The emperor's new clothes – opportunities and limitations applying AEM to geotechnical design work

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SUMMARY

In summer 2015, we acquired close to 6.000 km of Helicopter, time-domain airborne electromagnetic (AEM) data for regional geotechnical mapping for the Norwegian National Rail Administration. This survey and further experience from related Norwegian road planning projects demonstrated the unprecedented accuracy of modern AEM data. The extent of geotechnical site investigations can be drastically reduced, both in terms of time schedule, and costs if AEM derived bedrock models are included when soil investigations are planned. Geotechnical projects demand high resolution (meter scale) and AEM data is to some extent capable of delivering that. Some of our data matched the resolution of corresponding ground geophysics data. Here we present the way in which AEM can be used as bedrock models, sensitive clay delineation and to determine bedrock types. Our discussion leads us to the missing link between high vertical resolution in the first tens of meters for geotechnical work and the focus on simple, sub-vertical structures in exploration AEM. Ultimately, we should strive for the best of both worlds, shouldn't we?

Key words: AEM, Near Surface, Engineering, Geotechnical, Inversion

INTRODUCTION

Airborne Electromagnetics (AEM) has been an established exploration method for decades developed in the 1950s and '60s. With the introduction of drift-free and well-calibrated Helicopter time domain EM (HTEM) systems around the turn of the millennium, the AEM assortment of systems was disrupted and opened up for new applications. Frequency domain Helicopter EM (HEM), once a workhorse for near surface mapping, has since played a minor role. Yet HEM used to be the traditional method of choice for engineering surveys, robust in terms of infrastructure noise yet with limitations due to inherent drift and earlier calibration problems. Reports based on historic HEM instrumentation partially discourage geotechnical applications (Baranwal et al. 2014). HTEM has rather recently been increasingly applied in larger scale for engineering surveys. In northern Europe and especially Scandinavia, clay rich sediments make a perfect target for AEM bedrock topography mapping. In Scandinavia (as well as Canada and Russia), quick clay (highly sensitive, formerly marine clay) poses a serious risk to life and infrastructure. The subtle resistivity contrast between stable- and quick clay are a target for AEM surveys in addition to bedrock mapping. The combination of high resolution and sufficient penetration depth of HTEM adds sensitivity to major weakness zones, a bonus to such high-resolution geotechnical surveys. Over the last years, a number of research and demonstration projects triggered large-scale HTEM surveys in Norway for road and railroad design work. We illustrate our arguments with selected examples from these surveys. Having a closer look into recent developments in near surface and exploration AEM suggests somewhat diverging developments. Following the trend for 3D models, exploration research focuses on quick and simple inversions, for example reducing data to strike and dip parameters or 3D models with reduced resolution (McMillan et al. 2015, Fullagar et al. 2015 or discussed by Viezzoli et al. 2010). At the same time, the ground water and engineering marked seeks the highest (vertical) resolution possible, leading to models that almost outperform ground measurements (Anschütz et al. 2016a). These high-resolution models lack 3D resolution and the 3D models lack vertical resolution. We conclude with the question how high resolution near surface AEM and "strike/dip" 3D exploration AEM may mutually benefit.

METHOD

The scope of this paper is not the development and test of a new method in terms of physics, hardware or software. We thus keep the method section short. It is worth mentioning, that the SkyTEM 3ox systems are the driving force behind the arguments we lay out here. In our surveys we have used the 302 and 304 systems, our colleagues in Sweden (SGU 2015, not yet published) the 301 system. 301, 302 and 304 refer to a transmitter with 341 square meter in area and 1, 2 or 4 turns, respectively. For all systems only one turn is used for the low moment measurements resulting in time gates from < 10 µs to 2 ms. This bandwidth provides an excellent trade-off between high near surface depth resolution and moderate penetration depth. Processing and inversion was done with the Århus Workbench spatially constrained inversion with moderately loose vertical and horizontal constraints and automatic starting models to account for the heterogeneous geology ranging from outcropping resistive bedrock to tens of meters with conductive, marine clay. Bedrock topography interpretation involved a combination of resistivity thresholds, vertical resistivity gradient, manual picking and sparse geotechnical boreholes (Anschütz et al. 2016b).

GEOLOGICAL BACKGROUND

After decades with minor investments, linear infrastructure development has recently become a significant factor for the Norwegian geotechnical industry. Tens to hundreds of km with upgraded and new roads and railroads are currently being planned, designed and constructed. The typically demanding topography and geology requires costly and long lasting pre-investigation phases. The extent and thickness of marine clay and other glacial sediments as well as the occurrence of toxic black shale or bedrock weakness zones are factors that determine feasibility and construction costs and are all suitable targets for an AEM survey. Figure 1 gives typical examples of encountered bedrock geology and quaternary sediments. Bedrock mostly comprises medium to highly metamorphic sedimentary and igneous rocks with a high abundance of Gneiss, Schist and Phyllite. With the exception of highly conductive Cambro-Silurian black shales found around Oslo, the bedrock is highly resistive and makes a suitable AEM contrast to the conductive sediments. Tracking bedrock topography from AEM is feasible for large parts of the investigated lowlands. A minor part of the more than 6.000 km AEM data acquired in 2015 was not transferable to a bedrock model due to lacking resistivity contrast between bedrock and electrically resistive moraines or shallow surface weathering. Conductive Regolith is typically not found in Norway. In the highlands, above the marine limit and thus free of conductive marine sediments, bedrock topography tracking is limited to wetlands (bogs) that pose a good enough resistivity contrast for AEM.

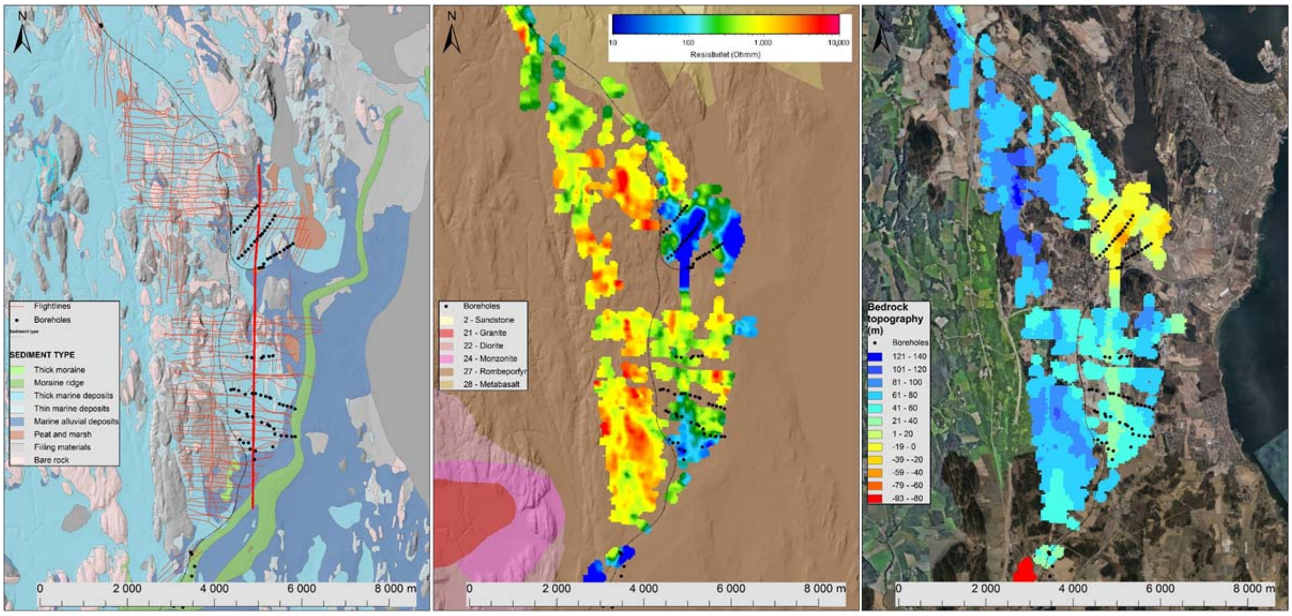

Figure 1: *Left*: Quaternary geology map typical for the survey area long with flight lines (red) and existing railway (black). We cannot provide detailed geographical information due to the high level of confidentiality when it comes to investigating potential rail or road alignments. *Middle*: Resistivity depth slice with average resistivity from 15 to 30 m below ground with geological map outlining various volcanic units over shaded DEM. *Right*: bedrock topography model derived from AEM data over an aerial image.

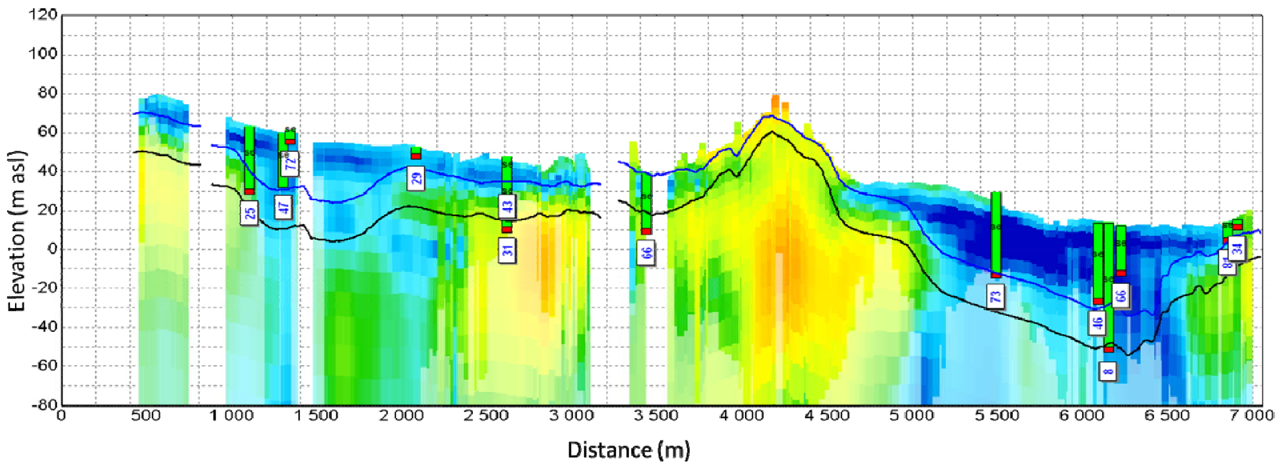

Figure 2: Resistivity model from S-N along one of the very few profiles with boreholes close to the AEM data (eastern profile, P2 in Figure 1). See Figure 1 for the resistivity colour scale. Off-line distance of boreholes denoted in meters below the bars, the bars extend until assumed bedrock. The blue and black lines illustrate the lowest and highest assumed bedrock.

RESULTS

Bedrock topography is the main target for geotechnical surveys in terms of stability and mass balance as well as for tunnel planning in terms of portal design and expected rock cover. Combined with sparse boreholes, we have previously computed detailed bedrock models based on spatial correlation of the datasets (Christensen et. al. 2015). For most of the data discussed here, we combine automatic and manual interpretation (Anschütz et. al. 2016b) largely based on the resistivity models and geological maps validated by boreholes at only a few locations (Figure 2). To quantify uncertainty we pick a maximum and minimum bedrock elevation, subjectively choosen based on resistivity contrast, depth, distance to boreholes, consistency with a priori data, etc. Sediment thickness varied from meters to tens of meters and the bandwidth and signal to noise ration of the HTEM data was sufficient to resolve sediment depths within the geotechnical relevant range. In some cases, we were able to interpret bedrock under up to 100 m of marine clay with resistivity lower than 10 Ωm, albeit with a higher uncertainty.

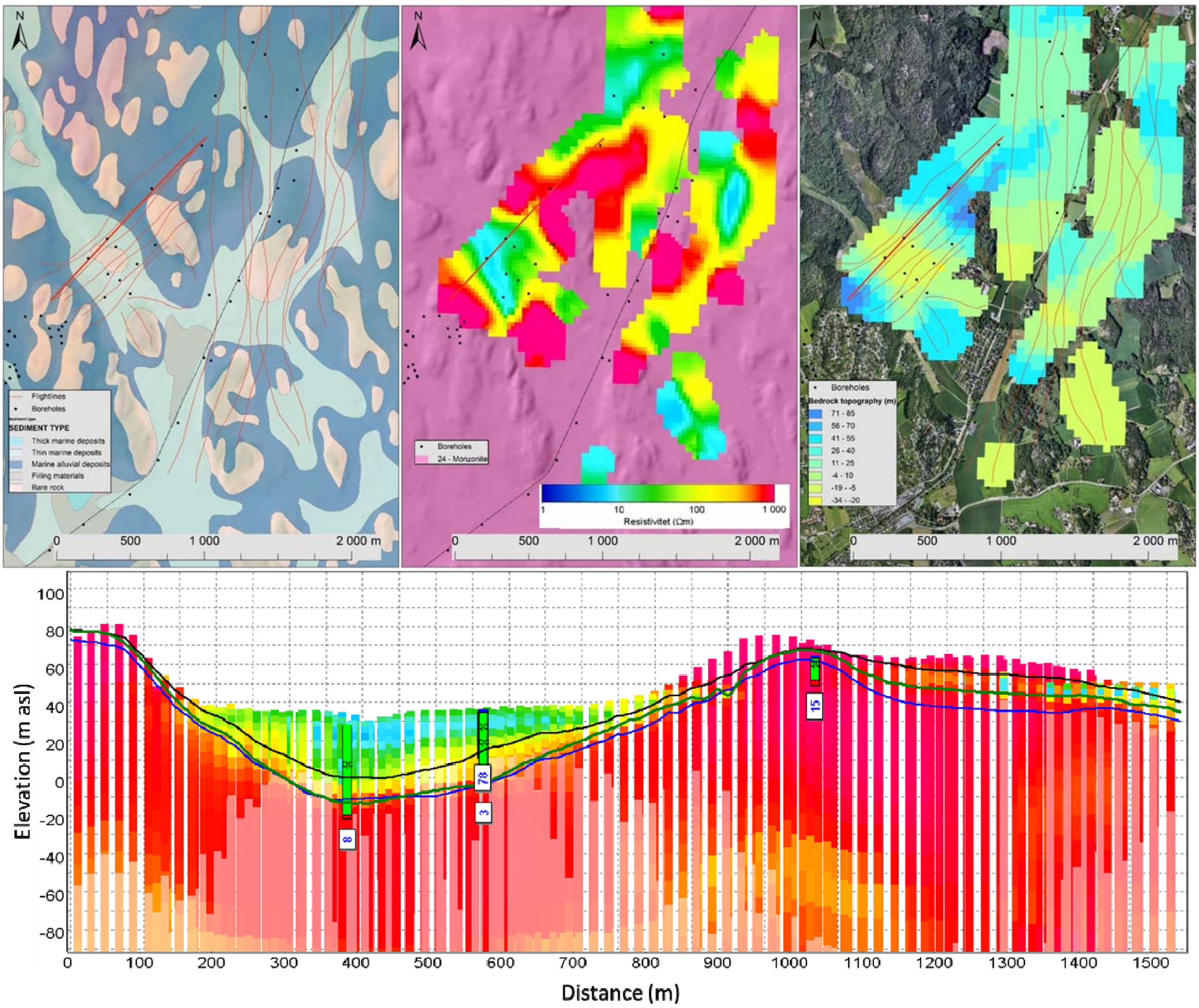

Figure 3: ***Left*****: Quaternary geology map along with flight lines (red) and existing railway (black) as well as borehole locations (black dots).** ***Middle*****: Resistivity depth slice with average resistivity from 0 to 15 m over geological map and shaded relief.** ***Right*****: Bedrock topography extracted from AEM models over an aerial image.** ***Bottom*****: Resistivity model from SW-NE along the profile drawn on the maps with boreholes and picked bedrock as in Figure 2. The green line shows an adjusted bedrock model, based on the boreholes that were integrated after the initial interpretation. The resistivity models result from a constrained inversion based on the green bedrock interface. Note the subtle variation in clay resistivity from below to above 10 Ωm indicating leached marine clay and thus a chance for sensitive "quick clay".**

Further to bedrock delineation, characterizing the sediment type is of additional value. Norway is prone to so-called quick clay, highly sensitive formerly marine clay that liquefies at failure and poses a serious geohazard. Electrical resistivity is a valuable factor when it comes to distinguishing un-leached (stable) and leached (sensitive) clay (Rømoen et al. 2010). The resistivity contrasts are subtle and consequently only accurate and high resolution resistivity models can provide the desired information. Previous field trials (Anschütz et. al. 2016a) have shown that this criterion is met for our data and we thus use the acquired resistivity models as indications of clay salinity and consequently probability for quick clay, provided the sediment layer is thick enough. The profile in Figure 3 clearly shows a valley filled with some tens of meters marine clay with some tens of Ωm resistivity, typical for leached marine clay. Geotechnical drillings confirmed the assumption and found sensitive quick clay. We are currently extending our interpretation to quick clay probability maps, based on a spatial search for sediments with resistivity typical for quick clay.

The results discussed so far focus on geotechnical issues such as depth to bedrock and sediment properties. For near surface HTEM systems the depth of investigations typically extends to some hundred meters depending on the geology. We utilize this deeper part of the data in areas that will be crossed with tunnels. Geophysical targets are weakness zones and/or black shale due to their impact on tunnel construction costs. In areas prone to the occurrence of uranium rich black shales the models outline highly conductive structures (resistivity around and below 1 Ωm) that can consequently be avoided if possible (not shown). The final data example (Figure 4) shows a potential tunnel alignment that was finally considered as not feasible due to lack of rock cover in the western part. The model also shows a strong conductor crossing the alignment, a thrust zone where Phyllite has been reworked to clay. Note that not all areas with low near surface resistivity are due to sedimentary cover,in the eastern part of the survey low resistivity indicates outcropping thrust zones rather than marine sediments.

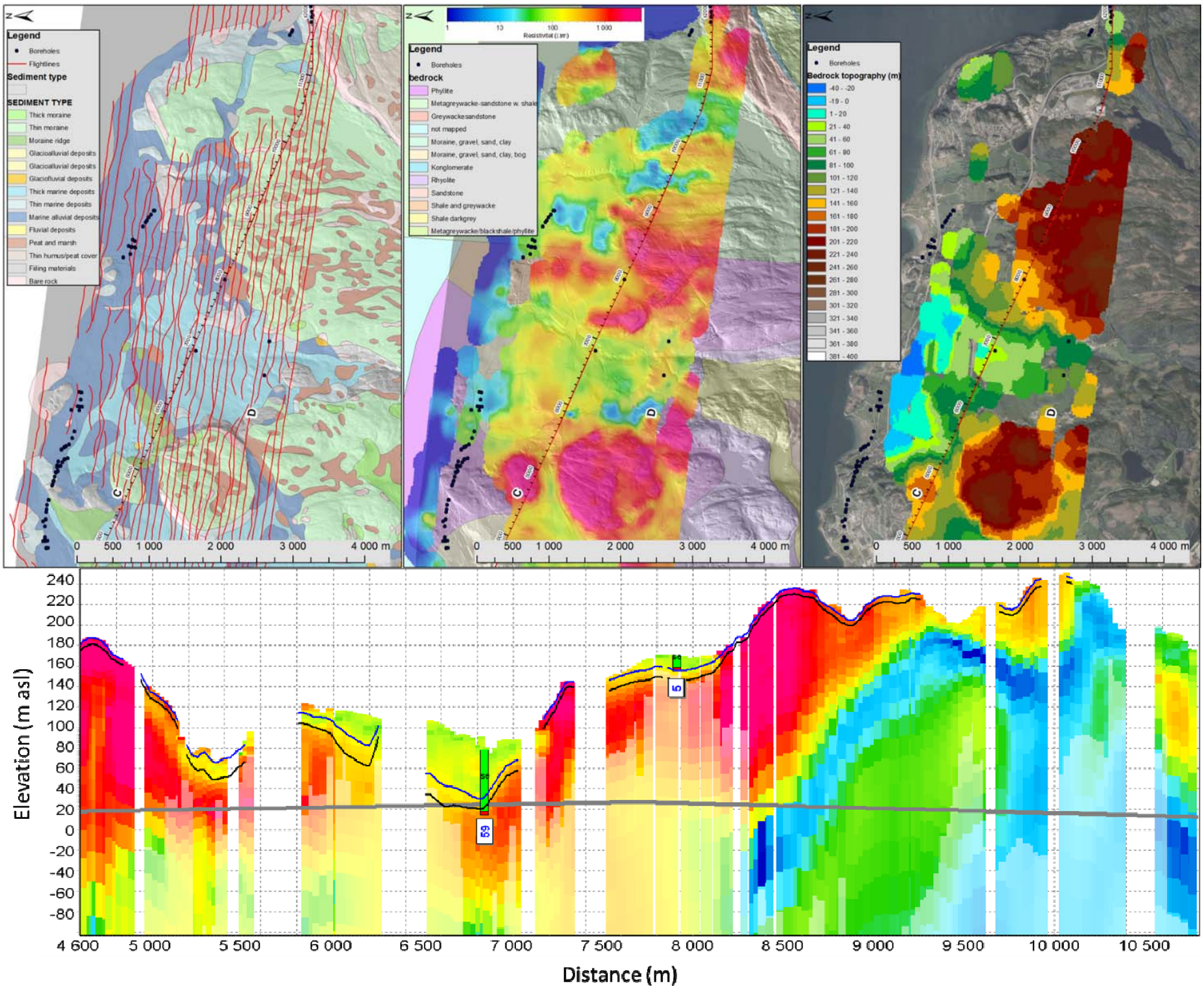

Figure 4: *Left*: Quaternary geology map a long with flight lines (red) and boreholes (black). *Middle*: Resistivity depth slice with average resistivity from 10 to 20 m below ground with geological map, over shaded DEM. *Right*: bedrock topography model derived from AEM data over an aerial image. *Bottom*: Resistivity model from W-E along the profile drawn on the maps with boreholes and picked bedrock as in Figure 2. The grey line sketches a potential tunnel alignment that would encounter a lack of rock cover at profile coordinate 6 500 – 7 000 m and crosses a low resistivity zone at 8 500 m as well as further east.

CONCLUSIONS

The times of fixed wing AEM as a prime exploration method along with minor HEM infrastructure surveys have long passed. Initially triggered by ground water exploration and consequently also exploration and lately geotechnical projects, HTEM has disrupted the AEM industry. The high efficiency, beneficial economics, survey robustness and data accuracy of modern HTEM makes it a strong candidate for early phase engineering investigations both in terms of geotechnical design (e.g. bedrock topography and stability) and engineering geology (e.g. weakness zones). Conclusions drawn from traditional HEM are partially positive and partially discouraging. Based on our experience with dual moment HTEM, vertical resistivity resolution is very close to ground measurements with the exception of the very first meters.

Acquiring accurate and high-resolution data is though only the starting point of a successful geotechnical AEM campaign. Processing, inversion and interpretation is the crucial element as for any other geophysical data. One must further not forget that without a geophysical contrast, no geotechnical parameter can be derived (resistive cover over resistive bedrock). A not yet resolved remaining challenge is to quantify uncertainty. Transferring data standard deviation and inversion sensitivity to a bedrock model uncertainty in meters is neither state of practice nor firmly established in academia.

With this paper, we want to inspire a more fundamental discussion: Engineering (and environmental) AEM seem to exist in a parallel universe to exploration AEM. High resolution is key for engineering and trumps over 3D inversions that often reduce resolution rather than enhance it. One-dimensionally modelled spatially constrained inversion has a clear limitation with 2D and 3D artefacts over steep structures. 3D inversion approaches, that mainly focus on vertical structures overcome this, but often vastly reduce the vertical resolution. How can these two parallel universes benefit from each other? Could the two approaches be combined in one workflow? Could a hybrid inversion provide the best of both worlds? The future will tell.

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