An Advanced Seismic Network in the Southern Apennines (Italy) for Seismicity Investigations and Experimentation with Earthquake Early Warning

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INTRODUCTION

The last strong earthquake that occurred in the southern Apennines, the Irpinia earthquake on 23 November 1980 (**M** 6.9), was characterized by a complex rupture mechanism that ruptured three different faults (Bernard and Zollo 1989). This earthquake was well studied, and the quantity of data available has allowed a very detailed definition of the geometry and mechanisms of faults activated during this seismic event (Westaway and Jackson 1987; Pantosti and Valensise 1990).

Even more than 20 years after the main event, the seismotectonic environment that contains the fault system on which the 1980 earthquake occurred shows continued background seismic activity including moderate-sized events such as the 1996 (**M** 5.1), 1991 (**M** 5.1) and 1990 (**M** 5.4) events. Moreover, the locations of the microearthquakes (taken from the database of the Istituto Nazionale di Geofisica e Vulcanologia, INGV) define an epicentral area with a geometry and extent surprisingly similar to that of the 1980 earthquake and its aftershocks (figure 1A). These simple observations suggest that it may be possible to study the preparation cycles of strong earthquakes on active faults by studying the microseismicity between seismic events. With this in mind, a seismic network of large dynamic range was planned and is now in an advanced phase of completion in the southern Apennines. Called ISNet (Irpinia Seismic Network), it is equipped with sensors that can record high-quality seismic signals from both small-magnitude and strong earthquakes, from which it will be possible to retrieve information about the rupture process and try to understand the scaling relationships between small and large events.

Due to its high density, wide dynamic range, and advanced data-acquisition and data-transmission technologies, the network is being upgraded to become the core infrastructure of a prototype system for seismic early warning and rapid post-event ground-shaking evaluation in the Campania region, which has seismic hazard that ranks among the highest in Italy (Cinti *et al.* 2004). ISNet will be devoted to real-time estimation of earthquake location and magnitude and to measuring peak ground-motion parameters so as to provide rapid ground-shaking maps for the whole of the Campania region. The information provided by ISNet during the first seconds of a potentially damaging seismic event can be used to activate several types of security measures, such as the shutdown of critical systems and lifelines (Iervolino *et al.* 2006).

The implementation of a modern seismic network involves many different research and technological aspects related to the development of sophisticated data management and processing. The communication systems need to rapidly generate useful, robust, and secure alert notifications. Here we provide a general technical and seismological overview of ISNet's complex architecture and implementation.

GEOLOGICAL SETTING, HISTORICAL AND RECENT SEISMICITY OF THE CAMPANIA-LUCANIA APENNINES

The southern Apennines constitute an active tectonic region of Italy that accommodates the differential motions between the Adria and Tyrrhenian microplates (Jenny *et al.* 2006), the source of almost all the seismicity in this region. Earthquakes originate in a narrow belt along the Apennine chain and are associated with young faults confined to the upper 20 km of the crust (Meletti *et al.* 2000; Valensise *et al.* 2003). Along with more recent in situ stress data analysis (Montone *et al.* 2004), analyses of seismological data for earthquake location, size, and mechanisms have shown that the southern Apennines are characterized by an extensional stress regime. The dominant mecha-

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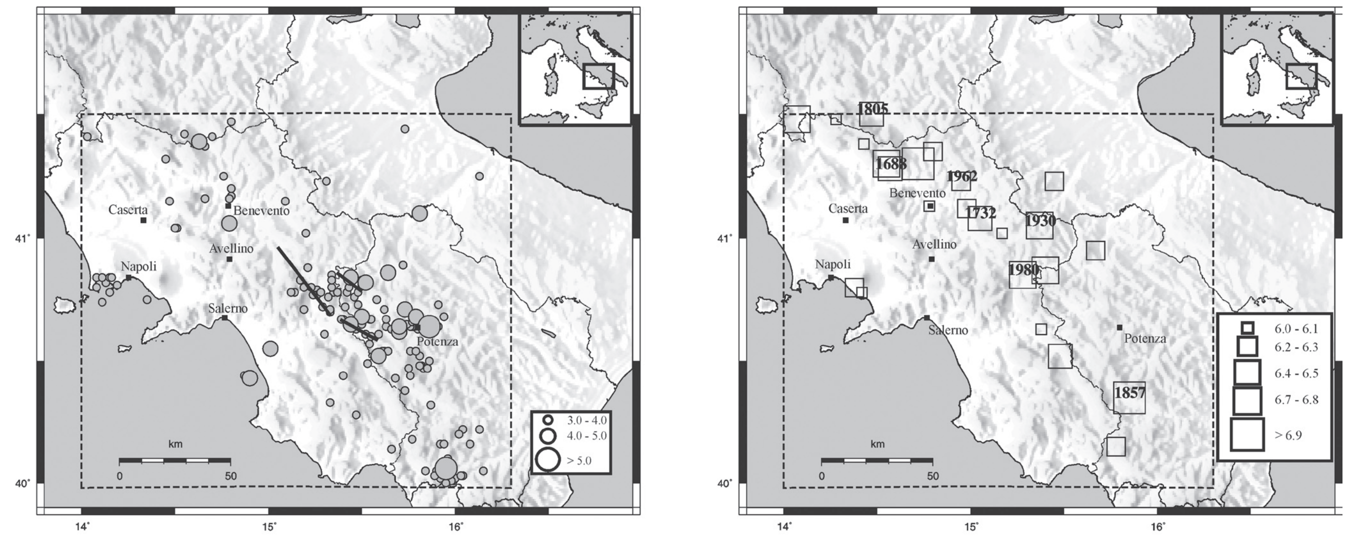


(A) (B)

▲ **Figure 1.** (A): Map of recent instrumental seismicity with M > 2.5 recorded by the INGV in the period 1981–2002 in the region defined by the dashed rectangle. Dimensions of the circles are proportional to magnitude. The black lines represent the surface projection of the three fault segments that broke in the 23 November 1980 earthquake (M 6.9). B) Locations of the main historical earthquakes retrieved from the CFTI database within the region defined by the dashed rectangle. The box dimensions are proportional to magnitude. The best-constrained historical earthquakes are reported along with their dates of occurrence.

nism is normal faulting, although there have been some recent (*e.g.*, 5 May 1990, Potenza, **M** 5.4; 31 October–1 November 2002, Molise, **M** 5.4) strike-slip earthquakes, the origins of which are still unclear (Fracassi and Valensise 2003; Valensise *et al.* 2003).

Historically, the southern Apennines have experienced numerous large disastrous events, including events in 1456, 1694, 1851, 1857, and 1930. The most recent was the complex normal-faulting Irpinia earthquake (23 November 1980, **M** 6.9) that resulted in about 3,000 deaths and enormous damage also to the city center (Westaway and Jackson 1987; Bernard and Zollo 1989). There is at present very frequent occurrence of small to moderate-size events. Moreover, as indicated in a recent study by Cinti *et al.* (2004), the southern Apennine region has a high probability of occurrence for **M** ≥ 5.5 earthquakes, thus making it a region with a high seismic risk level.

Figure 1A shows the recent instrumental seismicity for **M** > 2.5 recorded by the INGV seismic network in the area indicated by the rectangle for the period 1981–2002. Note that the seismicity is mainly concentrated around the three fault segments associated with the Irpinia earthquake, or along their continuation toward the northeast and the southwest, which shows high seismic activity. On the other hand, using macroseismic data integrated with geological, geomorphological, and geophysical data, it has been possible to retrieve location and fault geometry for a limited number of historical events (Fracassi and Valensise 2003). The locations and magnitude of the historic earthquakes retrieved from the Catalogo dei Forti Terromoti in Italia (CFTI) (Boschi *et al.* 1997) are shown in figure 1B. For the best-documented historic events, the dates of occurrence are also given.

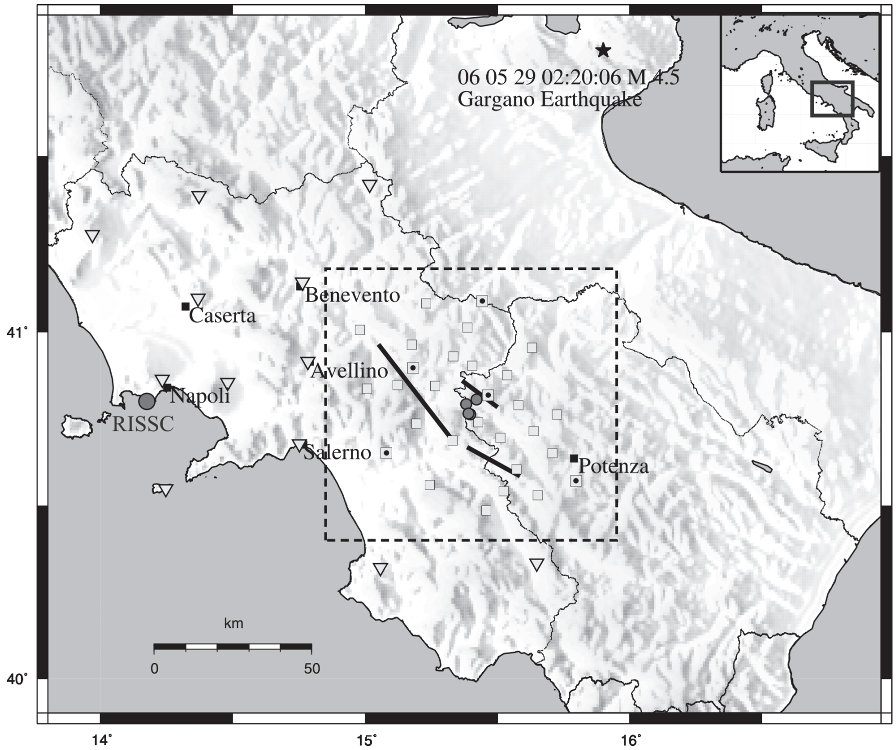
THE IRPINIA SEISMIC NETWORK (ISNet)

General Overview

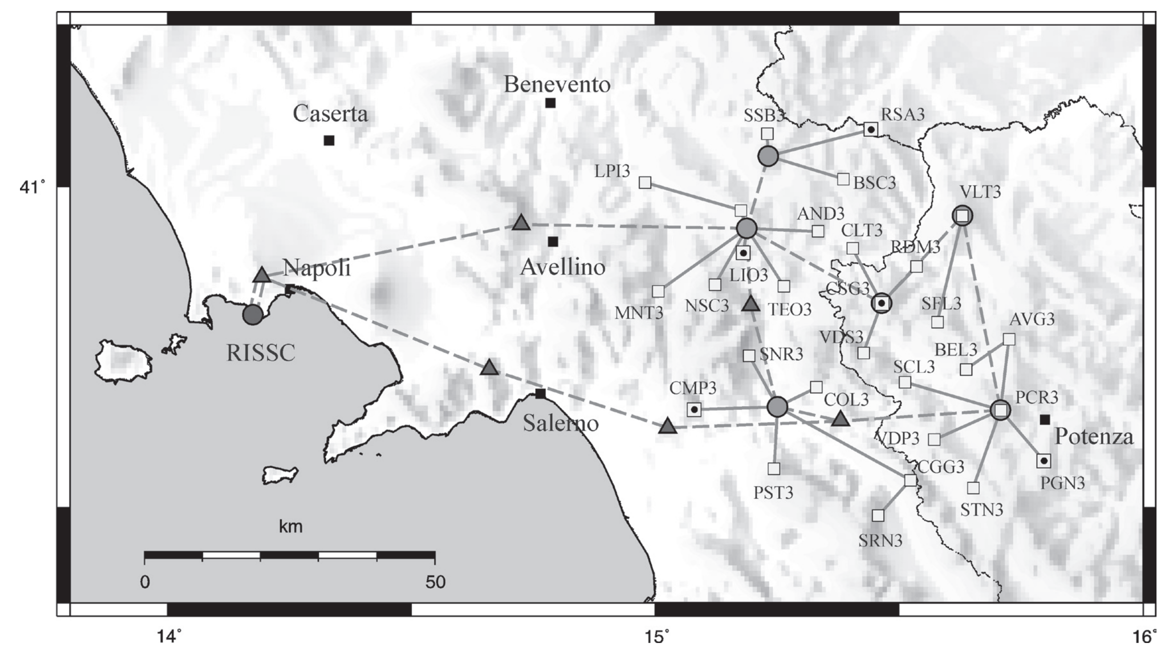
ISNet covers an area of approximately 100 km × 70 km along the southern Apennine chain and is deployed around and over the active fault system that generated the 1980 Irpinia earthquake. ISNet configuration does not follow a central site-communication model for transmission of seismic data from a remote site; it uses an extended star topology designed to ensure fast and robust data recording and analysis. The signals are acquired and processed at different locations in the network. This configuration leads to four fundamental network elements: the seismic stations, the local control centers (LCC), the central network control center (RISSC), and the data communication systems (Weber *et al.* 2007). Figure 2 illustrates the locations of the stations that comprise ISNet. The stations are deployed along two imaginary concentric ellipses, with the major axes oriented NW-SE and parallel to the Apennine chain. The interstation distances vary from about 10 km in the inner ellipse to about 20 km in the outer ellipse. Each seismic station is connected via radio link to an LCC (figure 3), which is itself linked to the RISSC by an E1 digital broadband (HDSL) wire line over a frame relay. Through the use of permanent virtual circuits (PVCs), the frame relay allows the central site to use a single phone circuit to communicate with the multiple remote sites (the LCCs). The whole data transmission system is fully digital over transmission control protocol/Internet protocol (TCP/IP), from the dataloggers, through the LCC, to the control room in Naples.

Subnets of Seismic Stations and LCCs

ISNet is composed of 29 seismic stations grouped in six subnets, each composed of a maximum of six to seven stations (figure 3



▲ **Figure 2.** Station map of the Irpinia Seismic Network (ISNet). The squares represent the ISNet stations. Seismic stations with the sensors Guralp CMG-5T/Geotech S13-J are shown as squares without a black dot and those with the sensors Guralp CMG-5T/Nanometrics Trillium are shown as squares with a black dot. Also shown are the Network Control Center (RISSC) and the M 4.5 Gargano earthquake (star). The 12 stations for post-event applications, under construction, are shown as inverted triangles.



▲ **Figure 3.** The ISNet communication system. The extended star topology and the subnets of the seismic network are visible. The squares represent the ISNet stations and the circles the Local Control Centres (LCC). The gray lines are the radio links between the stations and the LCCs, and the dashed lines are planned SDH carrier-class radio upgrades for early-warning applications. Also depicted is the radio ring between the LCCs and the two independent branches to the RISSC Control Centre in Naples that guarantees the necessary transmission redundancy. The triangles represent radio repeater points. The Network Control Centre (RISSC) and the main cities (black squares) in the region are marked. Squares with black dots correspond to stations equipped with the sensors Guralp CMG-5T and Nanometrics Trillium.

and table 1). The stations of each subnet are connected with real-time communications to a specific LCC.

The seismic stations are placed in 2-m × 2-m × 2-m shelters that are installed inside 6-m × 4-m fenced areas. Each station is supplied with two solar panels (120 W peak, with 480 Wh/day), two 130 Ah gel cell batteries (which avoids freezing damage), and a custom switching circuit board between the batteries. With this configuration, 72-h autonomy is ensured for the seismic and radio communication equipment. Each site is also equipped with a global system for mobile communications (GSM)/general packet radio service (GPRS) programmable control/alarm system connected to several environmental sensors (*e.g.*, door, solar panel controller, batteries) and through which the site status is known in real time. This alarm system has standby power for at least three weeks. The GSM modem will also be connected to the data-loggers and will be used as a backup data communication line. With short messages (SMS) and through the programmable GSM controller, the seismic equipment can be completely reset with a power shutdown/restart. The GSM also controls the device start/stop release procedure when the battery goes over/under a predefined voltage level.

The six LCCs collect and store the incoming data from the seismic stations of the subnet to which they are connected via digital radio. The LCCs are positioned near small towns (in a shelter) or in existing buildings with an AC power supply and fast communication connections. At some sites, the LCC also hosts a seismic station. In such cases, the sensors are outside in a shallow hole, at a depth of 1 m to 1.5 m, with the data-logger and other equipment located inside an adjacent building. Each LCC has gel batteries for 320 Ah, a GSM remote-control sys-

TABLE 1
The station codes, their locations and the sensors/data loggers of the Irpinia Seismic Network (ISNet) depicted in figure 2. Not listed are the stations for post-event purposes (inverted triangle figure 2) and under development.

Station Code	Latitude	Longitude	Elevation (m)	Sensors	Data logger	Location
AND3	40.92975	15.33310	870	Geotech S13-J, Guralp CMG-5T	Osiris-6	Andretta
AVG3	40.76185	15.72512	1213	Geotech S13-J, Guralp CMG-5T	Osiris-6	Avigliano
BEL3	40.71494	15.63686	498	Geotech S13-J, Guralp CMG-5T	Osiris-6	Bella
BSC3	41.01166	15.38497	972	Geotech S13-J, Guralp CMG-5T	Osiris-6	Bisaccia
CGG3	40.54191	15.52263	1062	Geotech S13-J, Guralp CMG-5T	Osiris-6	Caggiano
CLT3	40.90303	15.40433	588	Geotech S13-J, Guralp CMG-5T	Osiris-6	Calitri
CMP3	40.65213	15.07988	958	Nanometrics Trillium, Guralp CMG-5T	Osiris-6	Campagna
COL3	40.68716	15.33063	1066	Geotech S13-J, Guralp CMG-5T	Osiris-6	Colliano
CSG3	40.81805	15.46417	1250	Nanometrics Trillium, Guralp CMG-5T	Osiris-6	Castelgrande
LIO3	40.89653	15.18033	649	Nanometrics Trillium, Guralp CMG-5T	Osiris-6	Lioni
LPI3	41.00583	14.97916	881	Geotech S13-J, Guralp CMG-5T	Osiris-6	Lapio
MNT3	40.83697	15.00660	920	Geotech S13-J, Guralp CMG-5T	Osiris-6	Montella
NSC3	40.84688	15.12226	1270	Geotech S13-J, Guralp CMG-5T	Osiris-6	Nusco
PCR3	40.65135	15.70801	1350	Geotech S13-J, Guralp CMG-5T	Osiris-6	Picerno
PGN3	40.57212	15.79667	860	Nanometrics Trillium, Guralp CMG-5T	Osiris-6	Pignola
PST3	40.56022	15.24330	765	Geotech S13-J, Guralp CMG-5T	Osiris-6	Postiglione
RDM3	40.87538	15.53602	815	Geotech S13-J, Guralp CMG-5T	Osiris-6	Ruvo del Monte
RSA3	41.08788	15.44238	510	Nanometrics Trillium, Guralp CMG-5T	Osiris-6	Rocchetta S. Antonio
RSF3	40.96274	15.17508	850	Geotech S13-J, Guralp CMG-5T	Osiris-6	Rocca S. Felice
SCL3	40.69503	15.51161	870	Geotech S13-J, Guralp CMG-5T	Osiris-6	Muro Lucano
SFL3	40.78892	15.57828	1058	Geotech S13-J, Guralp CMG-5T	Osiris-6	S. Fele
SNR3	40.73619	15.19258	998	Geotech S13-J, Guralp CMG-5T	Osiris-6	Senerchia
SRN3	40.48636	15.45680	1060	Geotech S13-J, Guralp CMG-5T	Osiris-6	S. Arsenio
SSB3	41.08122	15.22925	666	Geotech S13-J, Guralp CMG-5T	Osiris-6	S. Sossio Baronia
STN3	40.52991	15.65138	828	Geotech S13-J, Guralp CMG-5T	Osiris-6	Satriano
TEO3	40.84417	15.26361	868	Geotech S13-J, Guralp CMG-5T	Osiris-6	Teora
VDP3	40.60544	15.57130	850	Geotech S13-J, Guralp CMG-5T	Osiris-6	Vietri di Potenza
VDS3	40.74089	15.42692	1154	Geotech S13-J, Guralp CMG-5T	Osiris-6	Muro Lucano
VLT3	40.95424	15.62984	1267	Geotech S13-J, Guralp CMG-5T	Osiris-6	Vulture

tem, a Cisco router, and an HP Proliant server with a 320-Gbyte hard disk. All of the instruments are connected to the batteries and 72-h standby power is guaranteed. All the LCCs use the Earthworm system for data collection and processing (Johnson *et al.* 1995).

Sensors and Data-loggers

Inside each seismic site, the sensors are installed on a 1-m^3 reinforced concrete base at least 0.8 m inside the soil. To ensure a high dynamic range, each station is equipped with two types of three-component sensors: strong-motion accelerometers and velocity instruments. Twenty-four sites are equipped with a Guralp CMG-5T accelerometer and a set of short period ($T_0 = 1$ s) Geotech S13-Js. The remaining sites have a Guralp CMG-5T and broadband Nanometrics Trillium (0.025-50 Hz band) sensors. To minimize the thermal effect for the last sites to be built, the accelerometer was placed in a 30-cm deep hole and covered with sand. Before installation, the sensor/data-logger pairs are fully calibrated for single-channel responses by an automated process. This calibration covers the entire frequency spectrum using LabVIEW/MatLab software package that provides the transfer function in graphical mode and in terms of poles and zero.

Data acquisition at the seismic stations is performed by an innovative data-logger produced by Agecodagis, the Osiris-6 model (http://www.agecodagis.com). Some characteristics of the Osiris-6 are a Σ-Δ 24-bit A/D converter, a 100-MHz ARM® processor with embedded Linux and open-source software, onsite data storage (through one removable 5-Gbyte microdrive or a compact flash card), serial and TCP/IP connectivity, global positioning system (GPS) time tagging, an integrated SeedLink server, and simple/flexible configuration via a Web interface (HTTP). The data-loggers have six physical and up to 24 logical channels, and each waveform can be analyzed with different sampling rates at the same time, for different purposes. (See Romano and Martino 2005 for an overview of the Osiris-6 data-loggers).

The external GPS receiver (RS-232) guarantees a timing accuracy that is better than 1 μs. A complete health status is available that assists in the diagnosis of station component failure or data-logger malfunction. The data-loggers store the data locally on their microdrives or send it via SeedLink to Earthworm in the nearest LCC in 1-s packets. The real-time analysis system performs event detection and location based on triggers coming from the data-loggers and parametric information such as arrival-time picks or not-yet-triggered stations provided by the other LCCs. A PostgreSQL developed database (ISNet Devices Manager) tracks the general configuration of the seismic network, such as the recorded channels, sampling rates for each channel, gain, sensor type, data-loggers, and other network devices, with IP addresses, station positions, and serial numbers for each device installed.

Current Data-communication Configuration

ISNet presently uses several different transmission systems. The seismic stations are connected via spread-spectrum radio links to the LCCs (figure 3). To transmit waveforms in real time from the seismic sites to the LCCs, two outdoor 1310 Cisco Wireless local area network (LAN) bridges that operate in the 2.4 GHz industrial, scientific, and medical (ISM) band are used for each link. Each LCC is connected through different technology and media types to the RISSC in Naples, as shown in table 2.

The two primary backbone data communication systems of the central site use symmetrical high-speed digital subscriber line (SHDSL) technology over a frame-relay protocol. Frame relay offers a number of significant benefits over analog and digital point-to-point leased lines. With the latter, each LCC requires a dedicated circuit between the LCC and the RISSC. Instead, the SHDSL frame relay is a packet-switched network, which allows a site to use a single frame-relay phone circuit to communicate with multiple remote sites through the use of permanent virtual circuits. The frame relay network uses digital phone circuits that can support up to 1.5 Mbps throughput for each single twisted-copper-wire pair. In the present SHDSL configuration, two twisted-copper-wire pairs are used to ensure 2 Mbps transfer. The monthly costs of long-distance digital packet-switched technology for fast data communication are much lower than for leased phone lines. With virtual circuits, each remote site is seen as part of a single private LAN, simplifying IP address scheme maintenance and station monitoring.

Each seismic site has a real-time data flow of 18.0 kbps (at a 125-Hz sampling rate for each physical channel), and the overall data communication bandwidth that is needed is around 540 kbps for 30 stations. ISNet supports this throughput under the worst conditions seen, and it has been designed to permit further developments, such as additional seismic or environmental sensors, without greater economic and technological investment. The currently used data transmission protocol is TCP/IP, but for early-warning-application data acquisition, we intend to adopt the connectionless user datagram protocol/Internet protocol (UDP/IP) to avoid unwanted overheads and "handshaking" between sending and receiving transport-layer entities before sending data segments. In early-warning waveform analysis, where single-packet error/missing does not influence decisions in a critical manner, this protocol is much faster and simpler to handle than TCP/IP.

The Network Control Centre (RISSC)

The seismic waveforms are stored locally on the data-loggers and in real-time at the nearest LCC. At present, only selected signals are transmitted to the RISSC in Naples, and this is done manually and only for research purposes. We are developing a storage system at the RISSC that acts after the triggering of an LCC (through Earthworm) or a station, which will have fully automated capabilities. For redundancy, we are also considering storing the complete datasets coming from each station at the RISSC, following a central site model. For this reason, we have installed a large storage cluster (6 terabyte HP storage server) at the RISSC on which all of the waveforms/events can be loaded. The RISSC tracks the seismic events and monitors the entire network, including the data-loggers and radio links, through commercial network and bandwidth monitoring software.

TABLE 2.
Specification of the ISNet data communication links.

Type	Frequency (GHz)	Bandwidth (Mbps)	# Number of Stations	# Number of LCCs	Comments
Spread spectrum Radio	2.45	54	27[3]	—	Throughput around 20–24 Mbps for links between 10–15 km (based on ethernet packets with an average size of 512 bytes).
Ethernet	—	100	2		Stations connected with ethernet cable to LCC infrastructure.
Wireline SHDSL over Frame Relay	—	2.048	—	2	At the central site (RISSC) the CIR[1] is maximum 1.6 Mbps depending upon number of PVCs[2]. At the remote (LCC) site the bandwidth is 640/256 kbps with CIR of 64kbps in up and download, over ADSL with ATM ABR service class.
Microwave Radio SDH	7	155	—	2	Nera Networks carrier-class microwave link. Connect two LCC with 155 Mbps (STM-1) truly full bandwidth available. First link constructed for early-warning applications.
Microwave Radio HyperLAN/2	5.7	54	—	2	The true usable maximum throughput of HiperLAN/2 is 42Mbps.

1. CIR Committed Information Rate.
2. PVC permanent virtual circuit.
3. Without the stations that are also LCCs.

ISNet Data Flow and Management

As shown in figures 3 and 4, the ISNet data and information flow can be managed on three different levels:

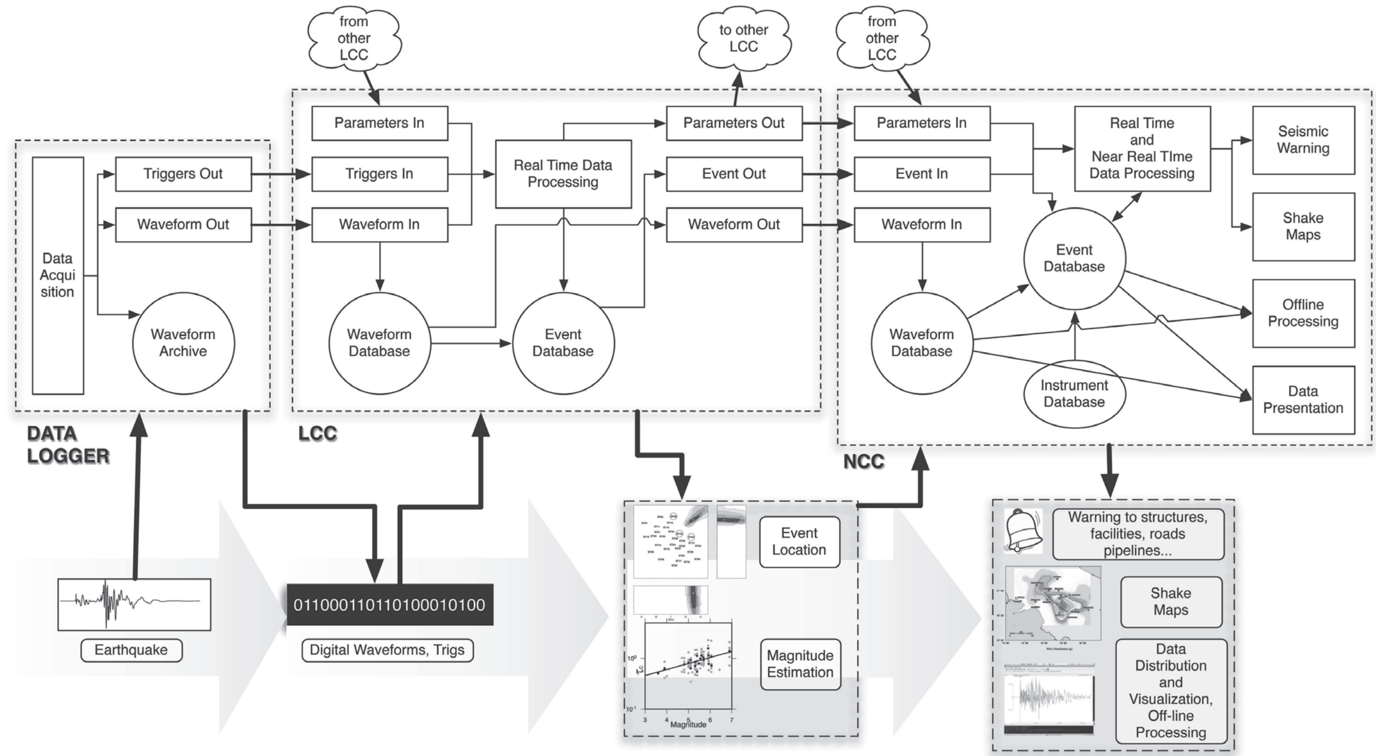
- recording sites
- LCCs
- RISSC in Naples

The LCCs run the Earthworm real-time seismic processing system and keep a complete local database of waveforms from the seismic stations directly connected to them. The system will perform real-time event detection and location based on the triggers coming from data-loggers and parametric information such as arrival-time picks coming from the other LCCs. Once an event is detected, the system will perform automatic magnitude and focal mechanism estimations. The results of these analyses are used to build a local event database, and at the same time, they are sent to the other LCCs and to the RISSC. Immediately after an event, the RISSC will calculate ground-shaking maps using data provided by LCCs and/or from the event database. Finally, the recorded earthquake data are stored in an event database, where they are available for distribution and visualization for further offline analyses (figure 4).

As indicated in the previous section, ISNet has a complex infrastructure and must be accurately managed for proper real-time functionality. The most important factor is station and transmission network availability. To check the availability status of the network, we need a real-time cross-check of different information sources. A large network is made up of many vendor devices for which the health status cannot necessarily be monitored by commercial software. To overcome these limitations, we are developing the ISNet Devices Manager (ISNM). The ISNM will be a complete real-time monitoring suite with a notification system to report failure or critical status of any of the network elements (figure 5). The collected data from each device will be stored in a database. Considering the network complexity, various information sources will be used: SMS, e-mail, simple network management protocol (SNMP), Internet control message protocol (ICMP), proprietary commands (Osiris), and netflow (Cisco network flow-control protocol).

Today, in the first phase of development, the network manager handles two kinds of data about the devices: user-inserted data and automatically collected data. ISNM is made up of four fundamental components:

- A Web application, based on JavaServer Pages, provides the user interface. The Web server is powered by the open-source standard Apache/Tomcat. A specific library of tags has been implemented to ease the interfacing of the Web server with a database server.
- A database for the ISNet devices, managed by a server running PostgreSQL. It is designed to store information related to all the sites and the data communication links between them, as well as the details of the installed devices such as servers, loggers, sensors, network and generic hardware, along with their configurations and mutual connections. The database thus stores the details of the state of the whole network, not only as it is at present, but also as it was at any given instant in the past, to correlate the status of devices and sensors with the seismic recordings.



▲ **Figure 4.** A schematic view of the data flow from the data-logger to the Control Centre in Naples and the three possible computational levels in the seismic network.

- A series of programs, written in Java, designed to periodically connect to a device and retrieve a subset of its internal parameters, such as the internal temperature, CPU load, or battery voltage. Those data are automatically attached to the history of the device in the database. The scheduling of this device's health monitoring is performed through the Web application, which also displays, in the form of graphs, the history of the state of the monitored devices. At the time of this writing, different tools have been created to interrogate different devices (loggers, network hardware). In the future, we plan to implement a universal tool based on the SNMP to easily integrate different hardware or new revisions of already supported hardware. Not all devices need to be actively monitored by the server: a class of devices at the stations is connected to several environmental sensors and programmed to send alarms when a critical threshold is reached. The alarms are sent as text messages over the GSM telephone line, stored in the database by a tool listening on the server, and highlighted by the Web application.
- A waveforms and events database, which is also actively under development. It is possible to submit to the server, through a batch process, several waveform files recorded by the stations that are related to an event. The process creates a record of the event and of the waveforms and links the latter to the sensors that recorded them and the device configuration at the time of the event. It is then possible to perform a query for events or waveforms by filtering date, site, sensor, component, magnitude, and distance.

The ISNM has a server/client architecture. The data collected at each of the LCCs will be sent in parameterized form to the server, which will then analyze the incoming information from all of the network elements.

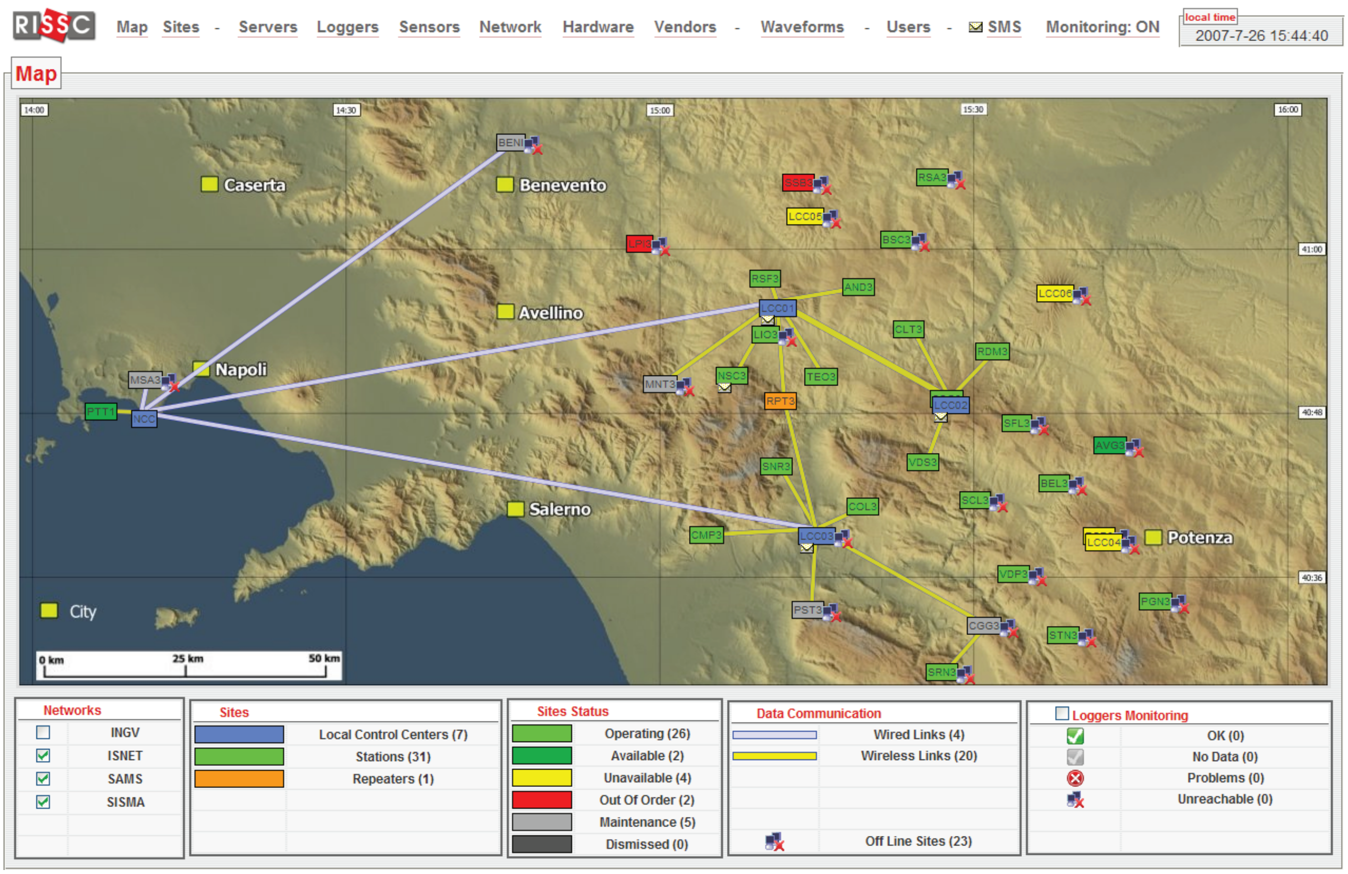
ISNet UPGRADE FOR SEISMIC EARLY-WARNING AND POST-EVENT APPLICATIONS

As described in the previous sections, ISNet has been designed and developed with modern communications, data acquisition, and data processing technology. However, in order to use it for seismic early-warning and post-event applications, it will need hardware and software upgrades (Weber *et al.* 2007). In particular, ISNet will have three new infrastructures integrated into it (figure 3):

- a proprietary data communication system connecting the LCCs to each other;
- a second proprietary data transmission system that connects some LCCs to the RISSC in Naples; and
- an integrated seismic network that covers the Campania region outside the source area.

Data Communication Enhancements for Early-warning Purposes

A reliable and effective data communications system is a main concern for all early-warning applications. Based on our experience in developing ISNet, we think that complete control and management of the telecommunication systems, from the



▲ **Figure 5.** Network map ISNet Devices Manager (ISNM) database home Web page. The key shows the color scheme for site types and status and the communications links. On the top of the http page the links to the single-network-element Web pages are visible. On each site Web page, different site description data are available (status, location, photo, notes and files, SMS alerts, installation date, etc.) and the installed equipment is listed (connection type with nearest data analyzing system, data logger, sensors, and radio hardware).

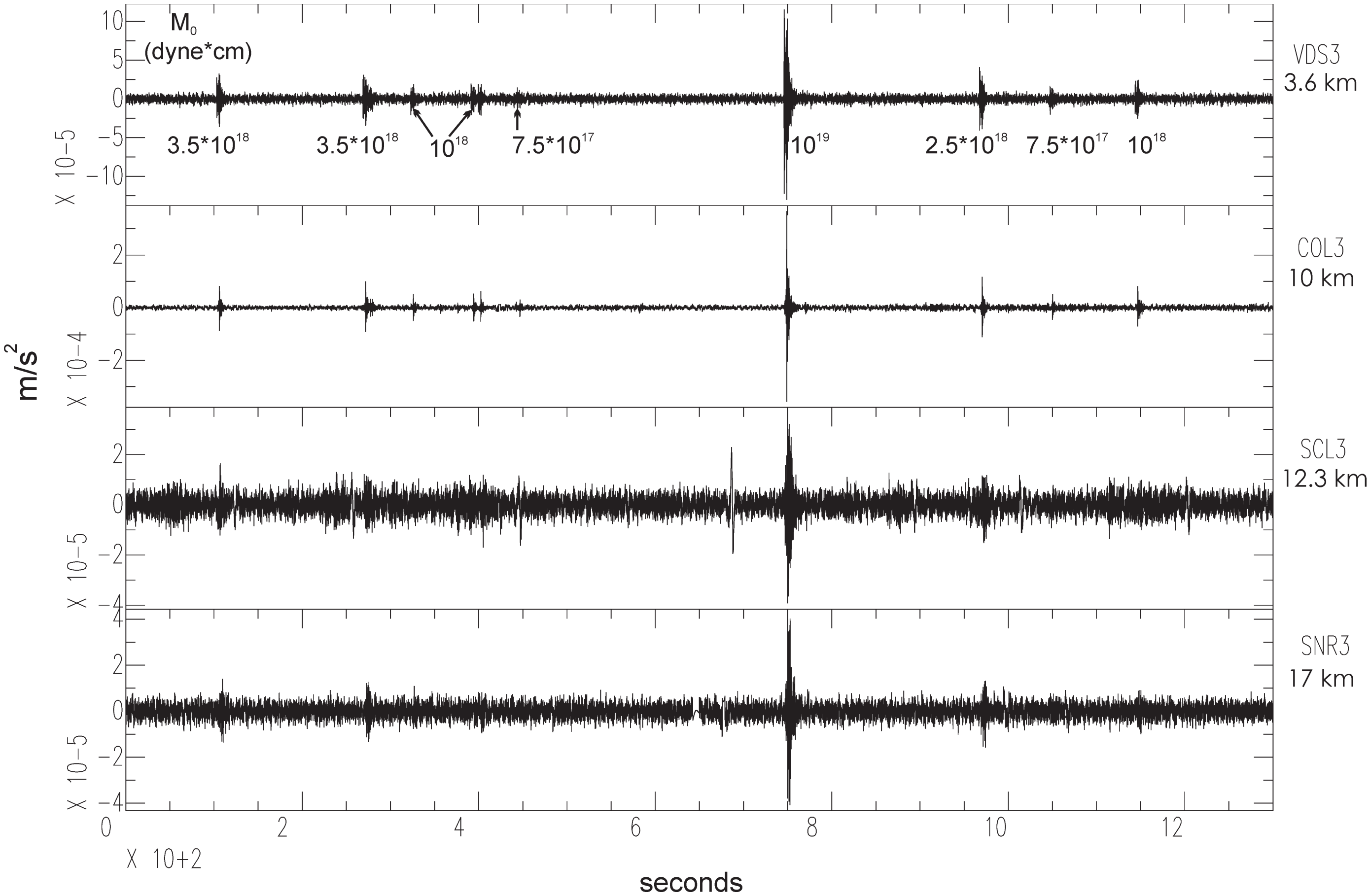
data-loggers to the RISSC, is necessary for effective experimentation with early-warning applications. Without it one cannot hope to understand latency, delay, failure, and weak points in complex data-communications structures designed to provide rapid information; identify elements where essential time can be gained; and determine what future technological improvements of the entire early-warning system are indicated.

To avoid data-loss from the entire network in the case of failure of one or more of the links and to provide a communications system that is under our control, we plan to upgrade ISNet in the near future with a multiple radio-path data communication network. Redundancy in telecommunications paths and the percentage of time that the system is not functioning are fundamental parameters to be considered when planning network enhancements. Two rings have been created in the network: the first interconnects the six LCCs, and the second connects the first to the RISSC in Naples. We think that by selecting suitable technology and radio devices, we can reach an overall system availability of 99.99% in the first development step and 99.999% when the network is fully up and running. To reach this high availability rate, we have selected a carrier-class telecommunications device for the radio link. The first link is still being completed and will be used for the first main tests (figure 3). The radio device has the capability of an ethernet mapped over synchronous digital hierarchy (SDH), with 155 Mbps (STM-1) throughput in a licensed 7-GHz frequency band.

Combining different technologies, such as satellite, radio, and digital wire lines, will make it easier and faster to accomplish these high availability rates. We will evaluate the use of these multiple communication technologies in three LCCs. We have also taken into account the following constraints when planning the new data communication system: system reliability and redundancy, low or no system damage during a strong earthquake, overall transmission delays less than 100–200 ms, and data security.

Integrated Seismic Stations

An important element in managing an emergency in the minutes after a strong earthquake is predicting the distribution of the damage in the region. Rapid ground-shaking calculation in terms of one or more strong ground-motion parameters such as peak ground acceleration (Pga), peak ground velocity (Pgv), spectral ordinates (Sa(T)) or instrumental intensity (I_{MM}) are key elements in this effort (Wald *et al.* 1999; Goltz 2003). Ground-shaking maps are usually generated by integrating data recorded during the earthquake with estimates performed by using pre-existing attenuation relationships. For the Campania



▲ **Figure 6.** Irpinia seismic sequence recorded at four ISNet stations (vertical components) arranged top to bottom as a function of the epicentral distance. The seismic moment (dyne-cm) is indicated above the corresponding event.

region, we retrieved an ad hoc attenuation relationship for peak ground-motion quantities applying the stochastic simulation method of Boore (1983) and source and attenuation parameters retrieved from the INGV earthquake waveform catalog (Convertito *et al.* 2007).

To produce reliable ground-shaking maps after a strong earthquake in the southern Apennines, we plan to install an additional network of 12 seismic stations in the Campania region (figure 2). Each station will be equipped with the same instruments as ISNet (Osiris data-loggers with accelerometers and velocity sensors). We will retrieve data from these stations through a GPRS/universal mobile telecommunications system (UMTS) and automatically download and process only after a trigger from ISNet. The 12 new regional seismic stations will be used only to retrieve peak ground parameters to compute ground-shaking maps.

EXAMPLES OF RECORDED WAVEFORMS

In this section, we show several examples of local and regional waveforms that have already been recorded by the accelerometer sensors of the ISNet network. In an operational period of 12 months with a minimum of six stations running, ISNet has recorded 124 local and regional events with magnitudes ranging between 0.7 and 4.8 (seismic moment Mo= 7.5×10^{17} to 1×10^{19} dyne-cm).

As an example showing the network sensitivity at a very low-magnitude level, we report in figure 6 the vertical acceleration records of a sequence of microearthquakes, with M_w computed by using the Hanks and Kanamori (1979) relationship in the range 1.2 to 1.9, that occurred in a 20-min time window and were located approximately at the network center (see locations in figure 2). In figure 6, the records have been arranged from top to bottom as a function of the epicentral distance so as to display the variation in the signal-to-noise levels as a function of seismic moment and distance from the earthquake source, whose depths range between 11 km and 23 km (as reported in the INGV earthquake database).

The seismic moment and the corresponding magnitude moment of these events has been calculated by measuring the low-frequency DC level on the *S*-wave displacement spectrum after the constant Q_S attenuation correction and applying the Brune (1970) model:

$$M_0 = \frac{4\pi\rho c^3 r}{R^c F^s}\Omega_0 \tag{1}$$

where the parameters of equation (1) have been selected as follows:

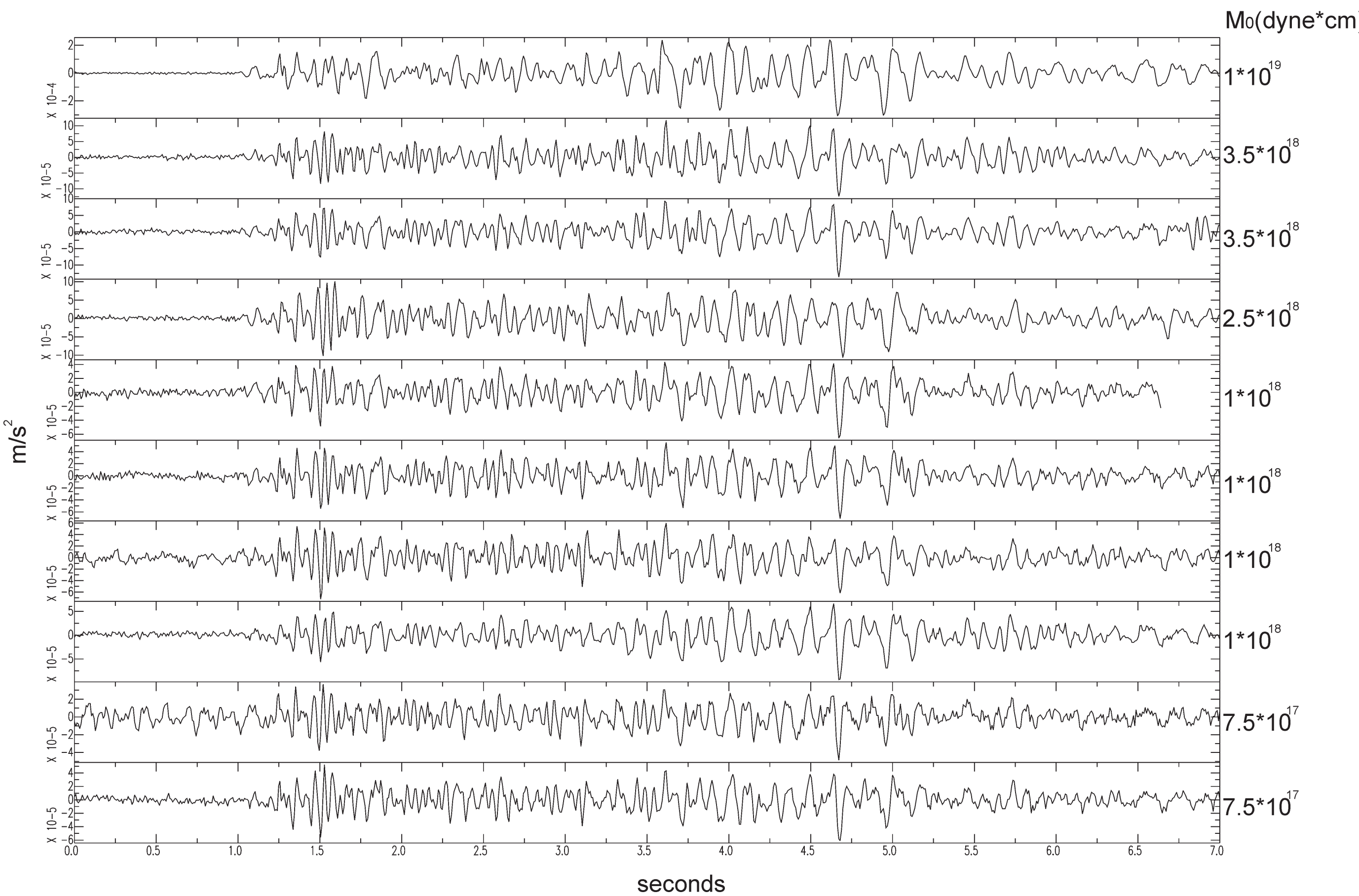
ρ = 2.7 g/cm^3 (density)
c = 3.6 km/s (S-wave velocity)
R^c = 0.6 (radiation pattern of S waves)
F^s = 2 (free-surface factor)
r = hypocentral distance
Q_s = 120 (Convertito *et al.* 2007)
Ω_0 is low frequency displacement spectrum amplitude in m·s.

A time window of 5 s bracketing the handpicked S arrival has been selected for this analysis. The estimated M_0 values are reported in correspondence with each event detected, as shown in figure 6. The values of M_0 greater than 1×10^{18} dyne-cm have been estimated as the averages calculated from the data recorded by four stations. By visual inspection of the accelerograms in figure 6, we can roughly estimate a maximum detection distance of about 10 km for events with seismic moment as small as $M_0 = 7.5 \times 10^{17}$ dyne-cm or 1.2 moment magnitude. Since the half-distance spacing between ISNet stations in its central area is about 10 km, we would expect to have at least two records for such small-magnitude events when they occur inside the network. However, more refined analyses based on the recorded noise levels are needed to better quantify the distance/magnitude detection thresholds. The example shown may provide an approximate indication of the acceleration network sensitivity.

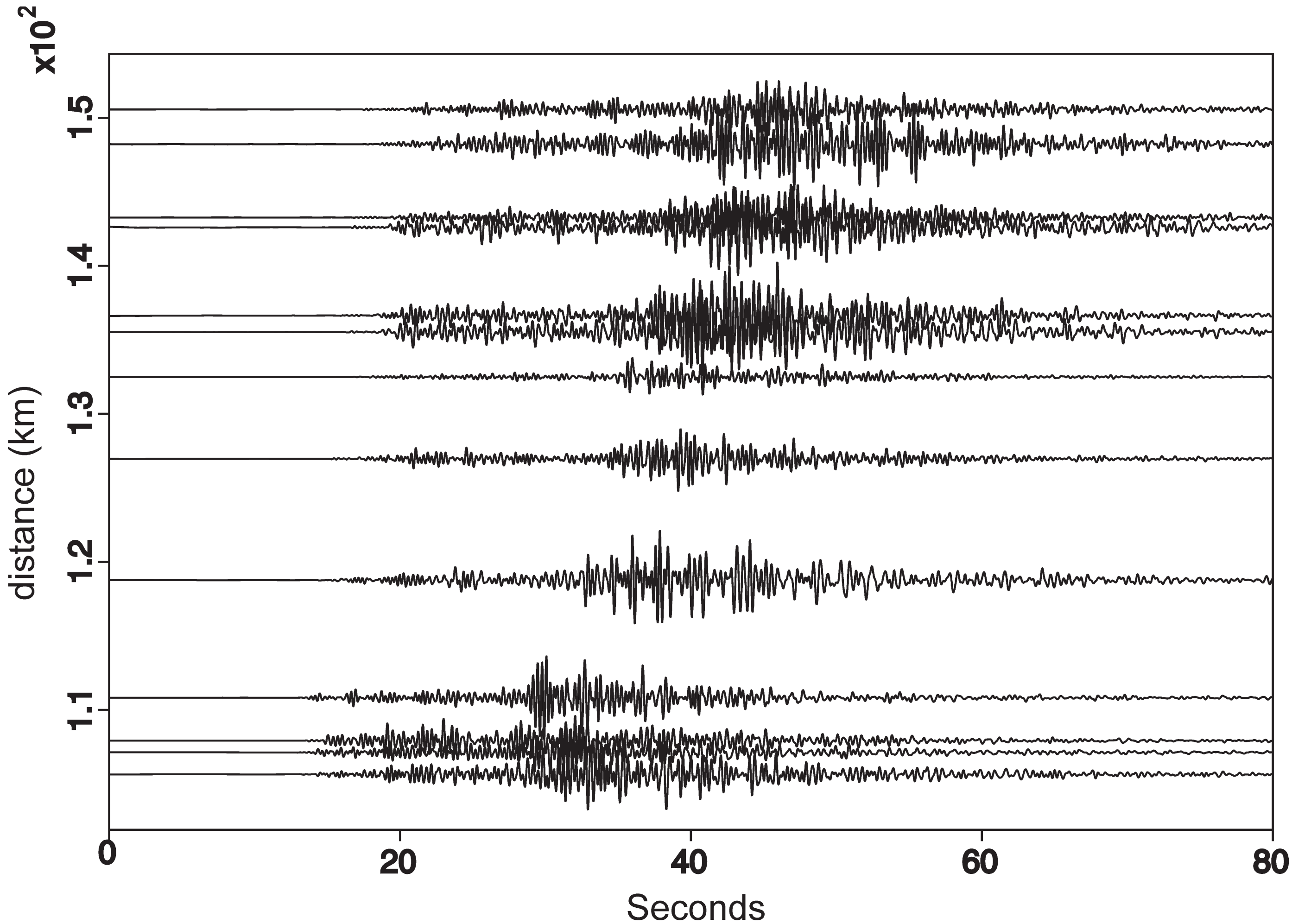
The north-south component waveforms of all of the events displayed in figure 6 and recorded at the same station (VDS3 in figure 3) have been aligned on the first P arrival and arranged according to increasing seismic moment (figure 7). These traces show a high degree of similarity over about one order of magnitude in seismic moment, indicating that the sequence originated from a rather small source volume and that the earthquakes have been produced by a similar faulting mechanism.

It is interesting to note the presence of coherent secondary arrivals along the coda of seismograms, probably generated by reflection and conversion of primary waves at shallow crustal discontinuities. The quality of recordings and the excellent signal-to-noise ratio for such a small-magnitude set of events suggests that it may be possible to use these earthquake records to obtain detailed information on the propagation medium.

During the period that the network has been recording, an event occurred in the Gargano area at a distance of about 150 km (figure 2) from the center of the network. This earthquake was recorded by the 13 stations of the accelerometric network (figure 8), and the S-wave displacement spectra from different ISNet stations are plotted in figure 9. The spectra have been corrected for the hypocentral distances and coefficients from equation 1 to obtain the seismic moment units on the spectrum-amplitude axis. We saw that despite an amplitude correction based on a simplified source model, both the Gargano event



▲ **Figure 7.** Irpinia sequence recorded at station VDS3 (plot of all horizontal component waveforms aligned at the first P-arrival time). Each trace is normalized at its own maximum amplitude.



▲ **Figure 8.** Gargano earthquake: An example of vertical-accelerometer component data recorded at 13 stations. The records are all scaled to the same maximum amplitude.

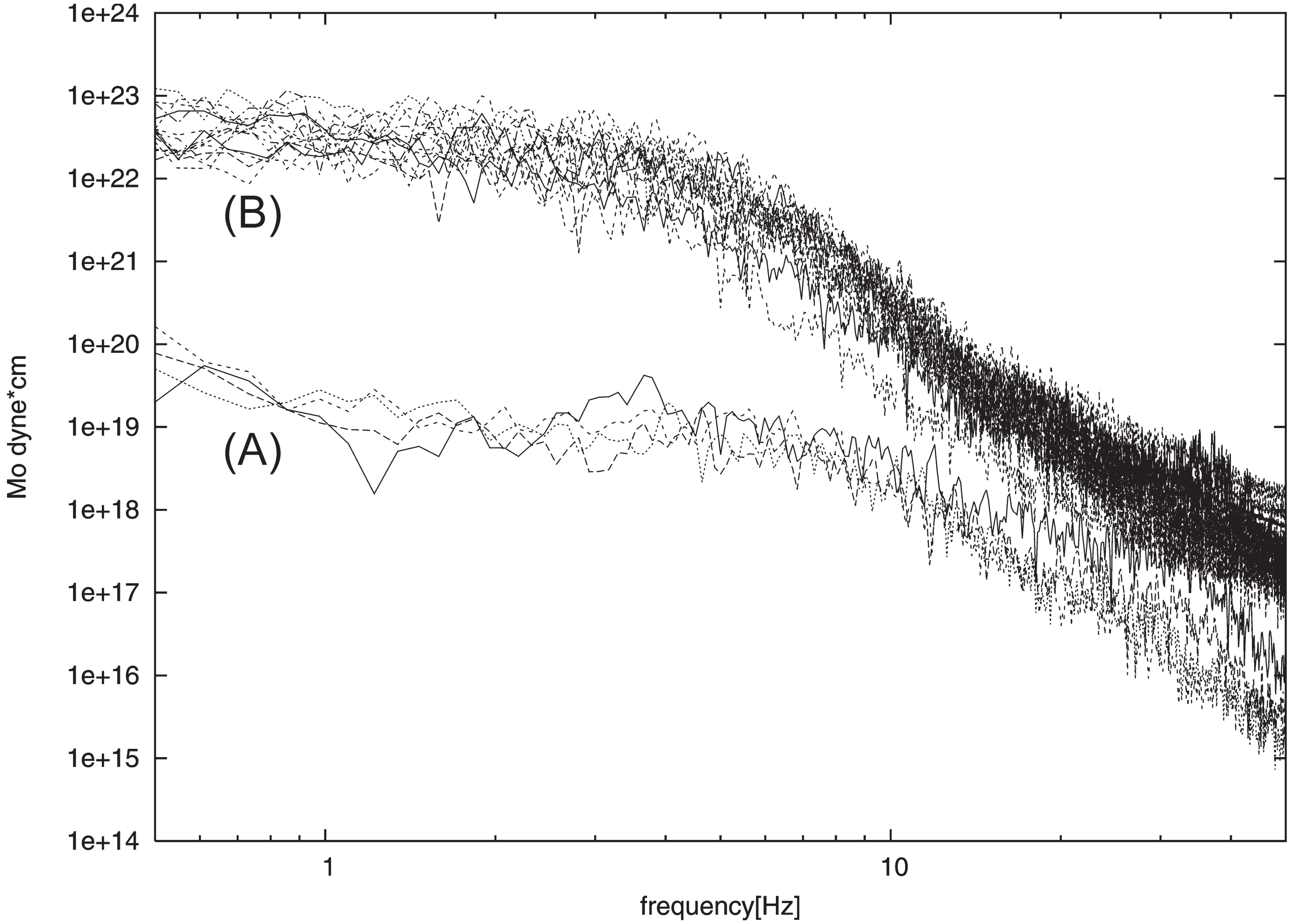
and the Irpinia seismic sequence show coherent spectral shapes among the different stations, implying an accurate calibration of the seismological instruments and lack of dominant spectral distortions due to site/propagation effects. As expected, a high corner frequency is observed for the smaller event (around 6–7 Hz) relative to the larger one (around 3–4 Hz), but the observed corner frequency ratio (around 2) is considerably smaller than the expected value (about 18) for constant stress-drop scaling ($\Delta\sigma = (7/16) \times Mo/r^3$ Keilis-Borok [1959]). The spectral analysis of events with smaller seismic moments shows that a low-pass cut-off frequency generally occurs at about 8–10 Hz, thus indicating that the observed violation of stress-drop scaling law is probably related to a high-frequency, earth-filtering attenuation effect, as suggested by Anderson and Hough (1984).

We note a good consistency of spectral shapes despite the relatively large recording distance. The measured value of seismic moment from strong motion data (5×10^{22} dyne-cm) provides an $M_w = 4.4$ using the Hanks and Kanamori (1979) relationship, which is consistent with the broad-band moment ($1.0 \cdot 10^{23}$ dyne-cm) and magnitude (4.6) estimated by EMSC (European-Mediterranean Seismological Centre). The Pga for this moderate-size event ranged between 0.002 and 0.030 m/s^2 for distances in the range of 105 and 180 km, which is consistent with the expected acceleration of an earthquake of this magnitude as predicted by the Sabetta and Pugliese (1996) attenuation relationship for Italy.

DISCUSSION

ISNet is an advanced, multicomponent seismic network that represents a key element in the prototype system for seismic alert management under development in the southern Apennines. The system is designed to provide real-time or near-real-time earthquake alert notification for early-warning applications and post-event rapid evaluation of ground-shaking maps.

This seismic alert management system is conceived as having levels of analysis and decision distributed over the seismic network nodes. This objective is realized through the implementation of virtual subnets managed by data concentrators (the LCCs). Each node of the network has to be able to process and analyze the first *P*-wave signal in real-time, providing the measured quantities (*e.g.*, arrival time, frequency, amplitude)



▲ **Figure 9.** North-south component displacement spectra for (A) the $M_0 = 1 \times 10^{19}$ dyne-cm event of the Irpinia seismic sequence displayed in figure 7; and (B) the Gargano earthquake ($M_w = 4.5$) located about 150 km from the network center.

to its closest LCC. As more stations record the seismic signal, the new measurements are sent to and processed by the LCC, which cross-checks the information from the different stations and outputs a progressively refined estimate of earthquake location and magnitude, along with uncertainty. Given this architecture, it is critical that specific procedures are in place to perform efficient, rapid, and robust data analysis.

With this in mind, we developed and tested on the ISNet system a real-time earthquake location technique based on the equal differential time (EDT) formulation and on a probabilistic approach for hypocenter estimation (Satriano *et al.* forthcoming). This technique uses information both from arrival times and not-yet-triggered seismic stations. With one recorded arrival, the hypocenter position can also be constrained by the Voronoi cell associated with the first triggering station. As time passes and more triggers become available, the evolutionary location converges to a standard EDT location. Synthetic earthquake locations using the ISNet geometry show that accuracy comparable to standard offline location algorithms is achieved 4–5 s from the first seismic station trigger.

For real-time magnitude estimates, we are investigating the advantages of using near-source, strong-motion records at close source distances. Based on a massive analysis of the European Strong Motion Database (Ambraseys *et al.* 2004), Zollo *et al.* (2006) have demonstrated that the low-pass-filtered, peak amplitudes of initial *P*- and *S*-wave seismic signals recorded in the vicinity of a current earthquake source correlate with the earthquake magnitude and can be used for real-time estimation of the event size in seismic early-warning applications. The earthquake size can therefore be estimated using only a couple of seconds of signal from the *P*- or *S*-wave onsets. Results of Zollo *et al.* (2006) suggest that estimations of earthquake magnitude in real-time procedures can be obtained by combining such measurements from initial *P*- and *S*-wave signals as a function of time from the first *P*-wave detection. The use of *S*-wave data for early-warning applications is feasible in cases where a dense strong-motion network is deployed around the potential earthquake source area (hypocentral distance less than 20–30 km), so that first *S*-*P* times are smaller than 2–3 seconds, which is true of events occurring inside the ISNet. The regression law proposed by Zollo *et al.* (2006) that relates early *P*- and *S*-peak amplitudes to magnitude can be usefully adopted to obtain real-time estimates of magnitude if the hypocentral distance can be determined using real-time location procedures such as, for instance, the method proposed by Horiuchi *et al.* (2005) or the new approach developed by Satriano *et al.* (forthcoming).

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