Chapter 8

Seismic Networks

(Version August 2011; DOI: 10.2312/GFZ.NMSOP-2_ch8)

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8.1 Introduction

In this Chapter, a brief description of seismic systems will be given. It is intended to provide an overview on basic ideas in seismometry and describes the existing possibilities in the market (year 2009). This Chapter should be of help during the planning stage of a seismic network. For more thorough information about particular elements and concepts in seismometry and seismic recording systems see Chapters 5 and 6, respectively. Note that this Chapter shares most of the figures and some paragraphs with Havskov and Alguacil (2006). Since one of the authors is the same in both, no related acknowledgment is given.

Before 1960, there were generally only individual seismic stations operating independently. Each station made its observations, which were usually sent to some central location. If several stations were operating in a country or region, it was possible to talk about networks. However the time lag between recording and manual processing were very large compared to modern seismic networks. In the 1960s, seismic networks started operating. These were mainly networks made for microearthquake recording, and the distances between stations were a few kilometers to a couple of hundred kilometers. The key feature used to define them as networks was that the signals were transmitted in real time by wire or radio link to a central recording station where all data was recorded with central timing. This enabled very accurate relative timing between stations and therefore also made it possible to make more accurate locations of local earthquakes. Recording was initially analog and, over the years, it has evolved to be nearly exclusively digital. Lee and Stewart (1981) provide a good general description of the pre-digital transmission networks.

With the evolution of communication capabilities to cover the whole world, seismic networks can now be local, regional or global. The main elements of a modern seismic station are the vault, the seismometer, the digitizer, storage and communication. The distinction between networks is primarily no longer due to differences in data transfer, accuracy of timing, or time lag between data acquisition and analysis, but rather the scope of investigation, spatial resolution, and quality of data in terms of frequency content and dynamic range.

Establishing a new network can be quite challenging and there may be some networks that have not fulfilled their expectations. The main reason for this was probably a lack of knowledge about networks, instrumentation and data processing techniques. Yet such specialized knowledge is unquestionably required if one expects to establish and operate a truly beneficial seismic network. For that reason, in addition to the general description of networks, this document will also outline the basic steps to follow in order to establish a new seismic network.

8.2 Seismic network purpose

The main purpose of seismic networks is to determine earthquake locations and magnitudes, to issue alarms, general or specific seismic monitoring and to provide data for research on the interior of the Earth. However, the most basic goal is the determination of accurate earthquake locations. For calculating the three hypocenter coordinates one needs at least the P onset times measured at three stations, or from 4 stations if also the origin time has to be determined as the fourth unknown parameter (see IS 11.1). If, however, the hypocentral distance can be determined for each station independently from the difference of onset times of different seismic phases, e.g., S-P, then 3 stations are generally sufficient (Fig. 8.1). Local, regional and global research into the Earth's interior is the oldest goal of seismology. Seismic networks are and will be probably forever the only tool that enables study of the detailed structure and physical properties of the deeper Earth’s interior.

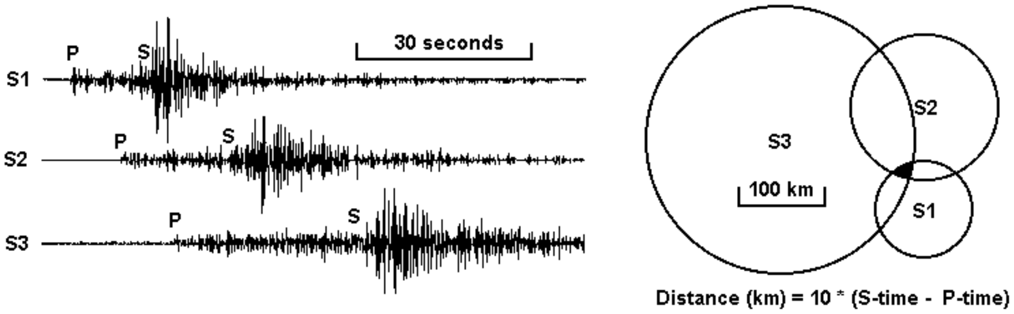

Fig. 8.1 Location by the circle (or arc) method. To the left is shown the seismograms at stations S1, S2 and S3 recording a local earthquake. Note that the amplitude scales are different. The stations are located at S1, S2 and S3 (right). The time separation between the P- and S-wave arrivals multiplied by the ratio $v_P.v_S/(v_P - v_S)$ of the P- and S-wave velocities gives us the hypocentral distance (distance from the station to the earthquake's focus at depth h). The epicenter, which is the projection of the focus to the surface, is found within the black area where the circles cross with some “overshoot”. The circles will rarely cross at one point, which indicates errors in the observations, errors in the model, and/or a subsurface source depth. With only two stations, we see that there are either two possible locations, or no possible location if the two circles do not intersect. With more than three stations, the uncertainty in location decreases. Minimization of large circle overshoot can be used to estimate the source depth (see Demo to EX11.1). Note that the “rule-of-thumb” formula given for the distance calculation in the lower right of the figure is for Sn-Pn only. It would be 8*(S-time – P-time) for Sg – Pg.

The seismic alarm function, which requires an immediate response after strong earthquakes, serves civil defense purposes with the goal of mitigating the social and economic consequences of a damaging earthquake. Governments, which often finance new seismic networks, emphasize this goal. A related self-organizing seismic early warning information network for Istanbul (SOSEWIN) has been described by Fleming et al. (2009). But seismic monitoring also aides in the long-term mitigation of seismic risk in a region or country as well as in resolving the seismotectonics. Seismic hazard maps of the region may be made which enable the development and implementation of proper building codes. In the long term, building codes are very effective in mitigating seismic risk.

Some cases of seismic monitoring related to seismic risk caused by human activity are of special political concern. This includes monitoring for seismicity induced by large dams or around large mines. Monitoring of seismicity in a volcanic region (see Chapter 13) is also dedicated to volcanic risk mitigation through the prediction of eruptions. Another important function of seismic networks is for explosion monitoring, particularly underground nuclear explosions. Seismic networks are essential to the monitoring of the international nuclear test ban treaty (see Chapter 15).

The purpose of a new seismic network largely defines the optimal technical design for it. Not every design serves equally well for different goals, and many fail completely for some particular goals. However, modern networks are more capable of dealing with several goals than older networks, which were more narrowly focused due to technical limitations.

8.3 Seismic sensors

8.3.1 General considerations

The choice of an appropriate sensor depends on the application, be it local, regional or global monitoring. The most important factors to consider for a particular application are:

- type of the sensor - accelerometer versus seismometer (compare, e.g., Chapters 11 and 15).;
- number of sensor components per seismic station;
- sensor’s sensitivity and dynamic range;
- sensor’s frequency range of operation; and
- sensor handling (i.e., how demanding are its transportation, handling, installation, calibration, maintenance etc.; see, e.g. Chapter 7).

8.3.2 Seismometers and/or accelerometers?

During most damaging earthquakes, weak-motion records made with seismometers installed close to the epicenter are clipped. Seismometers are very sensitive to small and distant events and are thus too sensitive for strong-motion signals. This was a very relevant aspect at the time of analog recordings. Traditionally, accelerometers have been considered for strong motion only and seismometers for weak motion. However, the latest generation accelerometers are nearly as sensitive as standard short-period (SP) seismometers down to frequencies around 1 Hz and also have a large dynamic range (up to more then 110 dB; e.g., the Episensor ES-T in DS 5.1). Consequently, for most traditional SP networks, accelerometers would work just as well as 1-Hz SP seismometers and they are similarly priced. At the same time, broadband sensors are now more affordable and have a larger dynamic range. In area where only moderate size earthquakes are expected, broadband seismometers may be sufficient. However, their gain towards higher frequencies (>10 Hz) may be less than for SP sensors. In terms of signal processing, there is no difference in using a seismometer or an accelerometer and correcting digital data for differences in the instrument response can make the signals look identical.

In high seismic risk areas where the main goal of networks is future seismic risk mitigation, strong-motion recordings play an important role, and two sets of sensors will have to be installed so that the system never clips. Although there are significant differences in strong and weak-motion network designs, today both types of sensors are frequently integrated into a single system. Six-channel data loggers with three weak and three strong-motion channels are cost effective and are the current state-of-the-art. They are capable of covering the whole dynamic range of seismic events, from the lowest seismic noise to the largest damaging events. The relative merits of these systems, as well as specific technical details of strong-motion networks, are addressed in the NMSOP_2 Chapter 7, section 7.4.6 on borehole strong-motion array installations, as well as in several reports and papers of the Consortium of Organizations for Strong Motion Observation Systems (COSMOS), which can be downloaded via the COSMOS website http://www.cosmos-eq.org.

8.3.3 One- and three-component seismic stations

Historically, many seismic stations and networks used single-component sensors - usually vertical seismometers. Many of them still operate. This was the case because the equipment was analog and the record was often on paper. If three components had been used, three times the amount of equipment would have been required but the information generated would not have been three times more valuable. It was also very difficult, if not impossible, to generate a ground-motion vector from three separate paper seismograms.

Today, in the era of digital recording and processing of seismic data, the situation is different. The price/performance ratio is much more favorable for three-component stations. Most data recorders and data transmission links are capable of accepting at least three channels of seismic data. The cost of upgrading the central processing facilities to accommodate an increased number of channels is relatively small and ground-motion vectors may be generated easily through data processing.

Since ground motion is essentially a vector that contains all of the seismic information, and considering the fact that many modern seismological analyses require this vector as input information, one-component stations are no longer a desirable choice for new installations (not considering seismic arrays which are discussed in Chapter 9). On the other hand, one-component seismic stations are still a choice where communication capability and economy are limiting factors.

8.3.4 Sensitivity of seismic sensors

Strong-motion accelerometers are relatively insensitive since they are designed to record the strongest events at small hypocentral distances. Their maxim on scale acceleration is usually expressed as a fraction of the Earth’s gravity, g (9.81 m/s^2). Accelerometers with 0.25, 0.5, 1, 2, and 4 g full-scale sensitivity are available today. However, modern accelerometers have excellent dynamic range and good signal resolution. They will produce valuable records of smaller events within the close-in epicentral region as well, where seismometer records may still be clipped unless a high-dynamic range recording system is used. Of course, one should order full-scale sensitivity, fitting to the maximal expected acceleration at the sites of the new network. Ordering too sensitive accelerometers may result in clipped records of the strongest and most important events in the region. Accelerometers with too high full-scale range cause diminished sensitivity and needlessly reduce data acquisition resolution of all future records. If the network only uses accelerometers, the most sensitive must be used in order to record small earthquakes if the purpose of the network is not exclusively strong motion.

Weak-motion sensors - seismometers - are usually orders of magnitude more sensitive, however, they can not record as large an amplitude as an accelerometer. They can record very weak and/or very distant events, which produce ground motion of comparable amplitudes to the background seismic noise. Some seismometers can measure ground motion smaller than the amplitudes of the lowest natural seismic noise found anywhere in the world. If one plans to purchase especially sensitive sensors, one must be willing and able to find appropriate, low seismic noise sites for their installation. Standard SP seismometers are in fact so sensitive that they will be able to resolve the ambient Earth's noise above 0.5 Hz in nearly all networks where they are installed. The self-noise of broadband seismometers is typically lower than the

Earth noise down to 0.01 Hz. If the sites are not appropriately chosen and /or have high seismic noise (natural and/or man made), a modern, highly sensitive seismometer is of little use, and a much cheaper sensor, like an accelerometer or a geophone, might be used. However, generally due to affordability and capabilities in terms of frequency and dynamic range, broadband instruments are becoming the standard.

8.3.5 Frequency range of seismic sensors

Today's weak-motion sensors are roughly divided into three categories.

The short-period (SP) seismometers measure signals from approximately 0.1 to 100 Hz, with a corner frequency at 1 Hz. They have a flat response to ground velocity for frequencies greater than this corner frequency. Typical examples are the Kinemetrics SS-1, the Geotech S13, and the Mark Products L-4C. The 4.5-Hz exploration-type geophone also belongs in this group. This sensor provides reasonably good signals down to about 0.3 Hz at a fraction of the cost of the 1.0-Hz sensor.

Broadband seismometers (BB) have a flat response to ground velocity from approximately 0.01 to 50 Hz. Typical examples are the Guralp CMG3T seismometer with frequency range from 0.008 to 50 Hz, the Wieland-Streckeisen seismometer STS2 with a frequency range from 0.008 to 40 Hz and the similar Chinese CTS-1 (see DS 5.1).

The very broadband seismometers (VBB) can resolve amplitudes of frequencies from below 0.001 Hz to approximately 10 Hz. The best performance at low frequencies is given by the Wieland-Streckeisen STS1 seismometer with frequency range from 0.0028 to 10 Hz (no longer produced). The Chinese JCZ-1 operates in an even wider range from 0.0028 to 50 Hz. However, also the Nanometrics Trillium, the Guralp CMG3T and the STS2 can, proper installation and shielding provided, resolve signals with frequencies below 0.001 Hz (see 5.53, 5.5.4, 7.4.4., DS 5.1 and IS 7.5). They are all able to resolve Earth's tides.

On all these different seismometers more information is given in DS 5.1.

The frequency limits shown above are the corner frequencies of the seismometer response functions. This means that analysis below the low-frequency corner and above the high-frequency corner is usually still possible, however, with reduced gain. How much we can extend this range depends on the sensor design, the instrumental self-noise (see Chapter 5, sections 5.5.5 to 5.5.7), the signal-to-noise ratio and beyond the upper corner frequency also on the sampling rate and the steepness of the anti-alias filter (see Chapter 6). The choice of the right sensor depends on its seismological application. In general, the flat portion of the frequency response function should cover the relevant range of frequencies in terms of displacement, velocity or acceleration amplitudes of interest in the investigation of a particular type of seismic event or seismic effect (see Fig. 5.3).

Strong-motion sensors (accelerometers) measure seismic signals between DC and 200 Hz (a typical example is the Kinemetrics' EpiSensor; see DS 5.1). However, they differ from the weak-motion sensors in that their output voltage is proportional to ground acceleration and not to ground velocity as it is usual for modern feedback-controlled broadband seismometers. For this reason, as compared to seismometers, accelerometers emphasize high frequencies and reduce low frequency amplitudes. Some strong-motion sensors in the market have no DC response but a low-frequency, high-pass corner at around 0.1 Hz. These sensors have an important drawback: their records can not be used for residual displacement determination, either of the ground in the near field of very strong earthquakes, or of permanently damaged civil engineering structures after strong events. They are considered as less appropriate for seismic applications where low-frequency signals are important too. The following table should help in the selection of appropriate sensors. It shows some typical seismological applications and their approximate frequency range of interest.

Tab. 8.1 Application description and approximate frequency range of interest.

Application	**Frequency range (in Hz)**
Seismic events associated with mining processes	5 - 2000
Very local and small earthquakes, dam induced seismicity	1 - 100
Local seismology	0.2 - 80
Strong-motion applications	0.0 - 100
General regional seismology	0.05 - 20
Frequency dependence of seismic-wave absorption	0.02 - 30
Energy calculations of distant earthquakes	0.01 - 10
Scattering and diffraction of seismic-waves on core boundary	0.02 - 2
Studies of dynamic processes in earthquake foci	0.005 - 100
Studies of crustal properties	0.02 - 1
Dispersion of surface waves	0.003 - 0.2
Free oscillations of the Earth, silent earthquakes	0.0005 - 0.01

8.3.6 Short-period (SP) seismometers

The SP sensors were historically developed as 'mechanical filters' for mitigating distracting natural seismic noise in the range 0.12 - 0.3 Hz. This noise heavily blurred small events on paper seismograms. However, with today's digital and high-resolution data recording and processing, this rigid 'hardware' filtering can easily be replaced by much more flexible signal processing. A need for sensors that filter seismic signals by themselves does not exist anymore. In addition, when filtering the seismic signal with sensors, we irreversibly lose a portion of seismic information and introduce undesired signal phase distortion. Nevertheless, the SP seismometers, as well as the cheaper geophones, are still a valid selection for several seismological applications, particularly for local seismology where low frequencies of seismic signal are not of major interest or do not exist at all. The traditional 1 Hz sensor might however disappear due to high construction cost compared to modern active sensors.

Most SP electromagnetic seismometers (EDS) are passive sensors with a flat response to velocity above the natural frequency. They are easy to install and operate and require no power, which allows use of smaller backup batteries for the rest of the equipment at remote station sites. They are relatively stable in a broad range of temperatures, which allows less adjustment (and inexpensive) vault designs. The electronic drift and mass position instability usually associated with active sensors are typically not a problem. They are, in short, a very practical solution for all applications where seismic signals of interest are not expected to contain significant components below 0.1-0.3 Hz.

There are also active SP seismometers in the market, which are either electronically extended 4.5-Hz geophones or accelerometers with electronically generated velocity output. These sensors are often cheaper and smaller. Their drawback is that they require power and are more complicated to repair. An example of such a seismometer is the Lennartz LE-1D.

8.3.7 Broadband (BB) seismometers

Today, the broadband seismometers are a very popular choice. They provide complete seismic information from about 0.01 Hz to 50 Hz and therefore allow a much broader range of studies than the SP records. Even if the prime objective of a network is to locate earthquakes that could be done with SP sensors, other usage of the data in scientific studies benefits from BB sensors.

However, the BB seismometers demand more efforts for installation and operation than SP seismometers. The BB seismometers require a higher level of expertise with respect to instrumentation and analysis methods. They are active feedback sensors and require a stable single- or double-polarity power supply. They also require very careful site selection in a seismological-geological sense as well as a better-controlled environment in seismic vaults in order to benefit from the low frequency part of their output (< 0.1 Hz), Older models are sometimes a bit tricky to install while newer models require less adjustments. Since they do not attenuate the 0.12 - 0.3 Hz natural seismic noise peak (see Fig. 4.7), their raw output signal contains much more seismic noise than signals from a SP seismometer. Consequently, useful seismic signals are often buried in seismic noise and can be resolved and analyzed only after filtering to remove the background noise. So, for all but the largest earthquakes, filtering is required even for making simple phase picks. BB sensors are often perceived as the ‘best choice’, however at high frequencies (>50 Hz) their gain is typically less than for SP sensors, and for example for microseismic monitoring the SP sensors will be a better choice.

8.3.8 Very broadband (VBB) seismometers

The VBB seismometers are utilized in global seismology studies. They are able to resolve the lowest frequencies resulting from Earth's tides and free oscillations of the Earth. Their primary purpose is the research of the deep interior of the Earth. Their only important advantage, however, as compared to BB seismometers, is their ability to record frequencies around and below 0.001 Hz. They are expensive, require very elaborate and expensive seismic shelters, and, as a rule, are tricky to install. They are ineffective for seismic risk mitigation purpose and some also lack frequency response high enough for local/regional seismology.

However, data from a VBB station are very useful to the international scientific seismological community. They are also excellent for educational purposes. For a large national project, installation of at least one VBB station is recommended and perhaps two to three in a very large country or region. Site selection and preparation for a VBB station requires extensive study and often expensive civil engineering work (e.g., Uhrhammer et al., 1998 and 7.4.4). The cost of preparation of a single good VBB site can exceed US$ 100,000.

8.3.9 Long-period (LP) passive seismometers

The long-period passive sensors are not a suitable choice for new installations and are not sold anymore. These sensors have a corner frequency or 0.05 to 0.03 Hz and, in that respect, are inferior to most (but not all) BB sensors. Their dynamic range is in the order of 120 dB. An LP sensor with a 24-bit digitizer still makes an acceptable low-cost BB station provided the sensors and the vault are already available. However, nonlinear distortion of such an installation may be problematic. Nevertheless, in the scope of new installations, long-period seismometers are of historical value only. Instruments based on the traditional design are becoming a popular choice for education in school seismology projects.

8.4 Seismic network configuration

8.4.1 Real and virtual seismic networks

When the hardware connection among seismic stations is established, the next question is how the data are sent along the connection and what protocols are used for the units to communicate. This will define, to a large extent, the functionality of the seismic network.

In the days of only microearthquake networks and one-way data transmission (from stations to central-recording site), it was quite clear how a seismic network was defined. Today, the situation is more complex. Nowadays, more and more seismic stations are connected to the Internet and data is available from world-wide distributed stations in near real-time. The stations usually also have a local recording capability. Typically, acquisition, communication and storage is provided by a single unit. Seismic networks are now mostly of this type of stations and the distinction between local, regional, and global networks does not exist any more in terms of hardware, data transmission and acquisition, but is merely a question of how the data are processed.

Due to the improvements in global communication which allows for easy access to data from around the world, the concept of virtual networks has emerged. The term virtual merely indicates that not all stations in the network belong to a single operator or a “real” network. In practice, most networks are virtual. Access to data from a station by another operator could be directly from the station, but often the data is received from the central system. However, in practice it makes little difference in the way stations are connected into either “real” or virtual networks. Examples of virtual networks are the Virtual European Broadband Seismic Network (VEBSN; see http://www.orfeus-eu.org/Data-info/vebsn.html), the GEOFON Extended Virtual Network (GEVN-GEOFON; see http://www.gfz-potsdam.de/geofon/) the Global Seismographic Network stations and arrays (code _GSN), the Federation of Digital Broad-Band Seismograph Networks stations (_FDSN). The “_” in front of the network code stands for virtual but many national networks become virtual by including data from stations by another operator within or outside the country. Examples of “real” networks are the Global Seismograph Network (GSN - IRIS/IDA) (code II) and the GEOSCOPE network code (G).

As most networks today are virtual networks, it will be assumed in the following that a network is virtual unless specifically noted otherwise.

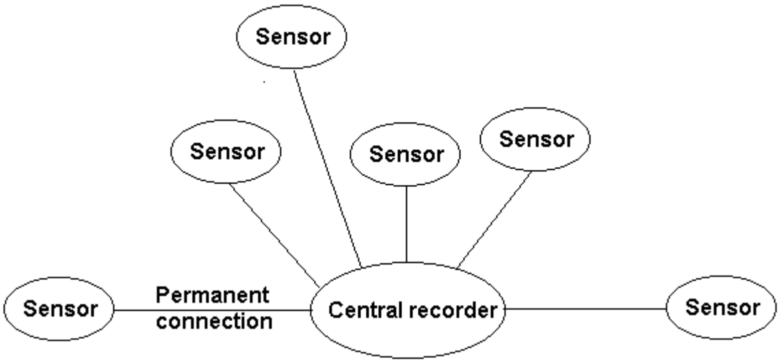

Fig. 8.2 Example of a real seismic network. The sensors are connected to a central recorder through a permanent connection like a wire or radio link. The latter may also be via satellite when the network covers large territories. The transmission may be analog with digitization taking place centrally, or an analog-to-digital converter (ADC) could also be placed at each sensor and the data transmitted digitally.

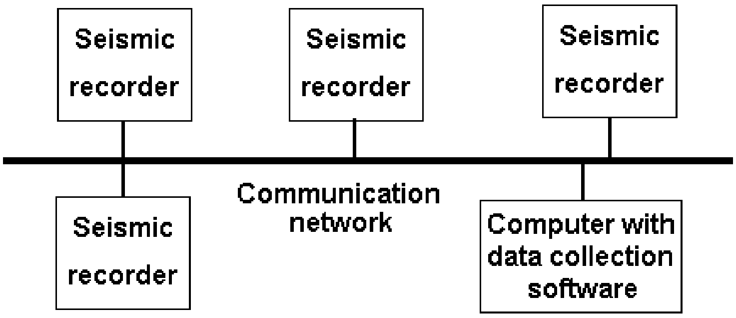

Fig. 8.3 Example of a virtual seismic network. The thick line is the communication network, which can have many physical implementations. The data collection computer collects data from some or all of the recorders connected to the network. This network could also be a real network if all stations belonged to a single operator.

8.4.2 Seismic networks

8.4.2.1 Stand-alone and central-recording based seismic systems

In the simplest case, a seismic network is a group of stand-alone seismic stations with a local recording medium. Many of the older networks, particularly analog ones, are still of this type. The information is gathered in person, either by collecting paper seismograms or by locally downloading digital data from stations into a laptop computer. There exist no communication links from the remote stations to the data center. Data can be stored locally on a removable memory medium like memory cards, or removable hard disk. Temporary networks are typically deployed in this way. Such networks can either record in continuous mode or in triggered mode. Earlier, triggering mode was the most common due to limitation in the storage capacity, while today, continuous mode is the most common. Triggering mode is now mostly used in strong-motion seismology where recordings are rare. As a permanent, national, or regional observatory seismic network, this design is rarely suitable.

Most modern networks involve near real-time data transfer from the remote stations to the central processing site. The real-time data can be received over a radio link, satellite or some form of Internet communication. It is quite common to have various means of communication within one network. Data is received by the client at the receiving end from the server at the field stations or another data centre. Most such networks now store continuous data. At present, most networks operate in this fashion. There can be a trade-off between the indispensable remoteness of the seismic stations and the availability of a communication link. However, satellite and possibly mobile phone based solutions are applicable in remote locations. It is also possible to bridge the distance to a point with permanent communication using short-distance spread spectrum RF links.

Most real time networks have a central trigger function and can, therefore, use coincidence detection algorithms in near real time (see 8.5.2).

It is common that networks use more than one system to acquire and process the data. It is also possible that some seismic stations are linked, but not sending data in real-time. It is, therefore, often necessary to make use of software that combines the different systems into one, and brings the data onto a single platform for interactive data processing.

The decision on which type of network to use depends on the availability of communication and the requirement for alarm functionality. For seismic networks with the exclusive purpose of monitoring general seismicity and/or to serve research purposes, there is no need for real-time data. The two main factors in deciding which network is the most appropriate are cost of ownership and quality of data. For research purposes, flexibility is also a very important issue. If an Internet based system is available at seismically quiet sites, this may be the least expensive way to construct a network Since communication costs are quickly decreasing and links are becoming universally available, real-time networks are now most common.

8.4.2.2 Examples

Example 1: IRIS is the largest global data centre and receives 1,000s of seismic channels in near real-time. The Global Seismograph Network (GSN) itself consists of more than 150 stations. The remaining data is provided by other networks from around the globe. Subsets of the data are combined into virtual networks, such as the GSN and FDSN networks. Data are made freely available as continuous near-real time data streams, or on request as continuous data files and event-based data sets. Very importantly, the GSN is currently re-equipped (completed by 2013) with standardized data collection systems based on the Quanterra Q330HR (high resolution) systems and has embarked on supplementing the yearly relative calibration procedures by network operators´ in situ calibrations with portable equipment, thus verifying sensor and system responses as well as sensor orientation and location. Moreover, complete instrument description is available for all data. A number of mechanisms are supported to provide the data. (http://www.iris.edu/data/request.htm). The real-time data is made available through LISS and SeedLink (see 8.6.4 and Chapter 10) and event data through tools such as Wilber, BreqFast and WebRequest. Fig. 8.4 shows the GSN network and Fig. 8.11 the type of communications used.

Example 2: The public domain SEISNET system is another software enabling establishment of semi-real time virtual seismic networks. SEISNET operates with other types of stations in addition to the GSN stations and also performs network detection and preliminary location

(Ottemöller and Havskov, 1999). It was developed for the Norwegian National Seismic Network and is also used in several other places. SEISNET is very flexible and can be adopted for virtually any type of field station.

Example 3: Another widely used and publicly available software is EARTHWORM (EW) (runs on Solaris, Linux, Mac OS X, and Windows), also see http://www.isti2.com/ew/ . It allows users to run real-time seismic networks of different purpose with emphasis on either real-time seismic data processing or data storage and user interaction. EW includes real-time data transport, automated event detection, phase picking, seismic event association and location, archiving, and other modules, and was originally developed by the U.S. Geological Survey's (USGS) Northern California Seismic Network (NCSN). EW is used by a world-wide community of ~150 institutions that operate the system or its derivatives and contribute to its development and maintenance. Instrumental Software Technologies, Inc. (ISTI) coordinates and leads this worldwide effort. EW modules are also used in other software systems such as HYDRA, used by NEIC, Earlybird used at the Alaska Tsunami Warning Center, and ANSS Quake Monitoring System (AQMS) used by the ~450-station NCSN, the ~400-station SCSN California networks, five other ANSS funded US regional networks, as well as by many other earthquake and volcano networks world-wide.

Example 4: The proprietary ANTELOPE software is yet another real-time seismic network software package on the market. It supports a wide range of seismic stations as well as other environmental monitoring equipment. ANTELOPE's open-architecture, modular, UNIX-based, real-time acquisition, analysis, and network management software supports all telemetry using either standard duplex serial interfaces or standard TCP/IP protocol over multiple physical interfaces. In addition to data acquisition, the seismic network functionality includes real-time automated event detection, phase picking, seismic event association and location, archiving, system state-of-health monitoring, interactive control of remote stations, automated distribution of raw data and processed results, batch mode seismic array processing and a powerful development toolkit for system customizing. It can handle continuous and event file-based data and uses relational database management formalism and the CSS v. 3.0 scheme for information organization. It runs on Sun Microsystems' Solaris OS on SPARC and Intel architectures. It was developed by the BRTT Company and Kinemetrics Inc. and is currently used by IRIS networks, the US Air Force, several seismic networks in the US, and about eight national seismic networks in Asia and Europe.

Example 5: Geofon network. The most used software in Europe is the public domain SeisComp – SeedLink system developed by GFZ (German Research Centre on Geosciences in Potsdam) (see http://geofon.gfz-potsdam.de/geofon//seiscomp/ and http://www.seiscomp3.org/) and the largest network using this software is the global GEOFON network consisting of GFZ stations and cooperating stations in other countries (see Fig. 8.5). The stations in the GEOFON network all send their data in real time to the GFZ in Potsdam. Rapid global earthquake information has recently become a major task of the GEOFON Program. E.g. GFZ is a key node of the European Mediterranean Seismological Centre (EMSC) and has the responsibility for rapid global earthquake alerts. The GFZ became also a leading force in earthquake monitoring for tsunami warning using SeisComp in the Mediterranean and the NE Atlantic as well as for the Indian Ocean.

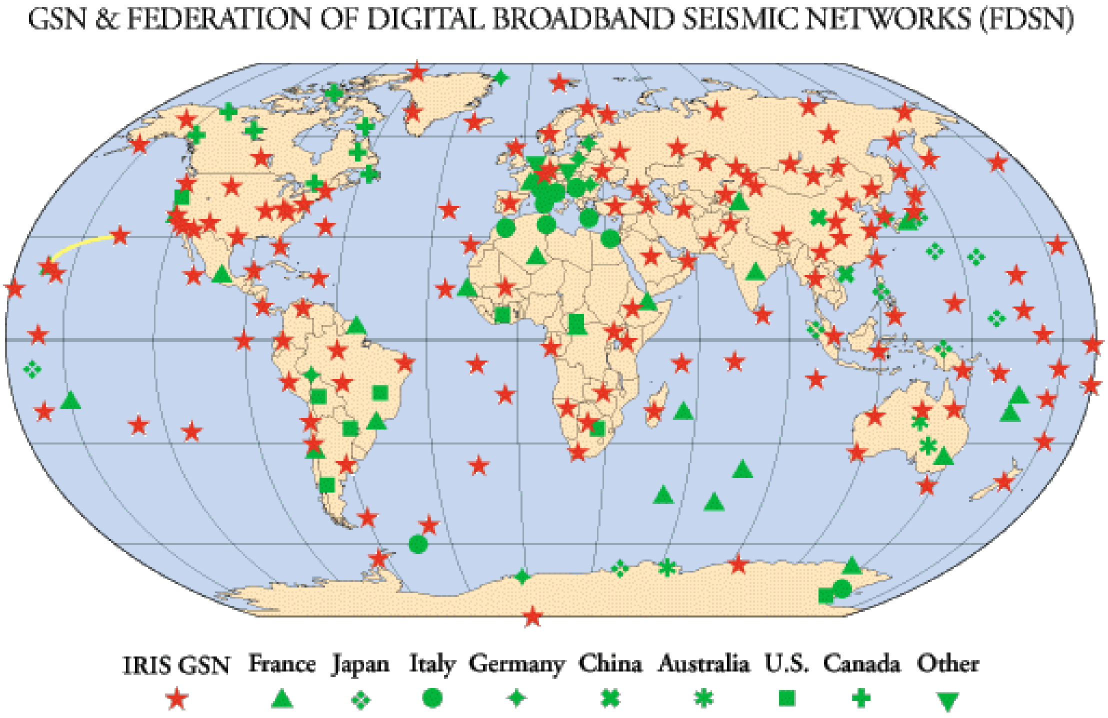

Fig. 8.4 The Global Seismic Network (GSN) and other global broadband stations that are members of the Federation of Digital Broad-Band Seismograph Networks (FDSN) (figure from IRIS home page http://www.iris.edu).

Fig. 8.5 The GEOFON network. Figure from http://geofon.gfz-potsdam.de/geofon/

8.5 Seismic data acquisition and data processing

8.5.1 Digital versus analog data acquisition

There exist three primary types of physical seismic networks with respect to the technology of data acquisition: analog, mixed, and digital.

8.5.1.1 Analog seismic systems

The analog seismic systems include sensors, which are always analog, analog signal conditioning, usually frequency modulated (FM) telemetry through radio (RF) or phone lines, analog demultiplexers, and analog drum or film recorders. Paper or film seismograms are the final result of a completely analog system. Analog systems have serious drawbacks and are no longer built. The low dynamic range and resolution of the acquired data (about 40-45 dB with single and about 60-65 dB with double, low and high-gain data transmission channels) lead to issues of incomplete data. On the one hand, many events have amplitudes that are too low to be resolved on paper or film records, while on the other hand, many records are clipped because their amplitude is too large for undistorted recording. In fact, only a very small portion of the full dynamic range of earthquakes that are of interest to seismologists are actually recorded distortion free on analog systems. Another problem is the incompatibility of paper and film records with computer analysis. This is a very serious drawback today because modern seismic analysis is almost entirely based on computer processing.

8.5.1.2 Mixed analog/digital systems

Mixed systems, frequently erroneously called digital, have analog sensors, analog signal conditioning, usually FM telemetry, and analog demultiplexers, but digital data acquisition at the central-recording site, digital processing, and digital data archiving.

Such systems also have a low dynamic range (usually FM data transmission links are the limiting factor) and therefore, they have the same disadvantage as the analog systems regarding data completeness and quality. However, they can accommodate off-line as well as automatic near-real time computer analysis. One can use most modern analysis methods, except those that require very high-resolution raw data. Such systems are still useful for some applications when the higher dynamic range of a fully digital system is not of prime importance and the purpose of the seismic network is limited to a specific goal. Advantages of these systems include low cost and low power consumption of the field equipment. Fig. 8.6 shows a typical setup. Many systems are still running, but no new ones are built.

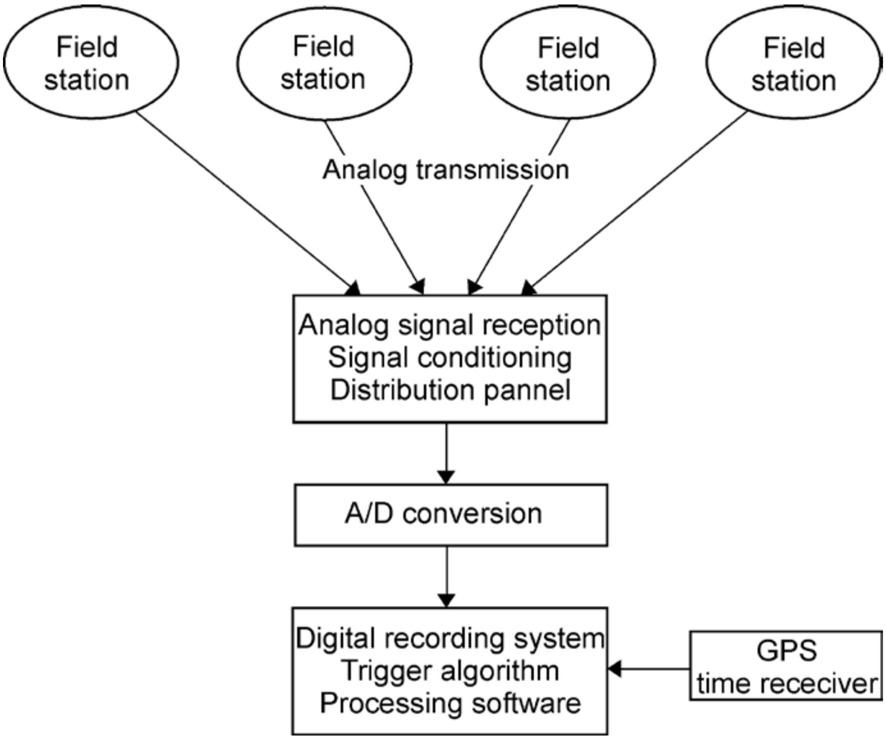

Fig. 8.6 Typical analog-digital network. The analog data is transmitted to the central site over fixed analog communication channels, usually FM modulated radio links or phone lines. At reception, the signals are put into a distribution panel where incoming signals are demodulated. Some filtering may take place before the data are digitized by a PC or similar recording system. Timing is done within the digital system. Today, very few alternatives to GPS exist.

8.5.1.3 Digital seismic systems

In digital systems, only the seismometers are analog. All other equipment are digital. The dynamic range and the resolution are much higher than that of analog and mixed type systems. These factors depend mainly, but not only, on the number of bits of the analog-to-digital (A/D) converter. 16- to 24-bit A/D converters are available today, which correspond to dynamic ranges of approximately 90 to 140 dB. In practice, however, the total dynamic range and the resolution of data acquisition is usually less than the number of bits an A/D converter would theoretically allow, since 24-bit converters rarely have a noise level as low as 1 bit. Nearly all A/D converters sold now are of 24 bit type. Fig. 8.7 shows a typical setup of a digital seismic network.

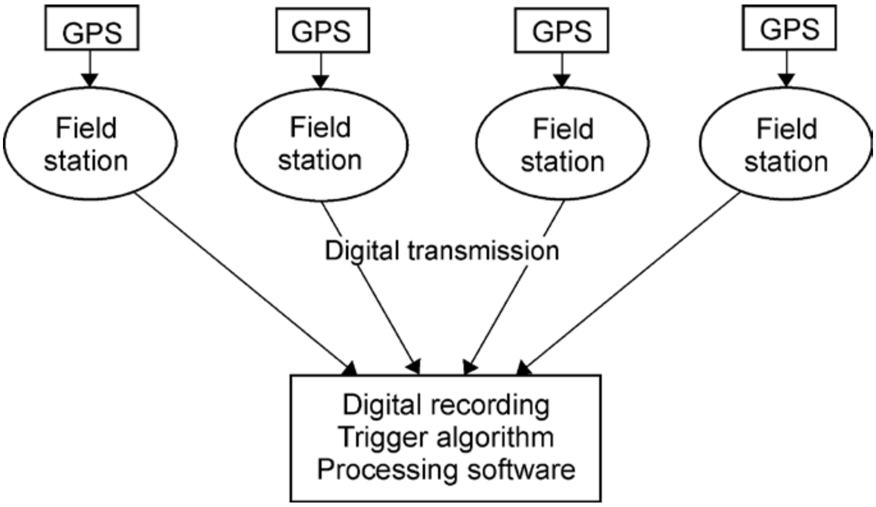

Fig. 8.7 Typical digital network. The digital data is transmitted to the central site over fixed digital communication channels. At reception, the signals enter the recorder directly. Timing normally takes place at the field stations, although some systems also time stamp the signal on arrival.

Buyers of digital seismic networks sometimes ask for additional paper drum recorders because they wish to continuously monitor incoming signals and/or believe drum recorders will serve as an excellent educational tool. However, there are a number of problems with paper drum recorders in digital systems. One problem revolves around the requirement for additional electronic components, such as digital to analog converters. Being mechanical devices, drum recorders are and will continue to be expensive, often costing more than a multi-channel digital recorder. They require continuous and specialized maintenance and consumables. On the other hand, nearly all modern observatory seismic software packages allow for the continuous, near-real-time observation of the incoming signals and some even simulate the traditional appearance of paper helicorder records. Once a user becomes familiar with a digital system, expensive paper drum recorders soon prove to be of little use and are thus a poor investment.

8.5.2 Trigger algorithms and their implementation

8.5.2.1 Continuous versus triggered mode of data acquisition

Continuous, digitally-acquired seismic signals by their very nature provide a large amount of data. A reasonably sized, digital, weak-motion seismic network operating in continuous mode will produce a large volume of data. In the past, due to limited storage capability, only the event data was stored. However, now this is no longer a problem and all data can be stored. Recent studies make use of continuous noise recordings, which shows that what previously was considered useless data can now provide valuable results (see Chapter 14). With modern networks it is no longer a question and continuous data must be stored.

The storage problem had frequently led seismic network users to operate their systems on a "triggered" basis (particularly the local and regional seismic networks that require a high frequency of data sampling). Triggered only systems still do continuous, real-time acquisition and processing of seismic signals, but only store signals associated with seismic events. Such systems do not store continuous time histories of seismic signals, but rather produce "event files". Obviously, systems in triggered mode will lose some weak events and produce a certain number of false triggers. The completeness of data inevitably is impaired because the efficiency of the trigger algorithms currently available is inferior to the pattern recognition ability of a trained seismologist’s eye.

The continuous seismic signal recording provides the most complete data, but processing and storage of all data can be difficult and expensive. Continuous recording can be achieved through the use of a ring-buffer system, where a fixed size is allocated to the data and the oldest data is overwritten by the newest. Some systems simply write data files and remove the oldest files when the storage capacity is reached. Most systems now record continuously and run a trigger algorithm only to produce detection lists. However, strong-motion systems typically still operate in triggered mode.

8.5.2.2 Trigger algorithms

The trigger algorithms used on a seismic recorded or in a central processing system are basically the same.

The amplitude threshold trigger simply searches for any signal amplitude exceeding a preset threshold. A detection is made whenever this threshold is reached. This algorithm is normally used in strong-motion seismic instruments, which are systems that do not require high sensitivity. Consequently, man-made and natural seismic noise will only produce infrequent triggers.

The root-mean-square (RMS) threshold trigger is similar to the amplitude threshold algorithm, but the RMS value of the amplitude in a short time window is used instead of 'instant' signal amplitude. It is less sensitive to spike-like, man-made seismic noise, however it is rarely used in practice.

The ratio of the short-time average to the long-time average (STA/LTA) of the seismic signal is the basis of the most frequently used trigger algorithm in weak-motion seismology. It continuously calculates the average values of the absolute amplitude of the seismic signal in two consecutive moving time windows. The short-time window (STA) is 'sensitive' to seismic events, while the long-time window (LTA) provides information about the temporal amplitude variation of seismic noise at the site. When this ratio exceeds a preset value (usually set between 4 and 8), an event is 'declared'. The STA/LTA trigger algorithm is well suited to cope with slow fluctuations of natural seismic noise. It is less effective in situations where man-made seismic noise of a bursting or spiky nature is present. At sites with high, irregular, man-made seismic noise, the STA/LTA trigger usually does not function well. For more details on STA/LTA algorithm and parameter setting see IS 8.1.

Several more sophisticated trigger algorithms are known from the literature. They are sometimes used in seismic networks but rarely in the seismic data loggers available on the market. In the hands of an expert they can significantly improve the event detections/false triggers ratio, particularly for a given type of seismic event. However, these triggers often require sophisticated parameter adjustments that can prove to be unwieldy and subject to error.

Every triggered seismic system must have an adjustable band-pass filter in front of the trigger algorithm. This is particularly important with BB and VBB seismometers where small earthquake signals are often buried in dominant 0.2-0.3 Hz seismic noise. The adjustable band-pass filter allows the trigger algorithm to be sensitive to the frequency band of one's interest. In this way such events may be resolved and acquired. Some recorders allow several trigger sets to be used simultaneously. This is needed if for example, a BB station has to trigger on microearthquakes, teleseismic P waves and surface waves which each require separate setting of filters, STA and LTA. The GSN Quanterra stations operate in this way.

8.5.2.3 Coincidence trigger principle

In seismic networks with standalone stations, each remote station has its own independent trigger. In such networks data are usually transferred to the central-recording site on request only or it is collected in person. These seismic networks have the lowest effectiveness of triggering and consequently, the smallest detection threshold and/or the highest rate of falsely-triggered records. The completeness of data is modest because not all stations in the network trigger simultaneously for each event. This approach requires a good deal of routine maintenance work in order to "clear" numerous false records from the local data memory if trigger thresholds are set low; if not, the network has a lower detection threshold. Remote stations may encounter 'memory full' situations due to having a limited local memory. Such networks absolutely require the careful selection of station sites with as low as possible man-made seismic noise. If low noise is not assured, an observatory quality network may be so insensitive as to be considered a serious project failure. However, such networks are frequently used as temporal seismic networks. They also function well where high sensitivity is not desired at all, for example, in most strong-motion networks.

Seismic networks that use the coincidence trigger algorithm are much better at detection thresholds and completeness of acquired data. In these systems, data are transmitted continuously from all remote stations to the central-recording site where a complex trigger algorithm discriminates between seismic events and seismic noise. The coincidence trigger takes into account not only signal amplitudes but also correlation in space and time of the activated stations within a given time window (the window allows for wave propagation). The trigger threshold level of such a robust algorithm can be significantly lowered, resulting in a more complete record of small events for the entire network. All stations in the network are recorded for every trigger, which greatly improves completeness of the recorded data.

8.6 Seismic data transmission

8.6.1 General considerations

While data transmission may not seem like an important technical issue for a seismic network, a poorly selected or designed data transmission system is one of the most frequent causes for disappointment and technical failures. The success of a seismic network operation rests largely on the reliability and the quality of data transmission, whether by dedicated lines or by internet.

Another very important but frequently overlooked factor is the cost of data transmission. In fact, these costs may largely determine the budget for a long-term seismic network operation. Many seismic networks all over the world have been forced to change to less expensive modes of transmission after some years of operation. The data transmission costs per year in a network established right after a damaging earthquake may seem completely acceptable at first, but may be viewed as excessive after just a few years of relative seismic quiescence. However, communication is becoming easier and cheaper and this should no longer be an issue.

There are some key technical parameters to consider in designing a data transmission system:

- the required information flow (channel bandwidth for analog links or data transfer rate with digital links);

- the distance to which data must be transmitted;

- the desired reliability (acceptable down-time of the links, that is, the maximum time period per year when the signal-to-noise ratio is lower than required (analog links) or bit error rate is higher than allowed (digital links).

- the communication system which will be used to establish the seismic network (Internet, proprietary WANs (Wide Area Networks), analog public phone network, ISDN, ADSL etc.); and

- the protocols that will be used.

These parameters must fit the available data transmission infrastructure in the country or region, the available network operations budget, and the network’s performances goals. Technical considerations, reliability, initial price and operational costs of data transmission links vary widely from country to country. Local conditions in a particular country or region are a very important factor in the selection of an appropriate data transmission system. It is essential to get information about the availability, reliability and cost of different approaches from local communication experts.

8.6.2 Types of data transmission links used in seismology

In seismometry there are several different kinds of data transmission links in use, from simple short-wire lines to satellite links. They differ significantly with respect to data throughput, reliability of operation, maximum distance, robustness against damaging earthquakes, and cost of establishment and operation. A table in IS 8.2 enumerates the most common types, their major advantages and drawbacks, and their potential applications.

Note that strong-motion seismic networks generate far less data than weak-motion networks and therefore, their design might differ significantly. Seismic data transmission links that are fully acceptable for strong-motion data may be inadequate for weak-motion data and data transmission links used in the weak-motion field may be an absolute overkill and too expensive for strong-motion networks.

8.6.3 Simplex versus duplex data transmission links

There are two basic types of digital data transmission links.

Simplex links transmit data only one-way, from remote stations to the center. These links are relatively error prone. Radio interference or fading may corrupt data during transmission and there is no way of recovering corrupted data, unless forward error-correction (FEC) methods are used (see 8.8.6.6). However, the FEC methods are rarely used except for satellite links. They require a significant bandwidth overhead, which is hard to provide using standard, low cost 3.5-kHz bandwidth RF channels. Simplex links usually use the type of error-checking that allows recognition of corrupted data but not its correction. The methods in common use range from a simple parity check or check-sum (CS) error detection to cyclic redundancy check (CRC) methods.

Duplex links allow data flow in both directions – from the remote station to the center and vice versa. Different types of error-checking methods are used, ranging from a simple parity check or CS error detection to CRC error detection. Once an error is detected, the data block is resent repeatedly until it is received correctly. In this way, a very significant increase of reliability of data transmission is achieved. Duplex is the standard with modern equipment and communication. However, duplex radio links nearly double the amount of the equipment and are therefore expensive compared to the simplex links.

Today, no commercial networks using simplex are constructed.

8.6.4 Protocols for continuous data transmission

The majority of new networks and many old networks will now record continuously and this has resulted in de facto standards emerging from major operators. The fist protocol was LISS (Live Internet Seismic Server, http://www.liss.org/) made by USGS and used on the GSN stations (see Fig. 8.8). The protocol sends 512 byte blocks of MiniSEED data on a socket and application on the receiver side can open a corresponding socket and continuously receive the data. LISS has the drawback that if data is lost, there is no way of requesting data since it is just a one way transmission.

This problem has been solved using the SEEDLink protocol that is implemented within the SEEDLink software (Heinlo and Trabant, 2003). This protocol is the same as LISS with an additional data block containing information about transmission status and request information. SEEDLink can therefore request missing data blocks which also makes it possible to request data back in time. SEEDLink is the most used public standard with retransmission and data from large data centres such as IRIS and ORFEUS can be received from their SEEDLink servers. Other real-time data processing systems such as Earthworm come with data exchange protocols. Another widely used protocol is CD1 developed for the International Monitoring System of the CTBTO. In additition, all major seismic equipment companies have developed their proprietary protocols for real-time data exchange, but they may also support the open standards.

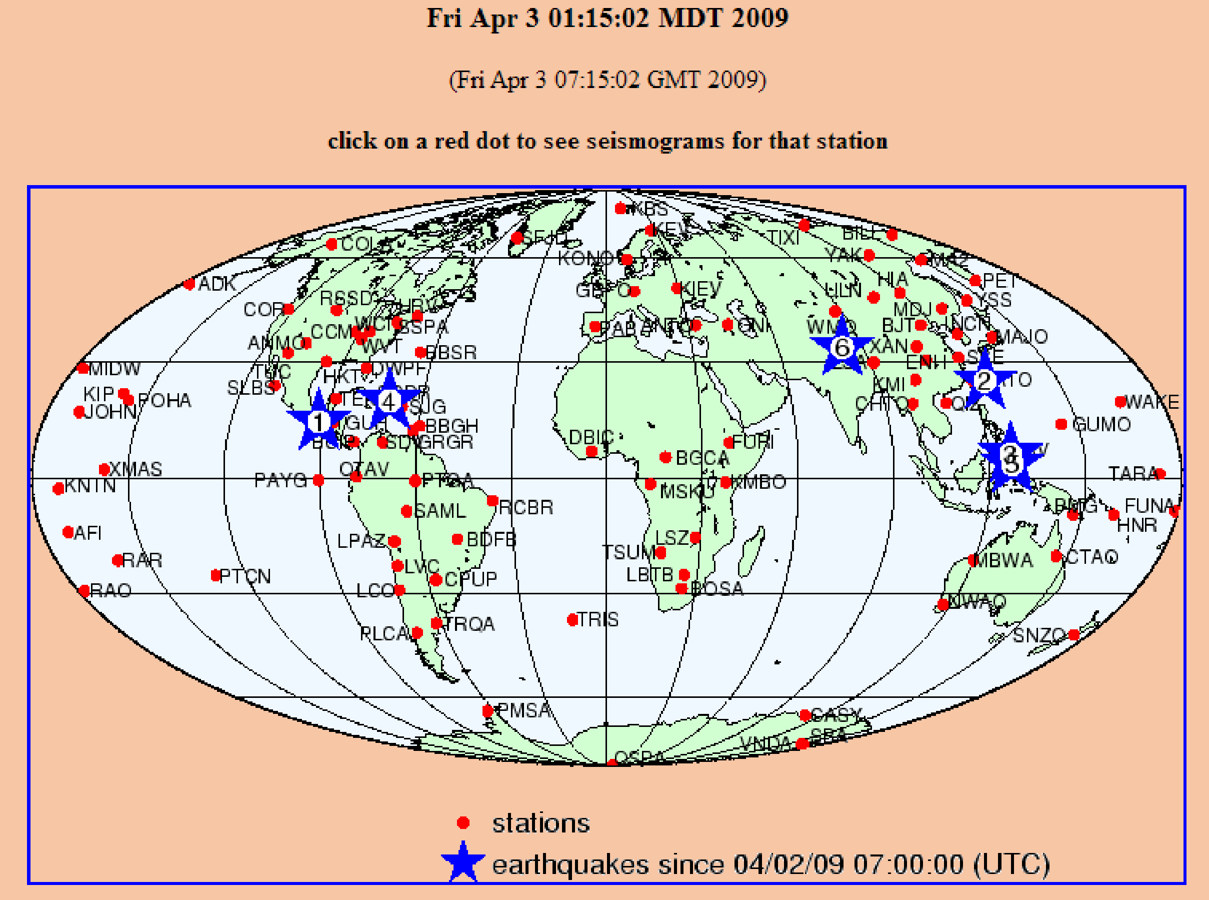

Fig. 8.8 LISS stations (red dots) April 3, 2009. The map shows seismograph stations which are transmitting their data live, via the Internet, to the Albuquerque Seismological Laboratory (http://aslwww.cr.usgs.gov/Seismic_Data/telemetry_data/map_sta_eq.shtml). The live data can be seen interactively by pressing the red dot.

8.6.5 Data transmission protocols and some examples of their use

Serial data communication and Ethernet are the most commonly used ways to transmit digital seismic data.

Most seismic digitizers will send out a stream of data in serial format and all computers have hardware and software to communicate with serial data. A serial line requires at least 3 lines: One for sending data, one for receiving data, and ground. If data only is to be sent or received, two lines suffice. The serial lines use either RS-232 protocol or the RS-422 protocol. The former can run on up to 50 m long cables and the latter on cables up to 2 km long. Serial line communications may be used by modems, radio links, fixed telephone lines, cellular phone, and satellite links.

Example 1: An example of one-way continuous communication (see Fig. 8.9), a remote station has a digitizer sending out RS-232 data, which enters a radio link to a PC, which reads the data and processes it. The communication is governed by the RS-232 protocols. Data acquisition system is done on the PC.

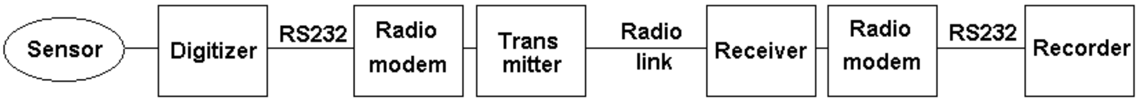

Fig. 8.9 One-way communication from a remotely installed digitizer via a digital radio link to a centrally located PC. The radio modem and transmitter /receiver might be one unit.

Example 2: Interactive communication with a remote seismic station (see Fig. 8.10). A user calls up a terminal emulator on his PC, connects to a modem with one of the PC's serial lines, dials the phone number of the modem connected to the remote station, and logs into the field station. Once logged in, several options are usually available. One is to browse a log file containing all triggered events in the local memory of the station. Another option is to initiate a download of event data. A very common way to do this over a serial line connection is to list the event file in ASCII form and then set up the terminal emulator at the local PC to capture the data. This is one way of getting data from a standard GSN seismic station. The advantage of this type of communication is that only very simple software is required and it is easy to access to many different seismic stations. This process can also be easily automated (see IS 8.3).

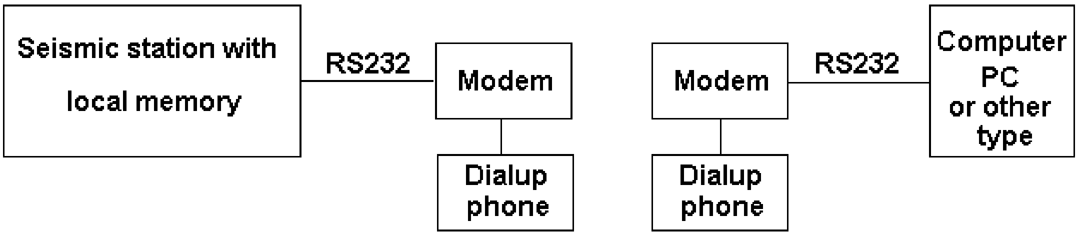

Fig. 8.10 Manual dial-up to a seismic station for data inspection and/or download. The dialing computer can be of any type as long as a terminal emulator program, such as Hyperterminal in MS Windows, is available.

Example 3: Interactive communication with a remote seismic station using proprietary software. The user starts up a manufacturer-supplied program on his local PC. The program handles all the communication to the field station purchased from this manufacturer. The user’s connection with the field station will be as if sitting next door. Data download, acquisition parameter settings, system state-of-the-health verification, and diagnostic commands (if applicable) are managed through simple menus, and the event files may be automatically transferred to the user's local PC. The process can be run manually or in an automatic, unattended mode at specified times. With some systems, remote stations can initiate the transfer of triggered seismic events. The advantage with this setup is that communication with a particular remote station is very easy. Unfortunately, most of the software systems in the market work only with one type of seismic station.

In high-speed local area networks, Ethernet most commonly connects computers. This low-level protocol is not what the user sees directly, but rather a high-level communication protocol working on top of the Ethernet protocol. TCP/IP is the most widely used protocol for file transfer and remote log-in. This is also the protocol used by the Internet although the low-level protocol used between the different Internet nodes might not be Ethernet. TCP/IP can also be used over serial lines and ISDN telephone lines. Today, most seismic recorders are able to communicate via TCP/IP protocol. A remote seismic station, which can be reached by TCP/IP either through Internet, satellite, ADSL, ISDN, or regular phone lines, represents the most general purpose and flexible system available.

Fig. 8.11 shows the most common way of establishing TCP/IP connections to a central data collection system. Dashed lines between routers indicate that the connection is made to one station at a time. Large central routers that can communicate with many ISDN nodes at the same time are also available.

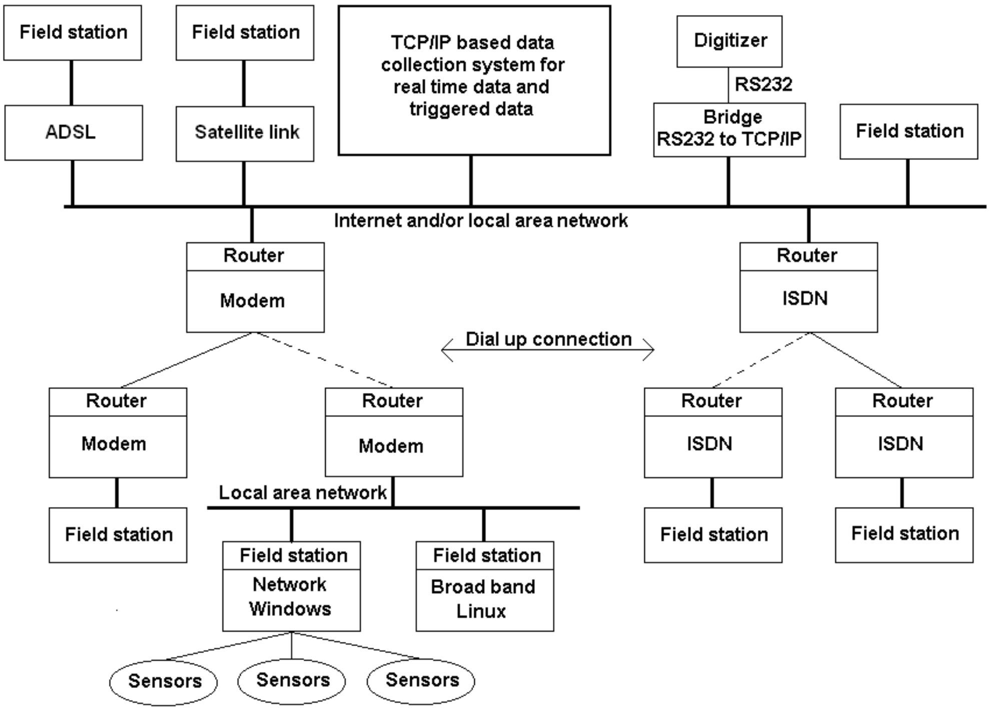

Fig. 8.11 Different ways of getting a TCP/IP connection to a central data collection system. The thick solid lines indicate permanent Ethernet connections.

Getting seismic data from a GSN station using Internet via a local computer is simple. The user uses the Telnet to login to the station. Once logged in, he can check available seismic data and use the FTP file transfer protocol to copy the data to the local computer. The process is easy to automate. Fig. 8.12 shows the communication links for the GSN network. It is seen that almost all stations have a permanent connection and consequently almost all continuous data is transmitted by the computer network to IRIS. Only going back to 2001, the majority of stations were dial up and data had to be sent to IRIS on tape.

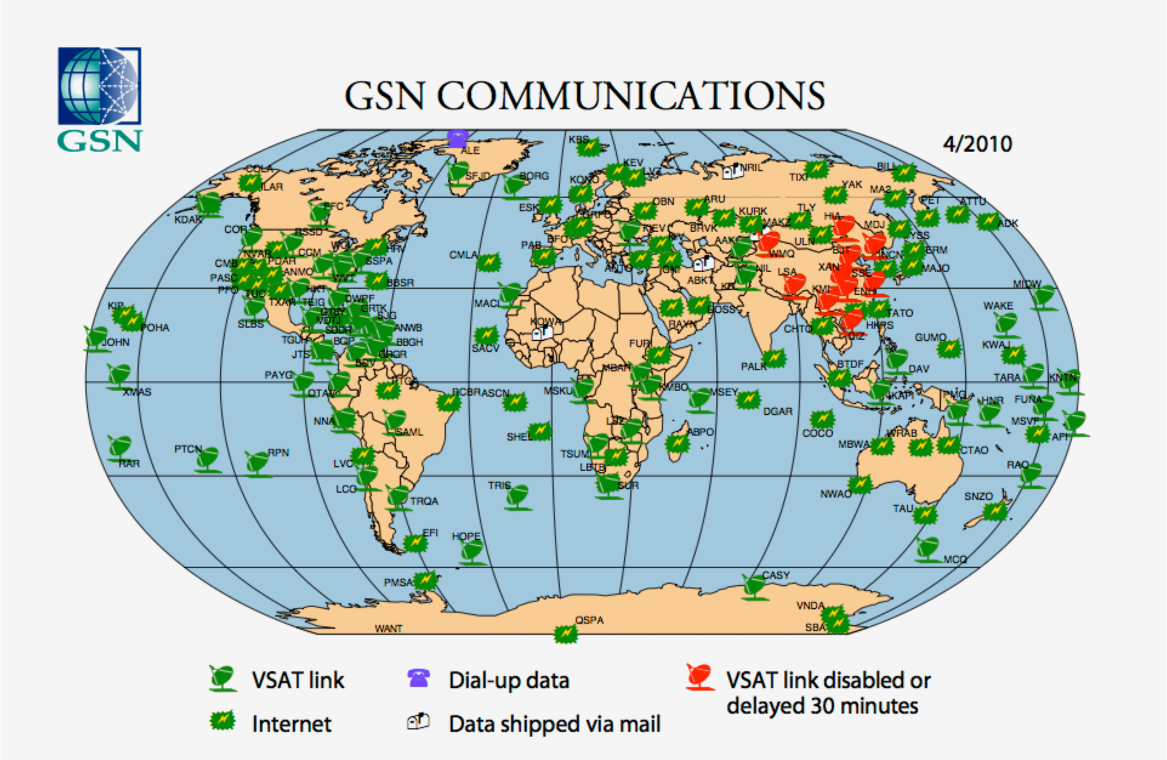

Fig. 8.12 Communication to GSN stations 2010. VSAT is a satellite connection (figure from IRIS home page http://www.iris.edu).

Some computers do not have direct access to the Internet but are able to send e-mail. Some seismic stations and centers, particularly in Europe, use a shared protocol for providing seismic waveform data semi-automatically by e-mail. This system is called AutoDRM (Automatic Data Request Manager; Kradolfer, U., 1996;). The user sends an e-mail request for particular data and the remote system automatically ships back the data by E-mail.

8.6.6 Compression of digital seismic data

Because of the high data rates from digital seismic stations and the throughput limitations of available data transmission links, data is often compressed before transmission. The compression generally can be expected to halve the quantity of seismic data. Earlier, different compression methods were used like zip for transmission of files or built in compression routines in modems. Now nearly all compression of seismic data is done using the Steim compression which is an integral part of the standard SEED format (see reference SEED (2007) and Chapter 10). The data is thus recorded, transmitted and stored compressed and is only decompressed when read for analysis. The Steim compression works by storing the difference between samples, which usually are much smaller numbers than the samples themselves and therefore can be stored in one, two, three bytes instead of 4 bytes.

With many compression algorithms, including the Steim compression, the degree of data compression depends on the amplitude of the seismic signal. Therefore the efficiency of the compression falls sharply during strong earthquakes. One should be sure that the local temporary memory and the link’s throughput will suffice in case of large, long-duration events.

8.6.7 Error-correction methods used with seismic signals

All digital communications experience errors. In the transmission of seismograms this is particularly fatal since just one bit of error might result in a spike in the data with a value a million times larger than the true seismic signal. Obviously, this could wreak havoc in trigger systems, and one byte missing in an event file might corrupt the whole event file.

One of the principles of error correction is that data is sent in blocks, e.g., 1 s long, and along with the block of data there is some kind of 'check-sum'. If the check-sum does not tally with the received data, a request is sent to retransmit that particular block of data. Obviously this type of error correction requires duplex transmission lines and local data memory at the remote station. If only one-way transmission is available, the errors can not be corrected using the check-sum method but they can be detected and appropriate action taken at the receiving end. However, loss of data is inevitable. Error correction can be utilized at different hardware and software levels and can be of various types.

Proprietary error correction is used in many systems on the market. In these cases, the system operates over dedicated links and all the responsibility for transmission and error correction lies with the system. An example would be a digital radio link to remote stations that uses a manufacture’s protocol for error correction. The protocol in this case would be built into the commercial product.

Standardized hardware error correction is another possibility. The hardware unit, where the data enters the digital link and where it comes out, has its own error correction built in. From the user's standpoint, it is assumed that no errors occur between the input and output of this hardware. The most common example of such hardware error correction is a telephone modem that uses internal, industry-standard error correction.

Computer networks use their own error-correction methods. When computers are linked with common computer network protocols like TCP/IP, error correction is built in from computer to computer. This is obviously the best solution, however it requires that the seismic remote stations operate quite sophisticated software. This is now the most common form of low level error correction.

Satellite data transmission links usually use forward error-correction (FEC) methods. FEC works on simplex links and doesn't require any retransmission of data blocks to correct errors. FEC is similar to check-sum error detection. By comparing the transmitted check-sum and that of the received data, corrections can be made. One drawback, however, is an increased data channel bandwidth due to a significant data overhead dedicated to error correction.

One should carefully consider the interplay between the error-correction system built into a seismic system with that of the particular communication equipment to be used.

8.6.8 Seismic data transmission and timing

All digital data acquisition and transmission systems create a certain time delay or latency. This delay depends on the digitizer, the digital protocol used for transmission and the computer receiving the data. For this reason, nearly all digital field stations time stamp the data at the remote station and subsequent delays in the transmission have no effect on timing accuracy. However, there are also digital network designs where the timing takes place centrally. This can be done if the digital data arrives at the central site with a predictable or measurable time delay. The central computer must then time stamp the data when it arrives in real time and later correct it for the known transmission and digitizer delays. One advantage with this system is that only one clock is needed for timing the network. A further advantage is a simpler and less expensive remote station consisting only of a sensor and a digitizer. The disadvantage is that timing accuracy is not as good as with time stamping at the remote sites because time delays are known only with a limited precision and they may also vary in time. Also if the central clock or its synchronization with GPS time signals fails, the whole network fails. Most networks are moving towards time stamping at the station because GPS clock prices are now a small fraction of total digitizer costs.

8.6.9 Notes on dial-up phone lines and selection of modems

Dial-up phone lines are sometimes proposed for seismic data transmission because they are readily available and apparently cheap. However, they have important limitations of which one must be aware. First, continuous seismic data transmission is not possible via dial-up lines. Second, their throughput is, in practice, frequently limited in spite of the high baud-rate capabilities of modern modems.

In practice, dial-up weak-motion networks based on phone lines can not 'digest' earthquake swarms and the numerous aftershocks after strong events. Therefore, they are an appropriate choice for low seismicity regions only. In addition, as they often do not function for several hours after strong events, due to either especially high usage of the public phone system or technical difficulties, they may not be the best choice for networks with the predominant purpose of giving seismic alarms. On the other hand, however, the USGS National Strong-Motion Program’s dial-up network of about 200 stations (out of a total of 645 stations) (http://nsmp.wr.usgs.gov/near_real_time.html) has successfully contributed to local ShakeMaps (http://quake.usgs.gov/research/strongmotion/effects/shake/about.html) in California since 1999. The data typically are downloaded, processed, and exported automatically to clients within 3-5 minutes after strong-ground shaking begins.

In many countries, public phone networks have specific properties and special ‘tricks'. Therefore it is advisable to purchase modems locally. In general, it cannot be recommended to use modems for a new network.

8.7 Some network examples

Along the lines described in the preceding section, some more examples are given of different types of seismic networks in operation, briefing both on their technical solutions and purpose.

8.7.1 International Monitoring System (IMS)

In recent years, a new global network, the International Monitoring System (IMS) has been set up aimed at monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT) (see www.ctbto.org, Chapter 15 of this Manual, and Barrientos et al., 2001). The IMS is composed of seismic, infrasound, hydroacoustic and radionuclide stations. The seismic network consists of 50 stations designated as "primary", mostly arrays (see Chapter 9), with real-time data transmission the IDC of the CTBTO in Vienna, Austria. In addition there are 120 "auxiliary" stations that provide data on request to the IDC. Many of the auxiliary stations are members of the Federation of Digital Broadband Seismograph Networks (FDSN; see Fig. 8.4 and http://www.fdsn.org). The IMS network (Fig. 8.13) is currently the largest and most modern physical real-time network in the world. However, when requesting data from auxiliary stations, it works like a virtual network where the real-time network makes the detections and preliminary locations and then requests additional information from remaining stations for improving these preliminary findings.

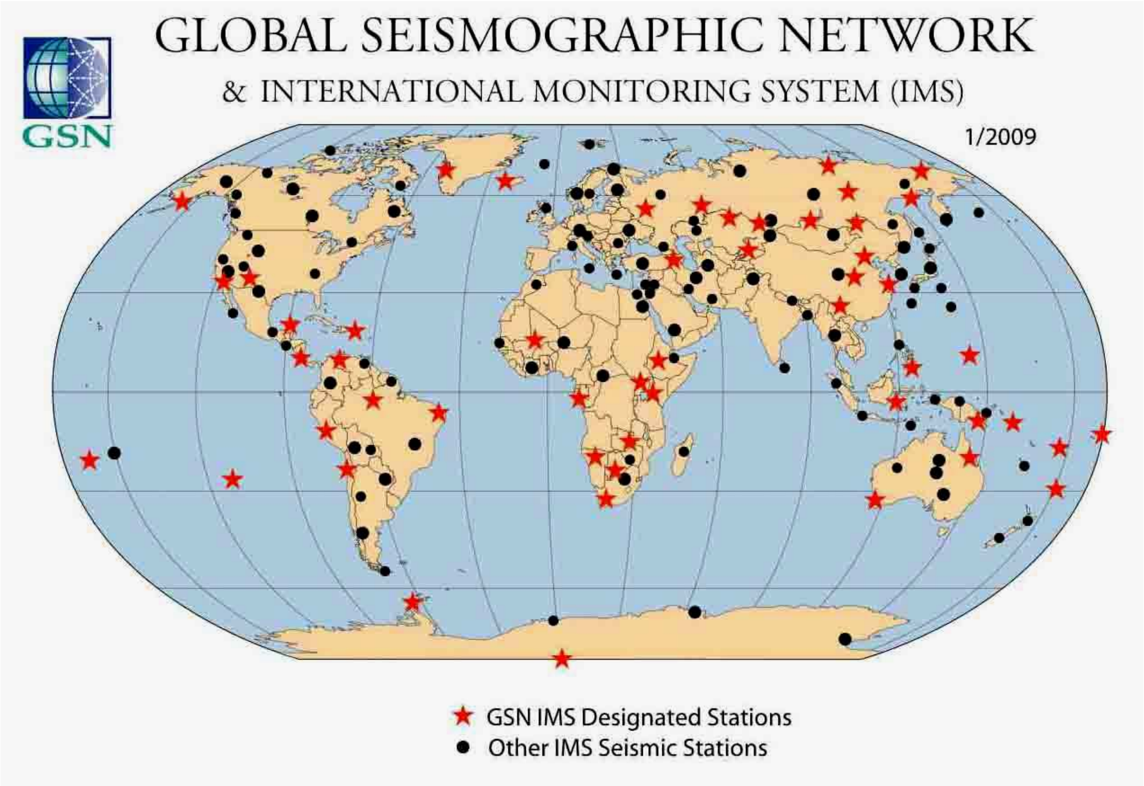

Fig. 8.13 Stations in the International Monitoring System (IMS).

8.7.2 Southern California Seismic Network (SCSN) (by E. Hauksson)

The authoritative earthquake-monitoring region of the Southern California Seismic Network (SCSN) extends across southern California, from the US-Mexico international border to Coalinga and Owens Valley in central California. The SCSN also reports on earthquakes in northern Baja California, Mexico, because these could possibly also cause damage in the United States. The region is home to almost 20 million inhabitants, including two of the ten largest cities in the United States (Los Angeles and San Diego) and the two largest harbors (Los Angeles and Long Beach) in the Nation.

The SCSN operates about 300 seismic stations and receives real-time waveform data from an additional 125 stations operated by partner networks (Fig. 8.14). The SCSN seismic stations can be divided into three groups. First, the most modern group of 167 SCSN stations consist of broadband sensors, strong motion sensors, and high resolution dataloggers for digitization and data communications. The data from these stations are used for real-time determination of earthquake locations, magnitudes, moment tensors, and amplitudes for ShakeMap. The second group consists of about 35 stations that are equipped with only strong motion sensors and a datalogger. These stations provide amplitudes for ShakeMap and occasional arrival-time picks. The third group consists of 125 short-period stations that use legacy analog, frequency-modulated (FM) audible tone technology and Earthworm digitizers for data acquisition. Although, the amplitude data have limited dynamic range, these stations provide arrival-time picks for improved location and depth determination as well as coda duration for determining magnitudes of small earthquakes.

The data flow path from the remote seismic stations includes the on-site equipment, the data communications path, and a data acquisition computer at the central recording site. The last mile data communications to each site may use copper wire, spread-spectrum radios, or optical fiber. The main long-haul data communications include digital phone lines (frame relay or T1 lines) and digital microwave circuits. The waveform data are acquired by front-end processors that broadcast the data on a private local network. Many computers that are connected to this network, capture and process the waveforms or capture the data for archiving. For instance, a processing thread of Earthworm modules carries out the real-time picking of arrival-times, association, and hypocenter determination. A different thread harvests amplitudes and determines local magnitudes. Similarly, an earthquake-early-warning processing thread captures the waveform data to facilitate development of algorithms to estimate the size of the event quickly.

The Southern California Earthquake Data Center (SCEDC) archives and distributes all SCSN data and products. As the SCSN processes the data for detected earthquakes, outside researchers can also access all the data in the database, within minutes or as soon as the data are entered into the archive. The SCSN products include the southern California earthquake catalog, event gathers (triggers) of waveforms for nearly all events back to 1981 and for some events extending back to 1976, continuous broadband waveforms from 1999 to present, continuous short-period waveforms since 2008, and continuous strong motion waveforms since 2010. The SCSN and the SCEDC have maintained and published a catalog of earthquakes above magnitude 3.25 since 1932 and above magnitude 1.8 since 1980 with consistent magnitudes over the whole time (Hutton, *et al.* 2010). See also: http://www.scsn.org; http://www.data.scec.org.

A complementary information about the California Integrated Seismic Network (CISN) is contained in IS 8.4.

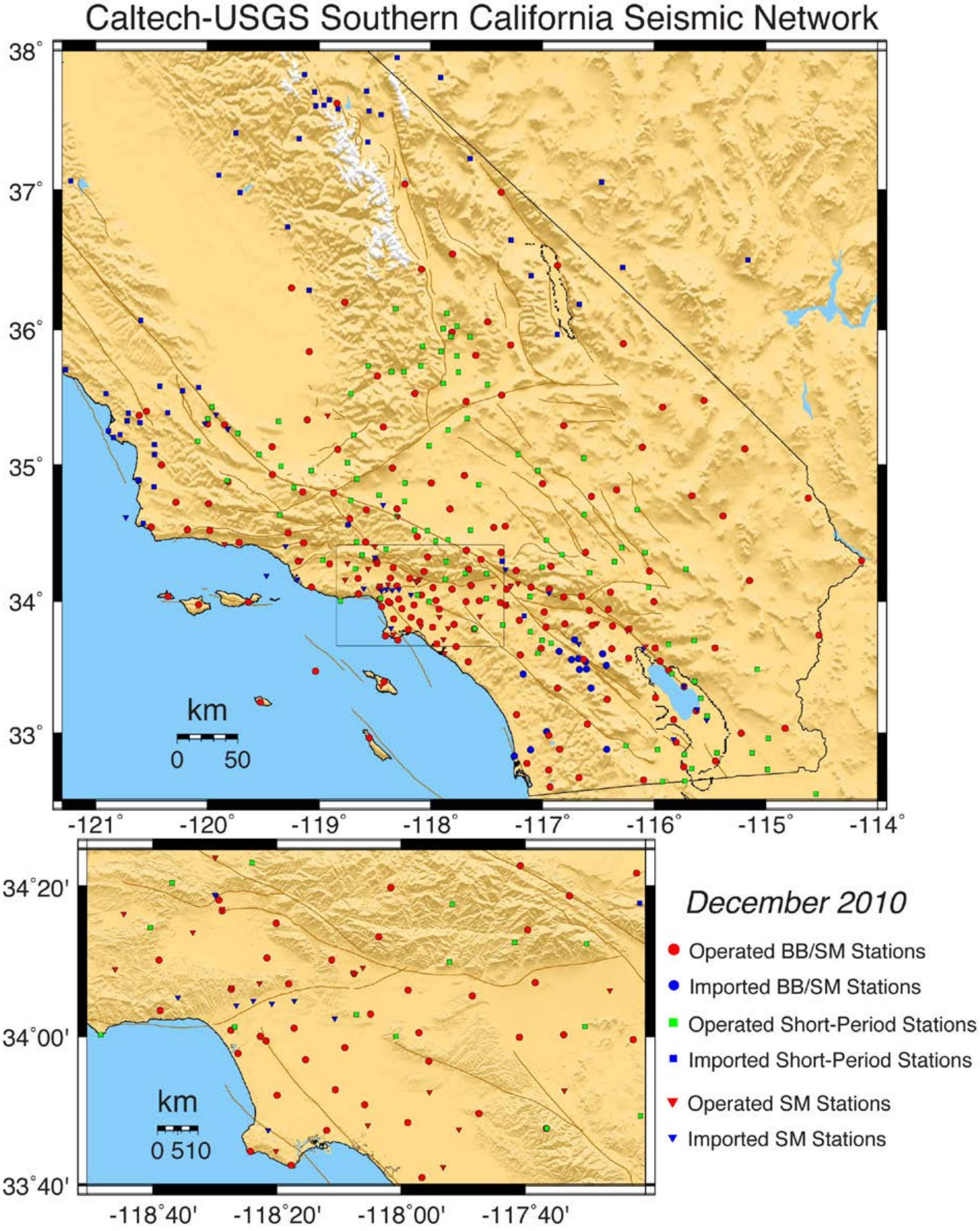

Fig. 8.14 The Southern California Seismic Network (SCSN) in 2010. Both SCSN operated (shown with red and green symbols) and partner network stations (shown with blue symbols) recorded by the SCSN are shown. BB- broadband seismometer, SM- strong motion instrument.

8.7.3 Japanese seismic networks (Hi-net, F-net, and K-NET/KiK-net), operated by the NIED (by Shin Aoi)

Four seismic networks are presently operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan (http://www.bosai.go.jp/e/) (Fig. 8.15).

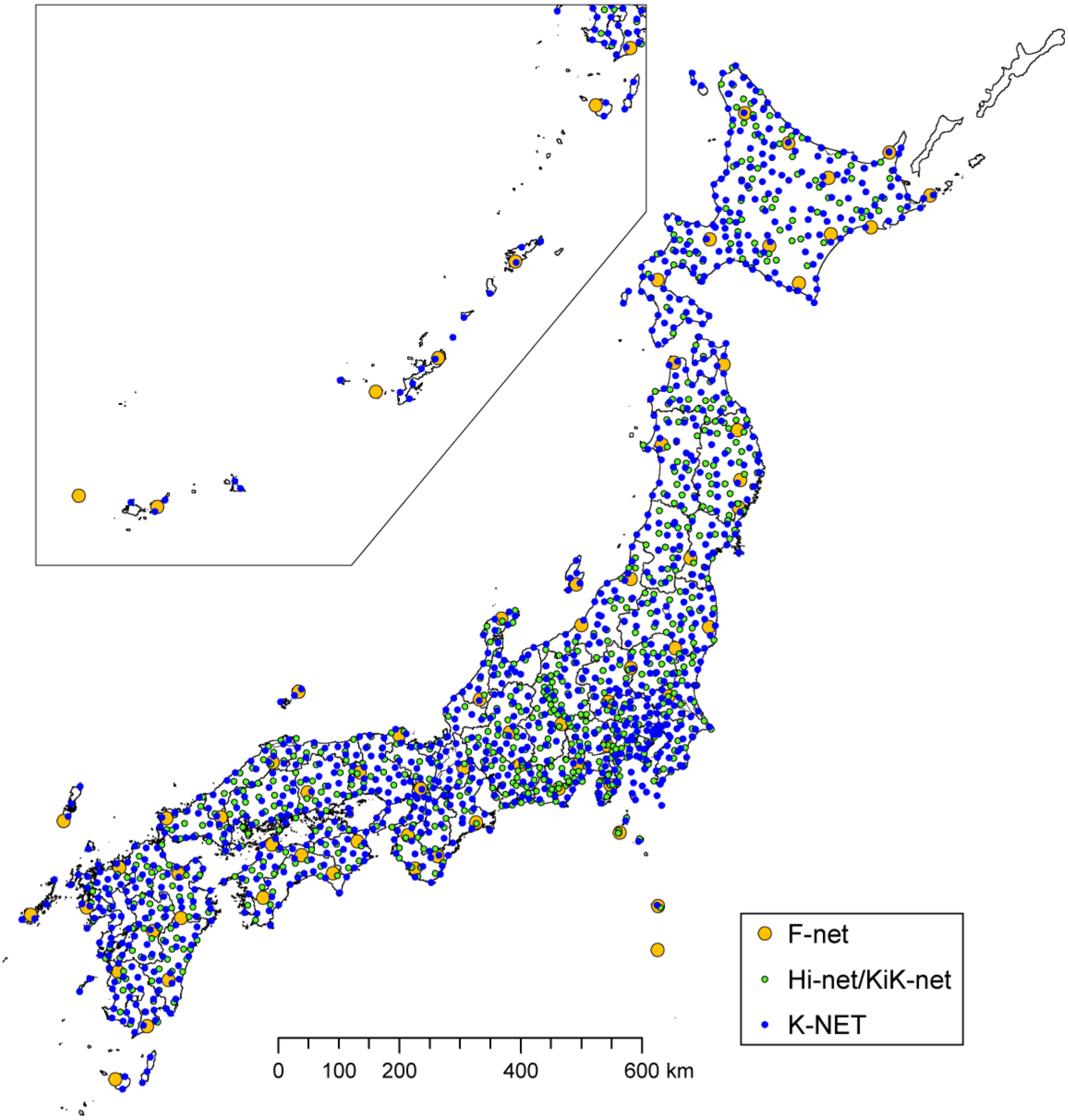

Fig. 8.15 Japanese Seismic Networks (Hi-net, F-net, and K-NET/KiK-net; status in 2010).

The first one is a high sensitivity seismograph network, named Hi-net, which comprises about 800 stations. At each Hi-net station a short-period, velocity-type seismograph is installed at the bottom of a borehole with a typical depth of 100 to 200 m (the deepest borehole reaches

3500 m depth). The second network is a broadband seismograph network, named F-net, which comprises about 70 stations. At each F-net station a broadband seismograph (STS-1 or 2) and a strong-motion sensor having a velocity-proportional response, are installed at the end of a horizontal tunnel of about 50 m length. Both Hi-net and F-net data are continuously transmitted to NIED via a TCP/IP network. The third network is a strong-motion seismograph network, named K-NET, which comprises more than 1000 stations. At each K-NET station an accelerometer is installed on the ground surface. The event-triggered data are automatically sent from each K-NET station immediately after the triggering. Another strong-motion seismograph network, named KiK-net, has its sensors installed in the same boreholes used by the Hi-net stations. Each KiK-net observation point is equipped with two accelerometers, one at the ground surface and one at the bottom of the borehole. Data collection procedure for the KiK-net is almost the same as that for the K-NET.

All data from these networks are freely available through the Internet. The Hi-net data are sent to the Japan Meteorological Agency (JMA) and used by the "Earthquake Early Warning" system, operated by JMA. Seismic intensities recorded by the K-NET, which is part of the nationwide seismic intensity network, are widely broadcast by television and radio stations. Many results, such as ground-motion prediction equations and underground structure models, have been obtained using a huge amount of data and related information from the above mentioned networks and largely contribute to a reliable seismic hazard evaluation. For more information, please see the webpages of the

- J-SHIS (Japan Seismic Hazard Information Station; http://www.j-shis.bosai.go.jp/?lang=en);
- NIED (http://www.bosai.go.jp/e/);
- Hi-net (High sensitivity seismograph network (http://www.hinet.bosai.go.jp/);
- F-net (Full range broadband seismograph network (http://www.fnet.bosai.go.jp/top.php?LANG=en);
- K-NET (Kyoshin strong-motion network (http://www.k-net.bosai.go.jp/);
- KiK-net (Kiban Kyoshin strong-motion network of vertical arrays (http://www.kik.bosai.go.jp/).

8.7.4 China seismic networks (by Liu Ruifeng and P. Bormann)

Since 2008 China has the following seismic networks (status as of December 2010):

- National Seismic Network with 145 stations, complemented by 2 small seismic arrays with 9 stations each;
- 31 Regional Seismic Networks with 792 stations in total;
- 6 local networks with 33 stations in total for volcano monitoring;
- 800 mobile seismic stations (600 for research projects, 200 for fast response deployments after strong earthquakes).

The National Seismic Network is an earthquake monitoring network with uniformly distributed seismic stations all over China. The average distance between seismic stations is about 250 km, except in the Qinghai-Tibet Plateau. Of the 145 stations of the National Seismic Network, 16 stations are equipped with Chinese made three-component very broadband seismographs of type JCZ-1, which have a flat velocity response from 360 s to 50 Hz and a flat acceleration response from 360 s to DC. At the other 129 stations, Chinese broadband seismometers of the type CTS-1 have been deployed, which have a flat velocity response from 120 s to 50 Hz. Detailed instrument parameters are given in the Data Sheet DS

5.1. The locations of these stations have been plotted in the top panel of Fig. 8.16 (top), with different symbols for these different types of instruments.

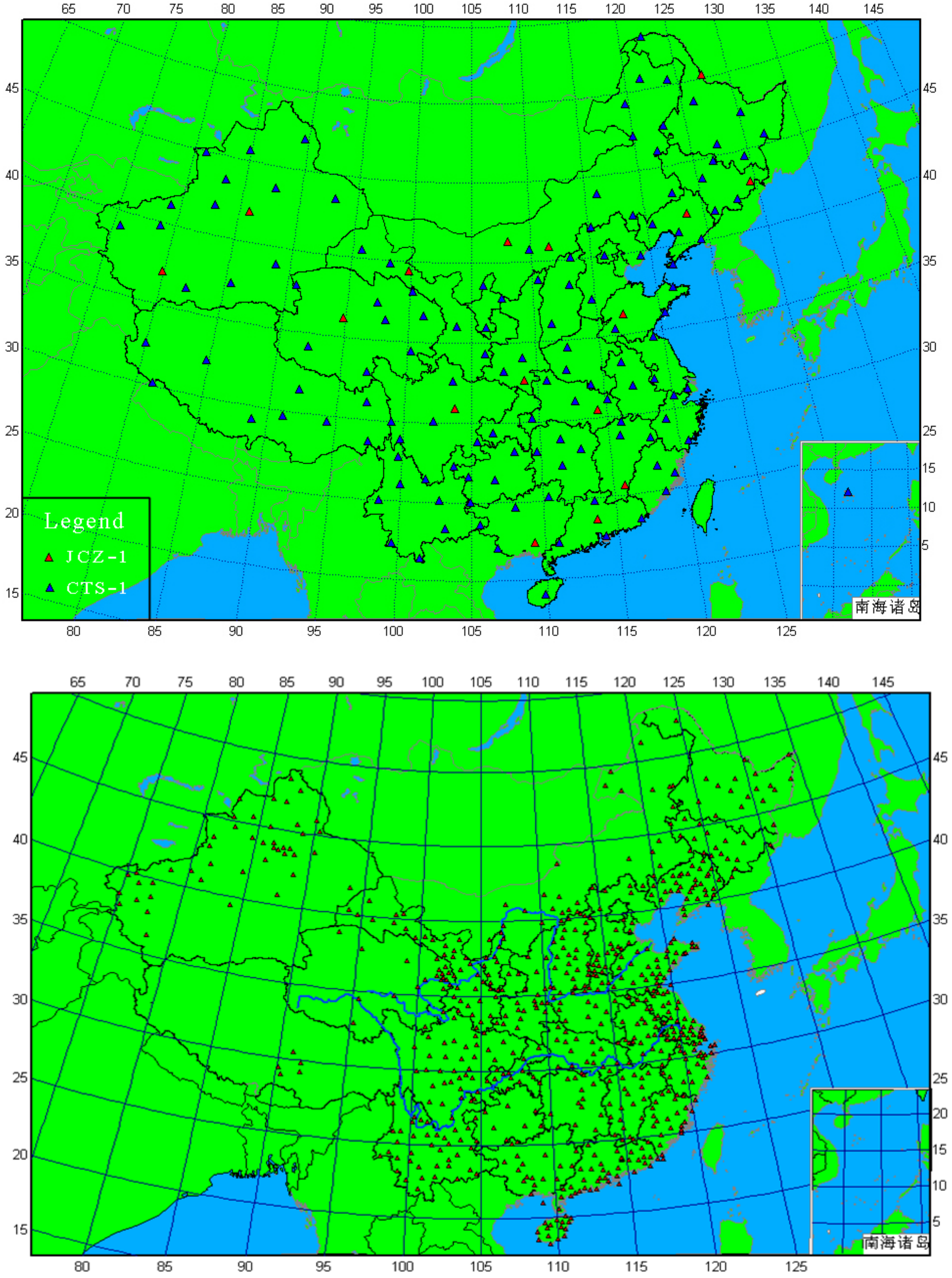

Fig. 8.16 **Top:** The China National Seismic Network and **Bottom:** the Chinese regional seismic networks.

Based on data from both national and regional seismic stations, CENC is capable of detecting M_L2.5 earthquakes in most areas on the Chinese mainland. In most of North China, northeastern China, central China, some parts of northwestern China and eastern coastal areas of China, events are detected down to M_L2.0 and in the key areas for earthquake surveillance and protection as well as in heavily populated major cities the detection threshold is as small as M_L1.5. The combined use of GSN and CENC data greatly increased the speed of information release and location accuracy of earthquakes in China's border areas or outside of China.

CENC produces fast catalogues in several steps. A first fully automatic catalogue is available after 2 minutes, the primary catalogue (including interactive measurements) for Beijing region within 8 min, for other regions after 12 min, and the final catalog for Beijing in 10 min, for other regions in 20 min. Besides this, CENC compiles all catalog data, also of the regional network centers. These data are available for general use via http://data.earthquake.cn and further information is provided on http://www.ceic.ac.cn. The quick production of specialized complementary data such as fault mechanism and moment tensor solutions, reconstruction of rupture processes, the production of shake maps and so on lies in the responsibility of the Geophysical Institute of the CEA in Beijing, which also serves as a back-up center for CENC.

8.7.5 German Regional Seismic Network (GRSN) (by K. Stammler)

The German Regional Seismic Network (GRSN) currently consists of 27 stations and the Graefenberg array (GRF), consisting of 13 stations. They are the seismological broadband backbone of Germany. These stations have been operated continuously since 1976 (GRF), and 1991 (first stations of the GRSN), respectively. All stations are equipped with broadband sensors, in most cases with Streckeisen STS-2 sensors which have a flat, velocity-proportional response characteristic in the frequency range 8.33 mHz to 40 Hz. The GRF array was upgraded from STS-1 to STS-2 sensors in the year 2006. These GRF stations are operated by the Federal Institute for Geosciences and Natural Resources (BGR) whereas the GRSN sites are operated in collaboration of the universities in Germany, the Geoforschungszentrum Potsdam (GFZ) and the BGR.

The stations installed aim at monitoring and collecting high-quality data from regional and global seismic events as well as at recording and locating events with Ml > 2 on German territory. All stations of GRF and GRSN are continuously recording, have a network connection via DSL or cell phone network and transmit their data in near-real-time to the Seismological Observatory of the BGR in Hanover using the SeedLink data protocol (except station GTTG which currently is using CD1 data protocol).

Since the local networks of the German states Saxonia and Thuringia also openly offer their continuous data via the Seismological Observatory of the BGR, these data are available there as well as those from the GRF and GRSN. These local networks operate currently 21 stations in total, mostly equipped with mid-period instruments Lennartz LE3D5s (flat response down to 0.2 Hz), only a few stations have broadband instruments like Streckeisen STS-2 or Güralp CMG 40T.

Fig. 8.17 shows the station sites of the Gräfenberg Array (GRF), the German Regional Seismic Network (GRSN) (yellow triangles) and of the associated local network stations (red triangles). More details on the stations of GRF and GRSN are given on the websites http://www.seismologie.bgr.de and http://www.szgrf.brg.de, which also provide information on available earthquake lists, bulletins, waveform data, station information, long-period and short-period dayplots of station recordings, the SHM analysis software manual as well as links to international and German seismic services and centers.

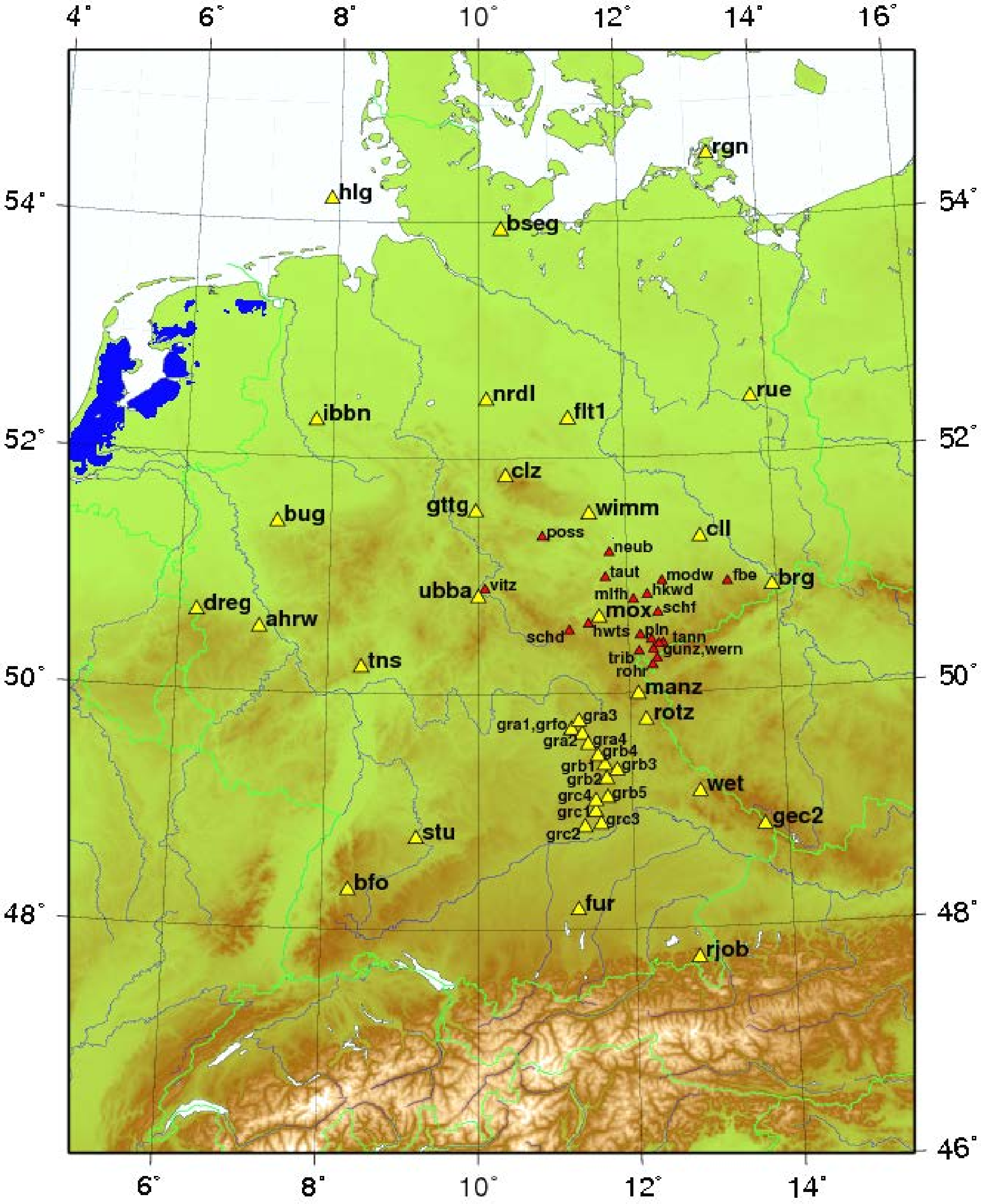

Fig. 8.17 Map of the station sites of the Gräfenberg Array (GRF) and the German Regional Seismic Network (GRSN) (yellow triangles) and associated local network stations (red triangles). Figure from http://www.szgrf.bgr.de/station_map.html.

8.7.6 Norwegian National Seismic Network

The network is a typical internet based real-time network operated by a combination of different systems. The network consists of a total of about 50 stations (Fig. 8.19), where some of the stations belong to networks in other countries. The three stations on Jan Mayen are the last ones still connected in an analog sub-network.. Stations are equipped with either short-period or broadband seismometer, digitizer, recording computer and communications equipment, The majority of the data is continuously collected in the NNSN system from field stations with SeedLink. The acquisition at the field stations is done with the SEISLOG software (Utheim et al, 2001) where both triggers and continuous data are produced. The central network triggering is done with EarthWorm. Triggers from EarthWorm and SEISLOG are merged and moved to the final SEISAN data base using SEISNET. Likewise the continuous data is collected from all systems, homogenized and moved to SEISAN using SEISNET.

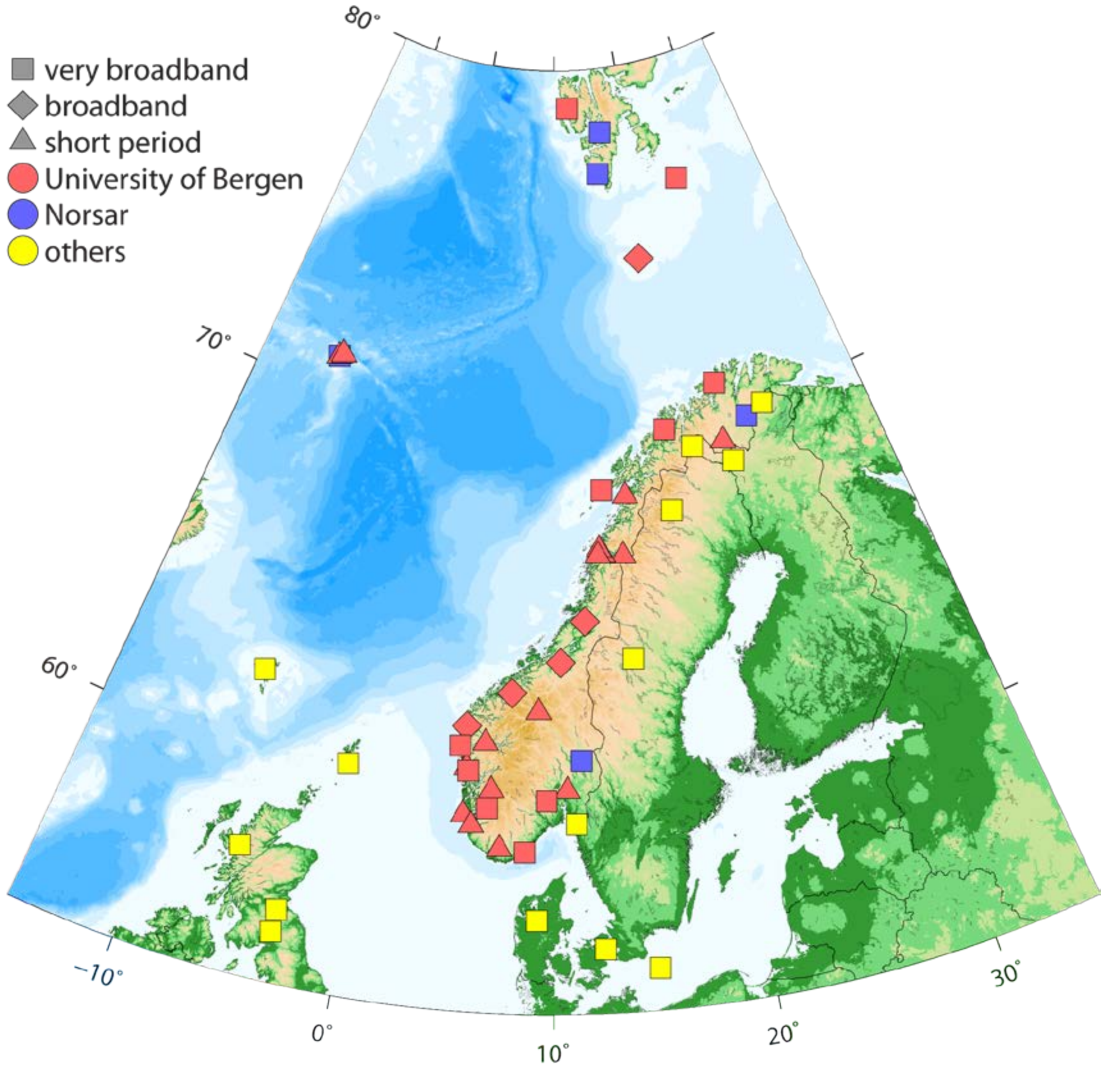

Fig. 8.19 Norwegian National Seismic Network (NNSN) and associated stations. Red and blue NNSN stations are operated by the University of Bergen (UiB) and NORSAR respectively and yellow stations are contributions from other networks.

8.8 Seismic shelters

8.8.1 Purpose of seismic shelters and lightning protection

Civil engineering structures at seismic stations assure a good mechanical contact between seismic sensors and non-weathered, solid bedrock. They protect equipment from temperature, humidity, dust, dirt, lightning, and small animals. The shelter should also provide a good, low-resistance electric ground for sensitive electronic equipment and lightning protection, as well as easy and safe access for equipment maintenance and servicing. The well-engineered seismic shelter structure must also minimize distortion of seismic signals due to structure-soil interaction and man-made and wind generated seismic noise.

Seismic sensors require a stable thermal environment for operation, particularly BB and VBB sensors. With passive sensors, mass position may change too much and with active sensors, temperature changes result in an output voltage drift, which can not be resolved easily from low-frequency seismic signals. This can greatly reduce the signal-to-noise ratio at low frequencies or even clip the sensor completely. Also, many active sensors require mass centering if temperature slips below a few °C or the temporal temperature gradient is too large. Less than 0.5°C peak-to-peak temperature changes in a few days should be assured for good results when using broadband sensors. This is not a trivial requirement for a seismic shelter. Extremely demanding (usually non-vault type) VBB shelters can assure even better temperature stability. Peak-to-peak temperature changes as small as ~ 0.03°C in two months (Uhrhammer et al., 1998) are reported for the very best shelters. Passive SP seismometers and accelerometers are much less demanding than BB and VBB seismometers with respect to the thermal stability of sensor environment. Many will work well in an environment with many degrees of temperature fluctuation.

Two vital, however often overlooked issues with potentially fatal consequences, if neglected, are lightning protection and grounding system. Lightning is the most frequent cause of seismic equipment failures. One needs to research the best lightning protection for each particular situation (lightning threat varies dramatically with station latitude, topography, and local climate) and then invest in its purchase, installation and maintenance. Several seismic networks have lost half or more of their equipment less than two years after installation because network operators simply neglected adequate lightning protection measures. A good, low-impedance grounding system keeps instrument noise low, allowing proper grounding and shielding of equipment and cables. It is a prerequisite for a good lightning protection system and is also absolutely required for an interference free VHF or UHF RF telemetry.

In some areas a light fence may be required around the vault to minimize man- and animal-made seismic noise and to protect stations against vandalism. The area covered by the fence may range from 5 x 5 m to 100 x 100 m, depending on several factors, e.g.: what kind of activity goes on around the site; the population density in the vicinity; the ground quality; natural seismic noise levels; and the depth of the vault. Note that fencing often represents a significant portion of the site preparation costs.

Inadequate site preparation and seismometer placement can easily wipe out all the benefits of expensive, high-sensitivity, high-dynamic range seismic equipment. For example, thermal and wind effects on a shallow seismic vault located on unconsolidated alluvial deposits instead of bedrock can make broadband recording useless. It is pointless to invest money in expensive seismic equipment only to have its benefits wasted because of improper site conditions.

8.8.2 Types of seismic shelters

The three main types of seismic shelters are:

- surface vaults which are the least expensive and by far the most frequently used, however they suffer the greatest level of natural and man-made seismic noise (see 7.4.2);

- deep vaults placed in abandoned tunnels, old mines or natural caves which are usually the best locations with respect to the price/seismic-noise-performance ratio, however, they may not be available and sometimes require extensive cabling, which can increase their cost (see 7.4.3);

- borehole seismic stations with depths from 10 to 2000 m are the best choice from the perspective of seismic noise. Improvement of the signal-to-noise ratio of up to 30 dB in ground velocity power density at about 0.01 Hz can be obtained by a 100-m deep hole. For high frequencies above 1 Hz the greatest gains in noise level reduction are realized within the first 100 m of hole depth. Wind-generated high frequency noise can be attenuated as well, however a complete shielding from it is possible only with a very deep borehole (Young et al. 1996). Boreholes are expensive. They may cost from US$ 5,000 to US$ 200,000 for the borehole itself, plus the cost of borehole type sensors, which are significantly more expensive than regular surface sensors. Boreholes are used principally in regions covered entirely by alluvial deposits where sites with good bedrock outcroppings are not available; or for the most demanding research work requiring low tilt-noise in horizontal component BB and VBB installations (see 7.4.5).

Shallow boreholes with a depth from a few meters to 15 m are sometimes used instead of surface vaults for pure economic reasons. A 15-m deep surface vault in a difficult terrain may cost more than a shallow borehole of the same depth. Seismic noise improvement in such shallow boreholes is negligible.

In terms of network cost, it might be cheaper to increase seismic station density to achieve a desired detection level rather than install a few borehole systems

8.8.3 Civil engineering works at vault seismic stations

Today, seismic stations are most often in the ground vault form. The massive, solid concrete "seismic piers", traditionally found in old seismic observatories, are no longer built. Above-ground buildings or shelters are not desired at all. In fact, above-ground structures are far less suitable than underground vaults because of potential structure-soil interaction problems as well as wind generated seismic noise caused by the above-surface structural elements. (Bycroft, 1978; Luco et al., 1990). Also, sufficient thermal stability of the environment is much easier to achieve in an underground vault. If small buildings of any kind already exist at the selected location, make sure the seismometer vault is placed far enough away to minimize wind-generated noise as recommended already in the old Manual of Seismological

Observatory Practice (Willmore, 1979) (see IS 7.3). The structure of the vault should be light and above-ground parts kept to a minimum, creating as little wind resistance as possible.

Surface seismic vaults usually measure between 1 and 2 m in diameter, depending on their depth, the amount of installed equipment and the desired ease of maintenance. They are from 1 to 10 m deep, depending on the depth, quality, and weathering of bedrock at the site. Round or rectangular cross sections are equally suitable. Examples of their design are given in Figs. 7.39 and 7.40.

8.9 Establishing and running a new seismic network

8.9.1 Planning and feasibility study

8.9.1.1 Goal setting

The very first step toward establishing a new seismic network is understanding and setting the network's goals. These goals can differ significantly (see Tab. 8.1 in 8.3.5). The same applies to the seismic system requirements. Also, just as each country has unique seismicity, seismotectonics and geological formations, so every seismological project has unique contextual combinations that one must consider in order to find the optimal system design for that project.

Several issues must be addressed:

- the user's interests in ranked order: local seismology (epicentral distances < 150 km), regional seismology (epicentral distances between 150 and 2,000 km), and/or global seismology (epicentral distances > 2,000 km);

- the main purpose of setting up a network is usually either to monitor a region's general seismicity or to perform special studies (monitoring of special seismotectonic features, of important civil engineering structures, of engineering and/or nuclear explosions, of man-induced seismicity, etc.);

- the relative importance to the project’s alarm function for civil defense purposes: Is the seismological research aimed at the long-term mitigation of the country's seismic risk or at the scientific research of the Earth's deep structure.

Many countries that have little or no seismic equipment should initially consider buying a system to monitor the region's general seismicity. They should expect the new system to help mitigate the region's seismic risk over a long period of time. Nevertheless, even for a project of such a well-defined scope, several questions must still be answered, including the country’s needs as well as its financial, personnel, and infrastructure capabilities:

- how big is the region to be monitored?
- what is the seismicity level in the region?
- what is the institution’s existing level of seismometry knowledge, and what are its resources for improving that knowledge?
- what is available in terms of communication infrastructure?

- how much money is available to establish the system?
- how many staff are available, per year, to operate and maintain the system, and to support research work using the system's data?

Having realistically quantified the above facts, one can then begin shopping for a seismic system that meets those criteria. There is always a trade-off between desires and reality. This procedure ensures that the new network will perform successfully in the existing environment, if carried out realistically.

If there are few or even no seismology experts available in the country, it is advisable to get help from consultants in the international academic world who are independent of commercial interests. In this early phase, focus on your country's specific socioeconomic needs and seismic awareness, and do not worry too much about specific equipment. Wait until the later phases of network design to contact sales and system engineers from seismic equipment manufacturers for help in defining the technical details of your system.

8.9.1.2 Financial reality

Often, newcomers to seismology do not know how to allocate their finances to obtain the optimal seismic network design. Too often they spend the majority of their network funds purely on purchasing equipment, even though an identically important expenditure is required for proper operation of this complex equipment. To make sure one has correctly prepared for the purchase of seismic network equipment, one's budget must include money for the following:

- a feasibility study that examines potential network layouts, site selection, and potential seismic systems;
- preparation of remote stations;
- installation of the central-recording site;
- purchase of the network equipment;
- cost of installation, training, maintenance, and long-term support;
- cost of salaries and training for the new scientific and technical personnel usually required;
- network operation costs, including personnel, data transmission, data processing hardware and software, printing, backup storage, consumables, and spare parts;
- network servicing and maintenance cost.

The five figures on the following pages show examples of funding proportion among several different established seismic network projects. The numbers in the figures show the amounts allocated to different tasks (normalized per single station), both in thousands of US dollars and as a percentage of the project's total cost.

Fig. 8.20 shows an approximate cost distribution (per station) for establishing and operating the global seismic network (GSN) during five years, according to the IRIS plan 1990-1996. The IRIS consortium is composed of universities in the USA and other countries with a research program in seismology. Not only did this network use the most demanding and expensive equipment available, expensive site preparation and worldwide maintenance were often required which increased the cost per station.

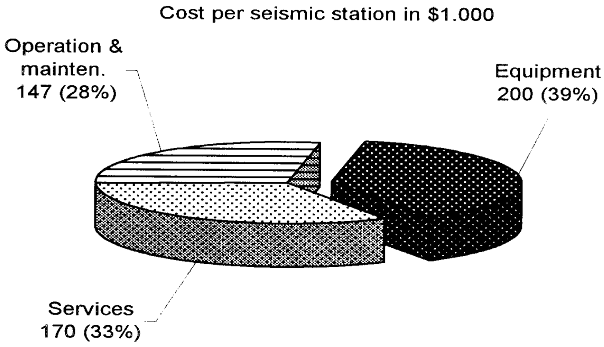

Fig. 8.20 Cost distribution of establishment and 5-year operation of a global seismic network (GSN) station. Number in ( ) is percentage of the project's total cost.

Fig. 8.21 shows details of the IRIS GSN system's establishment costs (excluding all operations costs; again, costs are averaged per station). Surface vault seismic stations are considered only. IRIS constructed many of the sites of GSN network as deep, expensive borehole installations. Even if they are not taken into account in this figure, IRIS still allocated substantial funds for the vaults and to tasks other than equipment buying.

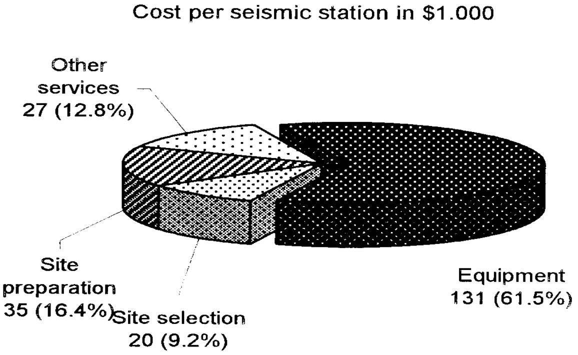

Fig. 8.21 Cost distribution of establishment of IRIS GSN surface vault seismic stations. In this and the following figures the number in ( ) is percentage of the project's total cost.

Fig. 8.22 shows a distribution of the finances which a developing country spent to establish a reasonably large seismic network, using analog RF telemetry. The country's significant investment in services (21.6%) paid for training at the factory and during installation, as well as one year of the manufacturer's full-time engineer support. These expenditures were critical for the successful start-up and operation of this network.

Fig. 8.23 shows a negative example of cost distribution, for a small, yet technologically demanding seismic network. Note the small amount invested in tasks other than equipment-purchases, particularly the site preparation works; 4.1% is surely not sufficient, making it difficult to believe that these sites could provide ample working conditions for such demanding sensors as very broadband (VBB) STS1 and STS2 seismometers. The relatively high amounts spent for services (9.3% for installation) came mostly because the purchasers desired a turnkey type of system. With no experiences in seismometry, the chances of efficiently using the installed equipment seem small.

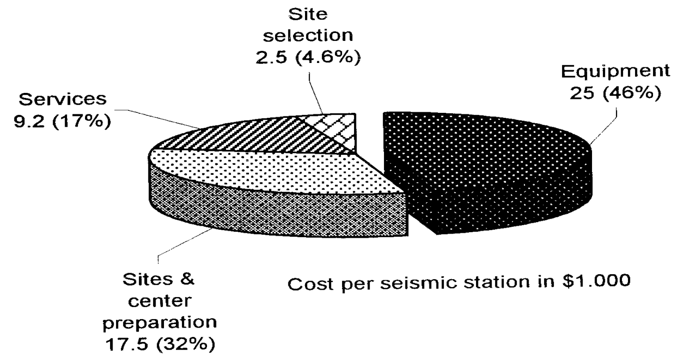

Fig. 8.22 Cost distribution of a relatively large national seismic network with 20 SP seismic stations, strong-motion instrumentation, and analog FM telemetry.

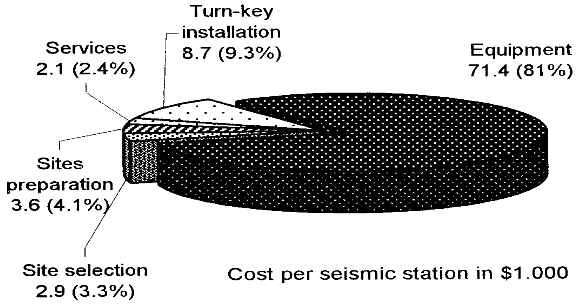

Fig. 8.23 Cost distribution of a small, technologically high-end seismic network with an inappropriate allocation of funds.

Fig. 8.24 shows another example of a national seismic network installed in a large country and using high-end technology and duplex, digital telemetry system. But again, despite the network's size, the most modern equipment, and the central-recording equipment for two centers, the country only invested about 60 % of its total project funds in the equipment. The other half of the money was spent on follow-up services, including a great deal of training and two years of full-time engineer support provided by the equipment's manufacturer.

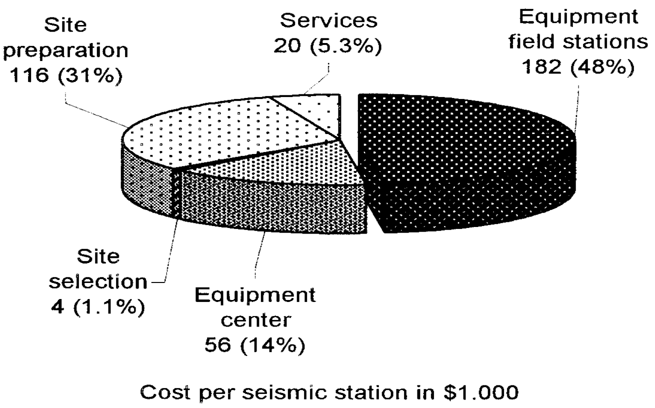

Fig. 8.24 Cost distribution of a very large national, high-end technology, duplex-digital RF and phone-line telemetry seismic network with two central-recording centers.

The funding distributions shown in Figs. 8.20 through 24 are approximate and for illustration purpose only. Generally, the prices of seismic equipment are somewhat lower today. Actual conditions (including the type of network, the level of existing local technical knowledge, local labor prices, and the type of seismic site preparation required) will change from country to country, thus significantly influencing distribution of the funds. Regardless, the main message of these figures stays the same: one should not spend almost all the allocated funds on equipment. Despite deviations and the differences in absolute cost, these figures seem to indicate that the percentages of the total cost for each task remain nearly the same from network to network. As a rule, one should allocate at least one third of the money for a feasibility study, for establishing the proper working conditions, and for gaining the seismic expertise necessary to exploit the purchased equipment.

8.9.1.3 Basic system engineering parameters

Once the goals are clear and the funds properly allocated, one has to clarify the entire project's interrelated seismological and technological aspects. Attention should be paid to:

- the size and the layout of the proposed seismic network (this should affect the choice of the type of transmission links for transmission of seismic data from the remote stations to the center);

- the seismicity level to be monitored - in other words, the amount of data one will deal with (this should affect data transmission equipment, central processing site's real-time and offline capabilities, whether the system will need continuous or triggered data recording capabilities, if and what type of trigger algorithm it will use, the type of data archive system; this should also affect the partitioning between weak-motion and strong-motion equipment);

- how accurate and where one wants the network's central-recording site to be located (this will affect the number of stations and the network's layout);

- the importance of the new system having alarm capabilities for civil defense purposes and the desired alarm response time (this should influence which data transmission links will be chosen, as well as how much real-time processing power will be needed at the central-recording site);

- the amount of technical reliability one expects from the system (this should affect the choice of data transmission links, how much hardware system redundancy one can afford for mission critical applications, like auto-duplicating disk drives, tandem computers, etc., as well as decision between ‘office-grade’ and industrial-grade computers);

- the desired robustness of the system in terms of functioning throughout damaging earthquakes (this should influence the selection of data transmission links, of power backup utilities for the remote stations and the central-recording site, and last but not least, of seismic vulnerability of the building that houses the central processing site).

After reasonably assessing these aspects and making a decision for each unique situation, one can then create a rough system design and begin selecting equipment that best matches these goals. Obviously, certain tradeoffs will need to be made.

8.9.1.4 Determining the layout of a seismic network

Determining a layout for one’s seismic network requires two steps: 1) determining the total number of stations required and their approximate locations, and 2) determining the final station locations. Since the first stage closely relates to the goals of the network and available funds, the network operator should delineate how many stations he requires and can afford to set up, and where approximately they should be located. Since the second stage typically requires knowledge of seismometry, seismo-geology, data transmission technology (if applicable), and seismic equipment capabilities and limitations, the operator, if not having the experience, may want to consult with others having the experience.

8.9.1.5 Number of stations in a seismic network

The number of seismic stations should be based on the goals of the network, the size of the network, and, of course, on the available funding. For space reasons we will not go into details on the minimum number of stations that are technically required for a given seismological goal, but following there is a short overview.

For determination of an event location (based on phase readings), the theoretical minimum is four independent measurements, such as three P-arrival times and one S-arrival time. However, remember that such results, due to their uncertainty, usually have little value. For a more accurate determination of location, six stations acquiring good records of an event should provide scientifically credible evidence of an event's location, and ten to fifteen stations with good azimuthal coverage all around the source (see criteria outlined in Table 1 and 2 plus Figure 1 of IS 8.5) and acquiring good quality records of the event should provide an acceptable basis for more sophisticated studies of the earthquake's source properties. IS 7.4 describes a program which permits detectability and earthquake location accuracy modeling of smaller size national networks. Examples of theoretical network optimization with respect to event location and other parameter determinations are presented and critically discussed in IS 8.7.

Larger countries or regions will require a greater number of stations, unless, of course, their interest is only in the strongest earthquakes. Yet, for networks covering a large region, large epicentral distances often prevent the triggering of distant stations, or the earthquake signals get buried in the seismic noise. Thus the total information available for a given event, unless it is a strong one, typically comes from only a portion of the total network. How one can assess under such varying conditions, with respect to precision-located “ground truth” GT5 critera (e.g., Bondár and McLaughlin, 2009), the quality of an operational authoritative location scheme applied in the real-time event information service of the European Mediterranean Seismological Center (EMSC) is described in IS 8.5. How ground truth reference events, suitable for network performance and location quality evaluation, can be identified and collected by way of own high precision network locations is described in IS 8.6. And Murphy et al. (2005) present a an example of the calibration of stations of the International Monitoring System (IMS) aimed at improving seismic event location.

Note that seismic researchers do not care much about the total number of stations in a network; what counts is the number of stations in the network that adequately record a given event ('adequately record' means that they triggered data acquisition, the records are not saturated and that the records have a high signal-to-noise ratio). Moreover, waveform analysis of digital, high dynamic range, three-component records leads to good results already with fewer stations. In principle, even a single well calibrated 3-component station can determine, via multi-phase phase identification and polarization analysis, the epicenter, source depth (if below the crust), origin time and magnitude of earthquakes with reasonable accuracy using global 1-D models and correcting for systematic biases (if any), that may depend on azimuth and distance or source region (see Chapter 11, section 11.2.6.2. and EX 11.2). For more details on location procedures and related problems, both for networks and single stations, see IS 11.1.

8.9.1.6 Layout of a new seismic network

Although the spatial distribution of the stations in a seismic network is very important for the network's capabilities of event determination, due to limited space we will only give a few, brief recommendations. For seismic arrays and their special location procedures and performance see Chapter 9.

On a map, subdivide the region to be monitored into a series of reasonably irregular triangles having approximately equal areas. Avoid very narrow, long triangles. Avoid thinking in rigid patterns, such as locating the stations into perfect triangles, circles or straight lines, because such rigidity may result in "blind spots" - that is regions with poor event location determination. The corners of these triangles are the approximate points where one will try to locate seismic stations. Take into account any existing seismic stations in neighboring countries or regions as well. If there are none, push some of the seismic stations as close as possible to the borders of the region being monitored.

The geometry of the network will determine the accuracy of location in different directions, and a reasonably regular grid will give most uniform location accuracy. The worst configuration is a network with stations that are aligned (see Fig. 8.25 as an example).

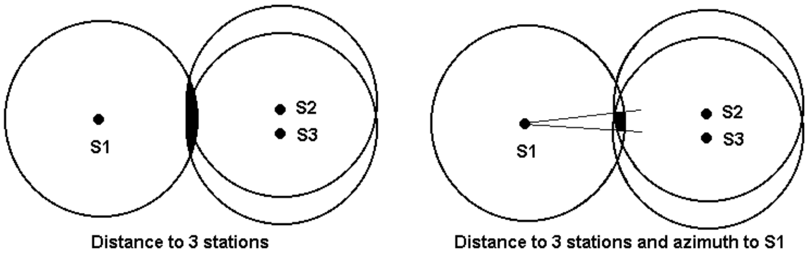

Fig. 8.25 Network geometry of aligned stations. The figure to the left shows three stations (S1, S2 and S3) almost aligned in the x-direction (left - right). The event has been located by using the distances to the three stations, and the shaded area in the middle gives an indication of the area within which the epicenter can be found. The figure to the right shows the same situation except that an azimuth determination has been made with three-component records at station S1. This limits the y-direction within which the epicenter can be located and thus reduces the epicenter error.

It is advisable to have realistic expectations concerning the earthquake depth determination based on phase readings. Previous studies (e.g., Francis et al., 1978; Uhrhammer, 1980; and McLaren and Frohlich, 1985) have shown that the accuracy of focal depths for shocks occurring in the vicinity of a seismic network is primarily a function of the geometry of the network, the number of the P- and S-phase arrivals read, and the adequacy of the assumed velocity model. Depths are generally more accurate for earthquakes where the distance from the epicenter to the closest station is less than the calculated focal depth for events located within the network or on its periphery. The accuracy of focal depths usually increases as the number of picked S-phase arrivals increases; however, systematic S-phase timing errors (due to mistaken identification of a converted phase as S) or "bad" S picks can degrade the focal depth estimation accuracy by several kilometers even when the azimuthal coverage is good (Gomberg et al., 1990). Estimate the depth of the shallowest events for which good depth control is desired then make sure that the average distance between stations in the seismic network does not exceed twice that depth. The latter is admittedly a tough requirement, especially in the large regions and in the regions where the events are typically shallow! Only a few small countries and practically none of the larger countries can afford such a dense network.

Yet, one can still temporarily afford to make the network denser in places. Buy a few portable seismic stations and then temporarily install them in any sub region of particular interest at the time. For example, such temporary networks are regularly established to perform aftershock studies in the epicentral region immediately after a strong event. At least for a time, this will drastically increase the seismic network's density in the region of interest, allowing the determination of much better locations, depths, and focal mechanisms. Such studies can be done with low-cost portable instruments since the main purpose is to get more phase readings.

Have realistic expectations also about the system's earthquake epicenter determinations. For events outside the seismic network, expect large errors in determining epicenters. Generally, do not expect reliable determination of events, unless the "seismic gap" (the largest of all angles among the lines connecting a potential epicenter with all the stations in the network that recorded the event) is less than 180 degrees. Thus, to increase the accuracy of epicenter determinations, especially for the events outside the seismic network, one needs to include data in the analysis from seismic stations in neighboring countries, as well as from any other available national or international sources. It is common practice to share near real-time data across the borders and integrate the data into a virtual seismic network. Acquiring this wider database is usually necessary for determining reliable event locations on the border or outside any seismic network.

8.9.2 Site selection

The matter of seismic site selection is too often not given sufficient depth of study and attention in spite of the fact that a weak-motion seismic network can only have a high detection threshold if the sites have satisfactory noise levels, no matter how technologically advanced and expensive equipment is. If seismic noise at the sites is high, all or a part of the benefits of modern equipment with large dynamic range are lost. If an excessive burst or spike-type, man-made seismic noise is present, high trigger thresholds and therefore poor event detectability will result. If stations are situated on soft ground, the VBB or even the BB recording can be useless and SP signals may be unrepresentative due to local ground effects. If the network layout is inappropriate, some event locations may be inaccurate or even impossible. For good results, many factors at the sites must be taken into consideration. A professional site selection procedure is therefore essential for success of any seismic network. There can also be specific reasons (e.g., political) why a station may have to be deployed in a particular place, but also then it may be possible to select the “better” site.

Generally, it is best to begin the process of site selection by choosing two to three times as many potential sites as one actually plans to use. Then each site is studied to see which sites meet as many of the criteria as possible. Gradually, one will eliminate the poorest sites and get down to the number of sites required plus two or three. By comparing the results of computer modeling of a few of the most likely network layouts (see IS 7.4) one will be able to make an informed decision about the best network.

Note that one should not rely too much on algorithms designed to optimize seismic network configuration (e.g., Kijko, 1977; Rabinovitz and Steinberg, 1990). This is because the theoretical optimum configuration can hardly ever be realized nor their predicted theoretical potential information gain be exploited under real conditions. Stations often can not be installed at the recommended locations due to factors such as inaccessibility, poor ground conditions, proximity of strong noise sources, lack of required power, or unavailable communication link.

On the other hand, these programs may be of help selecting the best of a few realistic network configurations (e.g., Trnkoczy and Živčić, 1992; Hardt and Scherbaum, 1994; Steinberg et al., 1995; Bartal et al., 2000). For an existing network, they could help decide how best to improve the network by adding new stations or which stations, if removed, would cause least harm to the network. Keep in mind, however, that the best configuration for locating earthquakes may not be optimal for source mechanism determinations, tomographic studies or other tasks (Hardt and Scherbaum, 1994). These various aspects of network optimization and performance assessment are richly illustrated and commented in more detail in a PPT tutorial, annexed as IS 8.7.

Here we will present only the basic steps of the site selection procedure. More details on this issue can be found in Chapter 7, sections 7.1 and 7.2.

The site selection procedure encompasses office and field studies. Off-site, "office" studies are relatively inexpensive and therefore the first ones to be performed. From an office, one can study maps and contact local authorities to gather information about potential sites. The first step is defining the geographical region of interest. The next step is to gather and examine existing geological faults, seismotectonic features, and all available information about seismicity in the area. If the main goal of the new network is monitoring general seismicity in an entire country, this stage is, of course, simpler. Then prepare a simplified map of regional seismo-geologic conditions showing the quality of bedrock. The rule is: the higher the acoustic impedance (acoustic impedance is the product of the density and the velocity) of the bedrock, the less the seismic noise and the higher the maximum possible gain of a seismic station. Next, study the topographical aspects of the possible locations. Moderately changing topography is desired. To study man-made and natural seismic noise sources in the region, one should evaluate road traffic, railway traffic, heavy industry, mining and quarry activities, agricultural development of the region, and any other sources of man-made seismic noise around the potential sites, along with the natural sources like oceans and lakes, rivers, waterfalls, animals, etc. (see IS 7.3). Much of the information we need can be found on maps, geographic information systems or obtained by asking questions of local authorities.

Real-time communication is a requirement in most modern seismic networks and will add some constraints to site selection. Communication is typically based on Internet technology for radio, satellite, mobile phone and fixed line links. Radio and satellite links are the most flexible as they can be deployed almost anywhere. Mobile phone services and coverage vary strongly, but may be an attractive option. Fixed lines such as ADSL are generally inexpensive and provide high data rates, but are not available anywhere. If the new network is a radio frequency (RF) telemetry system, one has to correlate RF data transmission requirements with seismological requirements. Topographic profiling of RF paths based on topographical maps is performed. The next section "VHF, UHF and SS radio-link data transmission study" explains why this is highly recommended.

If one plans to use main power, the availability of main power lines and the distances to which new lines would have to be laid must be checked. The alternative is batteries, preferably charged by solar panels. It is also very important to research land ownership, animal habitats, land protection and future land use plans for the potential sites. It makes no sense to undertake extensive studies if one will be unable to use certain sites because of property ownership issues, endangered or protected animal species issues, or if it appears that future development will make the site unsuitable for seismic stations.

The climate at the sites also influences site selection and preparation. Temperatures, wind, precipitation, insulation data (for solar-panel powered stations), lightning threat, etc. may all influence site selection.

Field studies are the next step in the site selection process. Expect to make several visits to each site. A seismologist familiar with seismic noise measurements, a seismo-geologist, and a communications expert (if we are considering a telemetry network) should all visit each site. They should verify the ease of access to the site, search for local man-made seismic noise sources, which may not be apparent from maps, perform seismic noise measurements (of at least a few days duration), study the local seismo-geological conditions at the site, investigate the local RF data transmission conditions (if applicable), and on site verify power and phone line availability.

Local geology should be studied to determine its complexity and variations as well as seismic coupling between local seismic noise sources and the potential station site. To the extent possible, uniform local geology is preferred for seismic stations. The degree of weathering that local rocks have undergone is another important parameter, although it can give an unreliable estimate of the required depth of the seismic vault. The ideal approach for high-quality site selection is to make a shallow profile at each potential site to make sure the vault will reach hard bedrock. If this is too costly, then expect surprises when you begin digging seismic vaults. Many times it is a matter of almost pure chance what one might run into. Note that in some areas it will not be possible to reach bedrock.

After all these studies one ends up with two or three potential sets of the best suitable seismic stations. The resulting network layouts are then studied for the best network performance possibly by computer modeling. By comparing the results, one will be able to make an informed decision about the final seismic network layout.

8.9.3 VHF, UHF and SS radio-link data transmission study

8.9.3.1 The need for a professional RF network design

The most frequent technical problems with radio-frequency (RF) telemetry seismic networks originate with inadequately designed data transmission links. Therefore we are discussing this topic separately. For more detailed description see 7.3.

The design of RF telemetry links in a seismic network is a specialized technical matter, therefore guessing and "common sense" approaches usually cause problems or even complete project failure. There are quite a few common misunderstandings and oversimplifications. The amount of data that must be transmitted and the degree of reliability required for successful transmission of seismological data are frequently underestimated. The significance of "open line of sight" between transmitters and receivers as a required and sufficient condition for reliable RF links is misunderstood. Frequently, over-simplified methods of link verification are practiced. However, the real issues in the RF link design and link reliability calculations are: the frequency of operation, Fresnel ellipsoid obstructions by topographic obstacles, the curvature of the Earth, the gradient of air reflectivity in the region, expected fading, potential-wave diffraction and/or reflections, time dispersions of the RF carrier with digital links, degradation of signal strength due to weather effects, etc. All these are specialized technical issues.

To prevent failures, a professional RF survey in planning a new seismic network is strongly recommended. It includes the calculation of RF links based on topographical data and occasional field measurements. A layout design based on a professional RF survey can significantly increase robustness of the radio network. The survey will:

- determine the minimum number of required links and RF repeaters in the network. Note that, in most designs, every RF repeater obviously increases the probability of link-down time and the price of the system;

- determine the minimum number of licensed frequencies required;

- determine the optimal distribution of RF frequencies over the network, which minimizes the probability of RF interference problems;

- chose in a less polluted RF space in the country;

- determine the minimum antennae sizes and mast heights, resulting in potential savings on antenna and antenna-mast cost.

The cost of a professional RF survey represents generally a few percent of the total investment. We believe that the combined benefits of an RF survey are well worth the investment, and are a major step toward the reliable operation of the seismic network.

8.9.3.2 Problems with RF interference

Radio frequency interference caused by other users of VHF or UHF RF space in many countries is quite a common and difficult problem. There are several reasons for that. In some countries, there is confusion and a lack of discipline in matters of RF space: army, police, security authorities, and civil authorities may all operate under different (or no) rules and cause unforeseen interference. In other countries, poor maintenance of high-power communication equipment results in strong, stray radiation from the side lobes of powerful transmitters. This radiation can interfere with seismological radio links. Extensive, unauthorized use of walkie-talkies can also be the cause of problems.

The best, and more or less the only solution is to work closely with local RF experts during the design phase of a seismic network. They are practically the only source of information about true RF space conditions in a country. Note that RF interference problems are generally beyond control of seismic system manufacturers and seismological community. All RF equipment, no matter who manufactures it, are designed to be used in an RF space where everybody strictly obeys the rules. One also has to, as much as possible, avoid other high-power RF space users (see IS 7.2).

8.9.3.3 Organization of RF data transmission network design

An RF layout design is always an integral part of a seismic site selection procedure. Theoretically the seismic system purchaser can perform it if he has adequate knowledge in this field. However, practice shows that this is rarely the case. Even if the RF survey is purchased from an independent company or from a seismic equipment manufacturer as a part of the services, the process still requires involvement of the seismic system buyer. For efficient office and fieldwork, the customer has to prepare beforehand an approximate initial seismic network layout, road and topographic maps, and climatic data. He has to make available knowledgeable staff members and well-informed local people acquainted with local conditions at the sites, who will join the site selection and RF survey field team. He should also assure efficient logistics during the fieldwork.

A detailed list of what to prepare is given in the IS 7.1.

8.9.4 Purchasing a seismic system

There are different ways of buying equipment for a completely new network. If the user has little experience, it might be desirable to get all equipment and installation from one company while if the user has sufficient knowledge or can get help from other institutions, only equipment should be bought and possibly from several different companies in order to get the best price/performance. Buying all from one company is often a more expensive solution. However, compatibility between the different components is essential, but more difficult to achieve when mixing. Some countries/institutions require that equipment (and installation) go through a bidding process. The bidding process may help to carry out a more systematic evaluation and pay off. Some institutions insist that all equipment and services are obtained from a local representative. While there may be good reasons for this, it can increase the cost.

A very important requirement for the new network is specification of how and in which format the data is delivered. Today, most equipment is able to produce data in one of the standard formats used for processing, however the data must also be easily available for integration into one or several of the standard systems used for processing. Just recording all data continuously is not much help if there is no user-friendly software available to access and extract any part of that data. So an integral part of the specification is a requirement that the data must be delivered ready for processing in a given processing system.

8.9.4.1 The bidding process

While sending out a Request for Proposal and asking for bids on a new seismic system may be a good way to get started, there are a number of important issues one must be aware of when requesting bids or proposals. First, certain technical requirements and business standards must be met in order to be able to compare "apples to apples" when it is time to analyze the system proposals received. Second, in order to find the most suitable system, one needs to invest a fair amount of additional time in research and investigation before sending out the bid specifications. Namely, some very important issues may be hard to define in the Request for Proposal. The proposals can easily give unclear information regarding the following crucial issues:

- reliability of the equipment;
- user friendliness of the system;
- availability of long-term support by the manufacturer including true availability of spare parts in the next years;
- financial stability of the manufacturer.

In the Request for Proposal one should include all relevant basic technical information, so that the manufacturer can put together the corresponding technical solution. However, we recommend that the Request for Proposal does not contain an over-detailed technical description of the desired system. With too many technical details, one can end up limiting one’s choices and even disqualifying the most suitable system just because a relatively unimportant technical detail can not be fulfilled.

Avoid buying brand new systems in the market unless you are really assured of excellent support from the manufacturer. Brand new systems frequently have more problems than older more tested systems. Their use will require a high level of knowledge and a really good working relationship with the manufacturer while solving these problems.

Some countries are required by law to accept the lowest bid. Unfortunately, crucial qualities like services, equipment reliability, user friendliness of the system, amount of factory testing, setup and long-term support might be easily lost if one bases the choice solely on the lowest price for all of the stated (but practically never really sufficient) requirements of the bid.

Manufactures of seismic equipment can offer a turnkey system whereby they will purchase all of the necessary components not made by them. They will include their administrative labor costs for acquiring these components. Do not assume that they will be able to purchase every item at prices lower than you will be able to. Federal, state, and local governments and universities (typical operators of seismic networks) often have secured special pricing from vendors that can be substantially cheaper than what seismic equipment manufactures can obtain.

8.9.4.2 Selecting a vendor

When evaluating the proposals, one should assess not only the technical qualities of the system, but also the quality of every manufacturer. It is a common practice that companies invite potential buyers to a promotion visit. This does not necessarily give relevant information on how well the system would perform. If a visit is desired, carefully select the people who will participate in these visits. In addition to a member fully responsible in financial issues, one member of the team should be the individual responsible for future operation of the network. Other members of the team should be those most knowledgeable and experienced in seismology, no matter what their position in the hierarchy or which institution they belong to.

Ask for visits with manufacturer's sales or system engineers. Data sheets themselves seldom give enough technical information about a seismic system. Sales and system engineers can provide all the details of a particular technical solution. Such visits, however, are less appropriate during the early stage of the project when one’s goals are not yet specifically set. It is understandable that sales representatives will be biased toward the equipment of the manufacturer they represent. Visiting other networks of similar size in different countries is often better spent money than visiting a company trying to promote their equipment and may give more realistic information of reliability and capabilities of different equipment. Reliability and company service are important. This information will mostly be unavailable from the company offers and only by talking to other users can one find out. It is in itself no guarantee that the company is large and well known, although such a company might provide good long term service.

8.9.4.3 Equipment selection

As already mentioned, data sheets of seismic equipment alone seldom provide enough information. In addition, it is not easy to compare the data sheets of various manufacturers because each one, to some extent, uses a different system of specifications, measurement units, and definitions of technical parameters. In most cases small differences in specifications have no importance in real life, like e.g. if a digitizer has 22 or 23 bit resolution. The seismic equipment has a hardware and software component, which are almost equally important. The acquisition unit (digitizer possibly integrated) usually has a user interface that allows to change settings and monitor operation, but also to monitor and control the seismometer. The software also provides the functionality for real-time data transmission. When selecting a system it is important to evaluate the overall integration and not just to look at the performance of individual components. So for example, the digitizer with the best dynamic range is of no use in a real-time network if it does not have all functionality for data transmission.

Ideally, we recommend buying one piece of key equipment such as a sensor, a data logger, processing software with demo data or an RF link and testing the product yourself. In the case of large projects with adequate financing, manufacturers will often loan equipment for testing purposes free of change. While it is ideal to get some firsthand experience before settling on which new system to purchase, this approach requires personnel who are knowledgeable about seismology and instrumentation.

The technical systems must be able to operate in the intended environment. Today most equipment is installed in protected locations like houses and vaults and communication is delivered by third parties (like a phone line), so in many cases there is no strict requirement for temperature and humidity. So paying extra money for a recorder which is able to sustain 2 m of water is wasted money if the unit is installed in a protected environment. Outdoor equipment today is GPS antennas which by default can be expected to be made for outdoor use and communication equipment. For the latter, usually only antennas are installed outdoors. The main indoor problem might be temperature and humidity.

Each technical system, or element in it, properly operates within a certain set of parameters, or "range". One should be familiar with these ranges and know where, within this range, the system will actually operate. If one or more of elements of the system are to operate at the extreme end of their operation range on a regular basis, most probably a different element or system should be selected. Note that there is always a price to pay for operating equipment under extremes. It is always best to have a safety margin in your system and do not expect it to operate continuously, efficiently, and reliably in extreme ranges.

8.9.4.4 The seismic equipment market is small

The global market for seismic systems and equipment is naturally quite limited. With very few exceptions, instruments are produced in small numbers. Inevitably, this sets a limit to the quantity and thoroughness of testing of the newly developed equipment. This is not a result of a lack of quality or commitment on the part of manufacturers in this field, but a simple, economic reality. Compared to industries with a far broader and more powerful economic base, like computer and electronic companies, seismic equipment moves into the field with relatively little testing, even by the most reputable manufacturers. In general, the equipment arrives with a higher than average number of bugs and technical imperfections that will need to be solved by the manufacturer and the user working in tandem.

Currently, most seismic equipment and technical documentation is less user-friendly and complete than desired. Customers are rarely given comprehensive and easy-to-follow instructions on how to setup and use the system. Equipment and software does not always arrive with the promised features. It may be possible to address some of these issues during acceptance tests.

8.9.4.5 Processing software

The majority of seismic network manufactures have relatively little experience in seismic signal processing and as a general rule, do not have adequate software. It simply does not pay to develop this kind of software. On the other hand, there are public domain software packages available, which can solve these tasks and these are often offered by the manufactures. However, very little training is offered and a new network operator may end up with an expensive network but very primitive processing tools. Therefore, obtaining adequate processing software and training is an important and integral part of the planning of a new network. Unfortunately this is often not the case and the value of the network can be greatly reduced.

8.9.5 System installation

8.9.5.1 Four ways of seismic system installation

Generally we can define four methods for the installation of a new seismic system.

1) The user installs the new system. Only ‘boxes’ are purchased. In this option, the customer is responsible for the proper functioning of the system as a whole and the manufacturer remains responsible for proper functioning of the elements, unless they are improperly used or installed. This approach gives the user great flexibility, but also the main responsibility. It is only an option if qualified staff can be appointed to this task and/or if local or international organizations can participate.

2) The manufacturer demonstrates installation on a subsystem (a few stations, a sub-network). The user installs the rest. In this case, the manufacturer and the user, share responsibility for the system functioning. This approach is often successful. However, the customer must have a certain amount of experience with seismic, computer, and communication equipment for this method to work.

3) The manufacturer installs the whole system with a full assistance from local technical and seismological staff that will be responsible for running, maintaining, and servicing the network in the future. Responsibility for making sure the system functions lies with the manufacturer. The main benefit of this approach for the users is that they learn an enormous amount during the hands-on installation and associated problem solving time. This is probably the most efficient method of training. The user should not expect savings and potential shortening of the installation time but rather some additional time and effort will be required from manufacturer. In our experience, this is the best way of installing a seismic network in a country where little or no experience with seismic equipment exists.

4) The manufacturer has the complete responsibility for installing a turnkey system and making sure it functions adequately without any assistance from the customer. In this case, the network will no doubt be successfully installed, but local staff members will not learn about its operation nor how to solve potential future problems. In general, this is not a desirable solution.

Two technical details relating to system installation should also be mentioned here. In the case that the system buyer will install the system or its parts, do not select the 'standard length' cables sometimes offered by seismic system manufacturers. The 'standard' cables rarely work well in the field. They are, according to Murphy's laws, always too short or too long. Do not loop or coil extra cable length because that will increase the threat of lightning damage, unnecessarily increase system noise, and in the end, you will be paying for the “extra” cable. Rather, ask for bulk cables with separate connectors or cables of a reasonable length margin and one-side mounted connectors only. During installation in the field they can then be cut to precisely the desired length. Note, however, that reliable, high quality soldering of connectors requires experience. Inexperienced technicians have little chance of performing the job correctly and poorly installed connectors are among the most frequent causes of problems at a seismic station.

8.9.5.2 Organization of civil engineering works

Whatever construction work is needed to prepare the sites, it is usually arranged and paid for by the customer of the new network rather than the manufacturer of the seismic equipment. Very large national projects may be an exception to this rule. Site construction will require a great deal of preparation and involvement by the system buyer. There are generally a number of good design alternatives from which to choose and we suggest hiring a local civil engineering contractor to design the best solution for a particular system and specific circumstances in the country. A seismo-geologist and a civil engineer should supervise the construction work. Their main responsibility is assuring that the enclosure is watertight and that the sensors have a good contact with solid bedrock. The system's manufacturer can usually provide sketches and suggestions for the procedure and may also supervise the work, but usually does not provide true structural engineering drawings for seismic shelters. Working in tandem with a local civil engineer is usually a better choice because the engineer will be familiar with all local circumstances that are unknown to the manufacturer of the seismic equipment. Local builders know best what materials and construction methods are available and workable in a particular country. Do not "over-engineer" the project; it is usually not necessary to have a big civil engineering firm design every detail, oversee all seismic site preparation, and then build the site.

8.9.5.3 Summary of recommendations for setting up a new network

- To ensure long term maintenance and get lowest possible operational cost, the user should build as much as possible of the network himself
- Study and visit other networks to learn the requirements
- Decide on communication
- Decide on type of network based on communication possibilities
- Decide on integration of all components into one system
- Make sure processing and data storage systems are in place (including training) before network installation is finished

Real time network

- If a real time network there are two possibilities to ensure real time completeness of data(retransmission):
  (a) Use public domain SeedLink with standard computers and digitizers. Several digitizers can be used. Requires some computer skills but is the cheapest and most flexible option.
  (b) Use a company system where digitizer, communication protocol and recieving software is a company standard. Only equipment from that company can then be used. Simple and reliable but more expensive and less flexible than a public domain system.
- Triggering: All real time system should have a trigger. It is recommended to use one of the public domain systems such as EarthWorm and Seiscomp.

Networks with no communication

This type of networks are mostly temporary but could also be permanent

- Chose a recorder with a standard interface and data recording format. Chose between
  (a) A black box with built in software and a simple way to tap out continuous data

(e.g. memory stick). Usually a reliable solution and it often represent a robust mechanical solution
(b) A PC with a digitizer and a public domain software. Requires more computer skills, protected housing but can be cheaper and more flexible.

- Make sure software is available for handling and integration of the continuous data into the processing software data base.

8.9.6 Running a seismic network

8.9.6.1 Tuning of seismic networks

Before a seismic network can function with its full capacity, it must be tuned to local seismo-geological and system conditions. Tuning is especially important for networks that run in triggered mode. Unfortunately, many operators are not aware of the importance of fine-tuning.

The local and regional Earth's structure, the seismic network dimensions and layout, regional seismicity, seismic noise levels at station sites, seismic signal attenuation in the region, all play a role in these adjustments. One will not be able to correctly tune the system's recording and processing parameters until one has acquired sufficient experience with natural and man-made seismic noise and earthquake signals at all the sites in the network and until one fully understands the parameters that have to be tuned. Therefore, tuning a network takes normally months of systematic work. Because of the long time required to accomplish this task, the system’s manufacturer simply can not do it. Only the network operator can correctly tune the network. Moreover, since seismic noise conditions at the sites may change with time, new stations may be added, the goals of the network may change, etc., re-tuning of the network will probably be required from time to time. In reality, tuning a seismic network is an ongoing task, which can not be done ‘once and for all.’

Actual tuning procedures are manifold. Besides appropriate gain setting and accurate quantification at individual stations, the most important tuning is that of the trigger parameters:

- trigger threshold values;
- detrigger threshold values;
- trigger time windows' duration and other parameters;
- weights of individual stations in coincident trigger algorithm;
- grouping of stations into sub-regions for a coincidence-trigger algorithm;

Detailed discussion of individual parameters is beyond the scope of this text. Note that not all enumerated parameters exist in every seismic network and that some adjustments may be missing from this list. A thorough description and parameter adjustment procedure for the short-time-average/long-time-average (STA/LTA) seismic trigger algorithm is given in the annexed IS 8.1 on “Understanding and parameter setting of STA/LTA trigger algorithms”. Further guidelines for other network tuning procedures may be added later as complementary Information Sheets.

The following are some of the offline seismic analysis software issues that must be studied and prepared for efficient routine observatory work, and parameters that have to be adjusted for correct analysis of seismic records:

- files containing information about data acquisition parameters (data acquisition configuration file(s));
- files containing data about geometrical configuration of seismic stations (network configuration file(s));
- parameter files containing sensor calibration data;
- Earth model parameters of event location program(s) (layer thickness, seismic-wave velocity, seismic station weights, epicentral distance weighing function, and similar parameters depending on the program used);
- automatic phase-picker parameters;
- magnitude scale parameters;
- preparation of different macros and forms for routine, everyday analysis of seismic signals.

Some parameters, e.g., for the Earth model, are often insufficiently known at the time of network installation and require long-term seismological research work, which results in gradual refinement of the model and increasingly better event locations.

No manufacturer can optimally pre-adjust all these parameters to the specific local conditions. Seismic networks usually come with a set of default values for all these parameters (factory pre-selected values based on 'world averages'). These values may work sufficiently well for the beginning of network operations, however, optimum seismic network performances requires reconsidering most of them.

8.9.6.2 Organizing routine operation tasks

Keeping one’s network failure-free and in perfect working order while waiting to record earthquakes year after year requires hard and responsible work and a lot of discipline. Well-defined personal responsibility with respect to altering network operation parameters and strict obedience to the established procedures is an absolute must.

This goal is generally not simple to achieve. Seismic observatory staff will have to operate in a highly professional and reliable manner with:

- clearly defined personal responsibility for each task associated with the routine operation of the network and for other everyday analysis and archiving activities;
- regular maintenance of hardware and software;
- continuous verification of all tasks and hardware operations;
- maintenance of precise records of all relevant activities that effect data parameters, availability, continuity, and quality, such as changes to network operational parameters, processing procedures, data archiving, equipment maintenance and repair.

Regular processing of seismic data requires that all details of how data is processed and stored is well planned and that personnel are adequately trained.

Network recording parameters should be changed only if there is an important and well thought through reason. Because any change to the recording parameters will affect the network's ability to detect earthquakes, these changes should be avoided as much as possible. From the point of view of monitoring seismicity, ideally, there should be no changes for years after the network is fully adjusted. Nevertheless, those changes that are inevitably required from time to time should be kept to a minimum and carefully documented and archived.

Careful and continuous documentation of network operation parameters in a logbook, log file, or in the seismic database itself, is essential. This operational information should contain all information about data acquisition parameters and their changes, a documentation of all station calibrations, a precise record of each station's downtime, descriptions of technical problems and solutions, and descriptions of maintenance and service work. The exact times of parameter changes must be thoroughly recorded. This time-dependent information must become an integral part of the seismic data archive because without it the data can not be properly interpreted.

Usually a seismic network team is divided into a seismological and a technical group. This is fine as it relates to every day network operation activities and responsibilities. However, as much as possible, the basic technical as well as basic seismological knowledge should be ‘evenly’ distributed among the members of both groups. This favorably influences the general quality of the work of a seismic observatory. It also helps very much in many of critical situations, such as following a severe, unexpected technical problem, following a large earthquake, during the rapid deployment of portable stations following a main shock, or when any other situation dramatically increases the amount of work for a limited period of time.

The technical group must accept that no matter how modern and sophisticated the seismic network is that they operate; their customers are the seismologists. Therefore the seismologists must define the goals of seismic network operation and its working parameters. Frequently personal frictions may appear if this issue is not clearly defined by the management.

Many seismological observatories in high seismic risk regions must have people on duty at the central-recording site 24 hours per day. This may be a more or less explicit government requirement in order to be able to quickly notify public and civil defense authorities in the case of a strong, potentially damaging earthquake. No matter how understandable such desire may be, however, this working regime is really feasible only in a very large seismological institution. Only they have enough seismologists capable of quickly and competently interpreting seismic data. Even a fully-automated central recording and processing facility requires verification and confirmation of automatically determined earthquake parameters by trained personnel. The interpretation of automatically determined earthquake parameters in terms of the expected intensities in a given region and the probability of potential fatalities and damage is still a matter of experience and is not yet a matter of automatic calculations.

In practice, the around-the-clock human presence at the observatory is often achieved using all of the available, but mostly untrained, personnel in order to formally fulfill higher authorities’ requirements. Of course, the actual value of such a 'solution' is questionable. If the alarms are of primary importance for a new network, one should consider using a system of a message on a mobile phone that will automatically alarm the institution’s seismologists and give a first rough location and magnitude in the event of a strong earthquake. The seismologist should in turn be able to access the database remotely, if not living very closely to the observatory, and interactively reassess and refine the first quick parameter estimates if required.

8.9.6.3 System maintenance

Maintaining a seismic network's hardware and software is a continuous activity that inevitably requires well-trained personnel. Nowadays, many vital operational parameters and equipment health at seismic stations can be remotely monitored. Such parameters are for example: backup battery voltage, presence of charging voltage, potential software and communication problems, absolute time keeping, remote station vault and/or equipment temperature, potential water intrusion, etc. These utilities significantly reduce the need for field service work and therefore lower the cost of network operation. However, regular visits to the stations are still necessary, though far less frequently than in the past. Yet, once per year seems a minimum.

Note that it is a mistake to simply put off visits to remote seismic stations until something goes wrong. Periodic visual checks of cables and equipment, of potential corrosion problems on equipment and grounding and lightning system, and for intrusion of water and small animals are important. Batteries, burned lightning protection elements, and desiccants must be changed regularly, and cleaning the vaults and solar panels will also help to eliminate technical problems before they occur.

When something does go wrong, the technical staff must be certain that they can respond immediately with the right personnel, action, and spare parts. One should always maintain a good stockpile of the most common spare parts and have a well-trained technician with a pager on duty around the clock. Having technical personnel, in addition to seismologists, on call 24 hours a day for potential action is a good practice in the observatory seismology business, however this is rarely possible and not really necessary with most networks.

Operators of large networks may not have the manpower or budget resources to visit all of their stations annually. The major differences in maintenance procedures for small networks versus large regional or national networks are response time to site outages, site sensor-calibrations, and preventive maintenance (PM) visits. A large, dense seismic network lessens the need for 100% uptime for all sites; maintenance visits for site outages can be scheduled with PM visits in an area, something that a small, local network of 10 to 20 sites can not afford. This eliminates the need for immediate technician response and a 'beeper' for field repairs. For example: The U.S. Geological Survey's Northern California Seismic Network (NCSN), a large, dense regional network (352 analog and 93 digital stations), visits their telephone telemetered sites every 20 months and solar-powered sites every 4 years for site electronic equipment exchanges. These maintenance intervals are possible due to the robustness and reliability of their electronic amplifier/telemetry packages and associated equipments.

Be aware that batteries require special attention. If the lightning damages are the most frequent source of technical failures during normal operation conditions of a network, then battery failures will be the number one reason for failures during main power failures and unusually high-periods of seismicity. It should be noted that the output voltage alone of a battery provides little information about its overall health and capacity. Many types of batteries may still have adequate output voltage while at the same time their charge capacity is reduced to a small fraction of its original strength. Batteries in this condition will not do the job in case of a long-duration power failure, as may occur after a damaging earthquake.

Ideally, all of the batteries in the seismic system should be laboratory tested once a year for their remaining charge capacity. The batteries should be fully discharged, then fully charged, and again discharged in a controlled manner and their true charge capacity determined. Once the measured charge capacity is less than 60% - 70% of their nominal capacity, they should be replaced with new ones. Relying solely on measurements of battery voltage will certainly lead to technical failures in the long run. The most important moment in the lifetime of the seismic network may happen only once a decade or less. One certainly does not want to miss it because of old batteries with insufficient charge capacity!

However, large networks may again not be able to laboratory test each battery once per year. The NCSN exchanges batteries using an operational window system for battery life (based upon the quality and the replacement cost of the batteries used, and their long-term experience with battery lifetimes) rather than with annual testing and rejuvenation. Their operational window for solar-panel batteries is 4 years (Tom Burdette, personal communication, 2002).

Non-chargeable batteries, particularly the lithium type, should be replaced regularly, in accordance with the manufacturer’s instructions, regardless of their output voltage at the moment of lifetime expiration.

8.9.6.4 Sensor calibration

Seismological observatories should calibrate all of the sensors in their seismic system regularly - ideally, once a year. Strictly speaking, only the seismic signals recorded between two successive sensor calibrations that show no significant change in the sensor frequency response function are completely reliable. Sensor and sensor calibration issues are also different for a dense network equipped with modern sensors. Modern sensors are very robust, and many broadband sensors have automatic self-leveling, self-correcting features that eliminate the need for annual calibrations. In addition, site electronics can be installed to provide regular, telemetered sensor tests for response and operation. These features, along with a dense network sensor configuration allow for sensors to be replaced and recalibrated on a regular schedule. For NCSN, the short-period sensors are replaced at 10-year intervals, unless a sensor fails beforehand. NCSN short-period sites have built-in calibrators that perform daily mass releases to test sensor operation and response (Tom Burdette, personal communication, 2002).

Seismic sensor calibration requires knowledge that often is not available locally. In digital seismology, the sensor transfer function representation in form of poles and zeros is most commonly used. Both issues are discussed in detail in Chapter 5 and the annexed Exercises and Program Descriptions. A comprehensive description of basics is also given in Scherbaum (1996, 2001, and 2007). A description of a popular seismometer calibration program UNICAL is given in Plešinger et al. (1995).

8.9.6.5 Archiving seismic data

After several decades, or even years, of operating a seismic network, the scientific and financial value of the recorded data is extremely high. Therefore, full attention must be paid to data archiving and a failsafe backup of the data. Seismology is a typical non-experimental science and lost or corrupted seismic data can never be regenerated. It is therefore an absolute must to provide a complete and reliable backup archive. The backups should be kept in a different physical location, no matter whether they are on paper, tape, disk, CD or other memory medium. Today, most networks record continuously giving very large data sets and one carefully needs to consider the backup options. Whenever possible, one copy (or the originals) should be stored in fire-resistant cabinets or safes. It is important to note that microfiche, film, and computer media require more protection than paper records. Paper records can withstand temperatures to 177°C (350°F), but computer media is damaged beyond use by temperatures above 52°C (125°F) and 80% humidity.

When one first sets up a seismic network, one needs to think thoroughly about organizing the data that is recorded in light of the fact that eventually the network will have many, many years of accumulated records. Often, this crucial aspect of seismic system organization is overlooked or left to on-the-spot decisions by whoever is in charge of the initial network operation. This may work fine for a while, but eventually everybody will run into serious problems if the archiving system chosen is inappropriate. It is necessary to carefully think through the archiving organization at the outset and to keep the long-term future in mind. At the same time archiving systems will be outdated in 5-10 years, and one has to be prepared to change to new systems regularly.

In a small, weak-motion network in a region of low seismicity that generates only a small number of events records each year, or in a small or medium size strong motion network, one can probably get by with a directory tree organization for the data archive, particularly if only event data is stored. However, it is now more common also for small networks to record continuously. Nevertheless, filename coding of events must be thoroughly thought out to avoid confusion and/or file name duplications. File names also should reflect complete date and time of each event. Larger networks in moderate to high seismicity regions might require a better-organized, relational database for archiving purposes. One should carefully consider the various options used by other seismological observatories and those available on the market before the network starts recording data. It is very painful to change the data coding or archiving method after several years of network operation, once thousands upon thousands of records are already stored. Today, the most common format for data storage is MiniSEED.

Very powerful professional databases may not be the most suitable choice for smaller networks, primarily due to their high initial and annual maintenance cost, and secondly, due to too many expensive build-in utilities which will never be used in seismology. However, they are the only choice for larger data centers with 1,000s of real-time channels. Special databases which have been developed by the seismological community for the needs of seismology, thoroughly tested in several existing applications, and accepted by many, seem to be the best choice at the moment.

If possible, it is advisable to keep the raw seismic data as produced by the digitizer (raw event files, or sequences of continuous data) in the archive along with the full documentation about the recording conditions (data acquisition parameters and accompanying information).

Processing and seismic analysis methods will change and evolve as time passes, so it can be useful to go back.

8.9.6.6 Dissemination of seismic data

International cooperation in the dissemination of seismic data is another prerequisite for the high-quality operation of any new seismic network. Broad-minded data sharing is the best way for a less experienced institution to get feedback about the quality of its own work and is also a widely accepted international obligation. Data formats for parameter and waveform data exchange are dealt with in Chapter 10.

The Internet is nowadays the most common way to disseminate earthquake information and waveform data through email, web-pages, etc. Other forms of communication such as fax, pager, mobile phone are also used for earthquake alert purposes. Some of the currently most relevant and often used Internet addresses of global, regional and national seismological data centers can also be found and directly linked via http://www.szgrf.brg.de and http://www.seismo.ethz.ch/seismosurf/seismobig.html.

Everyone can greatly improve their own work by observing and comparing their phase readings, event locations, magnitude determinations and source mechanism results with the results of others published in national or international seismological bulletins. Any seismic study should also include as much seismic information as possible from the neighboring regions and countries. Not only one’s own data, but also all available pertinent data from others should be used in seismic research work. Disseminating one’s own data will, in turn, facilitate easy and fast accessibility of data from others. It's very important to establish a generous data sharing relationship with other seismological institutions.

The U.S. Geological Survey National Earthquake Information Center (http://neic.usgs.gov) compiles data contributed from networks located around the globe in order to determine, as rapidly and as accurately as possible, the location and size of all destructive earthquakes that occur worldwide. This information is disseminated immediately to concerned national and international agencies, scientists, and the general public. The NEIC collects and provides to scientists and to the public an extensive seismic database that serves as a solid foundation for scientific research, principally through the operation of modern digital national and global seismograph networks and through cooperative international agreements. Similar services are provided by a number of agencies around the world.

Data from the NEIC is transferred to the International Seismological Centre (ISC) (http://www.isc.ac.uk/) for final bulletin creation about two years behind real time. The International Seismological Centre is a non-governmental organization charged with the final collection, analysis and publication of standard earthquake information from all over the world. Earthquake readings are received from almost 3,000 seismograph stations representing every part of the globe. The Center's main task is to re-determine earthquake locations making use of all available information, and to search for new earthquakes, previously unidentified by individual agencies.

Besides these global data centers for parametric data, there are many national, regional or global centers that provide access to seismological waveform data. Examples of global data centers are IRIS, GEOFON and GEOSCOPE, Data is also available from regional networks such as MEDNET or nationally operating networks, e.g. GRF/GRSN (see 8.7.5), ICC etc. Suitable starting links are provided, e.g., from the web sites of the US Advanced National Seismic System (http://www.anss.org/) and of the Observatories and Research Facilities for European Seismology (ORFEUS) (http://orfeus.knmi.nl).

Traditionally, seismic observatories of national seismic networks or larger regional networks regularly publish preliminary seismological bulletins (weekly, or monthly), final seismological bulletins (yearly), and earthquake catalogs of the country or region (yearly, but with a few years delay so that the data from all other external sources can be included in the analysis). These catalogs are one of the bases for earthquake hazard assessment and for risk mitigation studies.

Acknowledgments

The authors and the Editor are very thankful to John Lahr and Kent Fogleman of the USGS for their careful English prove-readings and complementary remarks that have helped to improve the original draft. Thanks go Egill Hauksson for contributing a new text and figure on the California Integrated Network, to Shin Aoi for providing an updated text and figure on the Japanese Seismic Networks, to Klaus Stammler for updating text and figure for the German seismic networks that transmit their data for joint processing at the BGR in Hannover, and to Liu Ruifeng for making available the new Fig. 8.16 and an extended power point presentation which allowed us to produce the summary text in section 8.7.4, which has been authorized by Liu Ruifeng.

Recommended overview readings

Barrientos et al. (2001)
Havskov and Alguacil (2006)
Hardt and Scherbaum (1994)
Hutt et al. (2002) (give details for list of references!
Lee and Steward (1981)
Rabinovitz and Steinberg (1990)
Uhrhammer et al. (1998)
Willmore (Ed.) (1979).

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