Real-time monitoring of seismic data using satellite telemetry

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Abstract
This article describes the ARGO Satellite Seismic Network (ARGO SSN) as a reliable system for monitoring, collection, visualisation and analysis of seismic and geophysical low-frequency data. The satellite digital telemetry system is composed of peripheral geophysical stations, a central communications node (master station) located in Central Italy, and a data collection and processing centre located at ING (Istituto Nazionale di Geofisica), Rome. The task of the peripheral stations is to digitalise and send via satellite the geophysical data collected by the various sensors to the master station. The master station receives the data and forwards them via satellite to the ING in Rome; it also performs all the monitoring functions of satellite communications. At the data collection and processing centre of ING, the data are received and analysed in real time, the seismic events are identified and recorded, the low-frequency geophysical data are stored. In addition, the general status of the satellite network and of each peripheral station connected, is monitored. The procedure for analysis of acquired seismic signals allows the automatic calculation of local magnitude and duration magnitude. The communication and data exchange between the seismic networks of Greece, Spain and Italy is the fruit of a recent development in the field of technology of satellite transmission of ARGO SSN (project of European Community «Southern Europe Network for Analysis of Seismic Data»).

Key words *satellite – monitoring – seismic data*

1. Introduction

In literature there are some kinds of satellite telemetry networks for monitoring, collection and analysis of various geophysical data. These networks are devised to work in emergency conditions and must guarantee the possibility of setting up high quality connections in difficult conditions, for example in the presence of strong earthquakes (Silverman *et al.*, 1989; Muller *et al.*, 1995).

The ARGO SSN offers the opportunity to improve and update the technology and instrumentation of the telemetry system presently used by ING for seismic data processing (De Simoni and Di Giovanbattista, 1988); it can also monitor geophysical data of different nature by realising programs for reduction of seismic risk.

A telemetry satellite network offers many of advantages compared to a network based on traditional techniques using telephone cable transmission or radio transmission.

Digital data transmission is not affected by electric noise of transmission lines as in the case of analogic transmission. On the same dynamic of the signal, digital data transmission via telephone lines is more expensive than telemetry satellite transmission.

The frequency band used by ARGO SSN, allocated to satellite communications in the international domain, is not affected by electromagnetic noise and therefore it prevents the sta-

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tions from disturbances caused by lightning.

ARGO SSN utilises the X.25 communication protocol which guarantees reliability on the monitoring and retrieval of errors during satellite communication.

The network also has a valid data timing system so that all peripheral stations receive the same time mark synchronously. These are only a few of the positive aspects of ARGO SSN which contributed to the extension of the ARGO project (Calderoni *et. al.*, 1992) to Greece and Spain.

2. Hardware configuration

The ARGO SSN digital telemetry system is based on a stellar model characterised by centripetal data traffic.

The multiple data flows coming from the peripheral stations connected with the network (fig. 1) are sent via satellite to the Fucino Operational Centre (master station) and forwarded again by a satellite relaunching to the ING station (fig. 2). The satellite reception frequency is in the range (14.0-14.5) GHz and the trans-

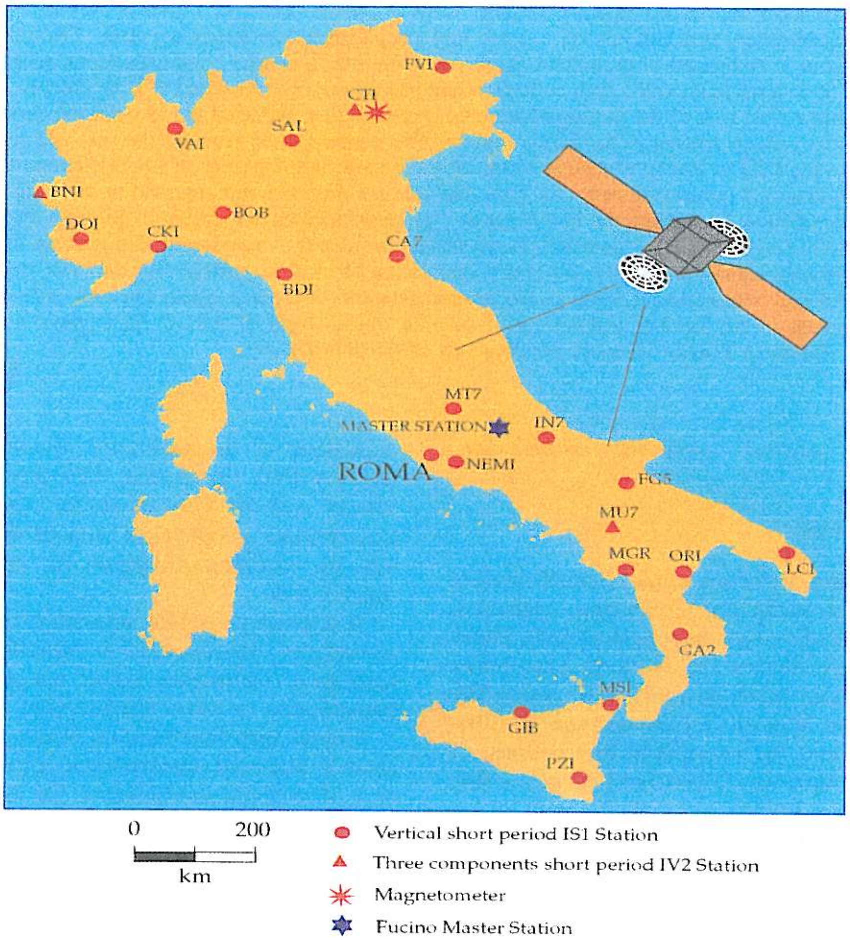

Fig. 1. ARGO Satellite Seismic Network Italian stations.

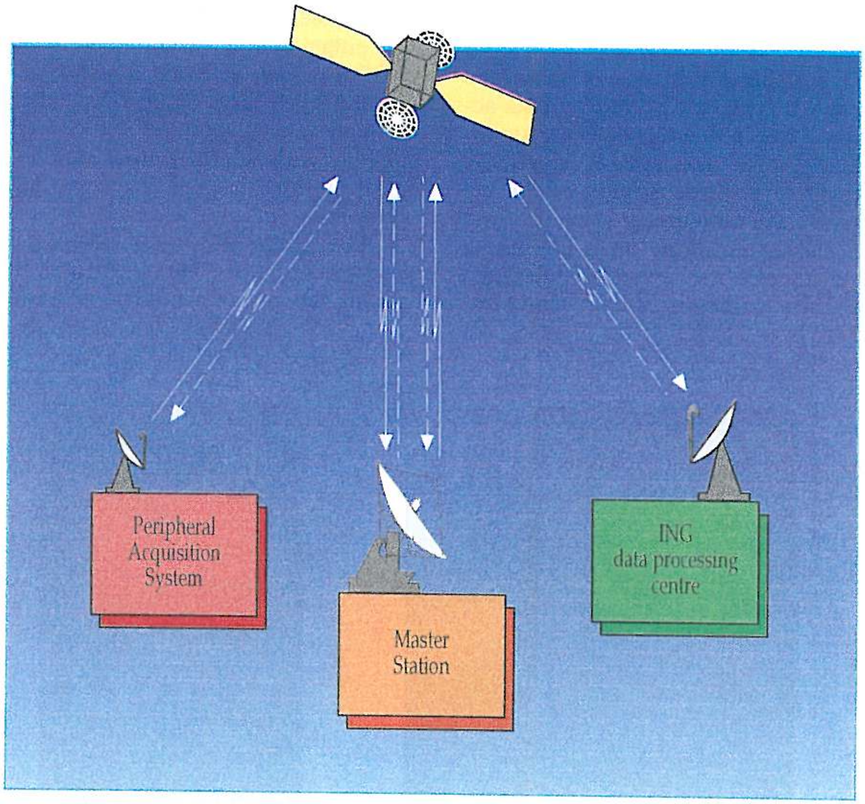

Fig. 2. ARGO SSN link between peripheral stations and ING data processing centre.

mission frequency is in the range (12.5-12.75) GHz (Calderoni *et al.*, 1992, 1994, 1996).

The ARGO SSN hardware configuration is composed of four main blocks: the master station, the peripheral stations, the ING station and the ARGO SSN data processing centre.

2.1. *Master station*

The master station is located in Central Italy at Piana del Fucino, about 135 km east of Rome, and represents the central node in satellite communications. The master station performs the following tasks:

– assigns the transmission capacity to the peripheral stations according to the kind of sensors used in each station;

– sends to the peripheral station the time mark reference, called Roll Over Counter, used for the timing of the acquired data;

– controls the satellite link between peripheral stations and ARGO SSN data processing centre;

– receives the data flows coming from the ING peripheral stations with a maximum transmission capacity of 4800 bit/s per station;

– concentrates the flows of the X.25 protocol data packets received from each peripheral station into a unique flow which is forwarded again via satellite to the ARGO SSN data processing centre.

The master station is under continuous surveillance.

2.2. *Peripheral stations*

The ING peripheral stations are structured in two different logical blocks: remote data acquisition and telecommunications systems. This partition makes the system extremely modular because the characteristics of the acquisition system are completely separate from those of the communications system. Thus, it is possible to upgrade the devices for data acquisition without modifying the communications system, but simply providing them in output either with a synchronous serial port with X.25 protocol, or in bit transparent mode.

The whole data acquisition and communications system is supplied with a backup power supply, with about 3 h of autonomy, which starts working in case of electric power failure in the station.

From every peripheral station the data flow is transmitted in three different X.25 packet configurations, called IS1, IS2 and IV2, de-

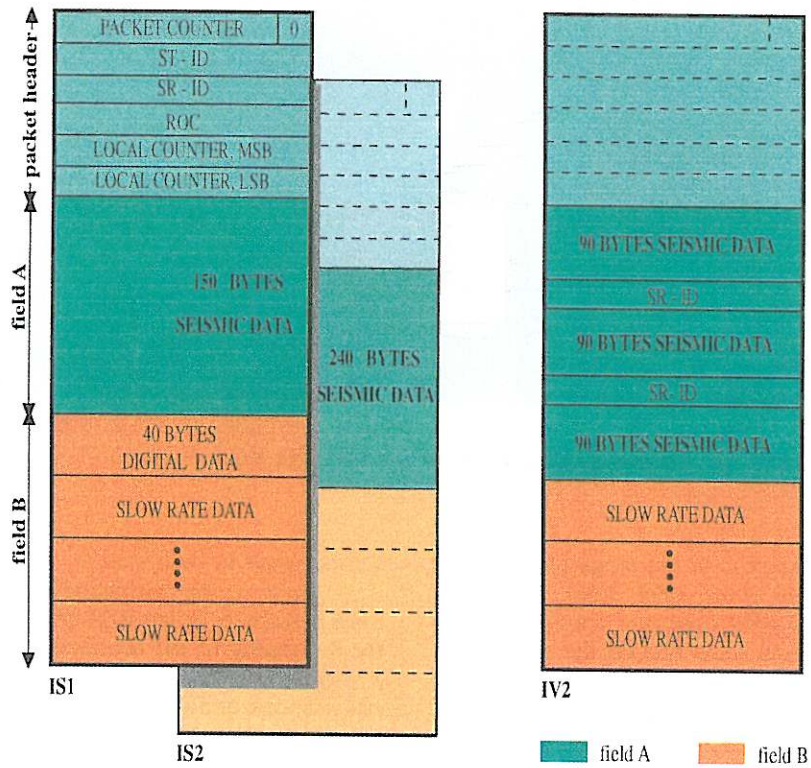

Fig. 3. The IS1, IS2 and IV2 data packet formats are composed of a common header that includes the packet counter, the station identification code (ST-ID), sensor identification code (SR-ID) and the time marks Roll Over Counter (ROC) and Local Counter (LC). Data fields are described in details as follows: IS1) a 150-byte field of seismic data, 100 Hz sampling frequency, is sent every second (field A); IS2) a 240-byte field of digital seismic data is sent every half a second (field A). Field B for IS1 and IS2 formats is composed of 40-byte digital data and 8 analogue channels of slow rate data (1/60 Hz sampling frequency; 12 bits per sample); it is sent once per minute. IV2) Three 90-byte fields of seismic data (set of three sensors), with 120 Hz sampling frequency, are sent every half second (field A). Field B is composed of 7 analogue channels of slow rate data (1/60 Hz sampling frequency; 12 bits per sample); it is sent once per minute.

pending on the kind of sensors used in each station (fig. 3); these can be a short period seismic sensor, a very broadband seismic sensor or three short period seismic sensors. All three packet configurations allow the transmission of low frequency data.

One of the capabilities of the peripheral stations is to receive on the data line one byte per second transmitted by the ING station. This byte is used to set the status of nine external digital outputs.

A suitable usage of these outputs is the realisation of remote controlled activities of the peripheral station such as tests and changes in the station parameters and sensor calibration.

2.3. *ING station*

The station located at the ING Rome acts as the ARGO SSN centre for data collection. The ING station receives via satellite a unique data flow from the master station which contains all the signals of the peripheral stations connected to the network. The satellite link between the master station and the ING station has a total capacity of 64 Kbit/s.

Another important task performed by the ING station is the acquisition of the DCF clock signal (Urbini, 1988) which is necessary to network data timing.

2.4. *ARGO SSN data processing centre at the ING*

The hardware configuration of the ARGO SSN data processing centre has been designed to achieve maximum reliability through the duplication of the main components to prevent data loss during the data acquisition processes. The system has been configured as a Computer Interconnect-based (CI) Digital VAX cluster to fully exploit the possibilities given by the hardware redundancy.

Another technique is used in the ARGO system to enhance performance reliability: when the computer sends a write command, the same data are written on two different disks. In this way, it is still possible to retrieve a copy of the data, even in case of fault of one of the two disk drivers.

3. Software configuration

At the master station, peripheral stations and ARGO SSN data processing centre, the firmware allows the transmission of the monitored data by means of an X.25 communication protocol through the underlying satellite transmission protocol.

The latter is totally transparent from the ARGO SSN point of view. The access to the ARGO SSN data is managed by Packetnet System Interface (PSI), an X.25 protocol based software communication product, installed at the ARGO SSN data processing centre. Next in the software chain we find the «true motor» of ARGO SSN, *i.e.*, the data acquisition software.

This was realised at ING, written in FORTRAN and C languages, and performs important real-time tasks:

- data reception and storage;
- seismic data on-line analysis;
- network status monitoring.

3.1. *Data reception and storage*

The data flow received at ING from the master station is split up into a number of acquisition processes equal to the number of transmitting peripheral stations in the network. This operation implies the recognition of the calling stations, the transmission format used by each station and in general the decoding of the information contained in each X.25 data packet header.

Depending on the data packet format received (fig. 3), the proper acquisition procedure is called.

When the data are received in IS1 format, they are temporarily stacked in a common structure which is read by the real time analysis routine every 10 s.

The result of the analysis routine is a flag that the routine sets «true» when a seismic event is detected. This event flag enables the seismic data storage for a time window whose length depends on the event detected according to the trigger logic, plus a 10 s pre-trigger window and a 40 s post-trigger window.

The IS2 format seismic data are simply received and stored in binary files without any on-line analysis.

The IV2 case is an extension of the IS1 format of a three-component station.

A routine dedicated to DCF signal gives as output, in a binary file, the Universal Time (UT) associated to the time marks of the network clock. This file is updated every minute and is accessed by all the running seismic data acquisition processes. So it is possible to determine the correct UT and to bypass a rare but possible reset of the network counters which could generate a wrong timing of the events triggered by the whole network. When the low rate data are transmitted, they are separated from the seismic data and recorded. Furthermore, the software is able to display a real time seismogram (with a delay of about 10 s) for immediate check of each peripheral station response.

3.2. *On-line analysis of seismic data*

Every 10 s on the continuous seismic data flow an on-line analysis is performed to allow a first rough selection of useful seismic signals from noise (fig. 4).

The good quality of the satellite telemetered signal removes the frequency domain filtering, necessary to clean up the signal of the background noise; through the seismic signal analysis, it was convenient to choose a selection algorithm able to distinguish the seismic events from noise based on more simple criteria applied in series, instead of a unique and more sophisticated selection algorithm (Console, 1987).

In the seismic data on-line analysis, a linear weighed combination of the following parameters, calculated on the signal cleaned of the offset, establishes the trigger threshold:

– the maximum amplitude reached by the wave between two contiguous zero crossings of the signal (fig. 4b);

– the STA/LTA ratio between short and long term modulus averages; STA is calculated on 30 samples and LTA on 300 samples. The short and long term averages are calculated taking into consideration the following intervals: STA, between sample $(i+269)^{\text{th}}$ and sample $(i+299)^{\text{th}}$; LTA, between sample i^{th} and sample $(i+299)^{\text{th}}$, where index i varies from 1 to 700. The STA/LTA ratio will be higher when an event arrives (fig. 4c). The long and short term averages can be varied dynamically;

– the maximum value of the signal power, calculated on 8 time intervals; it corresponds to the squared integral of 125 samples (fig. 4d); the number of data taken into consideration in each range of power can be varied dynamically;

– the normalised spectral amplitude of the signal (fig. 4e);

– the normalised spectral amplitude of the signal, calculated on 8 frequency bands (fig. 4f).

By means of the vector related to the FFT coefficients, it is possible to calculate the normalised area of the rectangle, whose height is the average value of the spectral amplitude of the signal and whose basis is one of the eight bands obtained via the bisection method, except for the first two bands with the same width corresponding to lower frequencies.

By assuming a normal distribution of the above mentioned parameters, their values external to the interval $(x_{\text{media}} \pm 2\,\sigma)$ are considered critical; a weighed linear combination of parameters calculated every 10 s of recording, establishes the characteristic trigger threshold of each station.

The weights are calculated by analysing long seismic noise recordings, according to the number of times a sample is included in the interval and to the total number of samples taken into consideration.

3.3. *Network status monitoring*

The continuous control of the network operation is a fundamental part of the acquisition process: in case of malfunction of one or more

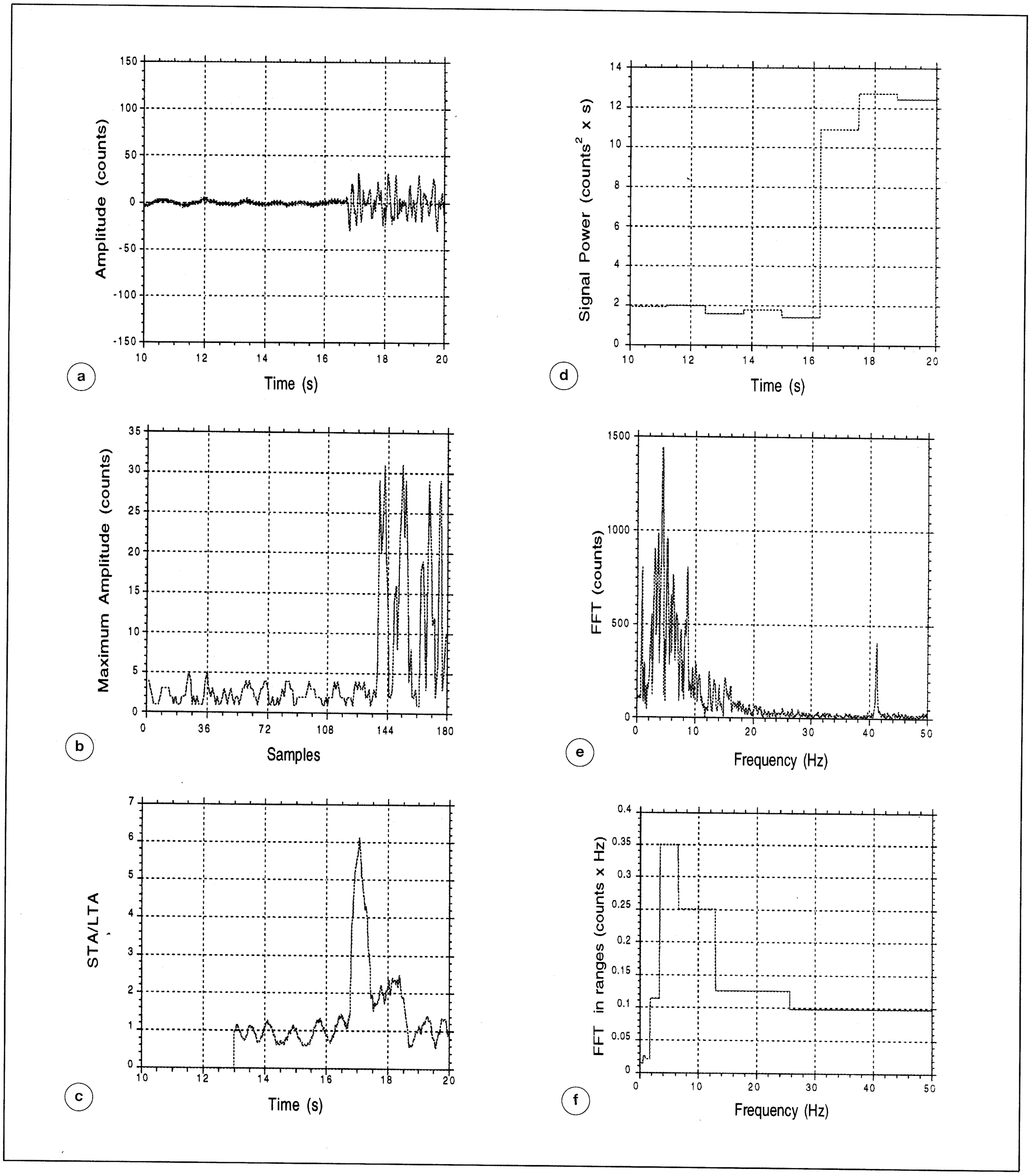

Fig. 4. Parameters calculated by on-line analysis on the time interval from 10 to 20 s of the seismic signal recorded. a) Time interval from 10 to 20 s of the seismic event shown in fig. 5; b) maximum amplitude of the signal as a function of values of maximum amplitude in the portion of the seismic file analysed; c) the STA/LTA ratio of the signal as a time function; d) the signal power as a time function; e) Fast Fourier Transform of the signal (FFT) as a frequency function; f) normalised spectral amplitude of the signal as a frequency function.

peripheral stations, the program should be able to record all the parameters useful to identify the time interval in which anomalous events have occurred and the nature of these events. For example, if an interruption of the power supply of a peripheral station occurs, the acquisition process of that station, running at the ARGO SSN data processing centre of ING, will stop and start again automatically at the first new call of the station. Thus the station inactivity, if not recorded by the acquisition program, could mask a real seismic event which occurred in the same time interval. In fact, only those seismic events selected by the on-line analysis routine are recorded, while the remaining signal received is discarded as noise.

The control routines of the acquisition program, are able to provide the information necessary for monitoring the network status. These routines are activated by:

– an error that stops the acquisition process;

– an error that does not stop the acquisition process;

– an operator control request.

In the first case, the information is recorded on a network activity log file when an acquisition process is stopped by a fatal error; in the second, they are recorded on an error log daily file when an error is detected. In the third case, the acquisition program is requested by an external event (an operator request) to download information concerning a particular station, a group of stations or the whole network.

From these log files, it is then possible to reconstruct the network operation status as a function of time and to calculate statistical information on the network operation.

4. Automatic interpretation of seismic events

The seismic data files recorded by the acquisition system are examined daily by means of automatic interpretation analysis. This process is then controlled by an operator through a graphic interface program that allows the display and interpretation of seismic events and provides the output on the seismic bulletin.

Automatic interpretation on a single trace consists of determining the arrival time of the first phase, the time corresponding to the end of the event, the amplitude and period of the wave with maximum amplitude.

Using these parameters the magnitude with duration (fig. 5a) and the local magnitude (fig. 5b) can be calculated for local earthquakes. The algorithm used is based on an analysis of maximum amplitude reached by the wave between two consecutive zero crossings of the signal cleaned of the offset, the period of half-waves and the symmetry degree of the signal.

The first onset corresponds to the instant when the maximum amplitude and the half-wave period in the first phase exceed the threshold value established by a detailed analysis of the noise characteristic of every station.

The maximum amplitude wave is calculated by selecting the four half-waves with maximum amplitudes and choosing the most symmetric one in time and amplitude.

The end of the event is identified by the amplitude distribution and the spectral content comparable to the station noise recorded during the first 10 s of any seismic file.

Figure 5 shows an example of automatic interpretation applied to a local seismic event recorded at the seismic station located on Crete Island (Southern Greece).

Taking a sample of 106 seismic events recorded at the Crete station, it was possible to calculate the spread mean between the arrival times of the first phase, the event duration, the amplitude and period of the wave of maximum amplitude estimated by the operator and the corresponding parameters calculated by the automatic interpretation program.

The statistical analysis of the spread mean has shown that 74% of events have an error of 0.03 s on the first phase picking, 70% of events have an error of 4 s on the event duration, and 96% of events have an error of 1 count on the amplitude and 0.01 s on the maximum amplitude wave period.

At present, it is necessary to implement and optimise the procedures used by the network for seismic data processing, for example transforming the automatic picking system which is still a prototype, into a definitive procedure.

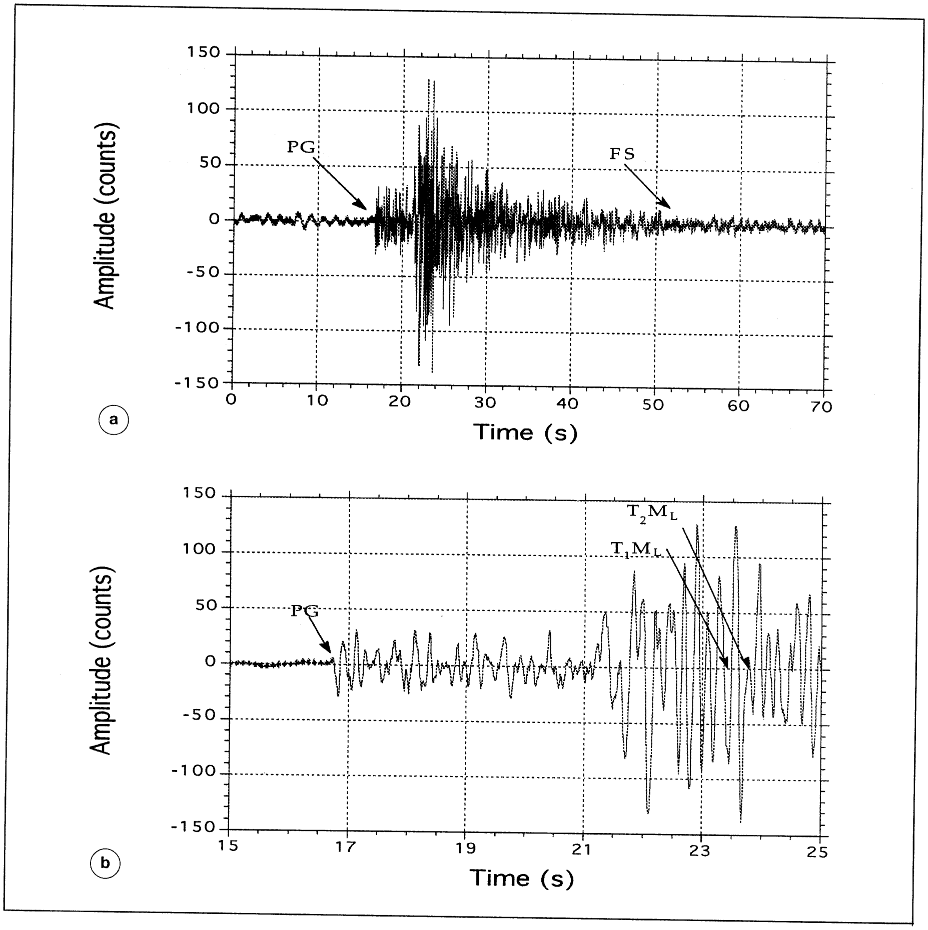

Fig. 5. Example of the automatic interpretation of the local earthquake of magnitude 2.2 located at about 33 km from Crete Island on 14 July 1995, at 02:07:59.54 and recorded by the Crete station. a) First phase (PG) and seismic event end (FS) detected by the automatic interpretation procedure; b) details of the first phase and the beginning T_1 M_L and the end T_2 M_L of the maximum amplitude wave selected by the automatic interpretation procedure.

5. Data acquisition timing

A correct and reliable timing of the monitored events represents a basic requirement that any seismic network has to meet (De Simoni, 1987).

In ARGO SSN the problem of time reconstruction of data has been solved by using three time marks, two composed of the values of two counters inserted in each X.25 data packet header (fig. 3), and one absolute reference time mark acquired as a time signal at ING.

Every 360 ms, the master station sends synchronously a time reference mark called Roll Over Counter (ROC), to all remote stations of the network and ING centre; the acquisition system of each remote station has a local time reference called Local Counter (LC) which is increased every 19.23 μs.

At ING, the DCF absolute time signal, the ROC and the LC are acquired; every minute the Universal Time (UT) is reconstructed and associated to the ROC and LC current values.

The data acquired at ING in the form of X.25 packets are timed through the ROC and LC time association, inserted in the X.25 packet header, with the absolute time of DCF and related ROC and LC of ING station, stored in a binary file which is accessible to all acquisition processes related to the stations connected to ARGO SSN.

With the combination of these three time reference marks, it is possible to associate the Universal Time to the datum acquired with an error of 0.01 s.

Figure 6 illustrates the increase in ROC and LC as a function of time.

6. Southern European Network

A development of the ARGO SSN is represented by the project Southern Europe Network for Analysis of Seismic Data which involves the national seismic networks of Italy, Spain and Greece (fig. 7).

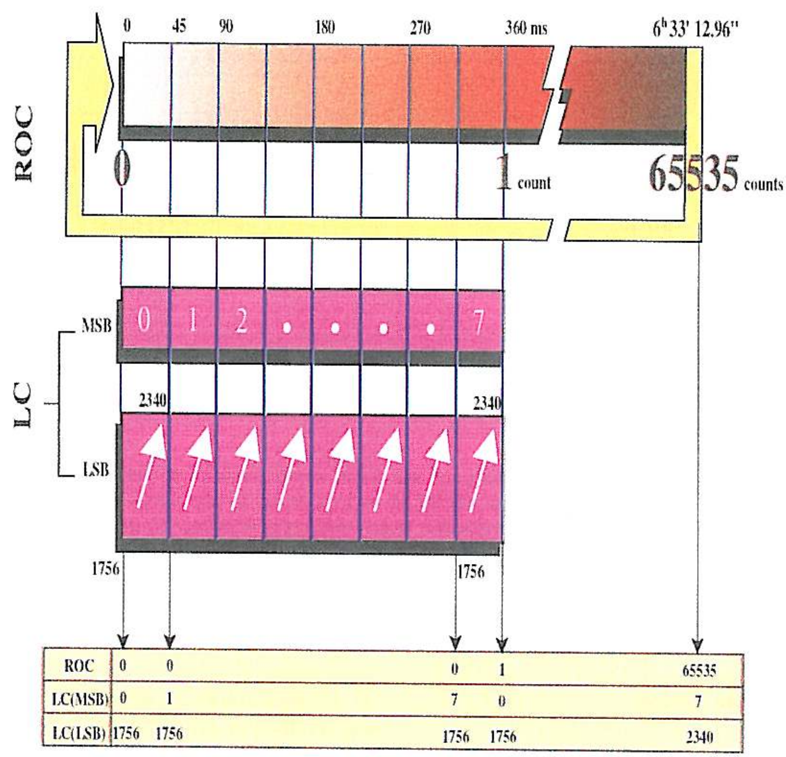

Fig. 6. Schematic description of the ROC and LC network counters. The complete rotation cycle of the ROC lasts 6 h 33 min and 12.96 s; in this time interval the ROC varies from 1 up to 65 535 increasing by 360 ms per step. The LC divides each 360 ms interval into 8 intervals of 45 ms which are identified through the Most Significant Bit (MSB) value of LC. In each 45 ms interval the Less Significant Bit (LSB) value of LC varies from 1756 up to 2340 increasing by about 19.24 μs per step.

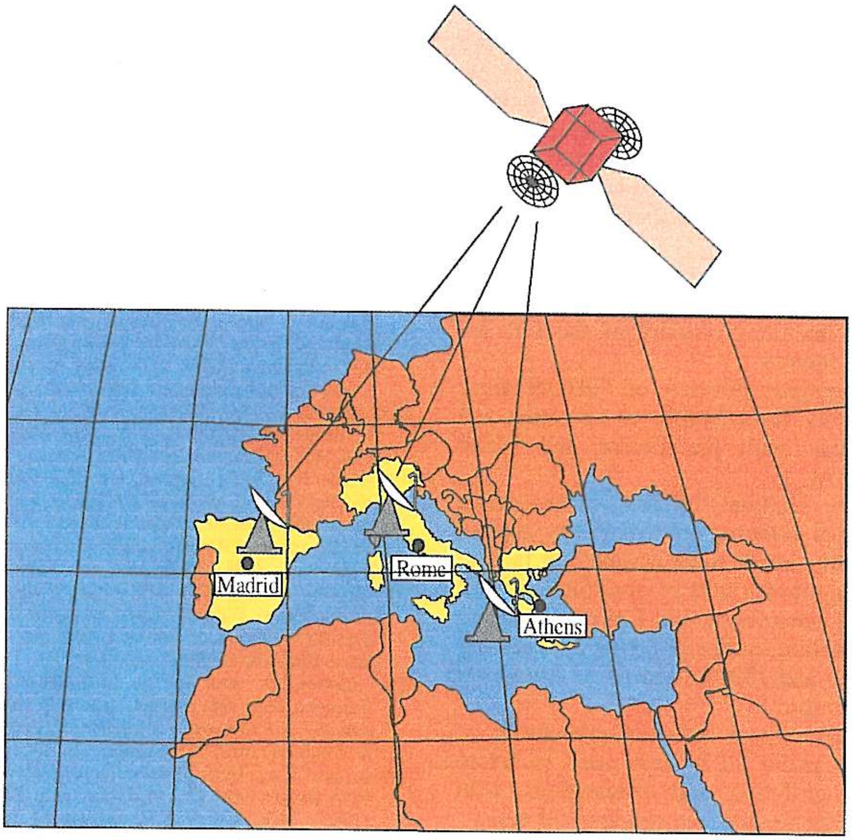

Fig. 7. Three centres in Italy, Spain and Greece involved in the Southern European Network project.

The project is almost complete and the objectives achieved are the following:

– The realisation of a distributed system for monitoring the seismicity of the area covered by the network; the three centres located at the National Observatory of Athens (NOA), at the Instituto Geografico Nacional de Madrid (IGN) and at Istituto Nazionale di Geofisica manage via satellite the seismic data exchange of the national seismic networks of Greece, Spain and Italy respectively.

– The realisation, in each centre, of a relational data base accessible via satellite by the other partners for the exchange of seismic data. The data base will be very useful in case of lack of completeness and uniformity of data related to the same seismic events which occurred in the Mediterranean area, and, in the future, to tackle seismologic topics in the same area.

– The realisation of a tridimensional cinematic model of the Mediterranean Sea by comparing different tomographic techniques used in the scientific domain.

– The realisation of software for historical seismogram digitalisation.

7. Conclusions

Over the years, the ARGO SSN has obtained a great deal of reliability concerning the processing of acquired data at remote stations, data time reconstruction, seismic signal-noise discrimination and monitoring of the network status.

The transmission of low-frequency geophysical data as activated with success at the geomagnetic station of Castello Tesino (Northern Italy): the proton magnetometer data of the station have been received daily at ING since 13 October 1995.

In September 1995 the EUTELSAT II satellite utilised by ARGO SSN was replaced by the ORION satellite positioned on the 37th degree of the equator.

The geographic position of ORION gives the opportunity for scientific co-operation and data exchange with the Centre and North American area.

The new satellite ORION sends out a stronger signal allowing the technology used in the peripheral stations to be updated. In fact, in the remote stations it will be possible to install paraboloidal antennas having 1 m diameter and 100 W absorption, unlike previous ones having 2 m diameter and 150 W absorption, used with the other satellite.

The hardware and software modularity of ARGO SSN make the system open to future technology evolution and connections with other networks monitoring geophysical data.

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