Resolving Ambiguity in TDEM Soundings

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Abstract

In shallow studies, TDEM is often measured only inside the loop and inverted for layered models. We examine some critical issues associated with 1D inversion of INLOOP data as this approach often leads to misleading models. This issue is due to the non-uniqueness of 1D INLOOP inversion. Without the ability to constrain the model to known geological parameters, the derived models will often be distortions of the true structure. The use of multiple data components in conjunction with a survey design deriving from geological knowledge helps locate more correct models.

Introduction

This situation arose as inversions were for a long time only available for central loop readings (Anderson, 1993).For our studies, we consider the standard impulse response. The current directed into a loop is turned off during each cycle and the magnetic response is measured with a coil with the current off. The currents subsequently produced in the earth migrate outwards and downwards with time with the rate of migration dependent on the resistivity structure. Thus, a sensor positioned inside the loop is further from the strongest current concentrations as time progresses. Therefore, receivers outside the loop will be more sensitive to the deeper materials as they are closer to current concentrations at depth.

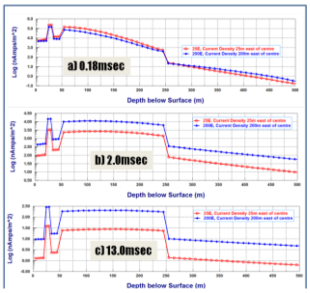

Figure 1: Current Density vs. Depth; (a) Early time (b) Late early time

Simple simulation of current migration beneath the ground will demonstrate. The amplitude of the horizontal electric field to our standard model (Fig.2) is computed using a 100m square loop, a base frequency of 2.5Hz and current of 25Amps. The horizontal current density (Fig.1) is shown as a function of depth at two stations; 25E inside loop (blue) and 200E outside (red). At early time (0.18ms) and shallow, the induced currents are more concentrated close to the loop center but at depth the current outside can exceed the current under the loop. By late early time (2 ms), the currents have migrated down to be concentrated in the conducting zone between 45m and 245m (Fig.2). Now the currents below the outside station are an order of magnitude greater than those below the loop and this difference increases to almost 2 orders by 13ms. In addition, for in loop data, we are limited to vertical components and only the decay rates and data amplitudes are targets of inversion. This is opposed to the use of OUTLOOP data which has additional inversion targets. Inversions can use multiple vertical data measurements as well as horizontal components for receivers outside. This allows for the extension of the search for the best fitting model to a significantly increased number of data. This now allows for under parameterized model inversions which have significant resolution benefits over smoothed parameter methods. Also two critical physical effects are readily observed in OULOOP data which when utilized in inversion increase the accuracy of the inversions. The first effect, observed in off time data, is the migration with time of a sign crossover in the vertical field. The second effect, in the horizontal component, is the time migration of the peak response outwards from the loop. These effects are simply the result of the induced currents migrating away from the loop with increasing time.

Utilization of Current Migration

We utilize the synthetic model in Figure 2. This model is site specific deriving from the understanding of shallow strata in the area north of the Taklimakan desert. The surface is covered with weathered volcanics and resistive due to dry conditions. Below, a local water table is observed as a thin conductive layer in the Quaternary sediments. Our target is the saturated or partially saturated deeper Jurassic sandstone which is the regional aquifer beneath the Neocene strata. This aquifer is not a single strata but rather a series of sandstone, mudstone and siltstone sedimentary layers with conductivities dependent upon water content. Below are unconsolidated, impermeable Paleocene rocks. The field data site is extremely flat with surficial vertical gradients of order 1.2°. Our synthetic instrumentation will emulate our field equipment. We utilize a small loop (100x100m) common to studies within this area, with a bipolar current waveform (2.5Hz) and a sharp linear turn-off (ramp). Synthetic INLOOP

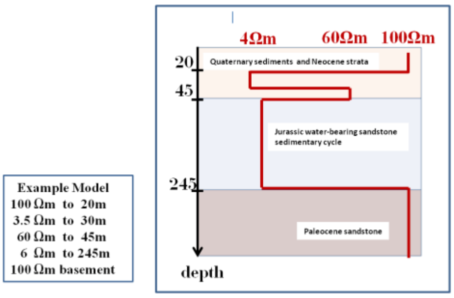

Figure 2: Synthetic Model Migration Studies

measurements of dBz/dt (Fig. 3) are in off-time. We utilize standard time windows with no extremely early windows so as not to overcomplicate the analyzes. Forward modeling algorithms use standard frequency domain simulations (e.g. Boerner, 1984) with a time transform accurately simulating our instrument's system response.

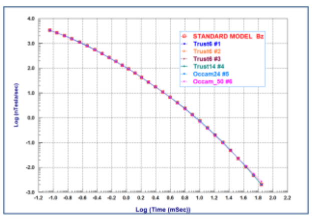

Figure 3: Model and Inversion responses

Figure 3 are the model response (red) with six model responses selected from our many inversion models using two applications (1X1D, EMIGMA). Displayed models (Fig.4) all differ significantly from our model. Synthetic data from five models are indistinguishable from the model's data while the sixth is indistinguishable in practice. The misfit in all cases was less than 1.6% (LS). All inversions used a uniform resistivity starting model. The first three inversions are five layers over basement utilizing a trust region technique (Jia *et al*, 2009) with different starting models. This technique allows for both thicknesses and resistivities to vary with constraints although no constraints were applied. All three detect the resistivity of the main conductive layer but not the correct boundaries. The fourth model is a 14 layer trust region model. Inversions 5 and 6 are smooth Occam type inversions. Generally, both inversions styles show a resistor at top, a conductive zone and resistor at the bottom. In the second

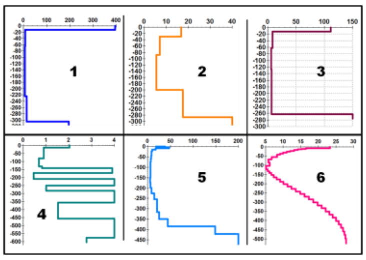

Figure 4: Six inversion models of the INLOOP response of our standard model

experiment, we perform the inversion adding two measurements outside at 150m and 250m from centre with a base frequency of 25Hz. Groom and Jia (2005) applied inversions to combined INLOOP and OUTLOOP data to demonstrate that outside data can accurately resolve deep structures. Auken et al (2005) studied the control of inversion depths using laterally constrained inversions with central loop data. The first inversion (Fig.5 left), is a 4 layers over basement, 3 station dBz/dt inversion (Fig.5, left) with a uniform starting model without constraints. The layers are well resolved in depth but resistivities

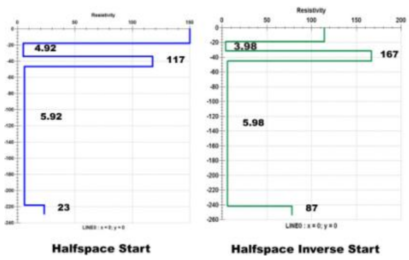

Figure 5: Comparison of model results from multi-separation strategy

are not optimum. In the second inversion, we incorporate Bx (Jia et al, 2009). Now depths are well resolved (Fig. 5 right). Conductive layer resistivities are accurate but resistive layers are not as accurate. The misfit criteria for both inversions was set very low and thus the fits are almost exact.

Case Study 1 – 2016 Survey

After some years working with survey strategies, we undertook field experiments near Hami,17km from the northern edge of the Turpan-Hami basin bordered by the Tian Sian range. Four small loop surveys were collected at two base frequencies with varying station locations (Geonics EM67, Protem).

Loop and station positions were surveyed to eliminate as much survey noise as possible. We anticipated that the ground to be highly one dimensional but the surveys were designed to verify the hypothesis. In

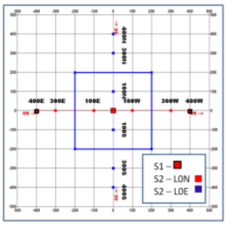

Figure 6: Survey 1 (6.25Hz) and Survey 2 (25Hz) stations

this report, we will describe our results for 2 surveys. After our synthetic studies of the geologically based model (Fig2), we increased the loop to be 200m square. The first survey at 6.25Hz (S1, Fig 6) measured (Bx/dt, Bz/dt) for 3 stations on L0N (400E, OE, 400W) with (0E,0N) being loop center. S2 measured 13 stations, 6 on L0N and 7 on L0E at 25Hz. 2048 stacks were read at all stations with 3 repeats using approximately 12A. The extra stations were measured to check the one dimensionality of the response as stations at equal distance should have identical vertical component responses with the horizontal responses flipping in sign. We show a portion of our inversion studies with the central loop studies with the central loop data of S1 (Fig.7). All 11 models fit the data almost exactly but apart from some agreement on resistivities between 50 and 125m, there is no concensus. Depth to the strong conducting zone varies between 35 and 60m and the depth to the bottom of the conductor vary between 125 to 142m while the resistivity varies between 7.7 and 12.9 Ωm.

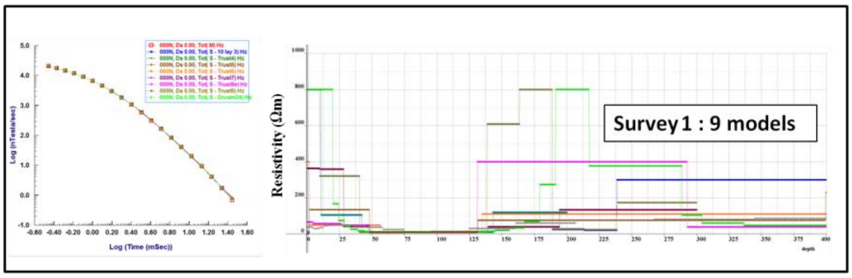

Figure 7: Survey1 (6.25Hz) 11 models: Left: Model fits to data, Right: Resistivity to Depth

The next step was to check that the responses at the reciprocal stations matched sufficiently closely to verify our layered resistivity assumption. We then further averaged and differenced the responses producing the compressed surveys with 2 stations for S1 (0E,400E) and 4 stations for S2 (0,100,300,400E). The next stage was to jointly invert the resulting data utilizing both vertical and horizontal field components. Our standard model derived from geological knowledge (Fig2) was the starting model. The results are shown in Figure 8. Simulation studies were then performed which verified that the model parameters were well determined except for the basement resistivity. Upon examining the remaining surveys, it was determined that the 4th zone must be sub-divided into two zones, the upper slightly more resistive layer and a lower slightly more conductive zone. A 5 layer over a basement inversion model resolved the depth to the basement as 615m (+/- 10) and the resistivity to be greater than 800Ωm.

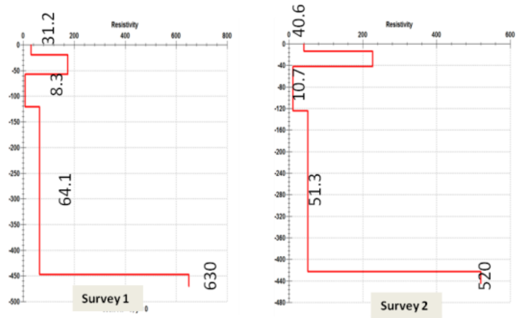

Figure 8: Joint Component and Station Inversions for S1 and S2.

Acknowledgements

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CONCLUSIONS

For TDEM soundings, the use of only a single measurement whether INLOOP or OUTLOOP leads to much ambiguity in the interpretation. Utilization of both INLOOP and OUTLOOP measurements and combining horizontal and magnetic components significantly lowers this ambiguity. The use of geological information both in survey design and in the inversion process are critical to accurate results.

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Author Biographies

Groom, Ross: PhD Physics University of Toronto 1988; Research Manager, Eikon Technologies LTD, Ontario, 1994-Present. Ross has spent over 30 years studying and developing numerical algorithms to effectively simulate the responses of geophysical instruments focusing on accurately incorporationg their system responses. He has worked on effective techniques to interpret and invert geophysical techniques. He has managed the developement of two extensive software applications, EMIMGA and QCTool.

Lei Yang; B.Sc,M.Sc, China University of Geosciences (Beijing). Since 2010, he has been performing transient electromagnetic surveys across regions like the Hami Basin, Huahai-Jinta Basin, Qaidam Basin, Yin'e Basin, and other parts of northwest China. His core responsibilities include mapping sedimentary layers and identifying fault types and orientations. Throughout his career, he has contributed to 22 projects involving transient electromagnetic measurements, leading 4 of them. He has received notable recognition, including a first prize in science and technology from China National Nuclear Corporation, along with multiple other awards.