Land-based TEM Data Processing: from Turn-off Ramp to Full Waveform

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Abstract

Data-processing methods only considering the turn-off ramp in transmitting waveforms are well established for land-based transient electromagnetic (TEM) methods. The turn-on ramp effects on late-time responses are generally neglected by data-processing methods. Our forward-modeling results of homogeneous half-space models show that the full-waveform effect which includes both effects caused by turn-on and turn-off stages is common for a wide range of conductivities. The inversion results for synthetic and field examples illustrate that the inversion algorithm which does not consider the full-waveform effects can lead to a higher resistivity in deeper parts of recovered models compared with the true model. Therefore, it is of vital importance to account for the full waveform effects in both forward modeling and inversion algorithms. We use synthetic examples to show how our inversion algorithms can improve the recovered model, and use real-data examples to show the importance of incorporating full transmitting waveforms in data-processing procedures.

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Key Points:

- The full-waveform effects are proven to be common for a wide range of conductive media, not only for highly conductive media.
- The full-waveform effects occur in late-time stages, and can lead to an inaccurate recovered model in inversion, especially at deeper parts.
- The base waveform used in data processing is updated from a turn-off ramp to a full waveform to improve interpretation results.
Abstract

Data-processing methods only considering the turn-off ramp in transmitting waveforms are well established for land-based transient electromagnetic (TEM) methods. The turn-on ramp effects on late-time responses are generally neglected by data-processing methods. Our forward-modeling results of homogeneous half-space models show that the full-waveform effect which includes both effects caused by turn-on and turn-off stages is common for a wide range of conductivities. The inversion results for synthetic and field examples illustrate that the inversion algorithm which does not consider the full-waveform effects can lead to a higher resistivity in deeper parts of recovered models compared with the true model. Therefore, it is of vital importance to account for the full waveform effects in both forward modeling and inversion algorithms. We use synthetic examples to show how our inversion algorithms can improve the recovered model, and use real-data examples to show the importance of incorporating full transmitting waveforms in data-processing procedures.

Plain Language Summary

The land-based transient electromagnetic (TEM) method has been widely used for mineral prospecting, hydrogeological investigation, and engineering geological exploration, and is also the promising geophysical method for detecting groundwater on Mars. There are many factors such as the full transmitting waveform can affect the accuracy of data interpretation. The transmitting waveform consists of the following continuous stages: turn-on, steady, and turn-off stages. At present, the effects of the turn-off stage on TEM responses are well recognized, and are routinely incorporated into data-processing algorithms. However, the effect of turn-on stages is generally ignored, which could lead to errors in data interpretation. Our goal is to investigate the full-waveform effects which refer to the effects of turn-on, steady, and turn-off stages, as well as cycle number. Our forward-modeling study using synthetic examples show that the full-waveform effects are common for a wide range of conductivities. With our 1-D synthetic inversion study, we find that when the full-waveform effect is not accounted for, the recovered model tends to possess higher resistivities in deeper parts of the model compared to the true model. We then show that the recovered model becomes closer to the true model when the full-waveform effect is incorporated.
1 Introduction

The land-based transient electromagnetic (TEM) method has been widely used in areas such as metallic and nonmetallic deposit prospecting (e.g., Oldenburg et al., 2013; Lu et al., 2021), hydrogeological investigation (e.g., Creighton et al., 2018; Blanco-Arrué et al., 2021), engineering geological exploration (e.g., Xue et al., 2007; Sandersen et al., 2021). It is also the promising geophysical method for detecting groundwater on Mars (Grimm, 2002, 2003; Grimm et al., 2009). For TEM data interpretation, one-dimensional (1-D) inversion methods are still routinely used, although three-dimensional (3-D) inversion methods are becoming increasingly more popular because of the development in algorithms and the advancement in computer technology (e.g., Yang et al., 2014; Liu et al., 2019).

Many factors can affect the accuracy of TEM data interpretation. For example, Flores & Peralta-Ortega (2009) demonstrate the induced polarization effects can affect their 1-D inversion results of the TEM data collected at a porphyry copper mine; Macnae (2016) reports the methods of fitting superparamagnetic and distributed Cole-Cole parameters to airborne TEM data. Another important factor is the transmitting-current waveform. For land-based TEM methods the most commonly used transmitting waveform utilizes a pattern of bipolar cycle. Figure 1a shows an example of a typical transmitting-current waveform for a single cycle. The waveform of a half cycle comprises four parts: turn-on, steady, turn-off, and ‘off-time’ stages. The first three stages together are referred to as ‘on-time’. The transmitting current increases gradually during the turn-on stage before it reaches the steady stage within which the current amplitude stays steady. Then, the transmitting current is turned off abruptly at the beginning of the turn-off stage. The measurement happens within the ‘off-time’ stage for most TEM instruments. After the ‘off-time’ stage ends, the transmitting waveform then repeats itself but with an opposite sign compared with the previous one. Another measurement stage then follows.
Figure 1. Diagrams of a typical transmitting-current waveform for one bipolar cycle, and the counteraction phenomenon between the TEM responses induced by the turn-on and turn-off stages. (a) A typical TEM transmitting waveform. (b) The decay curves for the TEM responses excited by the turn-on stage only, the turn-off stage only, and the full waveform consisting of turn-on, steady, and turn-off stages. Due to the contraction of the responses excited by the turn-on stage, the full-waveform responses are smaller than the ones excited by the turn-off stage. (c) A close view of the late-time curves in (b).

According to Faraday’s law of induction, the changing magnetic field associated with the abruptly changing current flowing in the source wires during the turn-on and turn-off stages will induce eddy currents in the subsurface. The two eddy current systems induced by the turn-on and turn-off stages, respectively, possess opposite directions. Both eddy current systems decay over time, and the second system will counteract with the first one if it has not completely decayed by the time the second system is induced (Figures 1b–1c). Due to the limited length of the steady stage used in realistic waveforms, it is often the case that the eddy current system due to the turn-on stage is still relatively strong by the time the current is switched off at the beginning of the turn-off stage. Depending on the conductivity of the subsurface, at the beginning of the measurement stage the second system may dominant the overall response. But the effect of the first system in the overall response often becomes relatively more important at late times as the second system also decays (Figures 1b–1c). A similar counteraction phenomenon can also happen for the eddy current system caused by the turn-off stage and the following eddy current system caused by the next turn-on stage. The secondary magnetic field or its time derivative, commonly measured in TEM methods, is associated with the decaying eddy current systems. Due to the counteraction phenomenon stated above, the data separately measured in the first two continuous measurement stages are therefore not equal, and have differences mainly in late-time data. When the conductivity in the model increases or the length of the steady stage decreases, the differences become larger (Zeng et al., 2019). Therefore, one of the reasons why TEM data
are measured after at least several and up to thousands of cycles of the waveform is to obtain stable TEM responses that do not change with cycle numbers. It is obvious that the TEM measured data are affected by the turn-on, steady and turn-off durations, as well as cycle number. Here the whole effects integrated from the effects of all the above waveform parameters are called as the full-waveform effects.

For models with modest conductivities, the largest influence of the full waveform on TEM data comes from the turn-off stage, and the effect of the turn-on stage mainly occurs in data measured at late times during the measurement stage. In practice, the TEM data suffer from cultural electromagnetic noises severely at late times when the response is small, and these noise-contaminated data are generally excluded in data processing. Therefore, it is acceptable for data-processing algorithms to neglect the effects of the full waveform. However, for models where there are significantly conductive anomalies, the electromagnetic field decays slowly with time which means the late-time data are still well above the noise floor, and should be considered in the data interpretation. In addition, the late-time data quality is improving due to the advancement of new denoising techniques (e.g., Wu et al., 2021; Wu et al., 2022). Therefore, it is important to develop data-processing techniques that can account for the full-waveform effects on TEM data. We will investigate the full-waveform effects in 1-D forward and inverse modeling using synthetic models, and two field examples.

2 Methods

The novelty of this study is replacing the base waveform, that is, the waveform assumed in the algorithms used for interpreting real TEM data, from a single turn-off ramp (Figure 2a) to the realistic full waveforms used by the actual survey instruments (Figures 2b–2d). As shown in Figure 2, Waveform 1 only contains a turn-off ramp, and is the base waveform adopted by the majority of data-processing methods for TEM datasets presently (e.g., Yogeshwar et al., 2020). Waveform 2 includes turn-on, steady, and turn-off stages. Waveforms 3–4 are waveforms of 50% duty, bipolar cycle, and add one and two cycles of Waveform 2, respectively.

In our 1-D forward modeling, the method of Li et al. (2016) is used to calculate the frequency-domain electromagnetic field excited by a rectangular loop source. Then, the 787-coefficient cosine and sine transforms are employed to obtain its corresponding impulse and step responses for a step-off waveform (Anderson, 1983). Finally, the time-domain responses excited
by a base waveform are calculated by the convolution method (Asten, 1987). This approach, referred to as ‘1-D analytic method + Convolution’, is validated by the 3-D full-time finite-element time-domain (FETD) method of Li et al. (2018) where a time-stepping algorithm was used to calculate the TEM responses. We denote the solutions calculated by the 3-D method by ‘3-D FETD + Waveform’.

Occam’s inversion method is applied to recovering subsurface electrical properties. The regularized inverse method seeks to minimize the objective function defined as follows (Constable et al., 1987; Key, 2009):

\[
U = \|\hat{\varepsilon}\| + \|P(m - m_0)\| + \mu^{-1}\left[\|W(d - F(m))\|^2 - \chi^2\right].
\]  

(1)

On the right-side of equation 1, the first, second, and third terms are the norm of model roughness, the measure of differences between the model \(m\) and a priori reference model \(m_0\), and the measure of data misfit between observed data \(d\) and predicted data \(F(m)\), respectively. We use \(\hat{\varepsilon}\) to denote the first-order difference operators which is essentially a matrix. Here, \(m\) is a vector of \(\log_{10}(\sigma)\), and \(\sigma\) is the conductivity for each layer. \(W\) is a diagonal matrix whose elements are the reciprocals of the standard deviation (SD) of data \(d\). \(\mu\) is the Lagrange multiplier. \(\chi^2\) is the root mean square (RMS) target data misfit. The objective function \(U\) is minimized iteratively by linearizing the forward-modeling operator \(F\) at the \(k\)th-iteration where the model is \(m_k\). Consequently, the formula used to calculate the next model \(m_{k+1}\) is given by

\[
m_{k+1} = \left[\mu(\partial^T \partial + PP) + (WJ_k)^T WJ_k\right]^{-1}\left[(WJ_k)^T W\hat{d} + \mu Pm_k\right],
\]  

(2)

where \(\hat{d} = d - F(m_k) + J_k m_k\), and \(J_k\) is the Jacobian matrix for model \(m_k\). The Jacobian matrix is set up via the perturbation of model parameters by 10%.
I (A)

$t_0$

Turn-off

Turn-on

Steady

$t_1 \ t_2 \ t_3$

Off-time

(b)

I (A)

$t_1$

Turn-off

Off-time

(a)

$t_0$

I ... $t_{19}$

Off-time

Off-time

(c)

$\begin{array}{c}
 t_8 \ t_9 \ t_{10} \ t_{11} \\
 t_4 \ t_5 \ t_6 \ t_7 \\
 \end{array}$

(d)
Figure 2. Four base waveforms analyzed in this study. (a–d) are for Waveforms 1–4, respectively.

3 Results

3.1 Synthetic models

The geoelectrical model used here is a homogeneous half-space with a resistivity of 100 Ωm. A transmitting loop is laid on the ground surface, and its size is 100 m×100 m. A receiver is placed at the loop center. Two transmitting-current waveforms adopted by the PROTEM instruments, and their corresponding time series are considered for both forward and inverse modeling experiments. The base frequencies of the two waveforms are 25 and 2.5 Hz, respectively. The two waveforms both have 50% duty and utilize a bipolar cycle (Woods, 2006). As a side note, ‘50% duty’ means that the durations of ‘off-time’ and ‘on-time’ are equal. For both waveforms the same turn-on and turn-off duration lengths are used and they are set to 1 and 0.01 ms, respectively. The steady durations are 8.99 and 98.99 ms for the two waveforms, respectively. In real-life surveys it is required to measure data after multiple cycles of a waveform. Here the cycle number is set to 8.25.

A term ‘relative difference’ rel_diff(t) at a given time gate t needs to be defined before analyzing the full-waveform effects. Its formula is given by

\[ \text{rel}_{\text{diff}}(t) = 100 \times \left( \frac{\text{resp}_{\text{base}}(t) - \text{resp}_{\text{ref}}(t)}{\text{resp}_{\text{ref}}(t)} \right), \]  

where \( \text{resp}_{\text{base}}(t) \) denotes the forward-modeling response excited by a base waveform, and \( \text{resp}_{\text{ref}}(t) \) is the reference response, which refers to the forward-modeling response excited by one of the two PROTEM waveforms with 8.25 cycles.

Figures 3a–3b show the relative differences between the responses (electromagnetic force, EMF) calculated with Waveforms 1–4 as shown in Figure 2 and the waveform with 8.25 cycles for the two base frequencies, respectively. As shown in Figures 3a–3b, the relative differences for the two methods of ‘1-D analytic method + Convolution’ and ‘3-D FETD + Waveform’ agree well with each other. For both the two base frequencies, the relative differences between Waveforms 1–4 and the waveform with 8.25 cycles increase exponentially with time, and all values are smaller than 3% expect for the last four times for Waveform 1. It means that Waveforms 2–4 qualify to be the base waveforms in TEM data processing, while Waveform 1 is
not effective when considering the late-time responses. Based on equation 3, the reference responses are inferred to be smaller than the ones excited by Waveform 1. This is largely caused by the fact that Waveform 1 does not consider the turn-on stage whose induced eddy current system can cancel out part of the responses caused by the turn-off stage. Effects of all previous turn-on and turn-off stages happened before the previous measurement stage at the final measurement stage are minimal because the relative differences observed for Waveforms 2–4 are much smaller than that of Waveform 1 as shown in Figures 3a–3b.

To investigate how the resistivity of the half-space models affect the full-waveform effects, we carry out a series forward modeling on a range of half-space models with resistivities ranging from 0.05 to 10\(^4\) Ωm. The same waveform parameters as used in the above experiment are also used here. Here we only consider the relative differences between the responses calculated with Waveforms 1–4 and the reference responses at the last time gates, namely 6.978 and 69.8 ms for base frequencies 25 and 2.5 Hz, respectively. As shown in Figure 3c, the relative differences decrease dramatically when the resistivity changes from 0.02 Ωm to 1 Ωm, and then stay basically unchanged as resistivity increases for the base frequency of 25 Hz. For the base frequency of 2.5 Hz which has a much longer steady stage compared with the one of 25 Hz, the relative differences do not even change noticeably between the first two resistivity values (Figure 3d). This is expected because as the base frequency becomes lower, the steady stage and the measurement stage all become longer, which then provides enough time for the effect of the turn-on stage for the case of Waveform 1 and the effect of the previous transmitting cycles for the cases of Waveforms 2–4 to decay. This numerical experiment demonstrates that the full-waveform effects are very common for a wide range of conductive media.

Now we investigate the effects of using different base waveforms in 1-D inversion taking the base frequency of 25 Hz and the half-space of 100 Ωm for an example. Gaussian random noises with a SD of 0.5–3% is added to synthetic EMF obtained from the forward modeling to generate observed data. Generally, the EMF’s signal-to-noise ratio (S/N) is high at early times, and then gradually decreases with time. Therefore, the SD gradually changes from 0.5% at early times to 3% at late times. We use an initial model comprised of 39 layers in the Occam’s inversion, and the layer thickness ranges from 5 to 40 m. The resistivity is 50 Ωm for all layers. The target RMS misfit is set to 1, and the maximum iteration number is 30. Due to different levels of random noises added into the observed data, we run the inversion code 20 times to
generate 20 models for each base waveform. The target misfit is reached within 3–7 iterations. Figures 3e–3h show the 20 recovered models for Waveforms 1–4, respectively. The recovered models obtained by using Waveform 1 as the base waveform can only reflect the true resistivity within 200 m below the surface (Figure 3e). The recovered models agree well with the true model when Waveforms 2–4 are used as the base waveform in the inversion (Figures 3f–3h). For all the recovered models obtained when using Waveform 1, they gradually deviate from the true model starting from the depth of 200 m, and the deviation becomes larger as the depth increases (Figure 3e). Obviously, Waveform 1 is proved to be problematic as a base waveform in TEM data processing because it does not account for the full-waveform effects.
Figure 3. The results of forward and inverse modeling for synthetic half-space models. (a–b) The relative differences between the responses calculated with Waveforms 1–4 and the reference responses for the half-space of 100 Ωm. The horizontal solid lines indicate a relative difference of 3%. (c–d) The relative differences between the responses calculated with Waveforms 1–4 and the reference responses for different-resistivity half-spaces. (e–h) The recovered models for the base waveforms using Waveforms 1–4.

3.2 Field data inversion

3.2.1 The Narenbaolige coalfield TEM data inversion

In this example, a TEM survey is conducted to delineate the shape of the subsurface basaltic body located in the Narenbaolige coalfield, Inner Mongolia, China. This resistive body is exposed on the surface, and is surrounded by conductive sedimentary rocks which include mudstone and sandstone. Two transmitting-current waveforms all with 50% duty, bipolar cycle are employed, and their base frequencies are 25 and 5 Hz. The real-life current waveforms are shown in Figure S1 in Supporting Information S1. The EMF data are measured at 30 gates ranging from 0.11 to 7.37 ms for the base frequency of 25 Hz, and from 0.51 to 19.75 ms for the one of 5 Hz.
A profile with 66 observation points, crossing through the basaltic outcrop, is chosen to test the full-waveform effects on data processing. Figures 4a–4d show the recovered models for the observation points at $x=680$ and 2040 m, which are located on the edge, and the central domain of this basaltic outcrop, respectively. For the base frequency of 25 Hz, the recovered models obtained considering Waveforms 1 and 2 show obvious differences below the depth of 100 m for the observation point at $x=680$ m, and below the depth of 200 m for the other observation point. The recovered models for Waveform 3 are similar with Waveform 2 (Figures 4a and 4c). For the base frequency of 5 Hz, the inversion results for Waveforms 1 and 2 agree well with each other (Figures 4b and 4d). The underlying reason for this agreement is that the full-waveform effects are still not evident at the last time gate (19.75 ms), which is much shorter than the corresponding duration of the ‘off-time’ stage (50 ms). The section views stitched from 1-D recovered models of the whole survey profile for the base frequencies of 25 and 5 Hz are shown in Figures S2–S3 in Supporting Information SI.

Figure 4. The inversion results in Narenbaolige coalfield. (a–b) The recovered models of the observation point at $x=680$ m. (c–d) The recovered models of the observation point at $x=2040$ m.
3.2.2 The Nantong mudflat example

A TEM survey is carried out to prospect geological structures at Nantong mudflat, Jiangsu, China. In this area, the sand layer is interbedded with clay within 500 m below ground surface, and the resistivity can be lower than 1 Ωm. The high conductivity of the area makes it suitable for investigating the full-waveform effects on TEM responses as higher conductivity has proven to be more sensitive to the full-waveform effects in our synthetic forward modeling presented above. We only invert for data collected at seven observation points within the same transmitting loop which has a size of 400 m×200 m. Its center coordinate is (1950, 0) m. The x and y coordinates are along the long and short sides of the source loop, respectively. For the seven observation points the x coordinate ranges from 1750 to 2050 m, and the y coordinate is fixed as 0 m. The transmitting waveform utilizes a 50% duty, bipolar cycle with a base frequency of 0.833333 Hz. The turn-on and turn-off stages are 0.5 and 1.0 ms long, respectively. Measurements are taken at 45 times ranging from -0.15 to 222.7 ms. The minus sign means that the first time is located in the turn-off stage. The magnetic field $b_z$ is recorded by a Crone SQUID sensor. As shown in Figure 5a, the magnetic field possesses a high S/N. Two observation points with x coordinates of 1800 and 1950 m were chosen to study the full-waveform effects.

The initial model consists of 46 layers with all their resistivities set to 1Ωm. We exclude the data recorded at the first gate in our inversion. Figure 5b–5c show the recovered models obtained by inverting all the off-time data at the two selected observation points while Figures 5d–5e show the recovered models obtained from inverting only the first 42 gates of the data (i.e., the last two gates are excluded). As shown in Figures 5b–5c, the recovered models for the four base waveforms agree well with each other within the depth of 100 m. However, they gradually diverge at depths greater than 100 m. The differences between the recovered models for Waveforms 1 and 2 are much larger than the differences between Waveforms 2 and 3 as well as between Waveforms 3 and 4. As shown in Figures 5d–5e, because the last two gates of data have been excluded inversion, the differences seem to be relatively smaller compared with those shown in Figures 5b–5c. Therefore, it is obvious that the full-waveform effects affect our inversion results and the impact can be mitigated by removing data from certain late-time gates. However, removing the late-time data from inversion when they have good data quality will inevitably lead to risks of discarding useful information of the subsurface targets that may only present in late-time data.
Figure 5. The measured TEM data and inversion results at Nantong mudflat project. (a) The decay curves of the magnetic data. (b–c) The recovered models by inverting 44-gate data. (d–e) The recovered models by inverting 42-gate data.

4 Conclusions

A comprehensive study of the full-waveform effects on TEM data is presented in this study. The forward-modeling results show that the full-waveform effects are common for a wide range
of conductive media, and further provide the theoretical basis for incorporating the full-
waveform effects in TEM data processing.

With both synthetic and field data inversion studies, we find that the full-waveform effects
can also significantly affect the recovered model if not taken into consideration in the inversion.
It is found with the synthetic example that the deeper part of the recovered model can have
higher resistivity values compared to the true model. Once the full waveform, including at least
the turn-on, steady, and turn-off stages, are used as the base waveform used in our 1D inversion,
the recovered model then approaches the true model very well. In the field data inversion, we
find that the recovered model changes significantly when different base waveforms are used in
the inversion algorithm, and late-time data greatly affect the recovered model. Therefore, we
believe that the full-waveform effects should be incorporated in the inversion algorithms when
they are routinely used in the processing of TEM data.

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Data Availability Statement

The data archiving is underway, and FigShare will be used to archive data. I have uploaded a
copy of data as Supporting Information for review purposes.

References

Anderson, W. L. (1983). Fourier cosine and sine transforms using lagged convolutions in
Survey.

Asten, M. W. (1987). Full transmitter waveform transient electromagnetic modeling and

https://doi.org/10.1190/1.1442302


