerations that will improve the EEW operation, reliability and efficiency. Even these requirements will not be of a strict and mandatory enforcement; but in fact they can be the difference of having a reliable and effective EEW or a poor one.

Table 3.1. Technical requirements for an EEW seismological network

	Basic Requirements	Recommended Requirements
Seismic sensor	- Should be adequate for monitoring of close-field earthquakes in terms of bandwidth, dynamic range, protection against ambient conditions, etc.	- Redundancy
Data acquisition system	- Should be adequate for the kind of seismic signal to record in terms of bandwidth, sample rate, dynamic range, adequate signal/noise ratios, resolution and local archiving	- Redundancy
Communication systems	- Must be "real-time" - Rugged to support remote site climatic conditions - Adequate for data transmission requirements in terms of bandwidth, SLA and reliability	- Redundancy - Minimum latency - Use of non-terrestrial communication system
Power supply system	- Rugged to support remote site climatic conditions - UPS or equivalent system installed	- Redundancy

All of the basic requirements listed in Table 3.1 are accomplished by most of the SISPyr stations because they are also used at SISPyr partners' Data Centers for "real-time" event detection and seismic alert. To the contrary, recommended requirements are globally not accomplished: in particular, there is not any station with some duplicated or redundant data sensor, data acquisition system, communication system or power supply system. To solve the problem, it is recommended to give redundancy to stations' equipment, especially to communication systems because their vulnerability is higher than the other ones. This redundancy also can be reached increasing stations density to allow some faults tolerance reducing the effect of changes at the station map distribution. In case of big event some terrestrial communication infrastructures could be damaged so if any station uses "only" terrestrial communication systems; it is in risk of losing communication link with Data Center. So, for a real time alert system, it is recommended to use satellite communications system, as it is the case for IGN and IGC-BRGM networks. If this is not possible, another option is to give redundancy to the communications network using different types of communication systems, including different base stations of services providers.

3.2.3. System latency and effective network coverage

A key parameter of the efficiency of any EEW is the notion of "latency": in other words, "coverage" of the seismological network has to be no longer defined by the question "what is the density of seismic stations in a given area?", but rather by "what is the density of seismic records in a given area and at a given instant?". So as to look after the SISPyr's EEW network with this view angle, we first monitored the average time-latency (defined as the delay between seismic signal is recorded at any seismic station and the time when the digitized signal is received at a data-centre) of each considered station over a time-length of 48h. This analysis exhibits that while there is a very variable time-latency from a station to another, 75% of SISPYR stations are associated to < 5s time-latency. Then, the complete system latency time represented by the so-called "warning time" (being the time at which the system is able to produce an alert) will be for a specific hypocenter the result of adding seismic P-waves travel times to the closest stations plus recording time-length, stations latency and data processing time.

Thus, under some hypotheses, this complete system latency may be regionally assessed in order to give ideas about possible benefits of a virtual Pyrenean EEW. Among these hypotheses, the most important one is the minimum number of stations considered to perform the automatic real-time analysis (including detection/location/magnitude assessment/etc.): we decided to vary this value from one (i.e. “onsite” EEW) to four stations. This kind of analysis leads to maps showing time necessary from origin time to be able to send out an alert in function of the epicentre location. As this time is not very explicit in itself, we decided to make it more explicit using the “blind zone” concept (see paragraph 3.2.4. below).

3.2.4. Simulatedl performance analysis

A very important notion in EEW is the one of “blind zone”, which designates the area where warning arrives after the seismic destructive waves (S waves and following surface waves). Thus, blind-zone represents the area in which an EEW is inefficient: its extension depends on many factors such as epicentral location and focal depth of the earthquake, topology of the seismological network, time-latency of close-field stations, fastness of the calculation process, etc.). Considering a typical V_S value of 3.4 $km.s^{-1}$ (Souriau and Pauchet, 1998) and neglecting focal depth, it is then possible to convert maps described in paragraph 3.2.3 into maps showing the extension of blind-zone in function of the epicentre location.

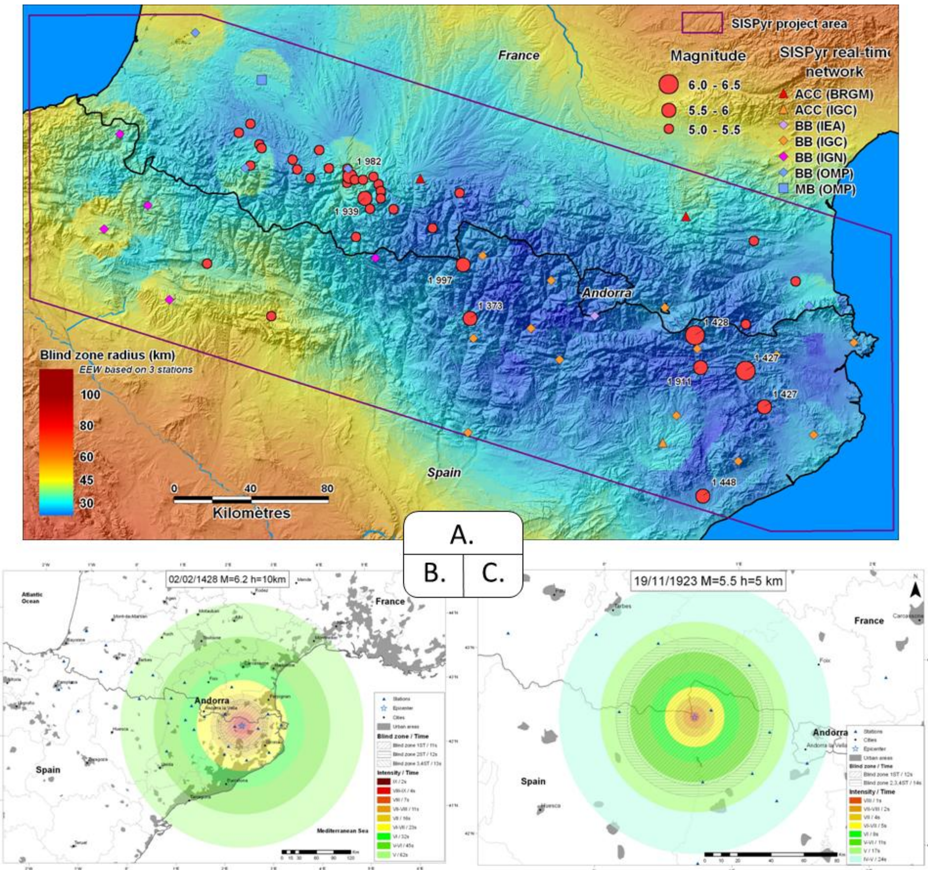

Figure 1. Simulatedl performances of a virtual Pyrenean EEW based on the SISPyr network A. Extension of the blind zone in function of the epicentre location with an EEW using a minimum of 3 stations. SISPyr seismic real-time network is also represented as well as the historical Pyrenean seismicity. B. and C. Intensity attenuation versus extension of the blind zone for scenario earthquakes corresponding respectively to the M6.5-1428 & M5.6-1923 damaging events.

This work has been performed in order to get first deciding factors on the opportunity of such a system in Pyrenees. Results can be either represented as regional maps showing extension of the blind zone in function of the epicentre location (see Figure 2.a), or as specific earthquake scenarios maps thanks to the use of intensity prediction equations (see **Figure** 1.b and 1.c). Coupling a regional approach with a look on historical major Pyrenean earthquakes, Figure 2.a shows that an EEW using a minimum of 3 stations would conduct to radius of blind-zone smaller than or equal to 54 km for 50% of considered past events and to 63 km for a 80% value. This 80% value falls to 41 km when considering a single station, and reaches 68 km considering a minimum of 4 stations. Nevertheless, maps such as **Figure** 1.a also indicate that performances of an EEW based on the SISPyr network would not be homogeneous in whole Pyrenees due to differences on seismic monitoring coverage (considering both spatial coverage and stations' latency). As a consequence, such a system would be much more efficient for earthquakes occurring in the easternPyrenean massif (cf. early warning scenarios shown on **Figure** 1.b and 1.c).

Specific analysis performed on earthquake scenarios (**Figure** 1.b and c) may be extended to regional scale considering that locations of historical events presented on **Figure** 1.a are representative of regional seismicity. Indeed, placing at each of these epicentres virtual earthquakes with magnitudes ranging from 5.0 to 6.5, it is then possible to assess correspondent theoretical isoseists as done on **Figure** 1.bc, and to compare them with warning times in order to deduce associated lead times (time interval between the arrival of the warning and the arrival time of the S waves). In order to interpret this new analysis in an easier way, we represent on **Figure** 2 only results corresponding to percentiles 50 and 80%, considering the VI intensity value as the minimum intensity for which an early warning is of some help.

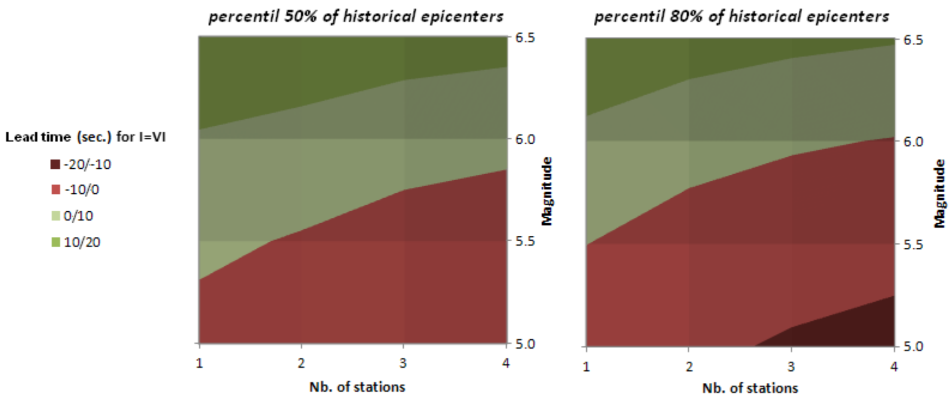

Figure 2. Simulated performance at regional scale of a Pyrenean EEW confronting past seismicity to estimated blind zones' extension. Configurations for which 50% (left) and 80% (right) of historical epicentres lead to positive lead times (i.e. blind zones smaller than isoseist I=VI) are indicated thanks to green colour gradation, while negative values are indicated thanks to red colour gradation.

Figure 2 clearly underlines that, unless to face major earthquake characterized by a broad sinister area like the ones of 1428 on Figure 1.b, performances of an EEW based on the current SISPyr network should – in order to be fully efficient on the whole Massif of Pyrenees – be able to emit alerts from an analysis on a very limited number of stations (1 or 2). Otherwise areas incurring damage (intensities greater than or equal to VI) risk lying within the blind-zone and accordingly could not benefit from early warning. In that cases, lead times of ten or so seconds are expected far from the epicentre, and it is highly probable that, in view of the relatively moderate Pyrenean seismicity, the associated intensities would be fairly weak (IV to VI) and do not justify the implementation of an EEW. It should be borne in mind, however, that besides that fact that these are only preliminary simulations based on robust hypotheses, intensity prediction equations does not take into account potential lithological site effects, which could cause damage at greater epicentral distances, in zones that could benefit from longer early lead times. Furthermore, in zones with better coverage by the real-time network, the lead times will be longer, thereby enabling the extent of blind-zone to be reduced.

Table 4.1. Real-time magnitude proxies' synthetic description.

Param.	Description	Main References
τ_c	Predominant period of the first few seconds of the P wave	Kanamori, 2005
τ_p^{max}	Effective period of the P-wave over a fixed time window	Allen & Kanamori, 2003
P_d/P_v	Peak Displacement/Velocity of the first seconds of the P wave	Wu and Kanamori, 2005 Wurman and others, 2007

4. TESTING METHODOLOGIES FOR RAPID ASSESSMENT OF PYRENEAN EARTHQUAKE STRENGTH

4.1. Tested methodologies

The methodologies selected to be applied in a test stage in Pyrenees are based on the empirical correlation between the well-known τ_c, τ_p^{max}, P_d and P_v parameters calculated on the first seconds of the P-wave (P_v parameter being very similar to P_d) – cf. Table 4.1.

4.2. Data processing and analysis

4.2.1. Waveforms catalogue

To be able to test on the Pyrenees different methodologies for estimating magnitude in real time, a catalogue of seismic signals representative of Pyrenean seismicity had first been compiled. An attempt was made to build a catalogue of waveforms, not statistically representative of seismicity all along the Pyrenean chain, but containing as many records as possible corresponding to all the magnitude ranges to be considered so as best to constrain our regression analyses. While particular attention must be paid to large-magnitude events (the highest probable value being on the order of 6.5) which are liable to produce the most damage, records of more moderate earthquakes should also be included so as to be certain we can distinguish them in the framework of a real-time analysis.

Considering the moderate seismicity that prevails in the Pyrenees and the progressive installation of seismological stations in the range, we have in a first time integrated into the catalogue all available data, regardless of the type of instrument or mode of transmission that was used, so as to have access to a maximum number of seismic traces. Nevertheless, due to the absence of real-time transmission on short-period SISPyr seismic stations and to the lower frequency band of these stations, they have been disregarded in our catalogue. In addition, since the methodologies for estimating magnitude in real time to be tested were based on an analysis of vertical recordings, only this component was considered. In practice, the catalogue is composed of accelerometric and BB records, provided by the various organizations that operate stations in the region (IGN, IGC, OMP, IEA and BRGM). In order to supplement this original catalogue, the RAP-Pyrenees (OMP/BRGM) accelerometric data covering the period 2001-2009 were added, together with additional accelerometric signals contributed by IGC. Finally, the waveform catalogue used in this study is made up of more than 2.400 records corresponding to 193 events with local magnitudes (calculated by IGN) ranging between 2.0 and 5.0 (see **Figure** 3).

4.2.2. Data processing

Firstly, data have been corrected from the instrumental response and then the P-wave arrival manually picked on the unfiltered vertical records. Afterwards, records have been bandpass-filtered between 1 and 50 Hz thanks to a Butterworth filter.

After a simple or double integration process, the peak displacement P_d and velocity and P_v, and the period parameters τ_c and τ_p^{max} are measured from the bandpass-filtered displacement and velocity records over a time window varying between 1 and 4 seconds after the first P-wave arrival. In order to avoid the “contamination” of the analysed time-window with S-wave arrival due to a time interval separating the onsets of the P and S waves shorter than the analysis duration, we reject all the records where P and S arrivals are not far enough apart so as to proceed to compute the various selected parameters. Rather than systematically picking the S-wave onset, we have considered the procedure proposed by Wurman et al. (2007) consisting in merely computing the simulated arrival time for the S waves and retaining only those records in which the interval between P- and S-waves’ arrivals are greater than or equal to the duration of the analysis.

In order to guarantee quality of our analysis, we also reject all the noisy records considering a minimum signal/noise ratio (SNR) equal to 60 for τ_c, 30 for τ_p^{max}, and 10 for peak parameters P_d and P_v. Finally, for the sake of homogeneity, we focalize our analysis on data recorded at a maximum epicentral distance of 100 km, which widely covers the maximum epicentral distance used in case of early warning application.

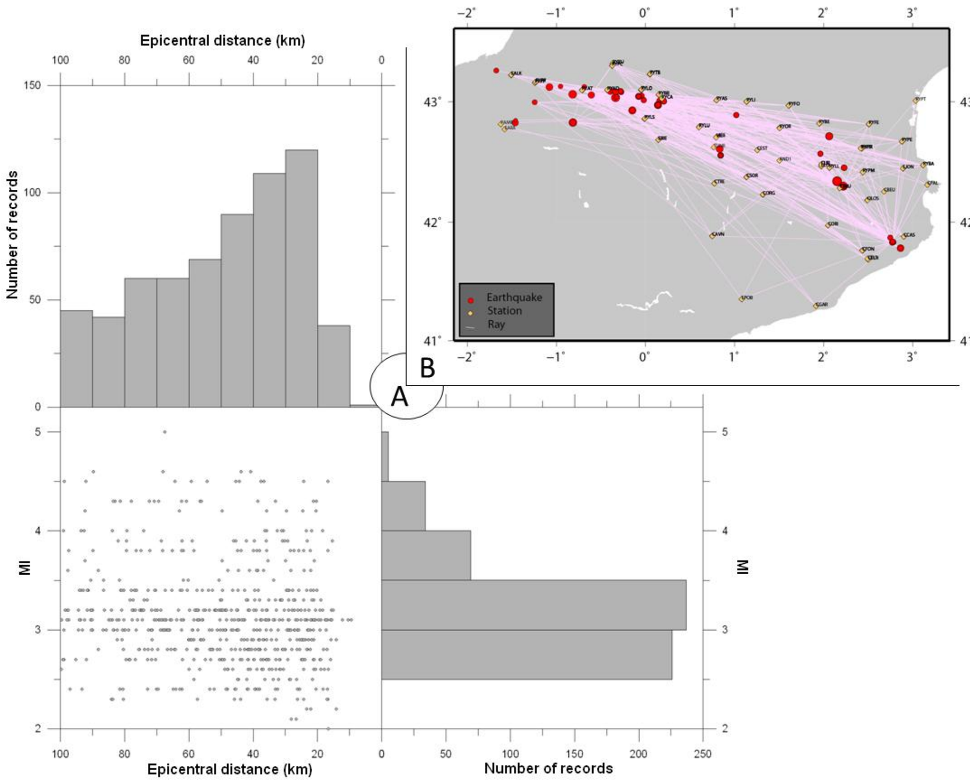

Figure 3. Representation of the study data-set. A. Distribution of the seismic signals versus magnitude and epicentral distance. B. Map of earthquakes included in the catalogue and of corresponding recording seismological stations.

4.2.3. Results

Once the "proxy" parameters of magnitude have been computed on the Pyrenean earthquake waveform catalogue according to the methodology described above, it is possible to compare these parameters with the reference magnitudes in order to try to establish empirical relations enabling magnitude to be estimated in real time from an analysis of the first few seconds of the P wave. The peak parameters P_d and P_v being function not only of magnitude but also of hypocentral distance, we have normalized them to a reference distance (fixed to 10 km) as suggested by Zollo and others (2006) in order to dispense with the dependency on distance. Thus, we can then establish correlations between magnitude and normalized peak values P_d^{10} and P_v^{10}. To reduce scatter as much as possible, it is better to study the values of the parameters under consideration averaged for each event rather than the results obtained station by station (Wu and Kanamori, 2005). To do so, we are not considering a mean of the indicators τ_c, τ_p^{max}, P_d^{10} and P_v^{10}, but rather a mean of their decimal logarithms, which are supposed to be linearly correlated with magnitude. Thus, and to avoid assigning too much weight to certain seismic traces, only those earthquakes for which we have at least two traces satisfying the selection criteria previously presented have been retained for analysis, thereby providing one mean per event. Example of results got with a 3s length time-window analysis are shown on **Figure** 4 while Table 4.2 summarizes all empirical correlations' parameters established for Pyrenees.

From a qualitative standpoint, examining Table 4.2 allows us to emphasize that initial magnitude estimates seem to be able to be derived from a very short analysis interval, which can subsequently be refined in the framework of an evolving approach. For example, shortening the analysis interval from three to two seconds in the instance of a single station situated at the epicentre comes down to decreasing the blind-zone by about 5 km. Moreover, it is very interesting to notice that empirical correlation found for Pyrenees are globally coherent with those ever found in other much more seismic regions of the word.

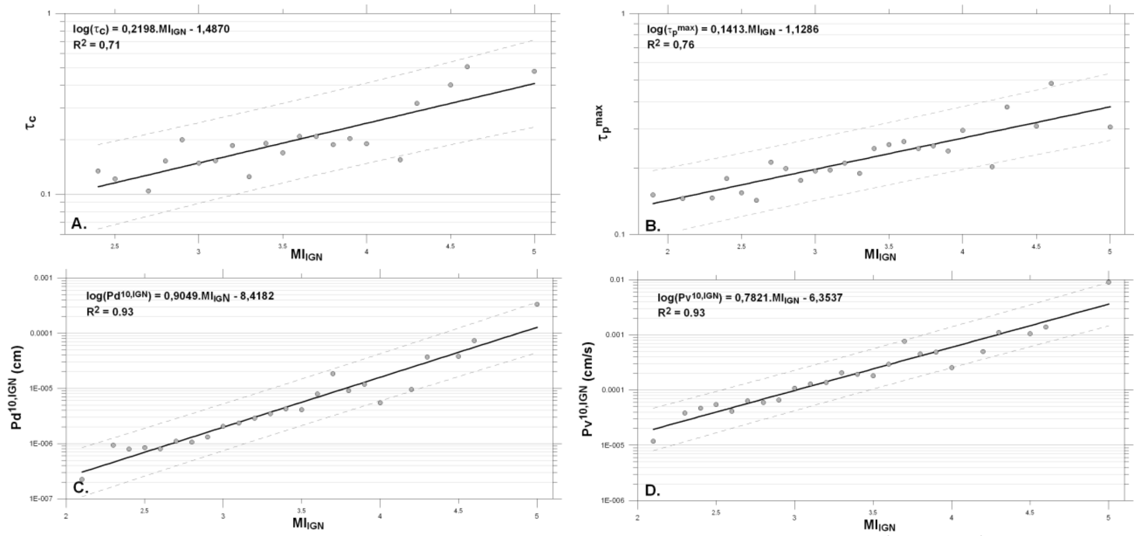

Figure 4 A, B, C and D**.** Empirical correlations linking proxy parameters τ_c, τ_p^{max}, P_d^{10} and P_v^{10} (mean per event) with IGN local magnitude for Pyrenean earthquakes. Calculations carried out on the traces of the catalogue that satisfy the selection criteria (analysis interval set at 3 s). The straight line obtained by linear regression is shown in black, while the grey dashed lines indicate the confidence interval at 95 % for a new observation.

Table 4.2. Summary of the empirical relations obtained for each parameter studied, for different analysis intervals, with a local magnitude IGN. SEc being corrected standard error.

Linear Relation: $\log_{10} y = a + b.Ml_{IGN}$										
y	**Analysis length**	***a***			***b***			**SE_c**	**SE_c (unit mag.)**	**R^2**
τ_c	1 sec	-1.6014	±	0.0689	0.2566	±	0.0198	0.07	0.29	0.88
	2 sec	-1.5267	±	0.0896	0.2326	±	0.0254	0.09	0.38	0.80
	3 sec	-1.4870	±	0.1154	0.2198	±	0.0319	0.10	0.46	0.71
	4 sec	-1.4899	±	0.1142	0.2230	±	0.0316	0.10	0.44	0.72
τ_p^{max}	1 sec	-1.1360	±	0.0611	0.1354	±	0.0178	0.07	0.52	0.72
	2 sec	-1.0750	±	0.0577	0.1246	±	0.0168	0.07	0.53	0.70
	3 sec	-1.1286	±	0.0564	0.1413	±	0.0164	0.07	0.46	0.76
	4 sec	-1.2291	±	0.0875	0.1691	±	0.0248	0.09	0.51	0.69
P_d^{10}	1 sec	-8.6609	±	0.1726	0.9279	±	0.0509	0.21	0.22	0.93
	2 sec	-8.7822	±	0.2049	1.0007	±	0.0604	0.00	0.00	0.92
	3 sec	-8.4182	±	0.1831	0.9049	±	0.0527	0.19	0.21	0.93
	4 sec	-8.4070	±	0.2175	0.8861	±	0.0617	0.21	0.24	0.91
P_v^{10}	1 sec	-6.5038	±	0.1803	0.7849	±	0.0531	0.22	0.28	0.90
	2 sec	-6.6589	±	0.1766	0.8536	±	0.0521	0.00	0.00	0.92
	3 sec	-6.3537	±	0.1582	0.7821	±	0.0455	0.17	0.22	0.93
	4 sec	-6.3027	±	0.1737	0.7377	±	0.0493	0.17	0.23	0.91

Furthermore, it is seen that although each of the parameters τ_c, τ_p^{max}, P_d^{10} and P_v^{10} would seem individually to be closely correlated with earthquake magnitude, some appear to be better proxies than others. Thus, from a statistical standpoint, the most satisfactory proxies are, in order, P_d^{10} and P_v^{10} (which are very similar by nature and cannot be considered as independent parameters), the frequency parameter τ_c, and lastly the frequency parameter τ_p^{max}. However, these different parameters can, to a certain extent, be considered as complementary. Thus, by averaging different magnitude estimations such as one coming from a frequency parameter (τ_c) and another one coming from an amplitude parameter (P_d^{10}), a better estimate of magnitude is obtained with a smaller standard deviation. For example, in the instance of a 3-second analysis interval with a 60 SNR threshold (so as to be able to estimate for each proxy parameter), the standard error associated with the determination of a mean magnitude of τ_c and P_d^{10} estimates is 0.41 for IGN local magnitudes. These results are slightly less good than the ones got with the P_d^{10}/P_v^{10} parameters individually, but should be more robust. This robustness of the τ_c/P_d^{10} combined estimator has been observed on an offline test performed on an Ml 3.9 Pyrenean earthquake occurred on 1st April 2010.

Due to the limited range of magnitudes considered in our analysis, it is not surprising to observe good correlation coefficients for analysis intervals shortened to 1 s (Table 4.2), as the events considered correspond to relatively short rupture times. In other words, the portion of the signal being analysed, however short it may be, bears the signature of most, if not all the rupture, and accordingly of the magnitude. A study by Murphy and Nielsen (2009) showed that a 1-second analysis was long enough to assess moment magnitudes smaller than 6.0 (2s $\rightarrow$ M<6.5; 3s $\rightarrow$ M<7.0). For larger magnitudes, the authors observe a saturation of the proxy being used (Pd). Theoretically, and taking into consideration a probable maximum magnitude of 6.5 for earthquakes in the Pyrenees, a 2-second analysis of the P wave would appear to suffice for determining the magnitude of Pyrenean events in real time.

5. USEFULNESS OF A PYRENEAN EEW

Another very important issue on the evaluation of the feasibility of an EEW in Pyrenees deals with the question of the end-users in order to assess if such a system could answer to an existing need or not. In particular, the question of "How usefully is an early warning for earthquakes associated to high return periods?" is preponderant and strongly linked to the potential end-users' seismic hazard perception. This aspect has been studied through the carrying-out of a survey, bound to Pyrenean potential end-users in order to evaluate their wishes in terms of earthquake early warning.

Rather than conducting our inquiry in an "open" way addressing to the whole of potential end-users, we favour to focalize on actors still well accustomed to crisis management and to the taking of preventive measures (often automatic or semi-automatic actions), represented by the industrial world and the managers of critical networks. Indeed, these actors are likely to be seeker of seismic early warnings and the most apt to act in consequence. In addition, it is important to notice that the operational release of an EEW is generally mainly conditioned by criticality of exposed elements. As a result, our survey has been focalized on a limited number of industrials and managers of critical networks and dams. Selection of targeted industrials and dams managers was done with the help of concerned French regional directions in charge of environment, considering in priority facilities at risks. In addition, this list of addressees has been completed with administrators of electric, gas and high-speed train networks. Given the limited number of identified addressees (around fifty), it has been favoured to mailed-questionnaires a survey based on telephonic interviews.

Results of this survey show a very favourable and enthusiast welcome of the idea of EEW by the French Pyrenean industrials, which seem to be likely to have use of early-warning even in case of moderate earthquakes. This survey also reminds us that for potential end-users of an EEW, it could be useful on condition that it provides reliable warnings associated to long enough warning-times.

6. CONCLUSION AND PERSPECTIVES

Thanks to improvements realized through the SISPyr project on the seismic monitoring of Pyrenees that allows pooling of real-time seismic data, it is now possible to test the feasibility of an EEW covering the Massif in order to emit early warnings few seconds before destructive seismic waves in case of major earthquake in Pyrenees like the 1967 Arette event occurs.

Even though regional EEW usually rely on dedicated seismic networks, a look on the SISPyr's real-time network shows that the existing stations may be used for early warning purposes. However, operational setting up of this type of innovative tool in Pyrenees technically faces to important difficulties due to 1) the moderate seismicity context of Pyrenees implicating strong attenuation of destruction effects with distance that implies that the EEW should be effective at short epicentral distances, and to 2) the current limited coverage of the real-time network as well as to the time-latency of the existing system. Consequently, a possible approach to bypass these issues would be to consider a "hybrid" system that would initially conduct an "onsite" analysis (from a single station) and then make the warning gradually more substantive by means of a regional approach (using several stations). In addition, network improvements would be necessary in order to make it safer, for example implementing redundant systems.

The exploration of an important set of Pyrenean seismic data gathered in the frame of the SISPyr project has also shown that the main real-time magnitude assessment methodologies dedicated to EEW are fully adapted to the Pyrenean context. Thus, it has been possible to establish some reference relations linking empirically different proxy parameters calculated in real-time (so called τ_c, τ_p^{max}, P_d and P_v parameters) to magnitude. Unfortunately, these empirical relations remain limited by their range of validity, which is restricted with respect to magnitude as a consequence of the instrumental data available in Pyrenees. Consequently, even though they exhibit interesting results for moderate events, they cannot be used as they are in case of strong earthquakes as they should. Indeed, while it is important to be able to distinguish in real time between small earthquakes and more powerful ones and, to this effect, have access to relations that are valid for small events, the principle of early warning is only pertinent for large, potentially damaging, magnitudes. As to the Pyrenean massif, the seismotectonic context thus raises the possibility of major earthquakes with magnitudes that could reach 6.5. Accordingly, we need to look into a way to extend the range of validity in magnitude of the relations established earlier, using synthetic records or adapting relations available for other world regions (e.g. Zollo et al., 2010).

Even though setting up of EEW in areas with moderate seismicity context still has to answer to many questions, it seems to be worth to take up this challenge as suggests strong interest of potential end-users. However, this could not be done without a strong implication of these end-users so as to develop a really useful tool adapted to their need, may be halfway between EEW and Rapid Response Systems (RSS) (Goula et al., 2008). Toward concept of "Early Response Systems" for moderate seismicity contexts?

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