



Validation of the SkyTEM system at the extended TEM test site 2010





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INTRODUCTION

The helicopter transient electromagnetic system SkyTEM (Sørensen and Auken 2004) has been used for resistivity mapping in a hydrogeological context since 2003 in Denmark and in recent years to a large extent worldwide as well. From the beginning, a very high data quality was demanded for the SkyTEM system to ensure seamless results when it was used together with the large amounts of existing high-quality groundbased TEM data. The high data quality is ensured by a comprehensive data quality control scheme, among other things including calibration at the Danish national TEM test site and a day-by-day documentation of repeatability at the survey-specific test site.

The national TEM test site was established to ensure that any TEM system used in the ongoing Danish groundwater mapping campaign can reproduce the reference models and match the upward continued responses of the reference model within narrow limits. The test site was established in 2001. In 2009 the test site was extended from being a point location with a known reference response and resistivity model to two crossing lines approximately one kilometer long (GFS 2010). This makes calibration, validation and tests possible for airborne TEM-systems that cannot make hovering spot measurements and allows as well testing of the systems in actual production mode.

In this report we present the validation results for the SkyTEM system at the extended test site. The validation of the SkyTEM system includes examinations of:

- model and data repeatability in the same altitude
- model and data repeatability in different altitudes
- agreement between the airborne data and models and the groundbased reference models and data

The validation and comparison will be carried out in model space and in data space. The comparison in data space is facilitated by an upward continuation of the SkyTEM responses to a nominal height and by an upward continuation of the of the reference models. Examples of the different validations types

are shown and commented in the report while a complete set of plots for the full SkyTEM data set is presented in the appendixes.

Being of international interest this GFS-report is written in English.

GeoFysikSamarbejdet 2010, Nikolaj Foged, Esben Auken, Kurt I. Sørensen and Anders Vest Christiansen.

EXTENSION OF THE NATIONAL TEM TEST-SITE

The extension of the national TEM test site was carried out with a precalibrated ground-based TEM-system, WalkTEM. WalkTEM is a groundbased TEM system sharing the technological framework with the SkyTEM system. At precalibration the WalkTEM system reproduces the reference data set within ~1%. The red dots and squares in Figure 1 show the positions of the groundbased TEM soundings. The original test site is at the line intersection (Figure 1). The TEM soundings were carried out in a central-loop configuration using a 40 x 40 m² transmitter loop placed edge to edge with 40 m spacing between soundings. Data were obtained from approximately 8 μ s to 10 ms, with a maximum transmitter moment of 13,000 Am². Data were then inverted with a least-squares inversion approach, modeling the full system response and using the laterally constrained inversion (LCI) concept by Auken et al. (2005). The inversion result for the E-W profile is shown in Figure 2a. A detailed report on the extension of the national test site has been published by GeofysikSamarbejdet (GFS 2010).

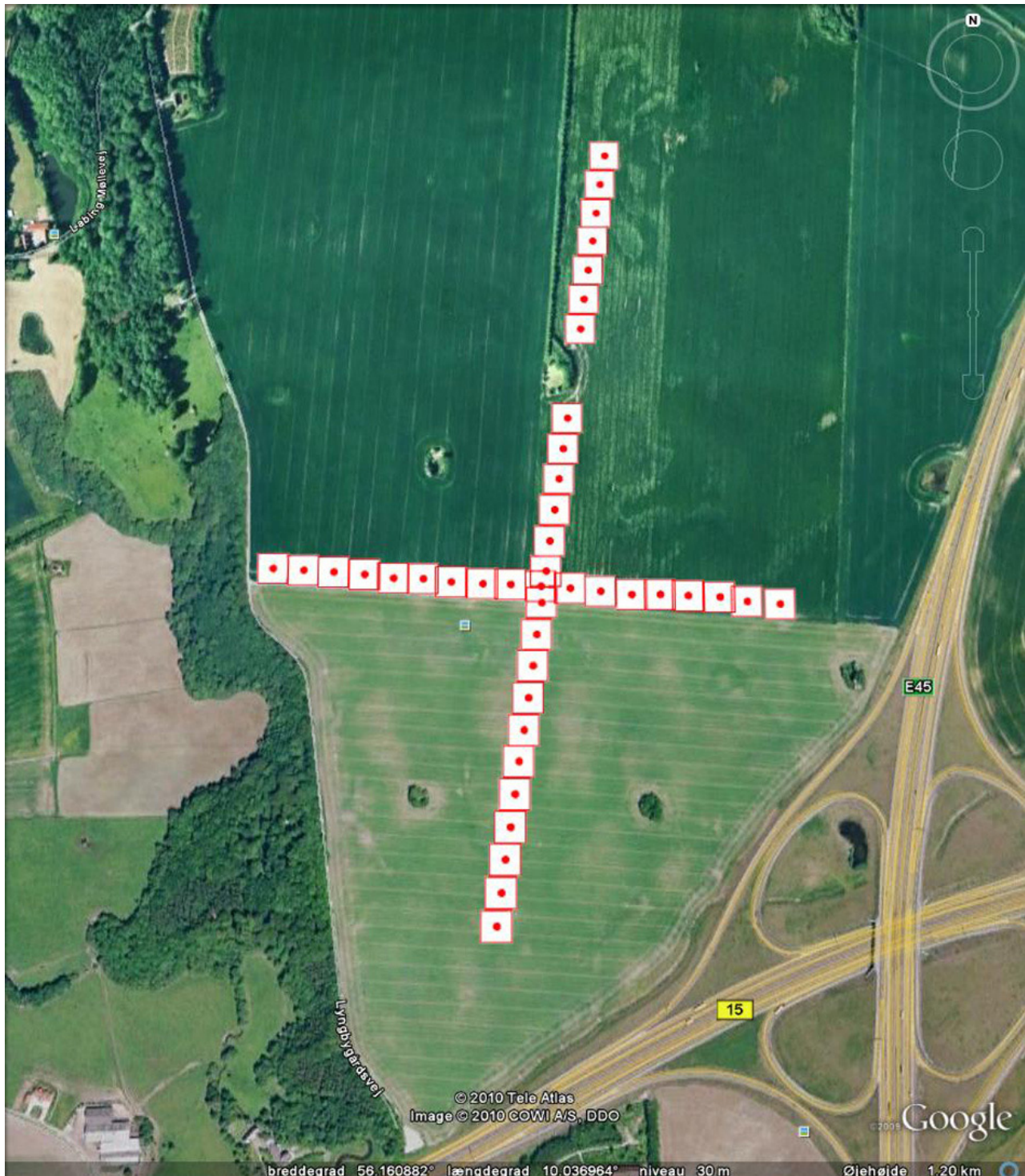


Figure 1 Detailed location map of the Danish national TEM test site. Red dots show the positions of the groundbased TEM soundings. The squares indicate the positions of the 40 x 40 m² transmitter loop

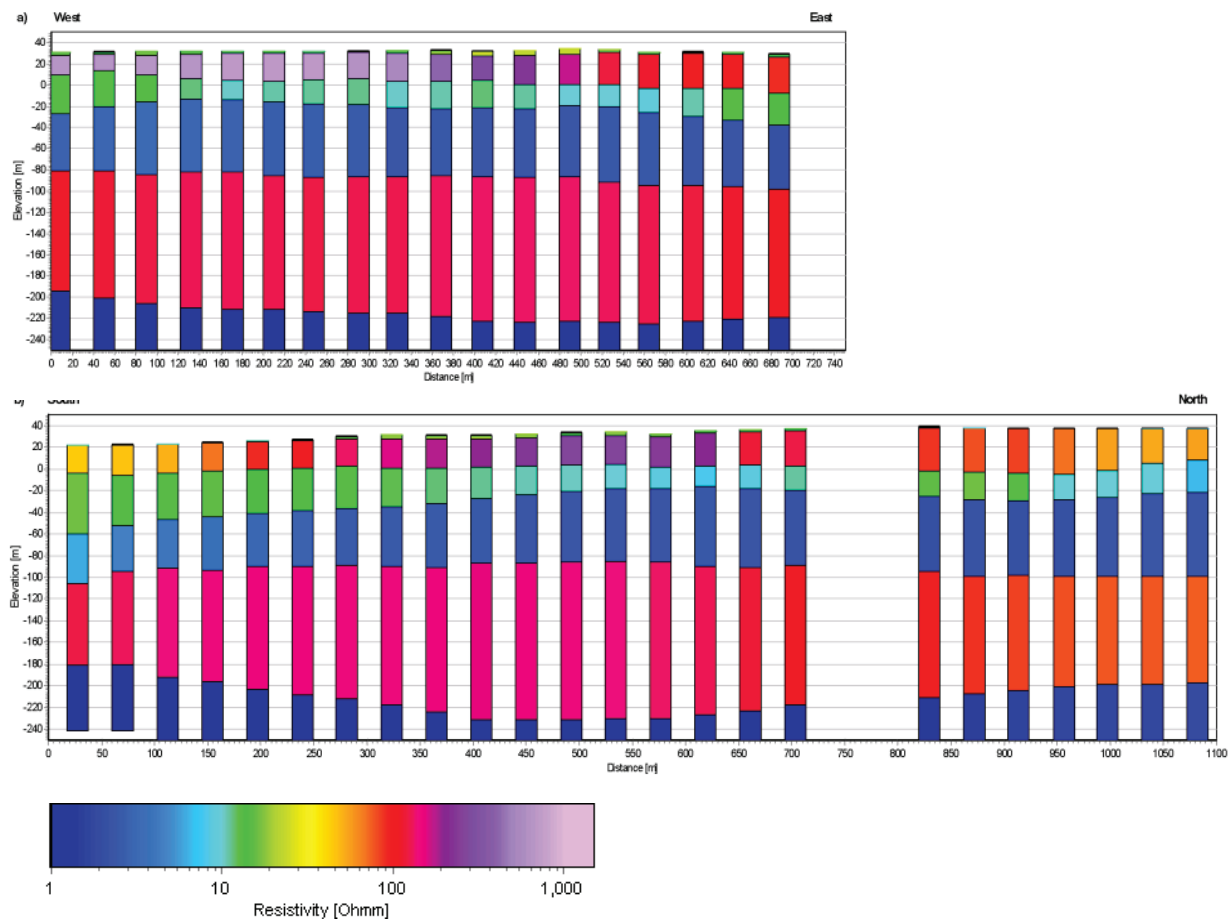


Figure 2 Resistivity sections of the two profiles in figure 1. a) West-East profile b) South-North profile



The SkyTEM-survey

The SkyTEM survey at the test site was carried out on 5th August 2009 by SkyTEM ApS. The raw data report (in Danish) for the survey by SkyTEM ApS is in appendix 4

SkyTEM set-up, data set

The SkyTEM data were recorded with a standard set-up using the largest transmitter frame at the time of $\sim 500 \text{ m}^2$. Data were obtained from approximately 10 μs to 10 ms using a low and a high transmitter moment sequential. Table 1 shows a brief overview of key system parameters and survey information. A detailed system description, additional survey information etc. are found in the raw data report in appendix 4.

Type	Value	
Helicopter speed	$\sim 45 \text{ km/h}$	
Tx-height	$\sim 15 \text{ m}$, $\sim 25 \text{ m}$, $\sim 35 \text{ m}$	
Line repetitions	Four of each line/height (two times in booth direction)	
	Low moment	High moment
Transmitter moment	$\sim 4500 \text{ Am}^2$	$\sim 180000 \text{ Am}^2$
Tx: on, off	1.0 ms, 1.25 ms	10 ms, 10 ms
Gate time	10.5 μs - 1 ms	0,14 ms - 9 ms

Table 1 Key parameters for the SkyTEM-system setup.

The full SkyTEM data set consists of data from the two crossing lines at altitudes of 15, 25, and 35 m, all repeated four times (twice in both directions).

Processing and inversion

The UTM positions of all 24 lines are plotted in figure 3. The electrical installations and fences associated with the highways to the east and south and the power line to the north cause coupling interferences in the data. During the process the coupled data have been removed.

In general, the agreement between the positioning of the different flight lines and the groundba-

sed reference lines is good. For the central part of the lines, the positions are within 20 m of the reference sections. At the beginning and end of lines the agreement with the reference sections is larger because of helicopter manoeuvre related to the incoming and outgoing from the flight lines. A small waterhole and a group of trees are located at the north part of the north-south profile. For the repetitions in altitudes of 15 and 25 m, the helicopter deviated from the reference line to avoid the trees, which is clearly seen in the flight paths (figure 3). SkyTEM data recorded in 35 m altitude had no tree top clearing problems and therefore no line deviations at the waterhole. The SkyTEM data deviating from line are kept and inverted as well. This needs to be taken into account in the later line comparisons. Also, note that there is no groundbased reference soundings/models at the waterhole.

Data processing and inversion were carried out in the Aarhus Workbench (Auken et al. 2009). Soundings were generated for approximately every 20 m. The SkyTEM data were inverted with the same LCI approach as used as for the groundbased TEM. For the SkyTEM data this includes modelling of the actual transmitter and receiver heights. The line repetitions were inverted in separate LCI sections, using a sharp layer boundary model with five layers (few-layer model). The data fit normalized with the data error is on average close to 0.6. This means that data are fitted well within the data noise.

Upward continuation of SkyTEM data to a nominal height

Part of the validation of the SkyTEM system is to examine the repeatability. To avoid issues arising from equivalent models, this repeatability study is carried out in data space as well as in model space.

The altitude strongly influences the recorded responses as showed in figure 4. Therefore, it is necessary to normalize data to a nominal altitude to be able to compare the responses from the different repetitions. This is done by an upward continuation.

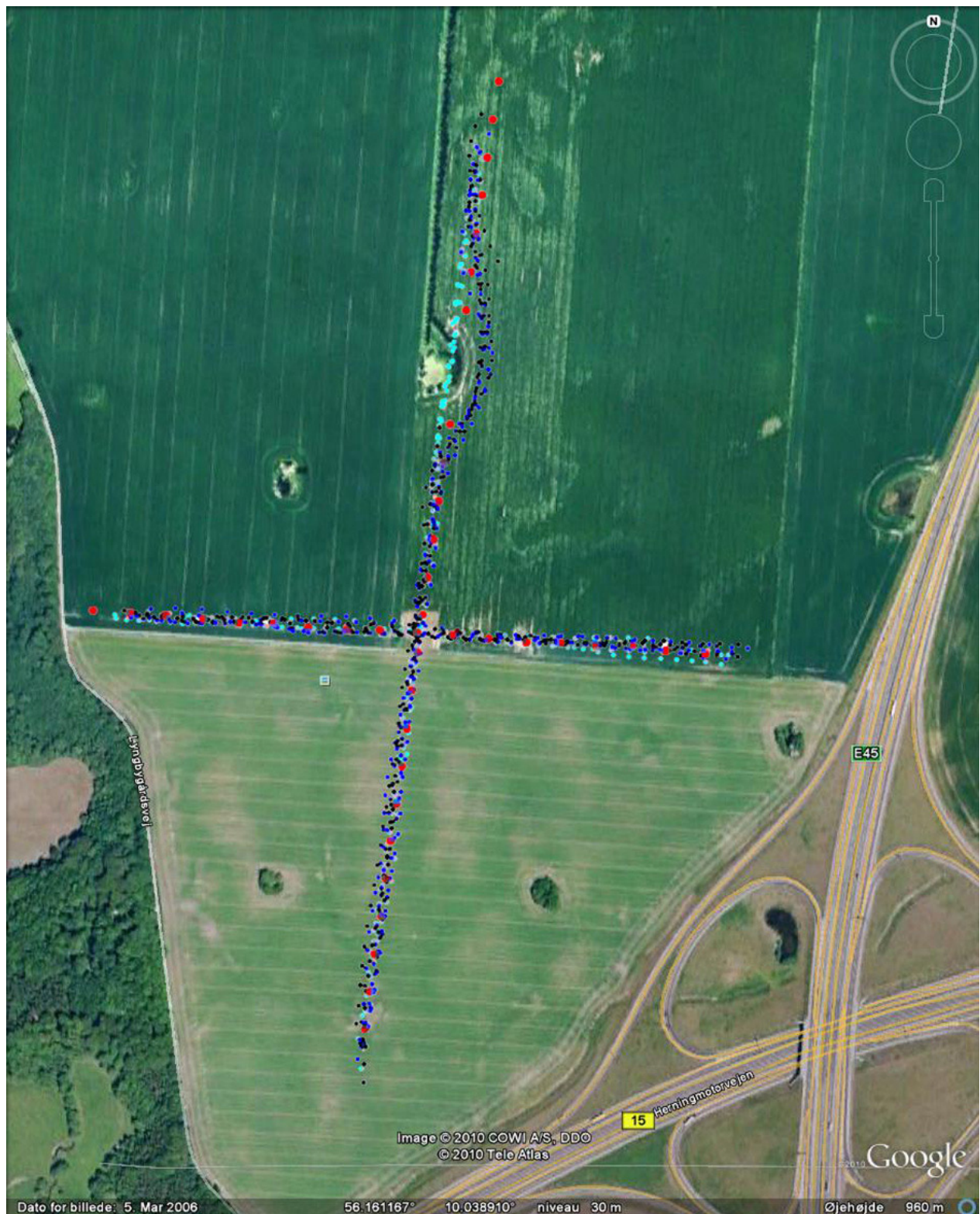


Figure 3 Model position of the different SkyTEM repetitions and the groundbased TEM soundings. Black, blue and cyan mark the four SkyTEM repetitions in the altitudes of 15, 25, and 35 m. Red dots mark the groundbased TEM soundings

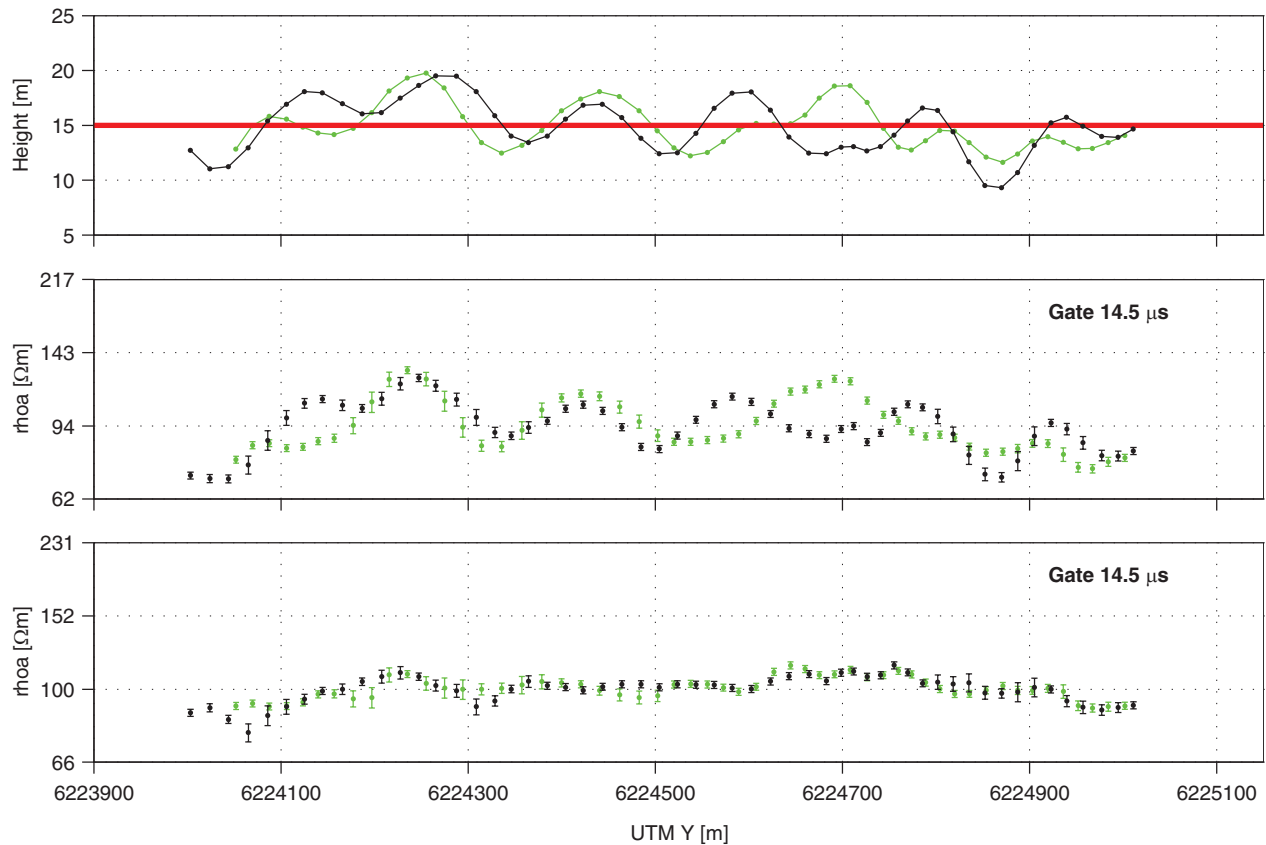


Figure 4 a) Altitude variations along the S-N profile for two repetitions in approximately 15 m. b) Recorded SkyTEM data for the time gate a 14.5 μ s. A direct comparison of the data is not possible because of the altitude variations. c) Upward continued data the nominal altitude of 15 m.

The upward continuation to a nominal altitude is done individually for all the soundings based on a gate-by-gate linearization of the forward response from the resistivity model with the altitude.

The upward continuation scheme is illustrated in figure 5 and includes the following four steps:

- 1 Inversion of the sounding to a resistivity model.
- 2 Calculation of the SkyTEM forward response, using the full system transfer function in the actual altitude and in the nominal altitude.
- 3 Calculation of a correction factor gate by gate from the two forward responses. $\text{CorFac}_{\text{gate } n} = (\text{Forward}_{\text{actual altitude, gate } n} / \text{Forward}_{\text{nominal altitude, gate } n})$

- 4 Application of the correction factors to the recorded data. $\text{Data}_{\text{norm}} = \text{Data}_{\text{Recorded}} * \text{CorFac}$

It can be shown that the linearization of $\log(\text{data})$ with altitude is a good first-order approximation for small altitude variations.

With this scheme the altitude variation is removed from the data whereas the noise characteristics of the individual sounding are kept. The three nominal altitudes are: 15, 25, and 35 m.

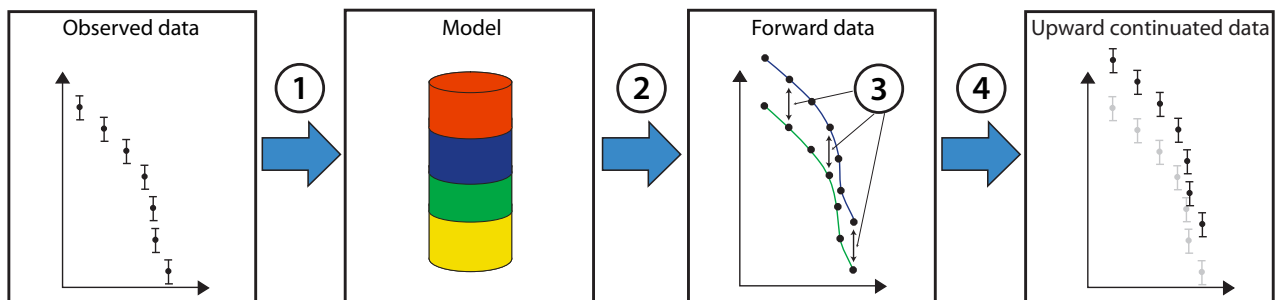


Figure 5 – Flow chart illustrating the upward continuation concept.

Upward continuation of reference models to a nominal height

An upward continuation of the groundbased reference sections to the three nominal altitudes is needed to validate the SkyTEM data against the reference sections in data space. The upward continuation of the groundbased reference data to a nominal altitude is done in a similar way as the upward continuation of the SkyTEM data.

The upward continuation scheme for the ground-based reference soundings is illustrated in figure 6 and includes only two steps:

- 1 Inversion of the reference soundings to a resistivity model.
- 2 Calculation of forward response for the reference model, in the nominal altitude, using the SkyTEM system transfer function

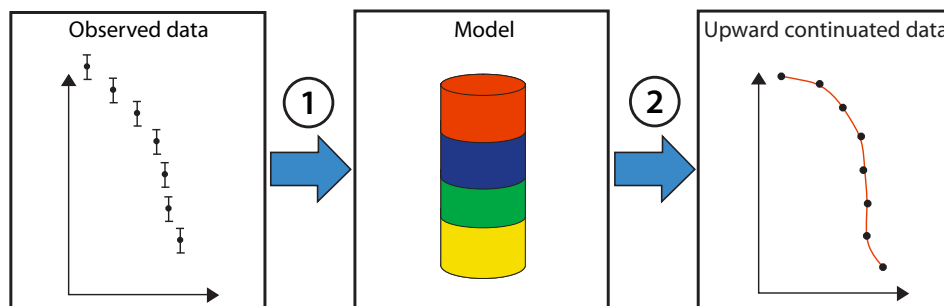


Figure 6 Flow chart illustrating the upward continuation concept of the reference sounding/ model to nominal altitude.

With this scheme we generate a synthetic response of what the SkyTEM system should measure over the reference lines in the nominal altitude. This makes it possible to compare and validate the SkyTEM data gatewise. The upward continued response will be referred to as the reference response.

This upward continuation and the later comparison with the SkyTEM data only make sense if both

of the following criteria are met: Firstly, the reference model must resolve the subsurface equally good as or better than the SkyTEM system. Secondly, the mapping method for the reference model and the SkyTEM system must be based on the same physical principles (e.g. EM and EM, not EM and DC). In our case, both criteria are met.



Validation results

Comparison of inversion results

The first validation step of the SkyTEM system at the national test site is a simple visual comparison of the inversion results. This is done with respect to:

- 1 Repeatability in the same altitude
- 2 Repeatability in different altitudes
- 3 Agreement to groundbased reference model sections

In this section comparison examples of the three different types are presented and commented. In appendix 1 the full set of inversion results are displayed including profiles in all three altitudes and four line repetitions, in total, 24 resistivity sections.

When comparing the inversion results, some issues, not related to the specific system, can result in dissimilarities in the inversion results:

- Footprint – footprint sizes differ with altitudes

- Position errors - The different line repetitions are not perfectly positioned on top of each other.
- Equivalent models - Different models can fit the same response within the data errors.

It is difficult to quantify the effect of the first two issues in the inversion results. The last issue will be eliminated in the later comparisons in data space. However, a direct comparison of the inversion results still provides a fair first-step validation of the SkyTEM system.

SkyTEM repeatability

Resistivity sections for two repetitions of the E-W-profile at a altitude of 25 m are shown in figure 7. The agreement between the two sections is generally good with only minor dissimilarities. The good repeatability is general for the four repetitions in the three different altitudes.

Figure 8 presents a comparison of the resistivity sections from 15 m and 35 m from the E-W profile. The overall agreement between the two sections is again very good.

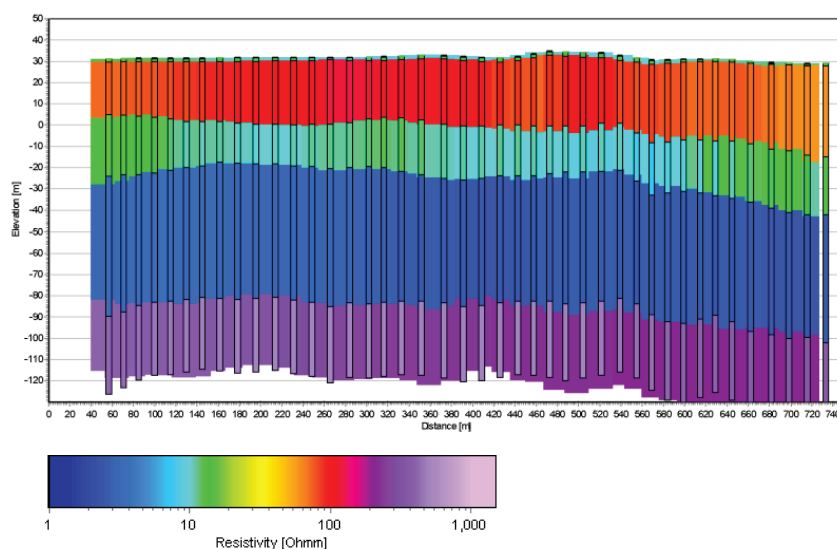


Figure 7 Resistivity sections from the E-W-profile at a altitude of 25 m plotted with double vertical exaggeration. Background section is repetition one, front bars repetition two.

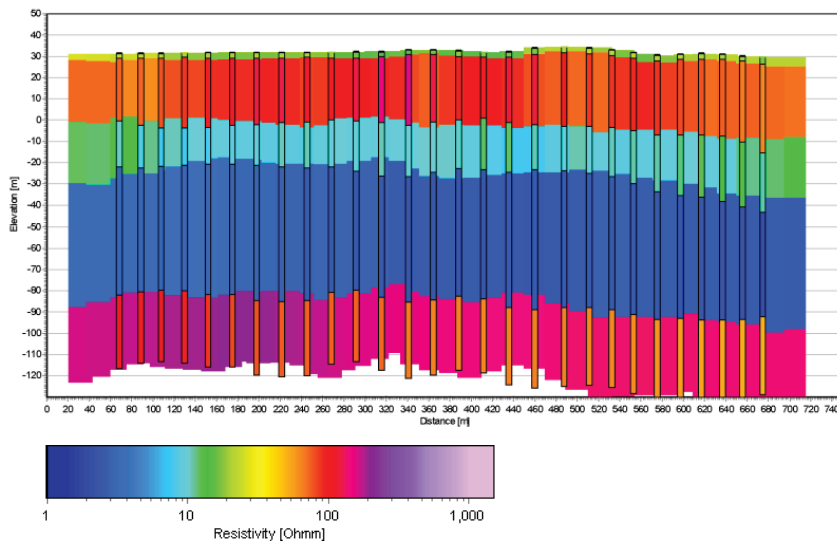


Figure 8 Resistivity section from an EW-profile at two different altitudes, plotted with double vertical exaggeration. Background section; altitude of 35 m. Front bars; altitudes of 15 m.

Table 2 shows the model parameter analysis (Auken et al., 2005) for a single model, stating how well the different model parameters are resolved. The poorly resolved model parameters are the resistivity of layer 5, resistivity and thickness of layer 1, and partly the resistivity of layer 3.

	Resistivity	Res-STDC	Thickness	Thk STDC	Depth	Dep STDC
Lag 1	17.9	1.618	3.8	2.020	3.8	2.020
Lag 2	141.1	1.516	27.1	1.134	30.9	1.048
Lag 3	11.7	1.055	28.2	1.038	59.1	1.028
Lag 4	2.6	1.020	58.4	1.034	117.5	1.008
Lag 5	368.2	2.060				

Table 2 Single model with the model parameters analysis for: Resistivities (ResSTDC), thickness (ThkSTDC), and Depth to the layer boundaries (DepSTDC). The model parameter uncertainties are stated as STD-factors.

Comparing the different model sections from figures 7 and 8, it is clear that the largest dissimilarities between the sections are seen for the poorly resolved model parameters. This suggests that the observed variations (e.g. on the resistivity of the bottom layer) in the different repetitions are most likely equivalence issues, since these parameters are poorly resolved.

Comparing the inversion results from the many line repetitions, we conclude that the SkyTEM system model repeatability in both the same altitude and different altitudes is good. Furthermore, this indicates that the resolution capabilities of the SkyTEM system are not noticeably affected by different recording altitudes in the interval from 15 to 35 m.

Agreement with the reference model section

The comparison to the reference section will disclose whether the absolute levels of the SkyTEM results are correct. Since the SkyTEM system prior to the survey was calibrated at the original reference site (intersection of the reference lines), we expect at perfect match at this location. The validation of the SkyTEM system against the reference sections will also be a check of the globality of the SkyTEM calibration scheme.

Figure 9 shows the comparison of a SkyTEM section from 25 m (background) with the reference section (bars), in this case for the S-N profile. The S-N section has a higher degree of lateral variation than the EW-section. Overall, there is a good agreement between the reference section and the SkyTEM sec-

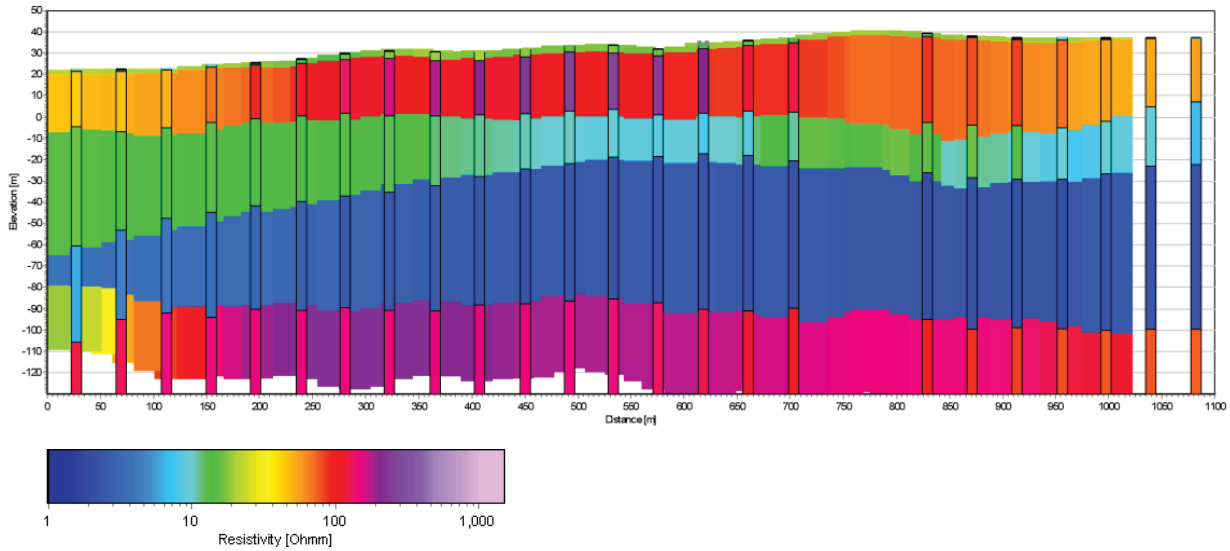


Figure 9 Resistivity section from an SN-profile plotted with double vertical exaggeration. Background section is a SkyTEM result from 25 m. Front bars show reference model.

tion. Note, for instance, how the small lateral resistivity variation in layer three is resolved in both cases. The largest dissimilarities are again observed for the poorly determined parameters: resistivities of layer two and five.

The disagreement of the deeper model part at profile coordinate 0-100 m is observed for all the repetitions. Just south of the end of the profile, a steep slope of 5-10 m towards the highway is observed. This strong surface variation may effect the ground-based TEM-measurements (reference model) and the SkyTEM measurements differently because of different footprint sizes.

The general good agreement with the reference sections confirms the quality both of the comprehensive calibration and quality control scheme and of the careful and high precision modelling of the SkyTEM-system.

Comparison in data space

It is essential that the comparisons are not only performed in the model space. As mentioned, inverted models that differ visibly may have nearly the same response due to equivalence problems. By compa-

ring in the data space these apparent differences will be neutralized. An evaluation in data space also reveals if the repeatability and agreement with the reference sections is equally good for all parts of the sounding curve/all time gates.

Similar to the model section a few examples will be presented in this section, while the full series of plots for all the repetitions are placed in appendices 2 and 3.

All comparisons are based on the upward continued responses in the nominal heights. Since the data from the different repetitions do not coincide geographically, the data are plotted against the UTM-Y coordinate for the N-S profile and against the UTM-X coordinate for E-W profile. The shown data values are late-time apparent resistivity (ρ_a), transformed from the observed db/dt values by the usual equation:

$$\rho_a = \frac{1}{\pi} \left(\frac{M}{20 \frac{\partial b_z}{\partial t}} \right)^{2/3} \left(\frac{\mu_0}{t} \right)^{5/3}$$



Where M is the magnetic moment of the transmitter, and t is the gate center time.

Panel b and c in figure 10 show data for the low-moment time gate at $115 \mu\text{s}$ from an altitude of 15 m, before and after the upward continuation respectively. The error-bars in the four colours represent the four different repetitions, while the reference response from the ground-based reference section is marked with red dots in the figure. The matching altitudes variations are shown in panel a. Panel c in figure 10 holds the plot of inte-

rest where one can make a direct data comparisons. For the upward-continued data we observe a good agreement between the four repetitions and the reference response throughout the section. In general, the SkyTEM-system repeats and fit the reference response within the data STD for this time gate.

Figure 11 shows data comparisons similar to that of figure 10 c, but for the three different altitudes of 15, 25 and 35 m. An equally good agreement in the different altitudes is observed.

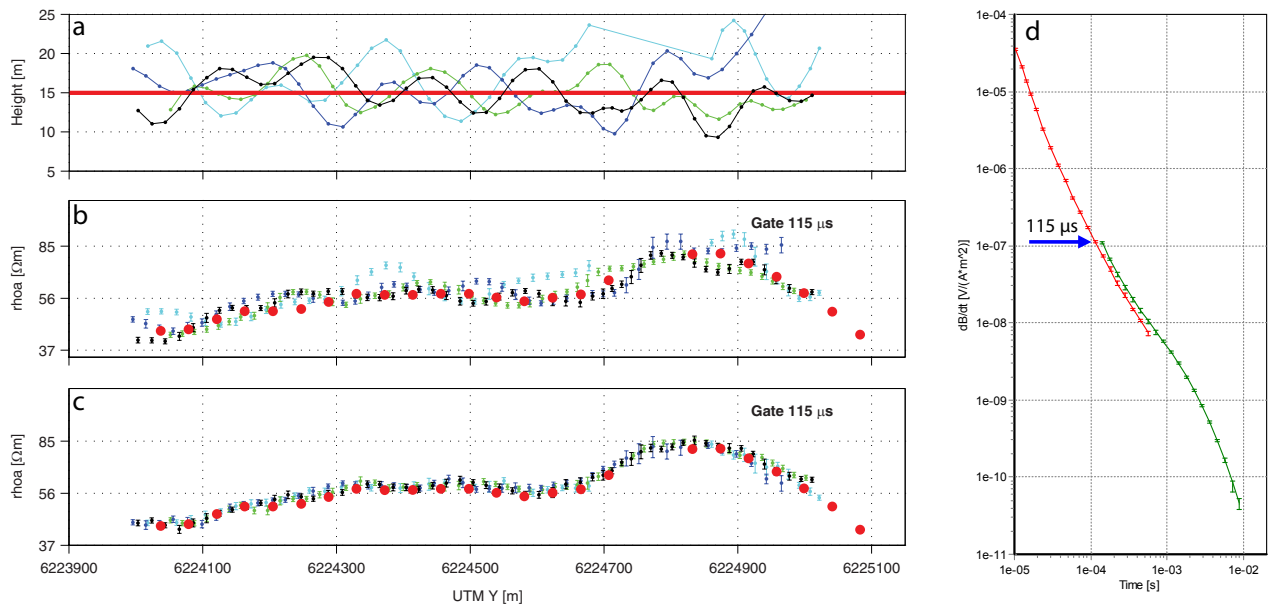


Figure 10 Data from the south-north profile, flying height $\sim 15 \text{ m}$. a) Flying height variations for the four repetitions in $\sim 15 \text{ m}$ indicated by four different colors. b) and c) error bars show data for the gate at $115 \mu\text{s}$ before and after upward continuation respectively. The color-coding is the same as used in panel a) and the red dots mark the upward-continued reference response, from the ground-based reference section. d) Typical sounding curve with red as low moment, and green as high moment.

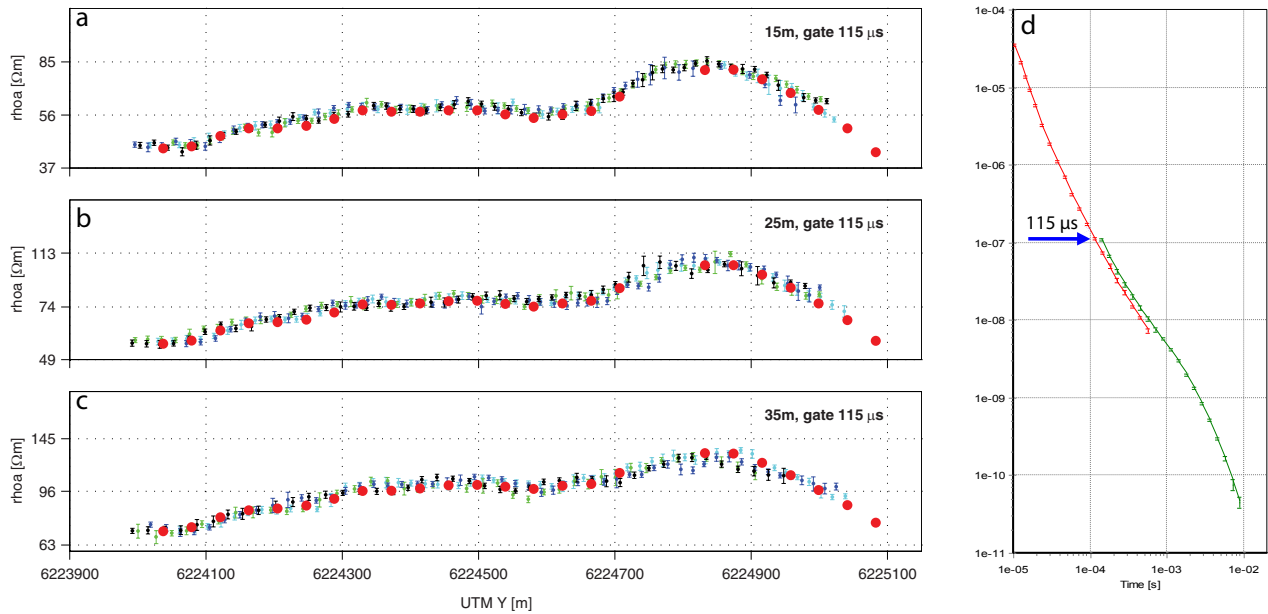


Figure 11 Data from the south-north profile for the gate at 115 μ s. In a), b) and c) marks the error bars data from the altitude of 15 m, 25 m, and 35 m, respectively. d) Typical sounding curve. Red is the low moment, green is the high moment.

Figure 12 shows the data comparison for an early and center low-moment gate and for a late high-moment gate. Data from the early time gate (top panel) is more scattered and especially at the ends of the profile the fit to the ground-based reference response is poorer than for the later gates (panel b and c), where the overall fit is good. At early times is the foot-print relatively small, which means that surface-near geo-

logical variations will have an impact if there are small offsets in the geographical positions between repeat lines. This is in accordance with the observations in figure 10 c), where the largest geographical mismatch is at the north end of the profile where the positions deviate from the line because of the water hole (see figure 2). At later times the foot-print is much larger and smaller geological variations are averaged out.

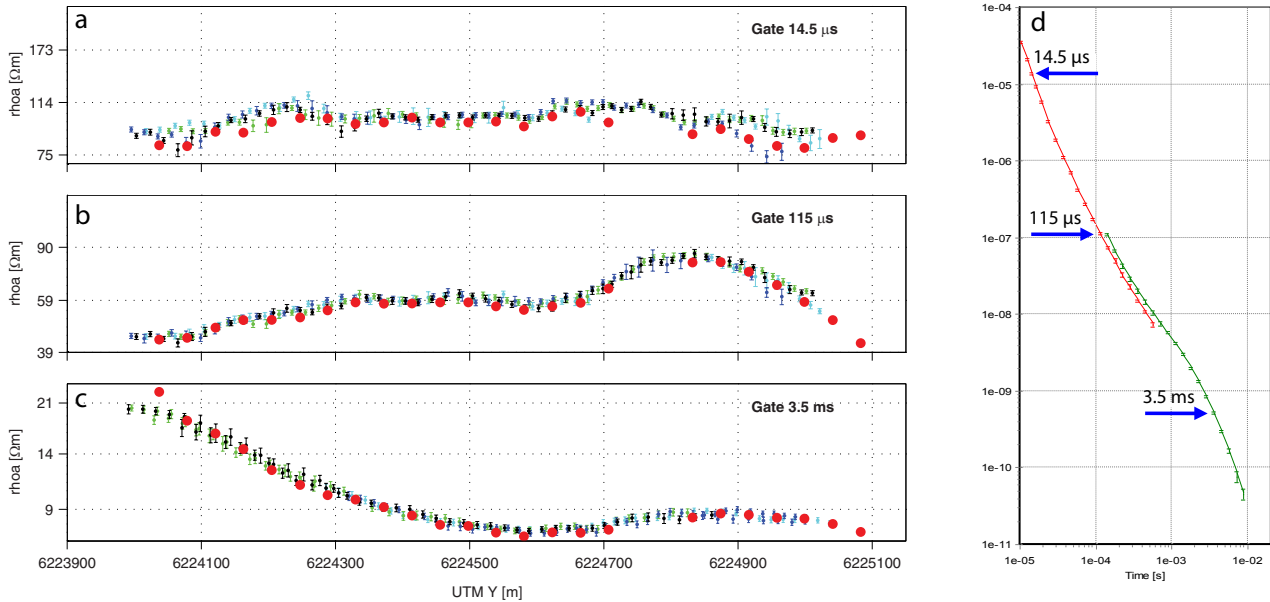


Figure 12 Data from the south-north profile at an altitude of 15 m. In a), b) and c) marks the error bars data from the gates at 14.5 μ s, 115 μ s, and 3.5 ms respectively. d) Typical sounding curve. Red is the low moment, green is the high moment.

The different data comparison shows that the SkyTEM-system repeats the test lines equally good in different heights and the agreement with the reference response is generally good and within the data STD. For the early time gates some

disagreements are observed, for parts of the line. These disagreements are most likely the effect of deviations from the line and/or 3D-effects. There is nothing indicating that it is system related effects.



CONCLUSIONS

The comprehensive test and validation of the SkyTEM system showed in this report confirm the high data quality of the SkyTEM system as well as its robustness, also documented in previous studies on the national TEM test site. The original national TEM test site required hovering measurements, whereas this test extends the conclusions to lines and survey conditions.

The direct comparison of inversion results revealed that the model repeatability of the SkyTEM system is good in both the same altitude and in different altitudes. Also, there are no directional problems, i.e. it does not matter in which direction the lines are flown. The agreement to the groundbased reference sections is also good, showing that the SkyTEM-system yields data of same high quality as the groundbased system.

The validation of the SkyTEM system on data level was set up to examine the responses gate by gate, which, among other things, rules out the equivalent model issue. The different comparisons in the data space show that the SkyTEM system repeats the test lines equally good in different altitudes, and the agreement to the reference response is good and in general within the data STD. Only for the early time gates, minor disagreements are observed for parts of the line. These minor dissimilarities are most likely effects of line deviations and/or 3D-effects.

Furthermore, the validation tests serve as a quality assurance that the high-precision modelling of the SkyTEM system, together with the robust processing and inversion scheme, is of high quality. The validation results for the SkyTEM system at the test site set standards for the data quality expected for an airborne system to qualify for the Danish national groundwater mapping effort.



REFERENCES

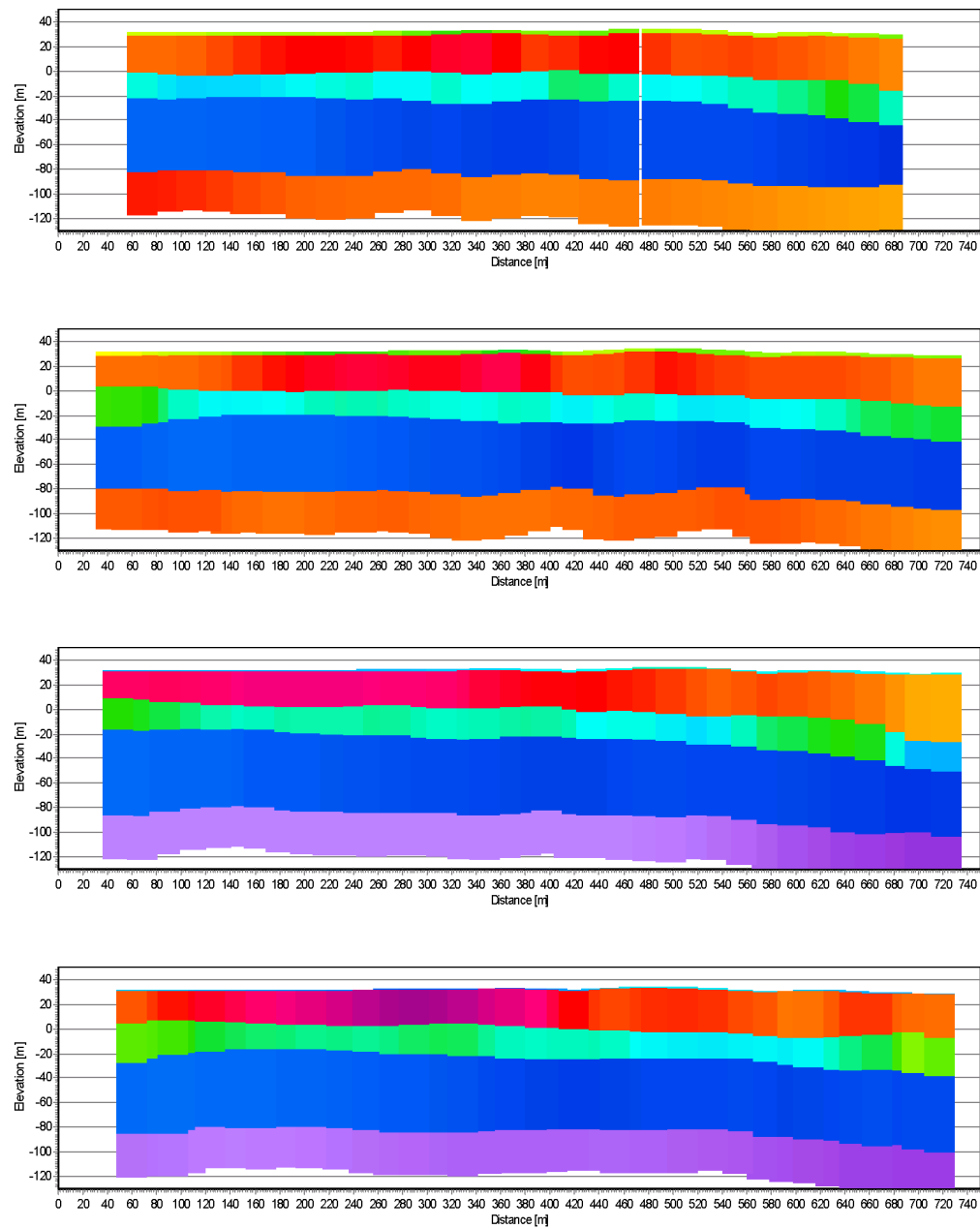
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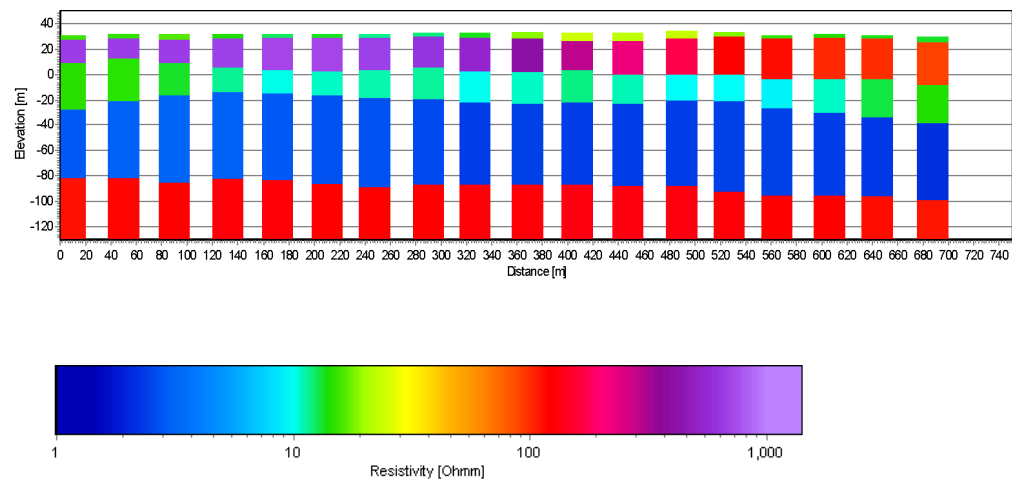
APPENDIX 1 - Inversion results

Inversion results from the two profiles, for the three altitudes of 15, 25, and 35 m, and for all four repetitions. Bottom section of each pages display the associated reference section (ground based TEM). Same scale for all sections and no vertical exaggeration.

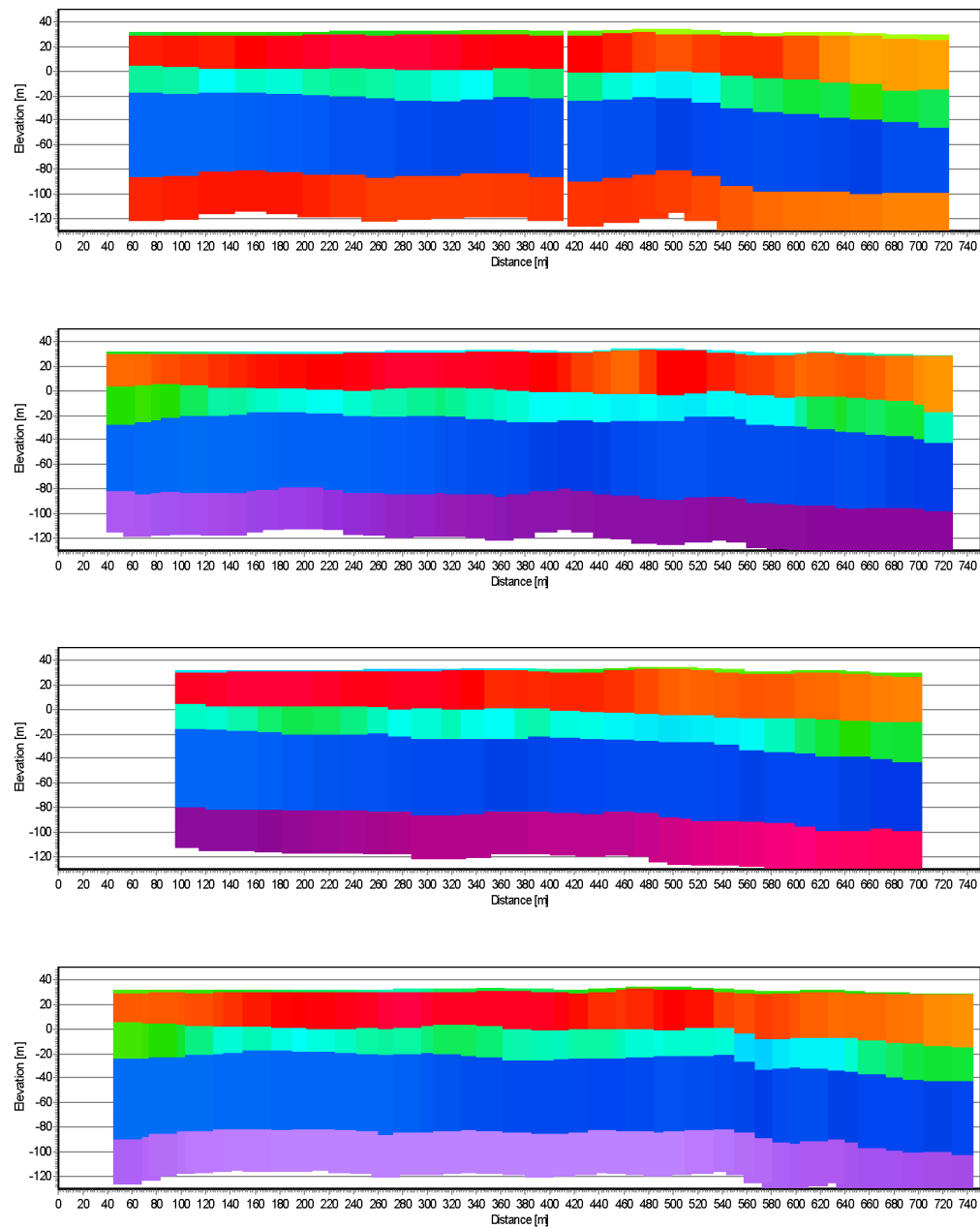
West-east profile, fly height ~15 m, four repetitions



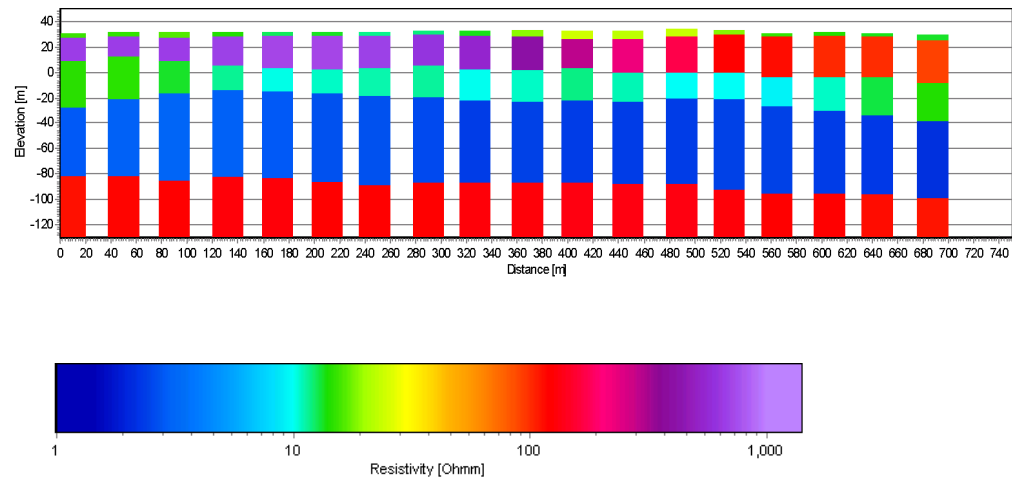
Reference section/ground based TEM



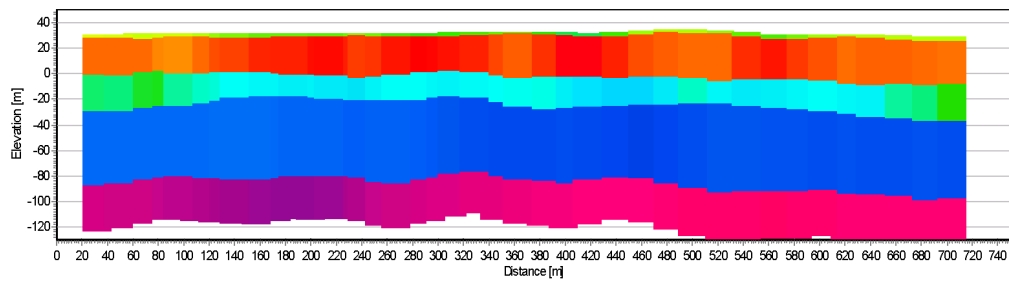
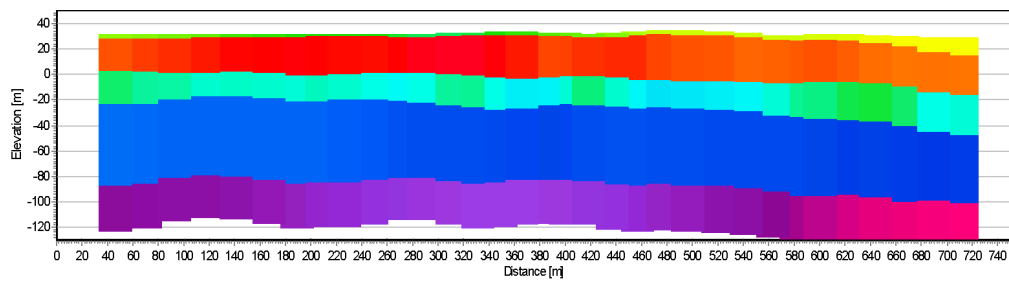
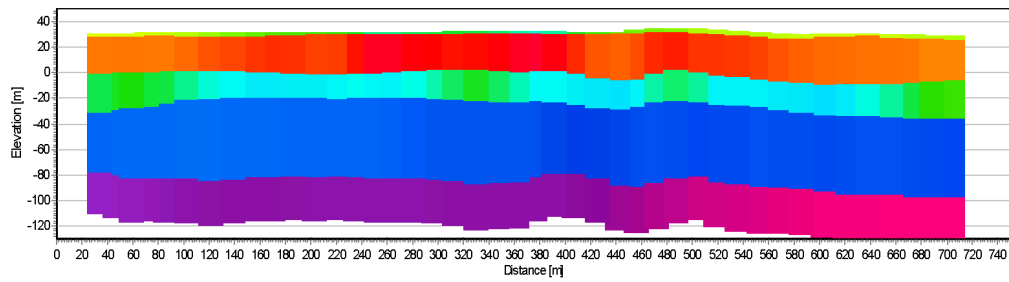
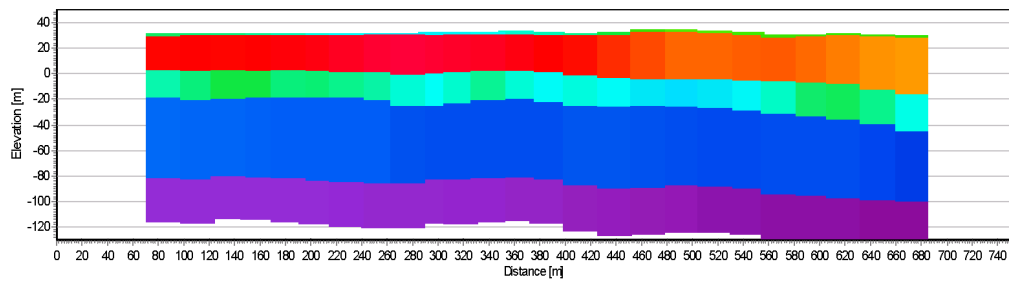
West-east profile, fly height ~25 m, four repetitions



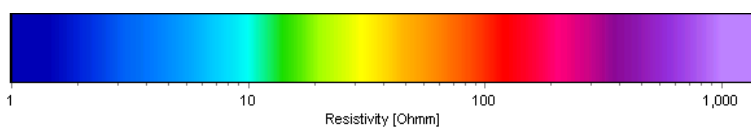
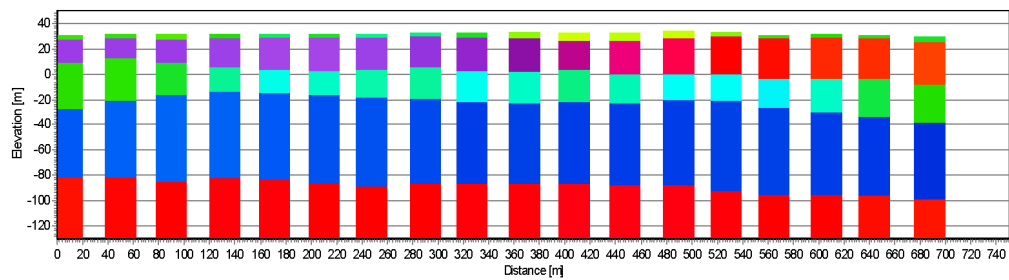
Reference section/ground based TEM



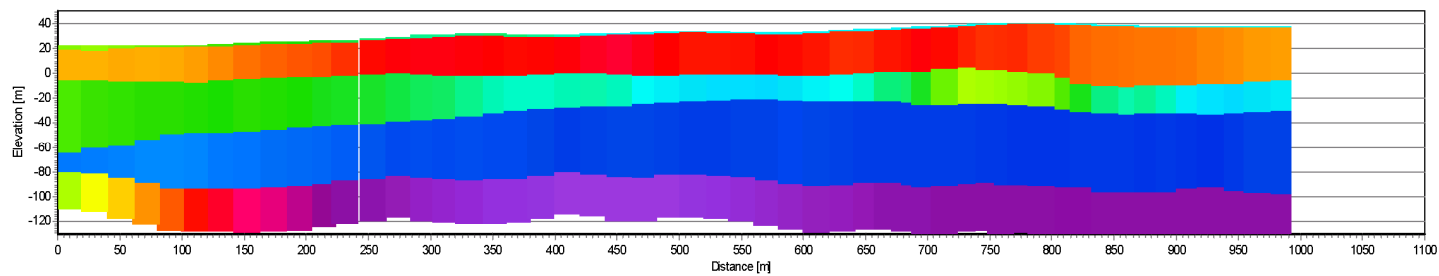
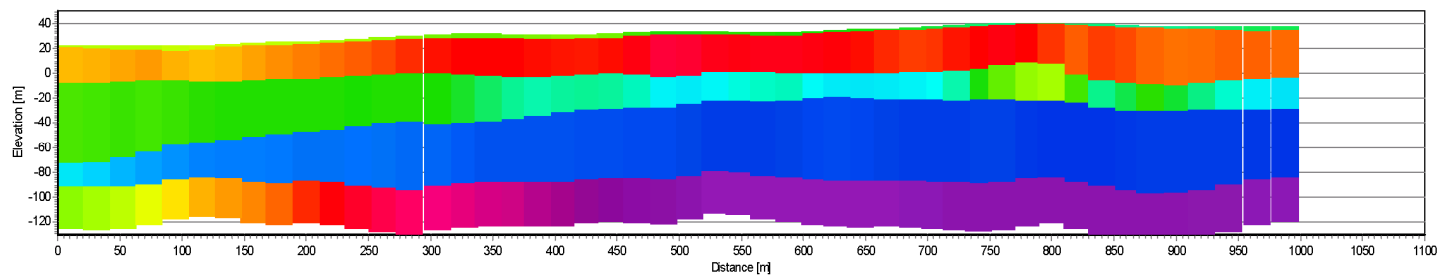
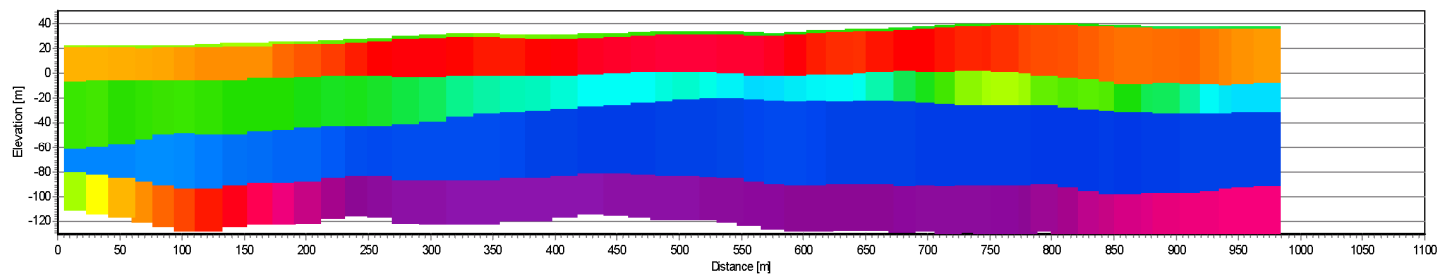
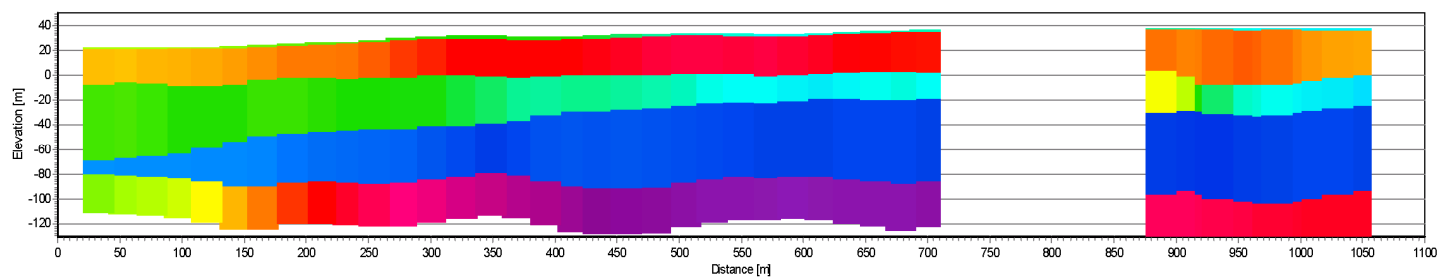
West-east profile, fly height ~35 m, four repetitions



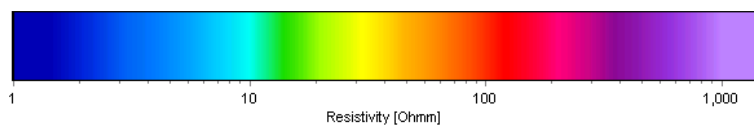
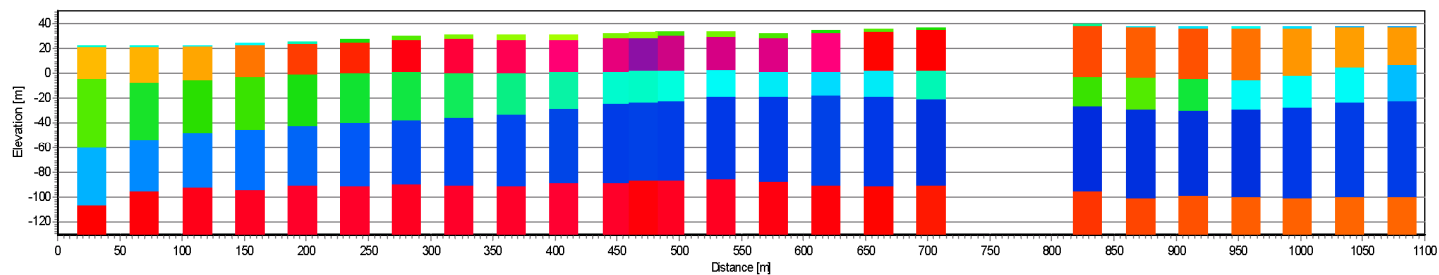
Reference section/ground based TEM



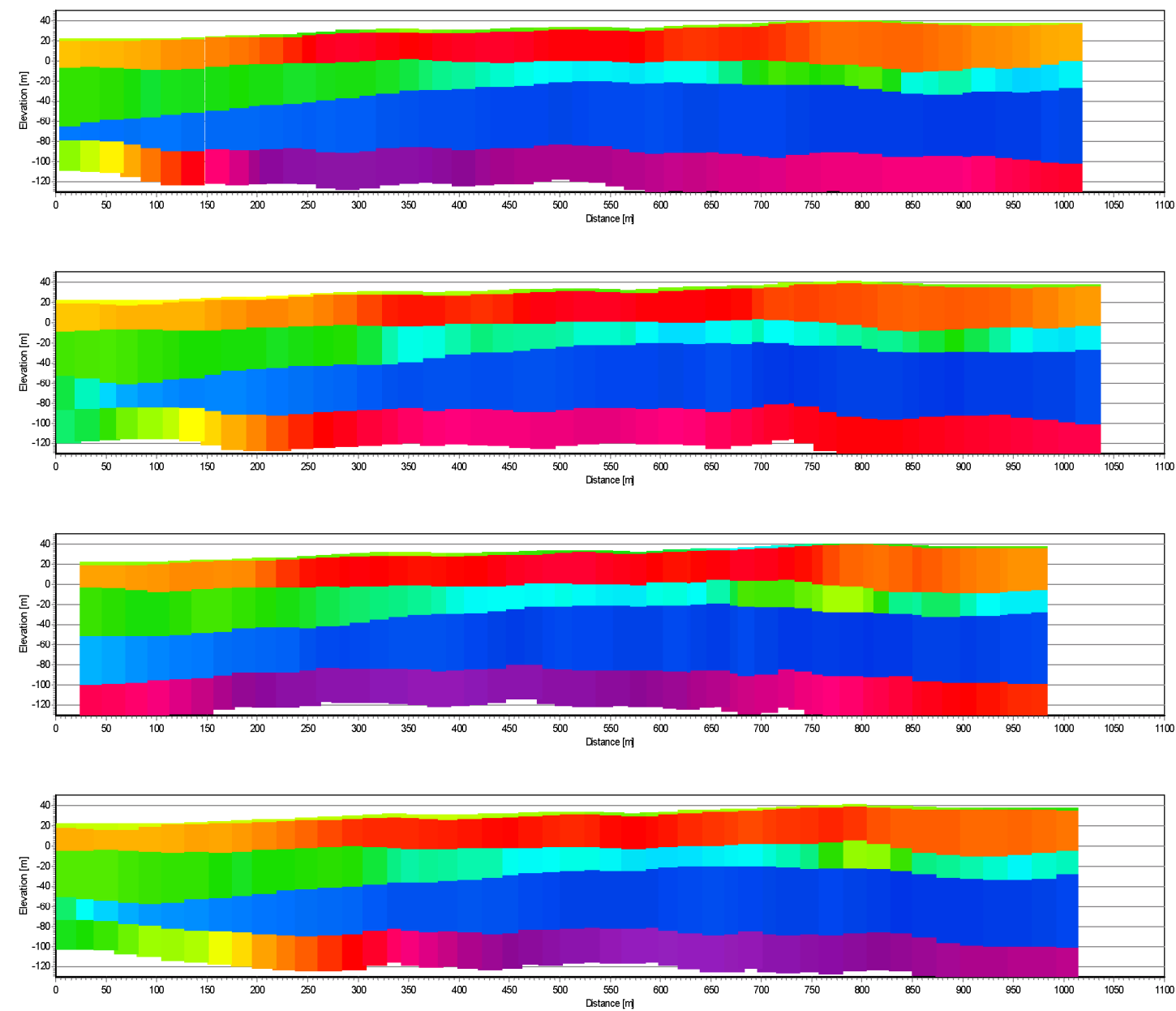
South-north profile, fly height ~15 m, four repetitions



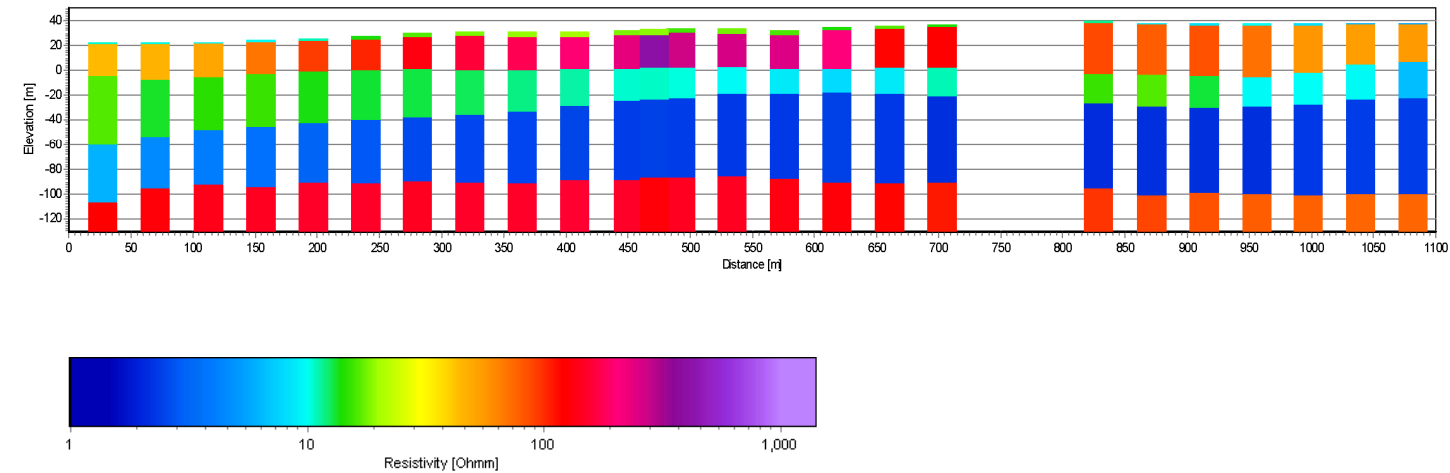
Reference section/ground based TEM



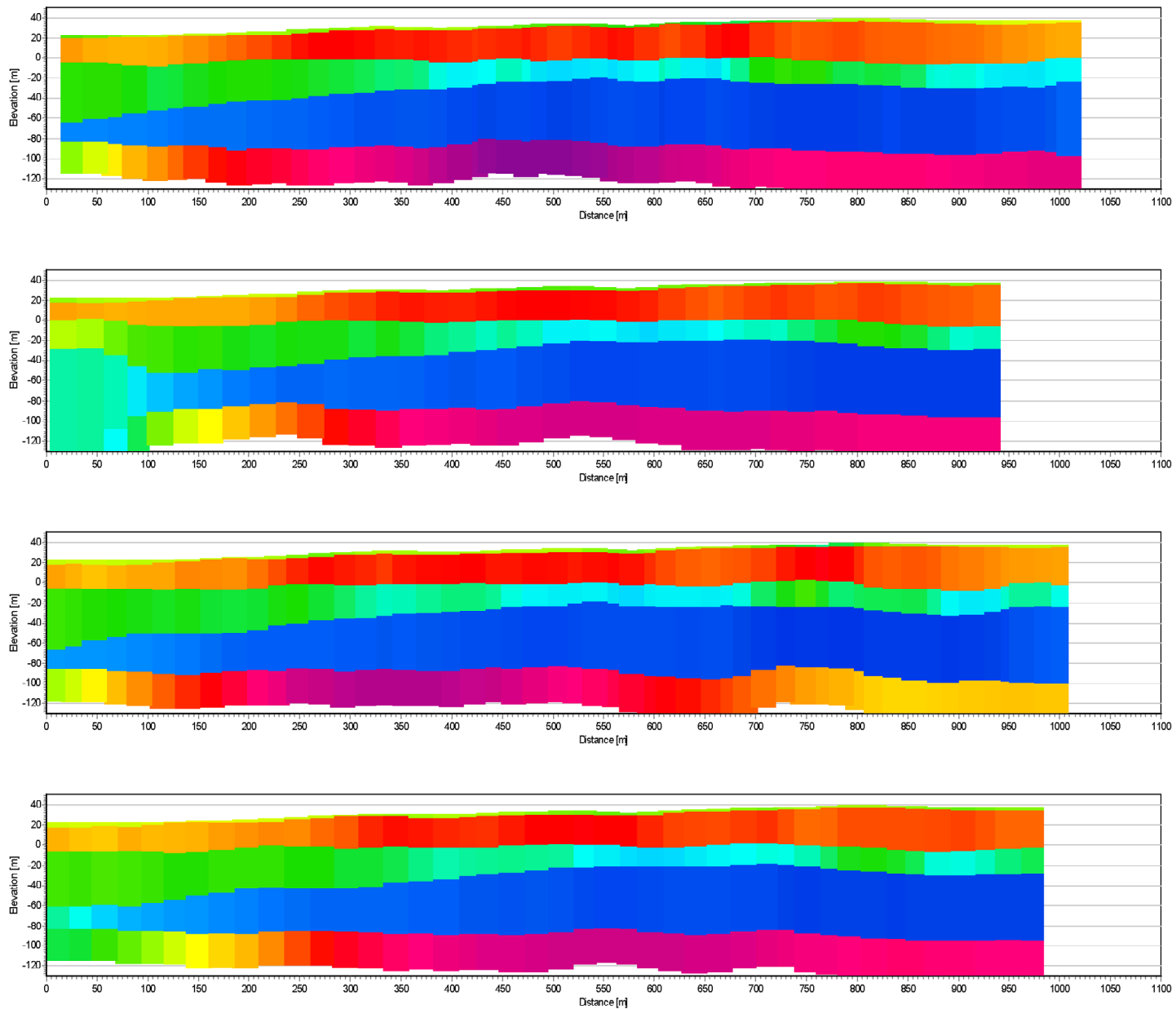
South-north profile, fly height ~25 m, four repetitions



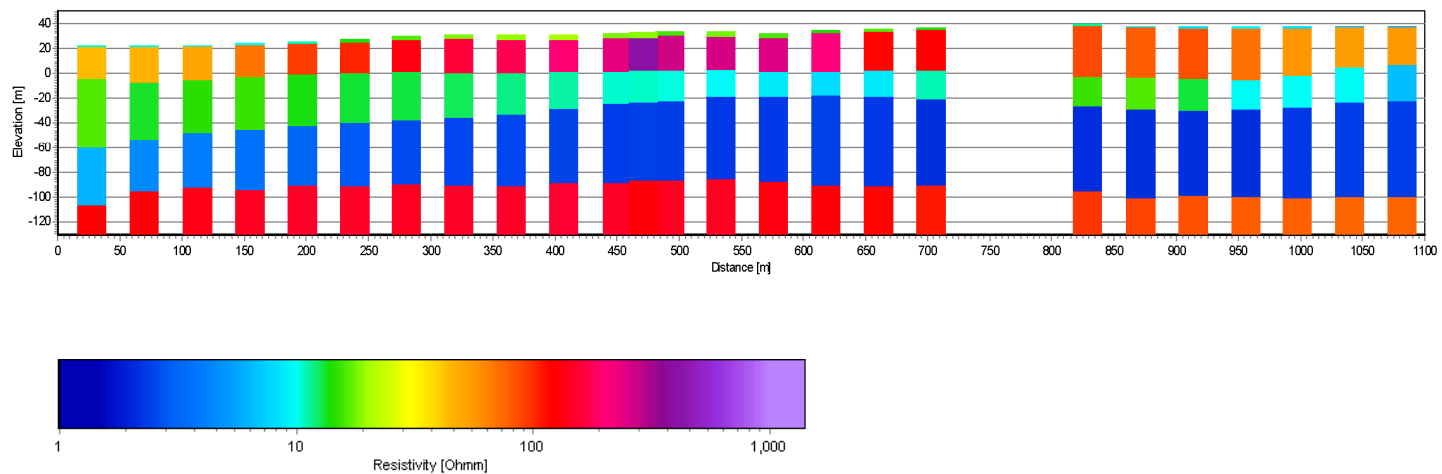
Reference section/ground based TEM



South-north profile, fly height ~35 m, four repetitions



Reference section/ground based TEM





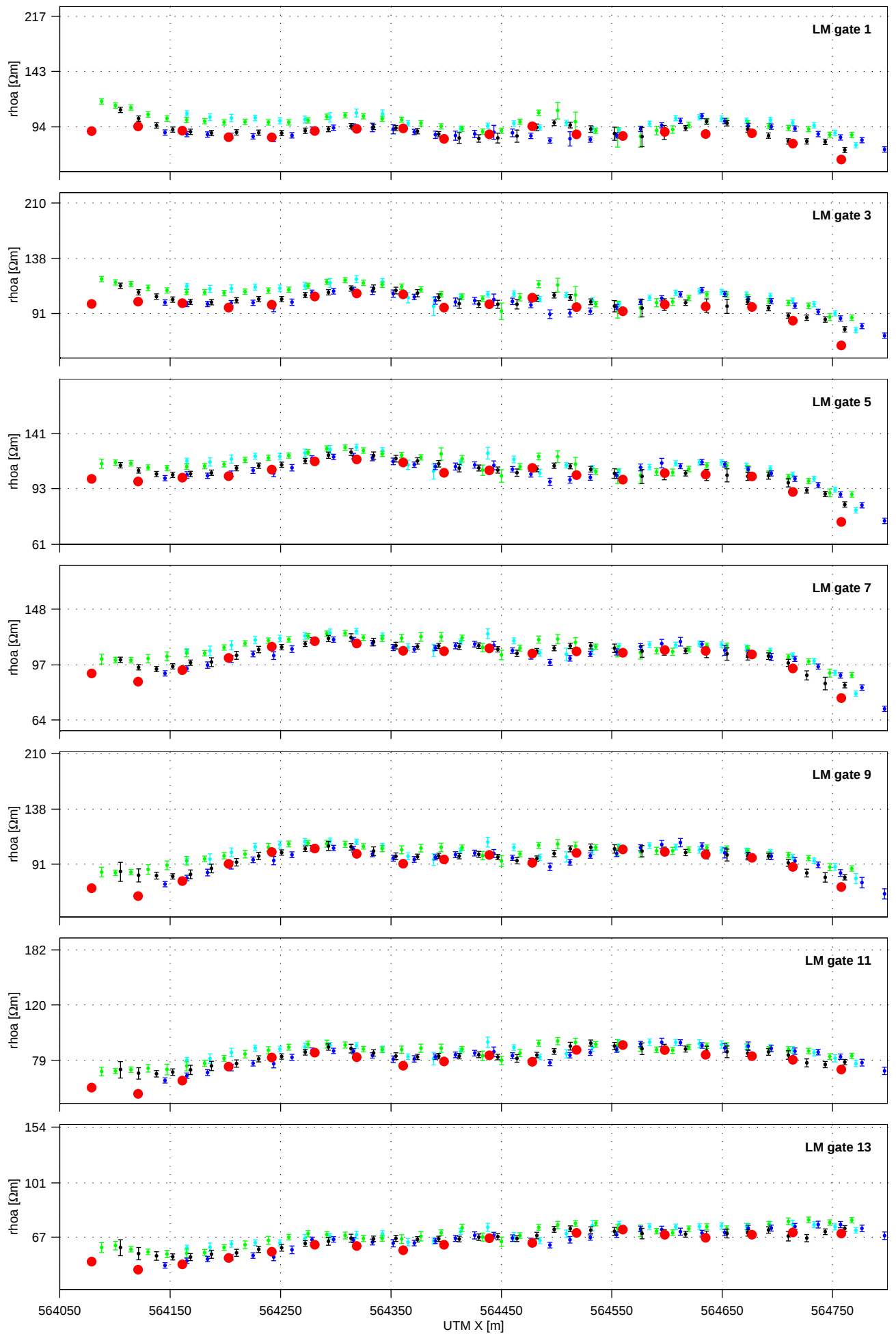
APPENDIX 2 - Data comparisons 1

This appendix holds the comparisons in data space. The comparisons are based on the upward continued responses in the three nominal altitudes of 15, 25, and 35m. The link between gate numbers displayed in the plots and the actual gate times is listed in table below (LM= low moment, HM=High moment). There is a plot for every second gate. Data plotted by the UTM-Y coordinated is from the N-S profile and data plotted by the UTM-X coordinate is from the E-W profile. The data values are late time apparent resistivity (ρ_a). The color-coded error bars represent the four different SkyTEM repetitions, while the reference responses from ground based reference sections are marked with red dots.

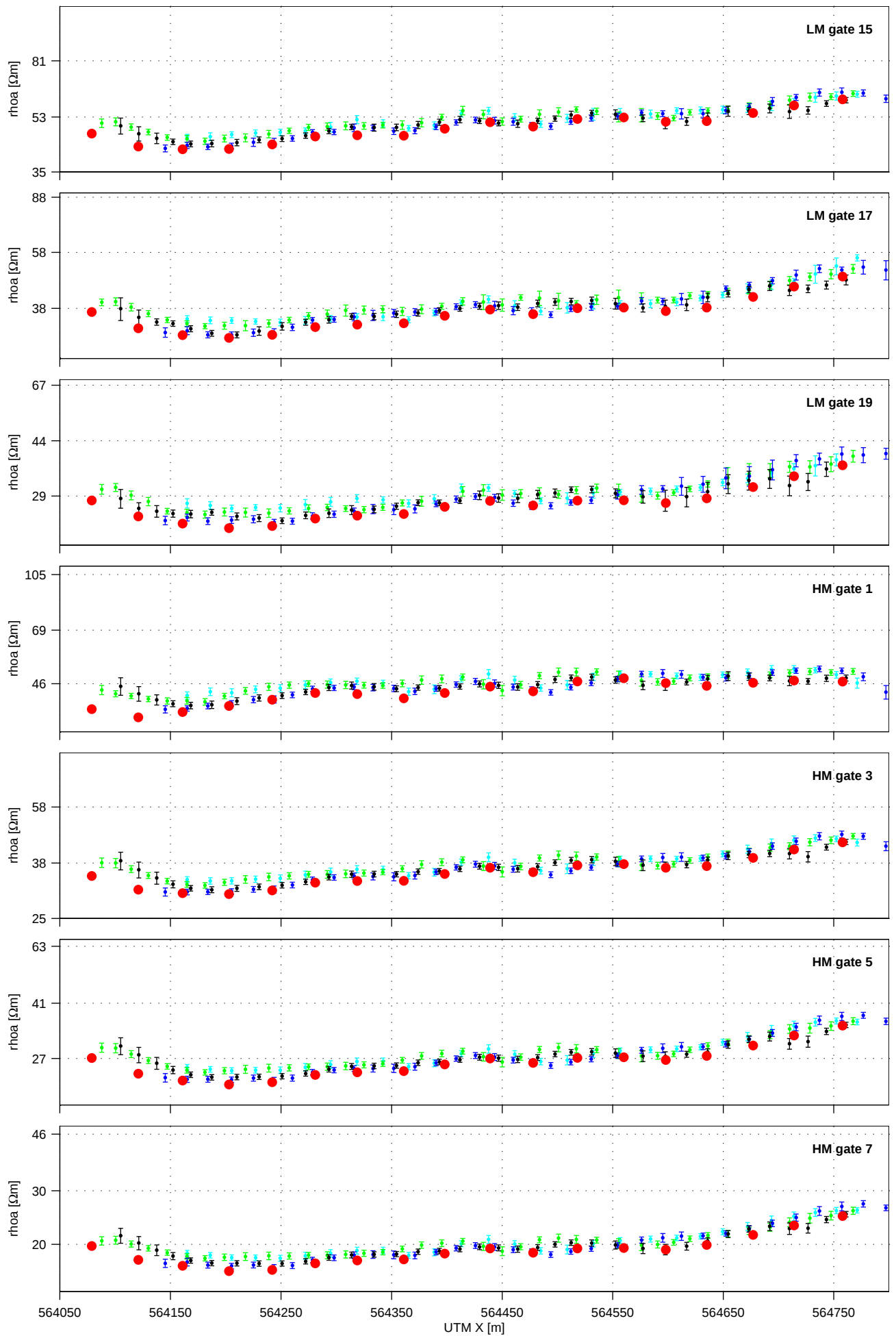
Gate time	LM GateNo	HMGateNo

1.0500e-005	1	
1.2500e-005	2	
1.4490e-005	3	
1.6500e-005	4	
1.9490e-005	5	
2.4000e-005	6	
3.0000e-005	7	
3.7490e-005	8	
4.6500e-005	9	
5.8000e-005	10	
7.2500e-005	11	
9.1000e-005	12	
1.1450e-004	13	
1.4220e-004		1
1.4350e-004	14	
1.7920e-004		2
1.8050e-004	15	
2.2570e-004		3
2.2700e-004	16	
2.8370e-004		4
2.8500e-004	17	
3.5720e-004		5
3.5850e-004	18	
4.4970e-004		6
4.5100e-004	19	
5.6620e-004		7
5.6750e-004	20	
7.1270e-004		8
7.1400e-004	21	
8.9720e-004		9
1.1300e-003	10	
1.4220e-003	11	
1.7900e-003	12	
2.2540e-003	13	
2.8370e-003	14	
3.5720e-003	15	
4.4970e-003	16	
5.6610e-003	17	
7.1270e-003	18	
8.8430e-003	19	

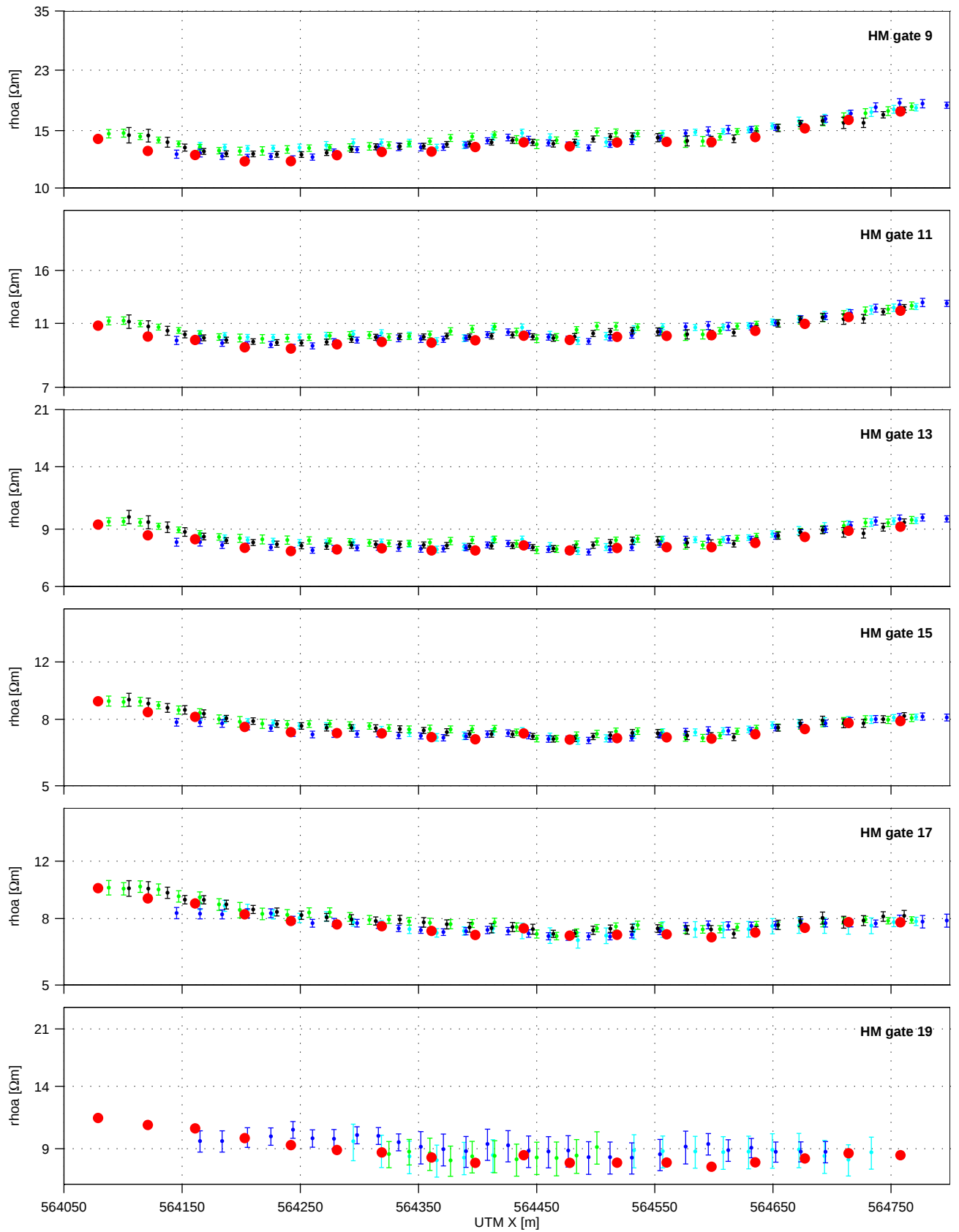
W-E profile, 15 m



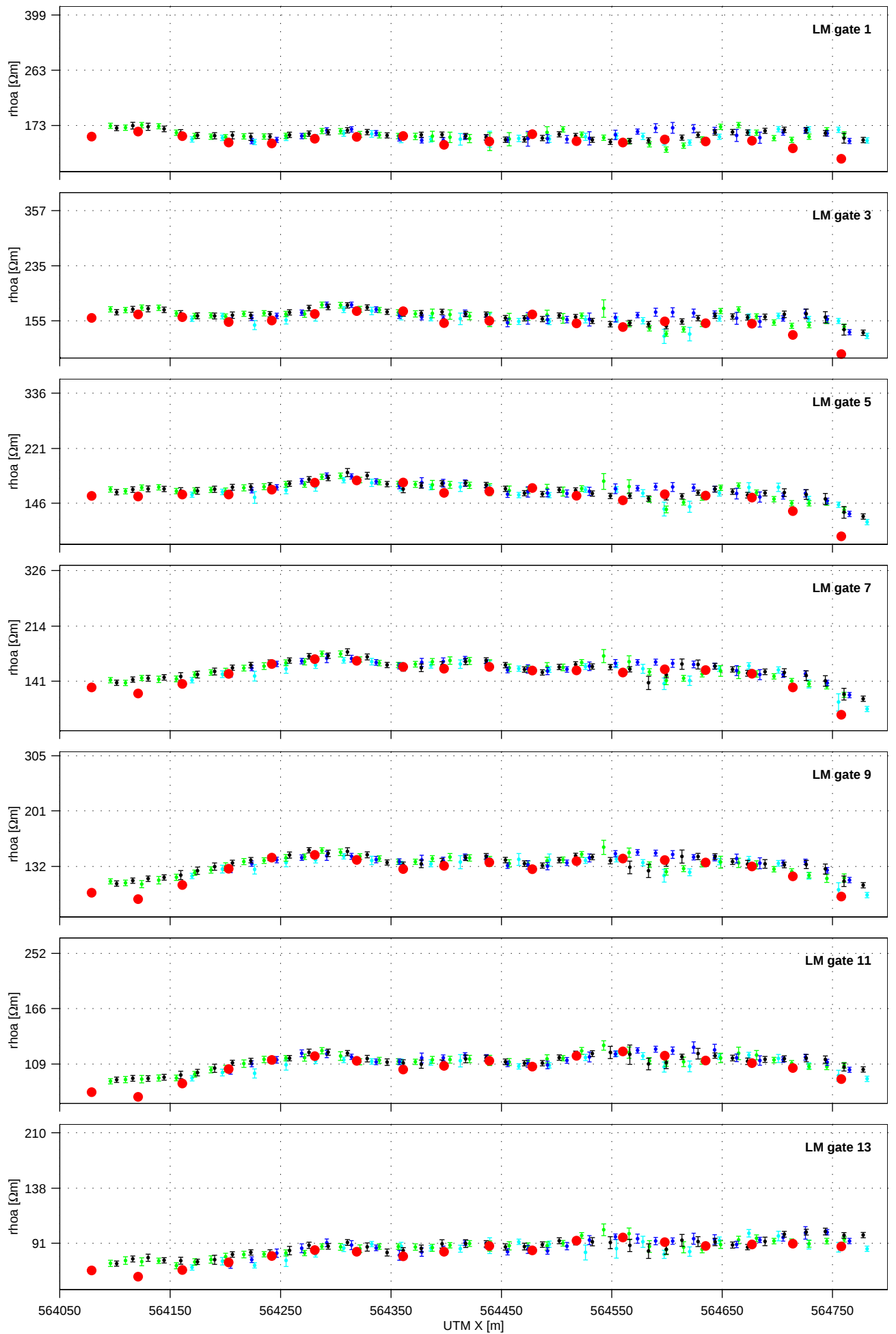
W-E profile, 15 m



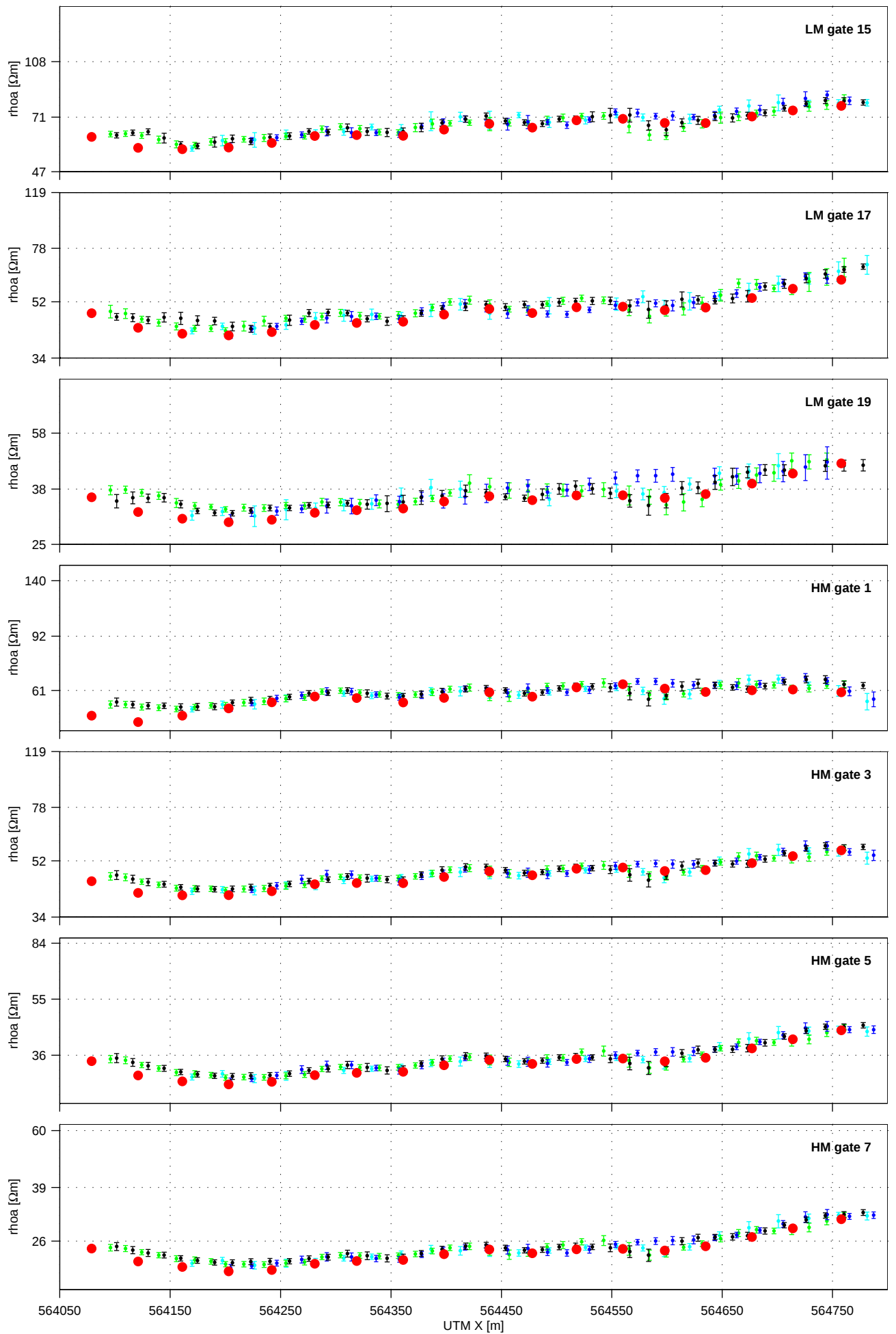
W-E profile, 15 m



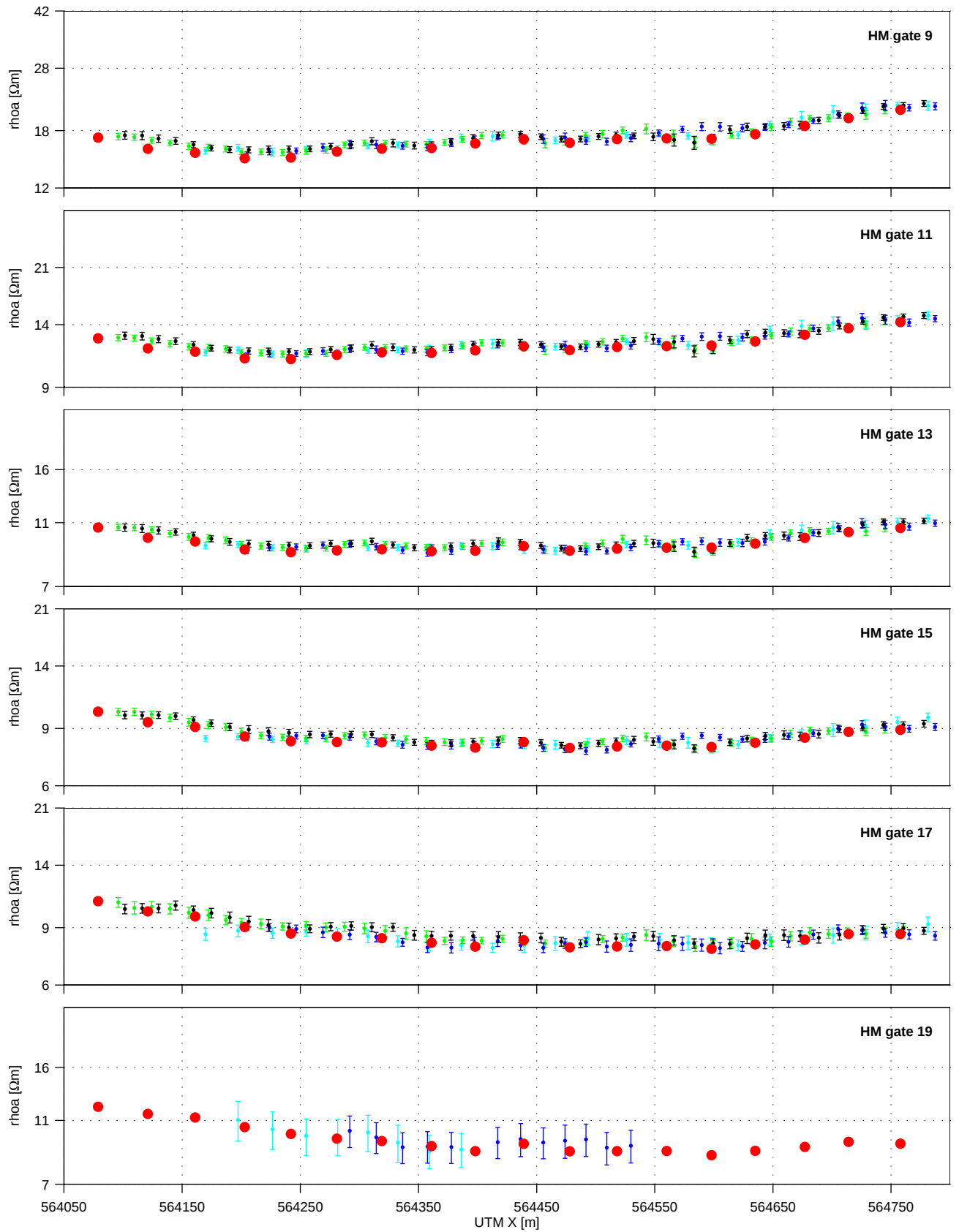
W-E profile, 25 m



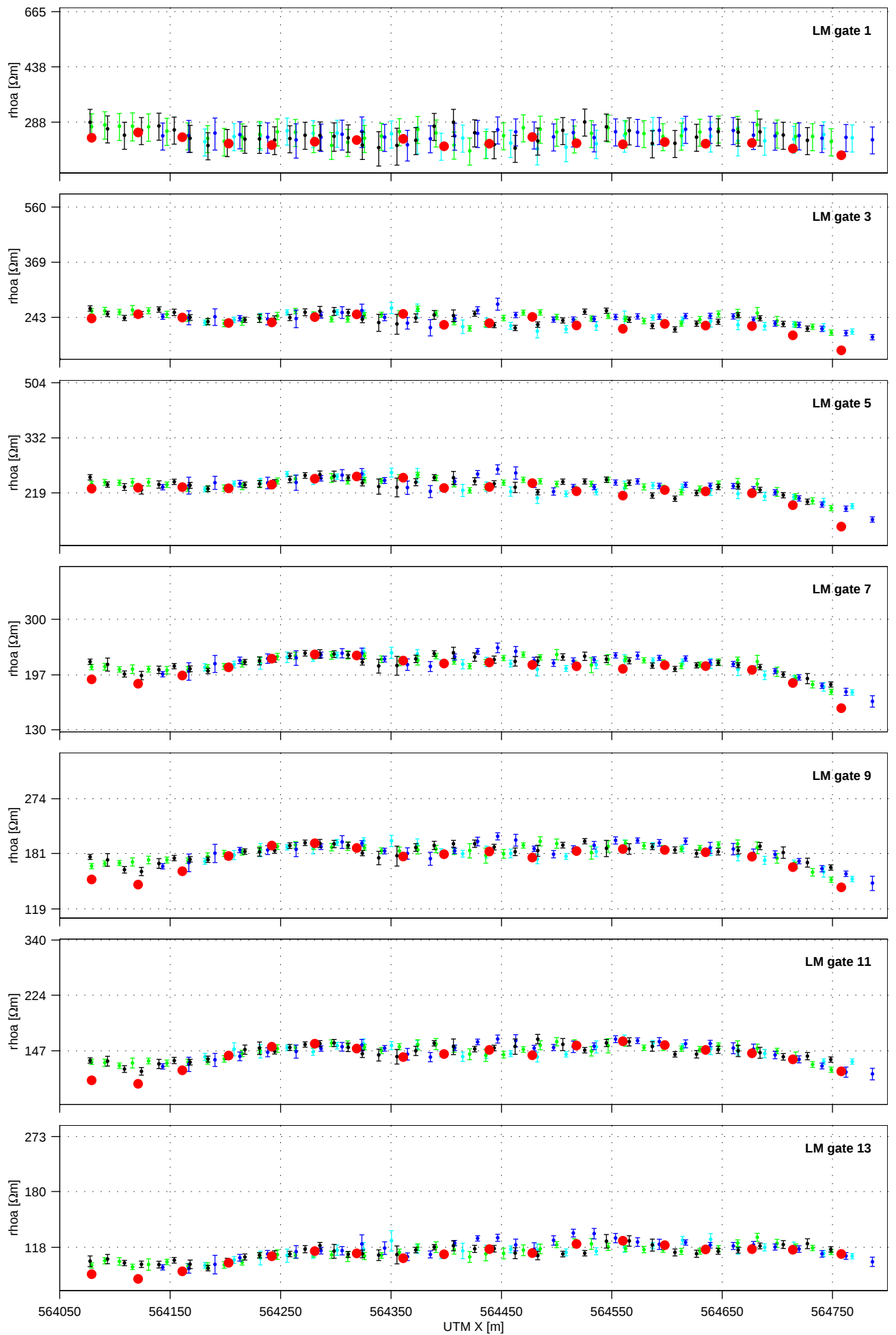
W-E profile, 25 m



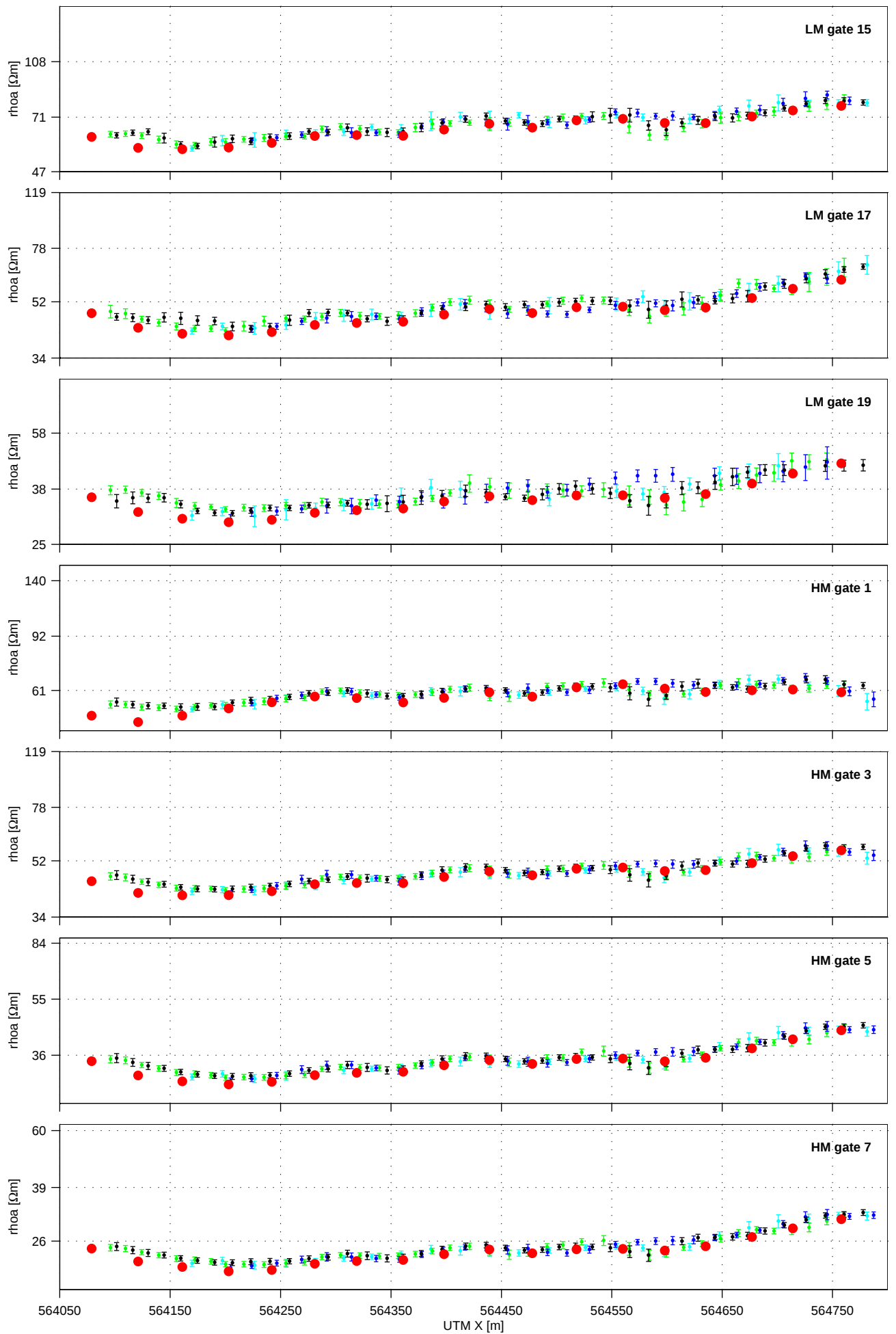
W-E profile, 25 m



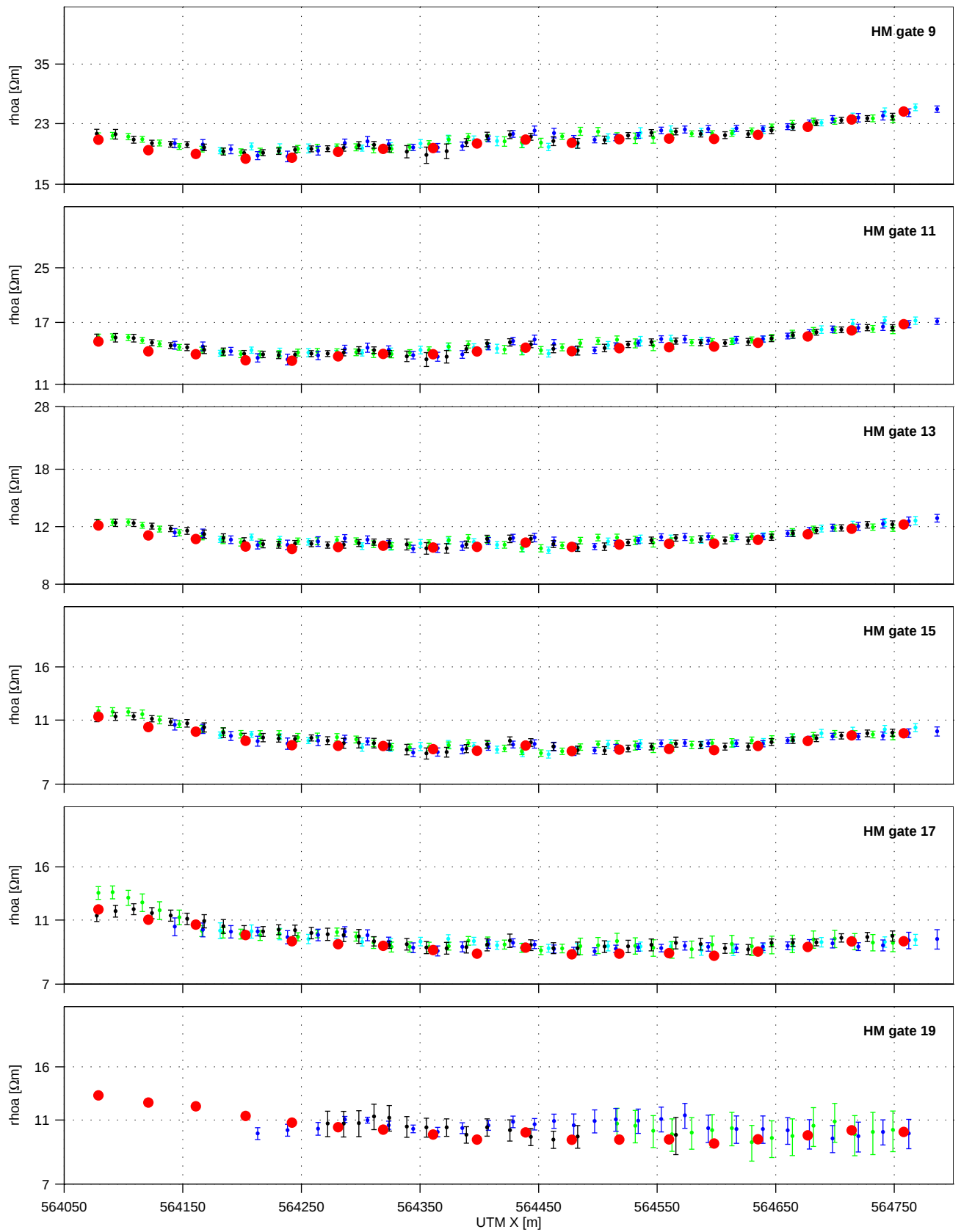
W-E profile, 35 m



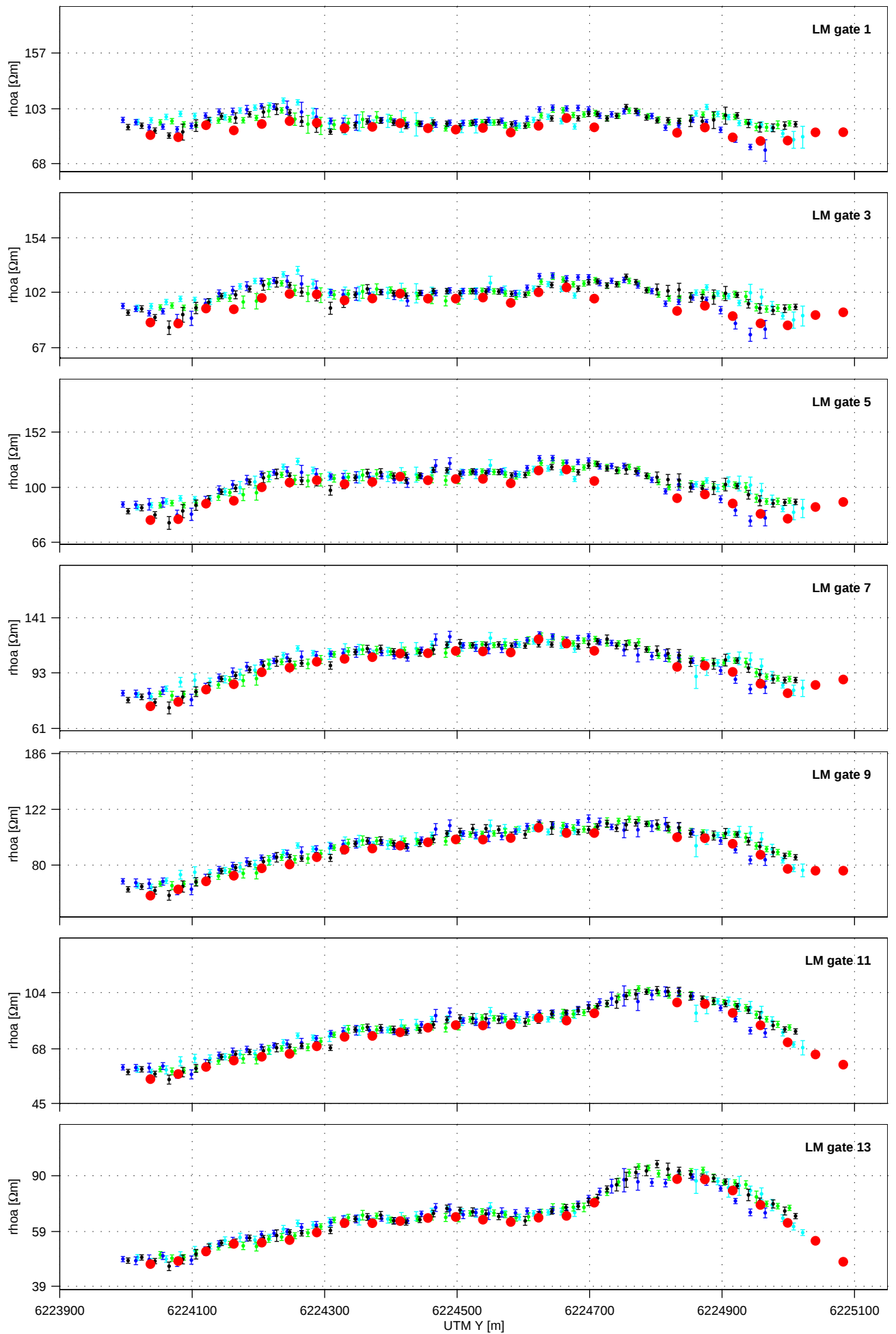
W-E profile, 25 m



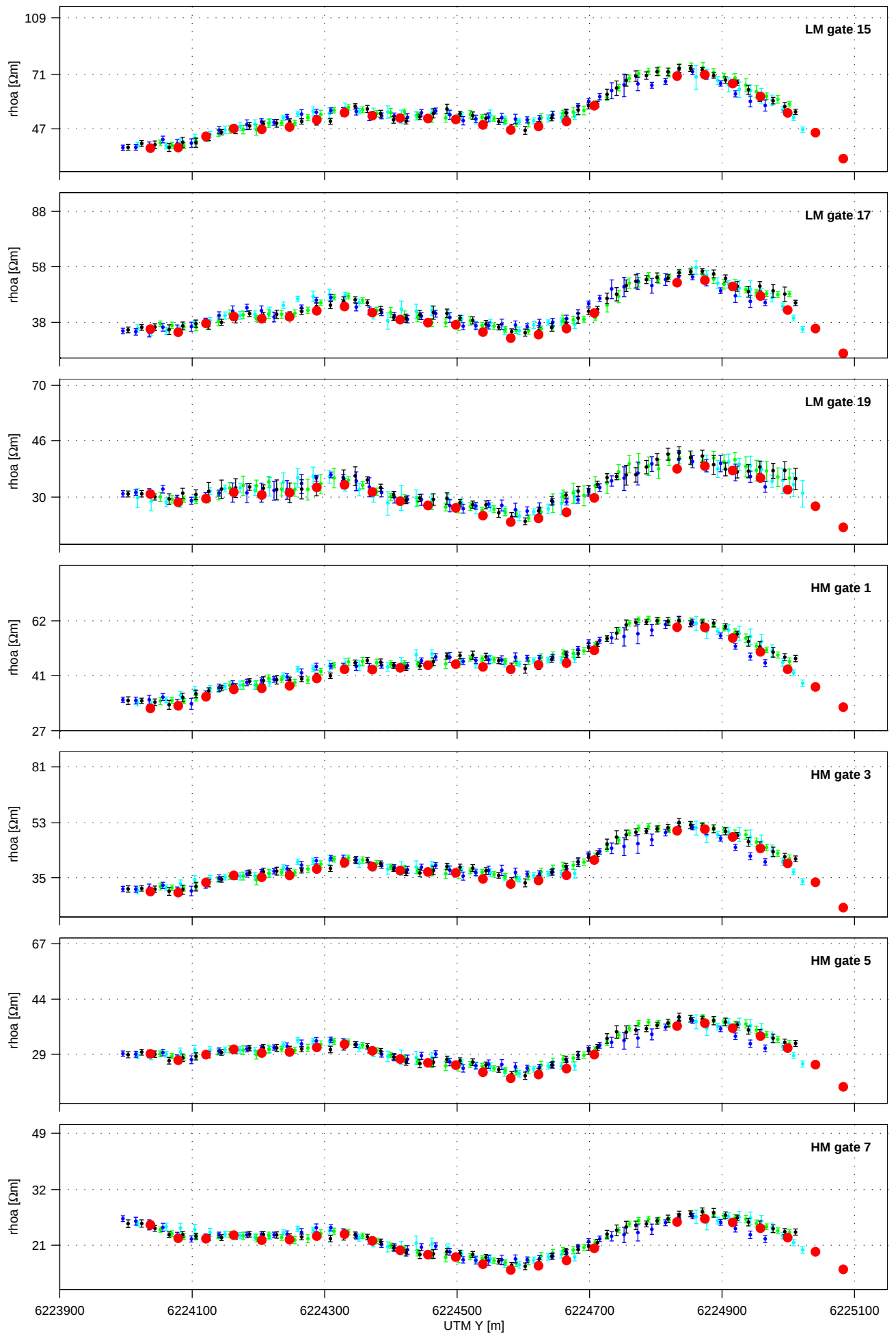
W-E profile, 35 m



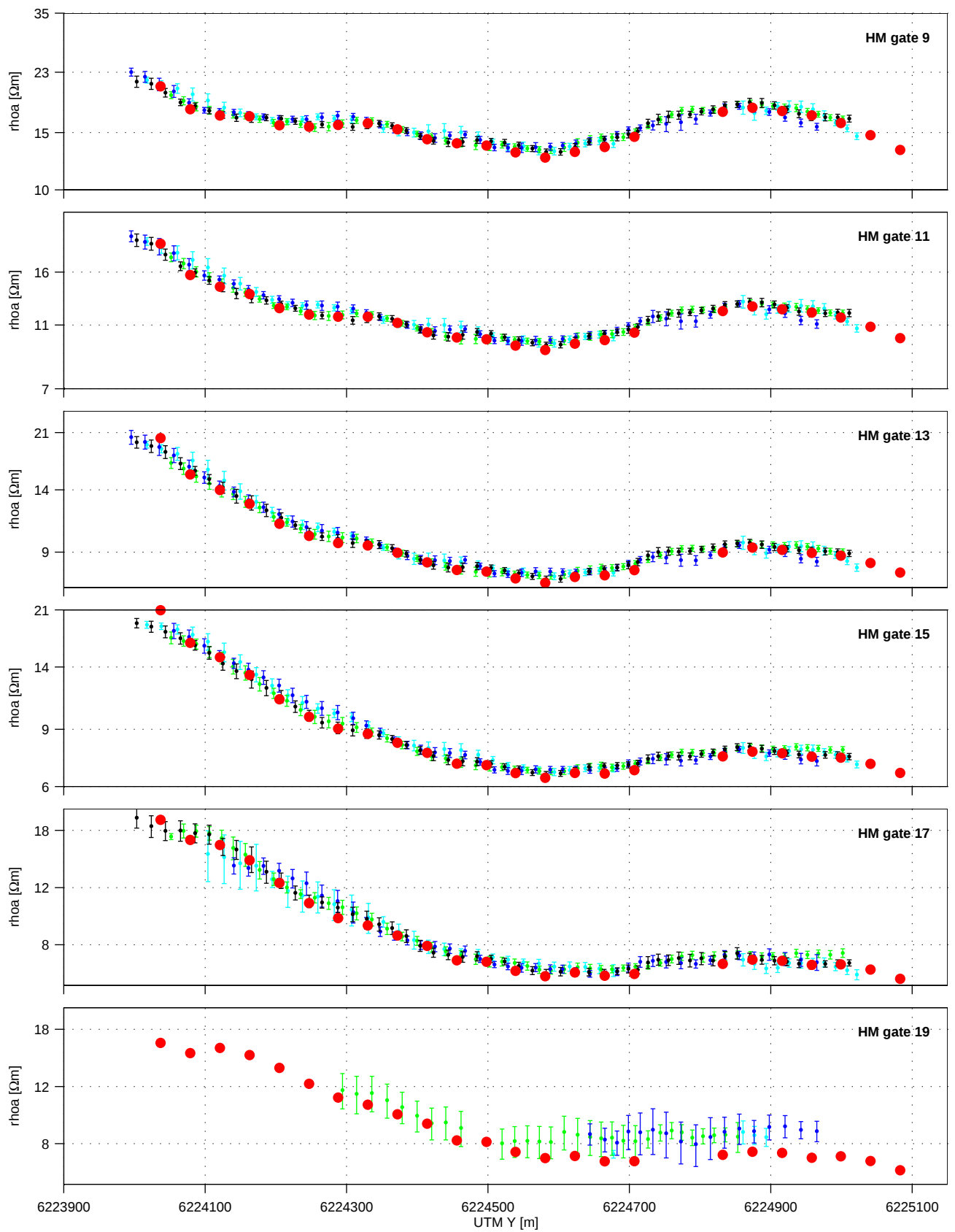
S-N profile, 15 m



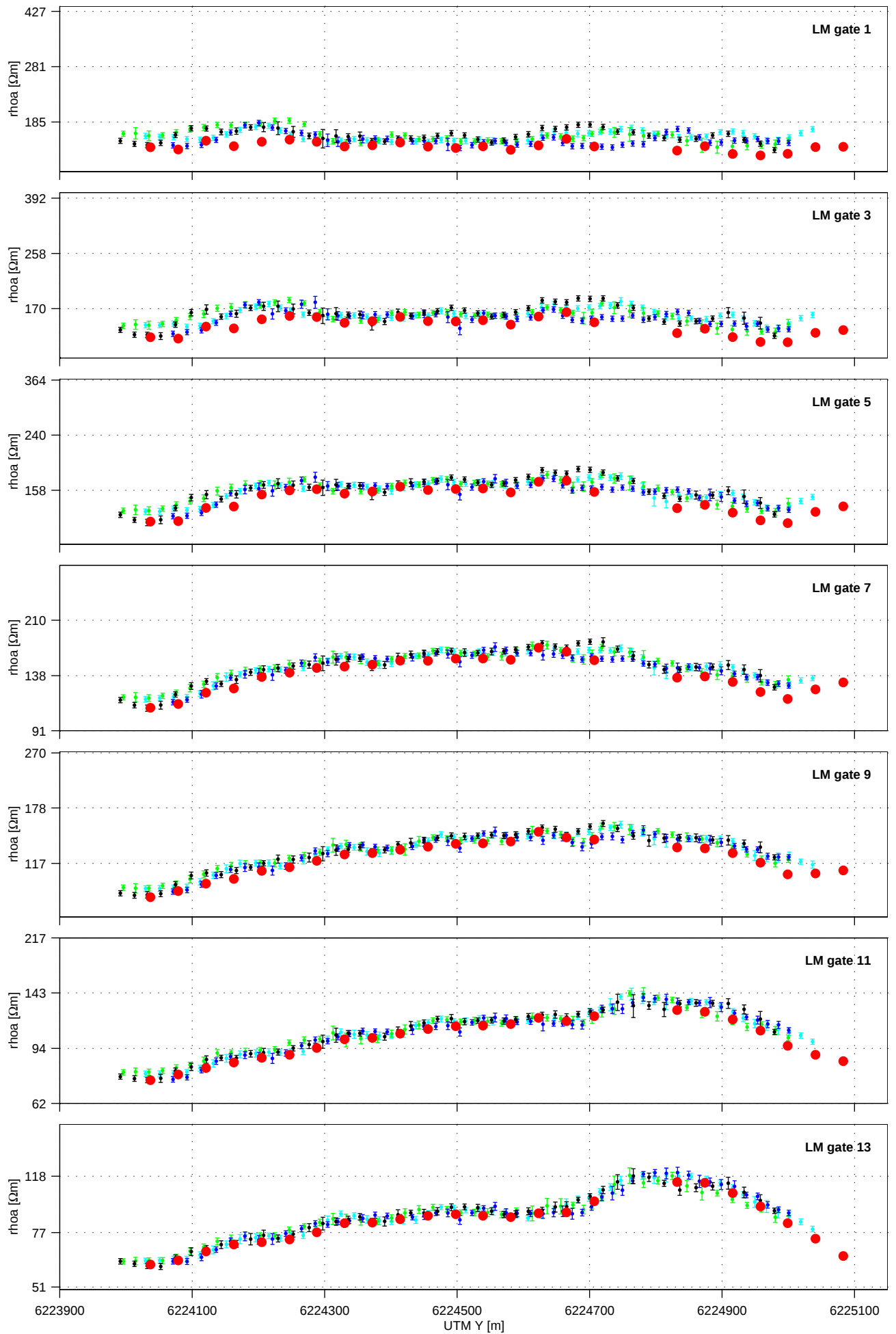
S-N profile, 15 m



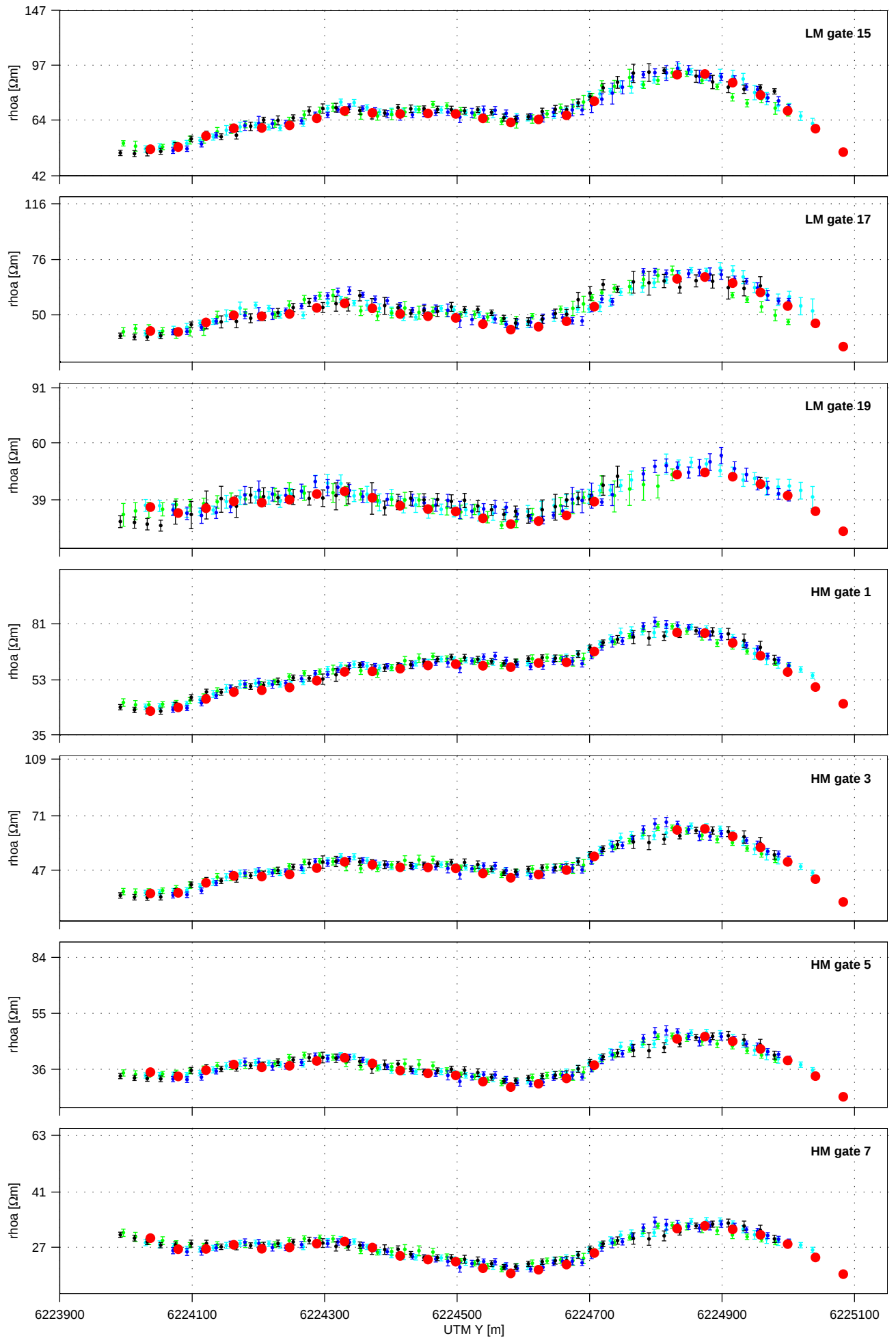
S-N profile, 15 m



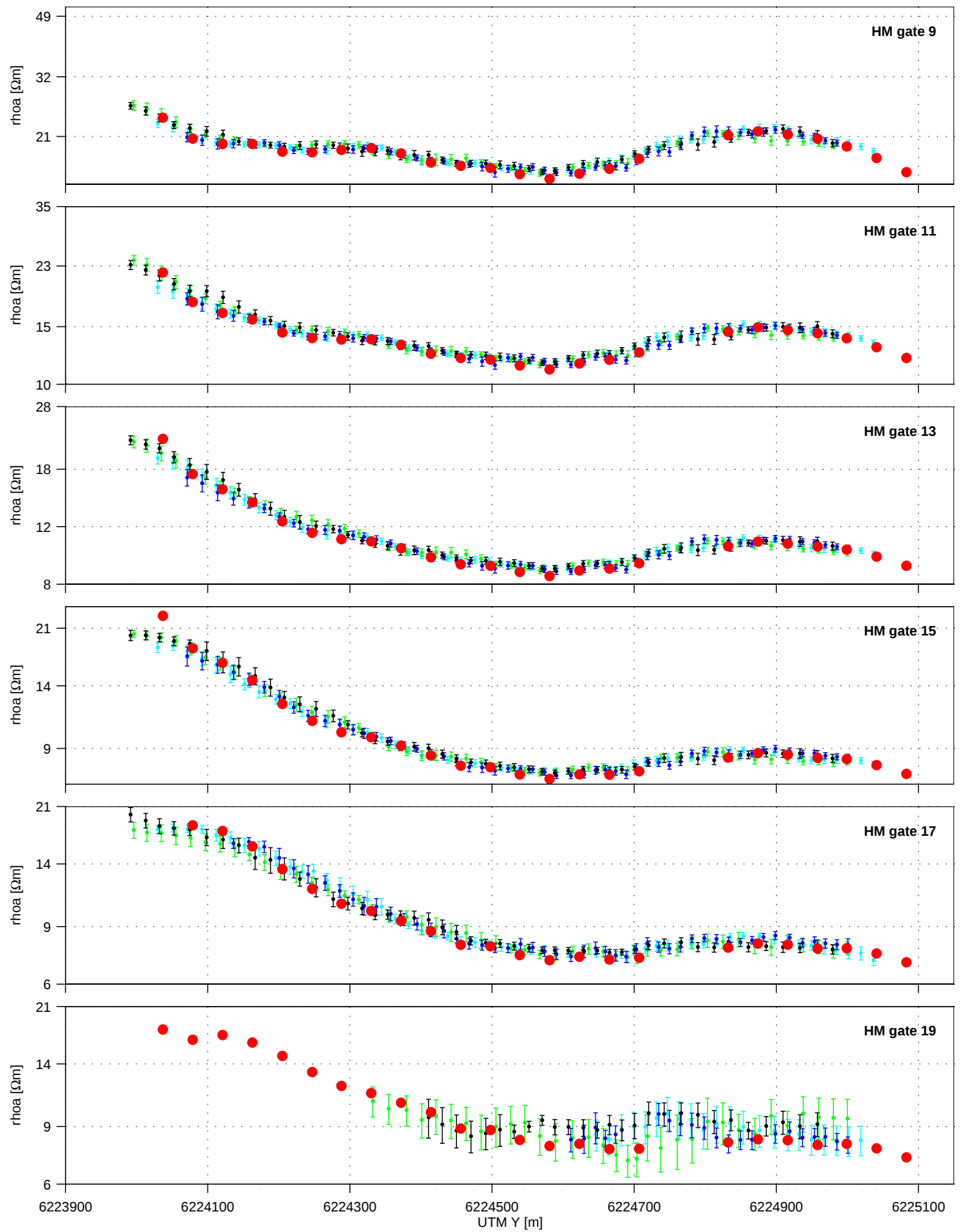
S-N profile, 25 m



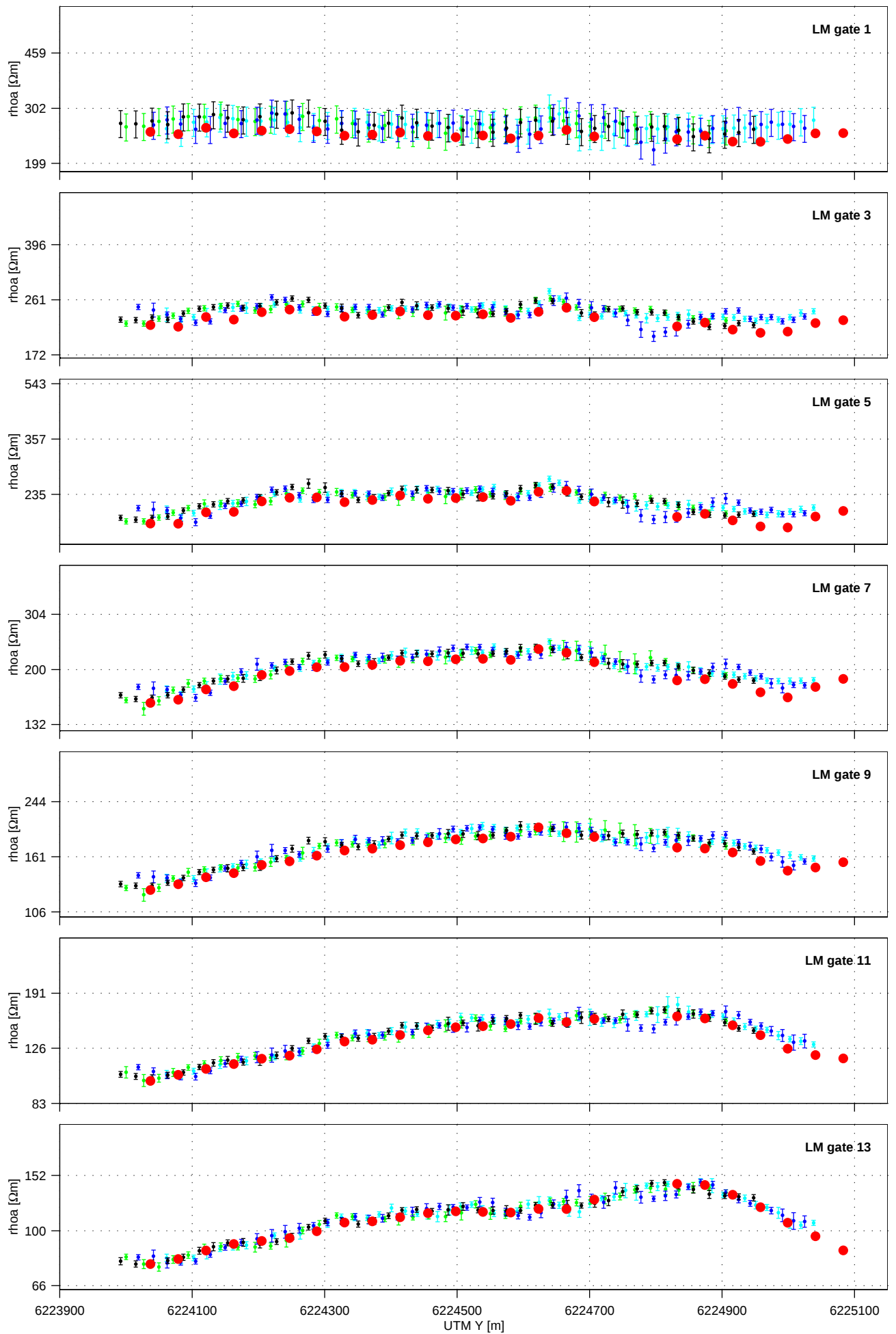
S-N profile, 25 m



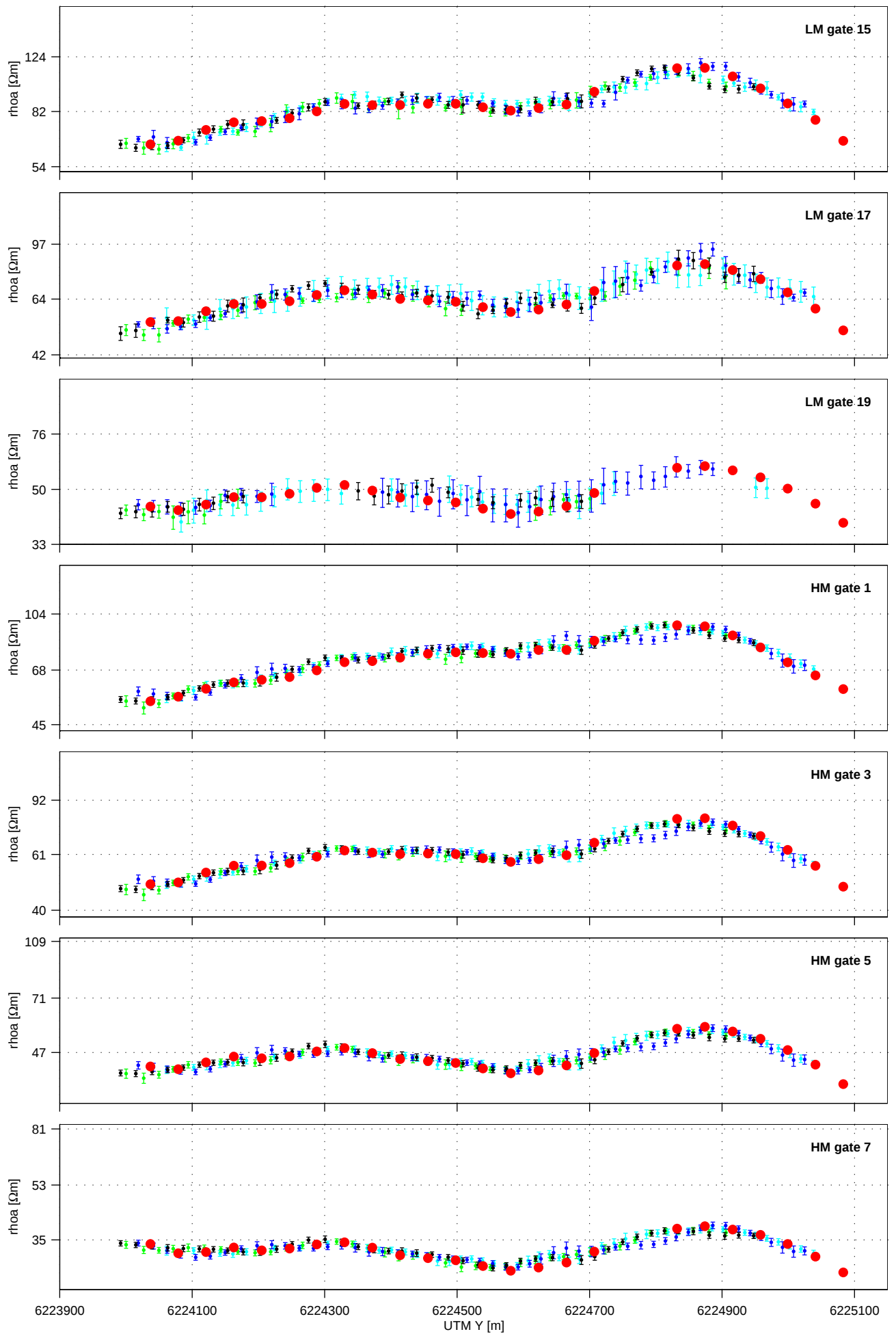
S-N profile, 25 m



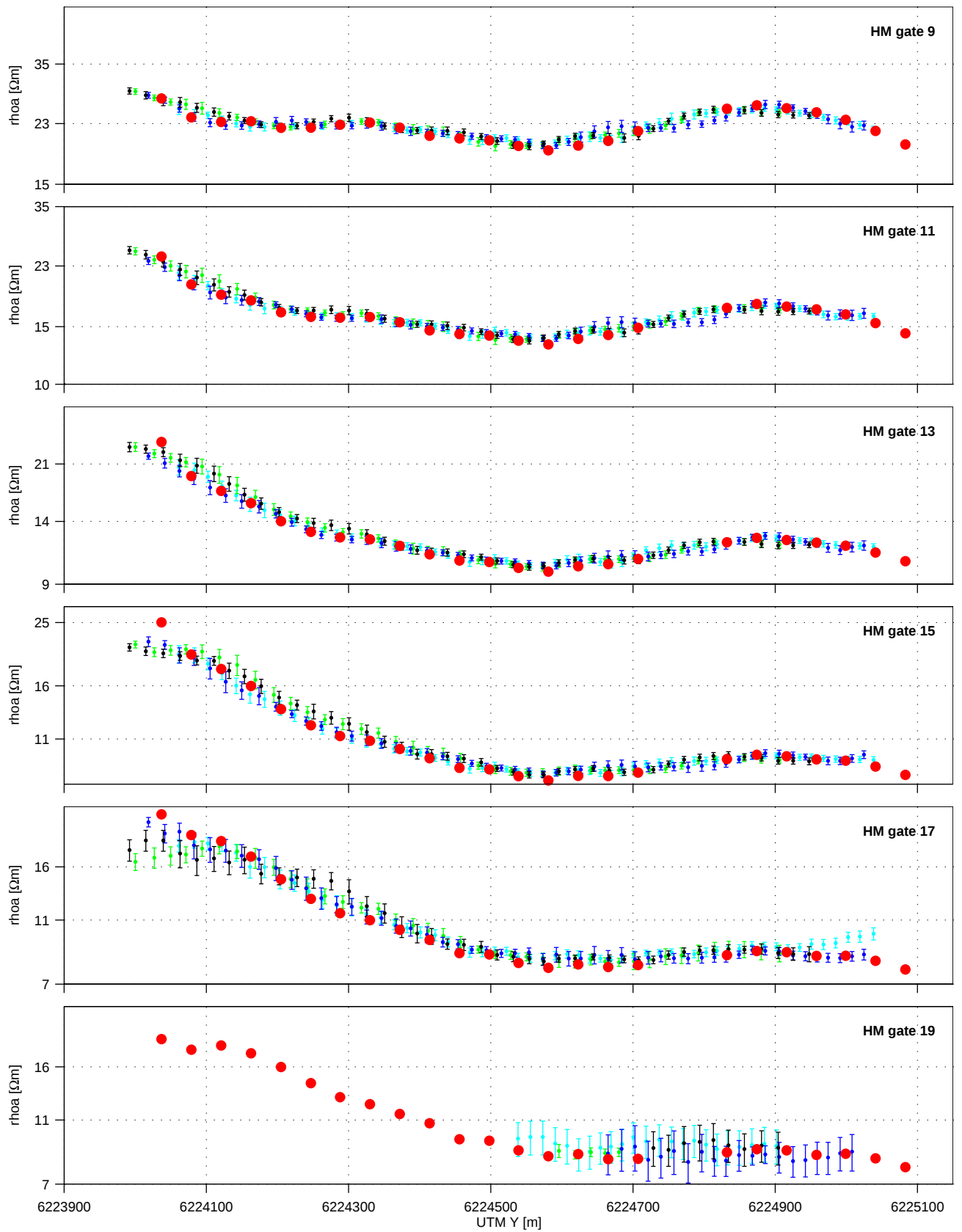
S-N profile, 35 m



S-N profile, 35 m



S-N profile, 35 m

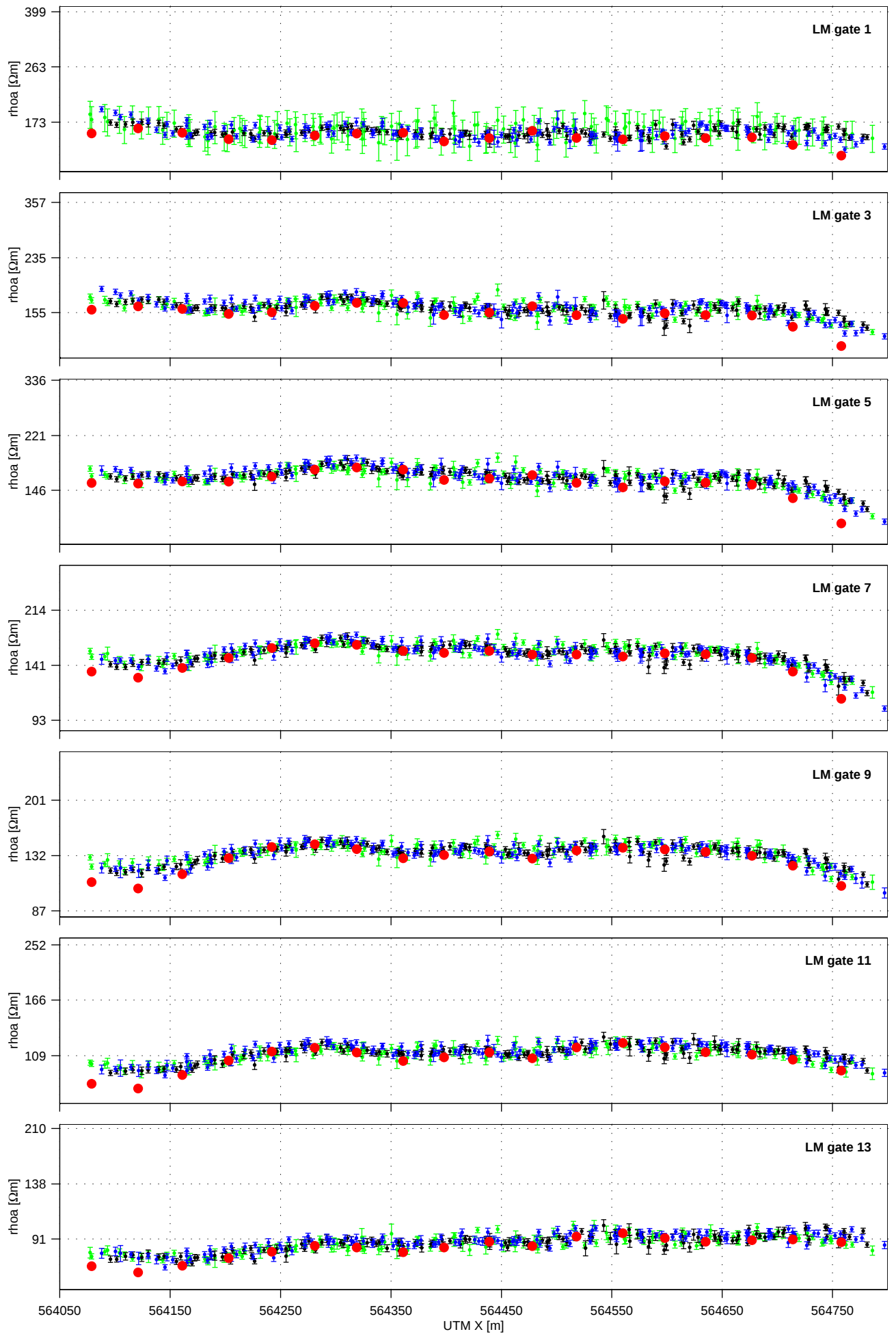




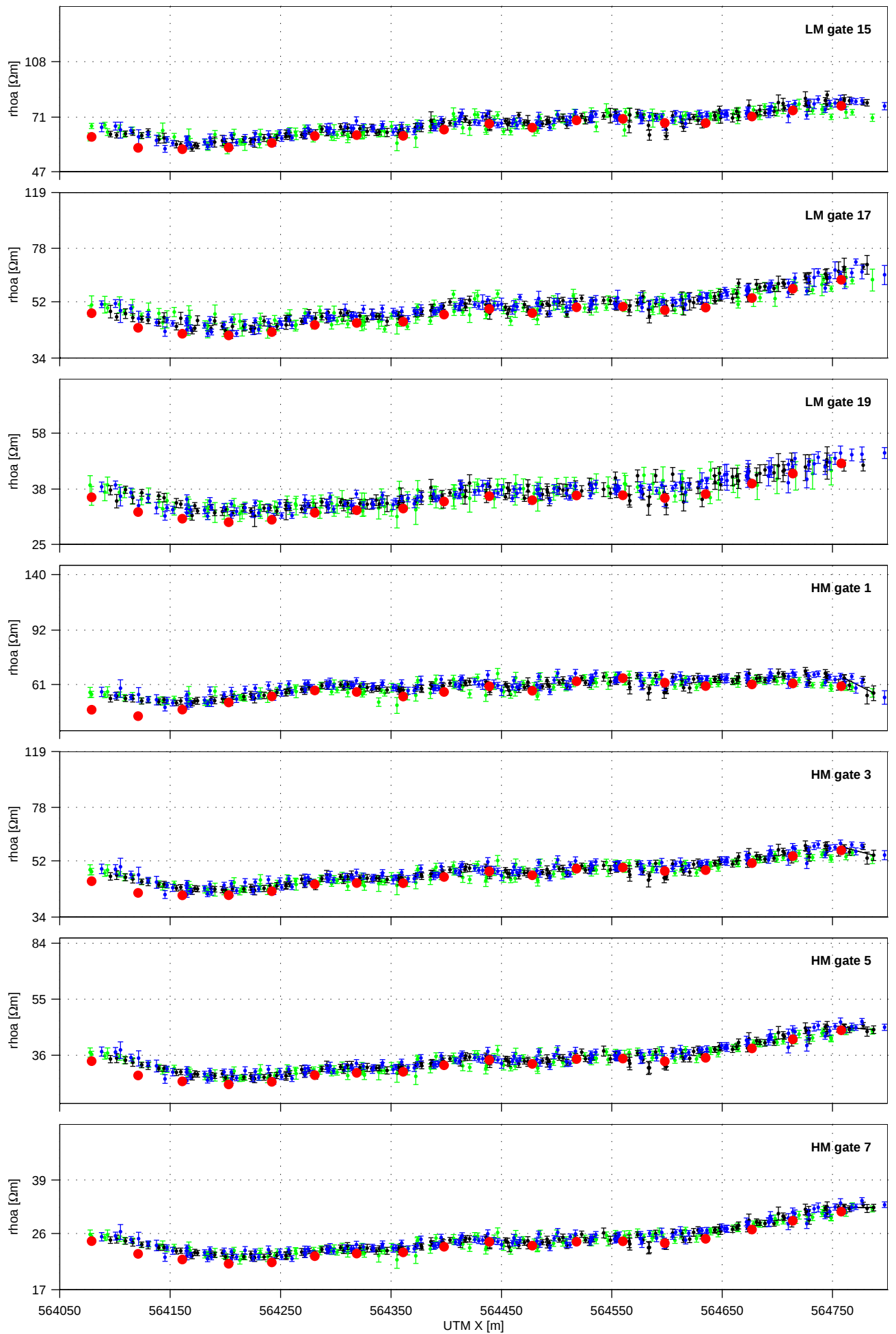
APPENDIX 3 - Data comparisons 2

The data comparisons in this appendix are for the case where all the SkyTEM repetitions for the three different altitudes have been upward continued to a nominal height of 25 m. The color-coded error bars now represent the three recording altitudes: blue=15m, black=25m, green=35m. The reference responses from the groundbased reference sections are marked with red dots. See appendix 2 for additional plot info.

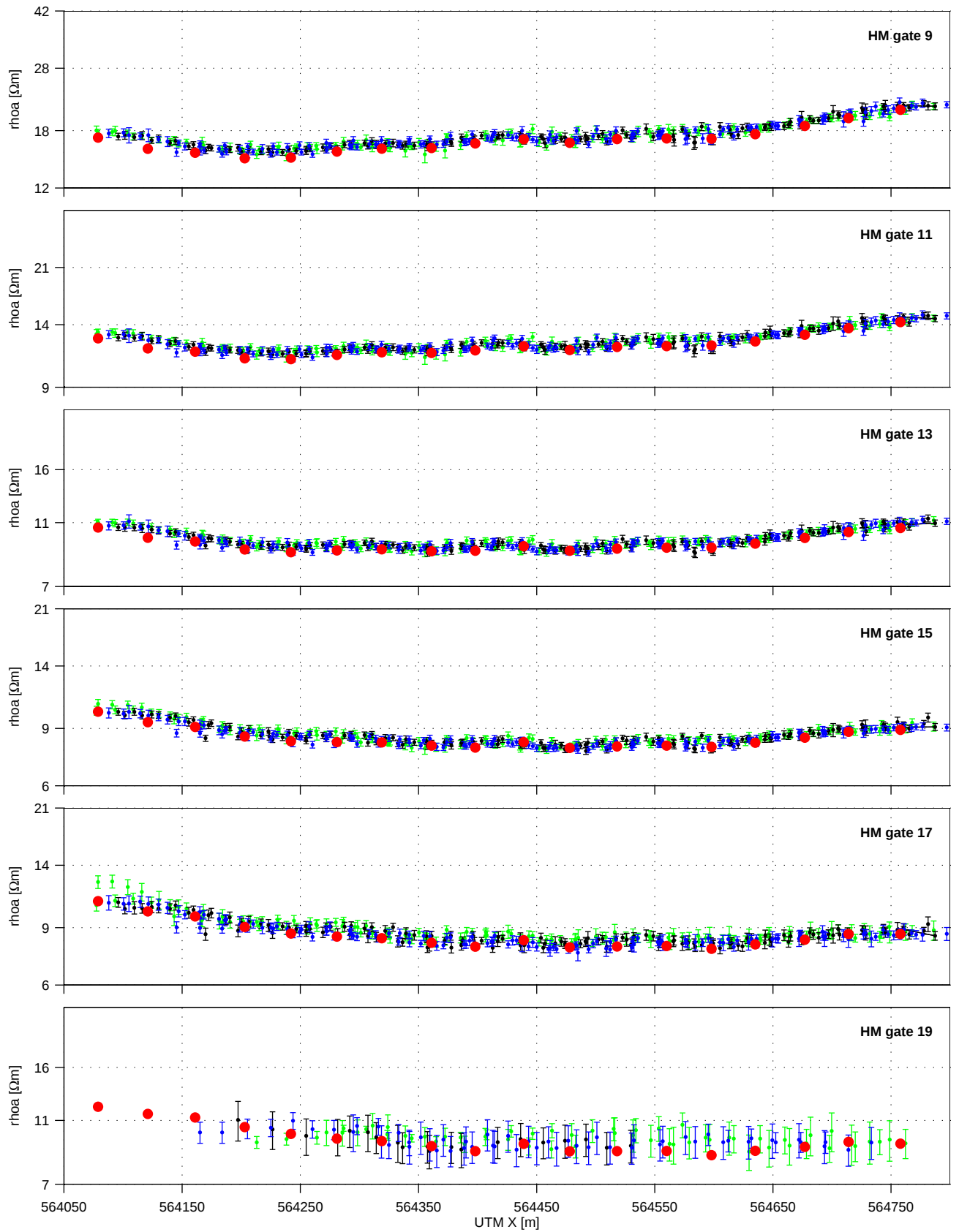
W-E profile, 25 m



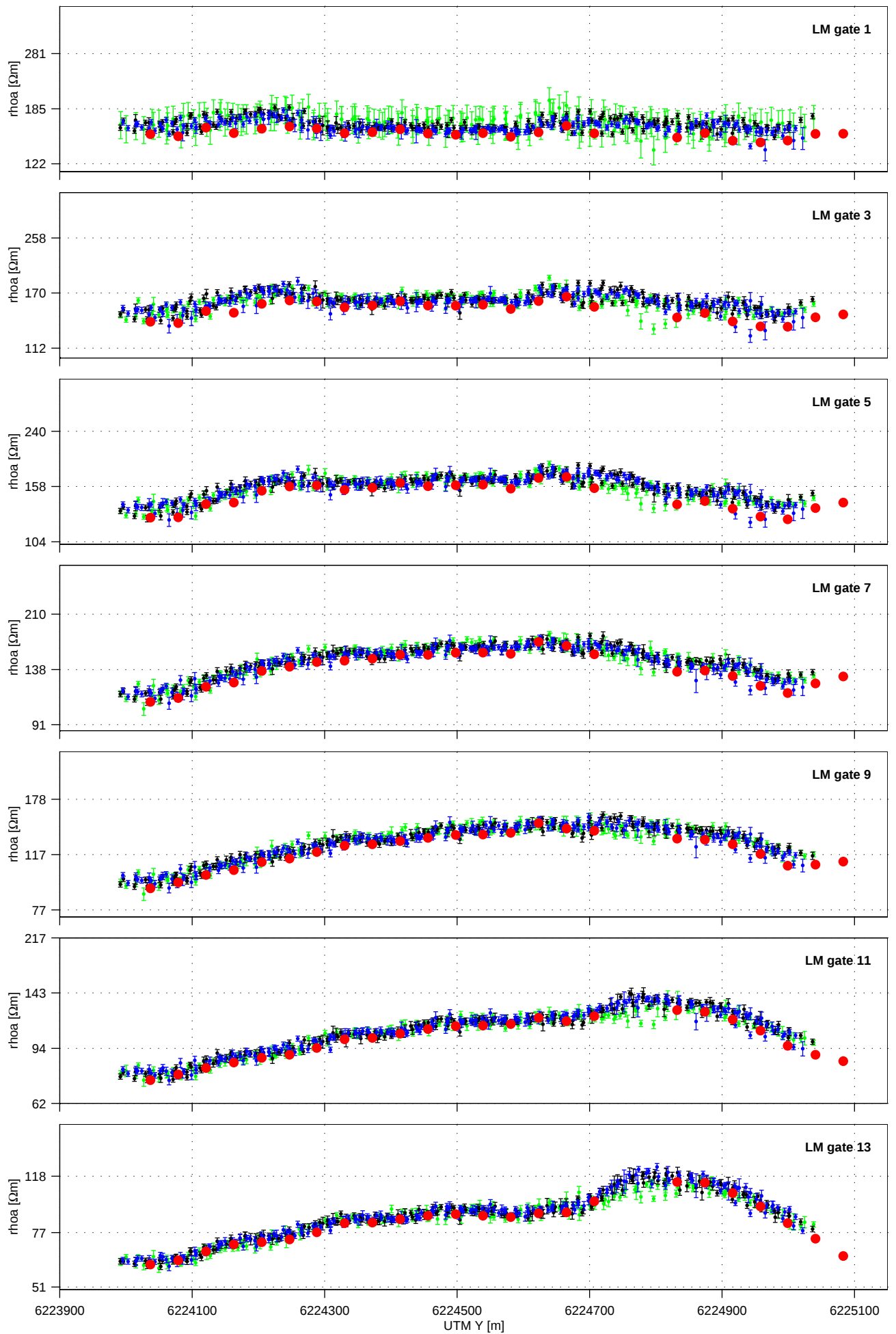
W-E profile, 25 m



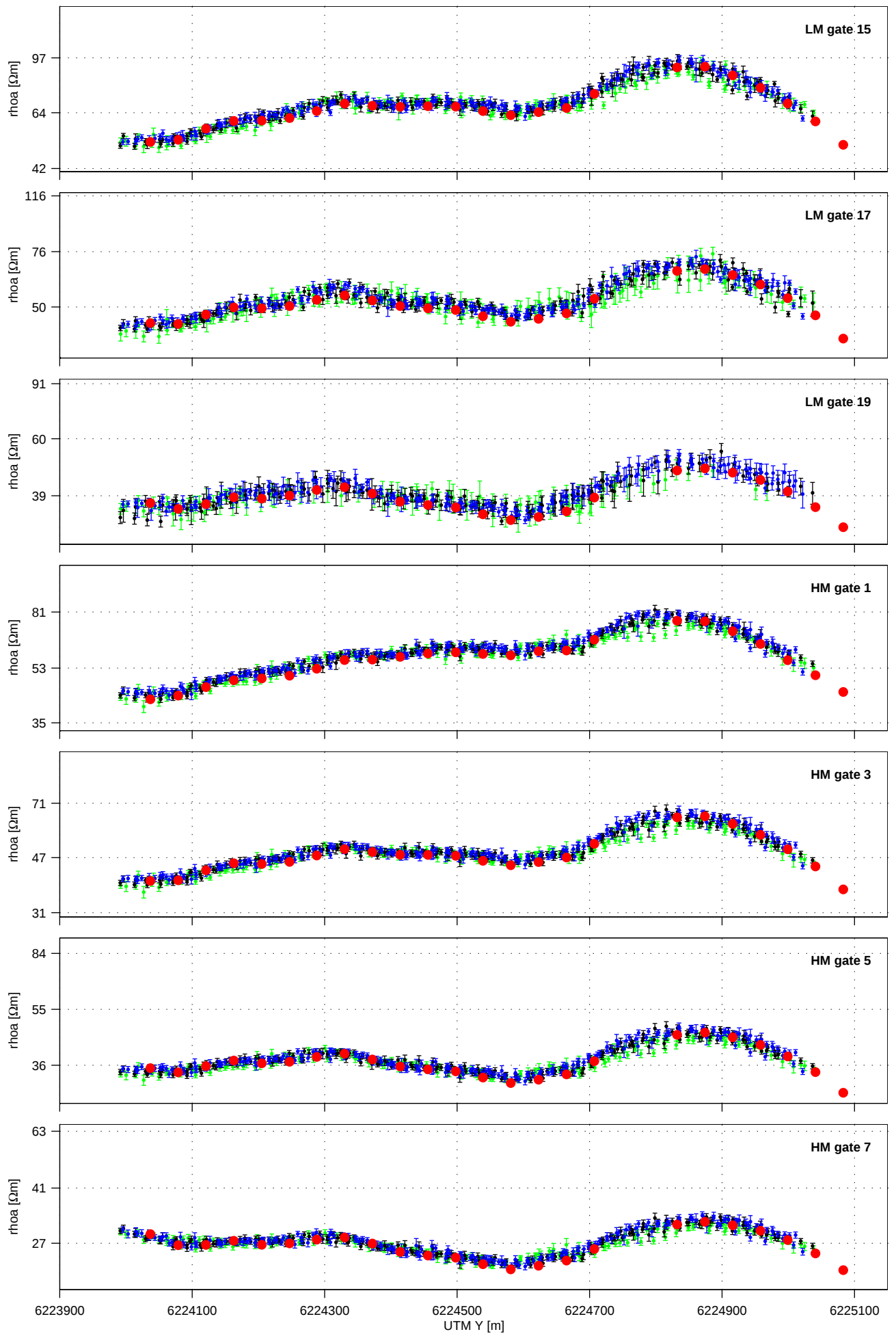
W-E profile, 25 m



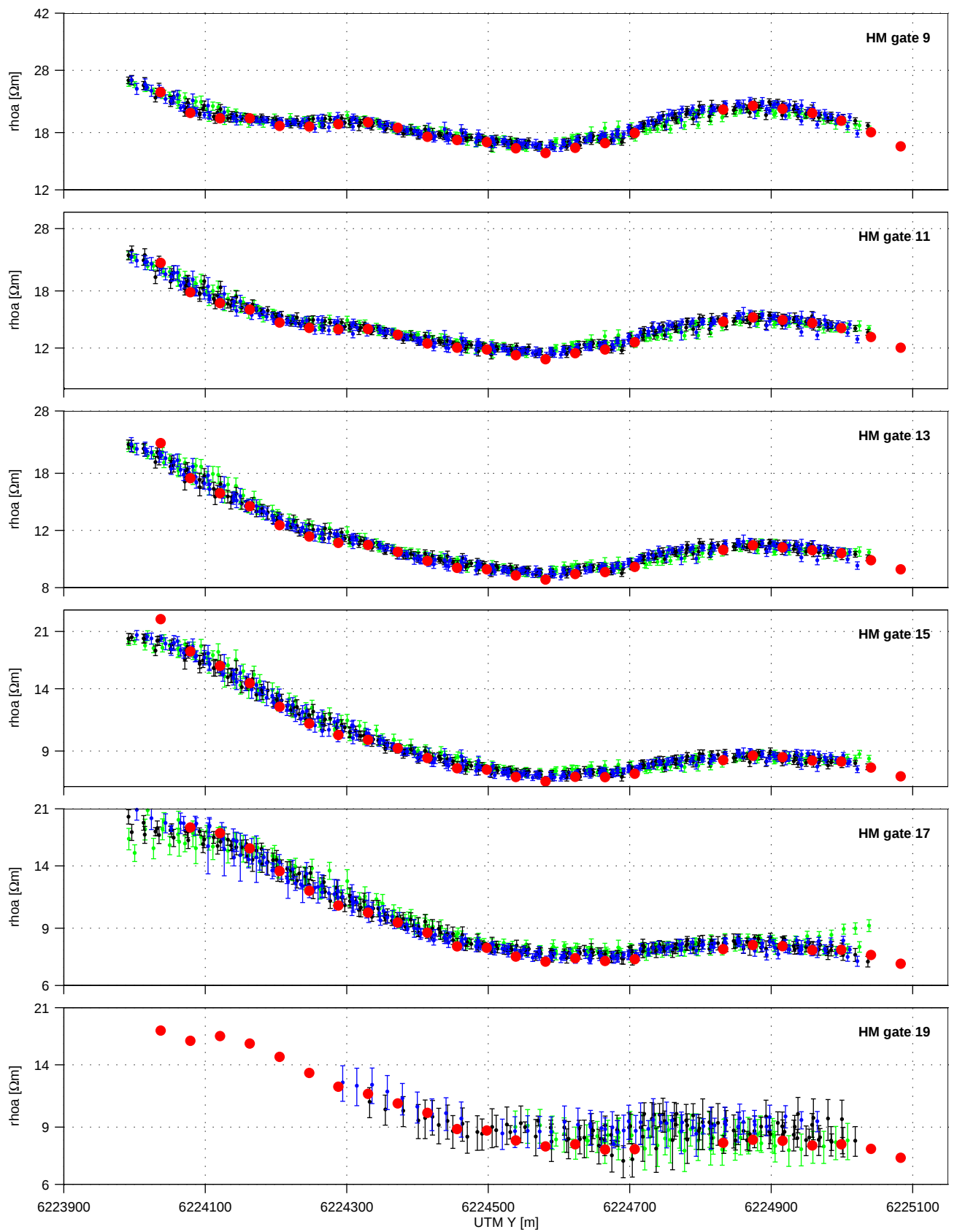
S-N profile, 25 m



S-N profile, 25 m



S-N profile, 25 m





APPENDIX 4 - Raw data report, Sky-TEM APS

The raw data report from SkyTEM ApS delivered together with the raw SkyTEM data. The report is in Danish.

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SkyTEM kortlægning for Århus Testlokalitet

Rådatarapport

November 2009
SkyTEM ApS



Dataark

Geofysisk kortlægning i områder med særlig drikkevandsinteresse (OSD) for GEUS, Afdeling for Grundvandskortlægning	
Datarekvirent	GEUS, Afdeling for Grundvandskortlægning Lyseng Allé 1 8270 Højbjerg
Kontaktpersoner	Anders Vest Christiansen
Lokalitet	Århus Testlokalitet
Fælperiode	8. August 2009
Planlagte antal linje km	15.4 km
Udførte antal linje km	15.4 km
Linjefastland	kryds
Gns. flyvehastighed	45 km/h (12,5 m/s)
Flyvehøjde af rammen	15m, 25m og 35 m
Projektleder	Solvej Traulner
Ansvarlig for rådatarapport	Ib Faber / Anne Have Rasmussen
Kvalitetssikring af rapport	Per Gisselø
Feltmedarbejdere	Per Gisselø Mads Kristensen
Helikopteroperatør	Koopmann Helicopter
Helikoptertype	Eurocopter BA
Piloter	Torben Koopmann
Sender moment	HM ~179960 Am ² SLM ~4450 Am ²
Frontgate	HM 70 µs SLM 0 µs
Målecyklus	1. HM 64 2. SLM 160 3. HM støj 64 6 x (1+2) + 1 x 3
Pulstider	HM On 10000 µs– Off 10000 µs SLM On1000 µs– Off 1250 µs
Data format	SPS (ASCII-format) ver.3 SKB (binært-format) ver.2

Indledning

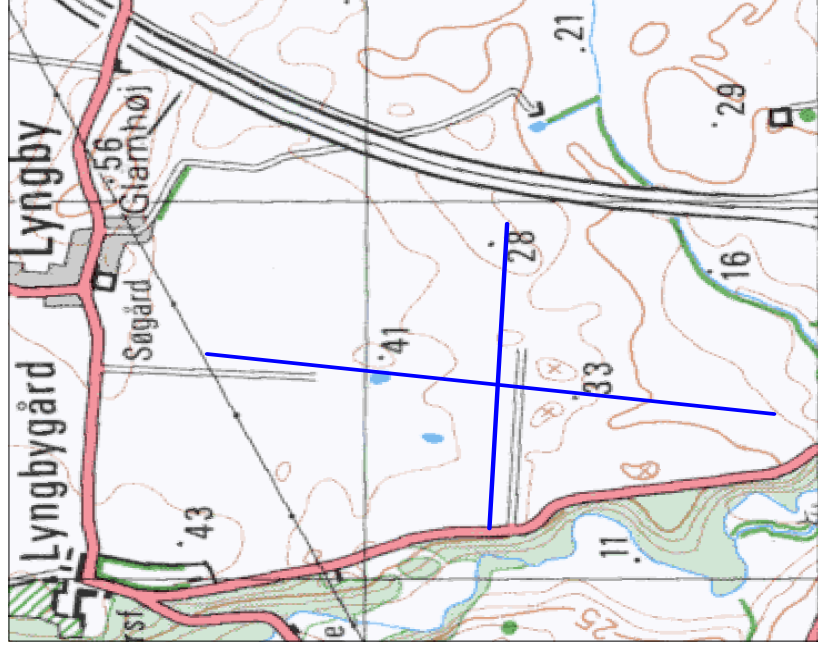
Denne rådatarapport behandler de indsamlede data samt kvaliteten af data fra en transient elektromagnetisk kortlægning foretaget af SkyTEM ApS den 8. August 2009. Kortlægningen er udført omkring Århus Testlokalitet for GEUS, Afdeling for Grundvandskortlægning

Kortlægningen omkring undersøgelsesområdet Århus Testlokalitet dækker et areal på 0,5 km² (Figur 1). I undersøgelsesområdet er der planlagt i alt 15,4 km flyvelinjer arrangeret i et kryds.

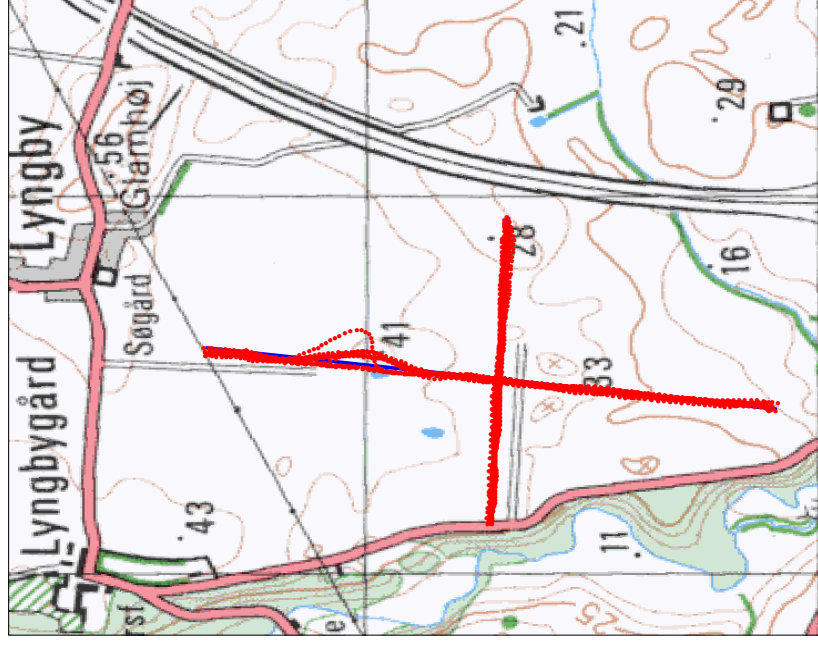
Figur 2 viser de fløjne linjer, efter at vendinger mm er klippet ud.

Formålet med kortlægningen er at indsamle informationer om jordens elektriske ledningsevne der kan bruges i sammenligning med andre systemer.

I denne kortlægning er der valgt et modificeret lavt moment samt et højt moment. Det modificerede lave moment er defineret ved en lavere senderstrøm, hvilket giver bedre mulighed for at indhente højopløselige data fra de meget overfladenære lag. De to momenter er i nærværende rapport omtalt som henholdsvis SLM (Super Lavt Moment) for det laveste moment og HM (Højt Moment) for det højeste moment, da disse betegnelser vurderes bedst dækkende for den anvendte indstilling.



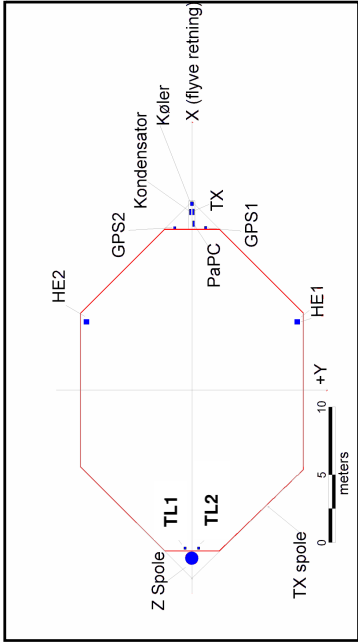
Figur 1 Undersøgelsesområdet omkring Århus Testlokalitet (blå linjer) direkte nord for linjerne ligger en kendt el-ledning (sort stiplede linje).



Figur 2 Undersøgelsesområdet med planlagte flyvelinjer (blå linjer), samt faktisk fløjne linjer (røde linjer).

Setup parametre

SkyTEM-målingerne er udført med et målesystem konfigureret som vist på Figur 3 og beskrevet nedenfor.



Figur 3 Senderramme (rød) med placeringer af måleenheder (blå symboler); Kondensator, køler, PaPc, HE1 og HE2 (højdemåler 1 og 2), TL1 og TL2 (vinkelmåler 1 og 2), Z spole (Z-orienteret modtager spole) og TX (sender). Origo af senderspølen er defineret som centrum af senderrammen.

Det anvendte måleudstyr kan identificeres ved følgende serie numre:

Enhed	Serie no.	GERDA identier
Sender	TX 12	dk.groundwaterinstruments.skytem_tx.12.001
TiB	06	dk.groundwaterinstruments.skytem_TiB06.001
Modtagerspøle Z	948	dk.groundwaterinstruments.skytem.receivercoil.948.001
Tilt meter (Bjerrre Technology)	546/547	-
Laser (MDL ILM3)	119/508	-
GPS (Holu GR-213)	860/714	-
Kondensatorboks	407	-
PaPc	32	-

Placeringen af instrumenterne er givet i nedenstående tabel:

Enhed	x	y	z
GP1 (GPS)	15,20	1,05	-0,25
GP2 (GPS)	15,20	-1,05	-0,25
HE1 (altimeter)	6,80	9,90	-0,10
HE2 (altimeter)	6,80	-9,90	-0,10
TL1 (inclinometer)	-15,55	-0,50	-0,35
TL2 (inclinometer)	-15,55	0,50	-0,35
RX (Z Coil)	-16,20	0,0	-2,13
TX (transmit.)	16,35	0,15	-0,30



Figur 4 SkyTEM systemet i luften.

Sendersystem

Senderspølen beskrives ved en 8-kant (se figur 3 og 4) med nedenstående hjørnepunkter, idet origo er fastlagt som centrum af senderspølen:

x	y
-15,34	-2,03
-7,13	-10,26
7,13	-10,26
15,34	-2,03
15,34	2,03
7,13	10,26
-7,13	10,26
-15,34	2,03

Areal af senderspølen er 494,4 m² og omkredsen er 81,1 m.

Det antages, at de målte SkyTEM data skal tolkes i Workbench, og det er her pt. ikke muligt at håndtere "skæve" duty-cycles, som det er tilfældet ved denne type opsætning af momenterne.

I geometrifilen står repetitionsfrekvensen derfor som $f_{\text{eff}} = 1/(4 \cdot \text{ONTIME}) = 25 \text{ Hz (HM)}$ og 250 Hz (SLM). Det er denne repetitionsfrekvens som benyttes af em1dinv.exe.

Den reelle repetitionsfrekvens som udstyret måler med er givet ved: $f = 1/(\text{On-tid} + \text{Off-tid}) \cdot 2 = 25 \text{ Hz Hz (HM)}$ og 222 Hz Hz (SLM).

For videre uddybning se afsnit 2.4 i "Vejledning og kravspecifikation for SkyTEM-målinger, processing og tolkning (http://www.hgg.geo.au.dk/rapporter/Vejledning_SkyTEM.pdf).

Parametrene for de to momenter ses i nedenstående tabeller.

Som energikilde til systemet er der anvendt en 6 HK Honda motor med en jævnstrøms-generator, som leverer en spænding på 70 V.

Superlavt moment (SLM):

Parameter	Value
Antal vindinger	1
Areal	494,4 m ²
Strøm	~ 9 A
Max. moment	~4450 Am ²
Repetitionsfrekvens	222 Hz
On-tid	1000 µs
Off-tid	1250 µs
Duty cycle	56
Bølgeform	Ekspontentielt opramning, lineær slukkeforløb, efterfulgt af eksponentielt slukkeforløb
Turn on wave form exp. decay constant	34500 s-1
Turn off linear ramp	3,13E+06 A/s
Turn off current end avalanche mode	1,4 A
Turn off free decay exp. decay constant	1,3E+06 s-1

Højt moment (HM):

Parameter	Value
Antal vindinger	4
Areal	494,4 m ²
Strøm	~ 91 A
Max. moment	~179960 Am ²
Repetitionsfrekvens	25 Hz
On-tid	10000 µs
Off-tid	10000 µs
Duty cycle	50
Bølgeform	Ekspontentielt opramning, lineær slukkeforløb, efterfulgt af eksponentielt slukkeforløb
Turn on wave form exp. decay constant	350 s-1
Turn off linear ramp	1,74E+06 A/s
Turn off current end avalanche mode	0,8 A
Turn off free decay exp. decay constant	1,3E+06 s-1

Modtagersystem

Modtagerspølen er placeret i 0-position, koordinaterne til centrum af spolen er vist i nedenstående tabel. I 0-positionen kan det antages, at primærfeltet er dæmpet med en faktor 0,01.

Spole	x	y	z
Z-spøle	-16,20	0,00	-2,13

De anvendte måletidsvinduer fremgår af Bilag I: Måletidsvinduer.
Modtagerspølen modelleres med et lavpasfilter på 450 kHz.

Modtagerinstrumentet er modelleret med et lavpasfilter på 300 kHz.

Modtagerspølen er orienteret således, at der for Z-spølen er positiv fortegn opad. Der er anvendt samme fortegn for både HM og SLM.

I * .skb-filerne header ses en kopi af det script der er anvendt i dataindsamlingen. Her ses bl.a. frontgates for de to momenter (se tabellen nedenfor). I instrumentet optræder en konstant forsinkelse på 2,5 µs i forhold til den opgivne frontgate værdi.
Under kalibreringen af data (kalibrering på Århus Testlokalitet s.15) er det fundet, at der er en tidsforskydning på SLM og HM på henholdsvis -0,7 µs og -2,0 µs. For SLM er frontgaten 0 µs og tidsforskydningerne har ingen effekt her, mens HM skal korrigeres som angivet i tabellen nedenfor. Det er den korrigerede værdi der bruges i geometrifilen for frontgaten.

Moment	Script	Forsinkelse	Tidsforskydning Kalibrering	Korrigeret
SLM	0 µs	-	-	-
HM	70 µs	2,5 µs	-2,0 µs	70,5 µs

Målecyklus

Der er anvendt en målecyklus med 160 serier på SLM, og dernæst 64 serier på HM, hvilket giver en samlet periode på 1,64 sekund. Endvidere måles 64 serier med støj, svarende til højt moment.

Modtagersystemets nøgleparametre er vist nedenfor

SLM:

Parameter	Value
Repetitionsfrekvens	222 Hz
Front gate	0 µs
Antal skud per cyklus	160
Antal gates målt	26
Gates udnyttet*	7-26

HM:

Parameter	Value
Repetitionsfrekvens	25 Hz
Front gate	70,5 µs
Antal skud per cyklus	64
Antal gates målt	37
Gates udnyttet*	19-37

*J Som defineret i geometri filen

Inklination

Instrument type: Bjerre Technology

Rammens vinkel måles ca. 2 gange i sekundet i to retninger. Der bruges 2 vinkelmålere, TL1 og TL2, som er placeret foran tårnet bagerst på rammen.

X måler rammens bevægelser vinkelret på flyveretningen og er positiv når fronten løftes over det vandrette plan og negativ når fronten ligger under det vandrette plan. Y måler rammens bevægelser parallelt med flyveretningen. Y er negativ når højre side løftes i forhold til det vandrette plan og positiv når højre side ligger under det vandrette plan.

Vinklerne måles med en nøjagtighed på én decimal.

GPS

Instrument type: GP1 og GP2: Hollux

Der måles med to uafhængige GPS'er (GP1 og GP2). GPS'erne er placeret på fronten af rammen.

Der anvendes to GPS'er, således at der ved et eventuelt udfald på den ene GPS stadig foreligger positionsdata fra den anden.

Hver GPS måler positionen ca. 1 gang per sekund.

Usikkerheden på GPS-positionen i xy-planet er fundet til +/- 10 m.

GPS parameter	
Sample rate	1 Hz
Usikkerhed	+/- 10m
Koordinatsystem	Latitude, longitude, WGS84

Højdemåler

Instrument type: MDL ILM3

Der måles med to uafhængige lasere placeret på hver side af rammen.

Laserne måler 30 målinger per sekund, og dækker intervallet fra ca. 1,5 m til ca. 130 m.

Mørke overflader, herunder vandoverflader, vil reducere styrken af det reflekterede signal. Ved flyvninger over mørke overflader kan der derfor forekomme et større antal målinger uden måleværdier (9999,99 er default værdien).

Målinger opgives med én decimal. Usikkerheden på den enkelte måling ligger på 10-30 cm.

Laser parameters	
Sample rate	30 Hz
Usikkerhed	10-30 cm
Min/ max range	1,5/130 m
Wave length	905 nm

Landingslokalitet

I kortlægningsområdet er der en stående aftale med lodsejer.

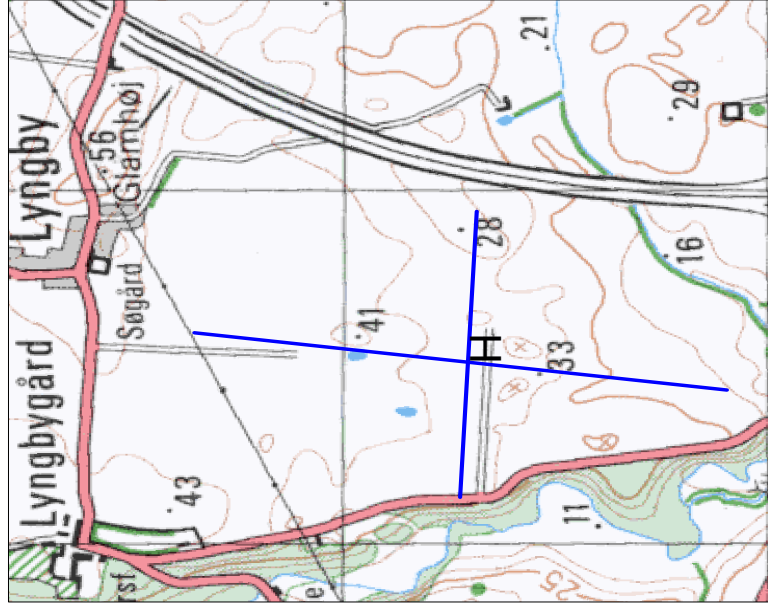
Niels Jørgen Bønløkke
Lyngbygård, Lyngbygårdsvej 25
8220 Brabrand

Tlf: 68287991

Aftalen omfattede anvendelse af et område på ca. 50 x 50 meter som landingslokalitet under dataindsamlingen. Placeringen af områderne ses herunder (Figur 5).

Ejer	UTM-E	UTM-N
Niels Jørgen Bønløkke	564440	6224460

Koordinaterne er angivet i UTM Zone 32N (Euref89)



Figur 5 Landingslokaliteten i kortlægningsområdet er angivet med et sort "H"

Flyveoperation

Helikopterpiloten har tilsigtet en flyvehøjde med rammen i 15m, 25m og 35 m, og med en gennemsnitshastighed på 45 km/t (12,5 m/s).

Den anvendte helikoptertype er en Eurocopter BA (se figur 6), ejet af Koopmann Helicopter og fløjet af pilot Torben Koopmann. Den samlede vægt af det anvendte måleudstyr udgør ca. 450 kg. Ved udregning af brændstof forbrug resulterer dette i en flyveperiode på ca. 150 min. regnet fra start til landing.



Figur 6 Helikoptertype anvendt til indsamling af SkyTEM data.

Kalibrering på Århus Testlokalitet

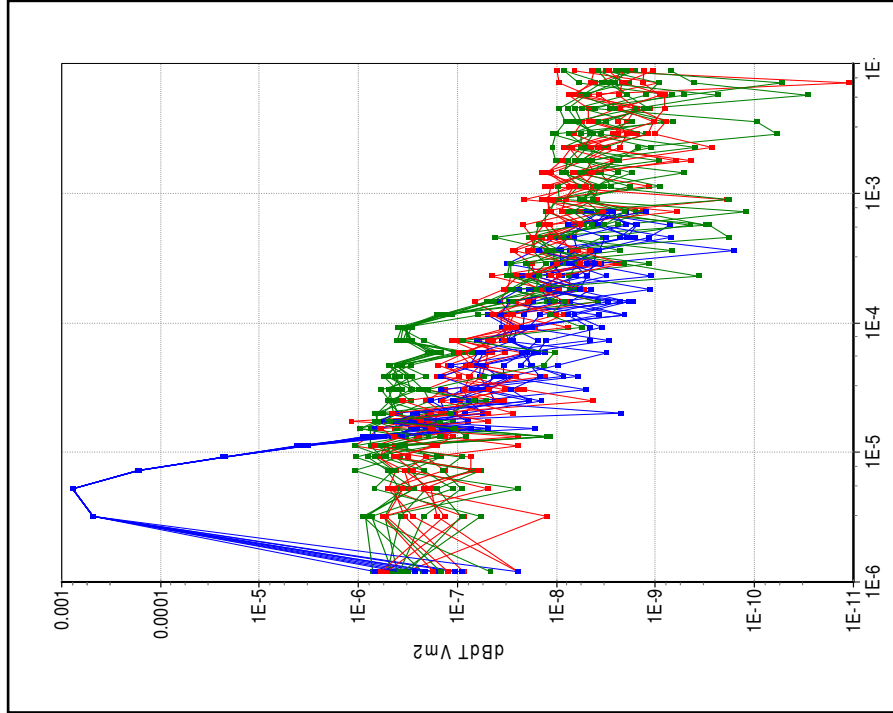
Den 4. August 2009 er der foretaget SkyTEM målinger over testlokaliteten i Lyngby. Disse målinger er foretaget med det udstyr og den måleprocedure, der er anvendt under selve kortlægningen. Målingerne dokumenterer at det komplette SkyTEM måleudstyr kan reproducere data fra testlokaliteten. Resultatet af referencemålingen og målingen af bølgeformen fremgår af Bilag II: Kalibreringsdata fra Århus Testlokalitet.

På baggrund af den geofysiske model for Århus Testlokalitet er der beregnet SkyTEM respons i forskellige flyvehøjder. Som det ses af Bilag II: Kalibreringsdata fra Århus Testlokalitet, er der opnået en god overensstemmelse mellem de målte data og referencedata.

Kalibreringen af SkyTEM konfigurationen giver følgende værdier:	
SLM niveauforskydning faktor (dB/dt)	0.92
SLM tidsforskydning μ s	-0.7 μ s
HM niveauforskydning faktor (dB/dt)	0.92
HM tidsforskydning μ s	-2.0 μ s

Højdetest

Den 5. August 2009 blev der i området omkring Århus Testlokalitet, Lyngby foretaget en højdetest i 1050 – 1150 m.o.h. Der blev lavet målinger for SLM og HM, hvor senderen var tændt samt støjmålinger, hvor senderen ikke var tændt. Testresultaterne (figur 7) viser hvordan SLM (blå kurve) rammer støjniveauet (rød kurve) ved omkring 10 μ s. Da SLM er målt uden frontgate ses der et bias signal på de første gates der ikke skal medtages i modelleringen af data. HM (grøn kurve) rammer støjniveauet omkring 100 μ s. Hvilken tørste gate der vælges at benytte i modelleringen skal vurderes i forhold til signálniveauet ved produktionsflyvningerne og bør vurderes i forbindelse med den første processering af data.



Figur 7 Højdetest foretaget i 1050-1150 m.o.h. dB/dt [V/m²] er plottet som funktion af tiden [s] og data er unormerede. Højt moment (HM) er grønne kurver, superlavt moment (SLM) er blå kurver og støj er røde kurver.

Produktionsrapport

I perioden 8. August 2009 er der fløjet i alt 1 produktionsflyvning i området.

Nedenstående tabel giver information om vejrforhold og kommentarer vedrørende hver enkelt produktionsflyvning:

Flyvning	Temp. (C)	Vind (m/s)	Sigtbarhed	Beskrivelse
20090805.01	25	5-7 SØ	God	Produktion

Produktionsdata

Nedenfor er angivet produktionsdata fordelt på de enkelte flyvninger.

De opgivne tider er angivet som UTC. I forhold til dansk normaltid er der fratrullet 1 time. For yderligere kommentarer til de enkelte flyvninger henvises til tabellen i produktionsrapport afsnittet ovenfor.

Linjerne er nummereret med 150.000 for de linjer der er fløjet i 15m, 250.000 for dem fløjet i 25m og 350.000 for dem fløjet i 35m. De linjer der slutter på lige hundrede (nnn201, nnn401, nnn601 og nnn801) er fløjet nord-syd og dem der slutter på ulige hundrede (nnn101, nnn301, nnn501 og nnn701) er fløjet øst-vest. F.eks er linje nummer 250.701 fløjet i 25m højde i øst-vestgående retning.

Flyvning	Start og slut tid		Linje nummer	
20090805.01	20090805	09:54:10.437	09:55:06.656	150101
	20090805	09:42:17.203	09:44:03.734	150201
	20090805	09:56:14.906	09:57:27.093	150301
	20090805	09:46:53.703	09:45:01.921	150401
	20090805	09:58:38.843	09:59:43.593	150501
	20090805	09:49:29.781	09:47:54.734	150601
	20090805	10:00:50.093	10:01:59.218	150701
	20090805	09:50:18.781	09:52:06.625	150801
	20090805	10:04:03.687	10:03:13.375	250101
	20090805	10:14:27.015	10:12:39.828	250201
	20090805	10:06:31.562	10:05:12.156	250301
	20090805	10:15:24.765	10:16:56.640	250401
	20090805	10:08:39.859	10:07:38.718	250501
	20090805	10:17:40.828	10:19:33.484	250601
	20090805	10:09:57.515	10:11:16.046	250701
	20090805	10:20:35.500	10:22:04.750	250801
	20090805	10:33:50.437	10:34:39.218	350101
	20090805	10:24:45.750	10:22:54.187	350201
	20090805	10:36:08.031	10:37:28.093	350301
	20090805	10:27:21.500	10:25:54.000	350401
	20090805	10:38:44.875	10:39:46.781	350501
	20090805	10:28:00.000	10:29:43.031	350601
	20090805	10:41:18.218	10:42:33.687	350701
	20090805	10:31:10.312	10:32:39.781	350801

For flyvningen er der i Bilag III Overvågningsparametre præsenteret flyvehøjde, flyvehastighed, vinkel af rammen, spænding ved udsendelse af strøm i spolen, spænding uden strøm i spolen, temperatur af senderen og intervaller med produktionsdata.

Der er intet at bemærke til overvågningsparametrene i øvrigt.

Forhold i forbindelse med tolkning

Lineære gates

Ved denne kortlægning er der anvendt en lineær fordeling af de første 9 gates i modsætning til tidligere, hvor alle gates var logaritmisk fordelt. Dette er gjort for at få en tidligere brugbar første gate og for at øge opløseligheden i de øverste lag af modellen.

Det betyder, at de enkelte gates i det tidlige forløb ikke er så 'brede' som tidligere og derfor i højere grad vil blive påvirket af støj. Ved indstilling af filtre forud for tolkningen skal dette forhold således tages i betragtning.

Brugbare gates i processeringen

I afsnittet under målecyklus er der angivet de gates, der medtages ved indlæsning i workbench med den medfølgende geometrifil. De er defineret som de første gates på SLM og HM, der i højdetesten ligger i niveau med støjen

I afsnittet, hvor højdetesten er beskrevet, er der på Figur 7 vist målte data i stor højde. Her er effekten af frontgaten meget tydelig (SLM er vist med en frontgate på 0 µs og HM er vist med en frontgate på 70 µs). Frontgaten har den effekt, at signalet fra modtagespolen ikke lukkes ind i forstærkersystemet før den tid, hvor frontgaten åbnes. Dette sker ved den tid, som er angivet i afsnittet omhandlende modtagersystemet og desuden angivet i geometrifilen.

På baggrund af den viste højdetest er det vurderet, hvornår bidraget fra lækstrømme i systemet (= bias) er reduceret så meget, at det målte signalniveau svarer til støjniveauet bestemt ved målinger, hvor senderen ikke er slået til.

Der er ved den beskrivelse udsortering af gates således ikke taget højde for signalniveauet i selve kortlægningsområdet. Ofte ses, at signalbidraget fra jorden er så højt, at det for HM ligger 1.5 – 2 dekader højere end niveauet for den bias, der ses lige efter åbning af frontgaten. Bidraget fra bias vil i disse tilfælde således antage 1-2% i forhold til jordrespons og her vil det være muligt at medtage flere gates på HM end angivet i den medfølgende geometrifil uden at det får fejlagtig indflydelse på inversionsresultaterne.

Hvilken første gate for henholdsvis SLM og HM, der skal benyttes i processeringen af data er således ikke entydig og skal vurderes i forhold til signal- og støjniveau i det aktuelle kortlægningsområde. De gates, der udvælges til brug under processing og tolkning, bør derfor vurderes og fastsættes i den indledende processing af data med henblik på at udnytte informationerne i data bedst muligt.

Digitale data

Rådata rapporten indeholder alle nødvendige data til processing og modellering af data.

Generelt er rådata opdelt på hver enkelt flyvning. Ved brug af mask fil i forbindelse med import af data til workbench vil filerne blive klippet så kun produktionsdata bruges i processing og inversion. Der vil altså blive set bort fra områder hvor der f.eks er transport flyvning eller hvis der er opstået problemer med måleudstyret.

Nøglen til sammenstilling af data er tiden. Tiden opgives i følgende format:

År måned dato timer minutter sekunder og tusindedelesekund. (yyyyymmddhhmmsssss)
Eksempelvis 2008 09 10 11 12 13 666

Tiden er UTC-tid dvs. fratrullet 1 time i forhold til dansk normaltid.

Den digitale afrapportering indeholder følgende punkter:

- Rådata som de lagres under selve feltarbejdet (filkatalog: ./Rawdata).
Datafilerne har fil efternavnet ".skb".
For hver flyvning genereres en sps-fil, som indeholder alle parameterdata: gps, højde, vinkel, spænding, strømstyrke, temperatur mv.
- GEO fil som dækker samtlige flyvninger. Geo-filen anvendes i forbindelse med processeringen i Workbench. (filkatalog: ./Geo)
- Mask fil i Workbench format, indeholder alle flyvninger. (filkatalog: ./MaskFile).

20090910_Calibrated_Viborg_494m2_SLM_HM_Z.geo
- Gis-tema over produktionsflyvningerne (filkatalog: ./MapInfo), som indeholder ID, Easting, Northing, Date and Time.
- Rådatarapport som pdf-fil, samt pdf-fil af parameterplots

Bilag I: Måletidsvinduer

Z-spole						
Gate No.	Gate start (µs)	Gate center (µs)	Gate bredde (µs)	Gate slut (µs)	Transmitter moment efter frontgate	
1	0.39	1.195	1.61	2.00	SLM og støj*	
2	2.39	3.195	1.61	4.00	SLM og støj*	
3	4.39	5.195	1.61	6.00	SLM og støj*	
4	6.39	7.195	1.61	8.00	SLM og støj*	
5	8.39	9.195	1.61	10.00	SLM og støj*	
6	10.39	11.195	1.61	12.00	SLM og støj*	
7	12.39	13.195	1.61	14.00	SLM og støj	
8	14.39	15.195	1.61	16.00	SLM og støj	
9	16.39	17.195	1.61	18.00	SLM og støj	
10	18.39	20.195	3.61	22.00	SLM og støj	
11	22.39	24.695	4.61	27.00	SLM og støj	
12	27.39	30.695	6.61	34.00	SLM og støj	
13	34.39	38.195	7.61	42.00	SLM og støj	
14	42.39	47.195	9.61	52.00	SLM og støj	
15	52.39	58.695	12.61	65.00	SLM og støj	
16	65.39	73.195	15.61	81.00	SLM og støj	
17	81.39	91.695	20.61	102.00	SLM, HM og støj**	
18	102.39	115.195	25.61	128.00	SLM, HM og støj**	
19	128.39	144.195	31.61	160.00	SLM, HM og støj	
20	160.39	181.195	41.61	202.00	SLM, HM og støj	
21	202.39	227.695	50.61	253.00	SLM, HM og støj	
22	253.39	285.695	64.61	318.00	SLM, HM og støj	
23	318.39	359.195	81.61	400.00	SLM, HM og støj	
24	400.39	451.695	102.61	503.00	SLM, HM og støj	
25	503.39	568.195	129.61	633.00	SLM, HM og støj	
26	633.39	714.695	162.61	796.00	SLM, HM og støj	
27	796.39	899.195	205.61	1002.00	HM og støj	
28	1002.39	1131.695	258.61	1261.00	HM og støj	
29	1261.39	1424.195	325.61	1587.00	HM og støj	
30	1587.39	1792.195	409.61	1997.00	HM og støj	
31	1997.39	2255.695	516.61	2514.00	HM og støj	
32	2514.39	2839.195	649.61	3164.00	HM og støj	
33	3164.39	3573.695	818.61	3983.00	HM og støj	
34	3983.39	4498.695	1030.61	5014.00	HM og støj	
35	5014.39	5663.195	1297.61	6312.00	HM og støj	
36	6312.39	7128.695	1632.61	7945.00	HM og støj	
37	7945.39	8845.195	1799.61	9745.00	HM og støj	

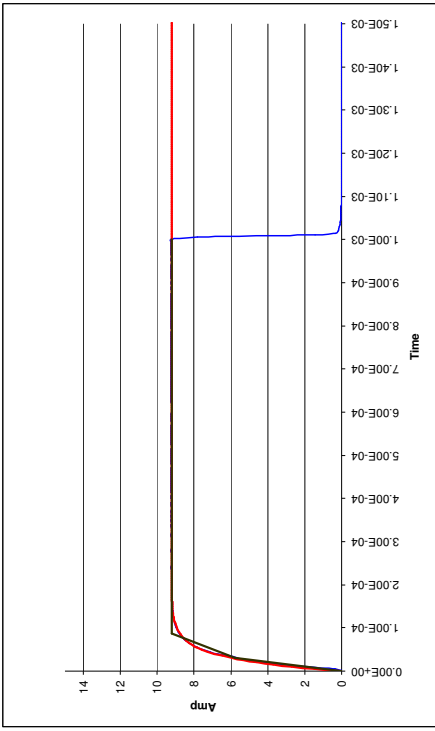
De opgivne tider skal korrigeres i henhold til de fastlagte kalibreringskonstanter.
Gate 17 er den første gate som ligger uden for frontgaten på HM.
* Disse gates udnýttes ikke for SLM da de ligger inde i bias signalet.
** Disse gates udnýttes ikke for HM da de ligger inde i bias signalet.

Bilag II: Kalibreringsdata fra Århus Testlokalitet

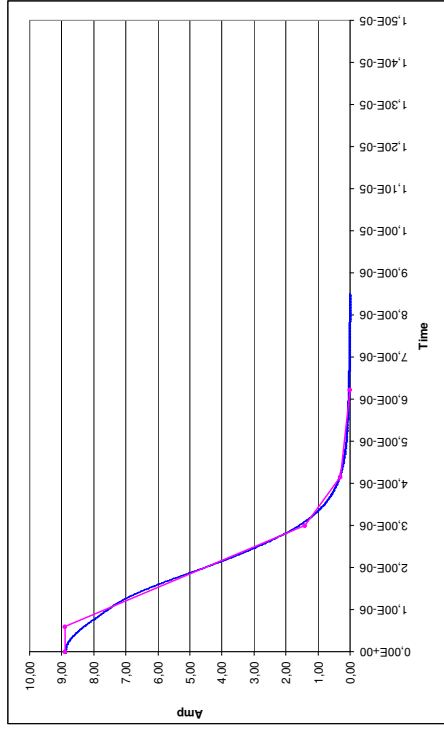
På Århus Testlokalitet er der med SkyTEM måleudstyret (i den konfiguration der er brugt i undersøgelsesområdet) foretaget målinger i forskellige højder over testlokaliteten. Resultaterne af disse målinger danner grundlag for finkalibrering af SkyTEM udstyret og kan ses herunder.

Bølgeform for SkyTEM

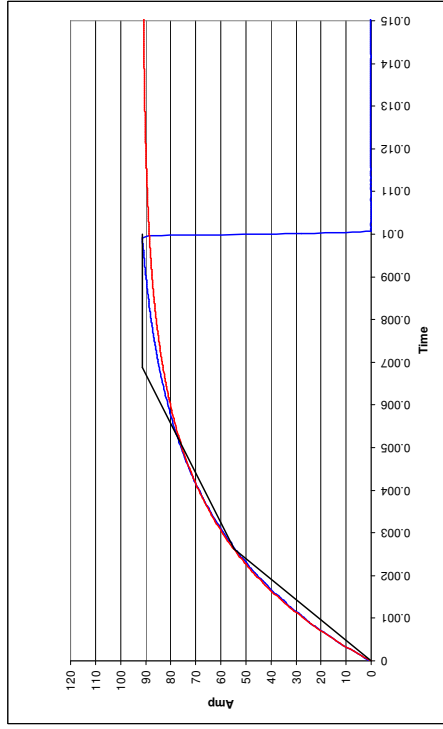
Den 4. August 2009 er der foretaget målinger af bølgeformen for repetitionsfrekvenserne 222 Hz (SLM) og 25 Hz (HM). På figur 15 til 18 ses henholdsvis op- og nedrampingerne for begge momenter.



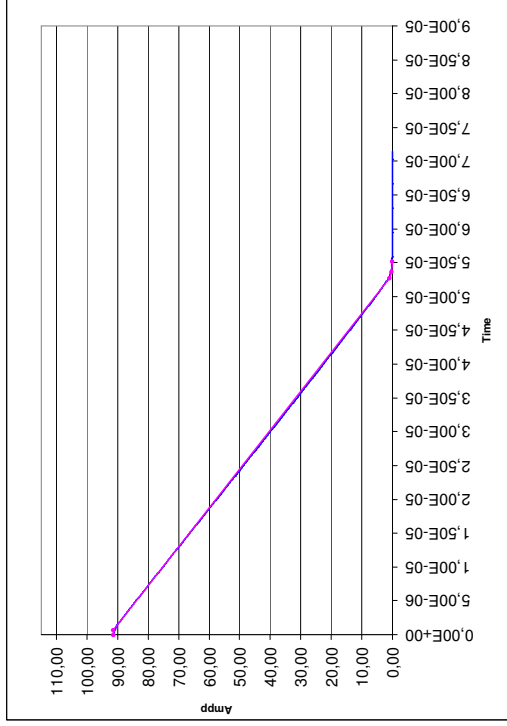
Figur 8 Oprampring ved 222 Hz (SLM). Den blå kurve er den målte oprampring [A] som funktion af tiden [s], rød kurve er den modelerede oprampring og sort kurve er modeleret bølgeform. Strømmen er 9 A og henfaldskonstanten $\tau = 34500$ s-1.



Figur 9 Nedrampning ved 222 Hz (SLM). Den blå kurve er den målte nedrampning [A] som funktion af tiden [s], pink kurve er den modellerede nedrampning. Avalanche mode er $1,3E+06$ s-1 fra 0,6 μ s. Det eksponentielle forløb er fra ca. 3,0 μ s til ca. 7 μ s. Henfaldskonstanten $\tau = 34500$ s-1.



Figur 10 Oprampning ved 25 Hz (HM). Den blå kurve er den målte oprampning [A] som funktion af tiden [s], rød kurve er den modellerede oprampning, og sort kurve er modelleret bølgeform. Strømmen er 91 A og henfaldskonstanten $\tau = 350$ s-1.



Figur 11 Nedrampning ved 25 Hz (HM). Den blå kurve er den målte nedrampning [A] som funktion af tiden [s], pink kurve er den modellerede nedrampning. Avalanche mode er $1,3E+06$ s-1 fra 0,75 μ s. Det eksponentielle forløb er fra 52,83 μ s til ca. 60 μ s. Henfaldskonstanten $\tau = 350$ s-1.

Op- og nedrampningerne er modelleret med følgende parametre:

SLM:

Repetitionsfrekvens 222 Hz (9 A)
Oprampning: $\tau = 34500$ s-1
Nedrampning: Avalanche mode 3,0 μ s – 0,6 μ s = 2,4 μ s
Lineær rampe, $dI/dt = (8,9-1,4)A / 2,4\mu s = 3,13E6$ A/s
Slut Avalanche mode = 1,4A
Henfaldskonstant eksponentielt forløb: $\tau = 1,3E+06$ s-1

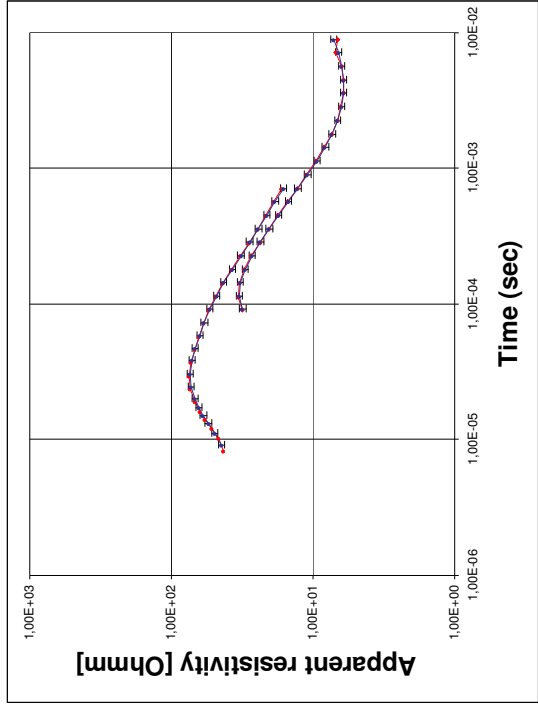
HM:

Repetitionsfrekvens 25 Hz (91 A)
Oprampning: 350 s-1
Nedrampning: Avalanche mode 52,8 μ s – 0,75 μ s = 52,05 μ s
Lineær rampe, $dI/dt = (91,3-0,8) A / 52,05 \mu s = 1,74E6$ A/s
Slut Avalanche mode = 0,8 A
Henfaldskonstant eksponentielt forløb: $\tau = 1,3E+06$ s-1

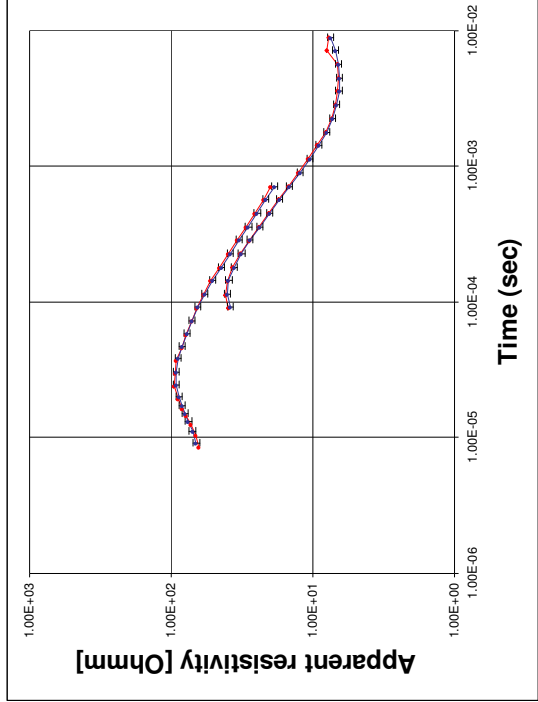
SkyTEM målinger på Århus Testlokalitet

Den 4. August 2009 er der foretaget referencemålinger med det komplette SkyTEM udstyr på Århus Testlokalitet ved Lyngby. Figurer 12 til 17 dokumenterer, at man med SkyTEM udstyret kan reproducere referencedata i udvalgte højder fra 0 til 30 m.

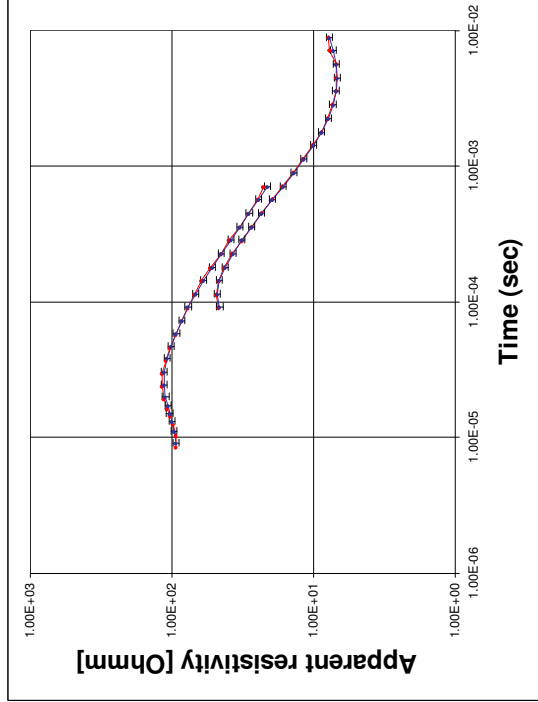
Referencedata for henholdsvis SLM (tidlige tider) og HM (sene tider) er præsenteret som blå kurver, og de målte SkyTEM data som røde kurver (se figur 12 til 17). Usikkerheden på de målte data er sat til 5 %.



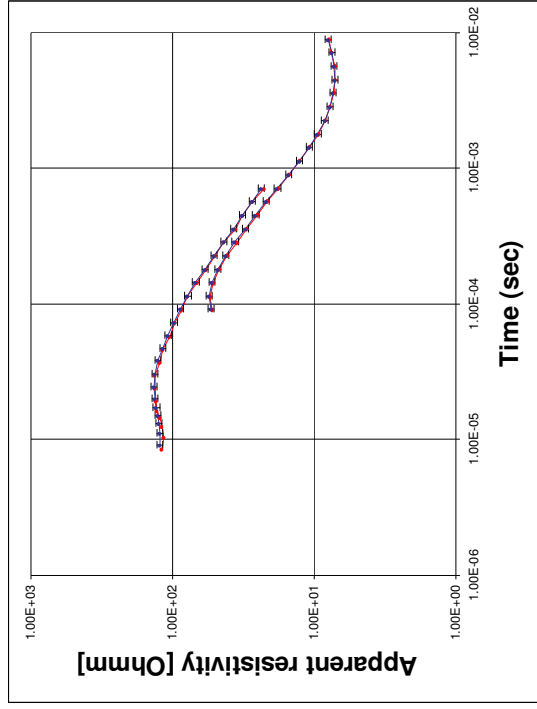
Figur 12 Ramme højde: 5 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.



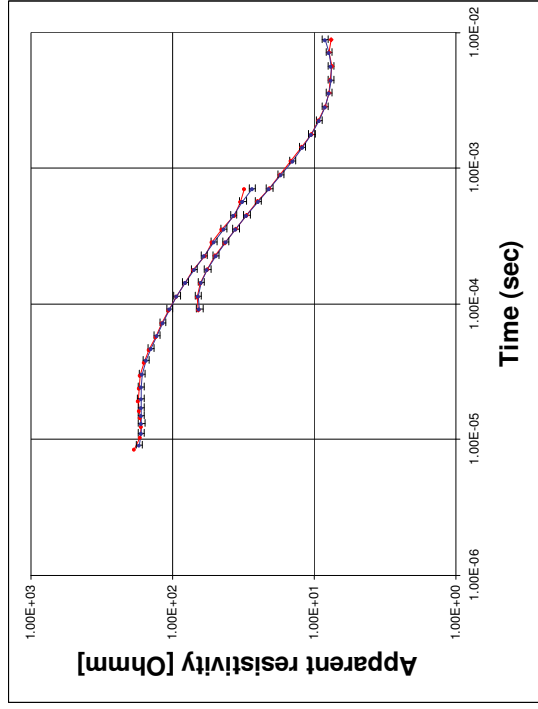
Figur 13 Ramme højde: 11 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.



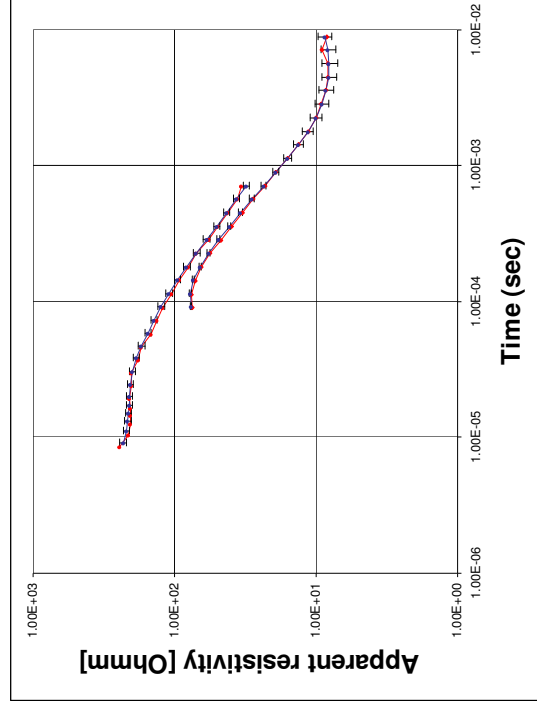
Figur 14 Ramme højde: 16 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.



Figur 15 Ramme højde: 20 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.



Figur 16 Ramme højde: 27 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.



Figur 17 Ramme højde: 33 m. De blå kurver er referencesonderinger beregnet for SkyTEM konfigurationen for SLM og HM. De er vist med 5 % errorbars. De røde kurver er data målt med SkyTEM.

Bilag III: Overvågningsparametre

For at kunne vurdere variationer i flyvehastighed, flyvehøjde og vinkel på rammen er disse data præsenteret på et parameterplot for hver enkelt flyvning. På parameterplottene ses desuden variationer i strømsstyrken, spænding på sender batterier og senderens temperatur.

Nederst på plottet er markeret de flyvelinjer som udgør produktionsdata, dvs. at transportflyvning - og i visse tilfælde flyvning over referenceområdet - er sorteret fra.

