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Broadband Magnetotelluric Instruments for Near-surface and Lithospheric Studies of Electrical Conductivity: A Fennoscandian Pool of Magnetotelluric Instruments

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Abstract

A set of three new tensor audiomagnetotelluric – magnetotelluric (AMT-MT) instruments have been assembled in Oulu. Their design is based on the MTU2000 magnetotelluric equipment that was developed earlier in the Uppsala University. The new instruments are broadband systems covering the period range from 0.001 s to d.c. Induction coil magnetometers are used to measure magnetic field in the period range of 0.001–1000 s and fluxgate magnetometers for periods longer than 10 s. The electric field is measured with two 50–200 m long orthogonal electric dipoles using non-polarisable Pb/PbCl$_2$ *electrodes. The MT systems are equipped with high dynamic range (24 bit ADC) data recorders having a maximum sampling frequency of 3000 Hz and possibility for dual band burst recording. Monitoring of the system health with SMS messages helps to maintain long period observations allowing continuous measurements and reducing the maintenance efforts and costs. The three new instruments extend the Fennoscandian pool of homogeneous MT equipments into 14 systems and allow synchronous array measurements. This makes it possible to use multisite data processing techniques and therefore considerably improve the data quality, especially in electromagnetically noisy regions. The instrument pool can be used in a broad range of applications to study the crust and upper mantle.*

Key words: magnetotelluric, audiomagnetotelluric, geophysical instruments

1. Introduction

The magnetotelluric (MT) method, which uses time variations of the Earth's natural electromagnetic field, can provide information on electrical conductivity of the Earth's crust and upper mantle from the depth of a few metres to the depth of hundreds of kilometres. The skin depth (depth of penetration, depth of investigation) depends on the period (frequency) of the electromagnetic field time variations and on the conductivity (resistivity) of the medium in which EM field propagates. For a given resistivity distribution of the subsurface, the depth of investigation increases with period. For a fixed period, the skin depth increases with the increase of the resistivity of the subsurface.

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In its basic form (*Tikhonov*, 1950), a magnetotelluric sounding requires simultaneous recordings of the magnetic field in one direction and the electric field in the perpendicular direction. Tensor magnetotellurics (e.g. *Cantwell*, 1960; *Sims et al.*, 1971) requires simultaneous recording of two horizontal magnetic (h_x, h_y) and two horizontal electric field components (e_x, e_y), usually perpendicular to each other. Tensor observations are superior to scalar magnetotellurics because they provide directional information of subsurface conductivity distribution (see a complete review e.g. in *Simpson and Bahr*, 2005). This allows for a much more accurate description of 3D environments. Inclusion of the vertical magnetic field makes it possible to carry out classical geomagnetic depth soundings (GDS). GDS is used to map current concentrations in the Earth. Modern inversion techniques, however, are able to make use of GDS data to infer conductivity distribution in the Earth, thus providing additional constraints to models based upon magnetotelluric data.

Traditionally different names of the magnetotelluric method have been used depending on the period (frequency) range used in investigations. In general, magnetotellurics can be considered as a class of methods, where individual methods differ on their period range (and therefore also on the source of the excitation field and instrumentation). In the radiomagnetotelluric (RMT) method, the frequency range is roughly 20–200 kHz and the depth of investigation ranges from 1 m to 100 m. RMT uses EM field transmitted from remote radio stations. In the audiomagnetotelluric (AMT) method, the source of EM field is mainly tropical thunderstorm activity, which is continuous and has some daily variations. The period range is c. 1 Hz – 20 kHz, which allows investigations to depths ranging from a few tens/hundreds metres to 10–15 km. The long period magnetotellurics (LMT) is used for investigations, where the period of EM-field variations is from 1 up to 100000 s. The sources of EM field in LMT periods are magnetospheric and ionospheric currents. In this case, the depth of investigation can be up to several hundreds of kilometres.

Classical magnetotelluric soundings require recordings of EM fields only at a single site. Then these measurements are repeated at different locations to cover the area of interest. However, single site observations can be strongly distorted by industrial EM noise. To handle the problem of local noise, remote reference technique was introduced (*Goubau et al.*, 1979; *Gamble et al.*, 1979), requiring simultaneous recordings at two sites separated by a sufficiently large distance that the industrial noise is uncorrelated between the sites. Moreover, recent developments allow using several simultaneous MT sites in order to obtain even higher quality data. Simultaneous recordings at several sites makes it also possible to estimate other transfer functions such as horizontal magnetic transfer functions, which bring additional valuable information about Earth's subsurface conductivity. Hence, two or more instruments are required for modern MT measurements.

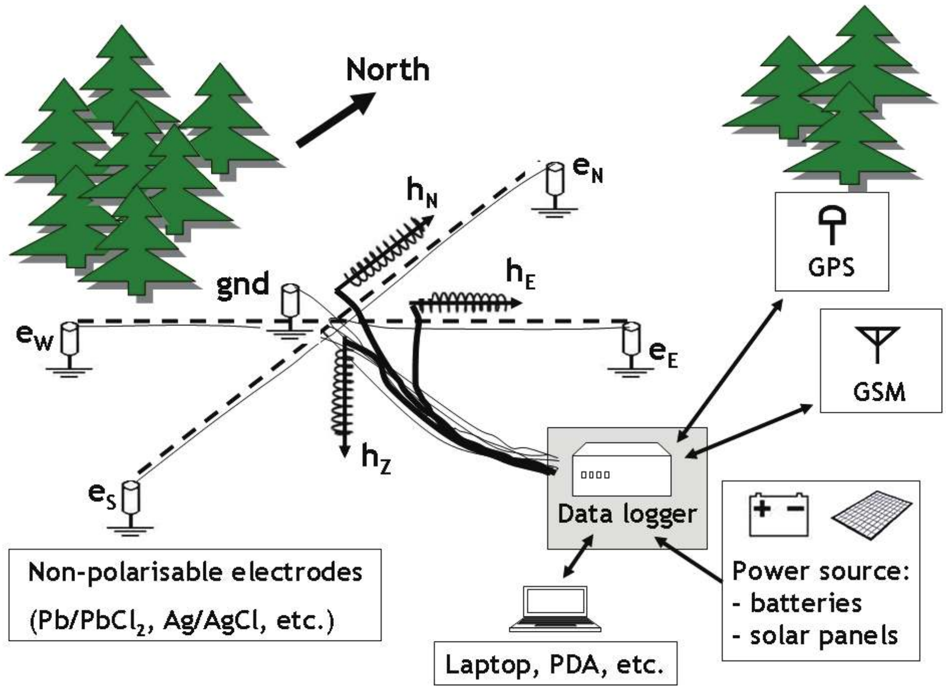

Fig. 1. Sketch of a magnetotelluric site. Electrodes distance varies typically from 50 m to 200 m. The system is normally oriented in geomagnetic coordinates. Sensors are usually buried at the depth of a few tens of centimeters to reduce temperature variations and, in the case of electrodes, to ensure wet environment and low contact resistance of electrodes.

A sketch of a magnetotelluric station is shown in Fig. 1. The magnetic field is measured in the AMT range by induction coil magnetometers and in the LMT range using fluxgate magnetometers. Electric field is measured using two orthogonal dipoles having typically a length of 50–200 m grounded with non-polarisable electrodes. We primarily use standard Pb/PbCl$_2$ electrodes, which are rather inexpensive and very stable. Electrodes are buried at a depth of a few tens of centimeters to reduce temperature variations and to ensure wet environment and low contact resistance of electrodes. A GPS receiver is a standard part of any modern geophysical equipment. It provides accurate timing and is needed for synchronization between simultaneous sites as well as for the determination of the exact site location. Data are usually collected on high precision, high dynamic range data loggers having a 24-bit ADC. A GSM modem is attached to the system for remote monitoring of the data stream and the system health of the instrument. In case of any failure a warning message can be sent, for example, via SMS message and proper action can be taken.

Magnetotelluric equipment should be designed to operate without maintenance for significant time duration (for LMT sounding several weeks, for AMT several days). It is achieved by minimizing power consumptions and by implementing, in addition to ordinary car batteries, other power sources like solar panels.

2. AMT and MT instruments in Oulu and Uppsala – a historical review

In Oulu the magnetotelluric method has been used since the pioneering work of *Benderitter and Hérison* (1974), *Korhonen and Pernu* (1975), *Benderitter et al.* (1978), *Pelkonen et al.* (1979), *Ádám et al.* (1982), *Kaikkonen et al.* (1983), and *Kaikkonen and Pajunpää* (1984). The first AMT-instruments were purchased in 1976 and 1981. Both were French ECA analogue scalar audiomagnetotelluric instruments, where only one magnetic component and perpendicular electric field component could be measured. Instrument did not provide impedance phase but only the amplitude, i.e. apparent resistivity, which was obtained at several fixed frequencies covering a range of 4.1–2300 Hz (new) and 8–1700 Hz (old). Yet the light-weight, portable, instrument has been used e.g. in thesis work as late as 2006 (*Martinkauppi,* 2006).

On 1983, the first five-component tensor MT instrument, analogue IZMIRAN-5 with Bobrov-variometers (quartz-fibre torsion magnetometers) were obtained, but it was in use only for one year.

On 1984, the first digital five-component tensor MT instrument was purchased from Aarhus, Denmark. It covered periods from 0.1 to 1000 s and had a 16 bit analog-to-digital converter with a maximum sampling frequency of 25 Hz. This instrument was used over 10 years for crustal studies in the Fennoscandian Shield (e.g. *Korja and Hjelt,* 1998). One of the advantages of this instrument was that the Uppsala University had two similar instruments, which made it feasible to conduct common field campaigns (e.g. *Korja et al.,* 1986). In Uppsala, the instruments were bought a couple of years earlier with the first measurements along the Fennolora profile (*Rasmussen et al.,* 1983; *Rasmussen et al.,* 1987) in 1983 and in Southern Sweden (*Roberts et al.,* 1983) also in 1983.

Simultaneously with the purchase of the long period MT instrument, a project to develop a tensor AMT instrument was commenced. A prototype was built and test measurements performed (*Adam et al.,* 1988) but the instrument was never brought into play.

In Uppsala, Metronix AMT-MT instruments GMS05 replaced the old Aarhus-Uppsala MT instruments in the early 1990-ies. One example of the use of GMS05 is the study of the Scandinavian Caledonides in Jämtland, Sweden (*Korja et al.,* 2008).

In 1997, four new long period MT instruments, funded by the Academy of Finland and the University of Oulu, were assembled in Oulu. They consisted of REFTEK data loggers (24 bit ADC with GPS-derived time synchronisation), fluxgate magnetometers from Lviv, Ukraine and tellurometers (amplification and filtering interface between sensors and ADC) from Oulu with $Pb/PbCl_2$ electrodes from Uppsala. These instruments, together with 46 other LMT instruments from several European research institutes, were used for the BEAR magnetotelluric array measurements on summer 1998 (e.g. *Korja and BEAR Working Group,* 2001; *Hjelt et al.,* 2006).

Although instruments meeting international standards for deep MT studies have been available in Oulu since 1998, the lack of tensor AMT instrument with modern specifications (see above) has made it impossible to conduct good-quality AMT studies.

Development of a new broad-band (AMT + LMT = MTU2000) instrument was initiated in Uppsala in 2000 after the Knut och Alice Wallenbergs Stiftelse provided support for the project in 1999. In 2003 eight LMT and three AMT instruments were finally assembled in Uppsala. Since then the instruments have been used in several field campaigns, e.g. in Poland (*Brasse et al.,* 2007), Denmark (*Smirnov and Pedersen,* 2008) and in Jämtland (*Korja et al.,* 2008). The design of the instruments is described in the next chapter together with the latest modification (FMTU2005) built in Oulu and funded by the Faculty of Natural Sciences of the University of Oulu.

3. Magnetotelluric systems: MTU2000 & FMTU2005

The instrument consists (Fig. 2) of an electronic box, which is specifically constructed for magnetotelluric measurements. The box has built-in amplifiers for the electric channels. It is designed to be waterproof and rugged, which makes it possible to bury the box in order to increase e.g. temperature stability and to use the box for transportation. The data are digitized and stored with the use of EarthData Ltd. data recorder. It is capable of very long term operation with basically unlimited data capacity and with the highest sampling rate of 3000 Hz. Data loggers are capable of dual band burst mode recording. For example, during AMT measurements we can get a continuous data stream with 20 Hz sampling rate for MT-LMT recordings and, at the same time, record with 1000 Hz sampling rate for two hours during night time (AMT recording), which is favourable because of the low level of industrial noise.

In the AMT-MT mode (0.001–1000 Hz), magnetic field components are measured using three broadband induction coil magnetometers LEMI-120 from Ukraine. In the LMT-mode (d.c. – 10 s) the magnetic field is measured with a three-component fluxgate magnetometer, also from Ukraine. In the Uppsala instruments, MFS05-coils from Metronix are used instead of LEMI-120 coils and a newer version of Lviv fluxgate magnetometers (suspended, water-proof) for LMT. Electric field is measured in both cases with two electric dipoles of normally 50–250 m long and with $Pb/PbCl_2$ electrodes.

The systems are also equipped with an option to use solar panels as a power source instead of standard 12 V batteries and GSM modems, which allow very long maintenance free operation of the instruments as well as remote control and monitoring of the system health.

To configure the system in the field, a computer with network connectivity is used. EarthData logger has also a facility to establish wireless network connections like WiFi and Bluetooth. We have developed a program package for effortless configuration of the logger to reduce possible mistakes in the field. After setting up the recorder, the data can be downloaded directly to a portable computer and processed there. Hence it is possible to estimate data quality and check the equipment operation in situ. If the local electromagnetic noise produces significant distortion of magnetotelluric transfer functions, the equipment is moved to another location. However, remote reference processing usually makes it possible to achieve satisfactory data quality even in the presence of such noise, if it is not correlated between local and remote sites.

Fig. 2. Components of an AMT-MT instrument in Oulu. 1 = Instrument box containing an interface board, data logger, GSM-modem, regulator for solar panels and battery inside the box and a cable interface outside. The latter has water proof contacts for sensors (nine contacts), external power, GPS antenna, GSM antenna, Ethernet port, USB port. 2 = $Pb/PbCl_2$ electrodes (five/instrument) and electrode cables (25–100 m), 3 = three induction coils and cables, 4 = three-component fluxgate magnetometer with electronics box and cable, 5 = data logger (EarthData Ltd), 6 = 12V battery (typically 50–120 Ah), 7 = GPS antenna and cable, 8 = GSM antenna and cable and 9 = rugged field laptop.

4. Determination of the internal noise of induction coils

The quality of the induction coils in the new MT system can be determined with parallel tests. It requires simultaneous recording of several induction coils placed parallel to each other. To reduce the influence of the coils, the distance between them should be at least the length of the coil. The internal noise of the field sensors can readily be estimated quantitatively from parallel recordings as described next (*Smirnov,* 1998).

Let us assume that system responses of the sensors are identical or they are measured precisely and that we have measured two signals from parallel magnetometers: $h_1(t)$ and $h_2(t)$. The difference between them will be defined by their internal noise and therefore an uncorrelated signal component will be a good estimate of the eigennoise of the coils. Taking the Fourier transform of the signals we have:

$$H_1 = H + N_1 \tag{1a}$$

$$H_2 = H + N_2 \tag{1b}$$

where N_1, N_2 are noise components of the corresponding magnetometer and H is measured magnetic field.

Subtracting Eq. (1b) from Eq. (1a) we have:

$$H_1 - H_2 = N_1 - N_2 \tag{2}$$

Then, multiplying Eq. (2) by H_1^* or H_2^*, where asterisk (*) stands for a complex conjugate, and taking mathematical expectation, we can reformulate the equation in terms of auto- and cross-spectrum. Cross-spectrum is defined as:

$$S_{XY} = \lim_{T \to \infty} \frac{1}{T} E\{XY^*\}, \tag{3}$$

where T is the length of the Fourier transformation (*Bendat & Piersol* 2008).

Making the use of the fact that the measured magnetic field H and noise N_1 and N_2 are all uncorrelated between each other, i.e. cross-spectra between the following components will be equal to zero ($S_{N1H} = S_{N2H} = S_{N1N2} = 0$), we will arrive at

$$S_{H1H1} - S_{H2H1} = S_{N1N1} \tag{4}$$

We can thus estimate the noise of the magnetometer 1 (similarly for 2) as:

$$N_1 = \sqrt{S_{H1H1} - S_{H2H1}} \tag{5}$$

It should be noted that we used assumption that the system responses of the coils are absolutely identical. In this case, the noise estimate is exact. In reality sensors are always somewhat different. In order to decrease the bias of the noise estimate it is necessary to select events with minimum strength of H field. The same procedure can be used to estimate the noise of the electric channels.

5. First laboratory and field tests

The first test that we carried out was a parallel test. It was made at a remote place, selected to be affected as little as possible by industrial noise. Three magnetic coils were placed in parallel and electric channels were short circuited to measure their noise as well.

In Fig. 3, narrow band filtered time series from induction coil magnetometers are shown. Signals filtered at 100 s are shown in the upper panel while signals filtered at 1000 s are in the lower panel. Signals from different coils are very similar indicating that the internal noise level of the coils is rather low. However, at the period of 1000 s, we can already observe differences between the coils.

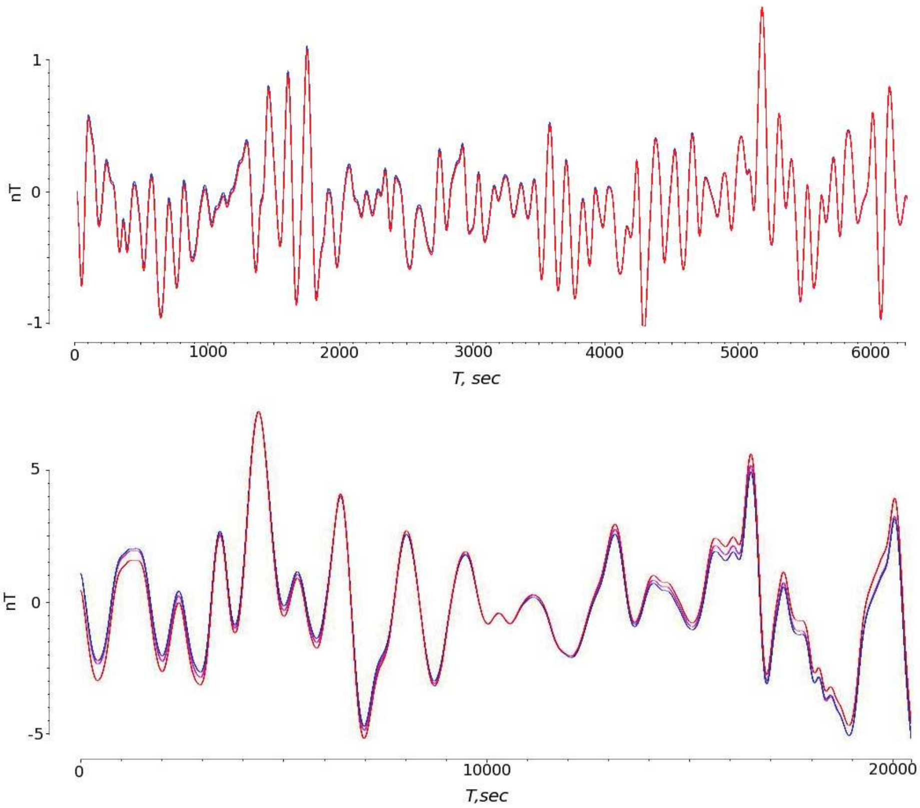

Fig. 3. Time series of magnetic field recordings from three induction coils in parallel set-up. The length of time series is c. 2 hours. (a) Signal is narrow-band filtered at 100 s and (b) at 1000 s. Different colours represent different magnetometers.

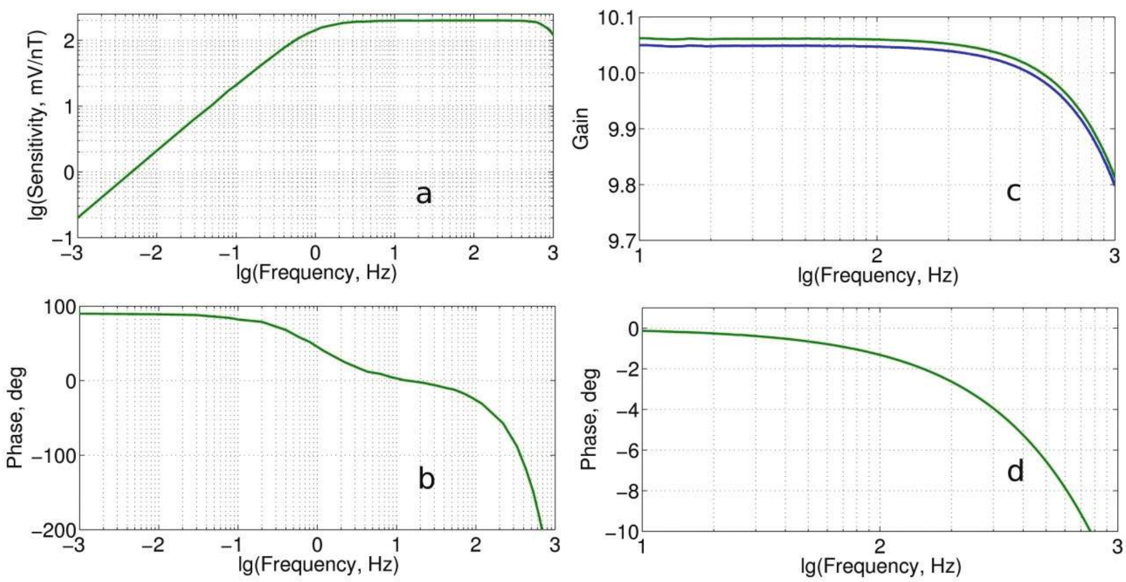

Fig. 4. Transfer functions of the two magnetic (H) channels (= difference between input and output signal as a function of frequency) and electric (E) channels. (a) Sensitivity of H channels, (b) phase of the transfer functions of H channels, (c) gain factor of E channels and (d) phase of the transfer functions of E channels.

Before any measurements all signal channels of the system were calibrated to obtain their transfer functions. Examples of the transfer functions for two electric and magnetic channels are shown in Fig. 4. The calibration of the electric channels was performed by feeding a sweep signal into their inputs and at the same time directly to the recorder. The complex ratio between output and input signals represents the channel transfer function. The calibration of magnetic coils was provided by the manufacturer.

Using Eq. (5) we have estimated the noise characteristics of the induction coils. The noise figures are slightly above the given specifications ($<1\text{x}10^{-4}$ nT/√Hz at 1 Hz), which might be due to certain difference in system response between different coils.

6. Field experiment examples

The latest version of the system was tested under field conditions in January 2007. Later on complete tests were carried out during field measurements in summer 2007 with two instruments allowing remote reference processing of magnetotelluric time series. These measurements were a part of the EMMA II recordings in Pudasjärvi-Kuusamo region in Finland. Magnetotelluric transfer functions were estimated using the robust remote reference code by *Smirnov* (2003). Main components (apparent resistivities and phases) of the impedance tensor are shown in Fig. 5. The results obtained from only one day recording cover a broad period range extending to periods of one hour. The magnetotelluric parameters are stable over the entire period range and have rather small confidence limits except for the dead band (1–10 s) and for the longest periods. The increase of the errors in the dead band is caused by the low signal-to-noise ratio and possible influence of industrial noise while at the longest periods the increase is due to limited amount of data and possible source effects.

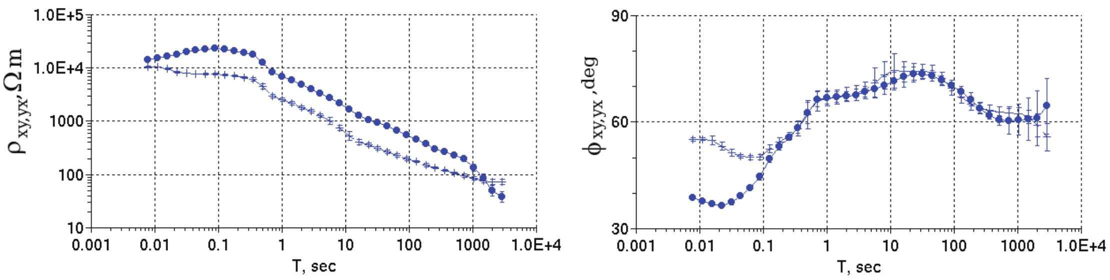

Fig. 5. Apparent resistivities and impedance phases from one day recording of the EMMA II array measurements in summer 2007 in Kuusamo-Pudasjärvi region in Finland. Dots represent xy component (geomagnetic NS), crosses yx (EW) component. Vertical bars show 95% confidence limits.

During the first long period array measurements of the EMMA project (EMMA I), ten Uppsala instruments were installed for about one year (Aug 2005 – Jun 2006) in Northern Karelia in Finland. In order to maintain such a long term survey we monitored data acquisition and system health using SMS messages that were sent once per two days. Each SMS message contains several consecutive samples from each field component and system health parameters (voltage, temperature and number of satellites in lock). Time series of monitored parameters are presented in Fig. 6.

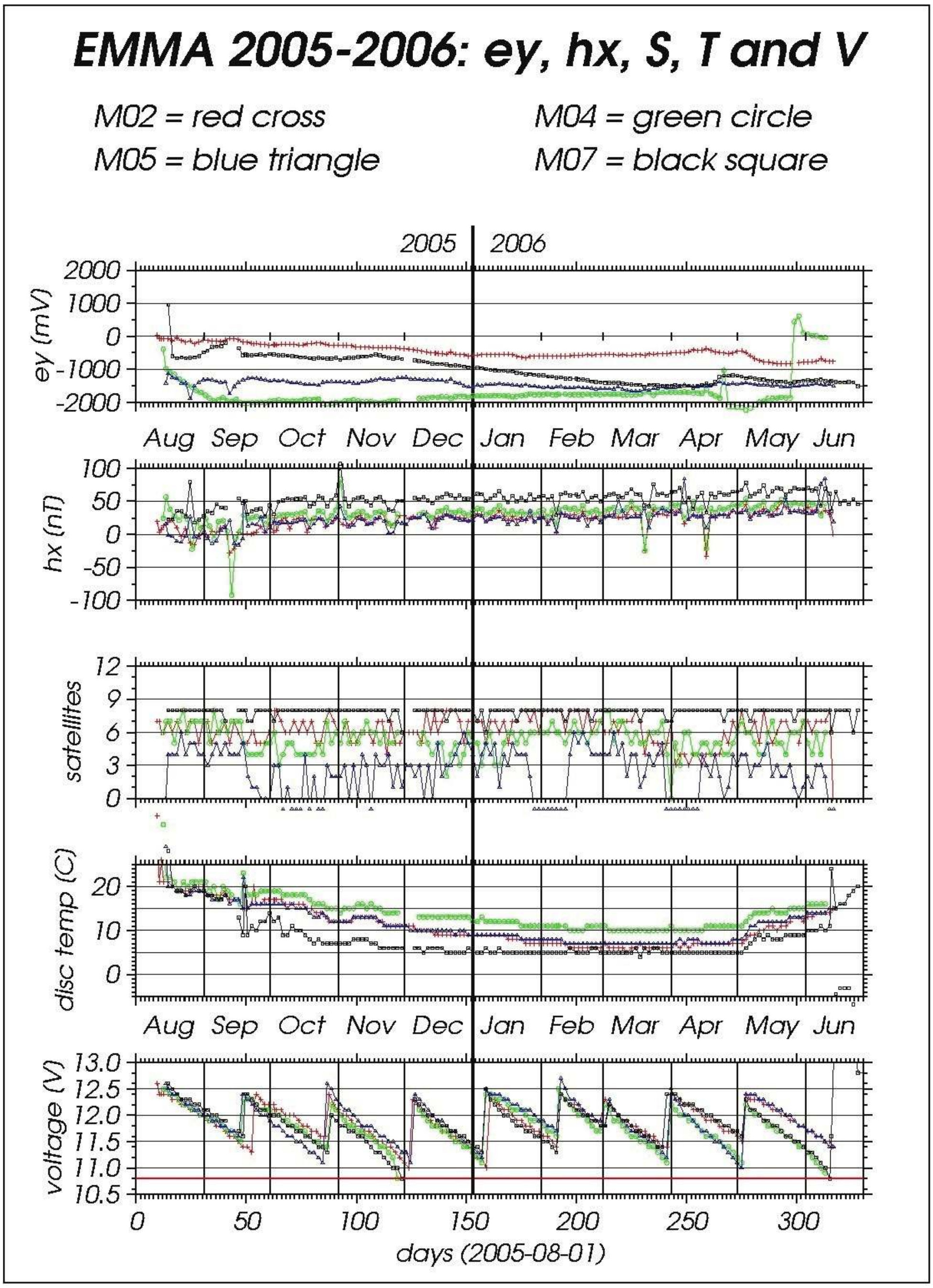

Fig. 6. GMS monitoring of the status of the system. Data are from four sites of EMMA I array measurements that lasted from Aug 2005 to Jun 2006 in Northern Karelia, Finland. Origin of the time-axis is 1st of August, 2005 Colours of time series in each panel denote different sites as indicated in the header above the panels. The two uppermost panels show e_y (EW) and h_x (NS) channels as examples of field monitoring. Note that on the e_y channel plot, the input voltage (mV), not the electric field strength, is shown. The three lowermost panels contain SMS time series of the number of visible satellites, temperature and voltage. Abrupt changes in voltage are due to replacement of batteries (four / site) during the maintenance visits. Red, horizontal line in the voltage plot denotes the lowest possible voltage of batteries. In all cases, the values shown in time series are an average of four consecutive samples.

Monitoring of the battery voltage helped us to run systems without interrupts to obtain continuous data. At the same time we kept the number of maintenance visits low. The red line in the voltage plot marks the lowest possible voltage of the batteries to keep the system in operation. At a few sites the voltage reached this limit once, but other systems recorded continuously over the entire recording period. The increases in voltage are related to the maintenance visits, when the batteries (four / instrument) were replaced without interruption of the recordings.

It is important to keep the temperature of the instrument constant to avoid drifts in time series of magnetic and electric components. During the installation phase, all instruments were carefully isolated underground. The temperature monitoring helped to track if the isolation of instruments were broken or required additional modification. As can be seen, temperature was always above 5 degrees in all sites.

7. Conclusions

New AMT-MT instruments were recently assembled in Oulu. Their design is based on MTU2000 magnetotelluric equipment that was developed earlier at Uppsala University. The new instruments are broadband systems that can cover the period range from 0.001 s to d.c. Induction coil magnetometers are used to measure the magnetic field in the period range of 0.001–1000 s and fluxgate magnetometers for periods longer than 10 s. The MT systems are equipped with high dynamic range (24 bit ADC) data recorder having the highest sampling frequency of 3000 Hz and possibility for dual band burst recording.

Monitoring of the system health with SMS messages helps to maintain long period observations allowing continuous measurements and reducing the maintenance efforts and costs.

The three new instruments extend the Fennoscandian pool of homogeneous MT equipments into 14 systems. The instruments can be used in a broad range of applications to study the crust and upper mantle.

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