Computers & Geosciences 35 (2009) 1296–1303

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Remote monitoring of electromagnetic signals and seismic events using smart mobile devices

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ARTICLE INFO

Article history:
Received 24 November 2007
Received in revised form
27 June 2008
Accepted 18 July 2008

Keywords:
Remote monitoring
Personal digital assistants
Electromagnetic signals
Seismic events
Wireless networks

ABSTRACT

This study presents the design and development of a novel mobile wireless system to be used for monitoring seismic events and related electromagnetic signals, employing smart mobile devices like personal digital assistants (PDAs) and wireless communication technologies such as wireless local area networks (WLANs), general packet radio service (GPRS) and universal mobile telecommunications system (UMTS). The proposed system enables scientists to access critical data while being geographically independent of the sites of data sources, rendering it as a useful tool for preliminary scientific analysis.

1. Introduction

During the past few years, the increased use of smart mobile devices, like personal digital assistants (PDAs) have changed the way we perceive our environment and have had a radical impact on our working lives. Currently, the small size and weight of these devices provide tremendous convenience and portability. Furthermore, with the rapid evolution of electronic technology, PDAs are now capable of accomplishing challenging tasks due to their increased central processing unit (CPU) capabilities and storage capacities. In addition, modern devices are also capable of connecting to both wired (e.g. LANs) and wireless networks (e.g. WLANs, GSM, GPRS and UMTS) and fully exploit their potentials (Myers and Beigl, 2003).

Second generation mobile telephone networks are widely spread and available all over the world. The introduction of general packet radio service (GPRS) offers access to enhanced data transfer speeds (up to 171 Kbps) (Sanders, 2003; Seurre et al., 2003). With the deployment of third-generation mobile technologies, such as universal mobile telecommunications system (UMTS), data transfer speed increased even more: up to 2 Mbps in stable position, and 384 Kbps in travelling speeds (Brand and Aghvami, 2002; Walke et al., 2003).

On the other hand, wireless local area networks (WLANs) are currently being used in a wide area of applications. The reasons behind the vast popularity of WLAN-related applications are mostly associated with increased portability, as opposed to wired LANs (Molisch, 2005). Today, WLANs offer satisfying transmission data rates with wide coverage. Furthermore, they are resistant to external interferences, caused by other wireless devices in close vicinity, while security in data transmission is satisfactory (Geier, 2001; Gast, 2002).

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doi:10.1016/j.cageo.2008.07.008

Recently, geophysical researchers have been analyzing electromagnetic (EM) signals preceding seismic events (SE). Some studies have examined the interaction between seismic activity and disturbances in radio broadcasts (Warwick et al., 1982; Hayakawa et al., 1996; Molchanov and Hayakawa, 1998b; Biagi et al., 2001), while others have dealt with the seismogenic electromagnetic emissions in different bands (Merzer and Klemperer, 1997; Nomikos and Vallianatos, 1998; Vallianatos and Nomikos, 1998; Asada et al., 2001; Kapiris et al., 2002; Pham et al., 2002; Eftaxias et al., 2003; Kapiris et al., 2003).

These EM phenomena have been observed in the lithosphere, atmosphere and ionosphere and have been associated with crack generation in the Earth's crust (Molchanov and Hayakawa, 1998a), and related to seismological events (Varotsos and Alexopoulos, 1984a,1984b; Tzanis et al., 2000). While studying shallow and intermediate depth earthquakes in the south Aegean area, the authors of a previous study (Nomikos and Vallianatos, 1997) found a strong correlation between EM emissions (41 and 54 MHz) and earthquakes. A further study by the same group (Vallianatos and Nomikos, 1998; Kapiris et al., 2002) demonstrated that the delay between EM emissions and consequent seismological events varied from 7 h to 11 days. Consequently, immediate inspection of the regional EM emissions can enable scientists to gain an understanding of the seismic activity of a given geographical area. For this reason, remote systems for monitoring and transmitting EM signals have been developed over the last few years (Vallianatos and Nomikos, 1998). These systems are responsible for measuring, digitizing and transferring EM field variations from observation stations to central storage systems located at scientific institutes, where review and analysis of EM signals can take place. However, the need for mobility and the desire for continuous EM-variations monitoring has made portable, lightweight, and location-independent EM signal monitoring system a necessity. Smart mobile devices like PDAs and modern wireless networking technologies are suitable candidates to address this need.

Until now, in the field of geosciences, the combination of mobile devices and wireless networking technologies has been used only in geographic information systems (GIS) (Casademont et al., 2004; Clegg et al., 2006). In particular, PDAs combined with global positioning system (GPS) modules have been used as mobile clients in GIS. In previous study, a platform for the commercialization of advanced geographical information services for the use in portable devices was presented (Casademont et al., 2004). The platform used mobile telephone networks and WLANs to provide access to the GIS service using a vector map player running on a PDA with a wireless access facilities and a GPS receiver. In another study, an attempt was made to assess and evaluate two currently available digital geological mapping systems: one based on a personal digital assistant running "ArcPad", and the second based on a Tablet PC running "Map IT" software (Clegg et al., 2006). The PDA-based system was found to be particularly advantageous for mapping projects in remote regions, where there is a limited power supply or where the total weight of equipment is an important consideration.

However, there is currently no reference in the literature regarding the design and implementation of a system for remote monitoring of EM signals and SEs using smart mobile devices. Moreover, there is no commercial product that can enable researchers to access to critical EM signal data and SE information while being geographically independent of the data source.

The aim of this study was to design and develop a mobile wireless application for monitoring EM signals and SEs, employing PDAs and wireless communication technologies such as WLANs, GPRS and UMTS (Fig. 1). The uses of such a system are becoming apparent (especially in a region of intense seismic activity such as Greece), as data monitoring should be available to scientists as soon as possible, irrespective of their location.

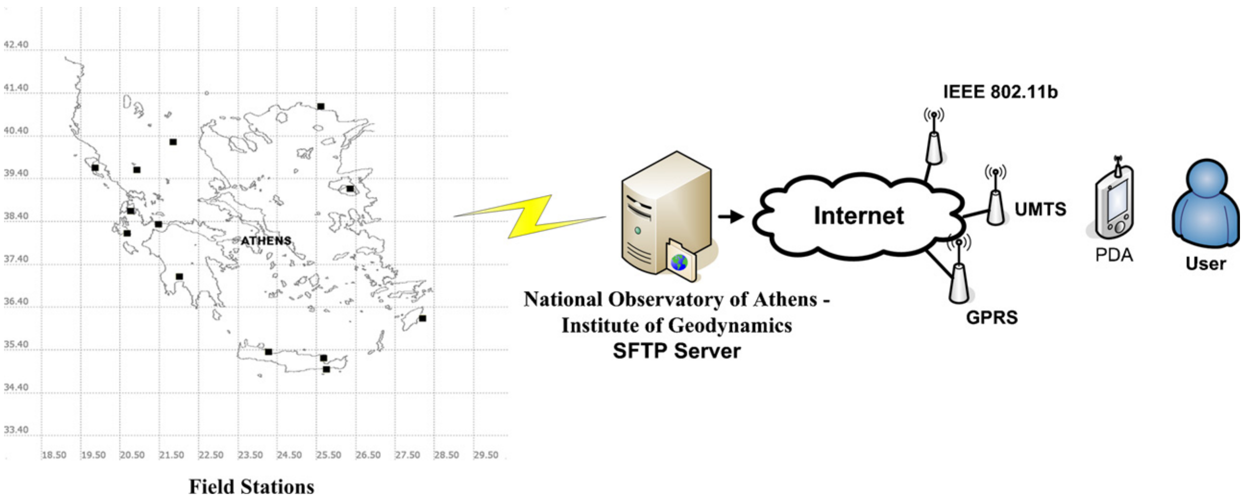

Fig. 1. Schematic representation of flow of EM data from field stations to NOAIG SFTP server, then distributed via different transfer protocols to PDAs and users.

Specifically, the key system requirements were established by examining the following scenarios:

(a) Following a crucial SE, a researcher needs to extract valuable information regarding the seismic activity of a specific geographic region, by constant monitoring of EM activity of the region. Thus, to fulfil the aforementioned need, a portable system is needed that provides scientists, even when out of office, with continuous and remote access to critical EM signal data and SE information. Thus, the system has to present data from all available EM signal frequencies and all deployed field stations in accordance with the needs of the geoscientist e.g. events within a specific range of magnitude. Moreover, signal data should be presented accurately, and with sufficient resolution in order to enable researchers to distinguish signal patterns of high importance.
(b) Part of a geoscientist's routine, when at the field station, is to assess the validity of EM measurements transmitted from the deployed field stations back to the data centre. This procedure involves the task of cross-validating the EM measurements gathered by the field station with those received at the data centre. Therefore, a tool that can assist in this procedure, by providing an on site visual verification of the gathered EM signals, is required. The main requirements of this tool arise from the fact that most field stations are situated at remote locations, away from sources of EM interference. Thus, system's portability and versatile connectivity are considered of very high significance.

This mobile application was designed and implemented with regard to these requirements, as a mobile clone of a desktop application called 'EQ Explorer' also designed and developed by the authors.

2. Materials and methods

The hardware platform chosen for the development of the prototype was the Qtek 9000 Pocket PC Phone that supports network access through its integrated WLAN, GPRS and UMTS modules. This PDA incorporated an Intel Bulverde CPU running at 520 MHz, flash memory up to 1 GB, and a crystal clear, high resolution screen capable of displaying 640×480 pixels.

The software packages used for developing the final application included: (a) Microsoft-Embedded Visual C++ version 4.0 (Software Development Environment and Compiler) and (b) Microsoft Windows SDK for Pocket PC 2003 Edition (Burdick, 1999; Boling, 2003). The application was developed on a typical desktop PC (Intel Pentium 4 @ 3.0 GHz with 1 GB RAM) running Microsoft Windows 2000.

A telemetric network for recording regional EM variations has been established in Greece in the recent years (Vallianatos and Nomikos, 1998; Kapiris et al., 2002). The network consists of 16 field stations scattered around the Greek territory (Fig. 1). Each field station records EM variations at both low and high frequencies (3 kHz, 10 kHz, 41 MHz and 46 MHz) on a 24 h basis, with a sampling rate of one sample per second.

Each field station consists of:

(a) Four receivers appropriate for measuring the electromagnetic field variations at 3 and 10 kHz in East–West (EW) and North–South (NS) orientations. These are constructed with wide band and low-noise amplifiers and switching band-pass filters that are tuned by crystal oscillators. The final stage is an RMS to DC converter, so that the output is a DC voltage, which is proportional to the power spectrum density of the magnetic field that excites the antenna (Vallianatos and Nomikos, 1998).
(b) Two receivers for measuring the electric field variations at 41 and 46 MHz. The receivers are constructed using the double superheterodyne technology and the output is DC voltage that is proportional to the electric field appearing in the antenna. The antennas used for these very high frequencies are horizontal half-wavelength dipoles tuned at these frequencies (Vallianatos and Nomikos, 1998).
(c) A datalogger with a sample rate taken on a channel basis every second. The average value of 60 samples for each channel is stored in compact flash memory (Koulouras et al., 2005). Signals from the field station are transmitted to the Institute of Geodynamics of the National Observatory of Athens (NOAIG) using a private network of leased lines (Vallianatos and Nomikos, 1998). NOAIG is the official Institution of Greece for the magnitude and epicentre calculation of every earthquake in the Greek territory. At NOAIG, the received EM signals are compressed (using the Lempel-Ziv-Welch (LZW) algorithm (Ziv and Lempel, 1977; Welch, 1984)), are backed up and, finally, are transferred to a secure file transfer protocol (SFTP) server, rendering them to available to researchers for the further analysis.

The developed application can connect to the NOAIG SFTP server using one of the three supported network connections (WLAN, GPRS and UMTS), available at the time of request, and receive, store, and display EM signal data from the SFTP folder (Fig. 2). Upon EM signal reception, the application decompresses signal data, employing a special implementation of the LZW algorithm designed to utilize efficiently the limited CPU resources of mobile devices. Signals are normalized and displayed on the device's screen. There is also the ability to cache EM data to the PDA's storage card to avoid unnecessary downloading of the same data, previously received by the system. The user can select to display signals of the four receiver frequencies simultaneously, from any one of the 16 field stations, and for a particular day for which data are available on the server. EM signals are continuously transmitted and stored in the NOAIG SFTP server which allows remote users to monitor EM signals constantly.

The developed application also has the ability to download and display the list of SEs stored at the NOAIG. The user has the ability to select a particular SE and

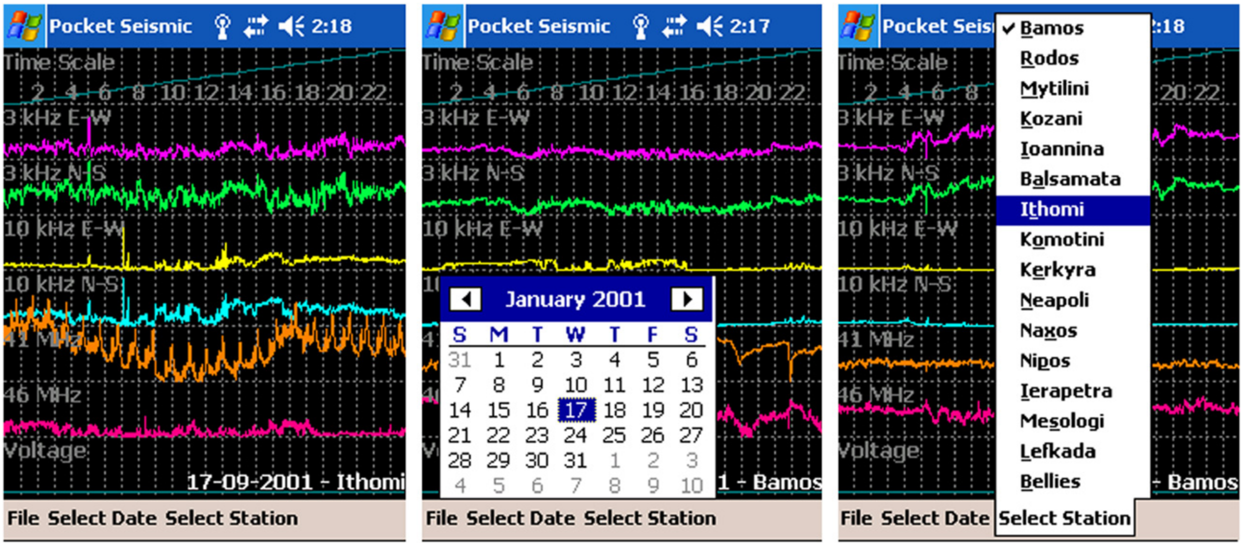

Fig. 2. Screenshots of the EM signal display application user interface on a PDA device. (a) Overview of developed EM signal interface. (b) Interactive calendar to allow dynamic acquisition of different EM signal traces for different time periods. (c) Dynamic selection of field station name allows retrieval of EM signal data from different field stations via NOAIG SFTP server.

retrieve further information such as the events date and time, the location of origin (geographic longitude and latitude), the magnitude and the depth. Finally, the user can filter SEs and display them according to their date of occurrence and magnitude, as in Fig. 3 for SEs between 5.0 and 6.0 ML that occurred in 2005.

The user interface of the application was designed and implemented in a simple, elegant way in accordance with the PDA's operating environment. The interface consists of a main menubar while the rest of the screen area is allocated to the display of the EM signal and SE data chart (Fig. 2). The user has an access to the application's features, such as the selection of the EM signal's recording station and date of occurrence. Moreover, the user can select the IP-address of the NOAIG or any other EM-data FTP server while he/she has the ability to modify the horizontal and vertical grid drawing settings as well as to enable or disable the appearance of a signal of specific frequency. Finally, the user has the ability to enable or disable the EM signal caching operation and the utilization of an anti-aliased line drawing algorithm (Xiaolin, 1991) to plot the EM data.

3. Results and discussion

The developed PDA application was designed to run on the application layer of the TCP/IP protocol suite (Tanenbaum, 1981). As a result, it can cooperate with any IP-based network protocol such as WLAN, GPRS and UMTS, as long as there is a compatible network card installed (internally or externally) on the device. Moreover, the application is fully functional even when the underlying connection protocol changes on-the-fly (from WLAN to GPRS/UMTS and vice-versa). This permits the user to either use a WLAN connection when in proximity to an area with WLAN support (close to the research centre, at any hot-spot around the city, etc.), or to be truly mobile with a GPRS/UMTS connection when outside the coverage of any WLAN. This dynamic switching renders the system truly mobile, delivering access to EM signals and SE information from practically anywhere to the user. Other communication protocols, like WiMax (Ghosh et al., 2005) and Bluetooth (McDermott-Wells, 2005), are expected to be fully compatible with the developed application because they are IP-based protocols.

For the transmission of one day's EM signals (~129 KB compressed) it takes approximately 2 s employing the IEEE 802.11b (WLAN) protocol, 10 s for the GPRS, and 5 s for the UMTS, including the servers' overhead and the general network additions (Table 1). The signal caching operation prevents unnecessary network utilization and decreases the application's response time. The time required to decompress, parse, normalize and display the received EM signal data is infinitesimal. Regarding SEs, the time required to receive information for 50 SEs (~3 KB compressed) is less than 1 s for all the supported network connections. It should be noted that as the number of requested SEs increases, the downloading time also increases proportionally; e.g. transferring time for 50 and 100 SEs is approximately 1 and 2 s, respectively.

The underlying security mechanisms of the communication protocols utilized, ensured the integrity of EM signal transmission. These mechanisms are the wired equivalent privacy (WEP) and service set identifier (SSID) for WLAN (Vines, 2002), A3, A8 and GEA3 encryption algorithms for GPRS (Kitsos et al., 2004) and the MILENAGE and KASUMI algorithms for UMTS (Niemi and Nyberg, 2003; Koien, 2004). Moreover, the SFTP server logon (user name/password required) procedure provided access to authorized users only, enhancing the security of the system.

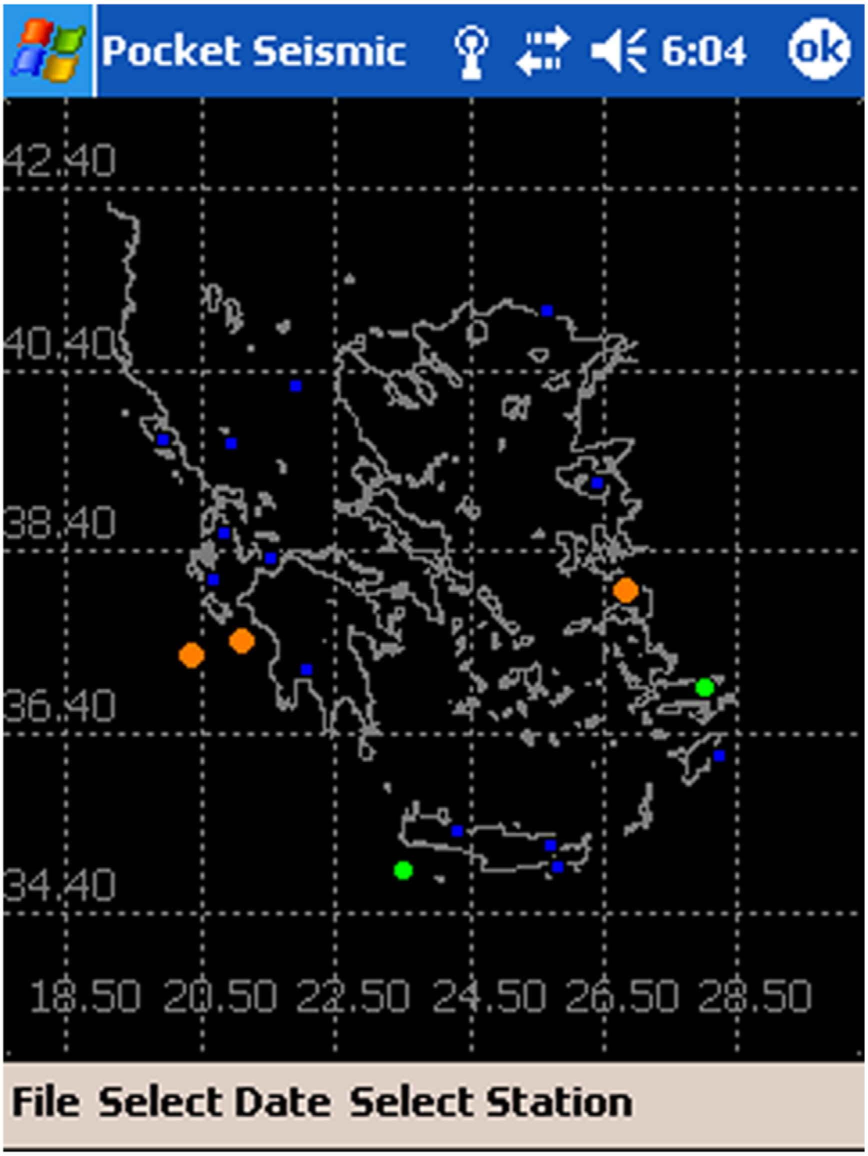

Fig. 3. Graphical representation of SEs between 5.0 and 6.0 ML in 2005. Square shapes (■) indicate field stations and green and orange circular spots (●) depict 5.0 and 5.4 and 5.5 and 6.0 ML events, respectively.

Table 1
Transfer time measurements of one day's EM signal data from NOAIG SFTP server to a mobile device employing all three communication protocols utilized.

	WLAN (s)	GPRS (s)	UMTS (s)
One day's EM signals transfer time (~129 KB)	2	10	5

After stress-testing the system for multiple times, network engineers (P.G. and D.C.) found its behaviour to be stable and predictable, but dependent on the network's load and status. For a user stable position, transfer failure rates ranged 3–5% and EM signals transfer speeds fluctuated on an average at 4 ± 1.2 and 1 ± 0.5 Mbps for WLAN and UMTS, respectively.

The system was also evaluated by a physicist (C.N.) with the following three scenarios:

(a) Retrieval of a list of SEs that occurred in Greece in 2003, filtering out the events with magnitudes between 5.0 and 6.0 ML. By selecting a specific SE the user had the ability to examine the event's related information along with the corresponding EM precursor signals from any of the 16 field stations. The analyst reviewed the EM signals up to 18 days from the origin time of the SE to assess the seismic behaviour of the region, remotely. The whole procedure lasted approximately for 5 min including data transfer of all EM signal information from 5 field stations for 18 days using a WLAN connection.

(b) Remote observation of the current seismicity of the western Greek territory (Ionian Islands), an area with high seismic activity (Papazachos and Papazachou, 1997). The user retrieved the current EM signals from all 6 field stations located in the area for the last 18 days. This provided a complete view of the current EM activity of the area remotely. The whole procedure took approximately 15 min including data transferral times of all EM signal information from 6 field stations for 18 days prior to the SE by using the UMTS connection.

(c) Reviewing of 18 days of precursor signals related to 14 SEs over 5.0 R between 1999 and 2004 that occurred in western Greece (terrain and Ionian Sea) and recorded by one field station located at Cephalonia Island. The physicist was asked to mark information rich signals on the PDA and on the desktop application at two different time periods 15 days apart. Comparative evaluation showed an agreement of approximately 95%, which obviously included intra-observer variability. Missed information rich signals on the PDA that were initially spotted on the desktop fluctuated at approximately ± 50 mV.

The physicist found the system easy to use, with results and handling comparable to the desktop application (Fig. 4). Although, the two applications (desktop and PDA-based) share common functionalities and features, many modules of the original desktop application had to be re-designed and re-implemented to fit the requirements of mobile devices, making the task of porting the original application quite a challenging task (Kiely, 2001). Some constrains that had to be considered, included the limited processing power and memory, as well as the small screen dimensions.

To avoid unnecessary network utilization, the PDA-based application employed an EM signal data caching mechanism. Accordingly, all new EM signal data received by the system were stored in a user-defined location (e.g. the PDA's storage card). Every time the user requests EM signals, the application checks if the desired data is present in the cache. If the data is already stored, the application rapidly loads it from the cache otherwise the EM signals are downloaded from the SFTP site. When the cache reaches a user-defined size, signal data is removed following the first in first out (FIFO) logic. This feature enabled the application to avoid unnecessary downloading of the same data, minimizing the system's waiting time and communication cost.

The utilization of the anti-aliased line drawing algorithm provided smooth rendering of the EM signal data on the PDA's display, but it significantly degraded the signal-plotting speed. This may be attributed to the repeated iterations that the algorithm performs to calculate the smoothed EM signal lines.

The primary objective for the design of the proposed system was to remotely monitor the EM activity of a particular geographic region for accessing its seismic behaviour. The system can also be utilized in the maintenance of field stations, allowing for on site visual verification of calibration measures. Additionally, the proposed architecture can form a base platform for a future integrated system that will incorporate services such as notifications for field station power failures, disruption of data flow, occurring SEs, and even other types of measurements such as crustal deformations.

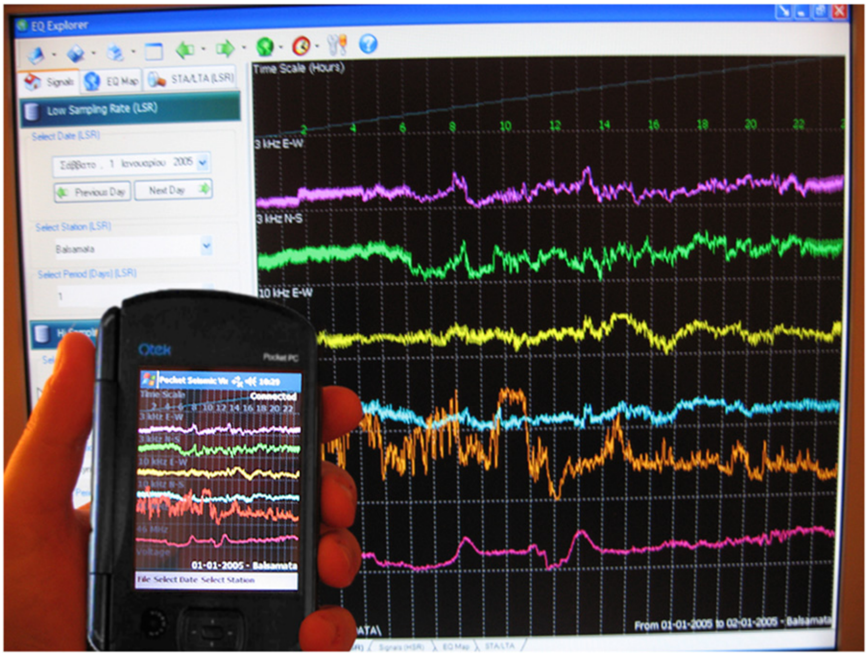

Fig. 4. Custom developed mobile application and its parental desktop application demonstrating signal traces for same date and station.

Future developments currently under investigation include the implementation of signal manipulation, processing and analysis functions. The functionality of streaming real-time EM signals from field stations to the mobile application is under consideration as a future extension of the system. Regarding EM signal processing and analysis algorithms, the integration of a special analysis algorithm based on the ratio of short-term to long-term signal average, is under investigation (Stavrakas et al., 2007). One of the most serious drawbacks of this undertaking is the limited processing capability of PDA devices. The solution to this limitation could come from the exploitation of teleprocessing systems, where the mobile device would assign computationally demanding tasks to a network of processing nodes.

4. Conclusion

Employing state-of-the-art technology, a novel PDA-based system was designed and proved plausible for application in the monitoring of electromagnetic signals and seismic events. This minimizes the time required for initial data retrieval, as the senior analyst can now access to critical data while being geographically independent from the data source.

As the number of access nodes or hot-spots around urban and semi-urban areas increase (especially with the introduction of WiMax), it will be increasingly easier to use these kinds of applications by connecting to open high-speed wireless networks, while at the same time reducing the cost of communication.

Acknowledgement

This work and its dissemination efforts have been funded by the research program “Arximidis I” of Greek Ministry of Education.

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