Automated integration of AEM data, VES and borehole logs

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SUMMARY

Airborne electromagnetic (AEM) surveys are widely used for hydrogeological applications. The areas targeted for AEM campaigns may present a great deal of ancillary information (e.g. resistivity logs, lithology, etc.) and integrating it with AEM data is fundamental. Yet, using this information either as a-priori or a-posteriori may bring out conflict between different datasets, preventing reconciliation everywhere. For instance, some borehole drillings may have been logged inaccurately, AEM data may present bias, or data may have been acquired at different times, with variations occurring in between.
In this study we present a way to integrate AEM data and other types of resistivity data (boreholes electrical logging and vertical electrical soundings, in this case), through an inversion scheme that identify automatically conflicting data without preventing the general convergence of the process. To do so, we make use of a generalization of the minimum support norm, the asymmetric generalized minimum support (AGMS) norm, for defining the data misfit in the objective function of an iterative reweighted least squared (IRLS) gauss-newton inversion. The AGMS norm in the data misfit puts a cap on the weight of non-fitting data points, allowing for the inversion to focus on the data points that can be fitted. Outliers are identified after the AGMS inversion and excluded, in order to complete the inversion process with a classic L2 misfit.
We present an application of this method in the Netherlands, on a SkyTEM survey complemented with a vast and open-source database of ashore resistivity logs, as well as vertical electrical soundings (VES).

Key words: Airborne EM, minimum support, hydrogeology, interface fresh salt groundwater

INTRODUCTION

In areas rich with ancillary data, their integration in the inversion is a must, for validation as well as for enhancing sensitivity. However, data integration is a tricky process, for many reasons: data may be biased, their supporting volume may differ significantly, along with their location, or they may have been acquired in different periods, with variations occurred in between, for instance due to the depletion of groundwater resources or seawater intrusion.

Conflicting data in an inversion process can easily prevent the proper convergence of the inversion, but culling too much data out might throw out important information. The removal of conflicting information is even more difficult when there is a significant amount of ancillary information, acquired over a long period of time.

To solve this challenge, we propose to use a generalization of the minimum support norm (Last and Kubik, 1983; Portniaquine and Zhdanov 1999), namely the asymmetric generalized minimum support AGMS norm (Fiandaca et al., 2015), for identifying outliers in a joint inversion of AEM data, vertical electrical soundings (VES) and borehole resistivity logs. We test the method on a synthetic example, mimicking a joint inversion of AEM data and borehole logs, with both correct and incorrect logging, as well as real data. The field case consists of a SkyTEM survey carried out in 2022, complemented with a vast and open-source database of ashore resistivity logs, as well as VES, acquired over many decades.

METHOD AND RESULTS

The inversion of AEM, VES and borehole logs is carried out in EEMverter (Fiandaca et al., 2023), a new inversion algorithm in which different norms are applicable in the objective function for both data misfit and regularization through the iteratively reweighted least squared (IRLS) inversion scheme (Farquharson and Oldenburg, 1998).
In particular, the penalty of the data misfit $x = d - f$ between data and forward response is expressed through the AGMS norm (Fiandaca et al., 2015) as:

$$\phi(x) = \alpha^{-1}\left[(1-\beta)\frac{(x^2/\sigma^2)^{p_1}}{1+(x^2/\sigma^2)^{p_1}} + \beta\frac{(x^2/\sigma^2)^{p_2}}{1+(x^2/\sigma^2)^{p_2}}\right] \quad (1)$$

where

$$\beta = \frac{(x^2/\sigma^2)^{\max(p_1,p_2)}}{1+(x^2/\sigma^2)^{\max(p_1,p_2)}}. \quad (2)$$

In (1) and (2), σ is the data standard deviation, p_1 and p_2 control the shape of the norm before and after $\frac{x}{\sigma} = 1$ and α determines the total weight of the penalty. Figure 1 shows the comparison between the L2 penalty and the AGMS penalty with p1=1, and p2=0.5 and α = 0.5.

With this choice of values for the norm settings the AGMS norm gives misfit 1 for $\frac{x}{\sigma} = 1$ (i.e. the same value of the L2 norm), with similar penalty for low misfit (because of $p_1 = 1$)

and a slow growth of the penalty when $\frac{x}{\sigma} > 1$ (because of $p_2 = 0.5$). This slow growth allows for applying the AGMS norm in an iterative minimization process, because a decrease in $\frac{x}{\sigma}$ gives a measurable penalty reduction.

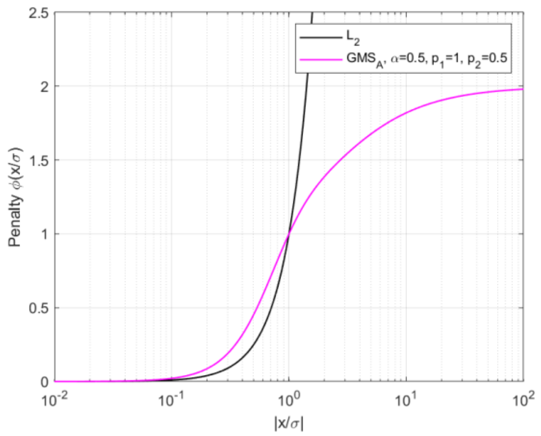

Figure 1. Penalty of the L2 and AGMS norms as a function of the difference $x = d - f$ between data and forward response, weighted by the data standard deviation σ.

This data norm is applied in a IRLS inversion composed of three inversion cycles (Fiandaca et al., 2023) with 1D forward/Jacobian computations: first a preliminary cycle which finds the best starting model without vertical variability of the parameters, through the use of a single-layer forward mesh; secondly, a cycle the AGMS norm is applied; lastly, the data norm is switched to the L2 norm, to reject the data with misfit above the set thresholds, and the inversion is carried out until the reach of the minimum misfit. In all cycles, borehole logs are treated as data, with the forward response of the logs consisting in the interpolation of the model resistivity at the log locations (Fiandaca et al., 2023).

Figure 2 presents a synthetic model mimicking a fresh aquifer comprised between an unsaturated sand dune and a brackish aquifer, and confined by clay layers. AEM data (Xcite system, New Resolution Geophysics) and three borehole logs are simulated and inverted with a classic L2 data norm and the AGMS norm, with three data scenarios:

- a first one, in which only AEM data are available (Fig. 2D and 2G);
- a second scenario, in which AEM data are complemented with the logs that bear correct information (Fig. 2E and 2H);
- a third scenario, in which one log contains wrong resistivity values (Fig. 2F and 2I).

Both L2 and AGMS inversions improve the model retrieval when correct log information is added, but a very different behaviour occurs when wrong data are fed to the inversions: the L2 inversion shows a significant artifact at the location of the wrong resistivity log, while the AGMS inversion is almost insensitive to the outliers.

The same inversion procedure was used on a SkyTEM dataset acquired in the Netherlands in 2022, around 25 kilometres west of Amsterdam (Fig. 3), together with 94 borehole resistivity logs, 91 VES, acquired in the same area over a period ranging many decades, in which the volume of the fresh groundwater has changed considerably. 'Excessive water abstraction from deep wells between 1903 to 1957 depleted the fresh groundwater. In 1957 the wells were stopped and infiltration with pretreated water from the river Rhine started. This enlarged the drinking water production capacity and restored the fresh water volume in the deep aquifer (Geelen et al., 2017; Olsthoorn and Mosch, 2020). The wells can still be used as a back-up system if the quality of the water in the river Rhine is not sufficient. For this reason, the integration of resistivity logs and VES with AEM data is particularly difficult: data will conflict not necessarily because of their different support volume or sensitivity, but because they were acquired over different periods of time. Consequently, with the AGMS inversion we aim at two distinct goals: improving the AEM inversion where borehole logs and VES information bring compatible information; identify the conflicting information, as a proxy of the variations that occurred on the fresh-sea water balance over the decades.

A 40 m x 80 m XY horizontal discretization and log-increasing depths from 5 to 400 m were used for the inversion, with the same three-cycle inversion scheme utilized for the synthetic case. Only borehole logs and VES data were rejected in the last cycle, the aim being to identify the information conflicting with the AEM data, which were carefully processed.

Figure 4 presents the rejection rate for both log data and VES data with the AGMS joint inversion, in comparison with the rejection rate computed after an AEM-only inversion, in which log and VES data do not concur in the model definition. The rejection of log data is not applied to entire logs, but value by value along the borehole depth. So the rejection rate indicates for each borehole log the fraction of values rejected. The overall rejection rates are presented also in Table 1.

Table 1. Comparison between rejection rates with AGMS joint inversion of AEM, VES and log data and with AEM-only inversion.

	Total data	Data rejected with AGMS	Rejection rate %	Data rejected with AEM-only	Rejection rate %
Borehole logs	33646	4399	13	12646	38
VESs	1815	1159	64	1475	81

As clearly shown by Fig. 4 and Table 1, the AGMS inversion has a much lower rejection rate, with very good compatibility between logs and AEM data, and poorer compatibility between the old VES data and the AEM ones. However, spatial patterns exist in the rejection fractions, which might be correlated with the variations occurred in the fresh-sea water interface. The AEM-only inversion has a much lower compatibility with the ancillary data, which is mostly due to equivalence problems instead of conflicting information.

Figure 5 shows in a 3-D view an example of data rejection in four borehole logs: most of the differences are only due to the vertical discretization of the inversion model, except for one of the logs in which the measured borehole data indicate a more conductive area at depth.

Finally, Figure 6 presents the comparison of the joint AGMS inversion and of the AEM-only inversion on an exemplary log, where AGMS inversion model fits much better the borehole information.

CONCLUSIONS

The inversion scheme proposed in this study allows an automated integration of AEM data and resistivity logs, as well as ground-based galvanic VES measurements, even in presence of conflicting information. The AGMS data norm puts a cap at the misfit penalty of outliers, and grants convergence to the inversion without culling valuable information out.

This approach allows to integrate to AEM surveys a great amount of ancillary data, without the need of careful and time-consuming data vetting: the accurate inspection of ancillary information could be reserved only to the data rejected by the automated scheme, with the kept data readily usable for further integration and interpretation.

Furthermore, this automated integration scheme is fully general, and can be applied not only to AEM data, but to any geophysical problem simply using the appropriate forward modelling.

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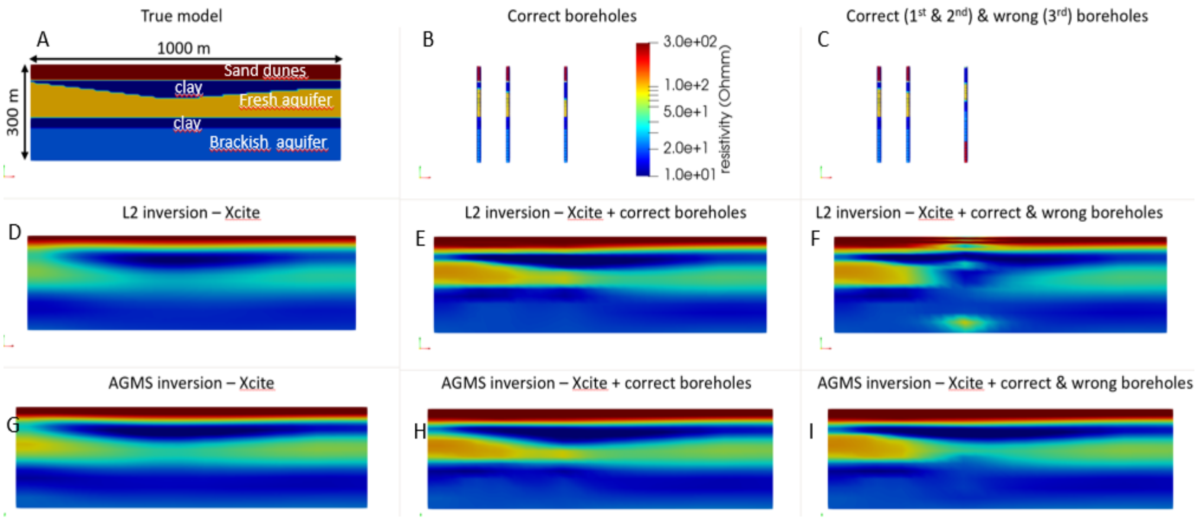

Figure 2. Conceptual model (A), boreholes information (all correct in B, one incorrect in C); model recovered by Xcite AEM data without drilling information using L2 norm (D) and AGMS norm (G); model recovered by Xcite with all correct drilling information using L2 norm (E) and AGMS norm (H); model recovered by Xcite with partially incorrect drilling information using L2 norm (F) and AGMS norm (I);

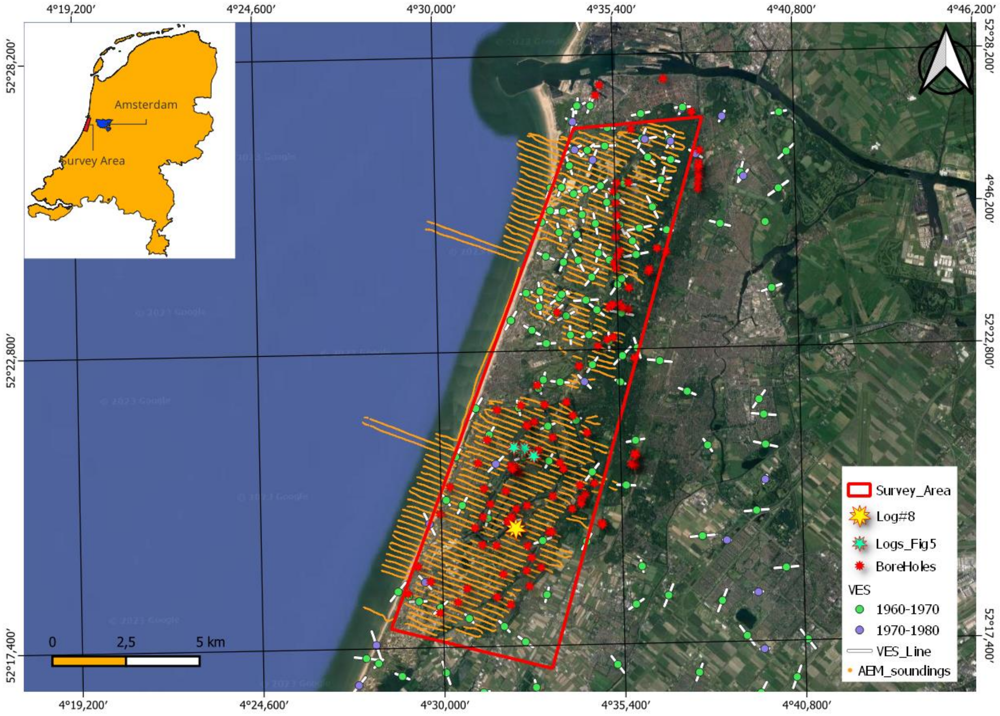

Figure 3. Survey area and sounding locations: red polygon – inversion area; orange dots – AEM soundings; red stars – borehole resistivity logs; yellow and green stars – logs presented in Fig. 5 and Fig. 6; green dots – VES soundings from the '60s; purple dots – VES soundings from the '70s; white bars: VES orientations.

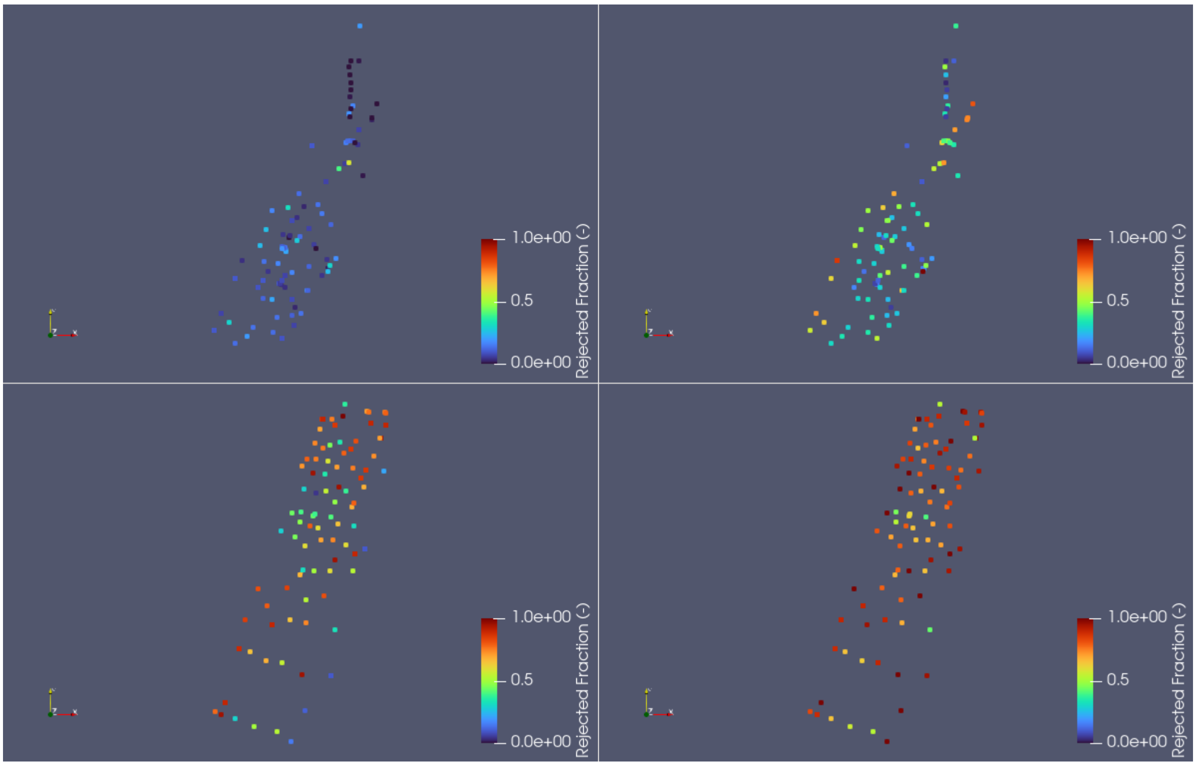

Figure 4. Plots of the fraction of rejected data with application of AGMS norm in joint inversion (left sections) and with AEM-only inversion (right sections); Top – rejections of log data; bottom – rejection of VES data.

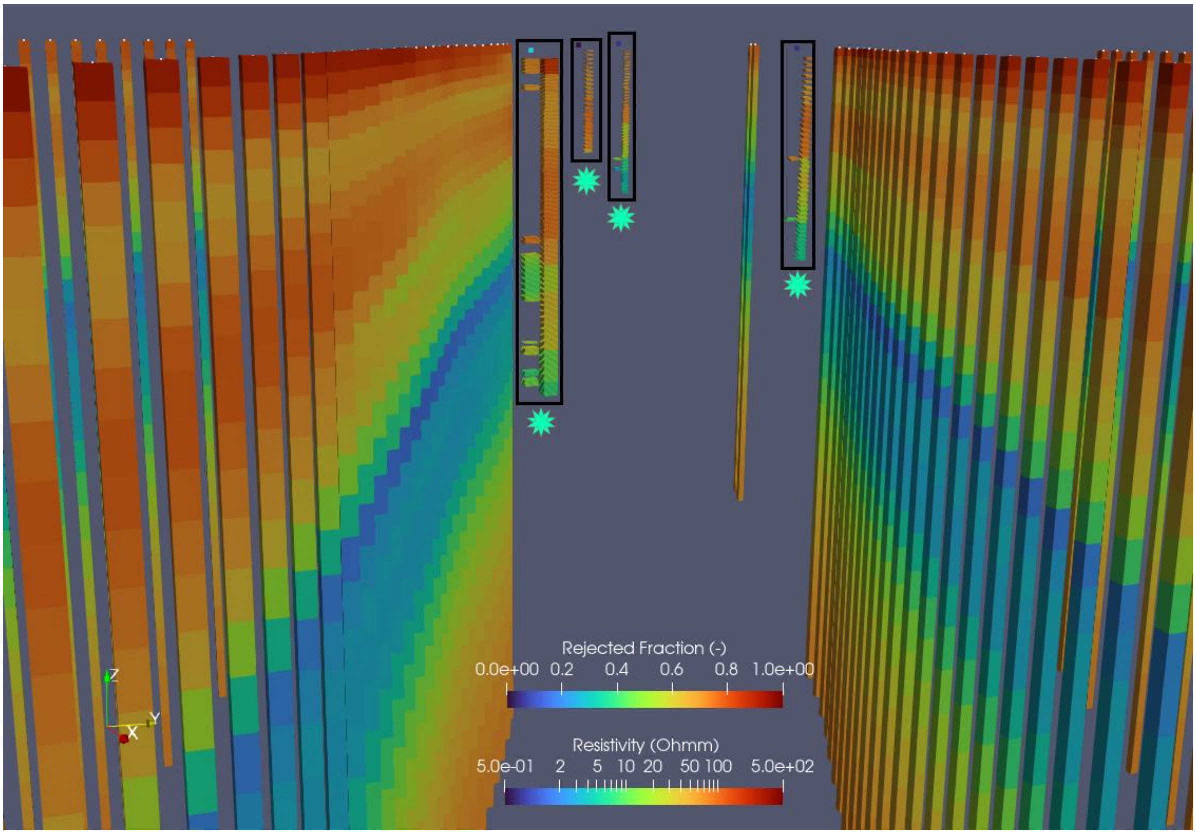

Figure 5. 3-D plot of 1-D forward models. Models framed in black: left – rejected log data; right – forward log model; dots – rejected fraction in colour code. All other columns represent AEM forward models. Locations of the framed logs are marked by green stars in Fig. 3.

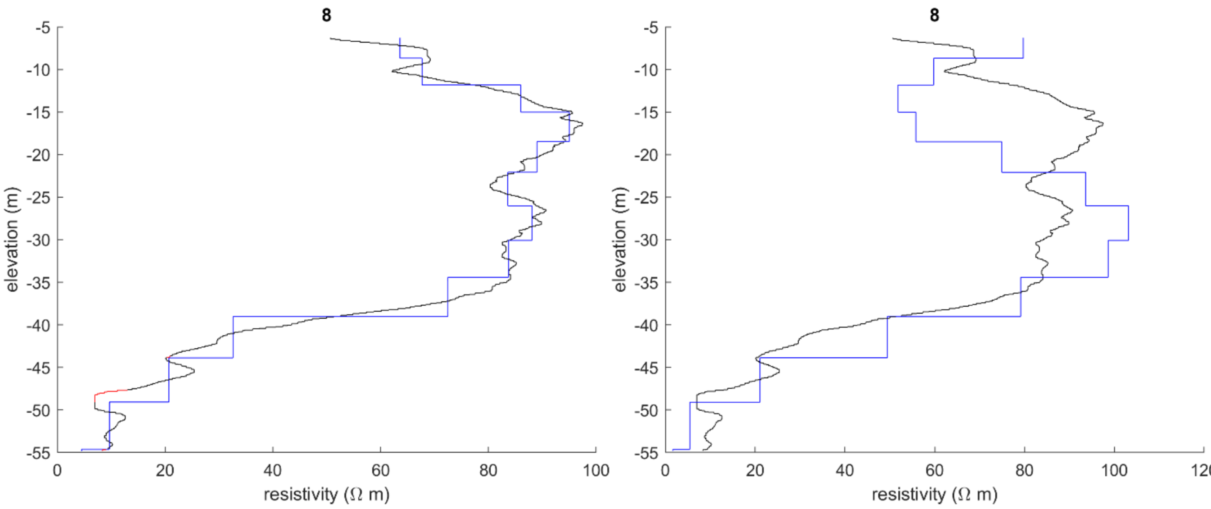

Figure 6. Comparison between Borehole#8 log (yellow star in Fig. 3) and inversion model. Left – AGMS joint inversion; right – AEM-only inversion. Blue lines – inversion model; black lines – resistivity logs; red lines – rejected data in resistivity log in the joint AGMS inversion.