KMS Technologies – KJT Enterprises Inc.

Chapter 5
The Field System and Field Procedure

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Chapter 5
The Field System and Field Procedures

The previous chapters explained the physical background, the data processing and interpretation of LOTEM data. In this chapter, the system hardware and field procedures are described. First, the individual system building blocks of a conventional acquisition system are considered leading to more advanced multichannel systems. Multichannel systems will move electromagnetic techniques into a technological state common to seismics. In the future, the large amount of data will bring the development of new multichannel processing techniques. These require new imaging methods and finally yield a subsurface image of much higher resolution.

After considering the general system concept, specific problems are addressed. The selection of them is strictly based on field experience and where most misunderstandings and errors occur. When synchronizing different receiver and transmitter systems, one is often faced with incompatible synchronization circuits. By properly designing the synchronization clocks one can easily circumvent this problem with little additional effort. At the same time, by choosing a proper synchronization design, one can incorporate safety devices into the system at a small additional cost.

Further, the mobile processing systems are discussed which are essential to maintain an optimum quality control during the ongoing survey. The quality assurance always grants continuous adjustment to the survey condition yielding a very high productivity.

When discussing the field procedures, emphasis is given at all stages to avoid a breakdown in the field and increase the amount of acquired data . The same objective guides us when systematically preparing the transmitter side. Systematic preparations can save several field days. In addition to the increased productivity, one should always consider special field techniques which allow an additional improvement of the signal-to-noise ratios. Special field procedures can also save significantly in the hardware cost and operation expenditures. Considering that a signal-to-noise ratio improvement by a factor of two can only be obtained by either increasing the transmitter current by a factor of two or decreasing the noise by twofold. An increase in current by a factor of two requires the generator power to be increased by a factor of four which soon reaches the practical limits. Thus, an improvement of the signal-to-noise ratios using improved processing principles and field procedures seems to be the more logical and less expensive way to go.

SYSTEM CONCEPTS

A deep transient EM system uses a grounded wire transmitter and a receiver system. Figure 5.1 shows a typical field setup of the **long offset transient electromagnetic (LOTEM)** sounding system. A grounded wire transmitter of approximately 1 to 2 km length, is layed out on the earth surface and earthed on both sides. Through this transmitter, a square wave current of several tens to several hundreds of Amperes is injected into the ground. The current step induces induction or eddy currents in the subsurface which propagate downwards and outwards with increasing time. A mobile receiver located at some offset (2–20 km) is used to record the electromagnetic response of the secondary currents in the form of the time derivative of the magnetic field and the electric field components. The signals appearing at the receiver caused by the induction currents in the subsurface are called transients. This is because when the current is switched abruptly, it starts at a high value and then decays with time to a constant level. Repetitive current switching cause transients to appear at the receiver site. They can then be stacked on top of each other to obtain an optimum signal-to-noise ratio using digital data processing techniques similar to those of the seismic industry.

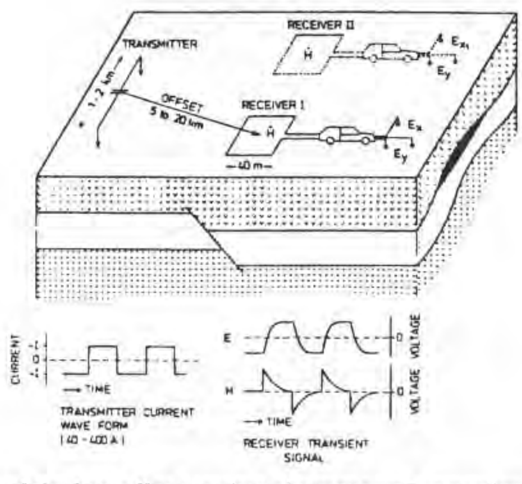

Fig. 5.1: Typical setup of the long offset transient electromagnetic sounding system.

A block diagram of the transmitter and receiver hardware components is given in figure 5.2. The transmitter consists of a standard three-phase generator which supplies the rectifier-current-switch assembly with 220–880 Volts AC. Other generators such as 400 Hz generators may also be used. The current switching after rectification is synchronized with the receiver with a high precision crystal clock. The receiver consists of magnetic and electric field sensors which send the signal directly to the preamplifier. Then via the amplifier it goes into the digital part of the data acquisition system. The data acquisition system described here is called DEMS IV (Digital ElectroMagnetic System, 4-th generation). It has the feature to record all the raw data on a removeable hard disc. It also allows real time quality control of all signal using a graphics display. The entire data acquisition system is portable and operated by a 12 Volt automobile battery. DEMS IV is a development based on the field systems described by Strack (1985) and is a single site system meaning that one receiver site is recorded at one time with one acquisition system. A newer multichannel data acquisition system, the TEAMEX system block diagram is shown at the bottom of the figure.

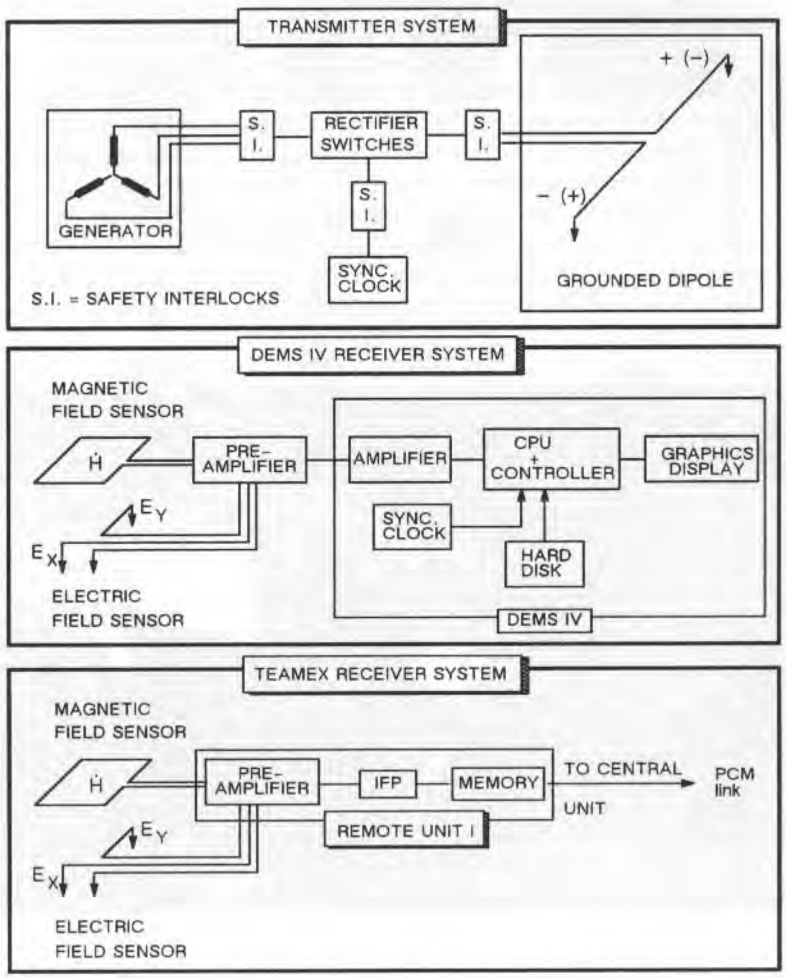

Fig. 5.2: Block diagram of the hardware building blocks for a LOTEM transmitter and receiver systems.

Routinely, copper–copper sulphate electrodes for the electric field and a large air loop as induction coil receiver for the magnetic field are used. For more rugged terrain one can use flux gate magnetometers (3 components) or induction coils. Only during recent years have the noise characteristics and the price of the latter sensors come within an acceptable range. Compared to air coils, ferrit core magnetometers are about twice as expensive and flux gate magnetometers about five to eight times. Figure 5.3 shows a picture of the induction coil takeout. The induction coil consists of a seismic cable with approximately 100 conductors connected in series. Its length may vary between 120 m to 200 m. The coil can either be laid out as large square loop (30 m to 50 m on the side) or with a smaller side length (10 m with several turns). Both ends are connected to the takeout. From the takeout the signal goes into the the preamplifier shown in the figure on the right. Before amplifying it, the RF – noise is filtered out. The amplification is done in several stages, each stage separated by an analog notch filter. This allows maximum amplification while suppressing as much noise as possible. An example of a LOTEM preamplifiers is shown in figures 5.4. When using the preamplifier in the field, it is important that the signal at the output of the preamplifier is at the maximum to have it less contaminated by the noise entering the signal transmission line. At the same time the amplification must be low enough that the signal does not drift significantly. Analog notch filters should be placed between the gain amplifiers to achieve a maximum preamplification. Figure 5.4 also shows the calibration unit left to the preamplifier. This calibration unit generates a

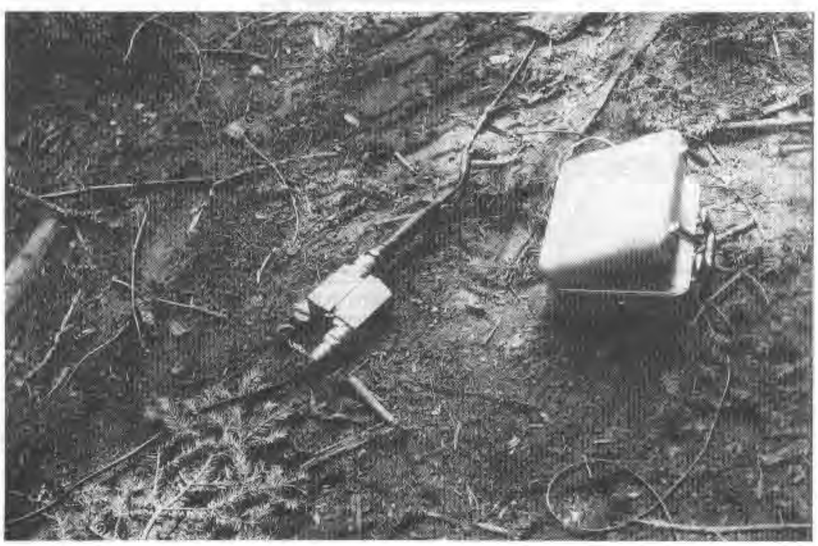

Fig. 5.3: Takeout and connector of the LOTEM induction coil which is made up of a 160 m long seismic cable. On the right side of the figure the preamplifier is displayed.

square wave signal which can be attenuated in binary steps. Using the output of the calibration unit as input to the amplifier allows a quick check of the gain factors. The calibration unit can be triggered by the synchronization clock to allow the recording of several stacks for system response evaluation.

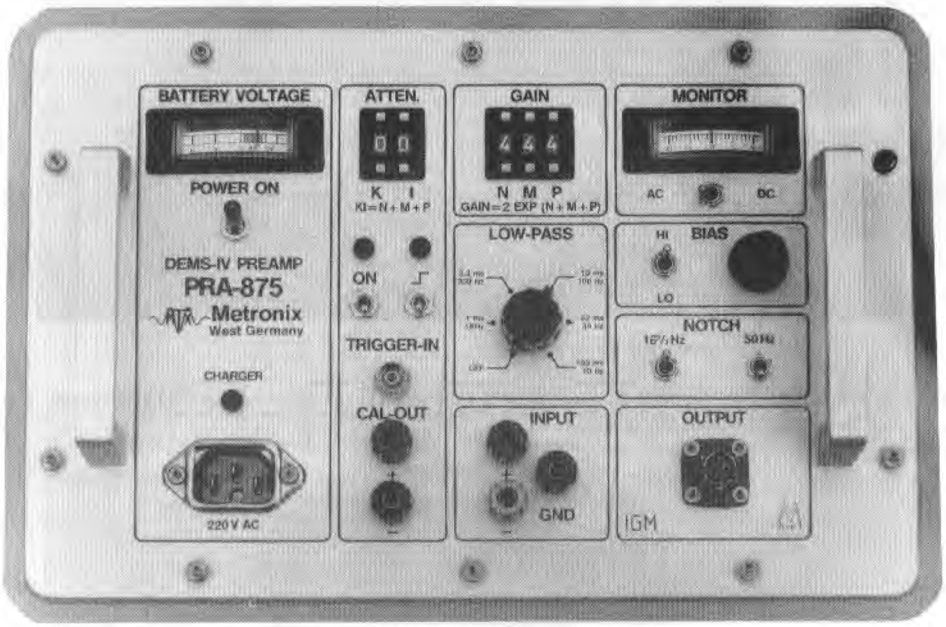

Fig. 5.4: LOTEM preamplifier showing on the left side of the preamplifier the calibration unit and on the right side the preamplifier control panels.

A 20 to 50 m long cable connects the preamplifier with the amplifier at the site of the digital data acquisition system. The acquisition system is located at a distance from the sensors because generally the receiver vehicle and the movements of the operators can cause unnecessary electromagnetic noise in the sensors. Figure 5.5 and 5.6 show examples of different single site acquisition systems of the DEMS IV generation. In figure 5.5 the original prototype version is shown (only the digital part). Figure 5.6 shows the commercial version of DEMS IV which also integrates the analog amplifier and the graphic display. Both systems have removable hard discs and especially modified for harsh field conditions. The comparison between both systems shows how rapid the size is reduced with new technology within only 2 – 3 years time. Multichannel remote units are only one sixth of the size of the DEMS IV system in figure 5.6 with twice the capability.

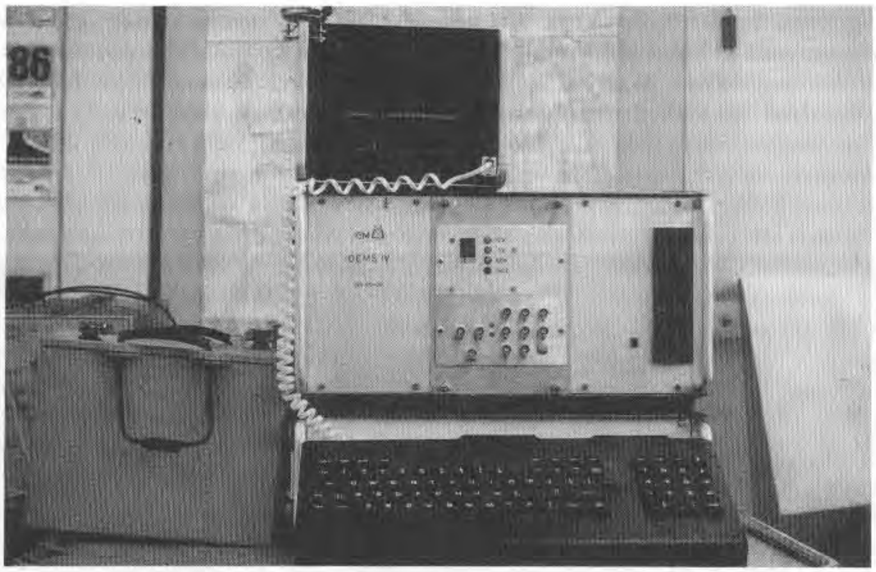

Fig. 5.5: Digital ElectroMagnetic System (DEMS IV) which is the heart of the LOTEM system. Here the original prototype is shown.

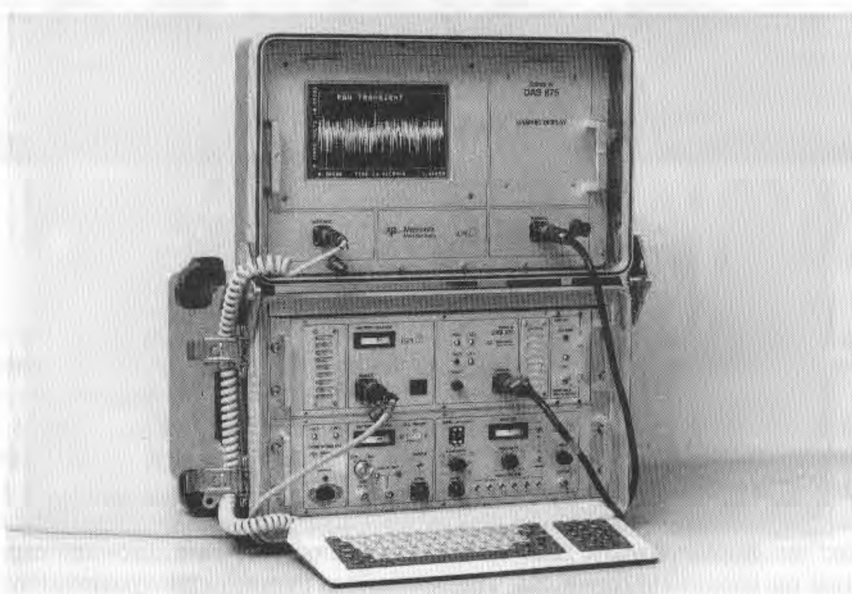

Fig. 5.6: Digital ElectroMagnetic System (DEMS IV) in a commercial version.

Transmitter Systems

The objective of the transmitter is to produce a direct current which is then turned off or reversed. Figure 5.7 shows two possible transmitter *wave forms*. Here, only bipolar current waveforms have been selected because the averaging of the signal of opposite sign is essential to avoid effect caused by the polarization of the transmitter electrodes. The bipolar continuous current waveform has the advantage of using twice the current to obtain a maximum source moment. Furthermore, larger generators show significant wear when used under changing load as with the bipolar waveform. The *bipolar continuous waveform* is sufficient when using larger offsets (> 5–7 km) and large investigation depth. In that case the ripple on the current from the rectifier assembly is negligible. When requiring higher resolution at shallower depth, the *bipolar waveform* is more appropriate, because one can eliminate the ripple from the generator when recording only during the off–time. The time between cycles of the same polarization is called the *repetition rate*.

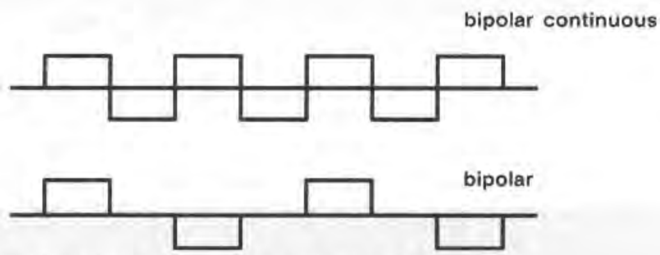

Fig. 5.7: Two possible bipolar transmitter current waveforms.

Hereto, it is still difficult to obtain a perfect square wave current waveform and a large output current. Although solid state transmitters delivering currents of up to 100 Ampere (peak–to–peak) are available, field reliability and safety are of major concern. One is thus sometimes forced to use electromechanical switches and to measure the system response carefully. Deconvolution of the system response including the ramp time will in most instances compensate for the effects. Figure 5.8 shows a schematic of an electromechanical *switchbox*. When designing a switchbox one should not forget to include safety devices (not included in the figure) which turn off the current once it falls below 10% of its maximum level. This can be accomplished using window comparators. The safety device is disabled just before the current reversal and it is enabled again immediately after the switching. From the field operations point of view, the easiest and most reliable generator is a standard three phase 380 V generator as used at any construction site. They are readily available anywhere in the world and can be replaced when problems occur. Figure 5.9 shows a picture of such a generator as we commonly use in Germany. For mining applications the use of 400 Hz aircraft generators is very common. They are significantly smaller and give a cleaner DC–

current. Their drawback lies in the availability of spare parts which can be an essential factor for field operations.

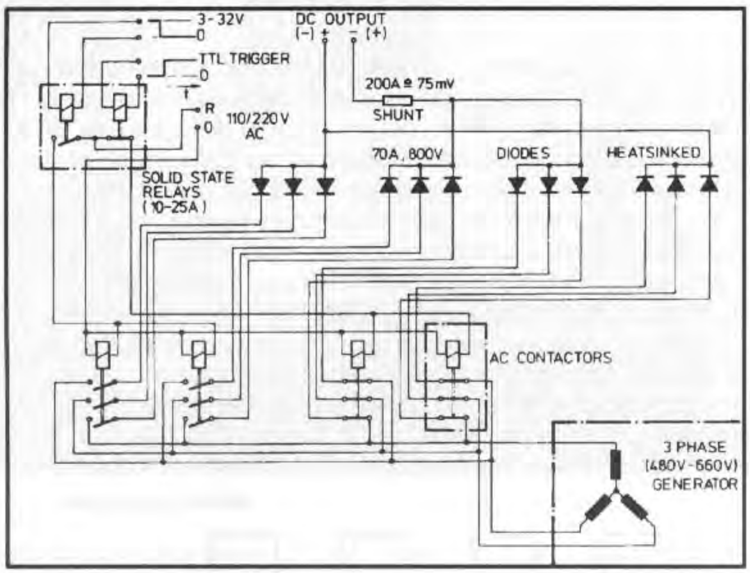

Fig. 5.8: Principal schematic of an electromechanical switchbox (after Strack, 1985).

Fig. 5.9: Standard construction generator used for LOTEM test surveys in Germany.

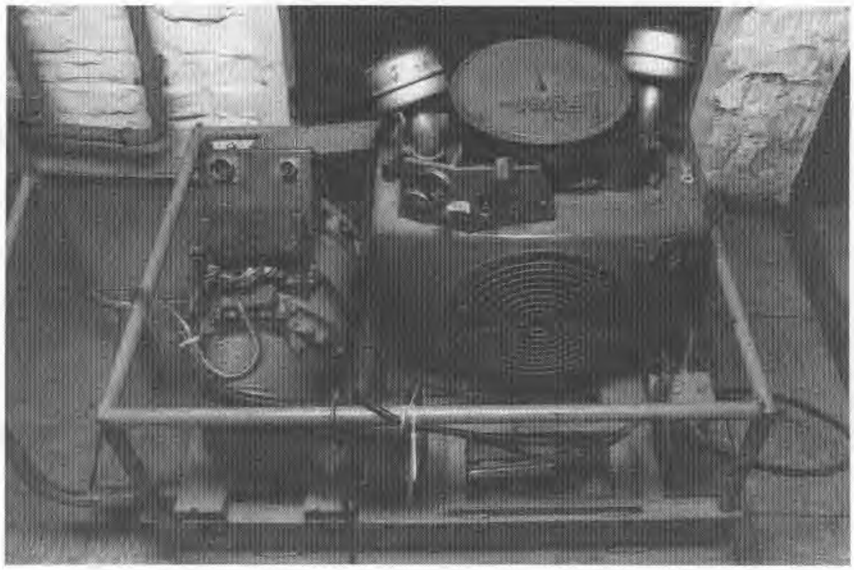

Fig. 5.10: 400 Hz 30 KVA generator as commonly used for mining applications. Connected to the generator can be solid state 25 KVA switchbox giving maximum output current of up to 50 Ampere (peak–to–peak).

Synchronization between Transmitter and Receiver

Synchronization between transmitter and receivers is an essential task. Because of the large distance between transmitter and receiver, the synchronization can either be done using satellite clocks or remote clocks which operate independently and are synchronized just before leaving the base camp. Satellite clocks have the advantage of an absolute time reference, however their functionality depends greatly on the availability of the units. The least expensive and most practical way is the use of remote clocks. Oven controlled clocks are generally more accurate but require significantly more power than temperature compensated crystals. The latter can be obtained with a relative accuracy of one part in 10^{-7}. The clock designer should consider the following:

- Minimum length of operation without recharging should be 2 days in case the nightly recharging is forgotten or the receiver crew has to stay overnight away from the basecamp.
- Relative tuning output of the crystals should be provided at a frequency high enough for the required accuracy (about 300 kHz or 100 kHz) but low enough to be monitored with simple field oscilloscopes.

- Clock rate is externally selectable.
- Various output signals should exist to allow flexible use of the clocks.
- The clocks should operate as master and slave.

A principal schematic of the synchronization clock is shown in figure 5.11. When selecting the components extreme care must be taken to guarantee reliable operation over a large temperature range.

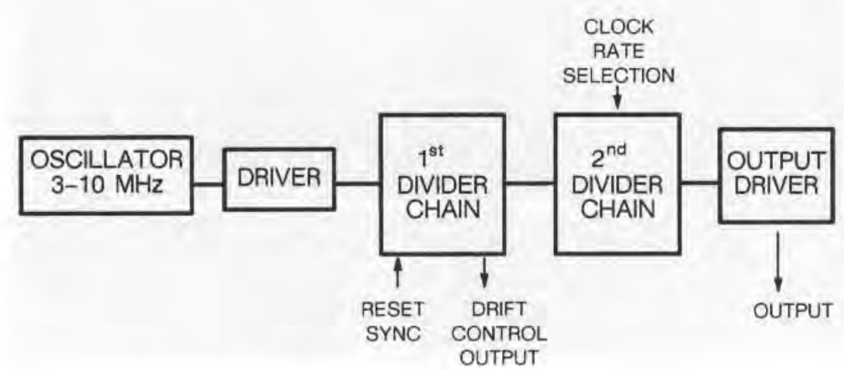

Fig. 5.11: Principal block diagram of a synchronization clock.

Figure 5.12 shows a picture of a synchronization clock as used with DEMS IV. The key switch for the power is essential to avoid accidental turn off and synchronization loss while operating. Below the dip switch, the code for the different clock rates is shown. Output is a 5 V TTL signal which is also provided in reversed form in case each trigger separately controls one of the two halves of switching assembly. Above the synchronization connector two LEDs are shown. Only one of them will only be lit when the two clocks to be compared are out of synchronization.

Figure 5.13 shows a diagram of the front panel of a more elaborate synchronization clock. This clock was developed after long field tests and accommodates most field requirements. Design criteria are:

- Low power consumption and operation for longer than 72 hours allowing the field crew to be away two or three days from the base camp.
- Input voltage for charger between 110 to 250 V, switching automatically.
- Charge status indicator to show the operator when he needs to go back to the basecamp.
- Clock rate selected as displayed on the switches to avoid errors due to false translation of switch setting tables.
- Two different high frequency outputs (3kHz and 300 kHz) for coarse and fine relative adjustment of the crystal drift.
- Pretrigger for safety interlocks at the transmitter and pretrigger for the acquisition systems. The pretrigger should be selectable in percent of the clock rate.

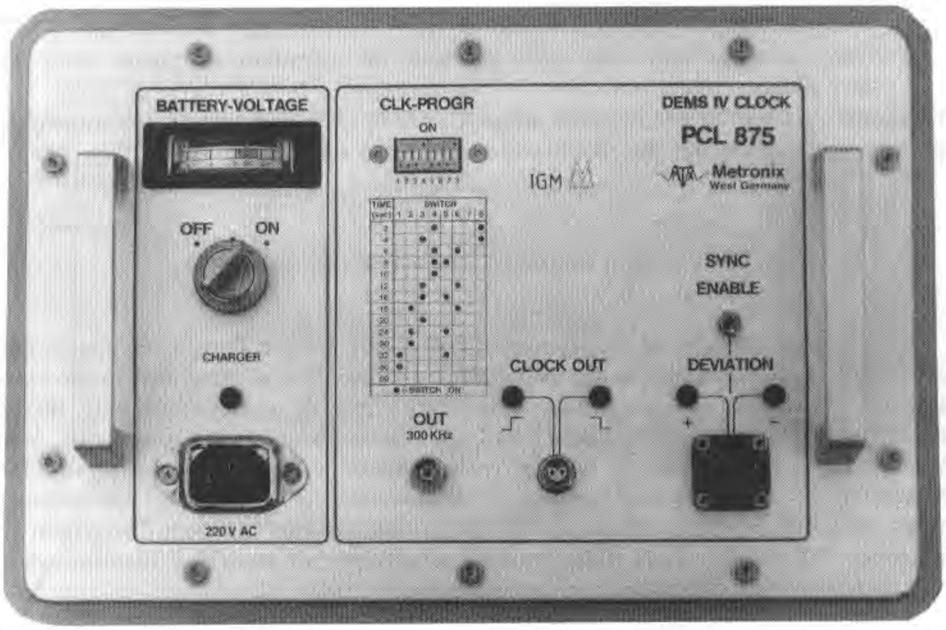

Fig. 5.12: Front plate of a simple synchronization clock.

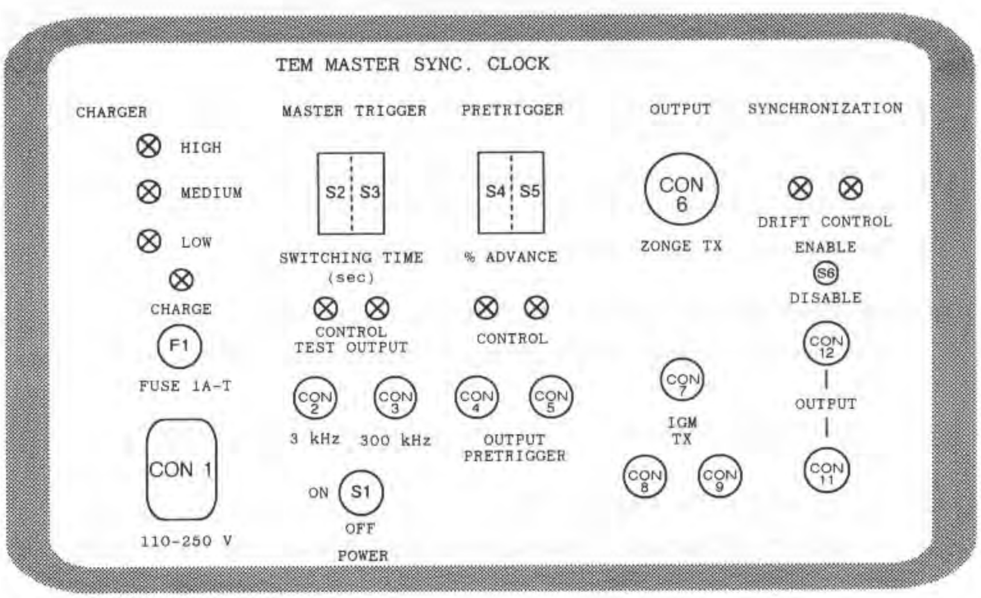

Fig 5.13: Front panel diagram of a multi-purpose synchronization clock.

- Multiple output for all standard transmitters for maximum hardware flexibility.
- Synchronization and clock drift indicator for operation as master clock and slave clock.

The standardization of the clock has allowed us to operate with almost any transmitter and thus significantly cut the mobilization and setup cost.

Advantages of using Multichannel Systems

One of the drawbacks of electromagnetic methods are the prevalence sparse data sets and the lack of sophistication in field instruments. This is attributed to the small number of researchers working in the field, the complexity of electromagnetic theory, and the limited resolution one can obtain with electromagnetic measurements. With the advancement of technology and increasing experience, one can obtain more data redundancy and denser spatial sampling. This increases the resolution of EM measurements. In this section, the advantages of using a multichannel transient EM system are discussed. The examples and considerations shown use data from case histories where the LOTEM technique has been successfully applied.

Figure 5.14 shows a typical field setup for a multichannel transient EM system. Many digital remote units (RU) are connected via a digital telemetry line. Each RU acquires two channels simultaneously. The reasons to use two channels in one unit are:

- One magnetic field component and one electric component can be acquired at the same site allowing joint inversion.
- At the adjacent stations, the same electric field plus an orthogonal field is acquired. The two electric fields allow mapping of the complete electric field.
- At the next station along the spread the orthogonal electric field and the magnetic field is acquired allowing a continuation of the signal laterally.
- The hardware is standardized to that of seismic systems.

This setup allows the application of the following interpretation tools:

- Joint inversion to give a more unbiased representation of the subsurface resistivity.
- Dipole - dipole mapping to directly recognize regional three-dimensional structure.
- Fast imaging of the magnetic fields.
- Recognition and removal of static shift using continuous electric field measurement in combination with magnetic fields.
- Noise compensation techniques for time synchronous measurement.

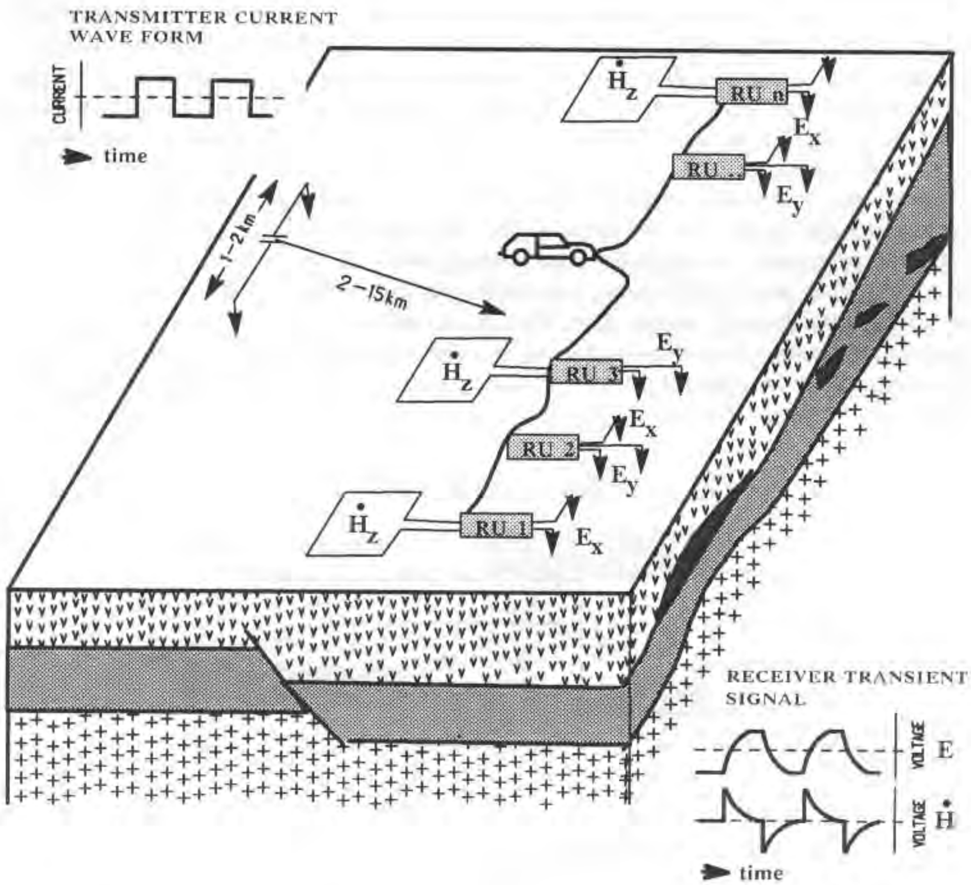

Fig. 5.14: Typical field layout for a multichannel transient EM system.

To fully appreciate the advantages of a multichannel system, one needs to consider the drawbacks of present single site systems. Among them are:

- Dynamic range limitation.
- Inaccuracies due to slight signal drifts.
- Limitations in noise and bandwidth.
- Signal-to-noise limitations associated with single channel processing.
- Wide spacing between stations due to a trade off between productivity and lateral resolution.
- Maintenance and cost per site.

The *dynamic range* problem can be illustrated using a deep crustal application where a conductor is to be found below a 20 km thick highly resistive layer. Figure 5.15 shows the voltage measured by an induction loop receiver for this geology. The transient response is calculated for different offsets of 5, 10, 20, 30 and 40 km. Note that the conductor response appears for all offsets at approximately the same time window and the amplitude lies between 0.1 and 1 μV. Deviation in the voltage response are to be resolved at this level. The DEMS IV system uses a 16-bit analog-to-digital converter with 3 bits of gain ranging. This means for a 10 V maximum voltage, it can resolve 1 part in 524 288 or 20 μV. The total dynamic range is in principle 6 decades. From our experience with the system, one can safely expect 4 decades of dynamic range. Incorporating the amplifier and preamplifier into the system (which use gains up to 500 000) one can give as safe resolution threshold figure 1 μV with a maximum of 3.5 decades dynamic range. This limit is marked in figure 5.15 by the arrow. The conductor response is still below the the resolution threshold, thus, in order to resolve the conductor from this figure, one needs to attenuate the signal at early times and amplify it above the threshold. From the figure, it can also be seen that there is an

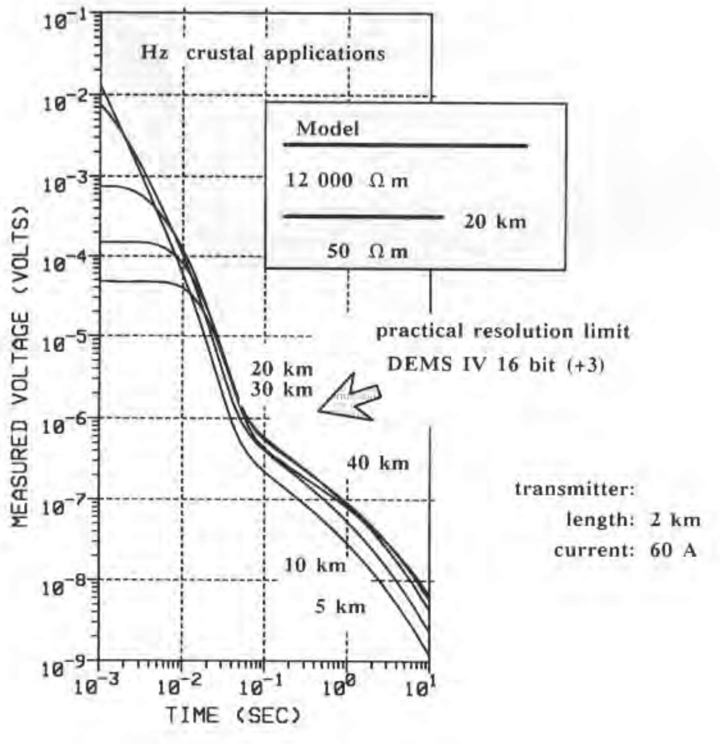

Fig. 5.15 Voltages responses for different offsets for deep crustal application.

optimum offset (20 to 30 km) at which the response from the conductor is strongest. All of this requires in the necessity for very careful survey design and survey fine tuning in the field.

When integrating state-of-the art seismic technology using an instantaneous floating (IFP) point amplifier, one can simplify the survey design and still resolve the conductor. The multichannel system we use, the TEAMEX system, has 90 dB (15 bit equivalent) IFP amplifier, 42 db (7 bit) initial gain and a 12 bit A/D converter. This yields a total dynamic range of 34 bits (or 1 part in 10^{10}) or without the initial gain amplifier 27 bits (or 1 part in 10^{8}). Using a 5 V full scale value the TEAMEX can in principal resolve $5.8 \cdot 10^{-11}$ V for the total range and $7 \cdot 10^{-9}$ V without the initial gain. This is far beyond of what is required to resolve the conductor in figure 5.15 at *any* given offset, The remaining limitations are now the noise and no longer the hardware dynamic range. The most important advantage in this is that one can now reduce the offset between transmitter and receiver and thus obtain a lot better lateral resolution. Also, the noise can be measured with accuracy and thus better removed by digital filters.

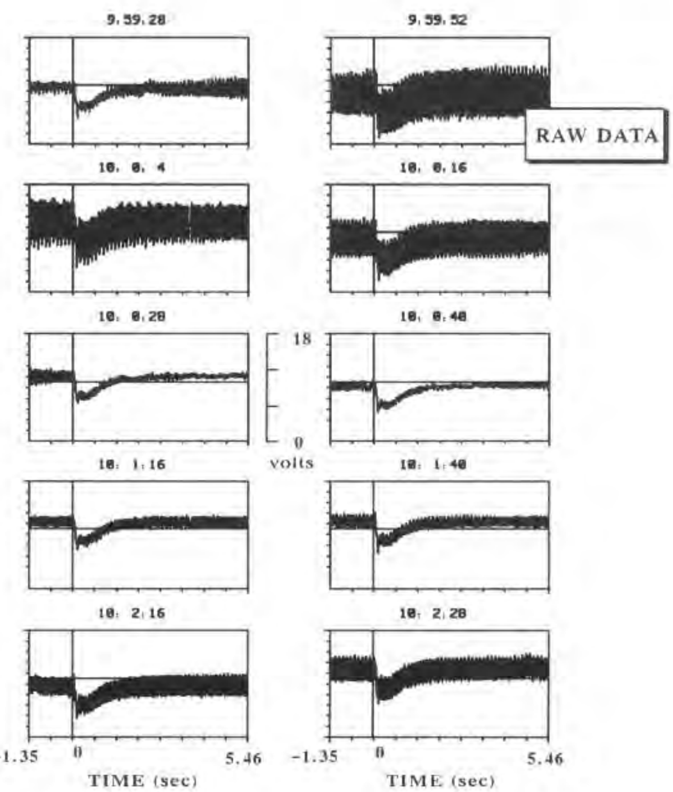

Fig. 5.16: Ten single magnetic field measurements (time derivatives) recorded consecutively.

When recording transients the signal is sensitive to *DC–drifts* because the TEM amplifiers usually do not contain low cut filters. The drift may be of external origin or from the connections of the instruments (thermal drift etc.). Figure 5.16 shows 10 consecutive single records for the induced voltage response of the magnetic field. Above the individual frames, the time of the recording is displayed. Within several tens of seconds the data drifts considerably. Because of this drift it is essential that an accurate reference level is calculated before selectively stacking the data.

For the illustration of *drift–induced* offset on the interpretation the following experiment was done. The data set of all records acquired at the same site (as in figure 5.16) was first digitally processed and the DC–level for each record removed and then

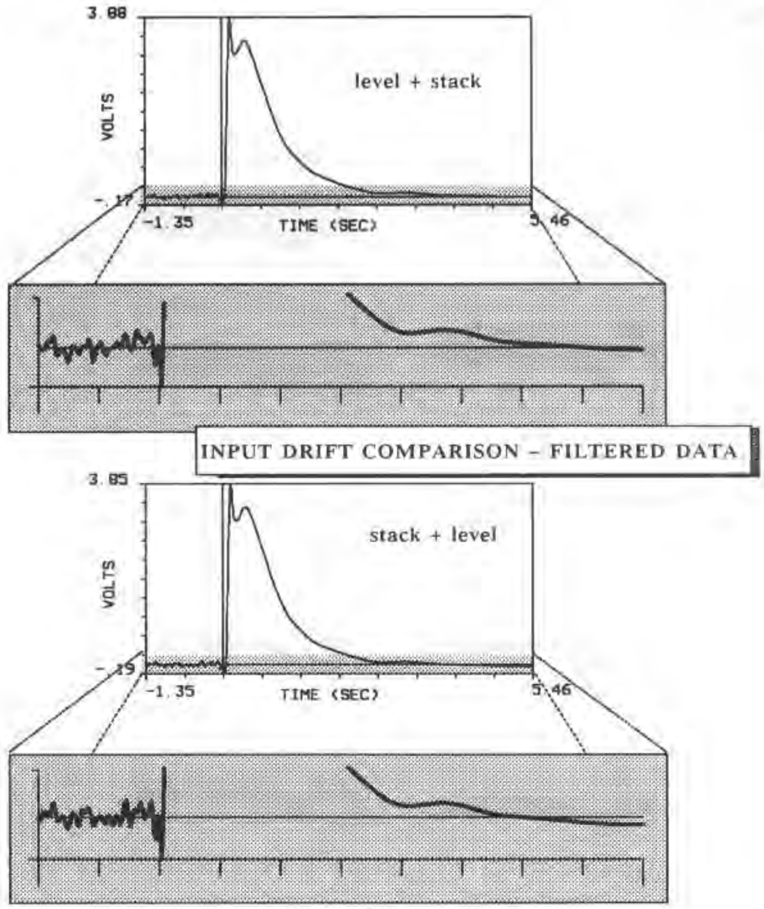

Fig. 5.17: Example of the experiment for comparison of the DC–level effect before and after stack.

selectively stacked. The same data were also selectively stacked and the DC–level removed. The result is shown in figure 5.17. The top graph in the figure displays the data which was DC–leveled prestack and then selectively stacked and the bottom the same data which was leveled poststack. Both data sets were filtered poststack with the same filter to visualize the difference in processing. Below both curves, a zoomed window of the shaded area is shown. The top curve stays about 0.8 seconds longer above the reference zero line. Since only positive transient data can be used for interpretation, the top has 0.8 seconds more usable data. The result from this experiment is that very accurate DC–level or reference level in the data is required before stacking.

To visualize the importance of an accurate DC–level even further, the synthetic apparent resistivity curves for a realistic earth model are calculated and displayed in figure 5.18. Superimposed on the theoretical curve are the early and late time resistivity curves from the same data after the DC–level has been perturbed by 1% or 1 ‰. Note that perturbed curves flair up from about 2 seconds for the ± 1% DC–level perturbation and from about 3 seconds for the 1 ‰ DC–level change. In both cases false high resistive or conductive layers would result during interpretation.

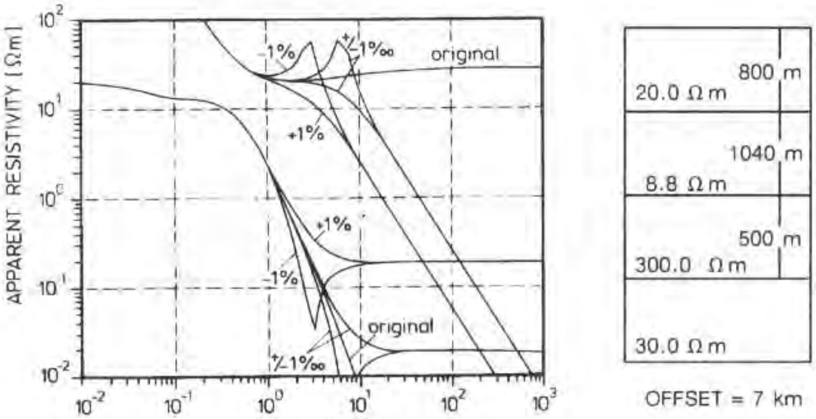

Fig.5.18: Effect of slight inaccuracies in the determination of the DC–level on the apparent resistivity curves. The notches in the perturbed curves represent the times when the signals become negative (negative values are displayed as absolute values).

The TEAMEX system significantly improves the reference level by integrating a microprocessor controlled leveling procedure which is done just before the transmitter clock switches using a pretrigger (either software or hardware). A block diagram of the procedure is shown in figure 5.19. The bias is calculated after analog–to–digital conversion. From the microprocessor, the bias voltage is fed back into the input after digital–to–analog conversion. The difficult part in this concept is to time exactly when the bias control is being done, because no bias control must be done while the recording is going on or any useful signal is present. In addition to the bias control just before the recording of a transient, the individual operational amplifiers are also drift controlled on operators request. This significantly improved the problems with the DC drift in the signal and also reduces the processing time.

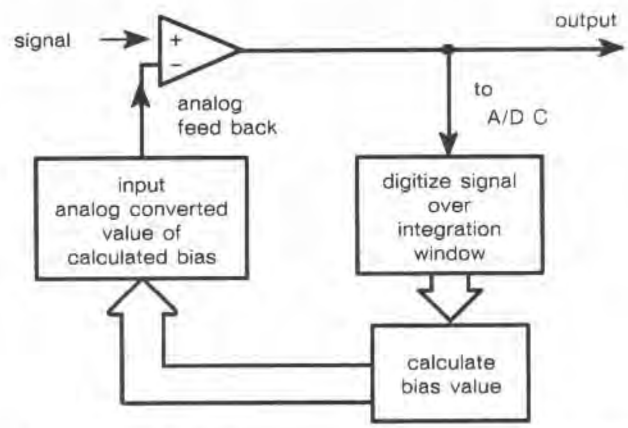

Fig.5.19: Principal block diagram of the microprocessor controller DC-bias circuit of the TEAMEX system.

To illustrate the *noise* and *bandwidth* limitations with single site systems, the signal path is considered in detail. Systems such as DEMS IV usually transmits the signal in analog form from the preamplifier to the amplifier. Apart from the noise interference at the sensor, unwanted noise distorts the signal at all stages as long as it is still in analog form. To avoid the influence of this noise, analog notch filters are commonly being used in order to obtain any signal at all. Figure 5.20 illustrates the different

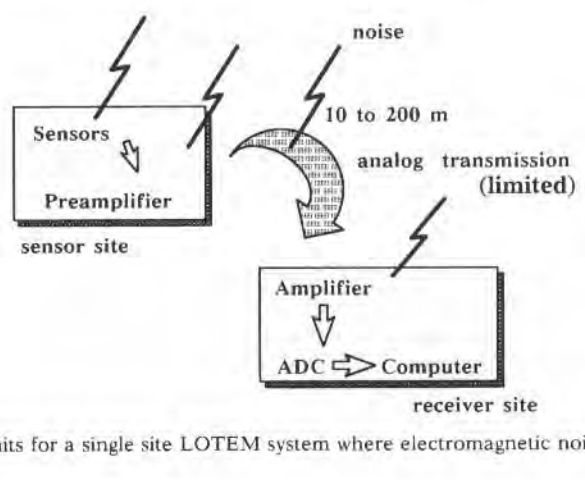

Fig.5.20: System units for a single site LOTEM system where electromagnetic noise can influence the signal.

building blocks where the noise gets into the system. Although extreme care is taken during data acquisition and processing even further improves the signal-to-noise ratio, the noise is not always satisfactorily removed. In these cases the interpreter has to accept noise in the final results. This noise exhibits itself in the large error bars of the inversion results and the scattering of the inversion models between adjacent stations.

An example for an interpretation where the noise can still be seen in the final results is shown in figure 5.21. Here, LOTEM measurements were done for crustal applications in an extremely noisy area in Germany. Even 68% confidence levels for the error calculation yields large error bars. The stations 26 and 27 in the middle of the profile in figure 5.21 show an additional layer at shallower depth with the other stations do not show this layer. This does not mean that this layer is not there. It was simply filtered out of the signal to obtain any useful information at these sites. Thus, the data for this profile is restricted in bandwidth due to the strong noise. The information on the shallow part of the section was outside the remaining bandwidth of the signal.

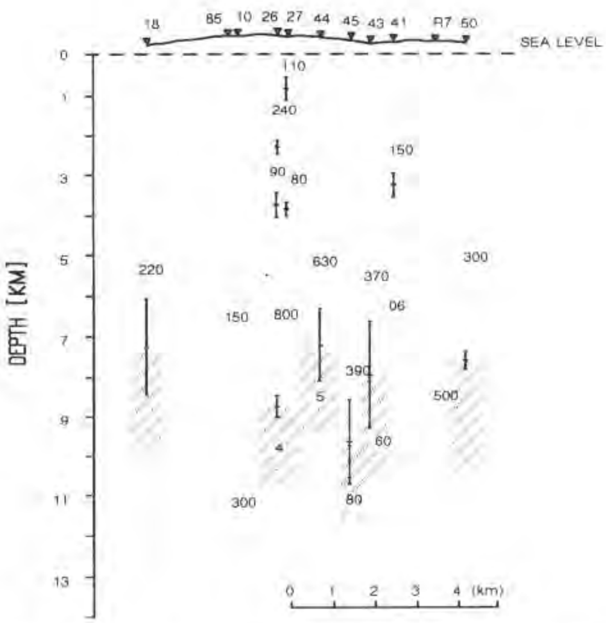

Fig.5.21: Example of an interpreted resistivity depth section where the noise in the signal can still be seen in the scattering of the depth to the conductor (shaded) (after Strack et al, 1990).

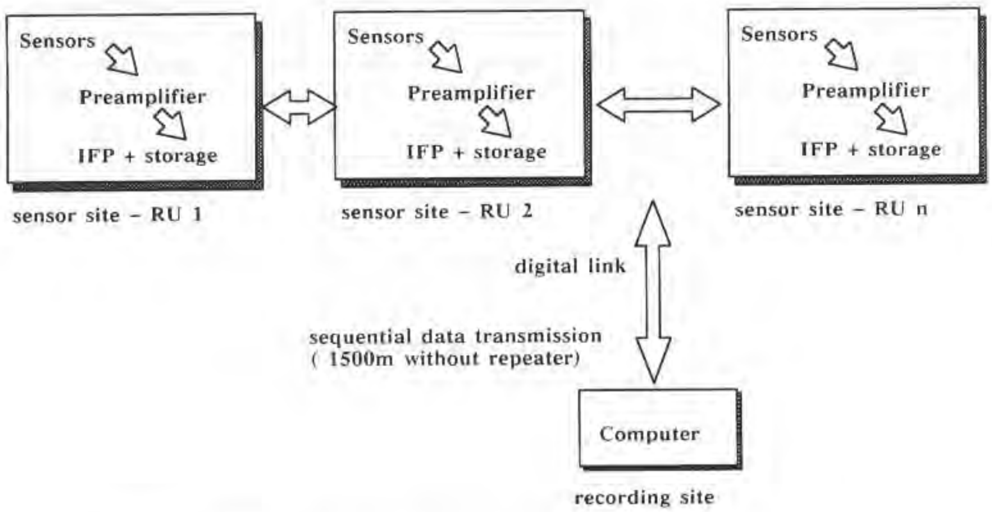

Fig. 5.22: Block diagram of the TEAMEX multichannel system.

The limitation due to *bandwidth* and *noise* can be reduced by minimizing the number of analog filters used in the system, by shortening of the analog transmission circuitry, and by digitizing directly at the receiver. The only remaining noise is entering into the system at the sensors. After the remote unit (RU), the data is in the digital form (see figure 5.22) and is thus no longer influenced by external noise.

To illustrate the effect of the different filters, comparative measurements were taken at a test site with known geology (compare chapter 7). The results of this comparison are shown in figure 5.23. The resistivity transforms derived from the TEAMEX, which are the logarithmic transforms of the data without system response deconvolution, data are shown as squares. Superimposed on this are the synthetic curves of the true earth model convolved with the system response of the TEAMEX system (bottom) and the DEMS IV system (top). Note that the curve with the DEMS IV system response starts at a later time than the corresponding TEAMEX curve. This means that the TEAMEX data has a shorter system response and thus a larger bandwidth.

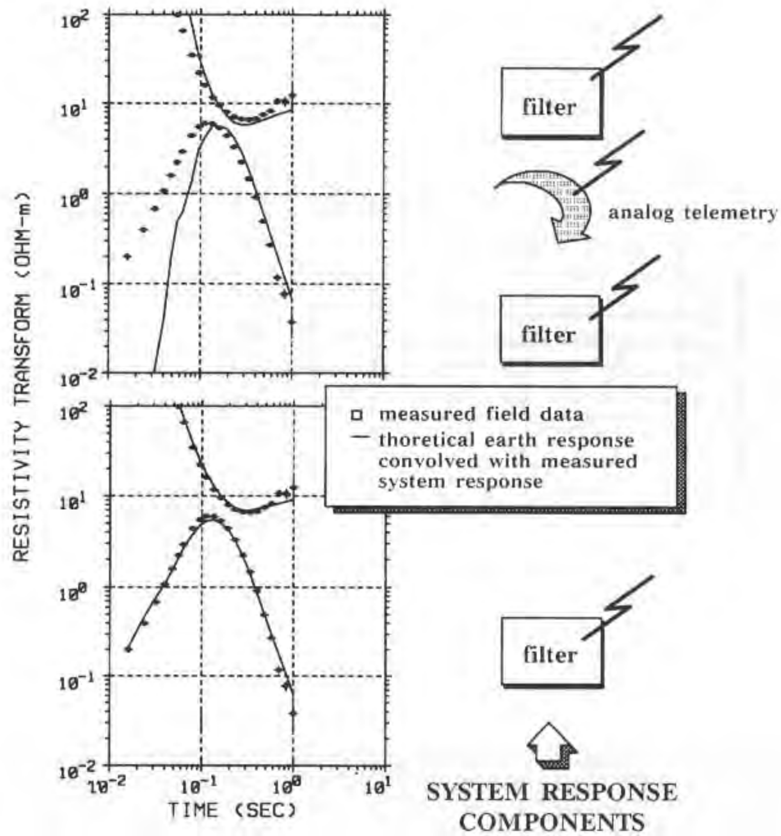

Fig. 5.23: Comparison of the different system responses of the DEMS IV and the TEAMEX systems. The graphs show the TEAMEX data in comparison with the real earth model convolved with the TEAMEX system response (bottom) and the DEMS IV system response (top).

Figure 5.24 shows the comparison of the interpretation of both data sets. The top displays DEMS IV data and the bottom the TEAMEX data. On the right are the respective Occam inversion results shown superimposed on the true earth model derived from well logs. The overlapping depth investigation range is shown cross-hatched. The match of the two interpretations is striking. Apart from the good fit the TEAMEX shows an additional layer at shallower depth. This layer might be attributed to the increased bandwidth of the TEAMEX system.

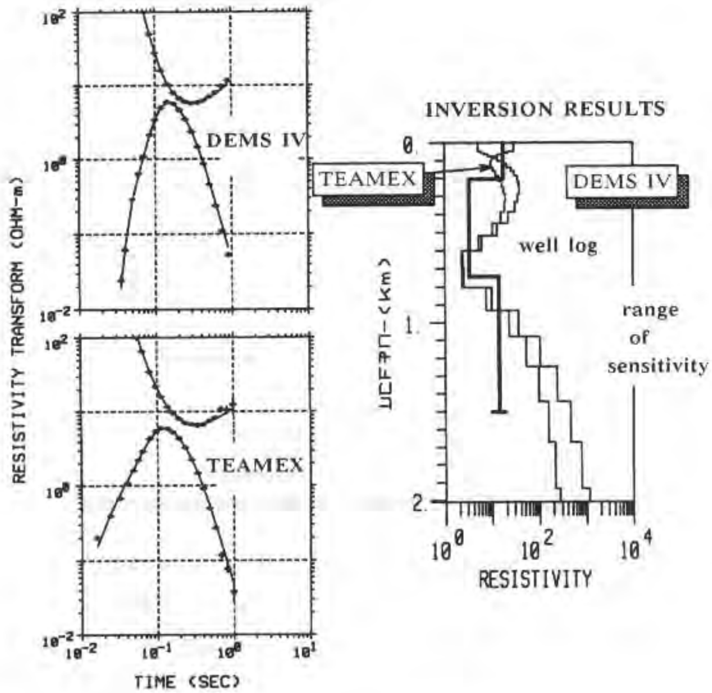

Fig.5.24: Comparison of the DEMS IV and TEAMEX measurements at the same site. On the left are the resistivity transforms and on the right the Occam inversion models.

When acquiring data with a single site system, signal-to-noise improvements can only be made using the data from this site. When using time synchronous multichannel measurements complete new noise cancellation techniques can be developed. Figure 5.25 (left) shows an example of a data set which was processed using only the

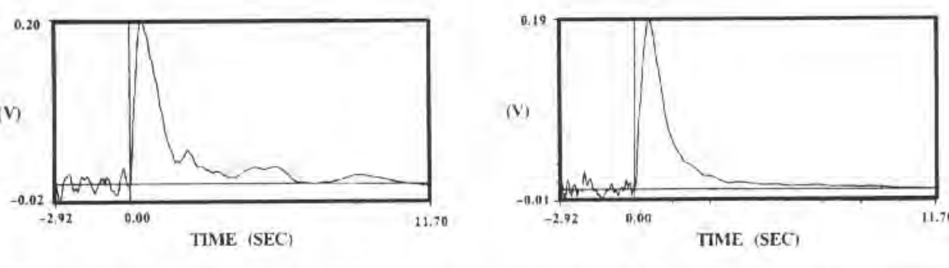

Fig. 5.25: Comparison of a single site processed data set (left) with the same data after noise processing (right) using multiple receivers.

data at this site. the right side of this figure shows the same data after the remaining noise in it was canceled using the local noise compensation technique which is based on time synchronous measurements and time dependent noise definition. The local noise compensation technique is described in more detail below. This type of noise compensation is only feasible with multichannel system because accurate synchronous timing of all receivers is required.

Even a careful designed survey, requires a trade off between productivity and lateral resolution. When interpreting the data, one often realizes that more data had to be taken at closer spacings. Following is an example where densely spaced data were acquired. Figure A.7.1 (bottom) (appendix 7) shows the resistivity depth section (color contours) derived from Occam inversions of measurements along a profile. The top frame displays the complete data set whereas the bottom displays only every third site. In the top section one can clearly see on the left side an anomalous zone which is either caused by real geology or a three-dimensional effect. Seeing this, the interpreter must immediately pay more attention to the details in this part of the profile. At the bottom of the figure this particular structure is significantly smoothed and from it one would probably conclude that one-dimensional inversion is sufficient for it. This structure would have been simply overlooked with too wide station spacing.

Last but not least, the *maintenance* and *cost* per site govern the applicability and success of a survey in many cases. Using many small identical remote units (RU) reduces the amount of spares which have to be carried, since the RUs are essentially non-user repairable and the failure of one means that only one trace less is being recorded. A photograph of a TEAMEX remote unit is shown in figure 5.26.

Fig.5.26: Photograph of a remote unit of the TEAMEX multichannel system.

Mobile Processing Systems

When acquiring field data continuous quality control is essential for optimum survey results. The quality control can be done in two different ways:

- Quality control directly at the site.
- Quality control in a mobile processing center at the *base camp*.

Quality control at the basecamp is the most reasonable option, because carrying out this task at the receiver site would result in lower production. For the mobile processing center one can either use PCs or workstations. Because of the tremendous amount of data and the need for batch processing and multitasking, the workstation option is favorable because it allows the interpreter the simultaneous control of all the processes. The advantage of using a workstation-based mobile processing center lies clearly in the ease of field operations. All data are maintained and handled by one system and additional data transfer and bookkeeping greatly reduced. Figure 5.27 shows the data processing and interpretation system as used by the University of Cologne. The units of the mobile processing system are marked by a bold border. The field system can easily be updated to a full mainframe system allowing communication with different computer systems.

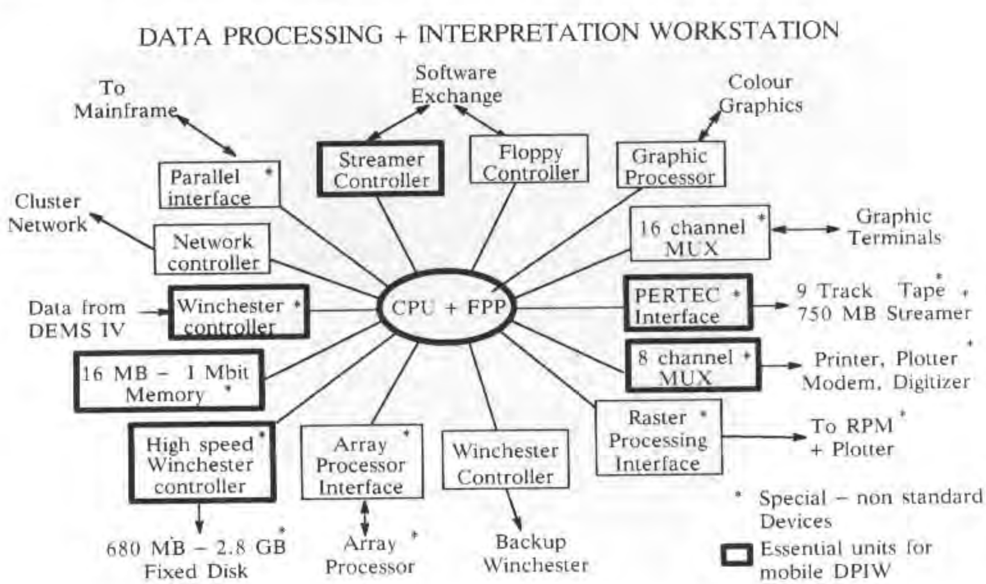

Fig. 5.27: Block diagram of the principal building blocks of the LOTEM data processing and interpretation workstation.

For very remote operations where transport and spare availability are important, the PC version may be preferable because PCs are more widely distributed than workstations.

FIELD PROCEDURES

Apart from the continuous bookkeeping during the data processing stage, significant care must be taken when carrying out the field measurements. In particular careful transmitter preparation can save significant time. Very meticulous bookkeeping of the synchronization and clock drifts can be vital for the survey and later interpretation. Complete control over the above may eliminate some of the questions when measuring the system response.

Transmitter Electrode Preparation

The data quality in LOTEM surveys can be improved by injecting the largest possible transmitter current into the ground. In dry areas or in areas with a resistive surface layer, the only way to achieve this is careful preparation of the electrode sites.

An electrode comprises several buried iron sheets which are all connected to the end of the transmitter cable as shown in figure 5.28. The individual sheets are separated by a distance **a**. If this distance is chosen too small, then the electric current density in the ground between the sheets is too high: the currents of an individual sheet would have little chance to spread out before they are hindered by the currents

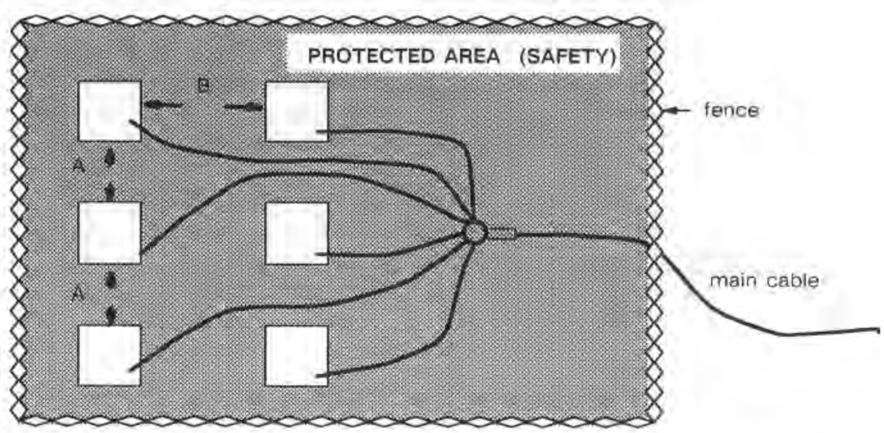

Fig. 5.28: Arrangement of six individual electrode pits at one end of the main cable. A fence is required to protect bystanders.

from the neighbouring sheet. In sedimentary environment, experience shows that the sheets should be separated by at least 5 m. Also, sometimes only 3 or 4 sheets suffice in order to achieve a small contact resistance and hence a high current. In an area with only a few meters of sediments overlying resistive units such as volcanics, sheet separations of 50 m may be required.

For connecting the sheets to the cables, a hole is drilled into the sheets and then the wire lug at the end of the cable is screwed onto the sheet as is shown in figure 5.29. The connection must be prepared very carefully because it will not be accessible once you cover the pit with soil.

The preparation of the pits for the individual sheets is shown in figure 5.29. First, a hole of sufficient size is dug until wet ground (water table) is reached; in Germany this requires 1–2 m depth. The bottom is then covered with a mixture of soil, salt, and lime: the salt increases the ground conductivity and the lime helps to keep the humidity which is important in dry areas. The use of bentonite is also possible, but bentonite tends to be more expensive than salt and lime. The iron sheet with the short piece of cable connected to it is then placed horizontally into the hole and covered with the same mixture of soil, salt and lime. When environmental concerns are important, one can use potassium or a mixture of potassium and salt. Next, the hole is watered and covered with the soil. For each hole a maximum about 50 kg of salt and 50 kg of lime is required, depending on the local conditions. For emergencies you can use a mixture of salt and laundry detergent, but for environmental reasons this is not advisable.

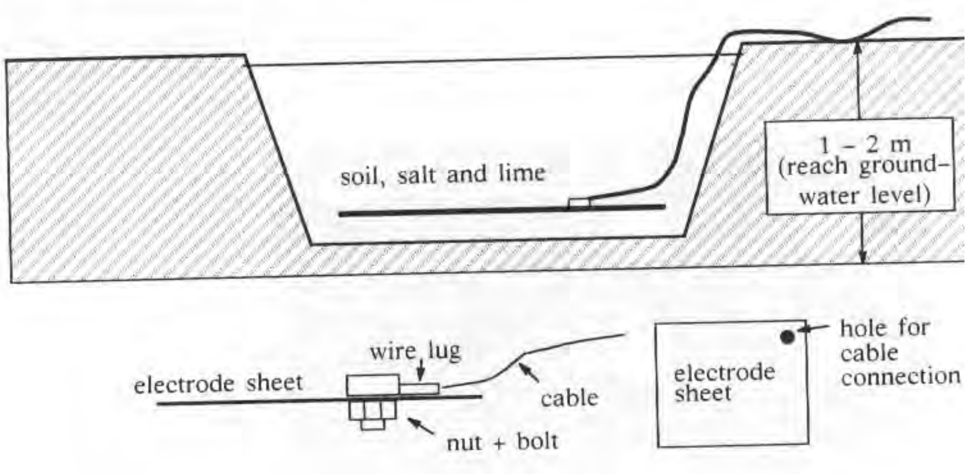

Fig. 5.29: Preparation of transmitter electrodes. Top: preparation of electrode pit. Bottom: conne tion to main cable.

The electrode sites should be prepared one day before the start of operations. Du ing operations it is extremely important to secure the area of the electrodes with f... and with a watch person because touching any part of the assembly cou from the neighbouring sheet. In sedimentary environment, experience shows that the sheets should be separated by at least 5 m. Also, sometimes only 3 or 4 sheets suffice in order to achieve a small contact resistance and hence a high current. In an area with only a few meters of sediments overlying resistive units such as volcanics, sheet separations of 50 m may be required.

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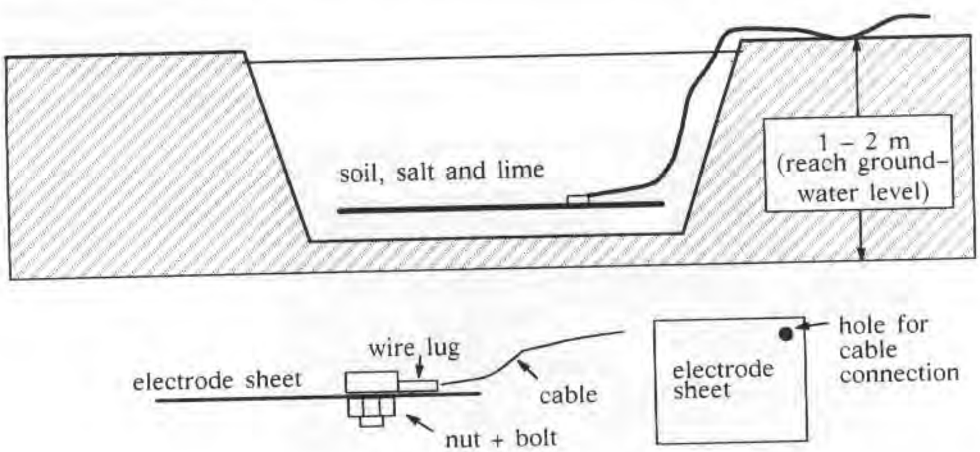

Fig. 5.29: Preparation of transmitter electrodes. Top: preparation of electrode pit. Bottom: connection to main cable.

The electrode sites should be prepared one day before the start of operations. During operations it is extremely important to secure the area of the electrodes with a fence and with a watch person, because touching any part of the assembly could possibly injure a person. For the same reason, it is also important to insulate all open metal parts with electric tape – for protection of the crew as well as safeguard against other people who could become injured by touching any non-insulated parts.

For low current (less than 30 A) operations, you can also use steel mesh as electrode material when you have the option to increase the output voltage on your transmitter. Significantly less electrode preparation is required when you use different output voltages of the transmitter.

Initial Transmitter Check Out

It has been our experience that it is possible to achieve very high currents with many different generators. In some instances these currents were so high that the switchbox suffered damage. Thus, we strongly recommend that you check out the transmitter, when you connect it for the first time.

This is done by connecting a 12 V battery to the transmitter instead of the switchbox and generator. Make sure the battery is fully charged. You then measure voltage and current as shown in figure 5.30, in order to calculate the earth resistance.

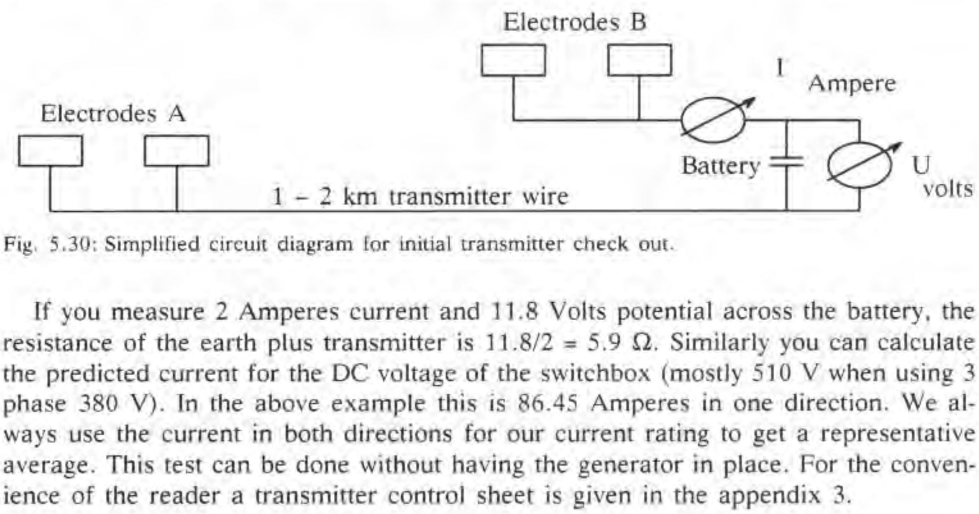

Fig. 5.30: Simplified circuit diagram for initial transmitter check out.

If you measure 2 Amperes current and 11.8 Volts potential across the battery, the resistance of the earth plus transmitter is $11.8/2 = 5.9\ \Omega$. Similarly you can calculate the predicted current for the DC voltage of the switchbox (mostly 510 V when using 3 phase 380 V). In the above example this is 86.45 Amperes in one direction. We always use the current in both directions for our current rating to get a representative average. This test can be done without having the generator in place. For the convenience of the reader a transmitter control sheet is given in the appendix 3.

Routine Daily Synchronization Check

Although clock synchronization seems to be a simple matter, extreme care is required because unrecognized clock drift can cause significant problems in later interpretation. Shifting of the data by even one sample point can change the data fit and matching of adjacent stations along a profile. Also, when deconvolving the system response improper synchronization can cause unpredictable results. The importance of proper synchronization is the main reason why the synchronization clocks have so many different outputs. To get a consistent record of the drift, the clock synchronization must be recorded in the morning and the drift at night. When using a clock for the first time during a survey it may also be advisable to record the drift of the clock just before synchronizing it. This way one can observe the aging of the crystal oscillator and retune the clocks before failures occur. A drift between two clocks in the range of 1 to 2 ms over a whole day is reasonable.

When recording the clock drift, one must make sure that the same trigger source is used for the measurement in the morning and also in the evening. Figure 5.31 is a block diagram showing how the clocks are connected to the acquisition system. The recording of the trigger signal with the remote unit of the same clock allows you to determine the delay between the time when the clock triggers and when the remote unit receives the trigger. This delay is caused by software and digital connections. The recorded signal is then used as reference to the signal from the second clock which allows you to determine the drift. When storing the records make sure you use a logical name assignment for the file and data such that you can find the records later for statistics. An example for a clock drift record sheet is given in appendix 3.

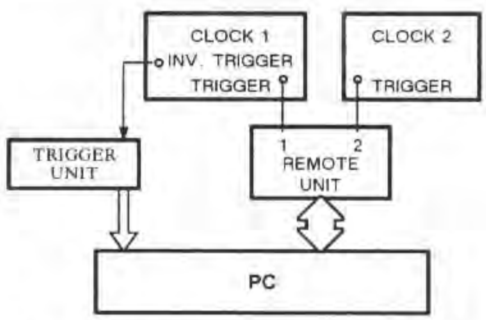

Fig.5.31: Block diagram of the daily synchronization control setup.

Measuring the System Response

One of the important tasks during a field survey is the careful record keeping of which analog filters are used at each station. The system response must be measured for each of these settings in order to remove the distortion due to the field system itself. The removal of the system response is done by deconvolution and was described earlier. In general, there are two different procedures which allow to obtain a careful estimate of the effect of the recording system.

The first procedure can be done in the laboratory and is sufficiently accurate, if the transients are long enough (i.e. longer than 1 second) and the ramp time of the transmitter is sufficiently short. Another alternative to this procedure can be done in the field using the transmitter switching unit (switchbox) to put a calibration signal into the analog electronics. The output of this first setup is equivalent to the current output in the field under the assumption that the switching characteristics do not vary much under load (which we found to be true for most switchboxes). The two switching units which are responsible for the current reversing are connected to a clean direct current power supply (a battery) in such a fashion that they simulate the output current wave form. A sketch of the system component setup is shown in figure 5.32. The output from the calibration gear is fed into the preamplifier and from there via the amplifier

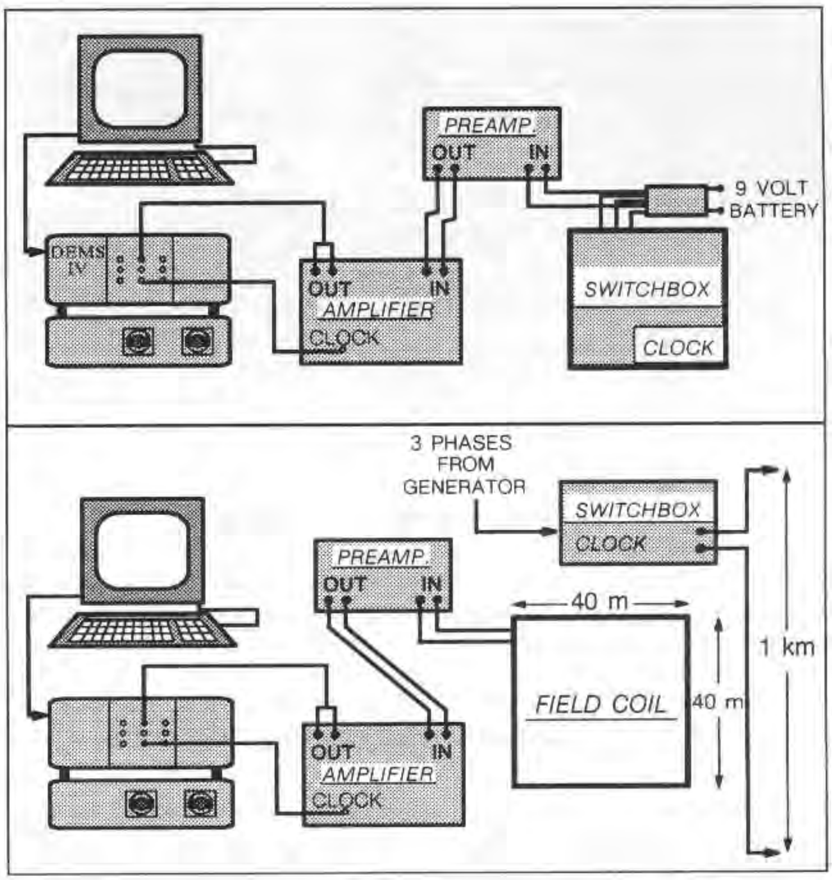

Fig. 5.32: System setup of the LOTEM equipment to record the system response. The top shows the setup using only the switchbox which is done in the laboratory and the bottom shows the setup including the entire system.

directly into the digital data acquisition system. The step output is being recorded in the same fashion as a transient, stacked and stored onto disk. Later, this output is differentiated, filtered, and windowed for deconvolution of or convolution with the system response.

The second procedure is similar to the first, except that now the entire system including the transmitter switching time (ramp time) including the electrode plants is taken into account. A system setup is displayed in figure 5.32 (bottom). The receiver in the field is placed directly next to the transmitter allowing you to record solely the system response of the transmitter. We recommend trying both methods in the field, and selecting the more stable method for each particular survey. It has also been our experience that for current controlled transmitters and short (less than one second) the second procedure is more reliable.

Figure 5.33 shows a comparison of two system responses from two different receiver systems recorded in the field. Both system responses were recorded at different times from the same transmitter. Their match is very good which means that the transmitter system and setup are stable. It also shows that the two systems have the same filter characteristics.

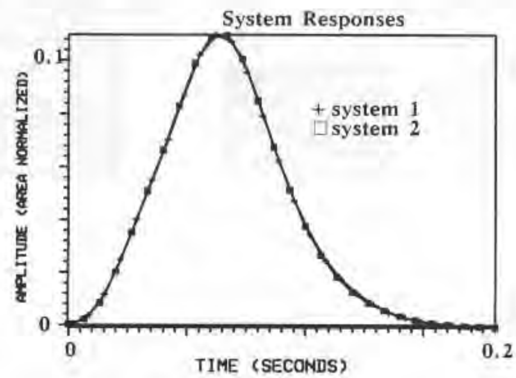

Fig.5.33: Two system responses for two different receiver systems measured in the field using the entire transmitter and receiver system.

General Considerations

In this section general guidelines are discussed to make a field survey productive and successful. Although some of them might seem trivial, they can sometimes be crucial for the success or failure of a survey. Emphasis is given to safety and smooth logistics. On the transmitter site extreme care is required because the high current (several hundred Amperes) and the high voltages (500–800 V) can easily injure a person. Apart from the safety features, one should also have additional staff to watch the transmitter wire and electrodes. When laying out the cable in the morning nobody should be near the wire on the back of the truck because the wire can make loops which could hit a person or in the worst case pull him/her off the truck. For pickup of the wire cable, winding devices called spitters can be very helpful because they allow the wire to be picked up at 10–15 km/h speed. A picture of such a cable winding device (spitter) is shown in figure 5.34. Using a spitter rather than a cable reel avoids the cutting and splicing of the heavy transmitter wire which takes time and creates possible error sources.

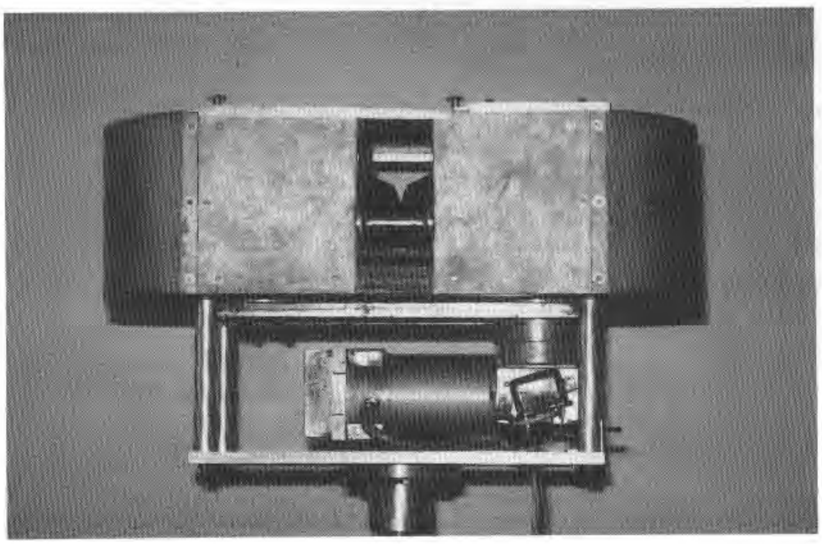

Fig.5.34: Cable winder ("spitter") which permits the pick-up the 25 mm^2 transmitter cable (1–5km) in ten minutes.

The accurate survey of the receiver and the transmitter coordinates is very important. If possible, this should be done before the actual measurement time. In general, unless the problem on hand requires otherwise, an accuracy of ± 10 m is sufficient. Greater accuracy is needed for the directions of the electric fields. The electric field dipoles should be parallel or perpendicular to the transmitter within 1^0 . Larger deviations can cause errors in the electric field calculation of higher than 5%. Because of the possibility correcting the magnetic fields using the *calibration factor*, as described previously, the geometry of the magnetic field sensors is less critical.

For smooth operation it is recommended that for each survey a task list as described in table 5.1 should be made. This allows the field staff to concentrate on problem solving rather than remembering what they could forget. To avoid unnecessary down times constant radio communication between transmitter and receiver is highly recommended.

Table 5.1: Task list of the daily routine tasks of a LOTEM crew.

MORNING:

- ❍ Synchronize receiver and transmitter clocks
- ❍ Get receiver coordinates for the day and possible transmitter current
- ❍ Check receiver for completeness and charging status
- ❍ Fuel check, radio check, map check

EVENING:

- ❍ Transfer data,
- ❍ Check coordinates of receiver sites and transmitter currents
- ❍ Is the system response available?
- ❍ Measure clock drift
- ❍ Charge all batteries
- ❍ Do all bookkeeping including field log
- ❍ Data backups

SURVEY TECHNIQUES

Different survey techniques for single site and multichannel systems are sometimes required for the selection of the survey task. The objective of the different field layouts is always to get as much data as possible with the best resolution. Further, a different noise cancellation technique, the local noise compensation technique (LNC) will be discussed because one of the key tasks is the improvement of the signal-to-noise ratios. The latter can be obtained by either increasing the signal or reducing the noise. An increase in signal can be achieved by an increase of the transmitter current. However, a current increase by twofold increases the generator power and fuel consumption by a factor of four. The same results can be obtained by decreasing the noise by only a factor of two.

Single Site Field Procedures

For single site systems one distinguishes between continuous electric field measurements and continuous magnetic field measurements (see figure 5.35). For the latter one or more magnetic field components are being measured at every site, while for the continuous electric field measurements the magnetic field components are only being measured every other site. The decision which one of the two modes to use is based on the exploration target. If the target is very conductive in a moderately resistive sedimentary environment (average resistivity: 5–10 Ωm), the magnetic field components are sufficient for the target resolution. In this mode the electric fields should be measured every other station only to make sure that no obvious 3-D structure distorts the interpretation. Crosschecks of this are being done by using the electric fields for dipole-dipole mapping and the magnetic and electric field joint inversion. The results from this should give a clear indication about the complexity of the interpretation. When preliminary field results indicate that the subsurface can be sufficiently imaged with the magnetic fields, the distance between the electric field site can be increased. Under no circumstances should the distance between the magnetic fields be increased because this could result in the missing of a geologic feature as illustrated in figure A.7.1.

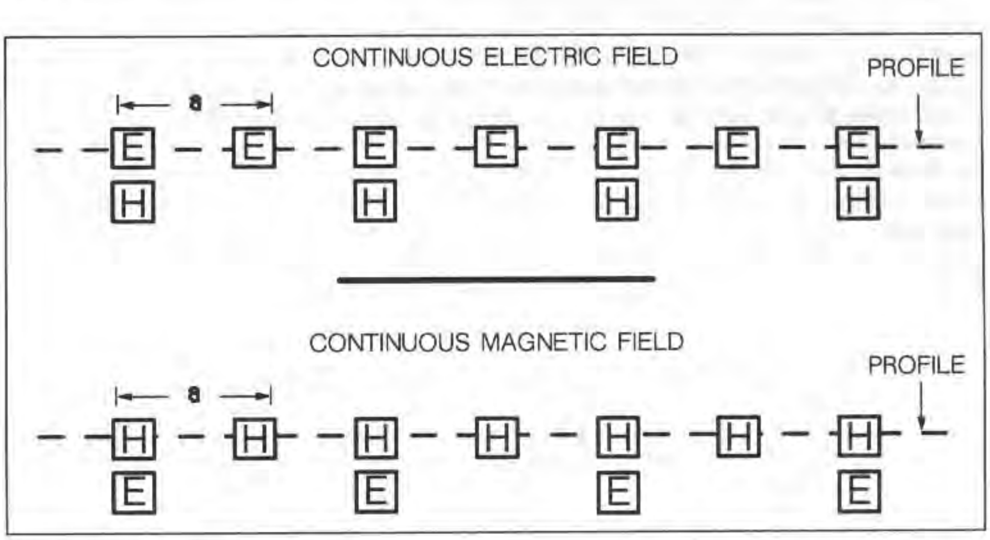

Fig.5.35: Receiver site for single site systems for continuous electric field and continuous magnetic field measurements.

The distance, **a**, between the sites is always a compromise between productivity and lateral resolution. We found for targets at a depth of 1 to 4 km, a distance between sites of 250 m to be the most reliable one. Larger distances often cause problems in the correlation of the results between adjacent stations and make the interpretation very lengthy and expensive.

When the target is more resistive, it is preferable to use the continuous electric field mode, because its electric field measurements are more sensitive to resistive structures. However, in this mode one must record the magnetic component at every other station to be able to correct for static shifts in the electric field.

Although novice operators always think differently, the production can be significantly increased by laying out the magnetic field receivers and electric field electrodes beforehand. The receiver operators should restrict themselves only to the recording and not handle the sensors themselves. A minimum production increase of 30% is not unusual when using this leapfrogging technique.

Multichannel Field Procedures

Using a multichannel system is very similar to carrying out a seismic survey. The maximum number of remote units is usually six given a 12 channel system. Figure 5.36 shows a split spread setup and a roll along layout for the multichannel system. For a small number of remote units the roll along technique provides higher productivity and also yields a higher number of vertical stacks at the overlap. When using more remote units (12 to several hundreds), the split spread configuration yields higher production. To reduce the passing of the cable crew along the spread (which causes noise) the moving of the spread should be arranged as shown in the figure. Practical, constraints often require the use of a modified or mixed version of the two layouts.

Both layouts discussed here are using one transmitter. When using multiple transmitters different modification of the layout can easily be done similar to seismic field procedures. For instance, you may use an inline–offset layout. In that case you should initially compare this type with the layouts described here to make sure you understand the lateral effects and the offset dependence of the signal for the survey area.

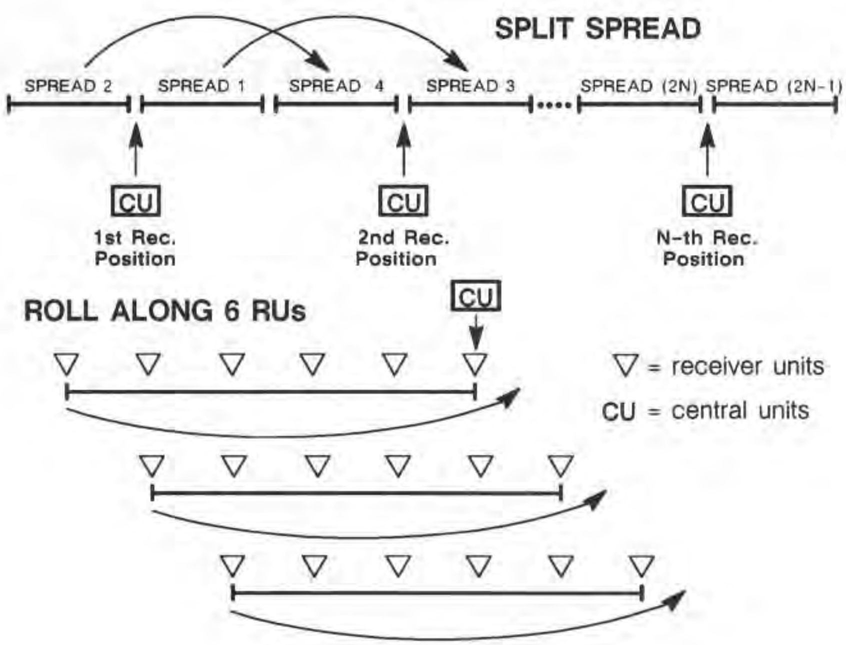

Fig.5.36: Multichannel layout for split spread and roll along configurations.

Local Noise Compensation Technique

One of the practical problems for all electromagnetic methods is the improvement in signal–to–noise (S/N) ratios, the objective being to achieve a higher data quality and to increase the depth of investigation. A way of improving the S/N ratios is to utilize artificial EM fields as done in frequency and transient EM (TEM) sounding methods (Nekut and Spies, 1989). Under the assumption that instrument noise of modern equipment is small and geologic noise is part of the information desired, the main problems for EM methods are broad–band artificial noise due to power lines, generators, railroad grids etc., natural noise such as spherics (caused by thunderstorm activity, etc.) and wind noise (Macnae et al, 1984). S/N ratios can be generally improved in three ways. Firstly, through survey design, with the appropriate choice of appropriate transmitter and receiver locations, of acquisition procedure (such as the number of single records acquired for stacking), and of the stacking technique (Strack et al, 1989). Secondly, in very noisy environments the noise can be reduced by analog filters implemented in the acquisition system and the signal can be increased by increasing the transmitter moment. Thirdly, after data acquisition the S/N ratio can be improved by digital data processing techniques.

Assume that we want to increase the S/N ratio by a factor of ten by either increasing signal strength or reducing the noise. A signal strength increase of ten requires the transmitter power or the acquisition time to be increased by a factor of 100. The same S/N improvement can be achieved by reducing the noise by a factor of 10 (see also Spies, 1988).

For controlled source EM methods, stacking is the standard noise reduction method. In very noisy areas extensive stacking is needed which requires long acquisition times. Analog filters generally cause problems due to their influence on the usable part of the signal spectrum. Thus, one must find new field procedures for very noisy environments to improve productivity and to increase the S/N ratio at the same time. In the magnetotelluric method (MT) the remote–reference technique is used to overcome the noise problem, provided that the noise in the MT array is uncorrelated with the noise in two additional components of the MT signals measured at a remote site (Gamble et al, 1979; Clarke et al, 1983).

Recently, for the in–loop transient electromagnetics (TEM) the *local noise prediction filtering* (LNPF) has been developed for noise reduction (Spies, 1988). LNPF is based on simultaneous measurements of three orthogonal magnetic field components at the same site and the calculation of a time domain filter which predicts the vertical noise component from the two horizontal components. This noise can be subtracted from the measured vertical component in the subsequent processing.

The *local noise compensation* (LNC) technique was developed specifically for the long–offset transient electromagnetic sounding (LOTEM). LNC differs from the LNPF technique in that a base station is used as reference site. Unlike LNC to the remote–

reference MT technique, where the noise must be uncorrelated, the LNC requires the noise to be correlated. Since the validity of this premise varies significantly with most noise sources, environments and geology, it must be tested on the beginning of the survey. The objective for the development of the LNC technique was to provide a noise cancellation technique for a multichannel TEM acquisition system with dense station spacing.

In very noisy areas a large number of single records must to be acquired to get sufficient data quality, especially, if the noise characterization is similar to the one of the signal. A low productivity results because of long recording time. Sometimes even with a high number of stacks the data quality is poor, as the noise characteristic is not strictly sporadic or periodic but a combination of both. When the noise is specific to the survey area, often no filters for the data set are available to the interpreter. Thus, the LNC technique was developed to reduce the number of poor data sets containing the above type of noise and to allow the application of LOTEM in very noisy environments, where it would be otherwise not possible.

The principle receiver setup is shown in figure 5.37. The transmitter is assumed to be several kilometers away. The base station is fixed and measurements are taken at this base station all day long. To take advantage of the correlated noise, measurements are made simultaneously at the various other mobile stations. These mobile measurements are much shorter in acquisition time, because fewer transients are recorded. During the subsequent signal processing the actual noise at the base station is obtained and thus – when the noise is spatially constant – also at the mobile stations. The noise from the base station at any particular time is then subtracted from the data, recorded at the mobile station at that particular time.

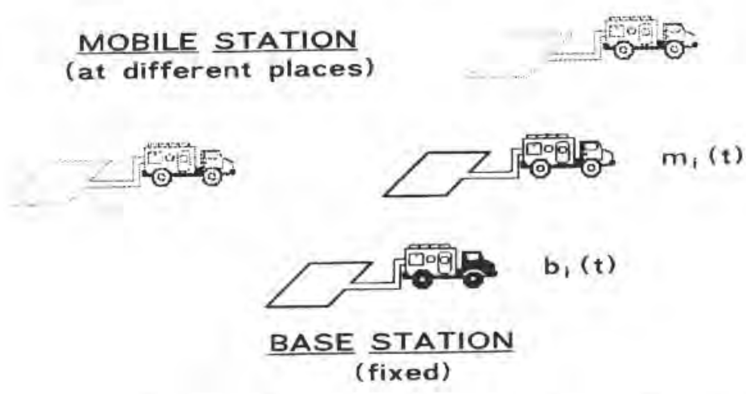

Fig. 5.37: Basic field setup for the LNC technique using two receivers (after Stephan, 1989).

Since, with controlled source EM methods the transmitter signal is present over the entire survey area, it is not possible to observe the noise at one receiver site while a signal is observed at another. In order to get only the noise at the base station, the following procedure has to be applied: initially, the stack of the base station data gives a very smooth stacked transient S, because a very large number of single signals b(t) exist as a result of the long acquisition time. This final stacked transient is termed 'base stack' and is essentially the local signal as shown in figure 5.38. Now, this accurate base stack is subsequently subtracted from each single record b(t) at the base station and the noise remains. An example for this noise is shown on the first row in figure 5.39. The left column in the figure shows an example of sporadic noise and the right side is an example of periodic noise. The two recordings are only 3 minutes apart demonstrating the time variability of the external noise.

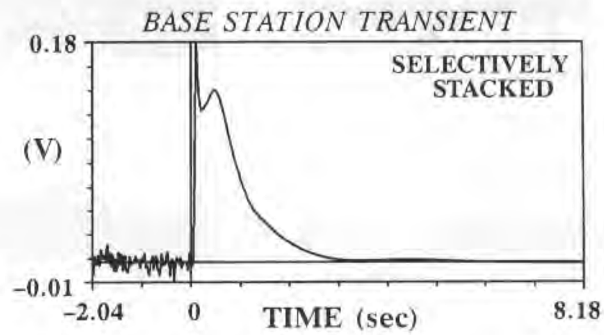

Fig. 5.38: Selectively stacked transient at the base station, which is termed 'base stack' (after Stephan and Strack, 1991).

$$n\ (t) = b\ (t) - S. \tag{5.1}$$

Once the noise n (t) at the base station is known, this noise can be subtracted from the single records m (t) of the mobile stations (the second row of figure 5.39) and a noise-compensated signal c (t) can be calculated by

$$c\ (t) = m\ (t) - n\ (t). \tag{5.2}$$

This noise-compensated signal is shown at the third row of figure 5.39. In both cases the noise can be successfully reduced.

Sometimes, under certain field conditions (i. e. different temperatures, vibrations, etc.), the synchronization clocks of the mobile and the base receiver systems drift apart a few milliseconds over the whole day. This time drift results in a phase shift of the periodic noise. In this case a simple point by point subtraction can increase the noise. To overcome these difficulties the clock drift is corrected by a time shift derived from the cross-correlation

$$CC\ (T) = \sum_i m_{i+1}\, n_i \tag{5.3}$$

as a function of the time displacement T between the mobile station signal and the noise of the base station. If the cross-correlation has its maximum for a certain displacement T', the noise in the two signals should be in phase. If now the noise of the base station is shifted by the displacement T', the clock drift is corrected without changing any of the timing reference of the mobile station data.

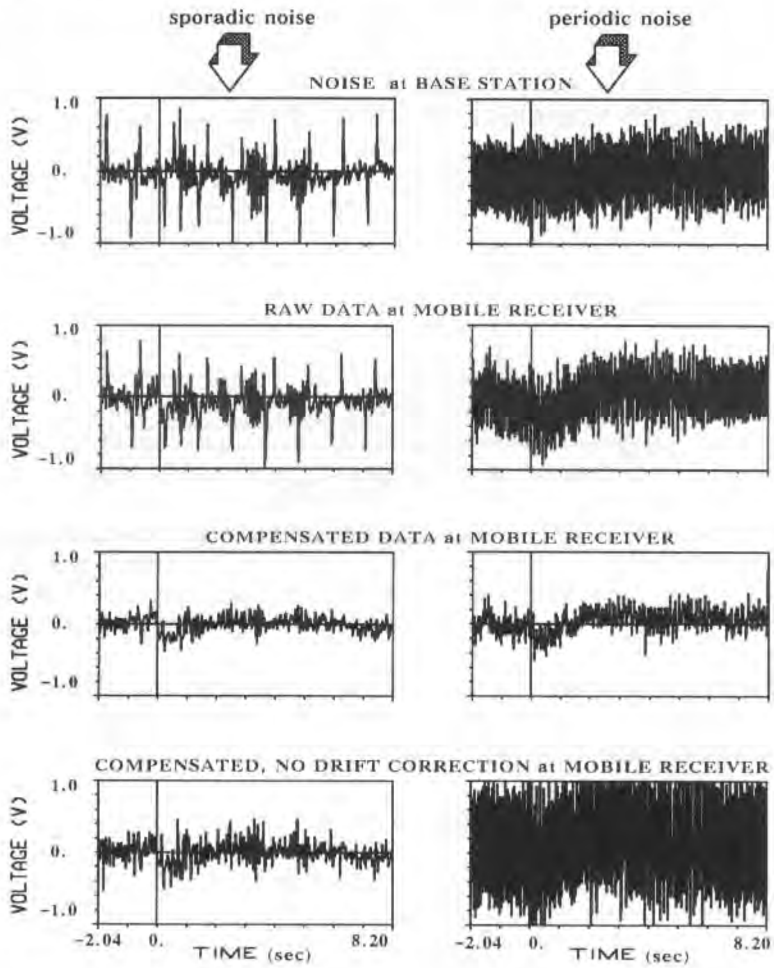

Fig. 5.39: Two examples of the processing sequence for the LNC technique (left column: sporadic noise; right column: periodic noise; data taken in Germany). Top: noise at the base station. Second row: raw transient of control measurement with a different receiver system. Third row: noise-compensated data. Bottom: compensated data without clock drift correction (after Stephan and Strack, 1991).

To illustrate the effect of clock drift, two compensated signals without clock drift correction are shown in the bottom row of figure 5.39. The periodic noise has been amplified (right side) and even the sporadic noise (left side) could not be as well reduced as shown in the third row of the figure. Thus, if this clock drift correction is routinely done before noise compensation, the noise compensation will work well. With these noise compensated signals the routine subsequent processing can be done.

To apply the LNC, the following conditions must be met and tested at the beginning of the survey:

- The noise must correlate over a certain range around the base station and this regional noise can not easily be reduced by standard processing.
- The receiver systems at the base station and at the surrounding mobile stations must be identical in their system characteristics, and the recording times in the data header must be synchronized to identify corresponding records.
- The very localized noise belonging to only one receiver site (i. e. wind noise or noise from nearby power lines) must be smaller than the regional noise.

The correlation of the noise in the survey area is the principal criterion needed to check whether or not the LNC can be applied. The last two conditions are technical problems or a task of the field planning (i. e. to avoid power lines). When using a multichannel system with central synchronization the second condition no longer applies.

Signal processing tests, i.e. with synthetic noise, were not considered useful to rigorously prove the methodology, because they can not simulate the complexity of problems occurring under real field conditions. Therefore, two survey areas with noisy environment were chosen to test the technique.

In the case histories below the measurements were done to check the applicability of the method. In each new survey area a control measurement is carried out in parallel at the site of the base station. It is observed with a completely different acquisition system using a second receiver coil laid on top of the base station coil. The objectives for this control measurement are as follows: First, to verify that the receiver systems have identical noise characteristics and second, to verify that the LNC technique yields an improvement in the S/N ratio of stacked data (and in interpretation). If this test is positive the next step is to move the mobile receiver several kilometers away (we have tested up to 4 km) to define the range where the LNC technique is applicable. Case histories are shown below for a survey area where LNC does not increase the S/N ratio of the stacked data although it apparently improved the single records, and for an area where LNC is successful.

The first field test was carried out during 1988 at the University of Cologne test area in Germany (Stephan et al, 1991). This is an extremely noisy area north of the Rhine–Ruhr industrial district with mainly manmade noise caused by nearby dense industrialization. Measurements undertaken at the beginning of the survey showed that the noise looked very similar at receiver sites several hundred meters apart.

The first LNC step was to process the base transient. Although a large number of stacks were observed, the base stack could only be obtained as smooth as shown in figure 5.38 after prestack filtering and smoothing. Even with extreme care it could not be guaranteed that the shape and amplitude of this base transient was not distorted by these filters. Consequently, the calculated noise at the base station could still contain some signal and the compensated data could be influenced by this signal.

For this survey, the control measurement (see figure 5.39) took only 30 minutes. In this area the noise characterization greatly varied with time, but the high frequency noise dominated. Thus, the normal prestack processing of these data such as low pass filtering, notch filtering and time variant smoothing and the selective stacking method (Strack et al, 1989) could reduce the noise level to such a degree, that the LNC technique yielded no further improvement in the quality of the stacked data. Figure 5.40 shows the comparison between the uncompensated (upper frame) and the noise compensated (lower frame) data of the control measurement. The data quality is low in both cases and a decision can not be drawn as to which data set should be used for further interpretation.

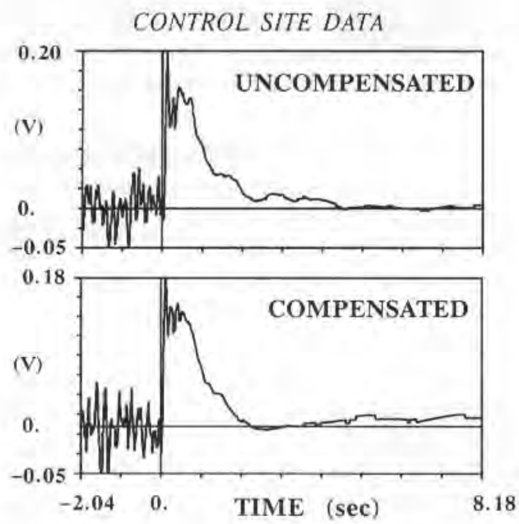

Fig.5.40: Comparison between uncompensated (upper frame) and noise compensated (lower frame) stacked transients of the control measurement at the base station (German survey) (after Stephan and Strack, 1991).

Although the LNC could successfully reduce the noise level in the single records (not shown) of the two examples above, there is no improvement visible in the stacked data. The same results were obtained at other mobile measurement sites located around the base station. Thus, the survey area was not suitable for the application of the LNC technique.

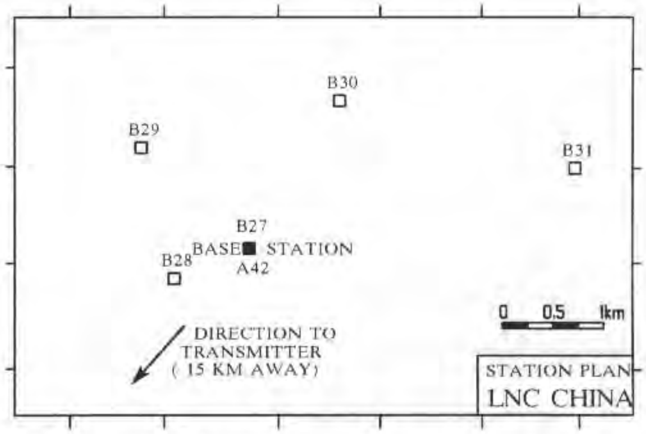

Fig.5.41: Receiver location map of the field test in China (after Stephan and Strack, 1991).

The second field test was carried out in a coal mining area in the Peoples Republic of China in 1988. In this area the mining equipment produced very strong sporadic noise which was very coherent over the entire survey area. The site location map of

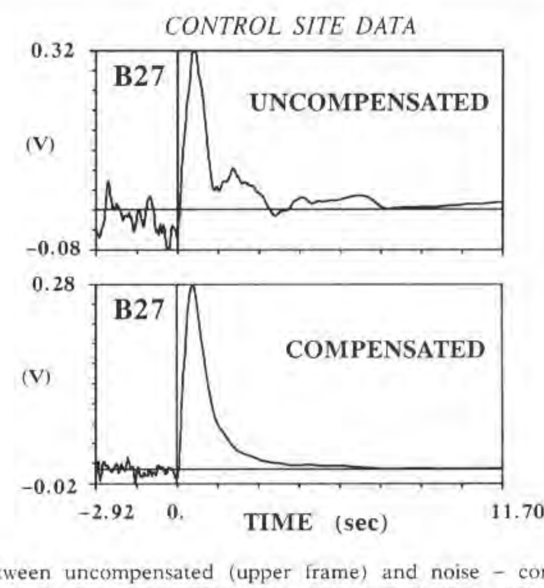

Fig.5.42: Comparison between uncompensated (upper frame) and noise – compensated (lower frame) stacked transients of the control measurement at the base station (China survey) (after Stephan and Strack, 1991).

these test measurements is shown in figure 5.41. Again, first a control measurement (location B27) at the base station site was processed. The uncompensated (upper frame) and the noise compensated (lower frame) stacked transients are shown in figure 5.42. The compensated transient looks smoother with significantly improved S/N ratio. The advantage of LNC can be better seen after transformation to apparent resistivities in bilogarithmic domain. The early stage transforms of the two curves in figure 5.42 are shown on the left in figure 5.43. The error bars are the standard deviations derived from selective stacking. The noise-compensated data have much smaller error bars and the curve looks much smoother. Especially at later times, the range of data points, which could be used for interpretation, is increased by about one decade in time.

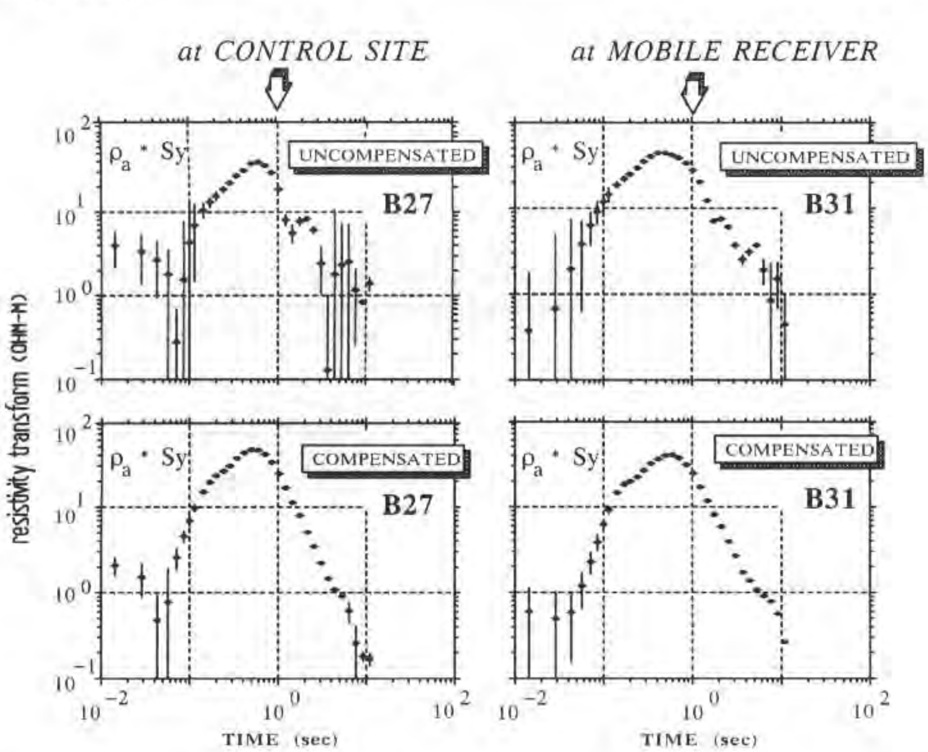

Fig.5.43: Comparison between uncompensated (upper frame) and noise - compensated (lower frame) resistivity transform of two measurements in China. Left side: control measurement B27 at the base station. Right side: mobile receiver station B31, 3.3 km away from the base station (after Stephan and Strack, 1991).

On the right of figure 5.43, a comparison between noise-compensated and uncompensated data is shown for the mobile station B31 located 3.3 km away from the base station. Even at this distance from the base station the LNC works very well. Figure 5.44 shows four single records from station B31. The original raw data are displayed on the left column, the noise-compensated data on the right column. Most of the high amplitude noise could be reduced. Only a few residual high amplitude spikes remain.

In addition, high frequency noise of low amplitude is increased, which is incoherent noise (i. e. wind noise) at the base station or the mobile site. Another effect increasing the high frequency noise is clock drift less than one sample interval, which can not be corrected by a time shift with respect to the cross-correlation maximum. However, this kind of high frequency noise can easily be reduced in the subsequent data processing such as low pass filtering, smoothing and stacking.

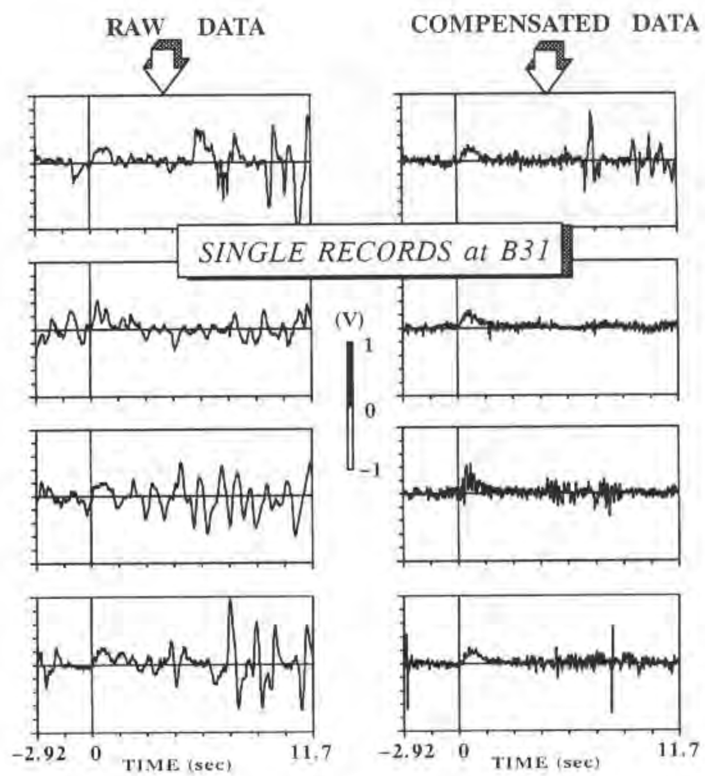

Fig.5.44: Comparison between four examples of the raw data (left column) and compensated data (right column) of the mobile station B31 (after Stephan and Strack, 1991).

For quantitative evaluation of the noise reduction, the S/(S+N) amplitude ratio is used. The (S+N) are the maximal amplitudes of each individual record averaged over all records of each station, because the individual records are dominated by noise. This (S+N) is calculated for the raw data and the noise-compensated single records. The signal S is the maximal amplitude of the final stacked transient. In figure 5.45, the improvement of this S/(S+N) ratio for all stations is plotted as a function of distance to the base station. For the control measurement B27 at the base station an improvement of 118 % could be achieved. For the other stations except of station B28 the improvement is between 26 and 60 %. The station B28 has to be considered separately, because at this site additionally high amplitude local noise from a telephone line was present. For this type of localized noise the LNC technique will not yield much better S/(S+N) ratios. But even at this station the time window of reliable data, which could be used for later interpretation, was increased (compare with figure 5.46).

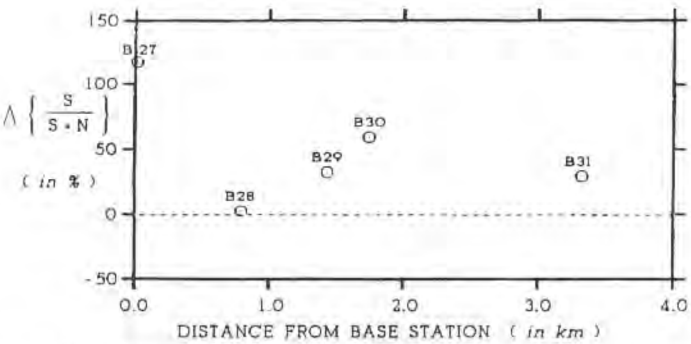

Fig. 5.45: Change in S/(S+N) ratio for all receiver locations as a function of distance from the base station (China survey) (after Stephan and Strack, 1991).

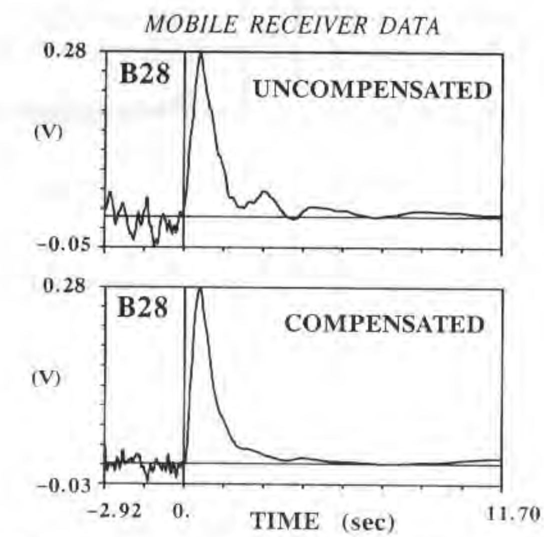

Fig.5.46: Comparison between uncompensated (upper frame) and noise compensated (lower frame) stacked transient of site B28, which was disturbed by telephone line noise (after Stephan and Strack, 1991).

In the first case history the noise could be successfully reduced in the single records, but there was no increase in data quality after stacking in comparison to data without LNC application. Standard filtering and selective stacking were robust and powerful enough for this mainly periodic, only sometimes sporadic noise. The LNC worked well on the raw data, but the amount of interpretable data was not increased for this survey area.

For the second case history, the LNC technique reduced the noise to such a degree that additionally one more decade in time of data was available for interpretation. This result could be obtained at all mobile stations, which were as far as 3.3 km away from the base station.

The two examples show that the LNC technique can be used in selected areas to increase the data quality. Comparing the signals at two close locations with respect to coherency of sporadic noise will quickly allow the determination of the suitability of the survey area. If this comparison is positive, the data quality and furthermore, the productivity, can be increased.

At first sight one might think that leaving a receiver at the base station all day would decrease the productivity. But this apparent loss in time is compensated by shorter acquisition time at the various mobile stations, because fewer transients have to be recorded for stacking. Thus, for the test area in China, where two receivers were used, the same number of stations were observed with LNC using a base station and one mobile receiver as with two mobile receivers and no LNC. Also, LNC yields one stacked transient at the base station with an extremely good data quality because of the high number of single records used for selective stacking. If more receiver systems are used with a multichannel system, the productivity can be increased even further.

A drawback of the LNC technique can be the slight increase of processing time, because first the base transient has to be completely processed, the noise has to be calculated and LNC applied to the mobile stations, before standard processing can start. However, the increase of available computation power removes this drawback.

The LNC technique should only be applied in areas where the regional correlation of noise is proven. This must be done at the beginning of each survey. Furthermore, extreme care must be taken with calculation of the base stack to obtain a noise-free signal. If this is not obtained, the noise that is subtracted from the mobile measurements may contain some signal and the interpretation results could be false. It has been our experience that LNC never decreases the quality of the data. In some cases – as in China – it was the only available remedy easily implemented in the field to obtain useful data.

SUMMARY CHAPTER 5

In this chapter, the general system design concept for deep transient electromagnetic sounding systems are outlined. A deep transient EM or LOTEM system consists of independent transmitter and receiver systems. Both are linked using high precision remote synchronization clocks. The acquired field data is generally interpreted using a mobile processing center at the base camp. This allows a very fast turn-around and continuous quality control of the survey data.

When preparing for a LOTEM field survey, one needs to consider very carefully the preparation of the transmitter electrodes. In order to inject a maximum current into the subsurface the preparation should be done using a mixture out of salt (or potassium), lime and soil directly around the electrode plates. Before starting the transmitter system the transmitter can be checked out using a battery. After preparing the transmitter and getting the transmitter operational the deviation of the current switching from a perfect square wave should be measured and included in the system response. Combining the transmitter system response with the receiver system response gives high quality data for later interpretation.

The survey techniques can be classified as single site survey procedures and multichannel procedures. For both setups the main objective is the highest possible data production to obtain a higher data redundancy and better quality data. To improve the data quality even further, one can use noise reduction techniques which permit the improvement of the signal-to-noise ratio significantly. Initial field tests have shown that *local noise compensation* can extend the signal by one decade, which would be equivalent to increasing the transmitter power by a factor of one hundred. Considering all these different field configurations one can very easily deploy multichannel acquisition systems and obtain data volumes and productions similar to those of a seismic survey.

PROBLEMS CHAPTER 5

1. Please list the principle building blocks of a LOTEM field system. Separate between transmitter and receiver system.
2. Why is the 'bipolar continuous' waveform the most used one?
3. What forms of synchronization between transmitter and receiver do you know (including the ones described in this chapter)?
4. Discuss the difference in dynamic range between DEMS IV and the TEAMEX. What are the consequences?
5. Explain the advantage of measuring the time derivative of the magnetic field using the DC-level.
6. What are the advantages in the noise reduction of the TEAMEX over conventional systems?
7. Please outline the setting up of a transmitter starting with the arrival on site and ending with the turn on of the current.
8. Explain the different concept in measuring the system response. How do they influence the processing and interpretation of the data?
9. Assume you have a 12 channel TEAMEX system and you would like to make sure that you have no gaps in the spread (RU fails while recording). How would you lay out the spread? Please use the maximum number of soundings as additional criterion.
10. How would you layout the spread if you wanted to do *local noise compensation* at the same time without loosing production?

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