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RAIS: a real time strong-motion network in northern Italy

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ABSTRACT

When compared to more seismically active regions, damaging earthquakes occur only occasionally in the central part of northern Italy. Nevertheless, the lack of a dense strong-motion network in this area was highlighted by the occurrence of the November 24, 2004, M_L 5.2, Salò earthquake. In 2006, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) section of Milano-Pavia began the installation of new strong-motion stations in central-northern Italy. At present, the Strong-Motion Network of Northern Italy (RAIS; Rete Accelerometrica Italia Settentrionale) includes 22 stations with an average inter-distance of about 20 km. All of the stations are equipped with Kinemetrics Episensor FBA ES-T sensors coupled with 24-bit digital recorders. Starting from 2009, 14 strong-motion stations have been sending data to the INGV acquisition center in Milan, in real time using TCP/IP over wi-fi links. Another eight stations still work in dial-up mode and send data through GSM modems. The real-time connections allow the use of strong-motion data recorded by RAIS for the generation of shake maps for Italy, the implementation of which represents one of the main tasks of the last agreement between INGV and the Italian Civil Protection Department. The RAIS data is stored directly at the INGV section of Milano-Pavia, which was realized using the MiniSEED format: the data management and exchange are carried out by the SeisComP package with the SeedLink protocol. Metadata dissemination is achieved through the website http://rais.mi.ingv.it, where the strong-motion parameters related to each recorded and processed waveform are made available.

1. Introduction

Strong-motion monitoring in Italy started in the early 1970's, when a national strong-motion network was designed and installed by the Italian national energy and environment agency (ENEA; Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile) and the Italian electricity company ENEL SpA. Since 1997, the Italian National Strong-Motion Network (RAN; Rete Accelerometrica Nazionale) has been run by the Italian Civil Protection Department (DPC; Dipartimento della Protezione Civile). In spite of the relatively large number of RAN stations (at present, about 250 digital stations and 120 analog stations; http://itaca.mi.ingv.it), they do not provide homogeneous cover of the Italian territory. In particular, most of the stations are installed in areas characterized by high levels of seismicity, such as the central and southern Apennines, and the Friuli and Sicily regions. This problem became apparent after the occurrence of the November 24, 2004, M_L 5.2 (M_W 5.0) Salò earthquake [Augliera et al. 2006]. This event was one of the strongest earthquakes to strike the northern Italy regions over the last 30 years.

On the basis of the official data provided by the Lombardia regional authorities, this earthquake strongly affected about 70 municipalities close to the epicenter area. This resulted in damage to about 3,500 buildings and 300 churches, for an approximate damage evaluation of 200 million euros. In the epicenter area, only the Gavardo analog strong-motion station (GVD; see http://itaca.mi.ingv.it) was triggered during the mainshock (on the S-phase). The peak ground horizontal acceleration recorded at an epicenter distance of 14 km was 71 cm/s². Due to the lack of other strong-motion stations installed in the surroundings of the epicenter, no further data are available for distances less than 90 km from the epicenter.

With the aim to ascertain high-quality near-source recordings in the case of future earthquakes in northern Italy, in June 2006, the Istituto Nazionale di Geofisica e Vulcanologia section of Milano-Pavia (INGV-MI) started the installation of a dense strong-motion network in the area surrounding the November 24, 2004, epicenter: Rete Accelerometrica Italia Settentrionale (RAIS; Strong-Motion Network of Northern Italy; http://rais.mi.ingv.it) (Figure 1).

Even if central-northern Italy is a region that is characterized by low seismicity (in terms of both energy release and occurrence of events), the importance and necessity of strong-motion monitoring in this areas has been demonstrated by the occurrence of some relevant historical earthquakes (Figure 2, bottom panel), such as the 1117 M_W 6.49 Verona earthquake, the 1222 M_W 6.05 Brescia earthquake, the 1695 M_W 6.61 Asolo earthquake and the more recent 1901

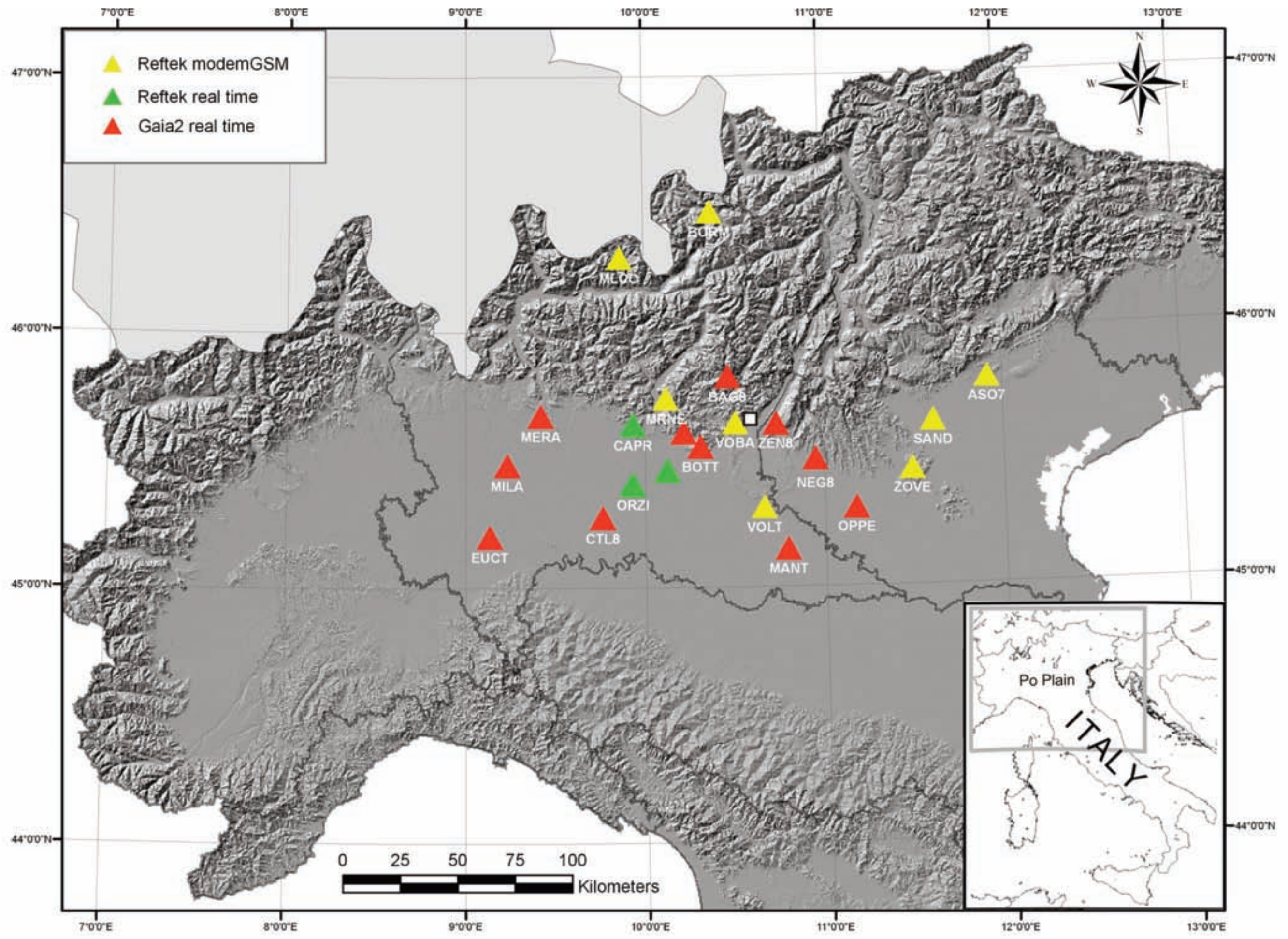


Figure 1. RAIS strong-motion network. Different colors indicate stations characterized by different recording systems or different data-transmission types (as indicated). White square, epicenter of the November 24, 2004, M_L 5.2, Salò earthquake.

M_W 5.67 Salò earthquake [Gruppo di lavoro CPTI 2004].

At present, after four years of recordings, the data stored at the acquisition center in Milan has allowed us to construct a high-quality dataset (Figure 2, top panel) composed of 103 events (about 2,000 three-components waveforms) with M_L ranging from 0.7 to 5.1 (the December 23, 2008, Parma earthquake).

This study is focused on the RAIS technological upgrade that has been performed in the last two years. The first phase of installations, as the main features of the first-generation RAIS (mainly based on a dial-up transmission system) and its detection capability, were described in a previous study [Augliera et al. 2009]. In the present study, the latest developments and the present configuration of the network are presented, with particular attention to site selection, acquisition system and data transmission. The final section of this study focuses on data processing and real-time dissemination, with the aim, in particular, to improve the generation of shake maps for events that occur in northern Italy.

2. Site selection and characterization

RAIS arose in the framework of a 2004-2006 INGV-DPC agreement. The first installations were founded through the project «Stazioni Accelerometriche» («Strong-Motion Stations»; http://accel.mi.ingv.it/progettoaccel/), while further developments were carried out through the last INGV-DPC S3 project «Fast evaluation of the parameters and effects of strong earthquakes in Italy and in Mediterranean areas». At the beginning, two of the main goals of the Stazioni Accelerometriche project were to improve earthquake detection in the area of central-northern Italy, and to ascertain a tool for strong-motion monitoring that can provide high-quality records in the case of strong events. The first phase of the project concerned the selection of sites suitable for seismic installations. In this way, three main aspects were considered: the locations of the seismic stations managed by other organizations (Figure 3), to avoid too high or too low a density of stations (both weak and strong-motion) in any particular area; the location of instrumental seismicity recorded in the region under study from 1981 (http://bollettinosismico.rm.ingv.it/ and http://csi.rm.ingv.it/); and the municipality of the area characterized by the greatest seismic hazard (http://esse1.mi.ingv.it/) [Gruppo di Lavoro MPS 2004], expressed in terms of the maximum peak ground horizontal acceleration, with a 10% probability of being exceeded in the next 50 years (return period, 475 years).

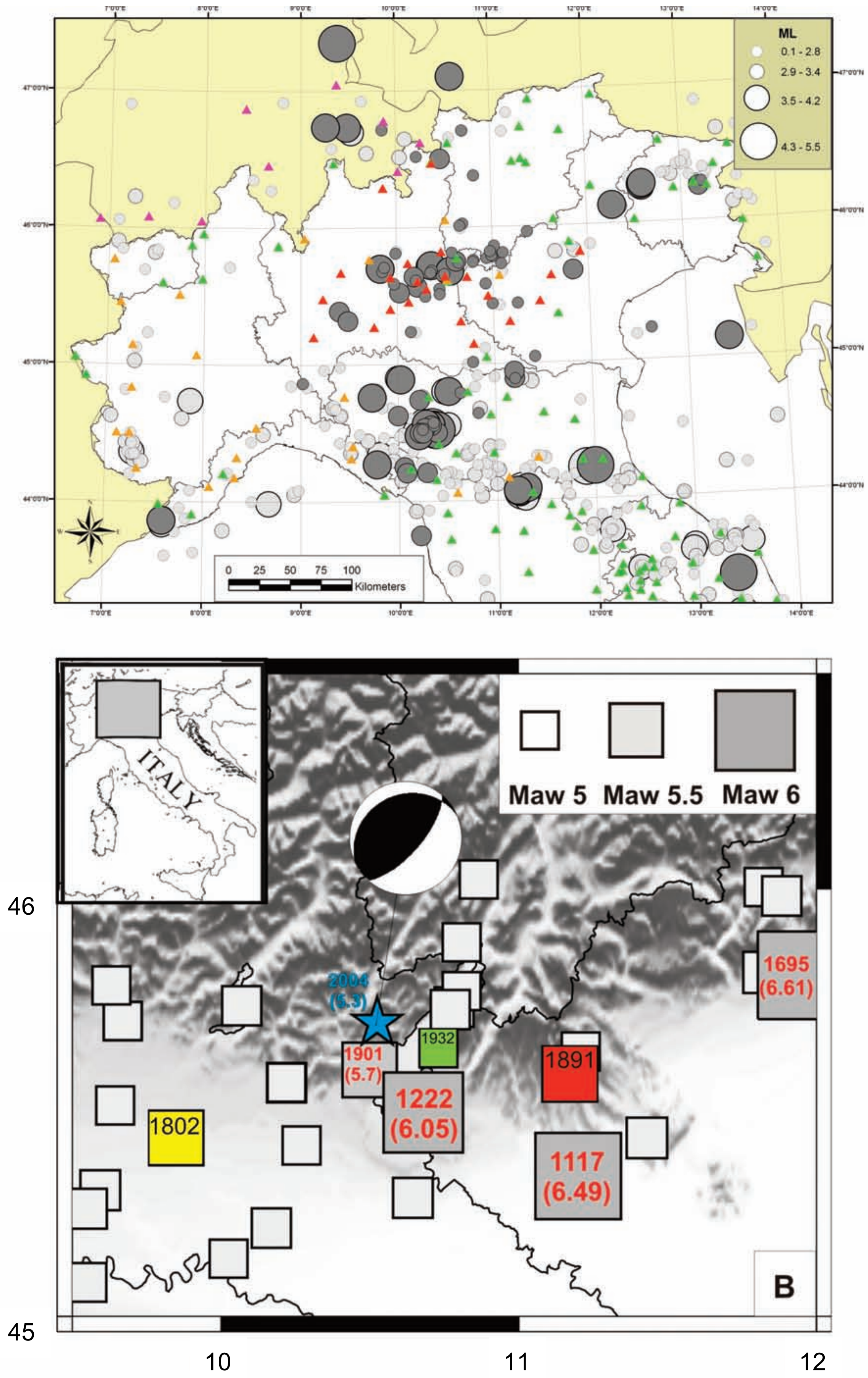


Figure 2. Top panel: events recorded by RAIS from June 2006 to June 2010 (dark grey circles) and background seismicity in northern Italy (light grey circles). Epicenter coordinates are derived from the official INGV instrumental bulletin (http://bollettinosismico.rm.ingv.it/). Red triangles, RAIS strong-motion stations. Bottom panel: historical seismicity of the area under study (from CPTI04) [Gruppo di Lavoro CPTI 2004]. Blue star, epicenter of the November 24, 2004, M_L 5.2, Salò earthquake.

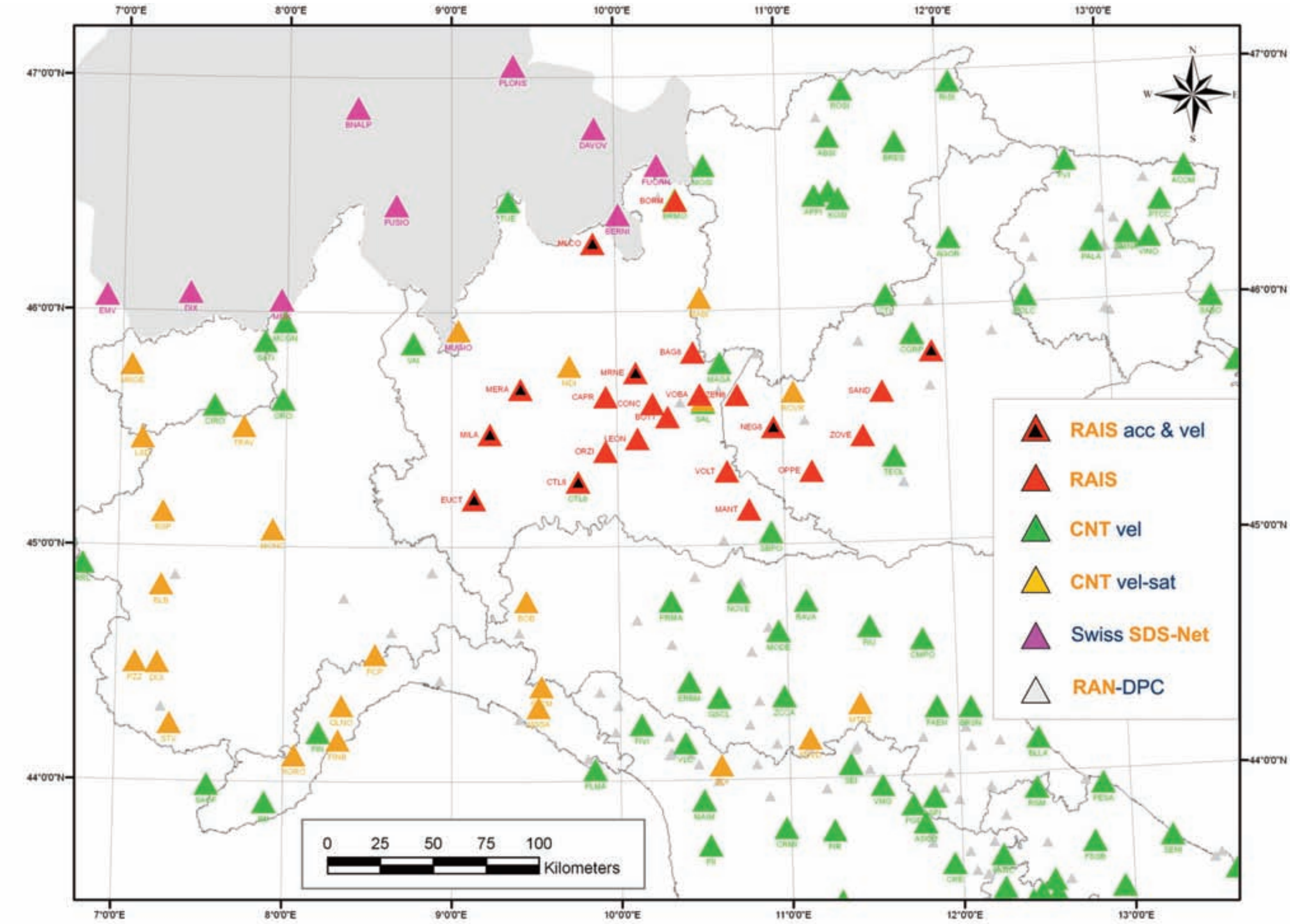


Figure 3. RAIS and national seismic networks in northern Italy and its surroundings. Red triangles, RAIS stations (http://rais.mi.ingv.it); black triangles inside red triangles, site equipped with both weak and strong-motion sensors; green triangles, velocimetric stations managed by the National Earthquake Center of INGV (CNT, http://cnt.rm.ingv.it/); yellow triangles, INGV-CNT satellite velocimetric stations; gray triangles, RAN strong-motion stations managed by Italian Civil Protection (DPC, http://www.protezionecivile.it/); violet triangles, SDS-Net velocimetric stations (http://www.seismo.ethz.ch/).

Figure 3 shows only the RAIS and the national network, but other local and regional networks that have operated in this area were considered; e.g. the Friuli–Venezia Giulia Accelerometric Network (RAF), the short-period seismometric regional networks of Friuli–Venezia Giulia (RSFVG) and of Veneto (RSV) managed by the Centro di Ricerche Sismologiche of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), and the Regional Seismic Network of Northwestern Italy (RSNI; managed by Dipartimento per lo Studio del Territorio e delle sue Risorse, Genoa University). For each site considered, the final selection generally represented a compromise between the network geometry, which depends on the monitoring purposes, and the characteristics that a given site has in terms of being suitable for an installation.

Considering the high degree of urbanization and industrialization in the area considered, all of the installations were preceded by microtremor analysis [Nakamura 1989]. Taking into account that it is difficult to achieve a low level of noise in this area [Peterson 1993], the selection was carried out in particular with the aim of avoiding any very unfavorable situations.

For each site, the quick horizontal-to-vertical spectral ratio (HVSR) and additional probability density functions [McNamara and Buland 2004] are computed following the procedures presented by Marzorati and Bindi [2006]. For the processing of the seismic noise, time series with durations of at least 30 min are considered, recorded with a broad-band sensor (sampling frequency, 100 Hz). These time series are divided into segments of 60 s with an overlap of 75%, to reduce the variance in the power spectral density (PSD) computations. For each window of noise, the mean and the linear trends are removed, and a digital Butterworth filter is applied, in the frequency range 0.1 Hz to 25 Hz.

At present, all of the sites where a RAIS station is installed are characterized from both the geological (http://rais.mi.ingv.it; link *caratterizzazione siti*) and geophysical points of view. For the geology, all of the information has come from 1:25,000 geological maps provided by the Lombardia region [CARG project 2003] or from 1:100,000 Italian geological maps [Società Geologica Italiana 1984]. From a geophysical point of view, for each site, an averaged HVSR is available considering the earthquake recordings from June 2006.

For each recorded waveform, an automatic procedure allows the step-by-step updating of the present averaged amplification function calculated for a single site. The processing of the recorded strong-motion data (sampling frequency, 100 Hz) includes the following steps: removal of the mean and the linear trends; 5% cosine tapering; and application of an acasual four-pole Butterworth band-pass filter between 0.2 Hz and 25 Hz. For each event, the Fourier spectra are computed considering different time windows (5 s and 10 s, starting 0.5 s before the S-phase onset).

To investigate the differences between the differently polarized horizontal components, directional spectral ratios are obtained by applying different rotation angles. In particular, for computing the directional spectral ratios, the NS and EW components are rotated clock-wise from the North by between 0° and 175°, in angular steps of 5°. This provides for the computation of 36 rotated components, which are representative of 36 directions of horizontal ground shaking. A summary of the products available at each site is given in Figure 4 for the Vobarno station (VOBA in Table 1).

Finally, taking into account both the geological and geophysical indications, all of the stations are classified following the provision of the Italian seismic building code [NTC 2008].

3. Instrumentation and installation

At present, RAIS is composed of 22 stations (Table 1): the strong-motion sensors are Episensor model FBA ES-T force balance accelerometer sensors (http//www.kinemetrics.com), which are characterized by a dynamic range of 155 dB. Generally, the full-scale is set to ±2.0 g. Figure 5 shows the typical arrangements of the installations. At each site, the accelerometer is housed in an *ad-hoc* built concrete basement, to which it is anchored (Figure 5, top right). Close to the concrete basement there is a plastic box with the dimensions of about 100 cm length, 80 cm width and 50 cm height. This box contains the digital recorder (GAIA-2 recorder in Figure 5, bottom left), a router for data transmission (TCP/IP protocol), and a stabilized power supply connected to a 12 v battery, to avoid a possible loss of electricity (Figure 5, bottom left).

The time synchronization of the signals recorded is

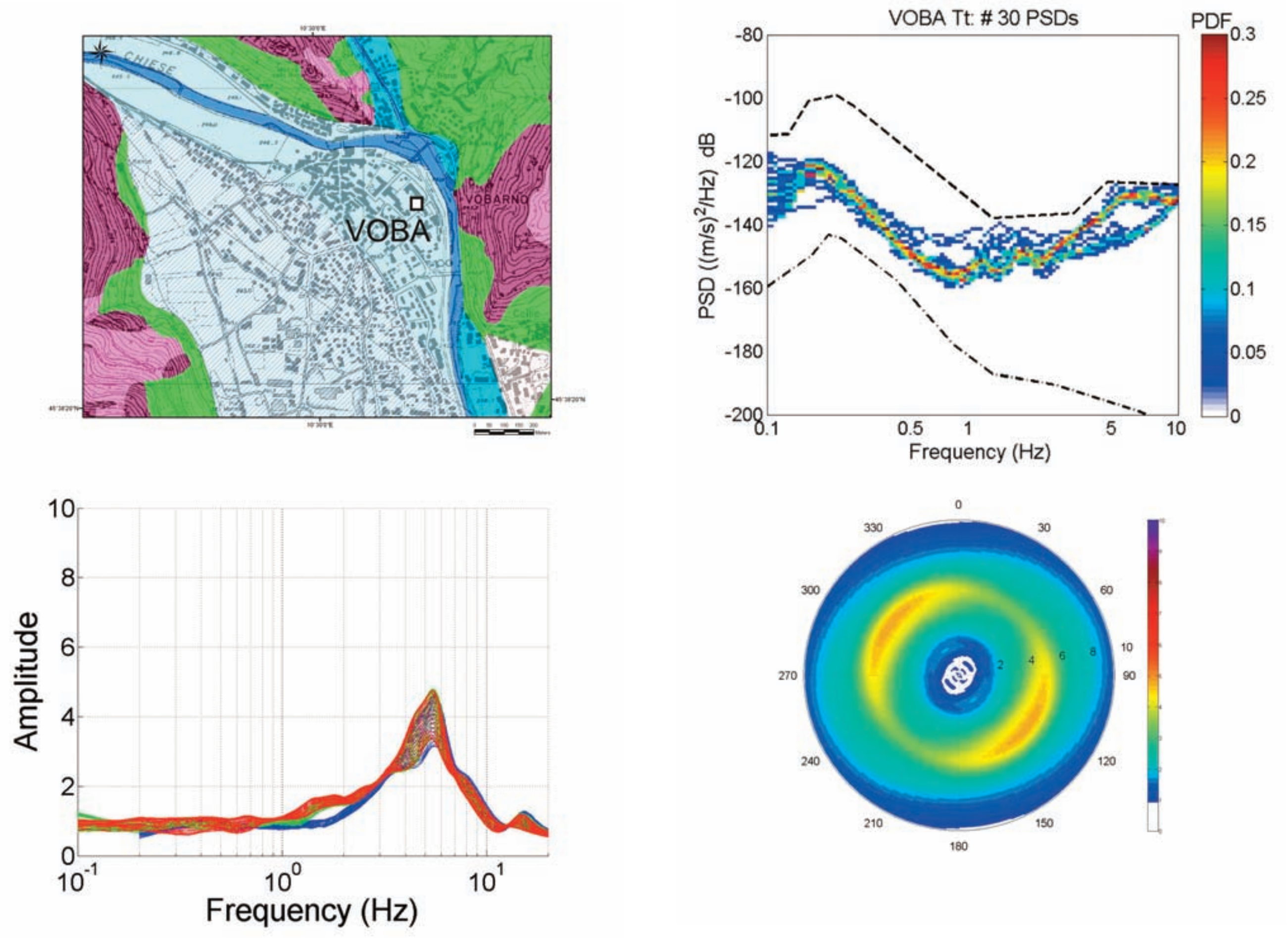


Figure 4. Site characterization of VOBA station (NTC08 B lithological class, see also Table 1). Top left: geological map (1:25,000 scale). Top right: probability density function of power spectral density performed on seismic noise. Bottom left: horizontal-to-vertical spectral ratio performed considering recorded earthquakes (different colors indicate different portions of the S-phase). Bottom right: frequency-azimuth polar plot (third dimension indicates value of amplification function).

Station (site class)		**Site**	**Province**	**Latitude (N)**	**Longitude (E)**	**Elevation (m)**	**Sensor**	**Full-scale (g)**	**Rec. System**	**Transmission**	**Since**
MILA	C	Milano	Milano	45.480	9.232	125	Episensor	(1.0)	Gaia2	Real Time	01.06.06
MERA	B	Merate	Lecco	45.672	9.418	350	Episensor	(2.0)	Gaia2	Real Time	25.10.05
EUCT	C	Pavia	Pavia	45.202	9.134	82	Episensor	(2.0)	Gaia2	Real Time	26.06.06
CTL8	C	Castelleone	Cremona	45.275	9.762	66	Episensor	(2.0)	Gaia2	Real Time	22.07.09
BAG8	A	Bagolino	Brescia	45.822	10.466	807	Episensor	(2.0)	Gaia2	Real Time	15.06.06
CONC	B	Concesio	Brescia	45.606	10.217	126	Episensor	(0.25)	Gaia2	Real Time	03.05.06
OPPE	C	Oppeano	Verona	45.308	11.172	20	Episensor	(2.0)	Gaia2	Real Time	24.09.09
BOTT	A	Botticino	Brescia	45.549	10.309	200	Episensor	(2.0)	Gaia2	Real Time	27.10.09
ZEN8	A	San Zeno Montagna	Verona	45.637	10.731	596	Episensor	(2.0)	Gaia2	Real Time	30.06.06
MANT	C	Mantova	Mantova	45.149	10.789	36	Episensor	(2.0)	Gaia2	Real Time	29.07.09
CAPR	B	Capriolo	Brescia	45.637	9.934	215	Episensor	(2.0)	Reftek	Real Time	31.05.06
LEON	C	Capriano del Colle	Brescia	45.458	10.123	92	Episensor	(2.0)	Reftek	Real Time	18.07.07
ORZI	C	Orzinuovi	Brescia	45.405	9.930	83	Episensor	(2.0)	Reftek	Real Time	24.04.08
VOBA	B	Vobarno	Brescia	45.642	10.504	292	Episensor	(2.0)	Reftek	Modem GSM	28.06.06
ASO7	A	Asolo	Treviso	45.804	11.918	221	Episensor	(2.0)	Reftek	Modem GSM	03.08.06
BORM	A	Bormio	Sondrio	46.469	10.376	1235	Episensor	(2.0)	Reftek	Modem GSM	29.11.06
MLCO	A	Chiesa Val Malenco	Sondrio	46.291	9.863	2030	Episensor	(2.0)	Reftek	Modem GSM	30.11.06
ZOVE	A	Zovencedo	Vicenza	45.453	11.487	376	Episensor	(2.0)	Reftek	Modem GSM	28.06.07
MRNE	A	Marone	Brescia	45.739	10.117	600	Episensor	(2.0)	Reftek	Modem GSM	10.07.07
VOLT	C	Volta Mantovana	Mantova	45.313	10.660	107	Episensor	(2.0)	Reftek	Modem GSM	09.11.07
SAND	C	Sandrigo	Vicenza	45.640	11.609	51	Episensor	(2.0)	Reftek	Modem GSM	19.12.07
NEG8	A	Negrar	Verona	45.497	10.948	167	Episensor	(2.0)	Gaia2	Real Time	29.06.10

Table 1. Main features of the RAIS stations.

ascertained via a GPS antenna installed near the station. At present, the network is characterized by two different types of digital recorders: 11 strong-motion sensors coupled to 24-bit Reftek 130-01 digital recorders (http://www.reftek.com); with the other 11 sensors coupled to 24-bit GAIA-2 [Rao et al. 2010]. This type of digital recorder was directly designed and produced by the laboratory of the INGV-CNT (http://cnt.rm.ingv.it). At present, all of the stations record signals in continuous mode, with a sampling frequency of 100 Hz.

4. Acquisition system and data transmission: a brief history, and the present

From June 2006 to the end of 2008, the Episensors installed were equipped with 20-bit Lennartz Mars88 Modem Control (http://www.lennartz-electronic.de/) or 24-bit Reftek 130 digital recorders. In both cases, the remote stations transmitted the data to the INGV-MI acquisition center using Global System for Mobile Communications (GSM) modems [D'Alema and Marzorati 2003, D'Alema 2007]. The GSM data transmission did not allow real-time determination of the engineering parameters, which actually represents one of the main goals for a strong-motion network.

In this initial period, the GSM data transmission system represented a relevant technological limitation, which forced the on-line data dissemination to have a time delay of the order of hours. In the framework of the recent 2007-2009 INGV-DCP S3 project, great efforts have been made to replace the highest possible number of GSM stations with a system that can record data in continuous mode and at the same time transmit the data in real time. This important evolution of the network started at the beginning of 2009, and it has led to the replacement of the Mars88 Modem Control digital recorders (without TCP/IP support, and thereby not suitable to transmit data in continuous mode) with 24-bit digital recorders. At the same time, the present phase (still in progress) has led the replacement of the GSM technology with TCP-IP connections.

At present, 14 stations of the total of 22 are connected to the acquisition center in Milan in real time. Eleven of these 14 stations are now equipped with GAIA2 digital recorders, while three others are equipped with Reftek-130 digital recorders. The other eight stations are still dial-up stations, and they send data via GSM modems. For the management of the real-time stations, the SeedLink protocol has been adopted. The format of the recorded data (previously recorded both in binary Reftek and Lennartz format, and then stored in sac format) has been upgraded, to introduce the MiniSEED format. We use the SeedLink system for real-time communication using TCP/IP protocols, and a SeisComP platform [Hanka et al 2000] for monitor plotting and disk recording.

For data acquisition, a procedure for events detection was developed. The locations are provided by the Italian National Earthquake Center (INGV-CNT, http://cnt.rm.ingv.it). In our case, a new event location represents a warning for RAIS data acquisition, and consequently the trigger for the fully automatic system. In particular, every 5 min the file of event locations (revised by the seismologist who is in charge of the seismic surveillance activities in Rome) are automatically downloaded.

Every time a new event occurs, the theoretical spectral amplitude of the earthquake is compared (in a fixed frequency band) with the average noise levels for each station of the network. The synthetic spectrum is computed by considering the omega-square source model [Brune 1970], and the source spectrum is propagated to each station by considering the 1/R geometrical spreading term. In this case, some bias (however negligible, considering our scope) can be introduced by the non-correspondence between moment (on which the theoretical scheme is based) and local (recorded) magnitude. The procedure is, however, conservative [Augliera et al. 2009]. At the end of the procedure, if the theoretical signal-to-noise ratio exceeds a fixed threshold for at least three stations, the INGV-CNT event-ID is stored and the procedure for the automatic download of the RAIS data starts. The event-ID represents the necessary information to merge the data previously processed by different seismic networks in a consistent way, when sent to the common server of INGV-CNT.

At the end of the process, the RAIS waveforms are available at our acquisition center and are ready to be processed by the automatic system. A summary of the procedure is shown in the flow-chart in Figure 6.

Figure 5. Typical installation arrangements. From top to bottom: external view; concrete basement where strong-motion sensor is anchored; plastic box that includes the recording system (open); plastic box (closed).

5. Data processing and dissemination

After the acquisition system, the RAIS data are available at the workstation of the acquisition center in Milan. The last step is represented by the data processing and dissemination. The analyses of the recorded data are automatically carried out using a series of codes that were expressly developed both in the Fortran77 and C languages, and in bash-shell. Each strong-motion waveform is processed using a standard procedure, as described by Massa et al. [2009], which includes baseline correction (performed by least square regression), mean removal considering the whole signal, application of a cosine-taper function (usually 5%), and filtering performed by an acasual 4th-order Butterworth digital filter (0.2-30 Hz).

For all of the processed waveforms, the peak ground acceleration (PGA) and acceleration response spectra (5% damped) for periods up to 4 s are calculated. Moreover, the automatic system also provides pseudo-velocity response spectra, displacement response spectra, Arias intensities

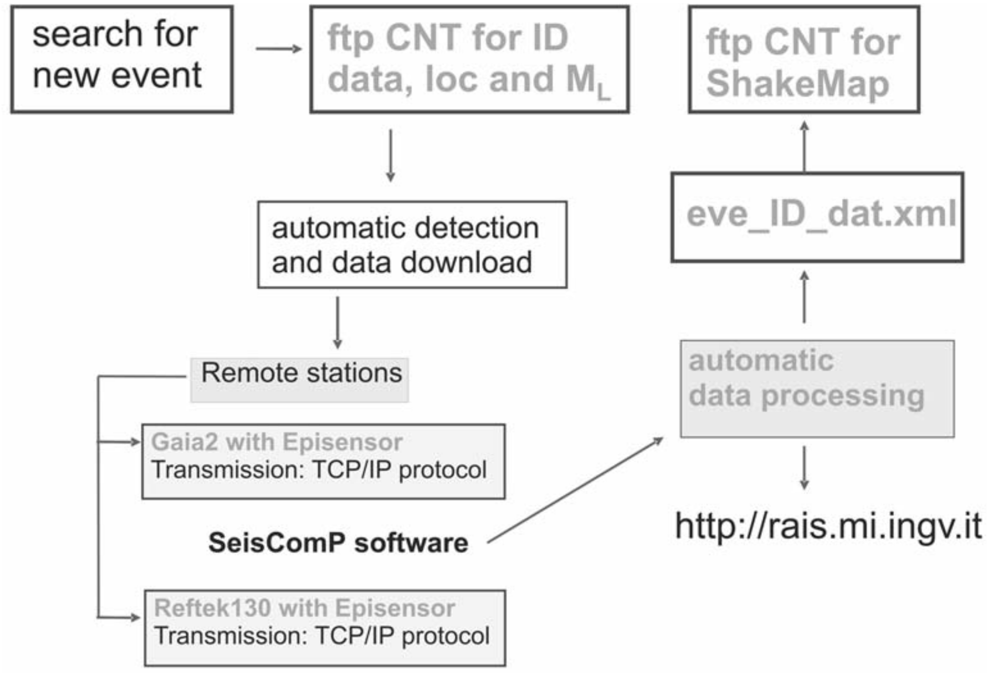


Figure 6. Flow chart representing the acquisition system and data transmission for the RAIS network.

[Arias 1970] and Housner intensities [Housner 1952]. Finally, after the integration of the acceleration time series, the peak ground velocity is also determined. For the site response, as discussed above, for each recorded event at each site, the earthquake HVSR is calculated, considering both 5 s and 10 s of the S phase. The metadata are collected on the website of the RAIS network (http://rais.mi.ingv.it), while all of the waveforms related to each event with a $M_L \geq 2.5$ are included in the Italian Accelerometric Archive (ITACA) and are downloadable from its website (http://itaca.mi.ingv.it). Moreover, since 2009, for each event with a $M_L \geq 3.0$, the PGA, peak ground velocity and acceleration response spectra values (for periods of 0.3 s, 1.0 s and 3.0 s) are sent to the INGV-CNT acquisition center, where they are merged together with all of the available strong-motion and velocimetric data, to improve the calculations with ShakeMap (http://earthquake.rm.ingv.it/shakemap/shake/) for these events that occur in northern Italy.

6. The 2006-2010 RAIS dataset

In the period from June 2006 to June 2010, the RAIS network allowed us to collect a relevant dataset, at least in terms of the number of earthquakes for this area with low seismicity. Over this period, 103 events (total of about 2,000 three-component waveforms) with M_L ranging from 0.7 to 5.1 were recorded in the epicenter distance range from 5 km to 250 km (Figure 7). For the magnitudes, the most relevant earthquake was recorded on December 23, 2008, at 15.23 UTC (M_L 5.1; Parma earthquake; http://rais.mi.ingv.it/statiche/PARMA-2008/HTML/main.html).

For the acceleration, the earthquake that produced the highest recorded peak was the July 14, 2008, M_L 3.5 Salò event. This relatively weak earthquake produced a horizontal acceleration peak of 33 cm/s^2 at Vobarno station (VOBA; see Table 1), which was located about 5 km West of the epicenter.

In general, as shown in Figure 7 (top left), the highest number of recorded events were in the magnitude range M_L 2.5 to 4.0. In this interval, the records homogeneously cover the hypocenter distance range from 10 km to 200 km. For magnitudes between M_L 0.7 (minimum recorded) and 2.5, the hypocenter distances range from 50 km to 75 km (Figure 7, bottom left). The same examination of the data can be made if the right panels of Figure 7 are considered. In particular, the bottom right panel shows PGA *versus* hypocenter distance for events with $M_L \geq 3.0$, where anomalous peaks for hypocenter distances close to around 100 km can be seen. This phenomenon is due to the not-so-negligible contribution of the Moho reflection in the areas located in the eastern region of the Po Plain, as demonstrated by Castro et al. [2008] and Bragato et al. [2009]. However, it is also not possible to exclude the contribution of local site effects for stations located in B and C lithological classes (see Table 1), as described in the Italian seismic building codes [NTC 2008].

To strengthen the benefit of the RAIS network for strong-motion monitoring of the area under study, in Augliera et al. [2009] a theoretical example was considered around some of the strongest historical events [Gruppo di Lavoro CPTI 2004] that have occurred in the northern Italy regions (Figure 2, bottom panel). In the case of a "re-occurrence", the May 12, 1802, M_W 5.67 Oglio Valley earthquake (maximum macroseismic intensity, I_{max}, of Mercalli–Cancani–Sieberg (MCS) VIII-IX; Figure 2, bottom panel, yellow square) would currently be recorded by five strong-motion stations (four belonging to RAIS) in the first 30 km. Similarly, the June 7, 1891, M_W 5.71 Illasi Valley earthquake (I_{max}, MCS IX; Figure 2, bottom panel, red square) and the February 19, 1932, M_W 5.01 Mount Baldo earthquake (I_{max}, MCS VIII; Figure 2, bottom panel, green square) would have produced non-saturated data at seven stations (six belonging to RAIS) and 12 stations (seven belonging to RAIS) for epicenter distances less than 30 km, respectively (for more details, see Augliera et al. [2009]). In particular, considering the hypothetical doublet of the November 24, 2004, M_L 5.2 Salò event (Figure 2, bottom panel, blue star), it is possible that a similar event would now be recorded by 11 strong-motion stations (six belonging to RAIS) in the first 30 km.

7. ShakeMap implementation at RAIS

Shake maps are very useful tools in the first minutes to hours after an earthquake has occurred, but their relevance progressively decreases as information about the actual damage becomes available. For this reason it is fundamental to have the data in real time.

At INGV-MI we have installed the ShakeMap package, developed by the U.S. Geological Survey (USGS) Earthquake Hazards Program [Wald et al. 2006], and we use this tool in agreement with the procedures developed by INGV-CNT for ShakeMap implementation in Italy [Michelini et al. 2008]. A dense and uniform spatial distribution of stations in the field is essential to produce reliable shake maps [Douglas 2007, Moratto et al. 2009], to minimize the uncertainties associated with ground-motion prediction equations [Wald et al. 2008].

To appreciate the role of the RAIS stations in the calculation of the shake maps, an example is given in Figure 8 for the July 14, 2008, M_L 3.5 earthquake that occurred near Salò. Figure 8a shows the shake map in terms of the instrumental intensity, as obtained by considering all of the available data (RAIS stations in yellow), while Figure 8b shows the PGA residual (in terms of the differences between the values of the ground-motion parameters) obtained by generating the same map considering or not the RAIS stations. Here, the green zone indicates positive residuals

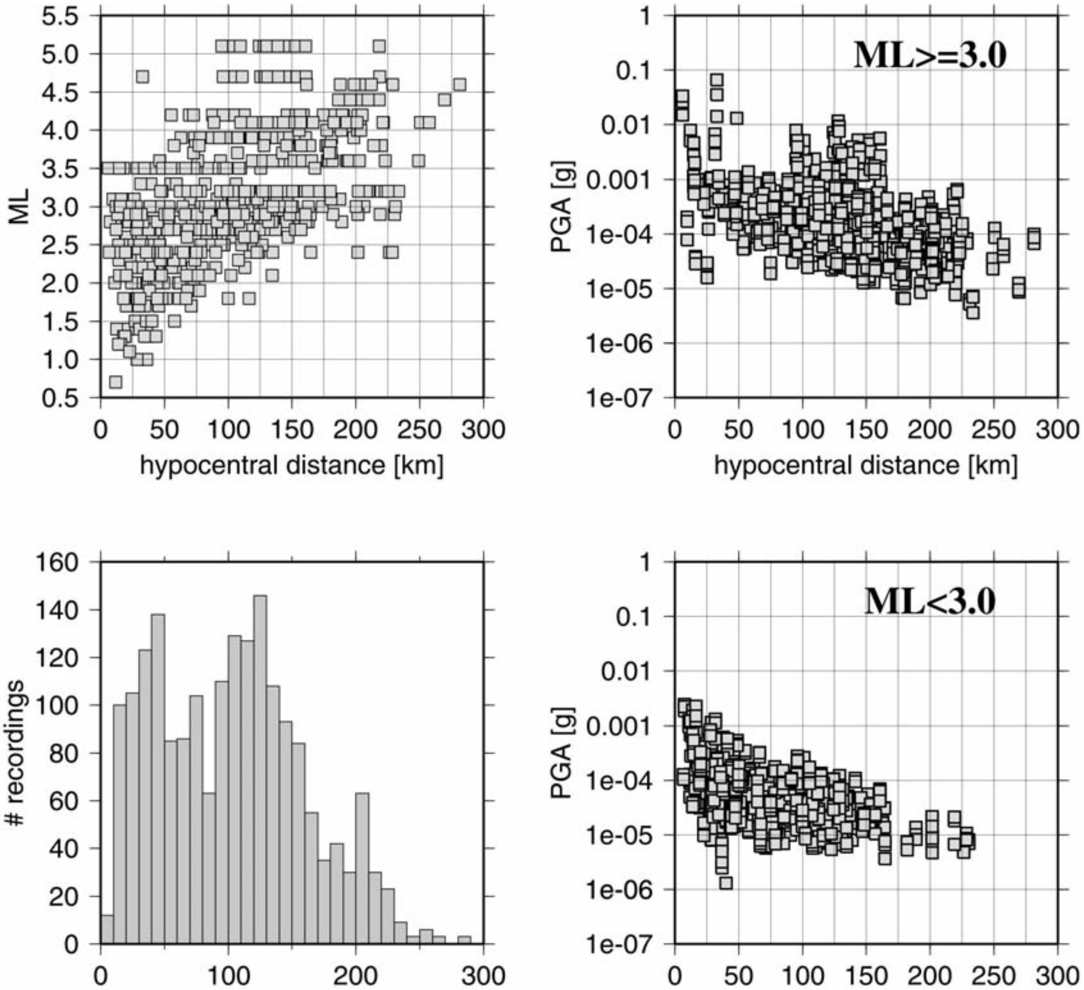
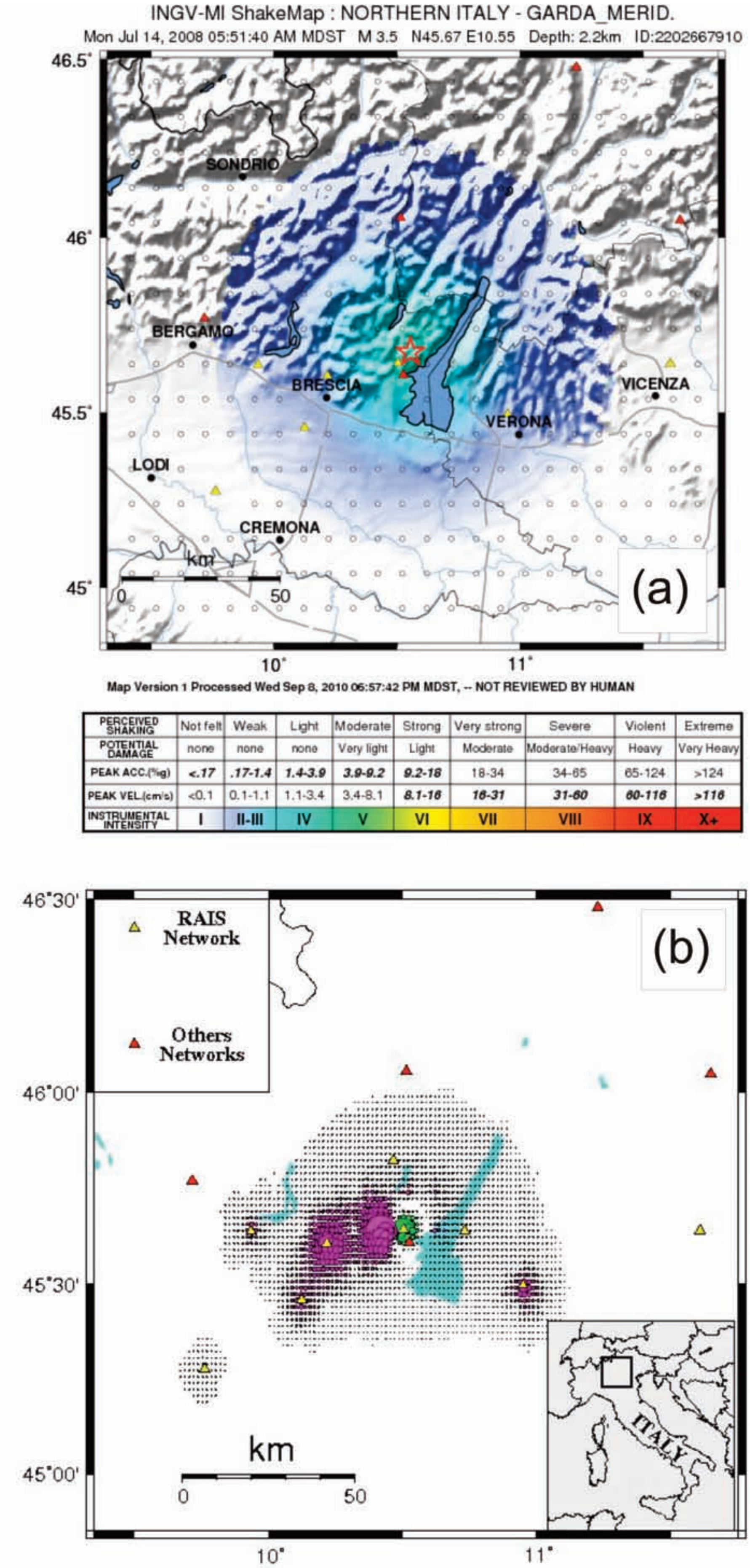


Figure 7. RAIS dataset from June 2006 to June 2010. Left: recordings represented as functions of local magnitude (top) and hypocenter distance (bottom). Right: maximum peak ground acceleration of each record, as $M_L \geq 3$ (top) and $M_L < 3$ (bottom) magnitude classes.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 8. (a) Shake map of July 14, 2008, M 3.5, Garda earthquake for instrumental intensity. Star, epicenter location. (b) PGA residuals obtained with and without considering the RAIS stations. Yellow triangles, RAIS stations; Red triangles, other networks.

(where the real data recorded by RAIS are higher than the synthetic data calculated by the empirical predictive model). Maximum differences are of the order of 18%. The magenta areas in Figure 8b indicate the negative residuals (where the real data recorded by RAIS are lower then the synthetic data calculated by the empirical predictive model). The maximum differences are of the order of 29%.

This result probably arises as the ground-motion prediction equation implemented by the INGV-CNT ShakeMaps package and used for the area under study [Morasca et al. 2006] tends to underestimate the shaking in the near source, and overestimate it in the far field. This demonstrates both the importance of real data availability, to be used as a test, and at the same time the importance of regional variability in the calibration of empirical predictive models.

8. Conclusions

Beginning from June 2006, a phase of installation of strong-motion stations in northern Italy started, in the framework of the 2004-2006 INGV-DPC agreement («Stazioni Accelerometriche» project). Over the last four years, subsequent installations have led to the construction of a new strong-motion network in northern Italy, known as RAIS. Over the last two years, through funds provided by the 2007-2009 INGV-DPC agreement (DPC-S3 project), technological improvement of the new network has been possible. At present, 22 strong-motion stations are installed in the central areas of northern Italy, with an average inter-distance of about 20 km (Figure 1). Fourteen of these 22 stations transmit data in real-time mode to the acquisition center in Milan. The recorded data is managed and stored in MiniSEED format by the SeedLink server using a TCP/IP protocol for real-time data communication, under a SeiscomP platform for monitor plotting and disk recording. At present, a phase of upgrading of the last eight dial-up stations (based on GSM technology) is in progress. In the period from June 2006 to June 2010, RAIS recorded 103 events (about 2,000 three-component waveforms; see Figure 2) with M_L ranging from 0.7 to 5.1. It is worth noting that the collection of high-quality strong-motion data represents a fundamental tool for earthquake engineering and seismology studies. Over the last few years, the RAIS dataset has represented (as it represents today) a useful source for the calibration of empirical attenuation predictive models computed both at local [Massa et al. 2007, Massa et al. 2008] and at national [Bindi et al. 2009] scales. Moreover, a total of 846 three-component records (in terms of PGA, peak ground velocity and acceleration response spectra, for periods of 0.3 s, 1.0 s and 3.0 s) related to 30 events with $M_L \geq 3.0$ have been sent to the INGV-CNT acquisition center to improve the shake maps (http://earthquake.rm.ingv.it/shakemap/shake/) calculated for the earthquakes that have occurred in northern Italy.

The records from the few stations that were installed inside buildings (e.g. ASO7, BAG8) have allowed us to investigate the soil–structure interactions [Massa et al. 2010]. It is worth noting that high-quality strong-motion records represent the input for each advanced structural analysis that combines ground-motion records with detailed structural models.

All of the metadata related to the events recorded by RAIS (together with information regarding stations and site characterization) are available on the website http://rais.mi.ingv.it. The waveforms of the events with $M_L \geq 2.5$ that were recorded in the period from June 2006 to December 2007 have been included in ITACA (http://itaca.mi.ingv.it), in the framework of the 2007-2009 INGV-DPC agreement (S4 project).

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