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The Static Shift Problem in MT Soundings

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ABSTRACT

The MT method, like all resistivity methods that are based on measuring the electric field in the surface, suffer the so-called telluric or static shift problem manifesting itself in an unknown multiplier of the apparent resistivity (a constant shift on log-scale). This phenomenon is caused by resistivity in-homogeneities close to the electric dipoles. Severe topography can also lead to static shifts. Except for very high frequencies, the shifts are independent frequency. Static shifts can be extreme in geothermal areas in volcanic environments where resistivity variations are often huge. The problem is made even worse by the fact that the shifts are often not random. All soundings in large contiguous areas can be consistently shifted up or down. Extreme examples of this are presented here.

It is sometimes claimed that the static shifts can be dealt with by resolving the shallow resistivity structure around the electric dipole by measuring at high enough frequencies. This would hold true if the earth can be considered as a pure Ohmic conductor. But at high frequencies other processes set in. Capacitance and induced polarization effects become important and lead to reduction of the electric field and consequently bias the apparent resistivity down at very high frequencies.

Various techniques to use the MT data themselves to identify and correct for static shifts have been proposed and tried. These "pseudo" corrections are usually based on some spatial averaging and/or some statistical assumptions about the shifts e.g. that the shift multipliers are random and that the product of the shift multipliers of individual soundings is close to one for sufficiently many soundings covering large areas. It is shown here that this assumption is far from being true in geothermal areas in volcanic environments.

Since 3D inversion of large MT datasets became available, some service vendors have claimed that the 3D inversion can cope with static shifts. By detailed modelling of topography, shifts of topographic origin can be modelled to some extent. But it has also been claimed that shifts due to shallow resistivity in-homogeneities can be dealt with by using fine model grids near the surface. The inversion would then introduce appropriate resistivity bodies at shallow depth. This has, however, not been demonstrated convincingly in the literature.

The central-loop TEM method is only sensitive to the near surface resistivity structure and topography at very early times. At late times their effects have practically disappeared. Here it is shown that a joint inversion of MT and TEM data is a consistent and effective way to correct for static shifts in MT soundings and should be used in 1D and prior to 2D and 3D inversion. If static shifts are corrected for by TEM, topography should not be modelled in the inversion; that would account twice for shifts due to topography. It is the view of the author that, except in special cases like thick and homogeneous sediments close to the surface, MT data alone should be considered as incomplete data for geothermal exploration.

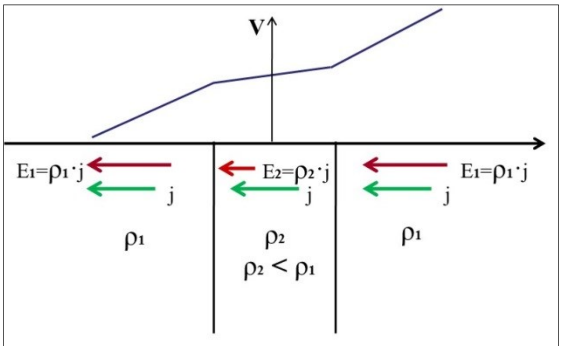
1. INTRODUCTION

The Magneto Telluric (MT) method is widely used to study the resistivity structure of the earth down to the depth of tens or even hundreds of kilometres. The MT method, like all resistivity methods that are based on measuring electric field in the surface, suffers the so-called telluric or static shift problem. The shift problem comes about because the electromagnetic field is distorted by shallow resistivity anomalies at, or close to, the sounding site and/or topography. Except at very high frequencies, the magnetic field is not much affected (Groom, 1988) but the electric field can be severely affected. At very high frequencies the electric field is distorted both by induced Eddy currents and galvanic distortion. At lower frequencies (below a few hundred Hz), most commonly used in geothermal exploration, the electric field is practically only subject to galvanic distortion and has an unknown frequency independent multiplier, relative to the undistorted field, causing shifts of the apparent resistivity curves when plotted on log-scale.

The unknown shift multiplier in the apparent resistivity directly scales the resistivity values obtained by interpretation of the soundings. According to the dependence of the depth of penetration (skin-depth) on the resistivity, depths to resistivity boundaries will be also be scaled by the square root of the multiplier. It is therefore evident that interpretation of un-corrected MT data can lead to drastically wrong resistivity models. The purpose of this paper is to review the telluric shift problem. It will be demonstrated, both by model calculations and extensive field data that the shifts can be severe, both up and down, and what is even worse, they can be systematic in large contiguous areas.

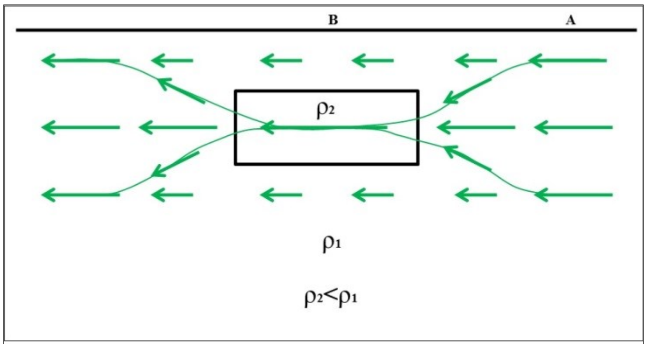
2. SHIFTS DUE TO NEAR-SURFACE RESISTIVITY INHOMEGENITIES

Static shifts caused by resistivity in-homogeneities close to the electric dipoles of the MT soundings can be thought of as arising from two phenomena: 1) electric field distortion due to the dependency of the electric field (voltage gradient) on the resistivity of the material where the voltage difference is measured and 2) current distortion (current channelling or repelling).



$$\rho_{a1} = \frac{1}{\omega\mu}\left|\frac{E_1}{H}\right|^2; \rho_{a2} = \frac{1}{\omega\mu}\left|\frac{E_2}{H}\right|^2 = S*\rho_{a1}; S = \frac{\rho_2^2}{\rho_1^2} \lhd 1$$

Figure 1: Electric field distortion causing shift.



$$\rho_{aA} = \frac{1}{\omega\mu}\left|\frac{E_A}{H}\right|^2; \rho_{aB} = \frac{1}{\omega\mu}\left|\frac{E_B}{H}\right|^2 = S*\rho_{aA}; S<1$$

Figure 2: Current distortion causing shift.

Figure 1 shows schematically the variation of the voltage and electric field (slope of the voltage curve) in the surface when a constant current density flows through 2D domains of different resistivity (extending infinitely deep). In this example $\rho_2 < \rho_1$ and the electric field (or the voltage difference over a given length) is lower in the low resistivity domain. Unless at very high frequencies where Eddy currents may be induced, this lowering of the electric field is independent of the frequency of the current. According to the definition (given in Fig. 1) the apparent resistivity will be lower in domain 2 than outside. If $\rho_1 > \rho_2$ the electric field and the apparent resistivity would be higher in the central domain than outside.

The other phenomenon, current channelling, is schematically illustrated on Figure 2. When current is flowing in the ground with a localised resistivity anomaly, it is deflected. If the anomaly is of lower resistivity than the surroundings, the current is deflected (channelled) into the anomaly and if the resistivity is higher, the current is repelled out of the anomaly. If the anomaly is close to the surface, this will affect the current density at the surface and hence the electric field and apparent resistivity. Like for the voltage distortion, this effect is independent of the frequency of the current density except at very high frequencies.

An observant reader will note that if the surface anomaly on Figure 1 would have limited depth extend, or generally limited spatial extend, current channelling will counteract the electric field distortion to some extent, but as will be shown below, the electric field distortion will dominate.

To demonstrate how these effects affect MT soundings, simple model calculations similar to those presented by Sternberg et al. (1988) are shown here. The model calculations are done by the 3D code wsinw3dmt (Siripunvaraporn et al., 2005). Two cases are presented. Case-1 is a 3m thick 300m x 300m low resistivity surface patch of 5 Ωm in a 500 Ωm surface layer of a simple layered model (443 m of 500 Ωm, 300 m of 10 Ωm, 10 km of 50 Ωm and 10 Ωm basement). Case-2 is a 300 m x 300 m and 30 m thick 5 Ωm low resistivity body at 13m depth in the 500 Ωm top layer of the same layered model as in Case-1. For planar view and sections through the models see Figure 3.

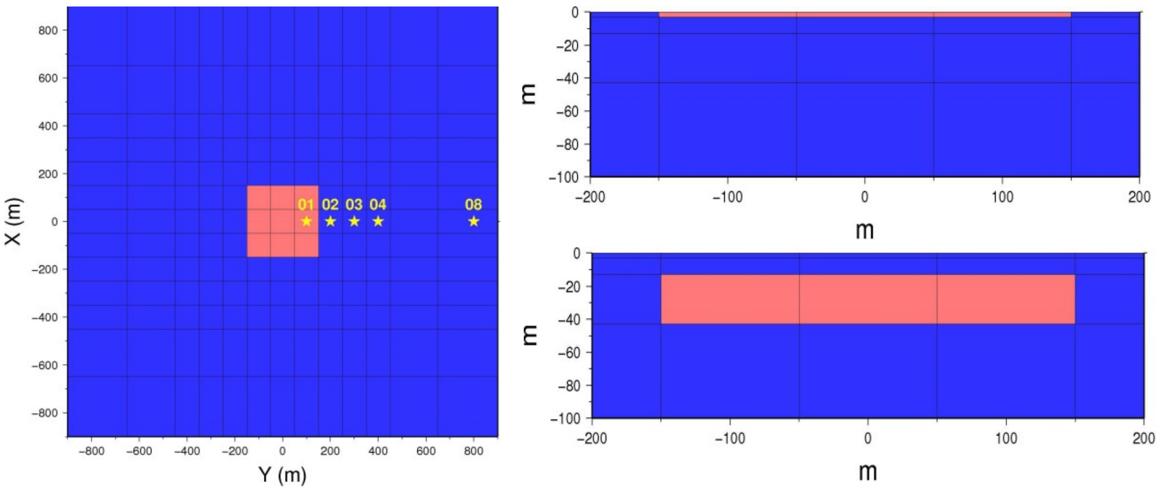


Figure 3: Left, planar view of resistivity anomalies; Case-1 (surface to 3m) and Case-2 (13m to 43m). Near surface vertical section at x=0 through model in Case-1 (top right) and in Case-2 (bottom right)

The MT response was calculated for 31 periods from 10^{-3} s to 10^{3} s and for five stations as shown on Figure 3 (station-01 at 100m, -02 at 200m, -03 at 300m, -04 at 400m and -08 at 800m distance from the centre of the anomaly). Figure 4 shows the calculated apparent resistivity and phase for the xy (Ex/Hy, red stars) and yx (Ey/Hx, green stars) polarizations respectively for stations 01 through 04 for Case-1. For comparison the coincident responses for the two polarizations at location 08 are shown (purple lines).

Figure 4a shows that inside the patch the apparent resistivity for both polarizations is shifted severely down by the same amount due to voltage distortion. At very high frequency (short periods), induced Eddy currents in the patch play a role and the phase deviates from that of station 08, but at periods longer than 10^{-2} s, the phase is practically undistorted while the apparent resistivity is scaled down (shifted on log scale) relative to that of station-08 by a multiplier practically independent of period (frequency). For station-02, 50m outside the patch (Figure 4b), current channelling causes the apparent resistivity of the xy polarization to be shifted down but the yx polarization to be shifted up. The x-component, parallel to the resistivity discontinuity, is reduced because some current is channelled away from the site and into the low resistivity while the y-component, perpendicular to the discontinuity, is increased by the current channelling into the anomaly. The phase is a bit distorted at very short periods due to Eddy currents. Further away from the anomaly, the shifts decrease and have practically disappeared at station-08, 650m outside the anomaly.

Figure 5 shows the apparent resistivity and phase for the xy and yx polarizations for stations 01 through 04 for Case-2. The shifts are similar to but more extreme than in Case-1 and the phase is distorted by induction effects to longer periods, especially above the conductive body. Figure 6 shows the apparent resistivity and phase calculated from the determinant of the impedance tensor for station-02 for both Cas-1 and Case-2. The figure shows that for the thin surface patch the determinant apparent resistivity is not shifted but for the berried low resistivity body it is shifted down. This is consistent with Figures 4b and 5b because apparent resistivity from the rotationally invariant determinant are in a way an "average" over all directions. The observation that the determinant apparent resistivity less affected by surface in-homogeneity close to the sounding site is of importance because it shows that, if TEM sounding is not available for static shift correction, inversion of the determinant apparent resistivity (or apparent resistivity derived from the average of the off-diagonal elements of the tensor) is less prone to errors than inversion of the individual polarisations.

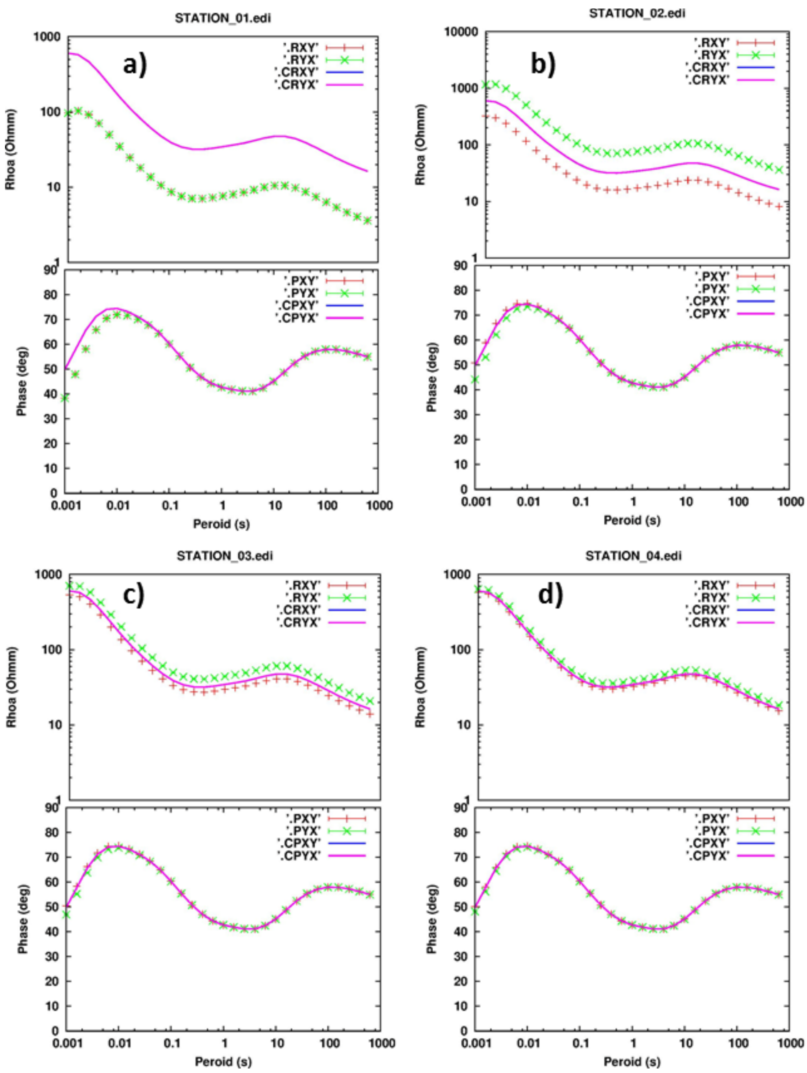


Figure 4: Calculated apparent resistivity and phase for Case-1 (low resistivity surface patch) for stations 01 (a), 02 (b), 03 (c) and 04 (d). The xy and yx polarizations are shown as green and red stars, respectively. The coincident xy and yx polarizations for station 08 are shown for comparison by purple solid lines.

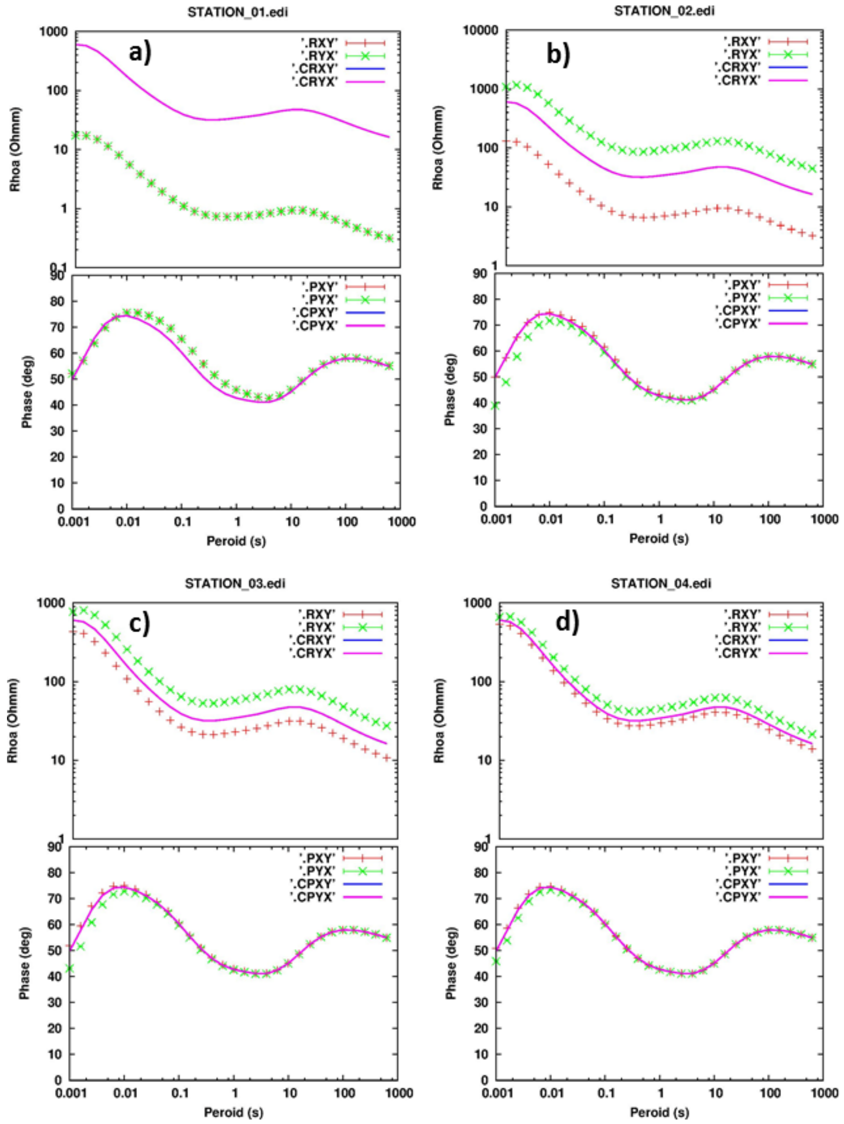


Figure 5: Calculated apparent resistivity and phase for Case-2 (low resistivity body at 13m depth) for stations 01 (a), 02 (b), 03 (c) and 04 (d). The xy and yx polarizations are shown as green and red stars, respectively. The coincident xy and yx polarizations for station 08 are shown for comparison by purple solid lines.

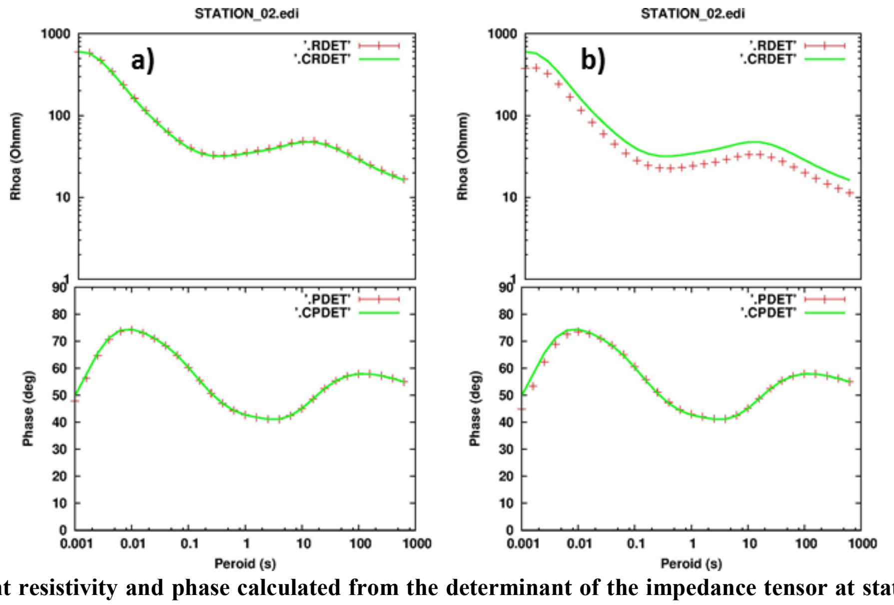


Figure 6: Apparent resistivity and phase calculated from the determinant of the impedance tensor at station 02 for Case-1 (a) and Case-2 (b).

We have seen here two examples where local resistivity anomalies close to the electric dipoles of MT soundings can result in severe shifts. Both of these circumstances are quite common in geothermal areas in volcanic environment. They are often characterised by very resistive surface lavas. Where the geothermal fluid reaches the surface there can be patches of very conductive clay alteration surrounded by very resistive lavas, producing severe voltage distortion. If the conductive clay minerals dome up to shallow depth but not quite to the surface, they can result in extensive current channelling.

3. TOPOGRAPHIC EFFECTS

Topography can also lead to static shifts by current distortion as shown schematically on Figure 7. The induced current density, flowing mostly laterally, is spread out in local topographic highs but concentrated in topographic lows. In the case of constant resistivity earth, this will lead to apparent resistivity lower than the true resistivity on topographic highs and higher in topographic lows.

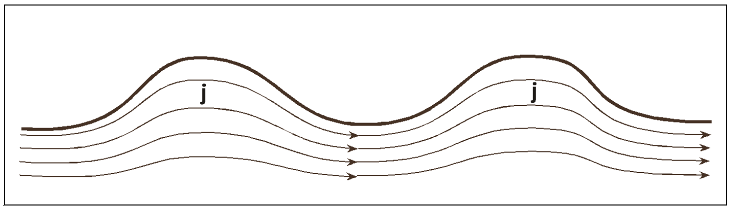


Figure 7: Distortion of induced current density in homogeneous earth due to topography.

An example of this is demonstrated on Figures 8 and 9. The data are from a joint MT and TEM survey of the Montelago geothermal prospect on the island of Mindoro in the Philippines (Hersir et al., 2014). The Montelago area has a very rugged topography characterized by very steep, 100-200 m high ridges and hills with narrow valleys in between. The Figures show static shift multipliers of the MT apparent resistivity derived from the determinant of the tensor. The shift multipliers were determined by joint inversion with central-loop TEM soundings at the same spots (within < 50 m; for further discussion of this procedure see below). Figure 9 shows that shifts down (S < 1) are much more common than shifts up. Figure 8 shows that the spatial distribution of the shift multipliers correlates with the topography, showing soundings at high altitude more shifted down than soundings at topographic lows. This is also seen on Figure 9 where the shift multipliers are plotted versus elevation of the soundings. Even though the Figure shows considerable scattering, it is evident that in general the shift multipliers decrease with increasing elevation. It should not be concluded here that MT data are generally more shifted down at high altitudes; the correlation here is because in this case the higher altitude data are on ridges or peaks, not on plateaus, and the low altitude soundings are generally in narrow valleys.

Figure 9 is quite informative. Firstly, it shows that shifts down are much more common that shifts up (several examples showing the same are presented below). Secondly, the scatter and general decrease of the shift multiplier with elevation shows that, in the case of substantial topography, shifts are due to both in-homogeneities at the sounding site and topography. Thirdly, it was found that, even in this rather extreme topography, a joint inversion with central-loop TEM (with small source loops of 100 m x 100 m) could consistently fit the TEM and MT data with the same model and resolve the shift multiplier, irrespective of its origin (in-homogeneities, topography or both).

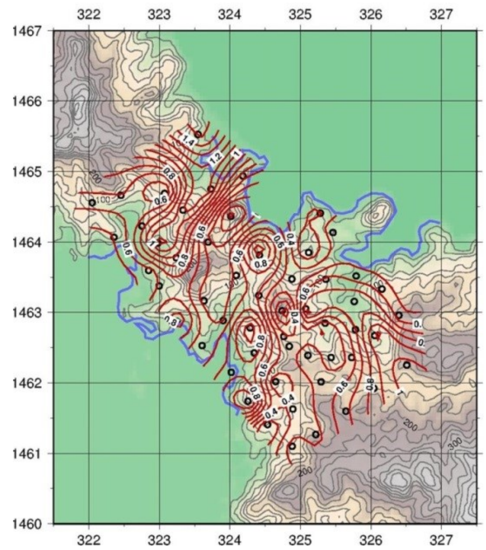


Figure 8: Spatial distribution of shift multipliers and Elevation in Montelago (black circles are MT/TEM stations). Coordinates are UTM km. (Modified from Hersir et al., 2014.)

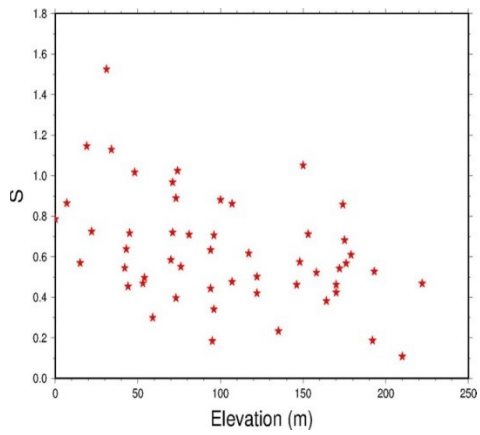


Figure 9: Static shift multipliers (S) in Montelago versus elevation.

4. ATTEMPTS TO MEND FOR STATIC SHIFTS

Several ways of dealing with static shifts have been proposed in the literature. An exhaustive literature survey will not be given here, but some of them are summarised by Sternberg et al. (1988). Some of these attempts make use of spatial filtering using closely spaced soundings or even continuous electric field profiling referred to as EMAP (Bostic, 1986). Jones et al. (1992) tried the assumption that at long periods the TE mode apparent resistivity should have a smooth spatial variation. Additional observations, like known thicknesses of geological units of different resistivity (from well-logs) have also been used. deGroot-Hedlin (1991) proposed to consider the shift multipliers as unknown parameters that are inverted for in 2D inversion by demanding smooth models and that the product of the shift multipliers for many soundings covering relatively large area should be close to one (sum of all shifts on log-scale zero). Ogawa and Uchida (1996) developed this idea further, by assuming that the shifts (log of shift multipliers) have Gaussian distribution around zero. Below these assumptions will be confronted with field data.

Groom and Bailey (1998) make a very interesting effort to amend distortions of the impedance tensor by local in-homogeneities close to the sounding site, by what is now generally termed as Groom-Bailey decomposition. Their approach does, however, not address the shift problem. They only deal with mixing of the components of the electric field components ("twist" and "shear") due to distortion by local resistivity anomalies but the frequency independent shift multipliers are not determined. Another weakness of their approach is that, apart from 3D local anomalies, they assume that the underplaying resistivity structures is either 1D or 2D. If this is the case, it might be worth while performing Groom-Bailey decomposition before static shift correction is done.

It is sometimes claimed that static shifts can be dealt with by resolving the very shallow resistivity structure around the dipole by measuring to high enough frequencies so that currents induced by the electromagnetic wave only penetrate shallow depths. This would hold true if the earth could be considered as a pure Ohmic conductor. But at very high frequencies other processes set in. At high frequencies the earth (rocks) does not behave like a pure Ohmic conductor. In addition to the Ohmic conduction capacitance and induced polarization effects become important.

To qualitatively understand the capacitance effect, we consider a simple electrical circuit analogy of alternating current running through parallel connected resistor of resistance, R and a capacitor of capacity, C (Figure 10). If the total current through the resistor and the capacitor is $I = I_0 \cdot e^{i\omega t}$, then the voltage is given as:

$$V = \frac{RC}{i\omega R + C} Io \cdot e^{i\omega t} \tag{1}$$

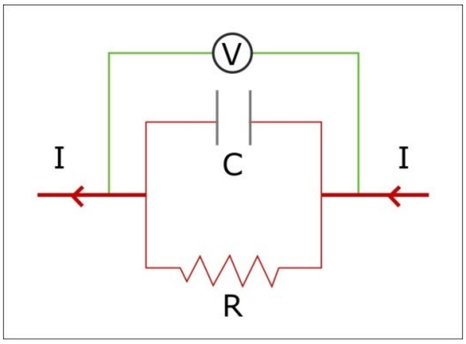


Figure 10: Simple circuit analogy of capacitance effect.

For low frequencies and low resistance R the effective resistance (impedance) is close to R and the voltage is in phase with the current. But for high frequencies and high resistance the effective resistance decreases and the voltage gets out of phase with the current. In terms of MT soundings, this means that in the case of very resistive surface layers, like dry lavas, the electric field is decreased at high frequencies making the apparent resistivity biased down and the phase gets distorted.

As mentioned earlier, the rocks in geothermal systems are subject to geothermal alteration. At temperatures lower than about 240°C the dominant alteration minerals are clay minerals and zeolites (Árnason, et al., 2000). These minerals are very conductive and form the so called low resistivity (clay) cap on the outer margins of the geothermal systems. In addition to high conductivity, clay minerals have high induced polarization (IP) capacity. The IP effect can be described as if the rocks have, in addition to galvanic conductivity, a frequency dependent complex conductivity (Bertin and Loeb, 1979):

$$\sigma = \sigma_0(1 + i\varepsilon_{IP}\omega/\sigma_0) \tag{2}$$

where σ_0 is the DC conductivity and ε_{IP} is a parameter similar to a dielectric permittivity. If the current density is $j = j_0 \cdot e^{i\omega t}$ then Ohm's law gives:

$$E = \frac{\rho}{i\omega\varepsilon_{IP}\rho + 1} jo \cdot e^{i\omega t} \tag{3}$$

where ρ is the DC resistivity ($1/\sigma_0$). If ε_{IP} is large (values as high as 0.8 ms/Ω have been reported (Bertin and Loeb, 1979)) and if the frequency is high the electric field is reduced and, like for the capacitance effect, the apparent resistivity is biased down and the phase is distorted.

The microscopic physics behind the capacitance and IP effects is similar (polarization) and equations (1) and (3) have basically the same form (ε_{IP} is like inverse capacitance). These two effects are discussed separately here because the former appears due to very high surface resistivity and the latter due to high IP capacity of conductive clays.

In geothermal areas in volcanic environments very resistive surface lavas are quite common and clay alteration is also common at, or close to, the surface. It is also commonly observed, when performing joint inversion of TEM and MT data, that the MT apparent resistivity is biased down and the phase distorted at the shortest periods (highest frequencies) and the two datasets cannot be fitted with the same model. But if a few of the shortest periods of the MT are discarded, they can be nicely fitted with the same model.

5. TEM, THE REMEDY

In the central-loop Transient Electro-Magnetic (TEM) method a loop of wire is laid on the ground and constant current transmitted in the loop. The current builds up a magnetic field of known strength. The current is then abruptly turned off. The magnetic field is left without its source and responds by inducing an image of the source loop in the surface. Due to Ohmic loss (heat), the current and the magnetic field decay and again induce currents at greater depth. The process can be visualized as if the induced currents diffuse downwards and outwards with time like a "smoke fringe" (Nabighian, 1979) as schematically shown on Figure 11. The decay rate of the magnetic field with time is measured by the induced voltage in a coil at the surface. The decay rate of the magnetic field with time is dependent on the current distribution which in turn depends on the resistivity distribution. The induced voltage in the receiver coil, as a function of time, can therefore be interpreted in terms of the subsurface resistivity structure.

It is clear from the discussion above, and has been thoroughly confirmed by model calculations (e.g. Sternberg et al, 1988), that near surface resistivity anomalies only affect the TEM at very early times. At late times the current distribution has diffused deep below near surface anomalies and their effects disappear. Similarly, topography can affect TEM at early times, but at late times, when the induced currents have diffused down below the topographic regime, the influence of the topography fates out.

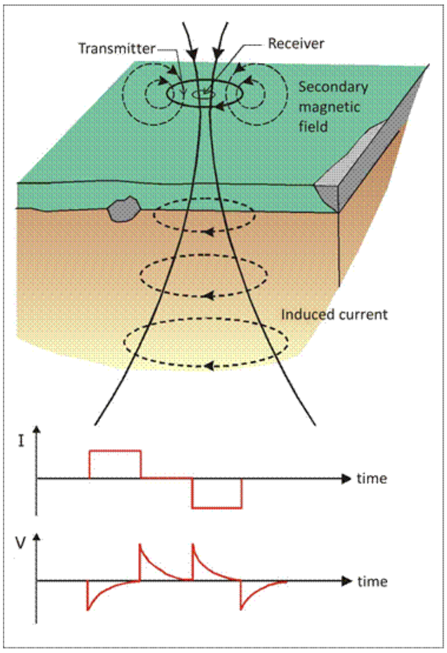


Figure 11: Schematic description of TEM soundings.

This is fundamentally different from the MT. In the case of MT, the electric field signatures of currents induced at great depths have to be conveyed all the way to the surface and hence are prone to near surface in-homogeneities as demonstrated above and frequently high frequency effects prohibit resolving the resistivity structure in the immediate vicinity of the electric dipoles. These properties of the MT and TEM methods have been known for a long time. In the late eighties people started to use TEM soundings to correct for static shifts in MT data (e.g. Sternberg et al., 1988). But some people still apply the MT method without proper static shift correction. This may be justified in areas with gentle topography and where the near surface rocks are homogeneous, such as sedimentary layers. High temperature geothermal systems in volcanic areas are the other extreme. They are normally characterised by very high resistivity contrast at the surface and shallow depths which are ideal conditions for extreme static shifts. Joint inversion of MT and TEM data at Iceland GeoSurvey has revealed shift multipliers a low as 0.1 (see below). If the shift was not corrected for, interpretation would give ten times too low resistivity values and about three times too shallow depths to resistivity contrasts.

Cumming and Mackie (2010) discuss the use of TEM for static shift correction of MT data. They question the applicability of TEM data collected with small loops in resistive environments. There is, however, no physical reason why TEM should not resolve the shallow resistivity structure in resistive environments, but big loops and/or large current may be needed to make the TEM data tie in with the MT data.

Watts et al. (2013) and Stark et al. (2013) question the use of TEM to correct for static shifts of MT in the case of extreme topography and show how TEM can be affected by extremely narrow, steep and high ridges (or valleys). The situations they consider are rather exceptional and the author considers that the example from Montelago above shows that TEM can be successfully used to correct for static shifts due to very rugged topography.

6. FIELD EXAMPLES

ISOR has been using MT soundings extensively for deep prospecting of high-temperature geothermal fields. Being aware of the static shift problem, ISOR developed software for joint 1D (layered earth) inversion of MT and TEM data (Árnason, 2006). In the data collection, care is taken to make both TEM and MT soundings in the same place (within less than 100 m). In the joint inversion, inversion is done for the model parameters and one additional parameter, a shift multiplier S. S is an a priori unknown parameter by which the MT apparent resistivity values have to be divided in order to fit the MT and TEM data with the response of a common model. The joint inversion is not just an efficient and objective way of determining the shift multiplier, it is also an important compatibility check of the data. If the TEM and MT data cannot be fitted with the same model, either TEM or MT data (or both) are distorted and soundings may need to be repeated. It is now the practice of ISOR to do such a joint inversion concurrently with the data acquisition to identify any corrupt data before leaving the field.

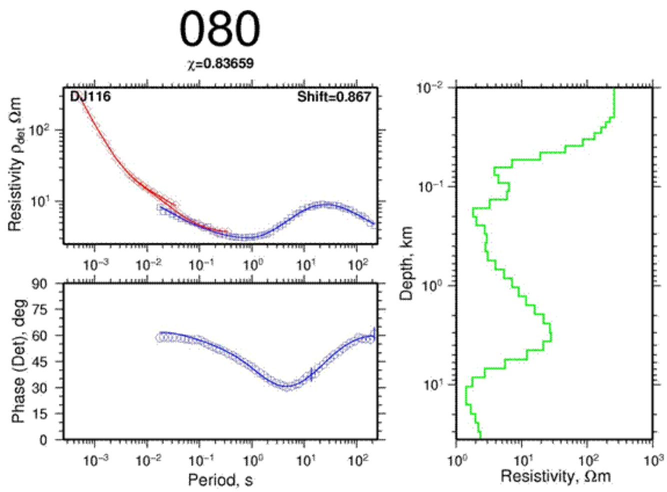


Figure 12: A typical result of joint 1D inversion of TEM and MT data. Red diamonds are measured TEM apparent resistivity, blue diamonds and blue circles are determinant of MT apparent resistivity and phase, respectively. Solid lines show the response of the resistivity model to the right. The shift multiplier is shown in the upper right hand corner of the apparent resistivity panel.

Figure 12 shows a typical result of a joint 1D inversion of a TEM sounding and the determinant apparent resistivity and phase of an MT sounding at the same place. In this case the shift multiplier (shown in the upper right hand corner of the apparent resistivity panel) is S=0.867, i.e. the MT apparent resistivity has to divided by this number to tie in with the TEM sounding (the time t after turn-off for the TEM data has been transformed to period T according to the transformation T = t/0.2 (Sternberg et al., 1988).

Below is some analysis of static shifts observed in three joint TEM and MT surveys in high temperature geothermal fields in volcanic complexes: The Krafla area in NE Iceland, the Hengill area in SW Iceland and the Asal Rift in Djibouti, East Africa. The first stage in the interpretation of the data is a joint 1D inversion of the TEM data and the MT determinant apparent resistivity and phase as described above. In such a joint inversion it was frequently observed that a satisfactory simultaneous fit could not be obtained for the TEM data and the shortest periods (highest frequencies) of the MT data. This is probably because the MT apparent resistivity is too low (biased down) at the high frequencies by the capacitance and/or IP effects discussed above. (The MT data are always processed using remote reference to avoid bias due to coherent noise in the magnetic field).

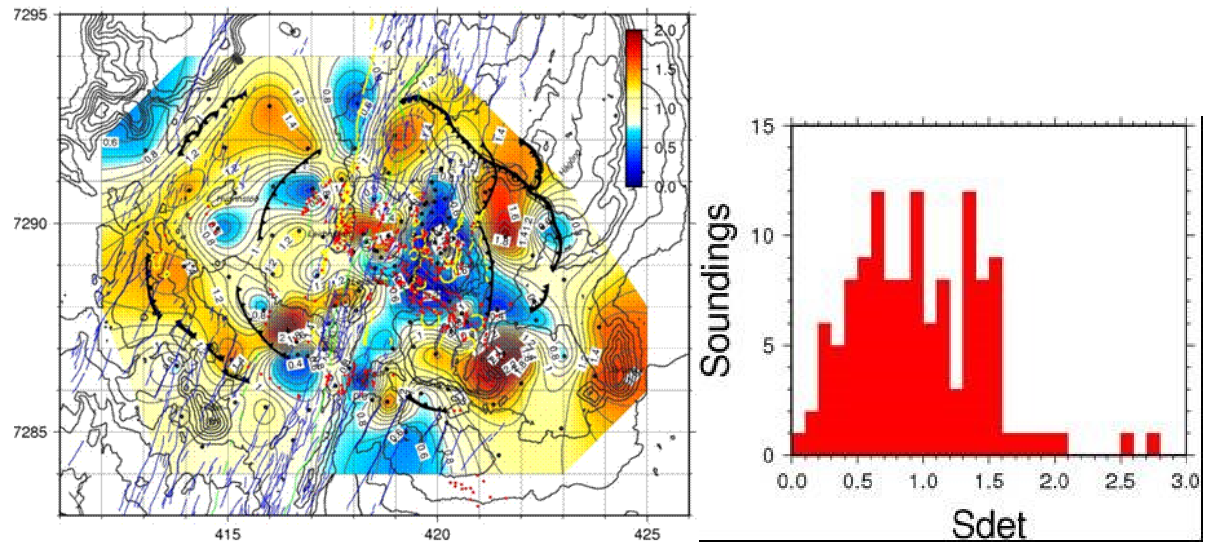


Figure 13: Map showing the spatial distribution (left) and histogram (right) of shift multipliers of determinant MT apparent resistivity in the Krafla area NE Iceland (Árnason et al., 2009). Red dots are geothermal surface manifestations. Coordinates are UTM km.

Figure 13 (right) shows a histogram of the shift multipliers of the determinant apparent resistivity for 124 MT soundings in the Krafla area, north Iceland, ranging from as low as 0.1 to 2.7. It is seen that multipliers less than one (shift down) are more common than greater than one (shift up). Figure 13 (left) shows the spatial distribution of the static shift multipliers in Krafla. The Figure shows that there are shifts up in contiguous areas on the outer parts of the survey area and severe shifts down in the central part were altered rocks reach the surface. The survey area in Krafla is rather flat and the observed shifts cannot be due to topography.

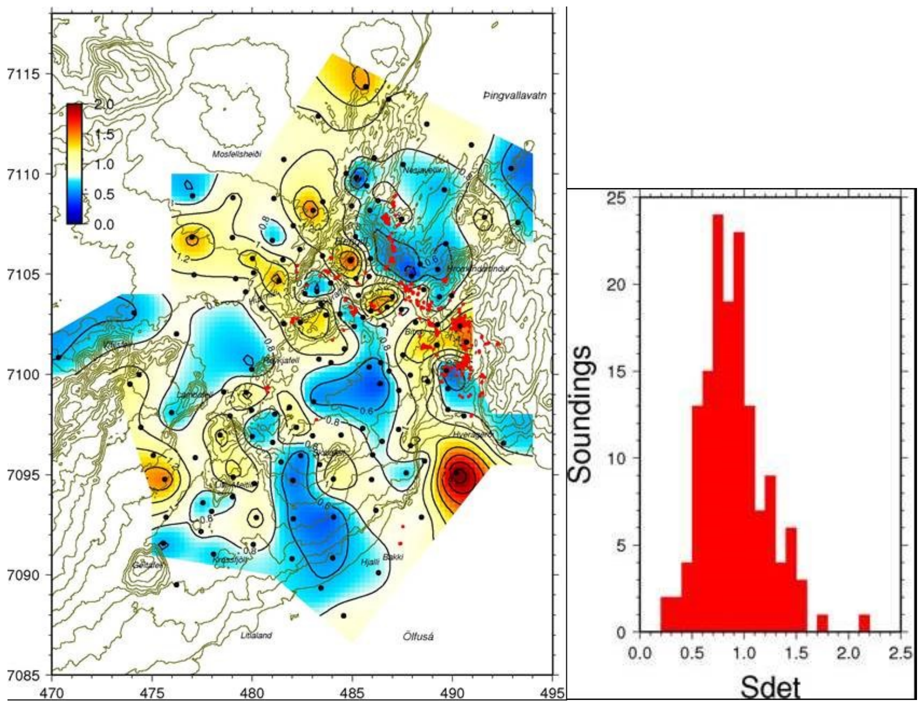


Figure 14: Map showing the spatial distribution (left) and histogram (right) of shift multipliers of the determinant MT apparent resistivity in the Hengill area SW Iceland (Árnason, et al., 2010). Red dots are geothermal surface manifestations. Coordinates are UTM km.

Figure 14 shows a histogram (right) and spatial distribution (left) of the shift multipliers of the determinant apparent resistivity of 146 MT soundings in the Hengill area, SW Iceland. The shift multipliers range from 0.3 to 2.3 and again values less than one are more common than the ones higher than one. The spatial distribution shows NW-SE trending areas with consistent shifts up or down, with the downshifts areas coinciding with intense surface (or near surface) alteration. The topography of the Hengill area is generally relatively gentle, except for the Hengill volcano which rises about 400 m above the surroundings. The map on Figure 14 shows no correlation between shifts and topography. On the contrary, it shows shift up along a NW-SE line crossing the mountain and shifts down to the NE and SW of the steep mountain.

A 3D inversion was performed for 60 MT soundings in Hengill area (Árnason, et al., 2010). The inversion was done for the full MT tensor. Prior to the inversion, a static shift correction of the tensor was done by individual joint 1D inversion of the xy and yx polarisations with the nearby TEM sounding. Fig 15 shows a histogram of the shift multipliers, both Sxy and Syx (a) and their ratio, Sxy/Syx (b). Fig. 15a shows that the distribution of Sxy and Syx is broader than the distribution of multipliers of the determinant apparent resistivity (Figure 14, right). This is in accordance with what the model calculations above showed (Figures 4, 5 and 6). Fig 15b shows that the ratio Sxy/Syx ranges from 0.2 to 4, but with the majority between 0.2 and 1.8. It is interesting to see that ratios less than one are more common than higher than one. The field layout was with the x-direction in magnetic north, N16°W, but prior to the shift correction and the 3D inversion, the tensor (and derived apparent resistivity) was rotated so that the new x-direction was along the strike of the fissure swarm through the Hengill volcano, N30°A. The reason for ratios less than one being more common could be that vegetation patches are elongated along the fault direction.

The final field example is from the Asal Rift in Djibouti, East Africa. Figure 16 shows a histogram (right) and spatial distribution (left) of the shift multipliers of the determinant apparent resistivity of 64 MT soundings in the area. The shift multipliers range from 0.1 to 2.2 and once again multipliers below one are much more common than above one. The spatial distribution shows severe shifts down in most of the survey area and few places of shifts up, mainly in the south part and the centre of the survey area. The Asal Rift is mainly a lava shield cut by, in some places big, NW-SWE trending normal faults, but relatively flat in between. There is no obvious correlation between shifts and topography seen on the map of Figure 16.

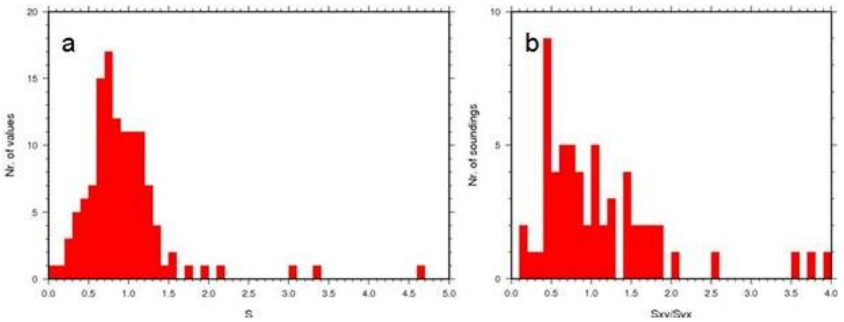


Figure 15: Histogram of the shift multipliers for the xy and yx polarisations of 60 MT in the Hengill area (a) and the ratio Sxy/Syx (b) (Árnason et al., 2010)

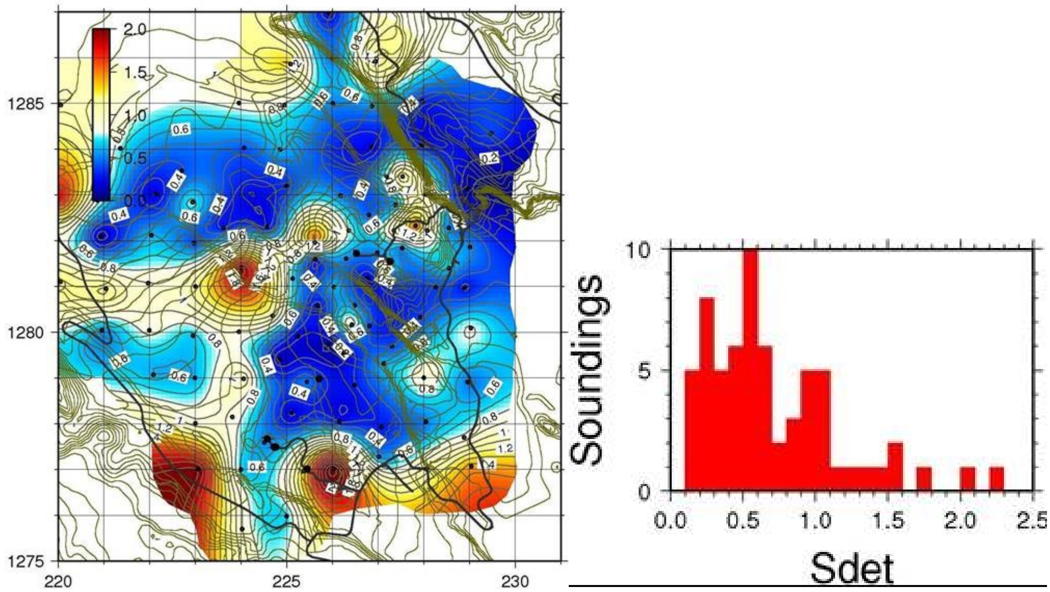


Figure 16: Map showing the spatial distribution (left) and histogram (right) of shift multipliers of determinant MT apparent resistivity in the Asal Rift in Djibouti (Árnason, et al., 2010). Coordinates are UTM km.

The maps on Figures 13, 14 and 16 show that the shift multipliers are not random, there are regions with consistent shifts, mainly shifts down. In the Krafla and Hengill areas the MT data are consistently shifted down where geothermal alteration minerals are found on the surface or at shallow depth. In the Asal Rift in Djibouti there are large areas where the MT data are consistently shifted down. It is obvious that if the shifts are not dealt with properly, the interpretation can give very false resistivity structure.

As mentioned earlier, some of the attempts to deal with the static shifts from the MT data alone make use of spatial averaging and some statistical assumptions. deGroot-Hedlin (1991) assumes that the shift multipliers are random and that the product of the shift multipliers is close to one (the sum of shifts on log-scale close to zero) for sufficiently many soundings covering large enough area. This assumption is tested in Table 1 which shows some statistics of the shift multipliers in Krafla, Hengill area and the Asal Rift.

Table 1: Statistics of shift multipliers.

Area	Nr. of soundings	Product	Mean	Geometric mean
Krafla	124	1.683e-10	0.969	0.834
Hengill	146	1.089e-10	0.905	0.855
Asal Rift	64	1.045e-16	0.702	0.563

It is evident from the Table that the assumption of deGroot-Hedlin that the product of the shift multipliers should be close to one is not valid, at least not for MT surveys in geothermal fields in volcanic areas. Different assumptions have been proposed for the statistical properties of the shifts (e.g. Ogawa and Uchida, 1996) and 2D, and even 3D, inversion including inversion for static shifts (Sasaki and Meju, 2006). It is, however, evident in all the examples shown here, that profiles could be run in areas where all the data are severely shifted nearly in the same way and comparison to other profiles that are shifted differently has little meaning.

Table 1 shows that shifts down are more common than up. One of the reasons is probably that it is generally preferred to locate the soundings on vegetated patches with conductive soil so that the electrodes get good contact to the ground. By doing this, the data are systematically shifted down.

7. CONCLUSIONS

It has been demonstrated that static shifts of MT data collected for geothermal exploration in volcanic environment can be a big problem. The shifts can be due to shallow resistivity in-homogeneities and topography. The former reason seems to be the dominant factor with the topographic effects superimposed. The shifts often affect soundings in relatively large contiguous areas in similar way. It is therefore clear that interpretation of MT data without properly accounting for the shifts can lead to seriously wrong resistivity models. It is demonstrated that joint inversion MT with a TEM sounding at the same place is an effective and consistent way to correct for the shifts.

After 3D inversion of large MT datasets became available some service vendors tend to claim that static shifts can be dealt with by the inversion. This has, however, not been convincingly demonstrated in the literature to the author’s knowledge. 3D inversion of MT data is a severely underdetermined problem and regularisation of the model is needed. Some sort of smoothness criteria is generally a part of the regularisation. But to deal with near surface anomalies, like the ones encountered in volcanic areas, the models need to be allowed to have considerable roughness in the near surface. Demanding smoothness at depth while allowing roughness near the surface calls for elaborate regularisation schemes and the resulting model will likely depend strongly on the scheme chosen. It is the view of the author that joint inversion with TEM is the safest and most consistent way to correct for static shift in MT data. As discussed above, this will also correct for shifts due to topography. A consequence of this is that if the MT data are shift corrected this way, topography should not be modelled in 2D or 3D inversion. This would account twice for the topography.

The author has experienced clients tempted by saving on geothermal exploration by not doing TEM soundings along with MT. But is should be kept in mind that resistivity models from MT surveys are often the basis for decisions on big investments in drilling. Saving on the cheap surface exploration resulting in misleading models can end up as very costly.

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