GEOPHYSICAL ASPECTS OF MAN-MADE ELECTROMAGNETIC NOISE IN THE EARTH – A REVIEW

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Abstract. The paper gives a summary of geophysical aspects of man-made electromagnetic noise in the Earth as follows:

— EM distortion effects of man-made constructions below and over the Earth's surface defined as 'passive-noise',
— field observation of EM disturbances due to 'active' man-made sources,
— EM source mechanism of some important active sources from a geophysical point of view,
— efforts in order to improve the signal-to noise ratio by instrumental, methodological and data-processing ways,
— application of man-made EM noise for geophysical prospecting.

The paper is based on world-wide EM noise survey studies published mainly in geophysical journals.

1. Introduction

The reliability of any electromagnetic method is governed by the signal-to-noise ratio at the receiver.

Noise of EM measurements includes (Ward, 1967):

— instrumental noise,
— terrain noise,
— disturbance field EM noise

(McCracken *et al.*, (1986) distinguishes 'geologic' and 'electromagnetic' noise.)

The 'terrain' or 'geologic' noise is partly treated in a recent review by Menvielle (1986) dealing with topographic distortion effects. 'Disturbance field' or 'electromagnetic' noise includes fluctuations from natural and artificial sources. In this paper a review on EM distortion effects of a man-made origin will be given.

Power currents have been used for almost hundred years. (The first DC central station was built by Thomas A. Edison in New York and began operation in 1882. The advent of the transformer, polyphase circuits and the induction motor in the 1880s and 1890s led to a wide spread use of AC power systems. The first significant AC energy transportation was realized between Lauffen and Frankfurt am Main in 1891, and the first three-phase electric railway line was built by the Hungarian Kálmán Kandó in Italy in 1902.) With the progress of civilization, the consumption of electric energy and as its concomitant consequence some by-effects are increasing all the time. Nowadays an EM noise free area can be hardly found in Europe.

The most important EM civilization by-effects are as follows: corrosion, prob-

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lems in transmission efficiency of electromagnetic energy and the appearance of parasitic EM fields around the Earth and in the Earth. In this paper the latter will be treated as this EM contamination sometimes makes the geophysical field measurements difficult and it also means an ever-increasing imminent danger for electromagnetic observatories all over the world (Murdin, 1986).

There are three main reasons for geophysicists to deal with man-made EM noise

— to get better signal-to-noise ratios in field measurements
— to overcome the problems, emerged with EM recordings in observatories
— to obtain geological information from EM noise, if possible.

In this paper, after a description of passive and active EM noise (the two main man-made noise types), the source mechanism of parasitic EM disturbances is briefly described. Then a summary is given on possibilities for the elimination of man-made EM disturbances from EM field measurements. At the end of the paper some ideas are summarized for obtaining geological information from man-made EM noise in the Earth.

Man-made EM noise effects outside the Earth will not be dealt with here. EM noise in the ionosphere and the magnetosphere is studied in the frame of Commission E of URSI (Kikuchi, 1985) and such studies are also published in papers dealing with environmental atmospheric planetary and space sciences: e.g. Madden and Thompson (1965), Dungey and Speiser (1969), Cannon (1982), Cannon and Roycroft (1982), Chernogor (1982), Chernogor (1984), Beamish and Tzanis (1986), etc.

On the field observation and geophysical application of man-made EM noise in the earth, papers have been published so far only sporadically, although the investigation of man-made EM disturbances is almost as old as their appearance in the earth. (The first papers were published by Michalke (1904), Maurain (1905), Girouse (1924), Arnold (1937) and Rössiger (1942). The ideas of using EM disturbance field of man-made origin for geophysical prospecting dates back to the fifties. The first review paper was made by Eigner (1984) collecting appr. 60 papers with a completeness in German publications.)

This review paper is based on papers published in geophysical journals, abstracts found in Referativny Zhournal between 1973—1986, the DIALOG Information Services, and field experiences, mainly of the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences.

2. Classification of Artificial EM Noise

Man-made constructions below and over the earth's surface create passive and active EM noise (Ward, 1983). Geophysical EM circuits completed through fences, pipelines, cables, power- and telephone lines, rails, etc. produce anomalies (*passive noise*) largely unrelated to subsurface geology. Some of these man-made developments also serve as sources of *active electric or/and magnetic field noise.* As will be seen the electric network disturbances produce parasitic EM fields in the earth which appear in EM field measurements as man-made EM noise in contrast to signals. EM noise may cause a misinterpretation (distortion) of geophysical data. An EM effect due to superficial man-made constructions may also distort the geophysical results.

For the sake of completeness man-made local disturbances which might cause EM noise in the receiving system, may be also mentioned:

— magnetic body of vehicles and moving metal vehicles, causing EM induction in the earth's magnetic field (e.g. Kuboki 1966, Fournier 1968),

— vibration (due to vehicles, industry, etc.) which make the magnetic sensors or electric cables oscillate in the earth's magnetic field.

Here this trivial EM noise group is not dealt with.

There are many borderlands of the man-made EM noise problem: e.g. the paper of Davis (1974) on piezomagnetic anomalies due to artificial ground loading represents one of them.

The main types of man-made EM noise in geophysical measurements are summarized in Table I.

TABLE I

Man-made EM noise in geophysical measurements.

Passive	Active	Other local man-made effects
(affect as compact or elongated superficial resistivity inhomogeneities)	(produce regular or irregular parasitic EM field in the earth)	
— conductive: power lines pipelines telephone lines cable systems fences, etc. — resistive: roads ditches, etc.	— electric power transmission lines — rectifiers — DC traffic substations — AC railway lines — arc furnaces — complicated mining electric networks — anti-corrosion systems — EM wave transmitters, etc.	— magnetic or EM effects of vehicles — EM induction due to vibrations of man-made origin — piezomagnetic anomaly due to artificial ground loading, etc.
— interaction with natural phenomena (magnetic storms, lightening, wind and ionization of the air, etc.)		

3. Passive Man-Made EM Distortions

Passive noise sources of EM measurements generally mean superficial resistivity inhomogeneities of a man-made origin.

Technical constructions (power lines, pipelines) may cause a redistribution of extreme natural electromagnetic phenomena such as magnetic storms, lightings, etc. This interaction between natural EM fields and man-made constructions has been exhaustivly treated. (See e.g. Pirjola (1985) or Lanzerotti and Gregori (1986) as the latest papers.) Here only 'pure' EM effects (that is without extreme interactions with natural EM fields) of man-made constructions below and over the surface are mentioned.

Passive distortion effects of man-made constructions can surely be avoided by placing transmitters and receivers well away from them. This is not always possible in areas of concentrated industrialization, and hence in the past important geological problems could not be attacked by EM methods in such areas (Ward, 1983).

In *resistivity sounding measurements* mainly the potential electrodes must be kept, as far as possible, at a safe distance from near lateral inhomogeneities. Localized inhomogeneities close to the current electrodes are considerably less harmful (Koefoed, 1979).

Elongated conductive inhomogeneities (buried pipelines, wire fences) distort the pattern of current flow in the ground only to an extent that they are connected to ground. Elongated resistivity inhomogeneities such as roads and ditches cause considerably less distortions.

Kimbark (1971) gives a summary on effects of compact and elongated buried objects. An experimental estimation of the current through and elongated conductive inhomogeneity is described by Koefoed (1979). DC response of buried cables have been analized by Wait and Umashankar (1979). Effect of well casing on surface electrical surveys has been theoretically studied by Holladay and West (1984).

In *inductive methods* the high-conductivity elongated inhomogeneities produce an extra induction term. A reduction of such noise by removing this extra induction is generally impossible. High-frequency methods such as VLF and airborne electromagnetics are especially distorted by fences, pipelines, etc. (Dupis, 1984; Shaub and Demenok, 1972).

Effect of pipelines on spectral *induced-polarization* curves is given by Parra (1984).

Ryazantsev (1978) summarized passive EM distortion effects due to mine- and other subsurface constructions.

A better understanding of these passive EM effects is possible by further numerical model calculations and analogue model experiments.

The theoretical background to this further work is given by Sunde (1949), Vanyan (1965), Ollendorf (1969), Wynn and Zonge (1975), Wynn and Zonge (1977), Nelson (1977), Watts (1978), Wait (1982), Bhattacharya *et al.* (1983), Wait (1984), etc. The latter gives a theoretical solution for a discretely grounded circuit.

4. Active EM Noise of Man-Made Origin as Recorded by Geophysical Measurements

In this chapter the main features of active EM noise are summarized as they were observed in the field. After giving typical EM spectra, the main results of geophysical field measurements of power harmonics will be at first summarized, then other noise types observed by low-pass analogue recording will be reviewed.

POWER HARMONICS AND HIGH-FREQUENCY DISTURBANCES

EM noise spectrum in Figure 1 indicates the ubiquity of the network frequency and its harmonics (Macnae *et al.*, 1984).

In their AMT paper, Strangway *et al.* (1973) refer only to spurious signals which can be generated in the magnetic field by vibration of the coil (due to wind) at the lowest frequencies. Later extensive AMT and MT field measurements met strong

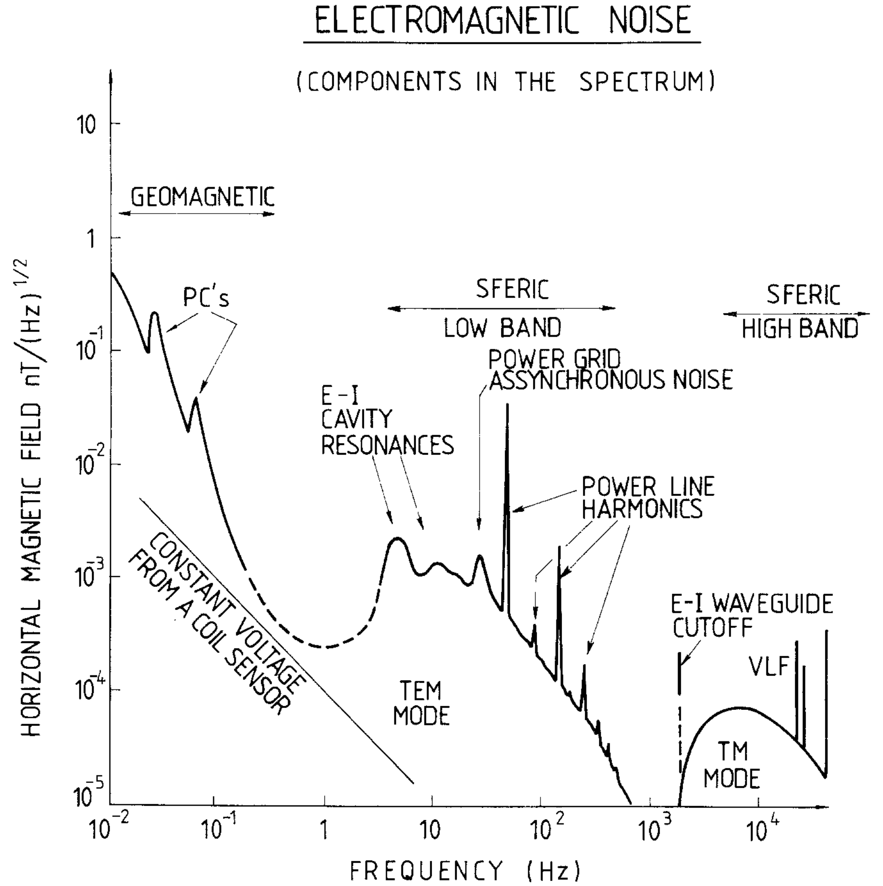

Fig. 1. Theoretical electromagnetic noise spectra, showing power line harmonics among the components (Macnae *et al.* 1984).

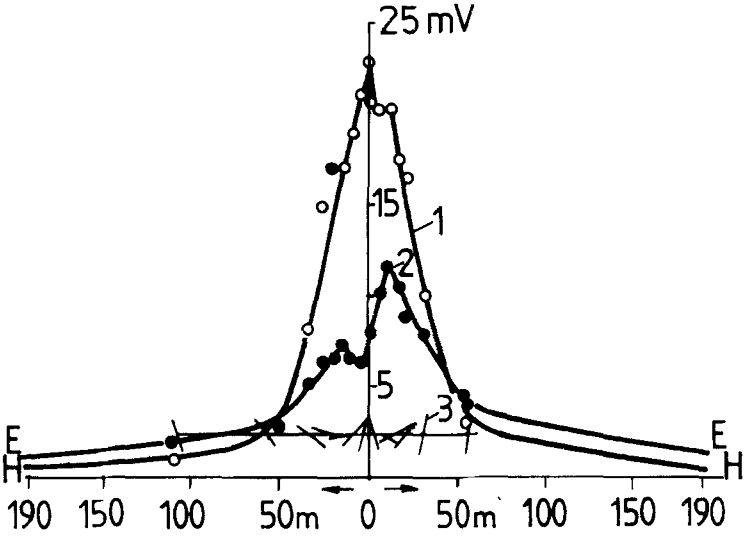

Fig. 2. Distribution of field strength of three-phase power transmission line in the immediate vicinity of the power line (Takács, 1979a); (1) H_t (total magnetic field); (2) E_x (horizontal electric field); (3) direction of H_t.

man-made disturbances, at least at sites in the neighbourhood of power lines (e.g. Nazarenko *et al.*, 1975; Benderitter *et al.*, 1978; Dupis and Théra, 1982; Hjelt, 1983; Ádám *et al.*, 1984; etc.). Hoover *et al.* (1978) observed *power line harmonics* 30 to 50 dB above the natural signal level in the absorption band around 2 kHz. Recent AMT studies in Finland (Lakanen, 1986; Hjelt *et al.*, 1986) found a seasonal variation in man-made EM noise due to electric heating.

EM harmonics in the vicinity of 50 Hz power lines were studied by several authors (e.g. Takács, 1979a; McCollor *et al.*, 1983). Figure 2 shows such harmonics in E_x and in the total magnetic field, H_t. Strong changes beneath the three wires are due to their asymmetric positions.

McCollor *et al.* (1983) showed by monitoring one of the phase currents and the neutral current that the source is the neutral current, being the algebraic sum of the three phase currents. The existence of odd harmonics (180 Hz, 300 Hz, 420 Hz) indicates that the power system is not perfectly balanced. The power line source current was found to be very stable, with exceptions of sudden step changes. Even harmonics in power lines are more strongly affected by geomagnetic variations than odd harmonics (Nazarenko *et al.*, 1975; Hayashi *et al.*, 1978).

Dupis *et al.* (1974) measured strong harmonics in vicinity of a DC power transmission line, as it is shown in Figure 3.

EM noise spectra or noise characteristics from mines were reported by Lefevre (1964), Ivanchenko and Bilan (1964), Grachev (1975), Geyer and Keller (1976), Ryazantsev (1978), etc.

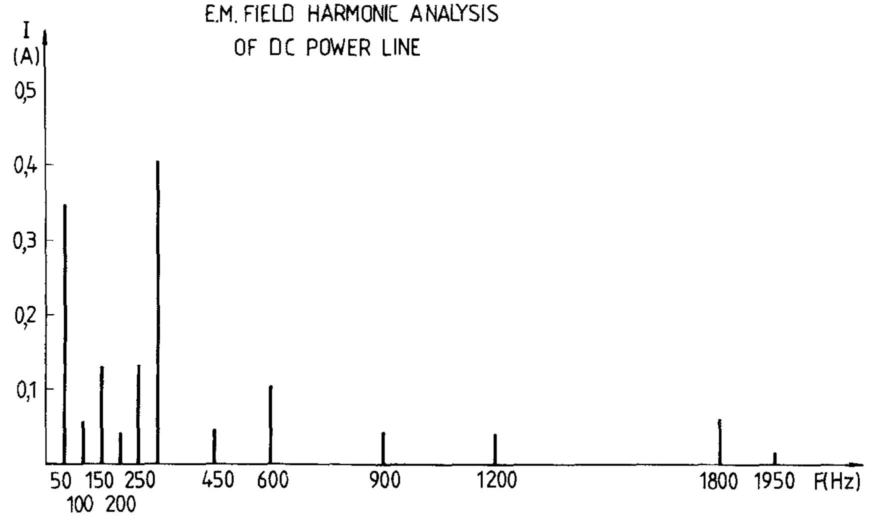

Fig. 3. EM field harmonic analysis of DC power line (Dupis *et al.* 1974).

MAN-MADE NOISE EFFECTS RECORDED BY LOW-PASS ANALOGUE SYSTEMS

Low-pass analogue recording systems at observatories and in the field usually record three main noise types (two of them are of man-made origin).

Figure 4 (Berdichevsky, 1960) shows irregular industrial noise, and induced electric field in the vicinity of a telegraphic line in a position of maximum EM coupling. A typical wind effect due to cable vibration in the Earth's geomagnetic field is shown, too (it is an exclusively natural phenomenon, at least in case of normal ionization of the air).

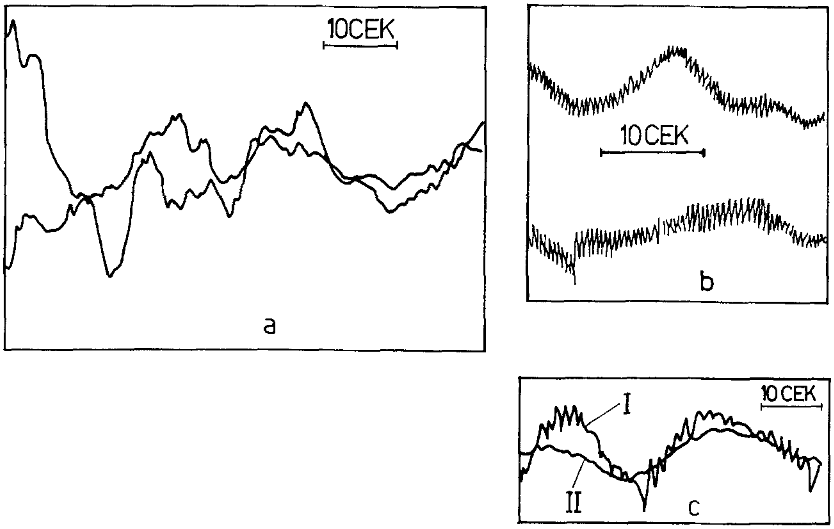

Fig. 4. Noise types observed at telluric recordings (Berdichevsky, 1960). (a) industrial noise; (b) inductive noise; (c) wind effect in channel I.

Dupouy (1950) in his experiments with the contribution of SNCF near Chambon-la-Forêt observed that the disturbances are particularly noticeable when the continuity of the power lines is broken following repair or traffic accidents.

The daily variance of leakage current intensity was described by Kishinouye (1951). Kovalevsky *et al.* (1961) found strong impulse-like disturbances having durations of several seconds. The direction of stray currents proved to be quite permanent. Similar papers (low frequency telluric and magnetic micropulsations of man-made origin) were published by Fraser and Ellyett (1964), Lokken and Shand (1964) and Jones and Kelly (1966).

Chaize and Lavergne (1970) give a brief description of the source mechanism. Current I_2 having an impulse-like character due to changing traction power in Figure 5 enters the earth at places where the rails are poorly isolated from the soil, and it is the wide spread of this erroneous current which may cause distant EM disturbances. Although their measurements were carried out in the frequency range 0.2—16 Hz, the simultaneous occurrence of perturbations at different frequencies implies a step-like character in their original form. Figures 6 and 7 show the total magnetic intensity and inclination as a function of distance from a DC railway line and from an AC power transmission line. EM contamination can be felt to a distance of appr. 30 km from a DC railway line. According to their measurements the distortion effect of an AC electric power line is considerably less.

It is an old experience that the areal extension of man-made EM disturbances depends on subsurface geology (Neuenschwander and Metcalf, 1942; Berdichevsky, 1960). In extreme situations (superficial high-resistivity basement) impulses can be observed at distances of 70—100 km from the source, the inductive effect can be felt at distances less than 1—1.5 km.

Yanagihara (1977) gives an analytical formula for the redistribution of rail currents and the magnetic field in case of one- or two substation systems, as a function of rail resistance and leakage resistance. (This latter was found to be between 0.5—1.5 Ohm · km depending on weather conditions.)

Sanclement (1974) and Hoogervorst (1975) described the character and magnitude of the noise recorded in Spain and in Holland.

Grachev (1975) distinguished regular disturbances and irregular impulses in mines. EM field perturbations may be transmitted and spread out by the mining

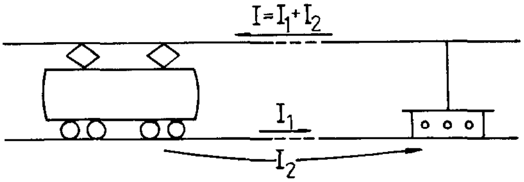

Fig. 5. Current circuit in DC railway systems. I is the current in the overhead power line. I_1 is the return current in the rails, I_2 is the return current in the Earth (Chaize et Lavergne, 1970).

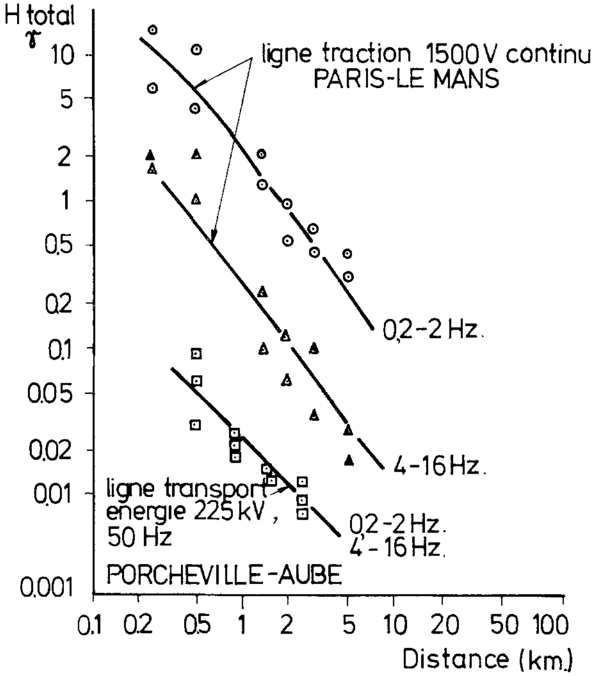

Fig. 6. Average intensity of magnetic impulses due to a DC electric railway line and due to an AC high-voltage power-transmission line (Chaize et Lavergne, 1970).

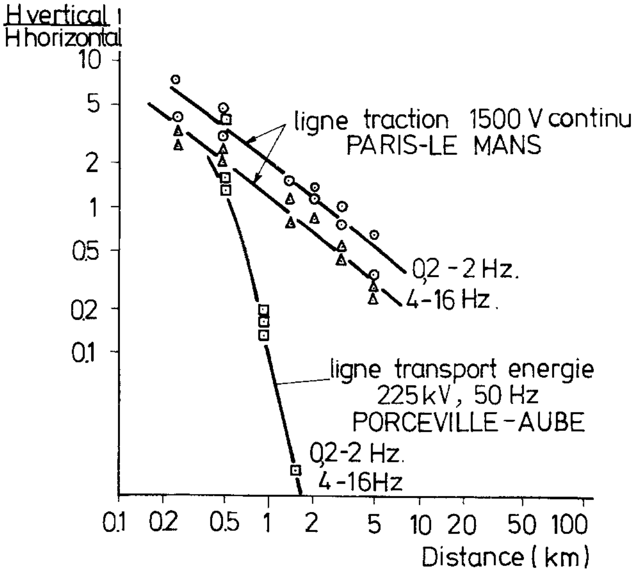

Fig. 7. Inclination of magnetic impulses due to a DC electric railway line and due to an AC high-voltage power transmission line (Chaize et Lavergne, 1970).

cables and pipelines in the whole mine. (Some impulses may give disturbances even at frequencies as high as several 100 MHz.)

In observatories numerous noise investigations were carried out. Many of them are collected in the review paper of Eigner (1984), mainly for the Fürstenfeldbruck observatory (Publications of the Fürstenfeldbruck Geophysical Observatory, Serie A, Nos. 7, 8, 11, 13, 14). Märcz and Verö (1970) for Nagycenk, Miguel (1964) for Toledo, Burkhart (1951) and Hofer (1985) for Fürstenfeldbruck, Mikerina (1962) for Voyeykovo have also interesting results.

Fournier and Rossignol (1974) and Kröger (1981) found strong disturbances of artificial origin in their MT records.

Ádám *et al.* (1986) gave a review of some types of disturbances found in analogue MT records. Most frequently square impulses are found in both electric and magnetic components, and a part of them is apparently uncorrelated with the corresponding components. At extreme sites (near to a crossing of an electric railway line and a pipeline having an active anti-corrosion system), very surprising sinusoidal distortions can be found: Figure 8, 9, and 10 show a section of the analogue record, the sounding curve and the spectra.

GEOPHYSICAL EFFECTS OF MAN-MADE EM NOISE ON VARIOUS MAGNETIC, ELECTRIC AND ELECTROMAGNETIC METHODS

Effect of cathodically protected pipelines on aeromagnetic surveys has been demonstrated by Parker Gay (1986).

Noise problems from the point of view of transient methods have been studied by Fitterman and Stewart (1986) and Sörés (1985).

Magnetic fields due to currents in submarine DC cables at first were observed by

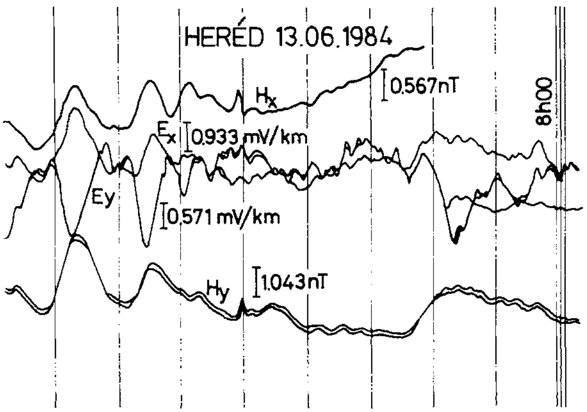

Fig. 8. Sinusoidal noise with a period around 1 min on analogue MT record in Heréd (probably due to an interaction of corrosion protection and an electric railway line) (Ádám *et al.* 1986).

mariners by significant compass errors (Kimbark, 1971). Grinkevich *et al.* (1973) relate a magnetic survey in a very disturbed area. Corwin and Hoover (1979) made SP measurements in a noisy area.

In the vicinity of big towns and industrial zones a superposition of different noise sources will be the normal case. And really, the description of field EM noise in

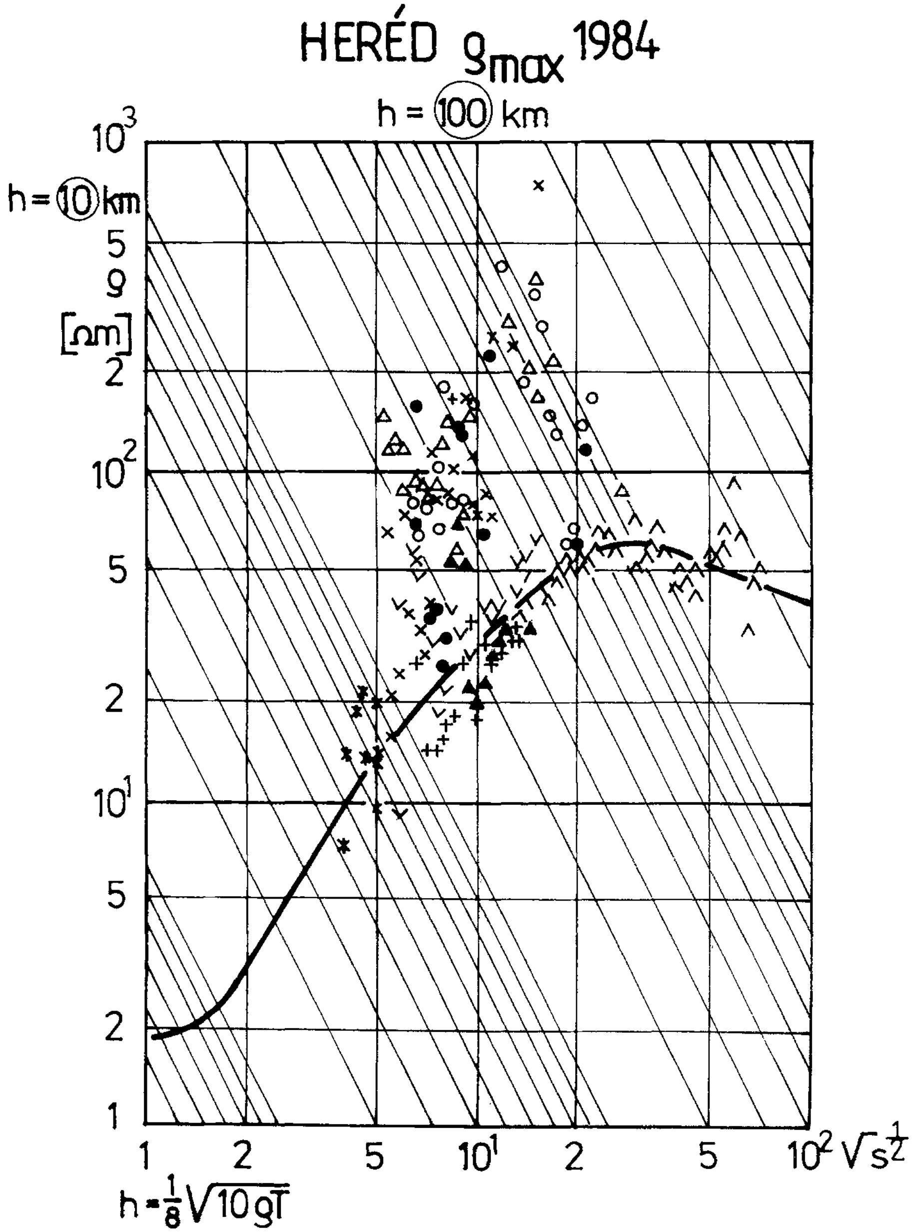

Fig. 9. Apparent resistivity values at an MT site in Heréd from different parts of the record according to the symbols (Ádám *et al.* 1986).

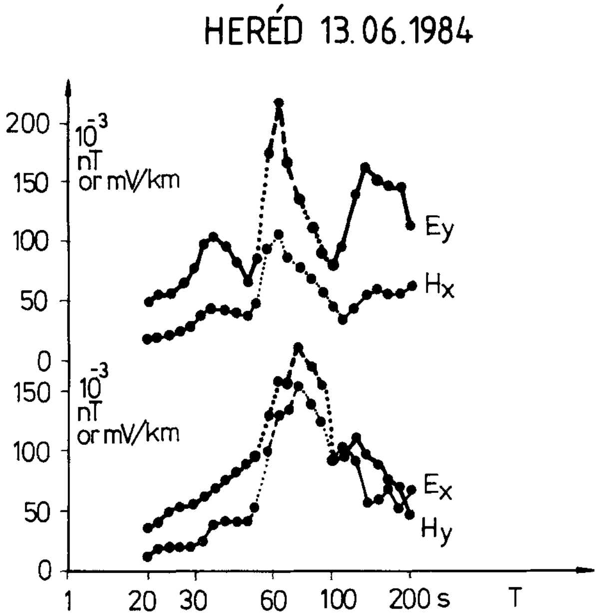

Fig. 10. Spectra of sinusoidal noise and real MT variations for the Heréd MT site (Ádám *et al.* 1986).

EM induction papers is getting to be found more and more frequently, e.g. Hutton (1985), Hutton *et al.* (1985), Schwarz *et al.* (1985), Berktold *et al.* (1985), Otten and Musmann (1985), Duprat and Gole (1985), Duprat *et al.* (1985), etc. At recent NWWA/EPA and IAGA conferences a number of such papers emerged: Duran (1984), Schnegg *et al.* (1986), Fontes *et al.* (1986), etc.

In summary papers mentioned in this chapter account for two main types of man-made EM noise in the Earth: harmonics which seem to be stable in time ('regular' noise) and sudden impulse-like disturbances ('irregular' noise), having ever increasing influence on various electric, magnetic and electromagnetic methods. Both the galvanic contact and the inductive coupling have their own importance. (So far only one geophysical paper has been known to be published on capacitive coupling between a power line and the earth (Eberle, 1977).

At the end of this chapter two publications which are also related to geophysical (but not electromagnetic) effects of active EM disturbances of man-made origin can be mentioned: Ollendorf (1969) calculated the geothermal fields of earthening sites, Prosuntzova (1984) dealt with civilization by-effects of man-made EM noise in urban areas.

5. Sources of Active EM Noise in the Earth

The most significant sources of active EM noise of man-made origin seem to be electric power transmission lines, some electric power equipment (both converters and consumers) and some special electric systems such as electric power networks in mines or corrosion protection systems. The first summary of man-made EM noise sources was given more than 60 yr ago by Girouse (1924). Here some information is collected about them from a geophysical point of view.

For *electric power transmissions* usually high-voltage three-phase AC systems are used, but in some applications high-voltage DC transmission lines have some advantages, e.g. in long water crossings requiring submarine cables, energy transmission through congested urban areas, in interconnection of AC transmission lines of different standards, etc. (Kimbark, 1971).

An ideal (perfectly balanced) AC power transmission system does not cause any active EM noise in the earth. In the case of unbalanced networks (i.e. in realistic situations) a current component appears, having equal amplitudes and directions in each conductor. This is the so-called zero-sequence current which usually flows through the soil. AC ground return paths — in contrast to those of DC — exactly follow the path of overhead wires.

Imbalance and other erronous phenomena of transmission lines are largely related to an imperfect technical realization of the whole electric power system. Classical papers of Carson (1926), Sunde (1949), then Ollendorf's (1969) and Kimbark's (1971) books and recently an IEE Conference Publication (1984) and an URSI conference material edited by Kikuchi (1985) are basic works in this field. Adequate chapters of the Standard Handbook for Electrical Engineers (1968) and special technical books as Harris and Ledwidge (1974), Delogne (1982), Arrillaga *et al.* (1983) are also proposed for study.

To determine EM distortion effects in the earth due to converters and consumers is by no means only a geophysical task: it has a great importance from the point of view of transmission efficiency, too.

Due to the continuous increase of automatization and motorization, the number of non-linear converter elements and consumers producing harmonics or representing asymmetric loading in the network increases all the time.

In the following the main sources are summarized on the basis of a study made by Hungarian electric engineers (Ipsits and Szepessy, 1982). EM distortion effects due to network disturbances in the electrotechnics are usually characterized by voltage changes:

- rapid amplitude changes, changes of envelope curves, voltage surges
- changes and distortions of the waveform, production of harmonics
- asymmetric distortion of the three-phase voltage vector.

Specification and allowed disturbing values are different in nearly every country, moreover, these values change from time to time, too. As an example, specifications of waveform distortions for several countries are demonstrated in Table II.

In some countries the network frequency itself may also change depending on loading.

The most typical equipments producing parasitic EM disturbances in medium- and high-voltage networks are as follows:

TABLE II

Specifications for the permissible value of the wave-form distortion (Ipsits and Szepessy, 1982)

Country	Voltage (kV)	y_n (p.c.)	D_{eff} (p.c.)	D_{ave} (p.c.)
New-Zeland	all	0.7		3
Austria	3—35	1—1.5	4	
	≧120	0.3—0.5	1	
Sweden	3—24	2.5	3	
	36—72	1.5	2	
	≧84	0.7	1	
Canada	12.5—138	1	4	
Japan	11—66	1	2	
	154	0.5	1	
Soviet Union	all		5	
Australia	220	1	3	
Finland	3—20	3	5	
	30—45	2	4	
	≧110	1	1.5	
France	all k=2n	1		
	k=2n+1	0.6		
South-Africa		1.5		
United Kingdom	<132			2.5
	132	2.5	1	
	>132		0.5	
Hungary (only proposal)	6—20	3	4	
	35	3	4	
	≧120	0.6	1	

Remarks: y_n (p.c.): waveshape distortion.
D_{eff}: voltage distortion tolerated by consumers.
D_{ave}: permissible harmonic content produced by consumers.

Rectifiers supplying electrolysis which represent the most significant sources of harmonics. The aluminium and chlorine electrolyzers need the highest power, that is a DC voltage of approximately 800 V, a current of 80 kA. (Values refer to a blast furnace in Inota, Hungary). Harmonic content of rectification can be theoretically calculated by the Müller-Lübeck rule, as demonstrated after Csáki *et al* (1973) in Table III.

DC traffic substations are employed mostly in suburban and underground railways, electric street car- and trolleybus lines. Loading of substations may be very changeable, they take high and sudden current impulses. (E.g. in Budapest the underground railway is supplied by a voltage of 825 V, and there are 10 power substations along the east-west line having a maximum impulse-like loading of 7000 A.)

Because of the extensive traffic power network in Budapest, some resonance phenomena were sometimes observed producing also additional parasitic currents.

General-purpose semiconductor electric drives serve for regulating the number of revolutions in areas like mine shafts, rolling mills, etc. They are characterized by

TABLE III

Harmonic content of rectifier switching having different p pulse number/period, according to the Müller-Lübeck rule (Csáki *et al.*, 1973)

Serial number	Frequency	Relative amplitude		
		$p=2$	$p=3$	$p=6$
1	50	1.00	1.00	1.00
2	100	—	0.50	—
3	150	0.333	—	—
4	200	—	0.25	—
5	250	0.20	0.20	0.20
6	300	—	—	—
7	350	0.143	0.143	0.143
8	400	—	0.125	—
9	450	0.111	—	—
10	500	—	0.100	—
11	550	0.091	0.091	0.091
12	600	—	—	—
13	650	0.077	0.077	0.077
14	700	—	0.071	—
15	750	0.0667	—	—
16	800	—	0.062	—
17	850	0.0559	0.0559	0.0559
18	900	—	—	—
19	950	0.0526	0.0526	0.0526
20	1000	—	0.05	—
21	1050	0.0476	—	—
22	1100	—	0.0455	—
23	1150	0.0435	0.0435	0.0435
24	1200	—	—	—

impulse-like loading due to the forced acceleration applied at such regulated drives.

In *long-distance electric railway power systems* DC (1500 V or 3000 V) or AC (15 kV, 16 2/3 Hz or 25 kV, 50 Hz, in US 11 kV, 25 Hz) is used.

Traction currents flow in a circuit consisting of power substations, overhead power lines, hauling vehicles, rails and the earth. In the vicinity of DC electric lines the EM disturbances are due to pulsations of traction currents.

In the AC case, usually one-phase systems are used which represent asymmetric loadings in the national three-phase network. Reactive power is taken from the network and produces harmonic currents, mainly in equipment which includes thyristors for current rectification.

Arc furnaces producing steel or ferroalloys can be regarded as asymmetric consumers. During the melting process strongly variable voltage surges appear. The velocity of current changes is in the range 2—20 Hz, having a typical current spectra.

Other equipment, such as interrupters and induction furnaces may also produce parasitic currents. The number of consumers whose operating frequency differs from that of the national network is increasing all the time (e.g. 400 Hz, 125 Hz, 75 Hz, this latter is used in railway safety systems. In some street lighting systems a square pulsed voltage of 20—50 kHz is applied). Electric fences produce an EM disturbance field at 2 Hz.

The parasitic EM field in the earth has mainly a galvanic, or inductive origin. Sometimes due to extensive high-voltage cable systems close to the earth (e.g. in mines) a capacitive coupling must also be taken into account (Barta *et al.*, 1982).

After reviewing the most important electric power equipment which may cause EM disturbances in the Earth, two special electric power systems, namely electric power networks in mines and corrosion protection of pipelines must be mentioned as a mine area is one of the most interesting fields for geophysical prospecting, and corrosion protection methods can produce very atypical EM disturbances.

Electric power systems in mines have a large variety due to the diverse operational specifications. Usually high electric power has to be concentrated in several points, covering a large area. The network is being continuously developed in time and space.

In most European mines medium-voltage networks having an insulated neutral are applied. To avoid the high capacitive leakage currents ($1—3\ \mathrm{A \cdot km^{-1}}$) due to the large extension of the network system of several kilovolts a compensated (inductive) earthening is applied.

In above-ground equipment usually directly grounded systems are applied.

In mining networks due to their complications some special disturbances also have to be taken into account besides the general erratic phenomena which may appear even if the safety requirements are satisfied.

Corrosion protection methods also produce parasitic EM fields. If pipelines are simply connected to rails directly or through a rectifier, these solutions belong more to passive noise sources. In some places galvanic batteries are installed. The most powerful (and from our point of view the mostly disturbing) method applies a rectifier supplied from the network. The prevailing current strength is controlled by a desired potential difference between the pipeline and the soil, thus serious interaction effects appear in the case of high pulsation activity and strong stray currents of another origin, too.

For the sake of completeness *EM wave transmitters* should also be mentioned as active EM noise sources, but they will not be dealt with in detail. (Details on unintentional radiation from industrial, scientific and medical radio-frequency generators can be found in the paper of Struzak (1985).)

Finally it should be regarded that all active EM methods produce man-made noise for other EM methods, which are well known and not dealt here in detail.

6. Some Possibilities for the Elimination of Man-Made EM Disturbances

There are many important geological problems to be solved by electromagnetic methods in any area, including those which are contaminated by artificial EM noise. A fight to overcome this difficulty of EM field measurements is going on in three different fields including instrumental, methodical and data-processing developments.

Noise and the required signal differ from each other in one or more specifications: waveform, spatial distribution (direction, local or regional extension) frequency spectra, etc. In the following these aspects are briefly reviewed, without dealing with noise suppressions by a simple enhancement of the useful signal. (Although it is worth remarking that a determination of the optimal sounding signal is given by Samoilov (1982).)

In case of artificially generated EM fields a possibility is to employ *special waveforms*:

In DC exploration it was Deppermann (1968) who introduced reversed square-like impulses in order to increase the signal-to-noise ratio.

In wide-band electromagnetic sounding Duncan *et al.* (1980) seem to have made a big step forward. In their generator a direct current from 1 to 5 A was reversed through a long wire bipole transmitter in a pseudorandom binary sequence, then the measured signal was crosscorrelated digitally in real time with an exact copy of the transmitter waveform. Due to the inherent ability of corsscorrelation analysis to reject uncorrelated noise, a sufficiently high signal-to-noise ratio can be achieved.

Dreyzin (1982) discusses a special accumulation method. Alfano *et al.* (1982) relate an analysis procedure and equipment for deep geoelectric sounding.

Low signal-to-noise ratios in the AMT range made it necessary to develop the so-called CSAMT method. (Goldstein and Strangway, 1975; Dupis, 1977; Sandberg and Hohmann, 1982; Schnegg and Fischer, 1984; Fischer and Schnegg, 1986, etc.).

Signal and noise can be separated on the basis of their *directional properties*:

Kovalevsky *et al.* (1961) and Hoogervorst (1975) studied the character and magnitude of the man-made impulse-like noise. They found these impulses quite unidirectional in time. To eliminate such impulses from telluric readings and also from geoelectric measurements a method is suggested by Fröhlich (1971). E.g. in the case of an artificially generated field the elimination is possible by simultaneous observation of the stray current potentials on an equipotential line of the generated field. He could distinguish impulses related to different sources at small distances near Aachen. Ádám and Szarka (1986) separate impulse-like disturbances coming from very close directions.

Noise can also be suppressed by *simultaneous measurements at two or more sites.* In this sense the MT remote reference has the greatest importance, as it is able to enlarge the suitable area for MT measurements.

Fischer (1982) gives a detailed description of the remote (usually: magnetic) reference method. Its basic idea is that source signals which do not satisfy the criteria of an incoming plane wave produce effects which are quite local and are, therefore, not correlated with signals observed at a distant station. The remote reference criteria are as follows: (a) linear relationship between the unperturbed signals at the measurement and reference sites and (b) perturbations at the two sites must be as little correlated as possible. Details can be found in Gobau *et al.* (1978), Gamble *et al.* (1979), Pedersen (1982), Clarke *et al.* (1983), Kröger *et al.* (1983), Jones and Jödicke (1984), Pedersen and Svennekjaer (1984), Jödicke and Grinat (1985), etc. Labson *et al.* (1985) adapted the remote reference technique for the AFMAG method. Gobau *et al.* (1984) propose to use three distant magnetometers to get additional information on the non-planar wave nature of the EM field.

The telluric-magnetotelluric method (Hermance and Thayer, 1975) also improves the signal-to-noise ratio.

Kozlov and Shaydurov (1983) apply remote reference synchronization in IP. (It must be mentioned that in Nos 76 and 77 of the Soviet journal 'Geofizicheskaya Apparatura' (Leningrad) several other papers were published too on special industrial noise suppressing solutions in EM, mainly in IP equipment.)

Frequency characteristics of man-made disturbances are also utilized to improve signal-to-noise ratio:

Application of built-in notch filters serves to eliminate the network frequencies (16 2/3 Hz, 50 Hz, or 60 Hz) and their harmonics. In some countries (e.g. in COMECON countries) the value of the network frequency may change between 49 and 50 Hz depending on load. According to 1 yr MT experience in Hungary by a Phoenix system, at least 75 p.c. of EM noise troubles originate from the changeable network frequency (Nagy, 1986, personal communication). In such areas only intelligent (e.g. phase-locked) filters can be applied.

In the case of the active EM profiling method it is a common solution to choose an operating frequency to be between power harmonics.

For MT measurements in highly industrialized areas such as Switzerland the remote reference technique does not seem to work at least in the AMT range (Fischer, 1982), but delay-line filtering proved to be quite effective, as is shown in Figure 11. (This is essentially a real-time filtering in the time domain. It might have also a potential ability in elimination of disturbances due to changeable network frequency, provided that the sampling is controlled by the real network frequency.)

Another real-time technique is given by Jones and Foster (1984). Dálnoki (1982) describes a device which allows an automatic change of the transmitter's frequency depending on the noise spectra in the frequency range 0.001—100 Hz.

For time-domain EM systems Macnae *et al.* (1984) give a summary on noise processing techniques.

Man-made EM disturbances can also be recognized on the basis of the *abrupt impulse-like character:*

The presence of stray currents can easily be recognized in most cases from their abrupt impulse-like character. Such an automatic recognition and elimination can be realized in the field. During digital recording, the abrupt impulses distort almost

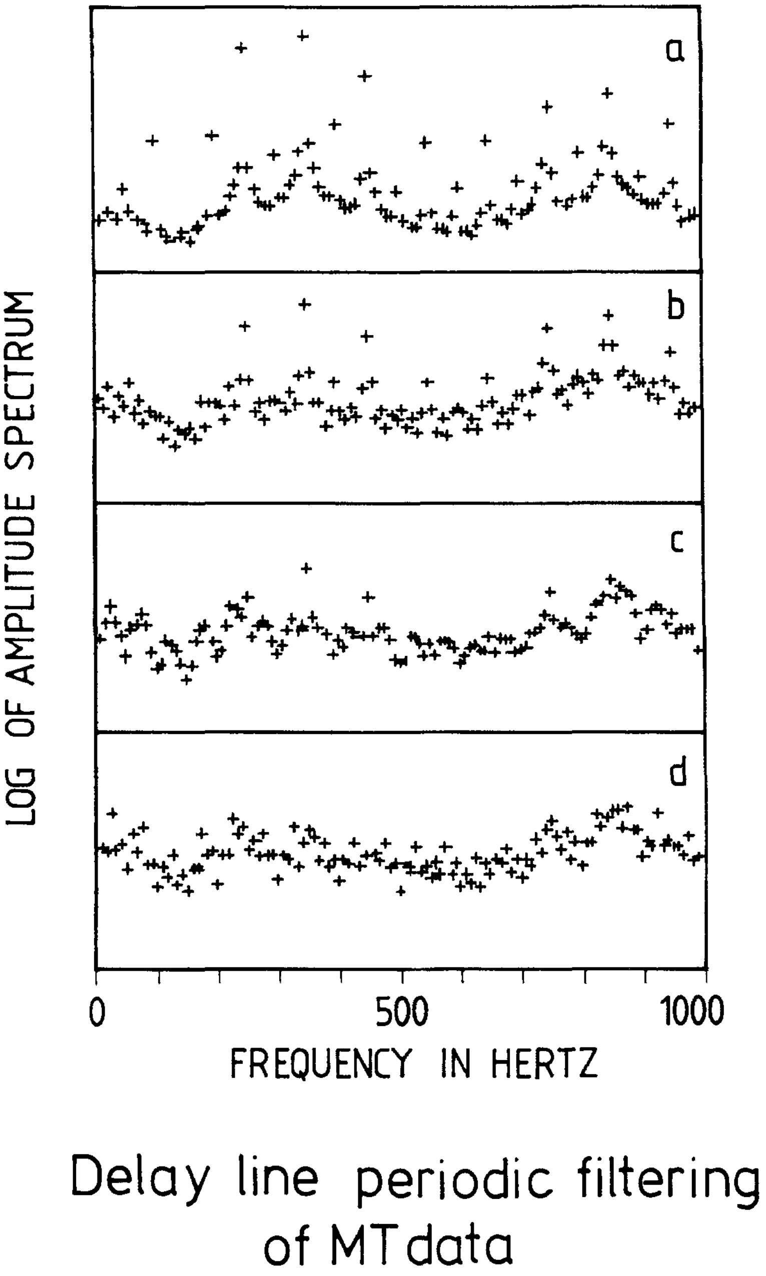

Fig. 11. Effectiveness of delay-line periodic filtering of MT data (Fischer, 1982). (a) no delay-line filter; (b) delay-line filter with $\delta = 60$ ms; (c) delay-line filter with $\delta = 20$ ms; (d) simultaneous application of delay-line filters b. and c.

the whole frequency range, sometimes up to several hundred megahertz (Grachev, 1975). Sergeev (1983) deals with special measuring problems of natural electric fields influenced by industrial noise.

A traditional *visual separation by analogue recording* has preserved its own importance:

According to Ádám *et al.* (1986) the analogue MT recording in some cases has its traditional advantages over digital recording. These include an easier selection of noise-free sections and a manual elimination of a few uncorrelated noise impulses. It must be remarked that so far the visual separation has been the most perfect and easiest way to distinguish natural pulsations and man-made disturbances.

As a summary conclusion it can be stated that computer-controlled data acquisition systems (as indicated by the numerous references) have further possibilities in increasing the signal-to-noise ratio, especially if they will take into account special as yet unemployed features of signals and artificial noise.

7. Geophysical Information Obtained from Man-Made EM Noise

Man-made constructions below and at the surface (regardless of whether they are active or only passive sources) usually hinder the EM field measurements.

Nevertheless, in some situations these constructions can serve as prospecting tools. E.g. geoelectrical ultra-deep soundings can only be carried out if already existing transmission lines are available which are not yet commercially used (Blohm *et al.*, 1977) or for large-scale magnetotelluric measurements pipelines might be applied (e.g. Heinrich and Junge, 1984).

The EM field produced actively by man-made constructions may be also applied to geophysical prospecting.

EM disturbances which have been used for geophysical prospecting can be divided into two groups:

— abrupt impulse-like disturbances having a duration of several seconds (irregular noise)

— network frequencies and their harmonics (regular noise).

Dupouy (1950) calculated horizontal electric conductance values near Chambon-la-Forêt from horizontal electric and magnetic fields of *abrupt impulse-like disturbances* due to an electric railway line.

Kishinouye (1951) could make SP measurements only at night. In the daytime he mapped the direction of stray currents which agreed with the SP anomaly map.

Kovalevsky *et al.* (1961) found the attenuation of electric components with the distance from the railway line to be a function of the subsoil resistivity.

Porstendorfer (1961a, 1961b) replaced in a mine the classical telluric technique by a vectorial mapping of stray currents including measurement of the vertical component. He found the stray currents to be channelled by high-conductivity veins.

Hogervoorst (1977) obtained geological information from the electric fields of impulses due to a railway power substation in Spain. He assumed a source consisting of the rails regarded as a closely spaced series of n ($n = 100$) equal current point sources, and the power station as one point source n times larger, and with the opposite sign. The difference of the measured and computed maps gave an indication of buried geological inhomogeneities.

Yanagihara (1977) found that a difference in observed/calculated ratio of the magnetic field was due to non-uniformity of the resistivity in the area.

Sapyzhak and Vanyan (1982) proposed a deep EM sounding by means of transients of electric impulses generated in a power line for melting ice on wire lines.

Szarka (1983) used related electric and magnetic square impulses of unknown origin in mapping high-resistivity basement structures. Ádám et al. (1986) gave a summary of how such noise impulses can be used to obtain geological information. In one of two measuring sites along the Periadriatic lineament they observed a strong induction effect; while several km away only square impulses could be recorded from the same source. This phenomenon was interpreted to be due to the high-conductivity Periadriatic line.

There have been numerous experiments to obtain geological information from *power harmonics*, too:

Hoover *et al.* (1978) on the basis of the ubiquity of harmonics suggested using them as signal sources. Takács (1979a, b) has elaborated various observational configurations to obtain geological information from 50 Hz power lines. Takács and Egerszegi (1981) found agreement between 50 Hz electric profile measurements and reflection seismic profiles. Electric mapping by 50 Hz EM fields was proposed to extrapolate structural elements already found by mining seismics or by the mining itself. An agreement was observed between 50 Hz profiles and CSAMT curves, too, as is shown in Figures 12 and 13 by Takács (1983).

A geophysical application of a 16 2/3 Hz EM field due to an electric railway line is known from the GDR (Pawlik, 1980; Legler and Porstendorfer, 1984).

Strangway *et al.* (1980) used in their AMT survey the electromagnetic field created by a power line current instead of weak natural signals. They call their method power harmonic magnetotellurics (PHMT).

McCollor *et al.* (1982, 1983) and Fisk (1985) measured 60 Hz and its odd-harmonic magnetic components. By means of a so-called characteristic crossover distance McCollor *et al.* (1983) obtained a resistivity variation with depth. A geological fault has been mapped as existing between profiles. Resistivity values inferred from crossover distances in their two different measuring profiles are demonstrated in Table IV. Russel (personal information to McCollor *et al.*, 1983) pointed out that subharmonic components might also be usable for EM exploration, but this technique needs further investigation.

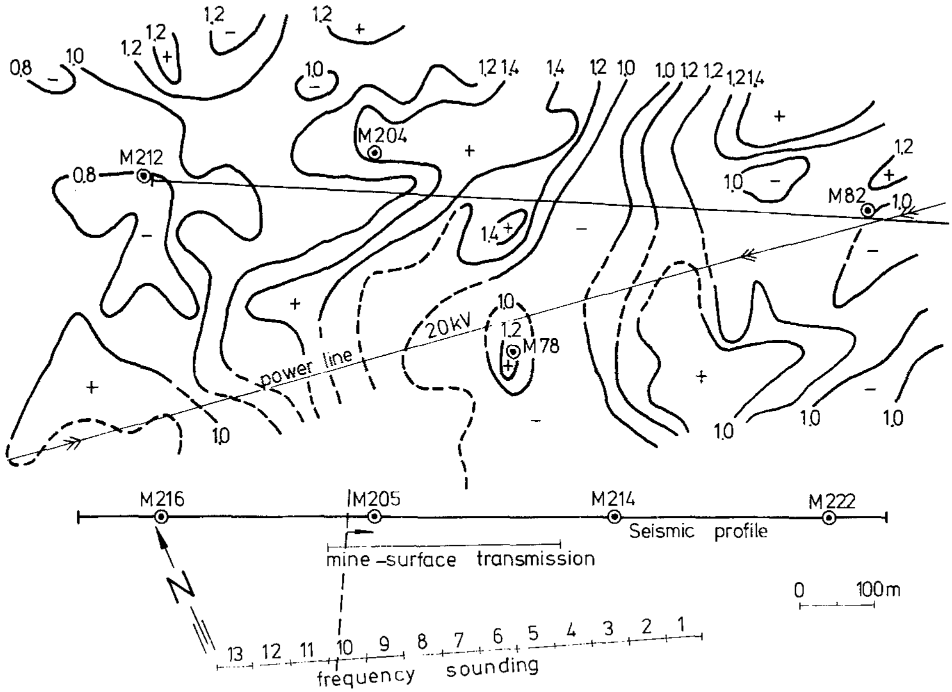

Fig. 12. Isoline map of the 50 Hz measurement over the Szuhavölgy mine shaft, Hungary (Takács, 1983).

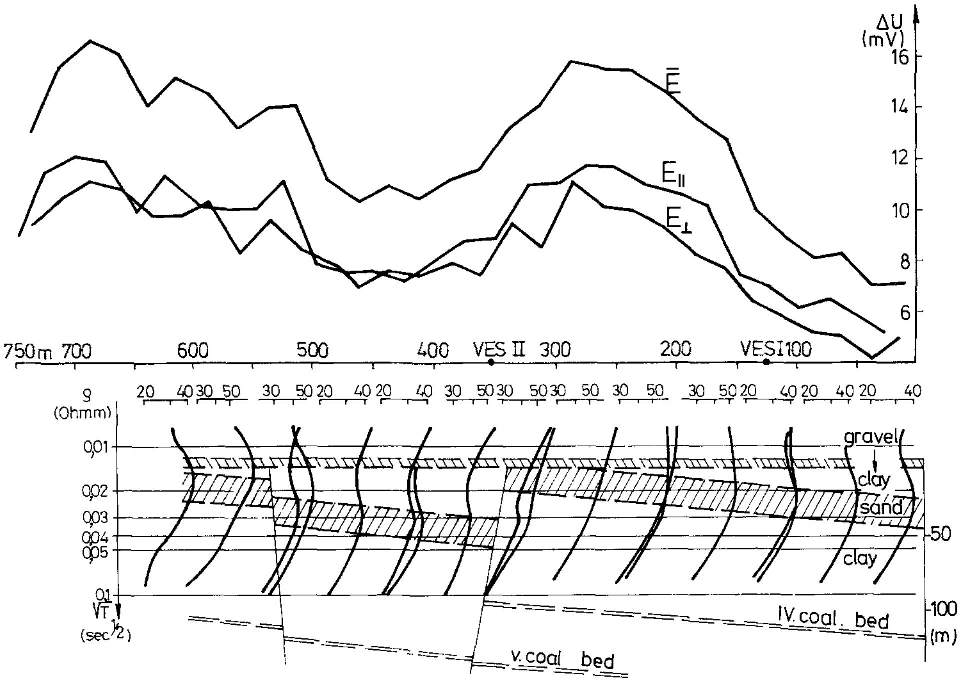

Fig. 13. Comparison of 50 Hz measurement and frequency sounding curves with the geological cross-section revealed by mine galleries in the Szuhavölgy mine shaft, Hungary (Takács, 1983).

TABLE IV

Resistivity inferred from crossover distance (McCollor *et al.*, 1983)

Profile	Harmonic frequency (Hz)	Crossover distance (km)	Resistivity (ohmm)
	300	5.5	1.8
AB			$\times 10^4$
	420	5.9	2.9
	180	3.0	3.2
CD	300	3.0	5.5 $\times 10^3$
	420	2.3	4.3

Remark: Crossover distance is defined by a distance from the power transmission line, where the magnetic field variation changes from the $1/r$ dependence to the $1/r^3$ dependence.

Smith *et al.* (1983) measured power harmonics with the aim of estimating the electromagnetic power radiated upwards into the ionosphere from such lines.

When discussing the perspectivity of man-made EM noise in geophysical prospecting, it must not be forgotten that man-made noise may be one of the sources of the AMT field itself as long as it fulfills the plane-wave condition at a survey site (Schnegg and Fischer, 1984; Lakanen, 1986). The piquancy of the affair lies in the fact that the AMT method has been generally known as a 'natural' method.

Application of man-made EM noise for geophysical prospecting can be found in numerous papers in the Soviet Union, as is indicated in the Referativny Zhournal (1973—1985). Ioffe *et al.* (1961), Yakubovsky *et al.* (1972), Orlov and Sarbash (1972), Orlov and Nadoko (1972), Korizin and Viguzov (1974), Orlov *et al.* (1974), Muzilev (1974), Veshev and Yakovlev (1975), Yegorov *et al.* (1977), Semenov and Berezin (1977) dealt with possible or already realized applications mostly in mining geoelectrics or in ore prospecting. Efimov (1980) described an instrument for the stray current method. Zakharov *et al.* (1980), Zakharov (1982) measured amplitude and phase of the harmonic magnetic field of industrial origin. Idarmachev and Kazaryantz (1981) tried to prognosticate barrage earthquakes due to a hydroelectric station in Dagestan by industrial currents. Gamoyan *et al.* (1983), Pershin and Shumakov (1984), Volkov *et al.* (1984) Bobrovnikov *et al.* (1985) have been the latest Soviet publications in this field.

From the Northern Czech coal basin Bezvoda and Procházka (1973) published a geological application.

Three recent patents (Fornahl and Menzel 1981; Antonova *et al.*, 1981; Ádám *et al.*, 1984) also indicate further perspectivities of this kind of EM prospecting methods.

8. Summary

In spite of a very poor and contradictionary definition of EM noise terminology it can be outlined from many sporadic publications that accomodation of geophysicists to the ever-increasing man-made EM noise in the earth includes

— studies on EM distortion effects of man-made constructions below and over the surface

— field observation of EM disturbances due to active man-made EM sources

— better understanding of the source mechanism

— efforts to improve the signal-to-noise ratio by instrumental, methodological and data-processing methods

— application of these usually hindering effects for geophysical prospecting, as far as possible.

In this paper the above mentioned aspects have been summarized mainly on the basis of papers published in geophysical journals.

Passive EM distortion effects are due to man-made constructions below or over the surface, they can be handled as resistivity inhomogeneities.

Disregarding some special disturbances, two main types of active EM disturbances of man-made origin can be observed: harmonics which are quite permanent in time (regular noise) and sudden impulses (irregular noise).

Active man-made disturbances are due to consumers and some other electric power elements which cause imbalances of networks. These unbalanced currents enter the earth as leakage currents or may act inductively or capacitively. Here the most probable sources have been summarized. As Eigner (1984) suggests, in any individual case concerning the source mechanism it is advisable to study electrotechnical papers published in the various series of IEEE Transactions and IEE Proceedings.

The application of man-made EM disturbances as an electromagnetic prospecting technique is constrained by numerous factors: man-made EM field must be present; it must penetrate into subsurface structures having geological interest; such EM anomalies must be well measurable by simple EM instruments. The mostly disturbed areas (e.g. a metropolis) usually seem to be too chaotic for this purpose. Nevertheless, in mine areas or in the vicinity of power lines, etc. such a prospecting technique may prove to be very useful. The source is always more complicated than those already used in classical EM prospecting methods. To calculate theoretical EM fields of such sources requires better knowledge of the source mechanism and correspondingly more sophisticated approaches, but this problem in most cases does not meet numerical difficulties.

From the references it seems that geophysicists in US and in Western European countries concentrate first of all on suppression of man-made EM noise by using their sophisticated field equipment, while the Soviet and other Eastern European geophysicists have more experiences in geophysical applications of man-made EM noise.

I hope that bringing to light these old and new geophysical papers on this subject might be useful for further EM induction research.

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