Responses to comments of Reviewer 1

Dear Reviewer 1:

We greatly appreciate your suggestions, and we hope our revisions have addressed your questions and made this manuscript better.

Sincerely,
Dr. Siming He

Comment 1. 1.show extracted measured spectra (i.e., the resulting "data" after noise removal and conversion to the frequency domain): |R(f)|, Phase(f).

Response.

We added Phase(f) to the experiment on synthetic SSIP data record. Figures 1 and 2 show the relative error of Phase(f) are calculated and compared at the three main frequencies when the noise RMS ranges from 0 to 0.9.

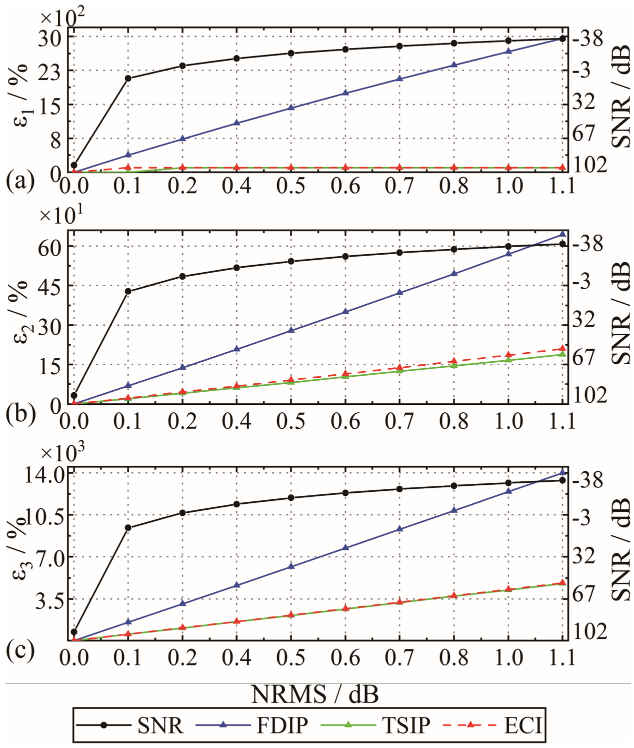

Figure 1. The effect of different degrees of Gaussian noise to the measures excitation signals in the phase-frequency characteristics. (a) SNR of the polluted potential signal. Complex resistivity relative error at (b) 80 Hz, (c) 160 Hz, (d) 320 Hz comparison using the three methods.

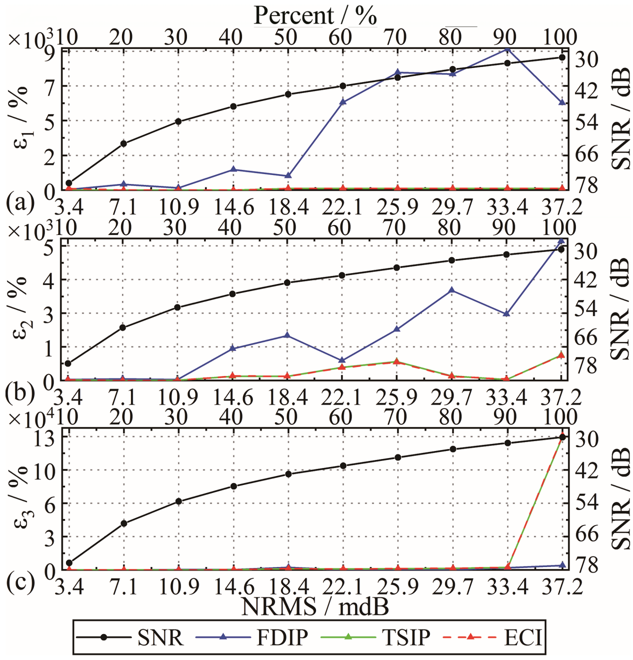

Figure 2. The effect of different levels of spike noises to the measured excitation signals. (a) SNR of the contaminated potential signal in the phase-frequency characteristics. Complex resistivity relative error at (b) 80 Hz, (c) 160 Hz, (d) 320 Hz comparison using the three methods.

From Figures 1 and 2, the results do not reflect the noise reduction performances of the three algorithms. Therefore, these results are not put into our manuscript. But |R(f)| and Phase(f) processed by three algorithms reflect their noise reduction performance well in the field experiment, as shown in Figure 3. So |R(f)| and Phase(f) in the field experiment are added to our manuscript.

This information is added on Page 9, line 16 and 17, Page 10, line 1 to 5 and Figure 3.

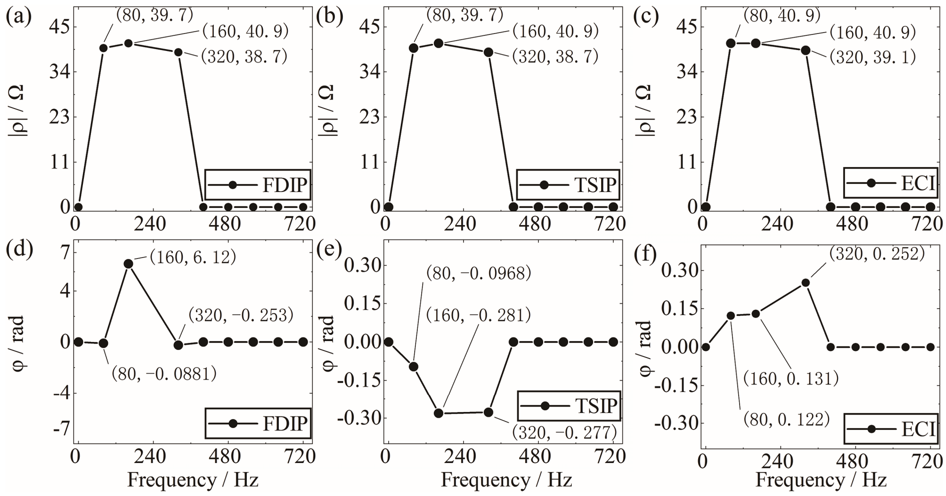

Figure 3. Complex resistivity spectrum calculated by the three algorithm (one period) in survey point No 21.

Comment 2. show phase results for the inversion results (if not easily included into the main text, additional magnitude/phase results for different frequencies could be supplied in a supplement)

Response.

The phase results for the inversion results given by Res2DInv software is shown as Figure 4. As we can see, this figure shows chaos information from the phase shift between $i(t)$ and $u(t)$ of the three methods. This is because the loss layer surrounding the shelter is very weak polarized, so the phase shift is very small, which cause the result easily contaminated by some random factors. Therefore, we have not figured out how to extract meaningful information out of the phase results, but it is possible that with proper strong-polarized experiment field there could be different results. We are eager to explore that in our next experiment plan.

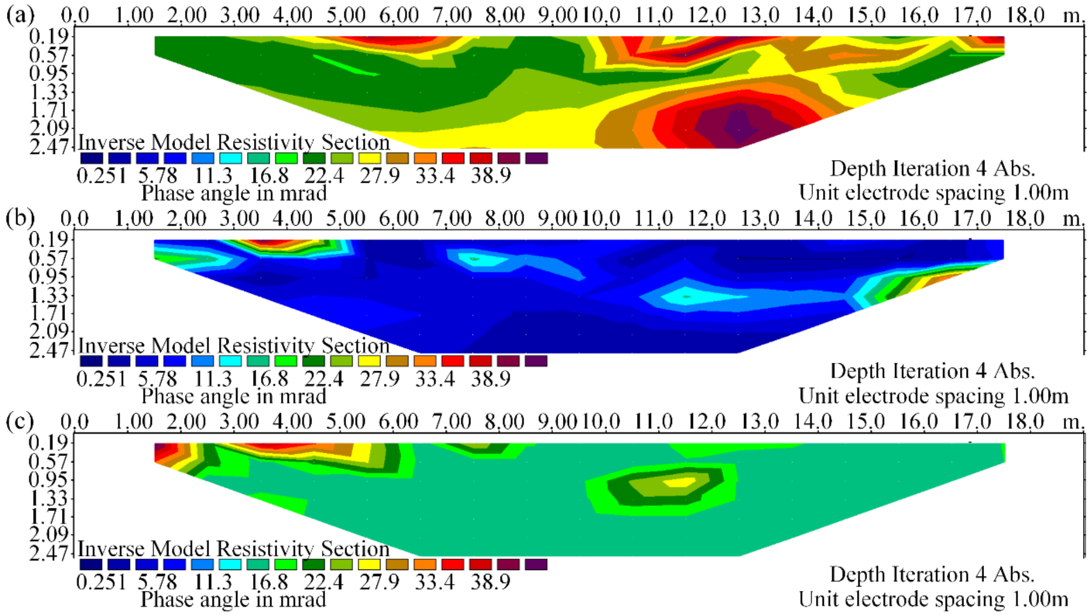

Figure 4. Inverted phase sections of the two high resistivity anomalies at 80Hz with using (a) the FDIP method, (b) the TSIP algorithm, and (c) the ECI algorithm.

Comment 3. Please employ a proper notation for complex entities. From my point of view most equations contain complex values.

Response.

We have modified some complex entities.

Page 4, line 19 to 23

Comment 4. page 4,line 17: "ZW-CMDSII" not defined - please provide a reference here as this seems to be related to the construction of a measurement system?

Response.

We have added reference the reference of ZW-CMDSII (Zhang, et al., 2014; He, et al., 2014;) to the paper.

Page 6, line 5 to 12

References

He, G. Wang, J. Zhang, B. Y. Li, M. and Ma, C.: Design of High-density Electrical Method Data Acquisition System, Instrument Technique and Sensor, 2014, 8, 18-19, https://doi.org/10.3969/j.issn.1002-1841.2014.08.007.

Zhang, B. Y. He, G. and Wang J.: New High-density Electrical Instrument Measuring System. Instrument Technique and Sensor, 2014, 1, https://doi.org /10.3969/j.issn.1002-1841.2014.01.009.

Comment 5. page 4/ECI approach: My understanding of the main point of the ECI approach is that you assume uncorrelated noise for applied voltage (n1), measured voltage (n2), and measured injected current (n3) (otherwise the cross-correlations between those quantities shouldn't be zero, as stated in page 4, line 19). If this reading of mine is correct, I would like to see more discussion on this: Is this always the case? What about electronic noise (e.g., from the ADCs involved) - shouldn't this superimpose on all three noise components? I understand that this is probably not an issue here, but it would be nice if you could guide the reader into the right direction. Also, this main assumption should be more prominently presented in your manuscript.

Response.

What you understand is basically right. In our experiment, the applied voltage $u_{\mathrm{T}}(t)$ is measured within the powering system, so the environment interference only introduce noise into the measured voltage and measured infected current. In fact, $n_1(t)$ mainly consists of the floor noise of the measuring instruments (including ADCs noise), and very feebly influenced the coupling effect of $n_2(t)$ and $n_3(t)$, while $n_2(t)$ and $n_3(t)$ mainly consist of the environment noise. This is why we consider the cross-correlation between $n_1(t)$ $n_2(t)$ or $n_1(t)$ $n_3(t)$ 'approximately' zero. We adjust the expressions in page 4 line 13 to 15 to make it more clear. As for the electronic noise, since they are Gaussian noise, Figure 5 shows how its energy is compressed by the cross-correlation computation. But what you suggest inspires us to more thoroughly consider different noise sources. So we make further discussions on the correlation behaviors of these noise as below.

In a real environment, this model is contaminated by the environment interference and measuring instrument. It can be categorized into three types: the Gaussian random noise, the impulse interference, and the particular frequency disturbance (Wang and Li, 1986; Yan et al., 2016).

For our system, we assume the three noises are linearly overlapping on the three sensors, along with some weak influence of coupling effects. So, the noises in the three sensors are only different in amplitude. Hence,

$$n_1(t) = B_1 g(t) + C_1 p(t) + D_1 s(t) \tag{1}$$

$$n_2(t) = B_2 g(t) + C_2 p(t) + D_2 s(t) \tag{2}$$

$$n_3(t) = B_3 g(t) + C_3 p(t) + D_3 s(t) \tag{3}$$

where $n_k(t)$ is the noise in sensor Y_k, $k = 1,2,3$, respectively. $g(t)$, $p(t)$ and $s(t)$ are separately Gaussian random noise, impulsive noise and particular frequency interference. B_k, C_k and D_k are the amplitudes of $g(t)$, $p(t)$ and $s(t)$, $k = 1,2,3$, respectively.

According to the properties of the correlation function, the cross-correlation results of the three kind of noise is as below:

A. For the Gaussian random noise, when $-NT \le \tau \le NT$ and $\tau \ne 0$, $R_{gg}(\tau)$ is shown in Figure

5.

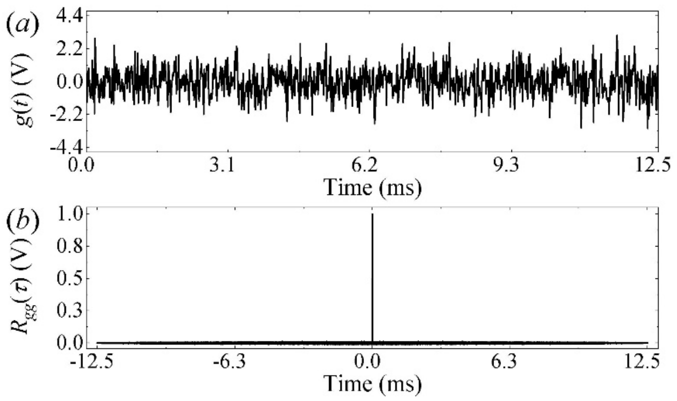

Figure 5. Waveform and autocorrelation for the Gaussian random noise $g(t)$. (a) its time domain waveform. (b) its autocorrelation $R_{gg}(\tau)$.

B. For the impulsive noise, when $-NT \le \tau \le NT$ and $\tau \ne 0$, it is considered that $R_{pp}(0) \gg R_{pp}(\tau)$, as shown in Figure 6.

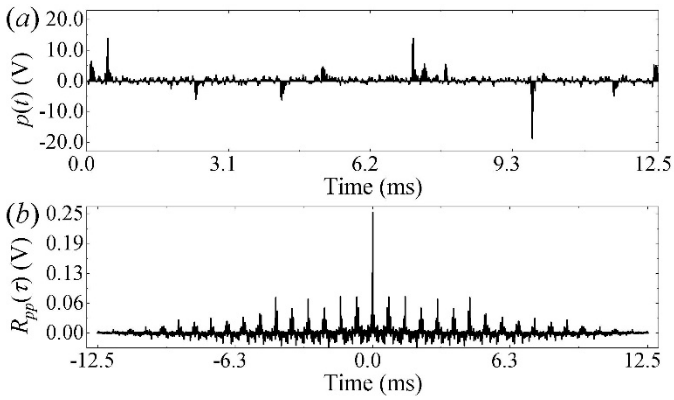

Figure 6. Waveform and autocorrelation for the impulsive noise $p(t)$. (a) its time domain waveform containing 20% of the outliers. (b) its autocorrelation $R_{pp}(\tau)$.

C. For the particular frequency disturbance, its autocorrelation has the same frequency with it, but when it is less effective for the transmitter output signal $u_{\mathrm{ab}}(t)$ than that of the $u_{\mathrm{mn}}(t)$ and $i(t)$, $D_1 D_2 R_{ss}(\tau)$ and $D_1 D_3 R_{ss}(\tau)$ can be effectively suppressed, as shown in Figure 7.

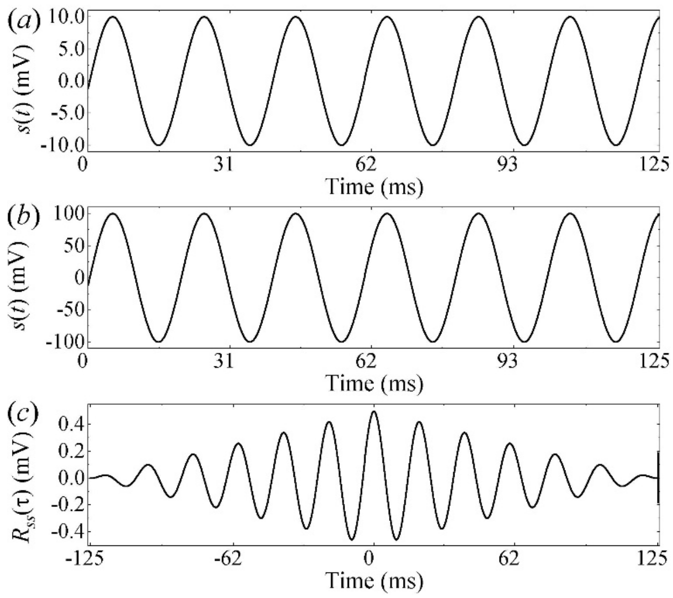

Figure 7. Waveform and autocorrelation for the particular frequency interference $s(t)$. The power-line interference (a) at $D_1 = 0.01$, (b) at $D_2 = 1$. (c) their cross-correlation $D_1 D_2 R_{ss}(\tau)$.

Based on the analysis above, it can be concluded that the influences of Gaussian random and impulsive noises are more effectively suppressed, while the particular frequency disturbance is attenuated to some degree when the noise is in lower intensity. Therefore, the proposed method has more value on denoising for Gaussian and impulsive random noises.

(2) In our experiment design, the noise sources and the system are considered independent and linearly superpositioned. Since our method demonstrates enhanced denoising ability to both kinds of noise, we think it is reasonable to say it has better denoising method. To further verify this assumption, we conduct an experiment on the denoising of mixed noises, as shown in Figure 8.

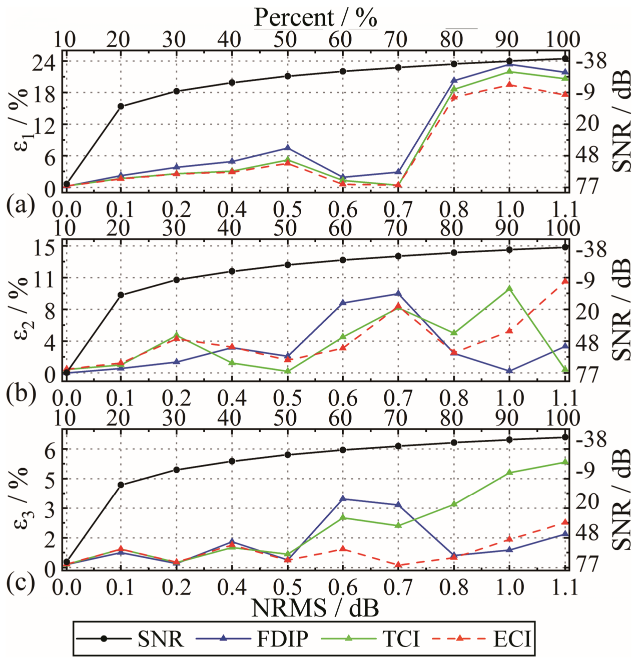

Figure 8. The injected current contaminated by simulated by sum of synthetic different degrees of Gaussian random noise and synthetic different levels of impulsive random noises, and RECR compared at three frequencies.

(a) SNR of the contaminated injected current. RECR at (b) 80 Hz, (c) 160 Hz, (d) 320 Hz comparison using the hybrid method and the others in the amplitude-frequency characteristics.

References

Wang, F.S., and Li, T., 1986, Industry of stray current resistivity observation and avoid interference distance: Northeastern Seismological Research, 2, 44–48. doi:10.13693/j.cnki.cn21-1573.1986.02.006

Yan, T. J., Wang, S. Q., Mang, Y. X., and Luo, X. Z., 2016, Influence of human interference on application of electrical prospect-ing and corresponding anti–interference measures , Mineral Exploration, 7, 634–639. doi:10.3969/j.issn.1674-7801.2016.04.016

Comment 6. Is NT specified? What interval was used for the synthetic and the experimental cases?

Response.

(1) NT is set 0.0125s in our experiment.

The information is added on Page 4, line 8 and Figure 4.

(2) The time interval is 0.0016ms, with sampling frequency of 625kHz.

Page 8, line 12

Comment 7. Fig 4: i(t) is the injected current, if I'm not mistaken. As such it should have a unit of Ampere, not Volts (same with the corresponding noise n3). If i(t) somehow has units of volts, please explain correspondingly (also in the previous text passages).

Response.

Thank you for pointing out our negligence. The relationship of the injected current signal between electrode A and electrode B is:

$$i(t)=u_i(t)/R_s\,, \tag{1}$$

where, R_s is a 1Ω sampling resistor, and $u_i(t)$ is the voltage at the sampling resistor.

Figure 4 is modified and the introduction is added on Page 5, line 10 to 14.

Comment 8. Synthetic case: It is not clear to me why you only add noise to the injected current and not to the measured voltage (n2) and the applied voltage (n1). Isn't that the whole point of your study? It would be nice if you could show that also for the synthetic case the cross-correlation of those noise components reduces to zero (p4, line19). I suppose this entails generating suitably uncorrelated random ensembles.

Response.

In our experiment the measurement line is 19m and in a stable environment, so we consider the system linear time-invariant and the noise from the current and voltage measurement are linearly superpositioned (Pelton, et al., 1983; De, et al., 1983; Vinegar and Waxman, 1984; De, et al., 1992; Garrouch and Sharma, 1998). Therefore, it is actually equivalent whether the noise is added to the injected current $i(t)$, the measured potential signal $u(t)$ or the applied voltage $u_T(t)$, the equivalent relationship is described as below

(1) When the measured potential signal $u(t)$ and the injected current $i(t)$ are contaminated by the noise $n_2(t)$ and the noise $n_3(t)$, we can obtain

$$y_1 = u_{\mathrm{T}}(t) + n_1(t), \tag{1}$$

$$y_2 = u(t) + n_2(t), \tag{2}$$

$$y_3 = i(t) + n_3(t), \tag{3}$$

The cross-correlation functions can be expressed as follows:

$$R_{y_1y_2}(\tau) = R_{x_1x_2}(\tau) + R_{n_1n_2}(\tau), \tag{4}$$

$$R_{y_1y_3}(\tau) = R_{x_1x_3}(\tau) + R_{n_1n_3}(\tau), \tag{5}$$

Thus we can assume that the cross-relation between $n_1(t)$ and $n_2(t)$, $n_3(t)$ $R_{n_1n_2}(\tau) \approx 0$ and $R_{n_1n_3}(\tau) \approx 0$, we can further obtain:

$$R_{y_1y_2}(\tau) \approx R_{x_1x_2}(\tau) \tag{6}$$

$$R_{y_1y_3}(\tau) \approx R_{x_1x_3}(\tau) \tag{7}$$

(2) When the noise $n(t)$ from the current and voltage measurement are linearly superpositioned, $n(t) = n_1(t) + n_2(t)$ and the injected current $i(t)$ are contaminated by the noise $n(t)$, we can obtain

$$y_1 = u_{\mathrm{T}}(t) + n_1(t), \tag{8}$$

$$y_2 = u(t), \tag{9}$$

$$y_3 = i(t) + n(t) = i(t) + n_2(t) + n_3(t), \tag{10}$$

The cross-correlation functions can be expressed as follows:

$$R_{y_1y_2}(\tau) = R_{x_1x_2}(\tau), \tag{11}$$

$$R_{y_1y_3}(\tau) = R_{x_1x_3}(\tau) + R_{n_1n_2}(\tau) + R_{n_1n_3}(\tau), \tag{12}$$

Thus we can assume that the cross-relation between $n_1(t)$ and $n_2(t)$, $n_3(t)$ $R_{n_1n_2}(\tau) \approx 0$ and $R_{n_1n_3}(\tau) \approx 0$, we can further obtain:

$$R_{y_1y_2}(\tau) \approx R_{x_1x_2}(\tau) \tag{13}$$

$$R_{y_1y_3}(\tau) \approx R_{x_1x_3}(\tau) \tag{14}$$

Based on the analysis above, it can be concluded that Eq. (6) and Eq. (7) are consistent with Eq. (13)

and Eq. (14).This is why we only add noise on the injected current to represent the overall noise summation.

The cross-correlation results are shown in Figures 5 and 6 in response 5

References

Pelton, W. H., and Sill, W. R.: Interpretation of complex resistivity and dielectric data: Geophysical Transactions, 1983, 29, 297-330.

De Lima, O. A. L., and Sharma, M. M.: A generalized Maxwell - Wagner theory for membrane polarization in shaly sands: Geophysics, 1992, 57, 431-440. doi:10.1190/1.1443257

Vinegar, H. J., and Waxman, M. H.: Induced polarization of shaly sands: Geophysics, 1984, 49, 1267–1287. doi:10.1190/1.1441755

Garrouch, A. A., Sharma M. M.: Dielectric dispersion of partially saturated porous media in the frequency range 10 Hz to 10 MHz: The Log Analyst, 1998, 39, 48-53.

Comment 9. While I think this step was taken to simplify the discussion, I think the simplification does not represent the problem at hand. As you stated in page 4, you also expect significant noise levels in n2 ("n2(t) and n3(t) may possess more massive energy..."), you should at least add suitable noise levels to n2 to test you algorithm. I still wonder why the current measurement entails such large noise components, given that this measurement is usually just a voltage measurement over a shunt resistor...

Response.

Sorry we did not put this clear enough in the manuscript. What we actually did was adding noise on the injected current to represent the overall noise summation in the system, as we explained in Response 8.

Since we consider our system as a linear time invariant system, whether the noise is added on the drive signal $u_T(t)$, the measured potential $u(t)$ or the current $i(t)$ are equivalent. When observing the field measured data, we found that the current signal is more heavily interfered by noise, as shown in Figure 1, so we decided to add noise on the supply current.

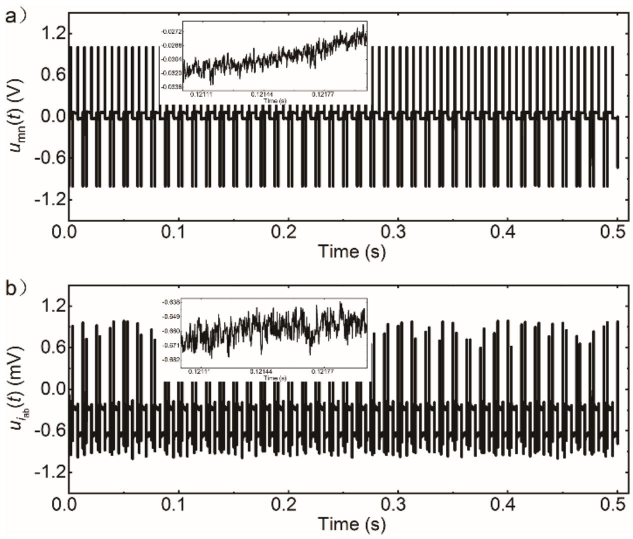

Figure 9. The time waveform of measured potential and supply current on electrode No. 53

Comment 10. Eq. 14/15: Is M defined in the text?

Response.

M is the length in the text as follows:

Page 5, line 12

Comment 11. Please use the same colorbar limits for all plots in Fig. 9. Otherwise a proper comparison is not possible.

Response.

Yes, we use the same colorbar limits for all plots in Figure 10 as follows:

Page 9, line 5

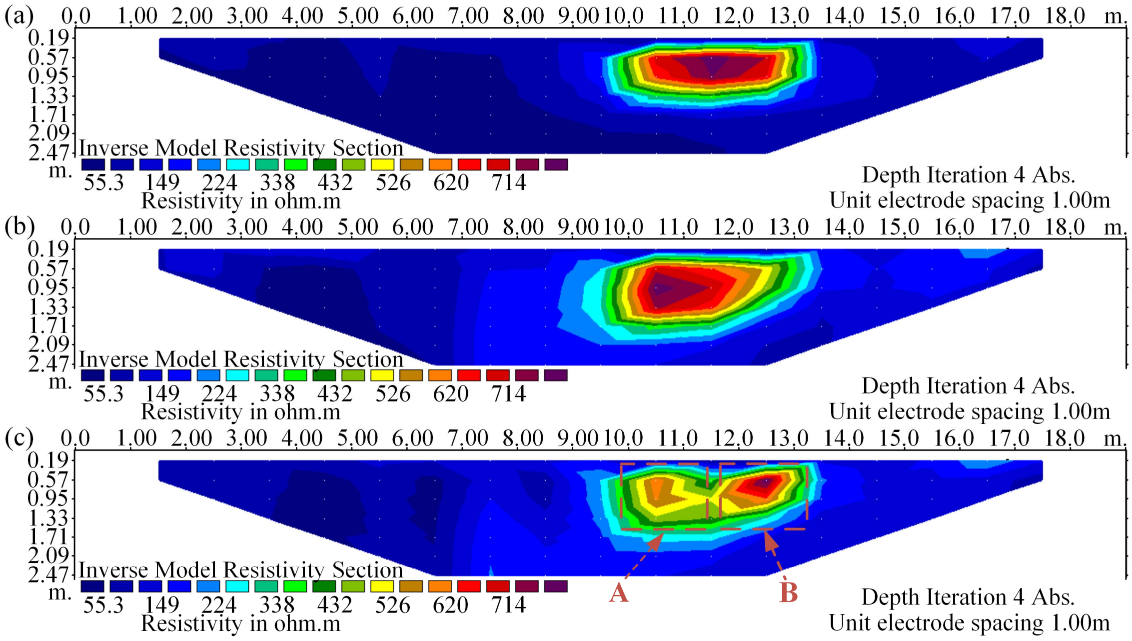

Figure 10. Inverted resistivity sections of the two high resistivity anomalies at 80Hz with using (a) the FDIP method, (b) the TSIP algorithm, and (c) the ECI algorithm.

Comment 12. the forward response of the final inversion model to the actual data. Does this analysis also follow the observed noise levels?

Response.

Sorry we are not so sure what you are referring to. In the actual field data, it is hard to extract the actual noise component. So we are trying to observe the noise level by calculating the SDs respectively, which help us evaluate the fluctuation degree of the processed signal, as shown in Figures 10 and 11.

As the figure shows, the ECI method has the lowest SD, which is why we deduce that our method has better denoising ability.

Page 9, and Page 10 line 1 to 6

Comment 13. Just to be sure (and perhaps encourage a slight extension of the last paragraph of the introduction to better clarify): The major point of this manuscript is that it takes into account also noise from the current measurement, which is not commonly done, right? For example Liu et al

2017, (10.1190/GEO2016-0109.1) seem to only assume noise on the primary potential measurements (The geophysics-paper also nicely shows pseudosections of both magnitude and phase - this would also be interesting here).

Response.

(1) In our field experiment, we did observe different noise levels both in potential and current measurements, in which the fluctuation in the current measurement is even acuter, as Figure. 11 shows.

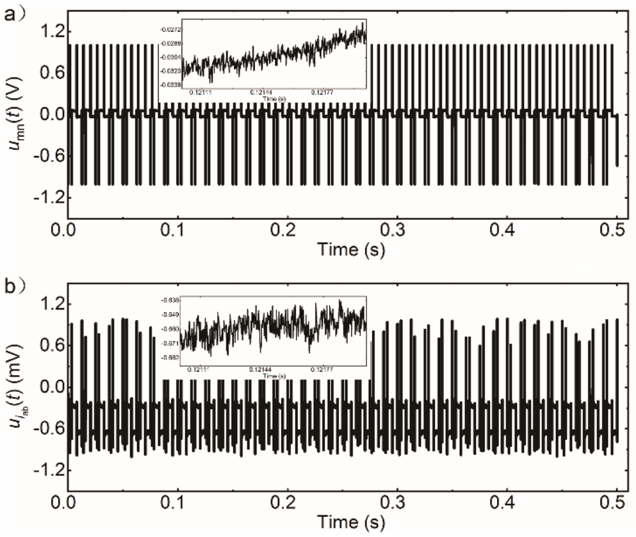

Figure 11. The time waveform of measured potential and supply current on electrode No. 53

(2) As stated Page 3, line 13 and 14, and Page 4, line 4 and 5 in our manuscript, that the denoising ability of the TSIP algorithm is limited is caused by that $i(t)$ is sensitive to $n_3(t)$. To solve this problem, the ECI algorithm is proposed. Therefore, that $i(t)$ is added noise to verify the noise reduction performance of the ECI algorithm.

(3) In fact, we think the it should represent the total noise summation in the system whether the noise component is added on the potential or current during calculation. From our understanding, the difference between us and Liu et al. is that they put this component in 'acquired potential U_0' (Eq. (5)), and we put it in I_{ab}. As we were trying to explain in response 8, this to operation should be equivalent during the cross-correlation process.

To clarify this, we added some explanations in the experiment section.

Page 5, line 17 and 24

Comment 14. In conclusion, I suggest to improve the presentation of the manuscript and to better work out the novel contribution of the ECI algorithm in comparison to the various other correlation-based noise-reduction algorithms out there, as well as to make sure your test cases compare to those of other studies (i.e., current and voltage noise).

Response.

As Liu. et al. mentioned, correlation noise-reduction algorithms applied on SSIP data processing is rarely reported, now all reported experiments we can find are Liu's research and 'Time-Domain Spectral Induced Polarization Based on Pseudo-random Sequence' (Li et al. 2013), as the TCI referring to in our manuscript. Liu's research is more of a screening method to find suitable signal sequence, rather than data processing method. Therefore what we can do is comparing our method with Mei Li's method. To be more accurate, we change 'TCI' to 'TSIP' when referring to Mei Li's research in the manuscript.

Page2, line 3 and 4

Reference

Li, M. Wei, W. Luo, W. and Xu, Q: Time-domain spectral induced polarization based on pseudo-random sequence, Pure and Applied Geophysics, 170(12), 2257-2262, https://doi.org/10.1007/s00024-012-0624-z, 2013.