Seismic monitoring of an Alpine mountain river

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Abstract

The Canfranc underground laboratory (LSC), excavated under the Central Pyrenees, is mainly devoted to the study of phenomena which needs “cosmic silence”, but also host a geodynamical facility, named Geodyn, which holds an accelerometer, a broad-band seismometer and two high-resolution laser strainmeters. During the routine processing of the seismic data we detected an unusual spectral signature in the 2-10 Hz frequency band, which does not correspond to the typical sources of seismic noise and which can also be recognized in the strain records. After checking against meteorological and hydrological data, we can relate those signals to variations in the discharge by the Aragon River, an Alpine-style river in the southern Pyrenees, located about 400 m from the LSC Geodyn facility. Four main episodes have been identified since early 2011, each lasting 1-2 to 6-8 days. Additionally, a limited number of shorter episodes have also been detected. Three types of river-generated seismic events have been identified, related respectively to moderate rainfall, snowmelt and flooding events associated to severe storms. Each of those types has distinctive characteristics which allow monitoring the hydrological events from the analysis of seismic and deformation data. A few previous studies have already described the seismic noise close to rivers with
larger discharge or in small-scale experimental settings, and we are showing here that
the so-called “fluvial seismology” can be useful to study the hydrological evolution of
Alpine style streams, and may have a potential interest for the civil authorities in charge
of the management of hydrological basins.
1 Introduction

This contribution is focused in documenting how water discharge variations in Alpine mountain streams can be observed and monitored using high-quality seismic and strain stations. Following a pioneering work by Govi et al. (1993), an increasing number of contributions have dealt with variations on the seismic noise related to changes in river flow. The origin of those signals has been associated either to water flow noise due to turbulence, to the impact on the river bed of the bedload particles carried by the stream or to acoustic waves generated by the interaction of water and atmosphere (Schmandt et al., 2013). Hence, a continuous seismic monitoring of river-generated seismic noise can provide significant constraints to hydrologic studies. Seasonal variations in seismic noise levels have been reported along the Trisuli river, a meandering and entrenched river crossing the Himalayas where discharge can reach 500-2000 m$^3$/s (Burtin et al. 2008). Hsu et al. (2011) have described seismic variations associated to large storms (typhoons) in Taiwan resulting in discharge levels ranging 100 to 4000 m$^3$/s. Recently, Schmandt et al. (2013) monitored a large controlled flood experiment in the Grand Canyon dealing with a peak discharge of 1300 m$^3$/s. Working at smaller discharge levels, Burtin et al. (2011) analyzed an Alpine stream with discharges ranging 1 to 5 m$^3$/s by acquiring simultaneously bed load, discharge and seismic measurements during limited summer periods. Our contribution focuses on an intermediate discharge scale, ranging from 2 to 100 m$^3$/s, by analyzing the seismic and deformation signals generated by an Alpine mountain stream, the Aragon River, located in the southern side of the central Pyrenees.
Considering not only seismic but also deformation response to changes of river physical properties is quite unusual (see, among few examples, Steckler et al., 2010 and Tiwari et al., 2014 for ground displacements from water loading). River discharge can be correlated to Earth deformation through elastic response of the crust to loading from flooding and poro-elastic effects due to water infiltration after rainfall, snowmelt, rainfall in the upstream drainage basin, and severe storms. Deformation signatures of different hydrological events (e.g. moderate rainfall) should be identifiable and thus linkable to river dynamics. For example, if a fault system is present, in case of moderate rainfall the higher permeability of the fault gouges with respect to surrounding rock would act as preferential infiltration paths, making pore pressure heterogeneous, while, in case of heavy rain, soil would likely saturate and pore pressure be almost laterally homogeneous.

The Canfranc underground laboratory (LSC), located inside a tunnel excavated in the rock under the Central Pyrenees, is mainly devoted to the study of phenomena which needs “cosmic silence”, as the detection of cosmic neutrinos or “dark matter” particles. As the site is located in one of the most active seismic areas in Western Europe, a geodynamical facility, named Geodyn, has been installed as part of the subterranean laboratory. This installation is intended to record continuously the whole geodynamic spectrum, from near-field seismicity to tectonic deformation, including earth tides and earth-core nutation. The seismic station is active since spring 2011 and includes a Titan accelerometer and a Trillium 240 broad-band sensor with a useful long-period range extended beyond 1000s, low self-noise and wide dynamic range. The accelerometer is scaled to assure that the signal will not saturate in case of a large seismic event close to the station and hence its sensitivity to low energetic events is small. Deformation data is
recorded using two near-orthogonally oriented high-resolution laser strainmeters which can provide precise measurements of the Earth crustal deformation. Both laser interferometers are based on the classical unequal-arm Michelson set-up and compare the optical length of a 70 m long measurement arm with that of a shorter fixed reference arm about 12-cm long. The change of optical length between both arms is related to strain (for a description of similar instruments see Crescentini et al., 1997 and Amoruso and Crescentini, 2009). The azimuths (clockwise from true North) of the two interferometers, referred to as Gal16 and Lab780, are 76° and -32° respectively. Unfortunately, strain data acquisition suffered several breaks, mainly because of power failures during local rain. Two external CGPS stations, one close to the tunnel and a second one used as more distant reference will be available in the next future.

The Geodyn facility is 350 m below the Earth surface and 800 m far from the tunnel entry and hence benefits from a lower level of seismic noise than usual permanent seismic stations, particularly at long periods, more affected by changes in temperature or air circulation. LSC is located in a narrow valley and the Geodyn facility is only 400 m away from the channel of the Aragon River (Figure 1). Meteorological data, including temperature, rainfall and wind measurements are available in the vicinity of the tunnel entrance. The presence of a nearby gauge station, also equipped with meteorological sensors, allows comparing our observations with the changes in water level and discharge in the river. Therefore, the site provides an excellent opportunity to test if significant information on the physical properties of the river can be retrieved from the analysis of the seismic and deformation data. The knowledge of those properties in headwaters is of particular interest for Mediterranean rivers, as their water resources mainly depends on the runoff generation in mountain areas.
The Aragon River, one of the left-hand tributaries of the Ebro, rises at 2050m, 7 km north of our observation point. It points to South for about 30 km until the town of Jaca, where it bends to the West. After merging with the Irati and Arga rivers, it gives waters to the Ebro River 195 km away from its origin. One of the river gauges maintained by the Ebro River Basin Authority (Confederación Hidrológica del Ebro, CHE) is located at about 5 km downstream of the LSC site, providing high rate lectures of water level and discharge. The discharges at this upper-stream location are small, with a mean value of 2.2 m$^3$/s (CHE, http://hercules.cedex.es/anuarioaforos/afo/estaf-datos.asp?indroea=9271). However, snowmelt episodes and severe storms during limited periods in spring and fall result in short-term discharges up to 100 m$^3$/s and can generate floods with a significant economic impact on society. As an example, the cost of the fall 2012 flood has been estimated in about 30 million of Euros, even if only the upper section of the Aragon River was affected severely.

2 Data and signal identification

In seismology, the term “noise” is usually used to design the ground movement not directly related to the arrival of waves generated by earthquakes. During the last decade, with the increasing availability of continuous broad-band seismic records, the study of such noise has become a relevant subject, and it has been shown that noise can provide significant information through the application of specific processing and interpretation techniques, among which we can highlight the retrieval of tomographic images of the lithosphere in regions without local seismicity (Shapiro and Campillo, 2004) or the
global-scale monitoring of the ocean wave height (Bromirski et al., 1999). This progress has been possible thanks to the understanding that different types of seismic sources are responsible for the energy observed in the different bands of the seismic spectrum. The lowest seismic band, with frequencies between 2 and 7 mHz, is dominated by the so-called Earth’s hum, generated by the conversion of storm energy to oceanic infragravity waves in large oceanic basins (Rhie and Romanowicz, 2004). The microseismic band, ranging roughly from 0.04 to 1 Hz, is generated by oceanic waves and comprises most of the seismic energy recorded in absence of large earthquakes (Gutenberg, 1951). The spectrum is dominated by the double-frequency peak, close to 0.2 Hz, associated to the interaction of oceanic waves traveling in opposite directions in open seas (Longuet-Higgins, 1950). The less energetic single-frequency peak, around 0.1 Hz, is classically interpreted as arising from oceanic waves striking the coast (Hasselmann, 1963). Frequencies higher that 10 Hz are dominated by human activities (traffic, industries etc.) even if other natural sources of noise, as blowing winds or rainfall, can also contribute (McNamara and Buland, 2004). Overprinting those relatively continuous signals, earthquakes appear as transient events covering a large part of the spectra.

The raw data recorded at the LSC broad-band seismometer are corrected for the instrument response and converted to acceleration following the usual procedures in seismic processing. As part of the those procedures, the noise levels of the seismic data are routinely checked, revealing a background noise in the lower part of the reference models (Peterson, 1993), thus allowing the detection of small energy features that may otherwise remain obscured. During this inspection procedure we have detected an unusual spectral signature, extending in a frequency band between 2 and 10 Hz, which does not correspond to the typical sources of noise. To better understand it, we
performed a frequency analysis of the signal, to obtain its power spectral density (PSD), an estimator of how the power or energy of the signal is distributed over the different frequencies. Figure 2c shows the obtained spectrograms, in which the color scale denotes the PSD, expressed in dB/(m²/s⁴), for the different frequencies and days of each investigated year. If we focus on the 2-10 Hz band, it can be clearly stated that high levels of energy (reddish colors) are not constant over time, but are rather limited to several time intervals each lasting 1-2 to 6-8 days during spring and fall seasons. A limited number of shorter (less than a day) episodes spread all around the year have also been identified. We have inspected the accelerometer data, but its sensitivity, scaled to assure unclipped data in case of large seismic events close to the station, is not enough to detect the signals here discussed.

As a first hypothesis, we suspected that those episodes could be directly related to meteorological phenomena, as it is well known that meteorological perturbations may affect the seismic record (McNamara and Buland, 2004). To explore this link, we recovered data from a meteorological station located in the vicinity of the Canfranc tunnel. Two parameters were inspected, the wind speed and the amount of rainfall. Wind can strongly affect the seismic noise, in particular in wooden areas as the movement of the trees is easily transferred to the soil. However, in this case there is no correlation between the wind speed and the seismic noise variation in the 2-10 Hz band. This is not surprising as the seismic station is located underground and the noise produced by the trees movement typically decays very quickly with distance. The recorded rainfall (Figure 2, upper panel) has an overall correlation with the seismic episodes, but the details of the seismic noise variation are not properly reproduced; significant rain is recorded some time before the seismic noisy intervals, but many of
the rainy days are not followed by relevant seismic signatures. We have then recovered flow measurements from the river gauge station A271 located 5 km south from our site, downstream of the small Canfranc reservoir (capacity: 3 hm$^3$, surface: 6 Ha). This station provides discharge, water level and rainfall measurements every 15 min, allowing a detailed comparison with seismic data. As it can be observed in Figure 2, the correlation between discharge and seismic amplitude in the 2-10 Hz band is very clear. Note that the river flood episodes are not directly related to the local precipitation, as the river is sensitive to the precipitation fall in all the catchment area.

The clear correlation between the anomalous seismic noise levels in the 2-10 Hz frequency band and the variations of the discharge in the Aragon River clearly suggest a direct relationship between both features. After 36 months of observations, it seems clear that the long-duration episodes occur in the spring and the fall seasons, clearly pointing to a direct relationship with river flow increments due respectively to snowmelt and large storms. Shorter episodes of seismic noise, usually not exceeding some hours of duration and involving a limited amount of energy, have been identified and related to moderate rainfall events, often with a very scarce effect on the river’s discharge. As it will be discussed in the next section, each of those phenomena (rain, snowmelt, large storms) results in a characteristic pattern of the spectral content of the seismic signal, and some of them have also been identified in the strain data recorded by the laser interferometers.

2.1 Moderate Rainfall episodes
We will first discuss the signature of the short-duration episodes of noise increase which appear in Figure 2 as thin green lines crossing the 2 to 10 Hz band of the spectra. A close inspection of the dataset shows that those episodes are coincident in time with moderate rainfall events and thus both processes can be related. We have chosen a representative episode of moderate rainfall in late November 2012 (see gray arrow in Figure 2), but similar features can be observed spread over the whole year. During this particular episode, lasting for 10-12 hours, a total amount close to 25 mm accumulated in the pluviometer of the gauge station. The vertical seismic acceleration band-pass filtered between 2 and 8 Hz (Figure 3a, upper panel) shows a clear increase of energy associated to this rainfall episode, beginning day 26/11/2012 (Julian day 331) after 6 AM and lasting for about 21 hours. Figure 3b compares the rainfall measures (green line) with the envelope of the vertical seismic acceleration (black line) and the discharge at the gauge station (red line). The first peak on the discharge (25/11/2012, 18:00) does not correlate either with the rainfall measurement or with the seismic signal, as it is probably related to a reservoir management action. During the rainfall episode, it can be observed that the increment in seismic noise is not coeval with the rainfall, starting about 4 hours after. The discharge level starts to increase at the same moment than the seismic noise, reaching a maximum value close to 3 m$^3$/s and then decreasing to the usual values close to 1 m$^3$/s about 20 hours later. The rain episode also induced a deformation recorded by the two interferometers (bottom panel of Figure 3a), resulting in extension along Gal16, oriented WSW/ENE, and compression for Lab780, oriented NNW/SSE.

To extract the maximum information from the seismic records we work in the frequential domain (Figure 3c) in order to investigate the distribution among the
different frequency bands of the seismic energy. In this case, the signal is divided in 20
minutes long windows with a 30% of overlapping to calculate the PSD estimator using
standard routines. The final image uses a color scale to present the level of energy in dB
for each frequency and instant of time. The rainfall episode is clearly identified by
increased levels of energy compared to the previous days. The maximum levels of
energy are located in the 2.5-5 Hz frequency band, even if energy spreads up to 8-10
Hz. The spectral content of the signal does not remain uniform along the episode, as the
frequency carrying the maximum energy (from now on referred as “dominant
frequency”) shows clear variations. At the beginning of the episode this dominant
frequency is close to 4 Hz, but in the next 3 hours it shifts down to reach 2.8 Hz. At this
moment the energy is maximum and a secondary high-energetic frequency can be
identified at 4.5 Hz. Later on, the dominant frequency inverts its variation sense and
starts to shift up, reaching its initial value, close to 4 Hz, 9 hours after the beginning of
the episode. Anomalous levels of energy around 4 Hz are still observed for 9 additional
hours for a total duration close to 21 hours. It can be noted than a secondary signature
can be detected between 6 and 8.5 Hz, showing temporal changes in its frequential
content consistent with those expected for a high mode of the main signal.

The comparison between rainfall measurements (green line) and seismic amplitude
(black line) shows that rain, starting 4 hours prior to the onset of the seismic energy
increase, is not directly responsible for the observed seismic noise. Rainfall is
significant for about 10-12 hours, while the seismic noise last up to 21 hours confirming
this lack of direct relationship. On the other hand, seismic noise and discharge have a
good correlation, suggesting that the observed seismic noise is related to the increase in
the river discharge after some hours of continuous rainfall. The strain records for
moderate rainfall events systematically show opposite deformations in the two interferometers.

2.2 Snowmelt episodes

Figure 2c allows identifying periods of noise increase in the 2-10 Hz band during the spring seasons of 2011 and 2012. Those periods are clearly related to discharge increases but do not show a good correlation with rainfall episodes. Being located in the upper section of a Pyrenean river, we explored the possible correlation of those periods with flow increases related to snowmelt. The Spanish ministry of Agriculture, Food and Environment has an ongoing program, named ERHIN, to evaluate the water resources from snowfalls at the different river basins (http://www.magrama.gob.es/ca/agua/temas/evaluacion-de-los-recursos-hidricos/ERHIN/default.aspx). This program provides a detailed estimation of the time evolution of the water accumulated in Pyrenean rivers catchment areas, based on thermal, hydrological and topography data and using classical deterministic hydrologic models and snowmelt simulation routines similar to those used by the U.S. National Weather Service River Forecast System (Anderson, 1973). For the Aragon River, this estimation encompasses the resources stock in the whole basin and not only in the main valley, but still provides a good approximation to the local snowmelt evolution upstream of our station. In a typical year, snowmelt in the Aragon river basin is mostly concentrated from mid-April to the end of May. The snow resources change during this period from 90 to less that 20 hm³. Both the 2010-11 and the 2011-12 seasons have been dry, with a snow volume less than 50% of the mean values for the previous 5 years in 2011 and just reaching 30% in 2012. During spring 2011, the snowmelt started at the
beginning of April and was almost finished 10 days later (inset in Figure 4). During spring 2012 the main snowmelt occurred in two stages from late April to mid May. Those episodes clearly correlate with the energy increases in the 2-10 Hz band identified in the seismic signal (Figure 2).

As in the previous case of rainfall, we have inspected in detail the seismic features observed during those periods. We will discuss here the 2011 snowmelt episode, most of its properties being common with the 2012 one. The first observation is the characteristic pattern detected in the vertical component of the seismic acceleration, once band-pass filtered between 2 and 8 Hz. An energy increase starting at about 14:00 GMT is clearly identified, remaining at a relatively high level for 12 hours and then smoothly vanishing (Figure 4a). This cycling lasts for 8 days, from 3rd to 10th of April (Julian dates 93-101) and matches the snowmelt period deduced from hydrographic models (see insert in Figure 4c). Note that the cycle is perturbed during the first two days by a large coeval rainfall episode, with an accumulated precipitation close to 13 mm (green line in Figure 4b). The discharge after this rain episode (red line in Figure 4b) increases suddenly to large values exceeding 15 m³/s, probably because the rain was more intense in the upper mountain range than in the vicinity of the gauge station pluviometer.

The spectrogram (Figure 4c) clearly reflects the imprint of the snowmelt cycle in the seismic records and reveals richer information than the simple analysis of the seismic amplitude, as clear variations in the frequency content can be detected during the time intervals in which the amplitude of the seismic signal remains constant. The dominant frequency shows a V-shaped pattern; each daily cycle starts around 14:00 GMT with a
dominant frequency initially located at 5 Hz, shifting down quickly to 2.8 Hz and reaching again 5 Hz at 6:00 GMT on the following day. Higher-than-usual energy levels are observed beneath this dominant frequency, also drawing a V-shaped pattern and extending down till frequencies of 2.2 Hz. After 18:00 GMT, the dominant frequency continues to increase till 8-9 Hz with clearly lower energy to finally become undetectable during about 2 hours and then starting a new diurnal cycle. The rainfall on day 093 disturbs this pattern: the frequency reaches a lower value of 1.6 Hz and the branch with increasing dominant frequency is not observed. The usual cycle is recovered one day later. The discharges during the snowmelt show also a daily cycle, at least for days 96 and 97 (Figure 4b). The higher values, close to 9 m$^3$/s are recorded from 21:00 to 02:00 GMT, within the periods of minimal dominant frequency in the seismic records, while values close to 5 m$^3$/s are recorded during the rest of the daily cycle. Note that these discharge levels related to snowmelt are three times larger than in the previously analyzed moderate rainfall episode. The seismic amplitude increases before the discharge and remains at high level during more time than it.

2.3 Severe storm episode

The upper section of the Aragon River is regularly affected by flood episodes, in particular during fall season, related to severe storms over the area. During fall 2012 the region was affected by an exceptional rainfall and hydrological event, estimated to have been the most extreme recorded instrumentally in the southern side of the Pyrenees (Serrano-Muela et al., 2013). As an example, the Yesa reservoir, located 60 km downstream, increased its water storage from 100 to 300 hm$^3$ (16% to 53%) in just 3
days. This flood episode has had a significant economic impact at regional scale, including destruction of urban areas and main roads, landslides and soil erosion.

The episode started around 12:00 on 19th October 2012 (Julian day 293), lasted for about 36 hours and was clearly recorded by the seismic instruments (Figure 2 and Figure 5a). Three distinct periods of rainfall can be discriminated, with a total amount of precipitation close to 230 mm (green line in Figure 5b). The first burst was the most important one, with accumulated precipitation exceeding 100 mm during a 5 hours interval beginning at 14:00 on 19th October. After a period with lower rain intensity, a second burst starts near midnight, with lower peak intensities but lasting more than 12 hours. After a rest period of about 3 hours, the last rain episode started around 16:00 and ended 6 hours later. Both the discharge and the envelope of the vertical acceleration (red and black lines in Figure 5b) follow the rain intensity variations with a delay close to 3 hours. The discharge reaches peaks between 70 and 100 m$^3$/s after the three rainfall burst and remains higher than usual for more than 6 days. The amplitude of the filtered seismic signal is now 3 times higher than in the snowmelt case. The spectrogram shows a greater complexity than in the previous cases, with high levels of energy in a wide range of frequencies extending from 1.5 to the upper limit resolvable by our data, 50 Hz (Figure 5c).

Three bands of energy can be identified;

i) The lower one, between 1.5 and 2.25 Hz shows a time variation of the dominant frequency, which follows the variations in the discharge. Peak discharge periods correspond to frequencies of 2-2.25 Hz, while the intervals with smaller discharge correlates with lower dominant frequencies close to 1.5 Hz. During the coda of the
episode, as the river discharge comes back slowly to its base level, the correlation between discharge and dominant frequency reverts to the situation described for moderate rain and snowmelt episodes, with the frequency shifting up as discharge vanish. From day 296 on, the observation of a relative high energy band shifting from 1 to 3-4 Hz suggests that a signal may exist at frequencies beneath 1 Hz. However, the large levels of energy beneath 1 Hz, associated to the microseismic peak, mask any other effects and prevent us to assess this point.

ii) An intermediate frequency band with higher energy can be identified between 2.5 and 6 Hz. In this case, the seismic energy is uniformly distributed over the whole frequency band, but its level changes following again the discharge variations. During the periods with high discharge, energy levels are around -125 dB, with a maximum of -120 dB coeval with the discharge peak near 17:00 on 19th October. Time periods between the three discharge episodes have energy levels around -130 dB, still significantly higher that the base value. During 21st October (Julian day 295), once the rain is over and the river comes back to its usual state, the width of this band progressively narrows, till focusing around 4 Hz by the afternoon of day 295. Later on, the dominant frequency starts to increase, miming what has been described for the lower band.

iii) The upper frequency band ranges from 10-12 Hz to the uppermost frequencies resolvable by our data, 50 Hz. It is separated from the previous one by an intermediate zone (6-10 Hz) with lower levels of energy, in particular during the periods with smaller discharge. The high energy interval in the afternoon of day 293 is also clearly identified in this band. The main difference with the previous band is observed after the last
discharge burst. In this case, the energy decreases uniformly to reach the base values (< -135 db) near midday, October 21, without any evidence of the narrowing effect described on the previous case.

Regarding strain data, Lab780 shows a large crustal extension (Figure 5a). Unfortunately, Gal16 data are not available for this event because of a power failure. However, the records for other rain episodes with daily accumulations close to 100 mm show extension on both instruments, with Gal16 extension larger than Lab780 one (Figure 6).

4 Discussion

The seismic noise variations associated to variations in the discharges on rivers has previously been explained by the impact on the river bed of the bedload particles carried by the stream, by the direct effect of the turbulence induced by the stream or by the joint effect of the two processes (Burtin et al., 2011), both generating elastic waves observable by nearby seismometers. In a recent contribution, Schmandt et al. (2013) suggested that the acoustic waves generated by the river flood may also contribute to the increase in seismic noise as a result of air-earth coupling. Discriminating among those origins is not easy, but a number of indicators are available.

One of the criteria used is to investigate the presence or not of hysteresis, a retardation of the effect when the forces acting upon a body are changed. In our case, hysteresis appears if the amplitudes of seismic waves for a given discharge are different on the rising and falling limbs. Hysteresis between stream discharge and transported sediment...
is commonly observed in sediment rating curves, suggesting that if hysteresis is observed on seismic data, the origin of the noise can be related to variations in the bedload transport; the depletion of the sediment supply to the end of the event will result in less seismic noise in the falling limb. Analyzing the Himalayan Trisuli River, Burtin et al. (2008) have observed clockwise hysteresis cycles between seismic amplitudes and discharge which they related to the motion of bedload. Hsu et al. (2011), also observed clockwise hysteresis consistent with a bedload sediment origin for the seismic noise recorded in the Cho-Shui River (Taiwan) during large storms involving discharges up to 4000 m$^3$/s. Reid et al. (1985) showed that for a coarse-grained river channel, long periods of inactivity encourage the channel bed to consolidate sufficiently so that the stream can only mobilize the bedload after a significant time interval, resulting in a counter-clockwise hysteresis between seismic noise and discharge. This hysteresis was not observed for floods that follow each other closely. In contrast, hysteresis is not expected if water turbulence is the only source of seismic noise as seismic amplitude and discharge should then be linearly scaled (Hsu et al., 2011).

In summary, large hydrological events often results in clockwise hysteresis cycles, while smaller events can show counterclockwise hysteresis as the bedload is only mobilized some time later of the beginning of the flood. In both cases, bedload transport appears as a significant contributor to the seismic energy.

Tsai et al. (2012), using a forward model, have shown a strong trade-off between the grain size distribution of the transported sediments and the seismic noise, but little dependence between the dominant frequency and the grain size. On contrary, Huang et al. (2007), studying experimentally the ground vibrations caused by individual rock falls and debris flows, concluded that motions of large particles results in peaks of energy
concentrated at lower frequencies than for smaller grains. Burtin et al. (2008, 2011) noticed that a critical stress value marks the minimum water flow value needed to mobilize the bed load particles. Beneath this threshold, an increase of water supply results in an enhanced transport capacity of the stream, a mobilization of larger particles and a frequency content shift to lower values, hence supporting the observations of Huang et al. (2007). Above the critical stress an additional increase of discharge fluvial stress do not produce changes in the noise amplitude as all the available material is already involved.

The moderate rainfall episode here analyzed has a maximum expression in the 2.5-4.5 Hz band and its amplitude closely matches the discharge evolution with the dominant frequency decreasing steeply as water flow increases and increasing when the flow vanishes. This is consistent with the observations of Burtin et al. (2011) and Huang et al (2007), both relating lower frequencies to the mobilization of larger particles. The counter-clockwise hysteresis observed between both parameters (Figure 7a), can be explained if we accept that the low discharge (not exceeding 3 m$^3$/s) cannot quickly mobilize the bedload. During the rising limb, the seismic noise would be generated by the water flow turbulence, while during the falling limb an additional contribution of bedload motion will increase the seismic noise for the same discharge, resulting in counter-clockwise hysteresis. Even if we have not found studies on the channel properties and the bedload materials in the upper Aragon River, Lana-Renault and Regüés (2007) have studied a catchment in the Arnas River, an affluent forming the valley located immediately West. The bedload was monitored using the volumetric approach. Even if nine of the twelve analyzed floods involved bedload transport, the bedload volume during the most severe episode (with an estimated returning period
exceeding 25 years) was twice as high as the average for ordinary floods. This fact suggests that most bedload is yielded during large events and that moderate rainfall episodes cannot easily mobilize a large amount of particles.

The daily cycle observed in the snowmelt episode shares a number of characteristics with the moderate rainfall event, in particular its frequency band and the shape of the dominant frequency variation. It is well known that during snowmelting water is not drained on surface but percolates through the snowpack, which behaves like a highly porous medium (Singh et al., 2000). As there is no surface melting during nighttime, the water inside the snowpack is recessed, resulting in a gradual decrease in the melt stream during the night. This process results in typical snow-melt hydrographs showing flow increasing sharply to reach maximum values between 15:00 and 21:00, followed by more gradual recessions (Singh et al., 2000). The time variations of the dominant seismic frequency match closely these characteristics, with the daily cycle starting at 14:00, showing a minimum value at 18:00 and increasing again till the morning. As for moderate rainfall events, we interpret that the dominant frequency is a proxy for the flow associated to snowmelt, with lower frequencies associated to larger flow and hence to the mobilization of larger particles. The analysis of the frequency content of the seismic energy can be used to assess the storage characteristics of snow-fed basins (Singh et al., 2000) as a classical hydrograph. As an example of the parameters which may be inferred, it has been shown that the difference between the time of melt peak and the time of peak discharge allows to estimate runoff travel times through the river basin. These travel times provide information about snowpack properties, in-channel flow velocities and distances to the primary snowmelt source areas, significant parameters for flood forecasting and reservoir operations (Lundquist and Dettinger,
In the case of the Aragon River, the analysis of the spectrogram of the seismic data provide a more detailed monitoring of the 2011 snowmelt season than the data coming from the downstream gauge station, which shows an abnormal pattern, probably affected by the management of the Canfranc reservoir (Figure 4b).

Burtin et al. (2011) noticed that sudden increases on water discharge result in increases in the seismic noise over a broad range of frequencies ranging from 2 to 60-90 Hz. The record of the seismic signal during the fall 2012 severe storm confirms this point and shows a complex frequency pattern strongly suggesting that different phenomena are contributing to the observed seismic pattern. In this case the frequency band between 1.5 and 2.25 Hz is activated and the dominant frequencies show a direct correlation with discharge, on contrary of anti-correlation described between 2 and 8 Hz during moderate rainfall and snowmelt episodes. Once the severe rain ends, the discharge and frequency variation becomes anti-correlated. Therefore, the dominant frequency evolution shows a threshold effect; for large avenues, with most of the available bedload mobilized, it follows directly the changes in water flow, while for lower levels of discharge the dominant frequency variations reflect the progressive increase/decrease in the size of the bedload particles.

The seismic noise in the 2.25 – 6 Hz band has a rather uniform energy level during each burst of rain, without evidences of a dominant frequency. This is consistent with the mobilization of all the available bedload once the local critical shear stress has been reached and is also consistent with the moderate clockwise hysteresis observed during the two last bursts of the episode (Figure 7b). The frequency content evolution once the rain stopped, with the seismic energy focusing near 4 Hz and then increasing again, can
reflect, as for the lower frequency band, the decrease in the size of the mobilized particles. Therefore, the seismic energy between 2.25 and 6 Hz can be attributed to the bedload carried by the stream.

The third frequency band identified during this event, covering frequencies larger than 10 Hz, seems to finish abruptly after the ending of the rain episode. Schmandt et al. (2013), related the origin of the seismic signal in the 2-15 Hz band to fluid-air interactions generated from breaking waves in a large rapid during the periods with maximum discharge, which would be converted to ground motion after an air-ground coupling process. However the setting of the LSC station, located at 350 m below the surface and 400 m away from the river channel, does not seem to favor an acoustic origin for the seismic signal. Additional data from infrasound instruments are needed to assess this hypothesis in our site.

When comparing the three case studies, it appears that the minimum value of the dominant frequency acts as a proxy of water flow. As discharges measured in the gauge stations increments, this value decreases from 2.8 Hz for the moderate rainfall event, to 2.2 Hz during the snowmelt events and 1.5 Hz for the severe storm event. This supports the hypothesis that bedload has a significant contribution to the seismic noise, as larger discharges will mobilize larger particles and hence result in lower dominant frequencies.

The deformations detected by the laser interferometers can be explained by the effect of water infiltration through the uppermost crust and seem directly related to rainfall. A different deformation pattern has been detected for heavy and moderate rainfall episodes. In the first case (daily rain accumulation exceeding 50 mm), both instruments
show extension, suggesting that heavy rain (i.e. large volume of infiltrating water) results in global pore pressure increase and strain follows pore pressure history. After-storm pore pressure decrease is linked to discharge (Figures 5 and 6). A possible explanation of the different strain behavior in case of moderate episodes (less than 50 mm of accumulated rain, Figure 3) could involve other poro-elastic effects linked to geological/structural environment. For example, water infiltration could mostly occur through higher-permeability paths, like the fault gouges close to LSC. In this case, pore pressure inside the fault gouges would increase more than outside and this would result in compression along the direction perpendicular to the fault trend and expansion parallel to it. As the local main structural faults are oriented sub-parallel to Gal16, this process results in compression along the Lab780 direction and extension along Gal16 direction. Pore-pressure lateral heterogeneity decreases as water table rises also in lower-permeability zones during heavy rainfall episodes; residual (small) pore-pressure lateral heterogeneity would still cause residual differences between the two interferometer extensions (Figure 6). In any case, more continuous strain data would be needed to confirm or disprove the hypothesized mechanisms.

5 Conclusions

We have shown that the continuous seismic and strain monitoring of the upper section of an Alpine river allows to investigate its hydrological evolution, even if the river discharges are modest. Geodynamical data can hence improve the information provided by classical hydrological gauge stations, as the inspection of the frequency content of the signal allows identifying characteristic hydrological events and monitoring their evolution. Three types of river-generated seismic events, each with distinctive
characteristics in the seismic and strain measurements, have been identified and related
respectively to moderate rainfall episodes, snowmelt season and large flooding
associated to severe storms.

The moderate rainfall and snowmelt episodes show similar variations of the seismic
frequency content in the 2-10 Hz band, despite of the large difference in the associated
discharges. In both cases the seismic signals can be used as a proxy of the river
discharge. The dominant frequency is anti-correlated with the river discharge, reflecting
the progressive mobilization of larger bedload particles. The seismic energy is therefore
related to the joint effect of water turbulence and bedload motions. The continuous
recording of seismic and deformation data seems particularly suited for long-term
studies on the characteristics of the snowmelt season in mountain basins, as it provides
detailed information of the daily and seasonal cycles and it is not exposed to changes in
the river channel geometry which may perturb discharge measurements in a
hydrological gauge station.

During severe storms the frequency pattern is different, showing three different bands.
The lower one, between 1.5 and 2.25 Hz, can be related to water flow, while the seismic
noise in the 2.5–6 Hz seems to be generated by bedload transport and the upper
frequency band could be related to air-ground coupling of acoustic waves, even if
additional data is needed to assess this point. This upper band of energy is only
observed when the water flooding exceeds the critical shear stress and can therefore be
used to assess the occurrence of flood avenues. Note that, as the seismological
community has a long experience in managing real-time data transmission using mobile
phone network or satellite connection, seismic data recorded nearby rivers may provide a valuable tool for civil protection authorities.

This study shows that the development of the so-called “fluvial seismology” in Alpine style valleys has a great potential for scientific investigations related to bedload transport or snowmelt evolution, but also for the assessment of hydrological hazards.

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Figure Captions:

Figure 1: Map of the upper section of the Aragon River. The locations of the LSC geodynamical facility and the A271 gauge station are shown.

Figure 2: Comparison between seismic and meteorological data. The upper panel shows the daily rain in the meteorological station located nearby LSC. The second panel shows in red the maximum daily discharge registered in the A271 gauge station. The lower panel displays the power density spectrum of the vertical seismic data recorded by the broad-band seismometer, with reddish colors representing high energy intervals. Black dashed boxes show the main hydrological events and their correlation with intervals of high levels of seismic energy in the 2-10 Hz band. Time scale is expressed in Julian days.

Figure 3: Moderate rainfall episode: a) Vertical acceleration band-pass filtered between 2 and 8 Hz (upper panel) and strain (arbitrary shifted) recorded by the two laser interferometers during the rainfall episode. Diurnal and semi-diurnal tides have been removed from strain records. b) Rainfall amount (green line), discharge (red line) and envelope of the vertical acceleration (black line). c) Spectrogram of the seismic signal in the 1-10 Hz band. Time expressed as Julian days of year 2012.

Figure 4: Snowmelt season. a) Vertical acceleration band-pass filtered between 2 and 8 Hz. b) Rainfall amount (green line), discharge (red line) and envelope of the seismic signal (black line) c) Spectrogram of the seismic signal in the 1-10 Hz band. The inset
shows the snow resources estimation (ERHIM program). Time expressed as Julian days of year 2011.

Figure 5: Severe storm event. A) Vertical acceleration band-pass filtered between 2 and 8 Hz (upper panel) and strain recorded by the Lab780 laser interferometer after removal of diurnal and semi-diurnal tides (lower panel). b) Rainfall amount (green line), discharge (red line) and envelope of the seismic signal (black line). c) Spectrogram of the seismic signal in the 1-45 Hz band. Note that the frequency scale is now logarithmic to better display the frequency variations.

Figure 6: Deformation data for heavy rainfall episodes recorded by both interferometers. Upper panels show recorded deformation after removal of the diurnal and semi-diurnal tides (upward, extension; downward, compression); Lab780 signal exhibits lower amplitude than Gal16 one. Middle panels show the accumulated rain (green rectangles, daily totals; red line, 15' interval values). Bottom panels are for discharge (purple rectangle, daily total; green line, 15' interval values).

Figure 7: a) Anticlockwise hysteresis between the seismic envelope (blue line) and the discharge (red line) during the moderate rain episode in November 2012. b) Clockwise hysteresis between the seismic envelope (blue line) and the discharge (red line) during the second and third bursts of rain of the fall 2012 severe storm. In both cases, green arrows and dashed lines show the difference between the rising and falling limbs. The inset illustrates the hysteresis cycle using a color-shaded time scale.
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