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Comparison between Sensors & Software and Malå GPR equipment based on test measurements at Bøaøyna, Stryn Municipality, Norway

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Comparison between Sensors & Software and Malå GPR equipment based on test measurements at Bøaøyna, Stryn Municipality, Norway

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1318 I Stryn

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Summary:

The aim of this report is to document the results of a comparative performance test between systems and antennas from two major GPR manufacturers namely Sensors & Software (S&S) from Canada and Malå from Sweden. The Malå RTA system utilizes a parallel endfire antenna configuration which facilitates measurements in rugged terrains as opposed to the bulky S&S perpendicular broadside mode equipment (PulseEKKO) which requires a relatively open terrain to operate. To carry out our tests, conversion of the S&S system to parallel endfire mode was required as well as measuring with Malå equipment on perpendicular broadside antenna configuration. Penetration depth and overall data quality was our main focus.

A selected transect at Bøaøyna has been surveyed multiple times using several different antenna frequencies. Measurements with 50 and 100 MHz antennas were duplicated, tested for both georadars and configurations, subsequently processed with the use of two programs suggested by each manufacturer (EKKO_project for S&S and RadExplorer for Malå) and eventually evaluated against each other. Our test was also supplemented by unique 25 MHz Malå (parallel endfire) and 200 MHz S&S (perpendicular broadside) measurements. Although these results were not directly comparable with any other dataset, they revealed useful information after being compared with the rest of our processed data.

Our results indicate that the Sensors & Software Pulse EKKO Pro gives an overall better performance due to functioning at lower frequencies than stated which yields larger penetration depths for the same frequency antennas. In addition it has a lower noise level which is portrayed in the data quality and probably higher transmitted energy which translates to better and stronger signal. It should be noted that regardless of the slightly inferior performance by the Malå radar, the snake (RTA) system has yielded satisfying results. Essentially this means that rough terrain can be surveyed with the Malå RTA system as opposed to PulseEKKO which is bulky and less applicable in rugged areas. Wherever possible though, the Pulse EKKO Pro system should be preferred.

Keywords: Geophysics	Electromagnetic measurement	Ground Penetrating Radar
Test measurement	Sensors & Software	Malå Geoscience
		Scientific report

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1. INTRODUCTION

In August 2010 the Geological Survey of Norway (NGU) conducted a test survey with two different GPR systems in a small area at Bøaøynaen, Stryn Municipality. Equipment manufactured by Sensors and Software (S&S) from Canada and Malå Geoscience from Sweden were used.

A previous test survey was carried out in Eikesdalen, Møre & Romsdal. Here, different georadar systems revealed discrepancies in penetration depths and resolution using a common frequency 50 MHz has (**figure 1)**. The reason for these discrepancies could be attributed to several factors such as 1) difference in soil moisture since GPR profiling was not carried out during the same day, 2) different time windows, 3) different processing proceedures and softwares, 4) differential performance of the systems as well as 5) different antenna configurations. A more systematic testing was needed in order to investigate and eventually pinpoint the source of these discrepancies. Such testing was achieved at Bøaøyna by measuring the same transect multiple times during one day (August 26th 2010), using georadars from both aforementioned manufacturers with several antenna frequencies and configurations in order to acquire comparable datasets.

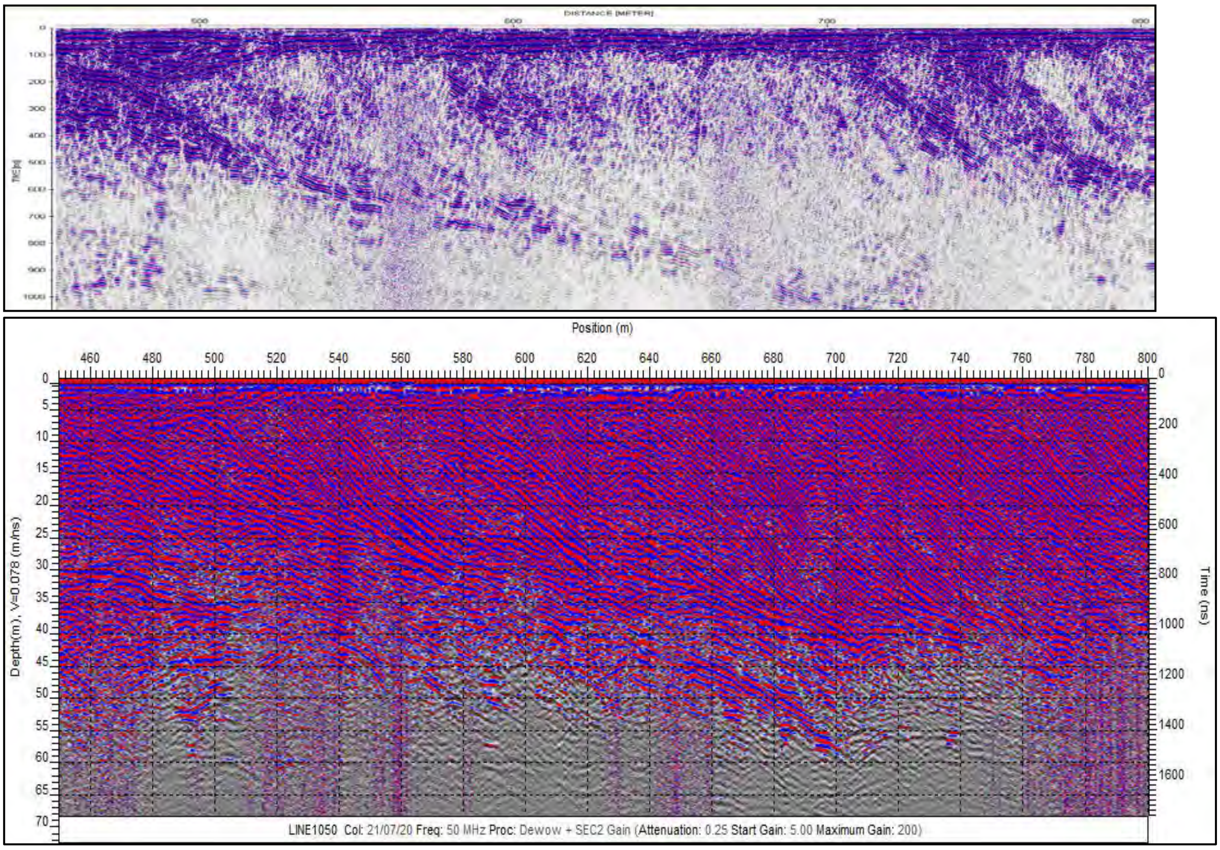

***Figure 1**: Single profile measured with Malå RTA (top) and PulseEKKO (bottom) Georadars and 50 MHz antenna in Eikesdalen. Each manufacturer has developed their own software for data processing and the GPR data were processed and presented in each of these designated programs. PulseEKKO results seem more detailed and with a larger penetration depth.*

In this new survey, data processing and presentation of results was carried out using the same softwares. In this sense, identical processing routines and visualization parameters were implemented on different datasets yielding comparable images.

RadExplorer v.1.42 developed by DECO Geophysical Ltd and distributed by MALÅ GeoScience and EKKO_Project V1/R3 by Sensors & Software were the programs used for this task. These proceedures allowed for consistent comparison of general signal and data quality, depth range and clarity of theresults acquired by the different GPR systems. The study is not only aimed at comparing the performance of georadar systems of two different manufacturers but also to verify whether Sensors & Software and Malå equipment follow the following rule: A higher frequency antenna should yield smaller penetration depth but higher resolution whereas a lower frequency should reach larger depths with lower resolution.

2. LOCATION AND GEOLOGICAL SETTING

The test measurements were performed in the northern part of the Bødalselva river delta (Bødal river delta), at the border of Lovatnet fjord lake in Stryn Municipality in western Norway. The region is characterized by deep glacially eroded valleys and fjords and the relief around Lovatnet lake exceeds 1500 m (**figure 2**). The Bødal river delta was constructed following the ice age and the deep basin allowed for the accumulation of thick, gravelly delta deposits. Glaciers are still present in the mountains. Streams in the area are exceptionally clean and groundwater are expected to be almost free of solutes. Together these conditions makes the river delta perfect as a test site due to the presence of relatively uniform/predictable geological conditions and possibilities for deep penetration of radar signals.

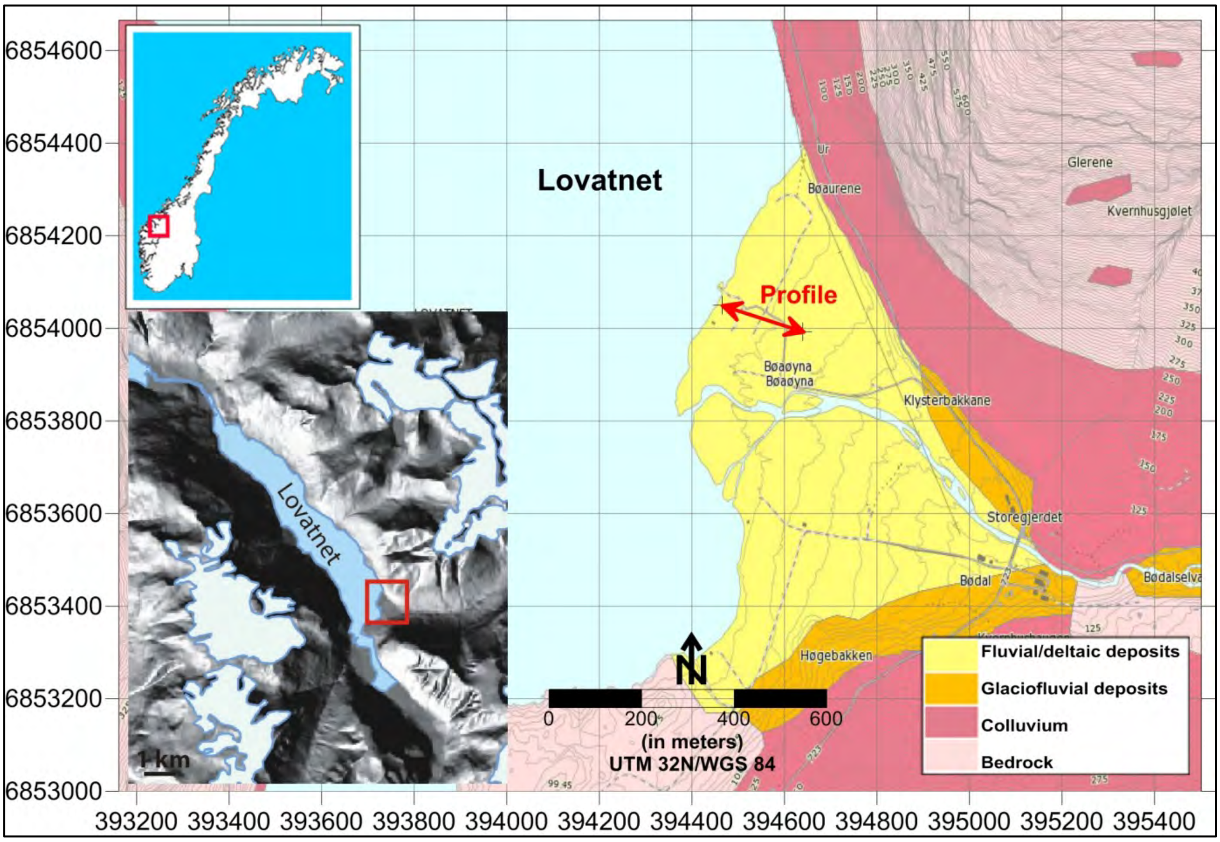

***Figure 2**: Geological setting of the study area at Bøaøyna. The transect where testing has been carried out is shown with the dotted red line.*

The starting point of the test profile is located at 394465 meters East and 6854050 meters North and the end at 394640 meters East and 6853993 meters North (UTM32N - WGS84). Its total length is about 185 meters and is oriented NW-SE (**Figure 2**).

The processed radar data acquired during the test surveys display clear images of delta deposits with inclined reflectors representing classical Gilbert-type delta foresets overlain by a topset package. The perfect conditions has allowed for a penetration depth exceeding 80 m which to the authors knowledge is world record for the GPR method in sand/gravel deposits.

3. GEORADAR SYSTEMS, FREQUENCIES AND ANTENNA CONFIGURATIONS

In the study we used two different radar system, with two different configurations and 4 different frequencies as presented below.

3.1 The Malå GPR system

Malå GPR systems used in this study with the following antennas: 25, 50 and 100 MHz RTA as well as 50 and 100 MHz standard unshielded antennas. RTA (Rough Terrain Antenna) was developed for use in difficult and/or inaccessible terrain (Aaltonen, 2003). This antenna is also called a "snake" since its configuration enables the antenna to smoothly slide between obstacles in rough terrains like a serpent (**figure 3, left**). This particular configuration is described as parallel endfire, where transmitter and receiver antennas are positioned in a row. Malå Rough Terrain Antenna (RTA) has the great advantage of being flexible in difficult terrains as opposed to standard antennas that are at least 1 m wide (**figure 3, right**) The standard antennas usually require the additional assistance of one person, while the Malå RTA can be operated by a single person even in densely vegetated areas. However, it is not possible with the Malå RTA antennas to do Common MidPoint (CMP) gathers for velocity analysis.

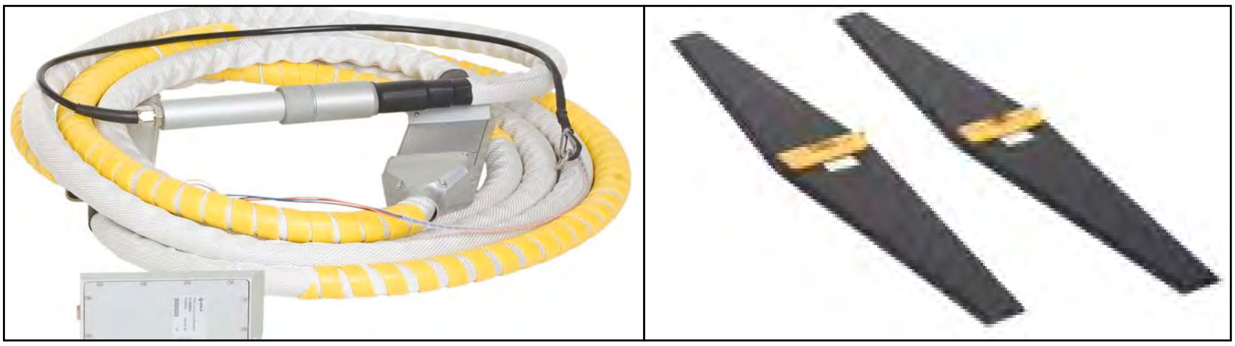

***Figure 3**: The RTA "snake" antenna (left) and standard unshielded 100 MHz antennas by Malå (right), (www.malags.com).*

3.2 Sensors & Software EKKO Pro GPR system

Sensors & Software EKKOPro Georadar system (**figure 4**), was applied in the present study using 50, 100 and 200 MHz antennas. The configuration used is perpendicular broadside and endfire for the 50 and 100 MHz antennas and perpendicular broadside for the 200 MHz antennas. This is a rather old system but it has undergone the PRO upgrade 5 years ago improving its performance. An accurate positioning system in the form of a DGPS has been attached to the Georadar which can be connected to the base station and ensure accurate location information. Data collected and processed with additional positioning and altitude information yield more accurate profile images and may also be utilized in 3D interpretation (Heincke et al. 2008 and 2009). The mentioned positioning systems were not applied in the present study.

***Figure 4**: PulseEKKO PRO 100 (setting is identical to the PRO 50 model - www.sensoft.ca).*

3.3 Antenna configurations

Possible antenna configurations are shown in **figure 5.** According to prior studies (Lutz et al., 2003), perpendicular broadside configuration should perform a better resolution than parallel endfire. However, parallel endfire configuration (such as the "snake" Malå RTA system employs) offers better maneuverability as opposed to typical perpendicular broadside settings which are difficult to operate in rough terrains and dense forest.

Generally, the length of the antennas controls the resulting frequency regardless of configuration.

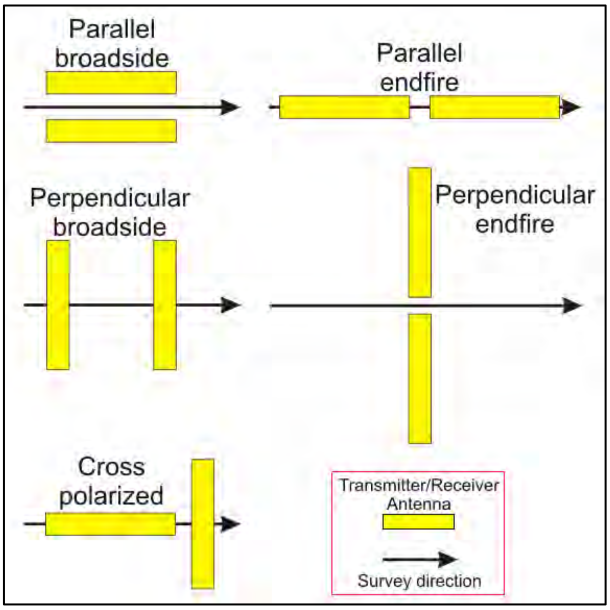

***Figure 5**: GPR transmitter/receiver antenna configurations.*

4. DATA AQUISITION AND VELOCITY CALCULATIONS

4.1 Measurements

The test transect shown in Fig. 2 was measured 10 times August 26th 2010. The utilized GPR equipment along with the antenna frequencies and antenna configurations for each measurement are shown in Table I. Sensors & Software unshielded antennas were used both in "perpendicular broadside" and "parallel endfire" mode. Malå RTA is a fixed "parallel endfire" configuration and cannot be used in "perpendicular broadside" mode. Malå unshielded standard antennas and used in a "perpendicular broadside" mode.

Nr	Georadar type	Frequency	Configuration	Antenna Separation
File 1	S&S	50 MHz	Perpendicular broadside	2 m
File 2	S&S	100 MHz	Perpendicular broadside	2 m
File 3	S&S	100 MHz	Parallel endfire	2 m
File 4	S&S	50 MHz	Parallel endfire	4 m
File 5	S&S	200 MHz	Perpendicular broadside	0.9
File 49	Malå RTA	100 MHz	Parallel endfire	2 m
File 51	Malå RTA	25 MHz	Parallel endfire	6 m
File 52	Malå RTA	50 MHz	Parallel endfire	4 m
File 53	Malå Unshielded	50 MHz	Perpendicular broadside	2 m
File 54	Malå Unshielded	100 MHz	Perpendicular broadside	2 m

***Table I**: Measurement modes and antenna configurations.*

The penetration depth of a GPR survey depends on the skin depth which is controlled by the conductivity of the ground and the frequency used. However, the time length for which the reflections are recorded, namely the time window T_w, also affects whether a survey can reach the skin depth or not. A high time window value gives enough time to the pulse to travel to deeper reflectors and back. The propagation velocity determines the depth that can be registered under optimal conditions. In our case a time window of 3000 ns is used for the 25 and 50 MHz Malå and the 50 and 100 MHz S&S antennas while a value of around 1500 ns is used for the 100 MHz Malå antennas and 200 MHz S&S antennas.

The resolution of the profiles is controlled by both the georadar central frequency and sampling settings employed and the ground properties. However, the sampling frequency is the factor controlling whether we can reach a maximum resolution or not and it ought to be high to avoid aliasing.

The sampling characteristics of the measurements are shown in **Table II**. The sampling interval has been calculated by dividing the time window to the number of samples per trace. The sampling frequency f_s was found by inverting the sampling interval, and after halving it, we obtained the Nyquist frequency f_N (=f_s/2) . In order to avoid aliasing in our data, the Nyquist frequency should be well above the central antenna frequency. As can be seen in **table II** this is very much the case. Therefore, our data do not suffer from resolution issues.

Equipment	Antenna Frequency (MHz)	Δt (ns)	f_s (MHz)	f_N (MHz)	Time Window (ns)
S&S PB/PE	50	1,6	626	313	3000/3000
S&S PB/PE	100	0,8	1250	625	3000/3000
S&S PE	200	0,4	2500	1250	1500
Malå RTA PE	25	3,95	254	127	3105
Malå RTA PE	50	1,95	512	256	3057
Malå RTA PE	100	0,8	1150	625	1603
Malå Unshielded PB	50	1,95	513	256	3057
Malå Unshielded PB	100	0,8	1250	625	1603

Table II: Sampling characteristics of each profile repetition (PB= Parallel Broadside, PE= Parallel Endfire).

4.2 Velocity calculations

The propagation velocity in the study area has been calculated equal to 0.08 m/ns through CMP analysis with the use of the PulseEKKO Georadar (**figure 6**). It follows that the registration depth is 120 meters for 3000 ns and 60 meters for 1500 ns time windows, respectively. Therefore the profiles performed with S&S equipment using 100 MHz antennas have potentially larger registration depths than the Malå profiles for the same frequency antenna (see Table II).

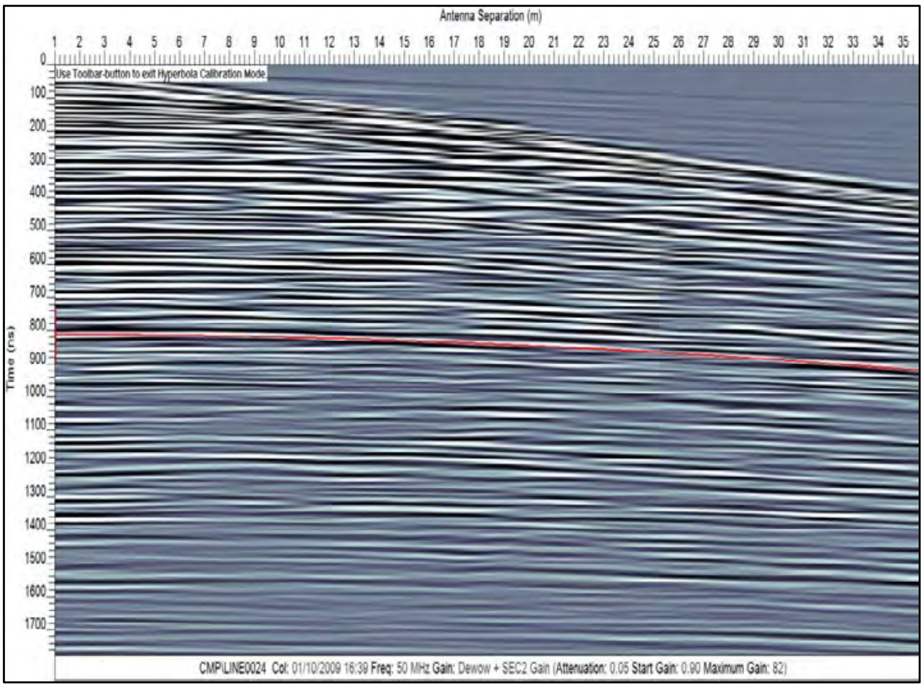

Figure 6: *CMP hyperbola fitting to determine the propagation velocity (0.08 m/ns).*

The CMP measurement was performed on October 1st 2009, almost a year prior to the actual test profile measurements which were done on August 26th, 2010. Despite the weather conditions being dry during both CMP and profile measurements, the days prior to the latter were characterized by heavy rain which can have affected the ground conditions above the groundwater level. However, the affected layer is only expected to be a few meters thick. Therefore the average calculated velocity is not expected to be significatnly different from the average velocity during data acquisition.

***Figure 7**: GPR profiling at Bøaøyna with the use of Georadars from Malå RTA (left) and Sensors & Software (right). Lovatnet lake is located in the background.*

***Figure 8**: Malå 50 MHz Unshielded antennas on Sensors & Software cart (left) and S&S EKKO Pro in endfire mode (right).*

5. PROCESSING ROUTINES AND SOFTWARES

Each GPR profile was processed with the use of two software programs: a) EKKO_project V1 R3 (Sensors & Software 2013) which is the designated software for processing S&S data and b) RadExplorer 1.42 (DECO Geophysical 2005, Bouriak, S. et al 2008) from Malå Geoscience. RadExplorer is capable of handling different GPR data formats (S&S data included).

However, EKKO_project does not offer the possibility of importing Malå data. For comparing our results data should be processed using both programs. Therefore we have also employed REFLEXW 5.5.2 (Sandmeier 2010) in order to convert Malå data into S&S format.

The processing modules utilized for each program are described in the following section. Both programs allow the user to compile a processing routine with parameters of his choice and then apply the exact same scheme to multiple profiles. However, the modules available in EKKO_project and RadExplorer for compiling a routine are not identical and therefore, we cannot make a compilation which is identical for both programs. What we can do, is to apply the same routine to the profiles within each individual software. In this sense, results are only comparable for each software separately.

5.1 EKKO_project routines

We have compiled routines in EKKO_project which contain dewowing, first break editing (wherever applicable), SEC2 gain control type and ultimately conversion to depth. Dewowing removes unwanted low frequency 'wow' from GPR trace while preserving high frequency signal and is implemented before any other module of the routine. Editing the first break changes where the first break occurs. The first break is the best estimate of the time of the first onset of signal in the dataset and is automatically picked for PulseEKKO datasets as opposed to Malå data where first break editing has to take place manually. Spreading & Exponential Calibrated Compensation (SEC2) applies a combined constant and exponentially increasing gain as a function of time. Applying this process with suitable parameters makes the amplitudes of signals returned from similar targets at different depths appear similar. We have used increased attenuation rates and high maximum gain in order to increase gain for signals from deeper targets (later times) to clarify the maximum depth penetration limit. Conversion to depth has been achieved with the use of the CMP calculated velocity of 0.08 m/ns. Visualization of the EKKO_project results has been done using the default color scale and settings (Sensitivity 100%, Contrast 50%).

5.2 RadExplorer routines

The routines constructed for RadExplorer contain the following modules: DC removal, time-zero adjustment, background removal, bandpass filtering, AGC amplitude correction and finally conversion to depth. DC removal removes the constant component of the signal i.e. shift from the zero level. Time-zero adjustment performs the same task as in first break edit in EKKO_project. Background removal is subtracting the mean trace determined in the window with fixed size running along the profile from the whole set of traces. Bandpass filtering is used to increase the signal/noise ratio. The filter is controlled by the main frequency itself and is a simple trapeziform zero-phase filter. AGC amplitude control stands for Automatic Gain Control and is a module which equalizes the amplitudes along the traces. This is achieved by calculating the gain factor for every position of the window by sliding down the trace with an interval equal to the chosen operator length. We use small operator lengths in order to highlight the maximum depth penetration without hurting resolution. Conversion to depth uses the CMP calculated velocity of 0,08 m/ns. The RadExplorer results are displayed with the default color scale and a small enhancement in additional scalar (bias is kept equal to 0).

5.3 Presentation of results

Any changes or modification in the above described routines will be given in the result presentation section. In all other cases, this is the backbone of the whole procedure and has been kept stable throughout processing. It should also be noted that even though images between the two programs are not directly comparable, the above routines have been planned in order to lead to images with similar characteristics. Finally, the processed results display all reflectors emphasized in order to highlight the resolution. This also helps to clarify the point where the noise level becomes higher than the signal level defining the maximum penetration depth.

6. PROCESSING RESULTS AND DISCUSSION

In this section we present and discuss the results from the processing of the test measurements along the Bøaøyna transect. Results are presented for 50, 100, 25 and 200 MHz antennas, respectively. Checking the actual measuring frequency in the profiles compared to the manufacturer's specification is a parameter which needs to be defined before any comparison takes place. This can be achieved after plotting the Average Frequency Spectrum (AFS) for each profile repetition and locating the central frequency. Another useful tool when comparing GPR data is the Average Trace Amplitude plot (ATA). This plot displays the rectified signal amplitudes (in microVolts) for one or more GPR lines and it helps us display how rapidly the signal amplitude decays to the background noise level. It should be noted that by background noise level we are referring to the signal amplitude before the initiation of transmission.

6.1 50 MHz antennas: AFS and ATA

The average frequency spectrum (AFS) plot for all profiles measured with the 50 MHz antenna using an option offered by EKKO_project and RadExplorer software is presented in **Figure 9** (for detailed arithmetic estimations check **table IV**).

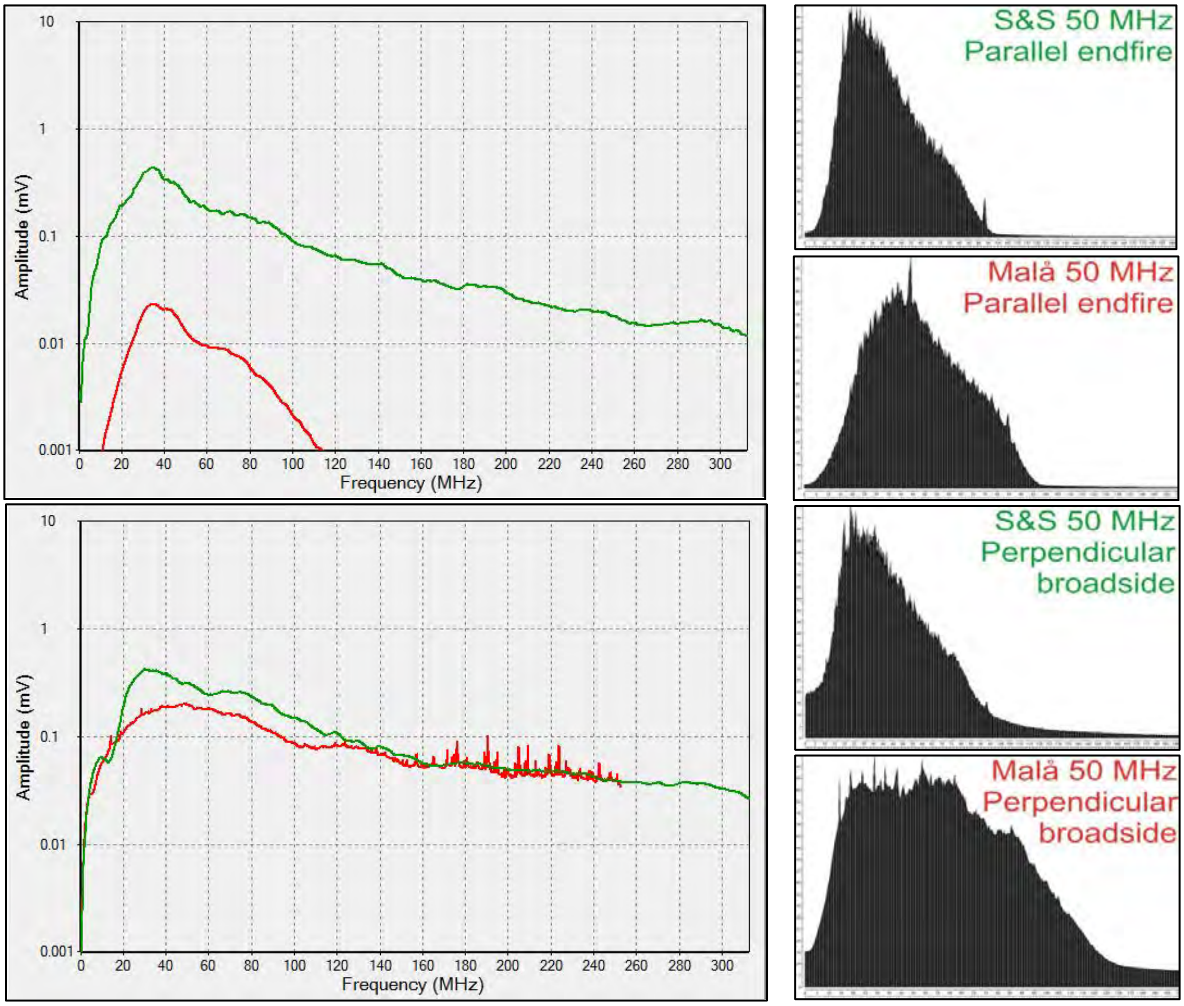

Figure 9*: Average Frequency Spectrum (AFS) plot of all radagrams measured with the 50 MHz antenna on parallel endfire and perpendicular broadside mode for Malå (red) and PulseEKKO (green) as extracted from both EKKO_project (left) and RadExplorer (right).*

As can be clearly seen, peak frequencies for all systems and configurations vary from about 35 MHz to 50 MHz indicating that the resulting divergence between the processed images should not be significant. However, the spectrum for the Malå unshielded antenna system with perpendicular broadside configuration is too broad and does not cluster well around the central frequency, a fact indicating that there is some problem with this particular dataset. The ATA plot for all four 50 MHz antenna datasets is shown in **figure 10**.

Initially, a large difference in signal amplitude can be observed between parallel endfire and perpendicular broadside antenna configurations when using the Malå Georadar. Standard unshielded antennas in perpendicular broadside mode may have a stronger signal but the background noise level is also very high. However, no such difference can be observed between the two configurations when PulseEKKO system is used. The PulseEKKO perpendicular broadside configuration displays only a slightly stronger signal which decays following a similar pattern compared to parallel endfire until ~2500 ns where glitches start to appear. This is not the case with Malå equipment where the signal decays almost equally for both types of configuration reaching background levels already at ~1200 ns. Essentially, this discrepancy is a strong indication that the PulseEKKO measurements are of better quality and can reach larger depths compared to the Malå measurements. As for the PulseEKKO glitches at late times (over 2500 ns), they are due to old firmware and can be dealt with easily with the installation of a newer version. By doing this the PulseEKKO signal could potentially reach the background noise level on an even later time than 2500 ns. This could lead to an even larger penetration depth than the ones documented here. In any case, we expect the S&S equipment to perform better for this particular antenna frequency compared to Malå equipment. Malå RTA measurements, on the other hand, are expected to reach shallower depths with resolution deteriorating in deeper parts.

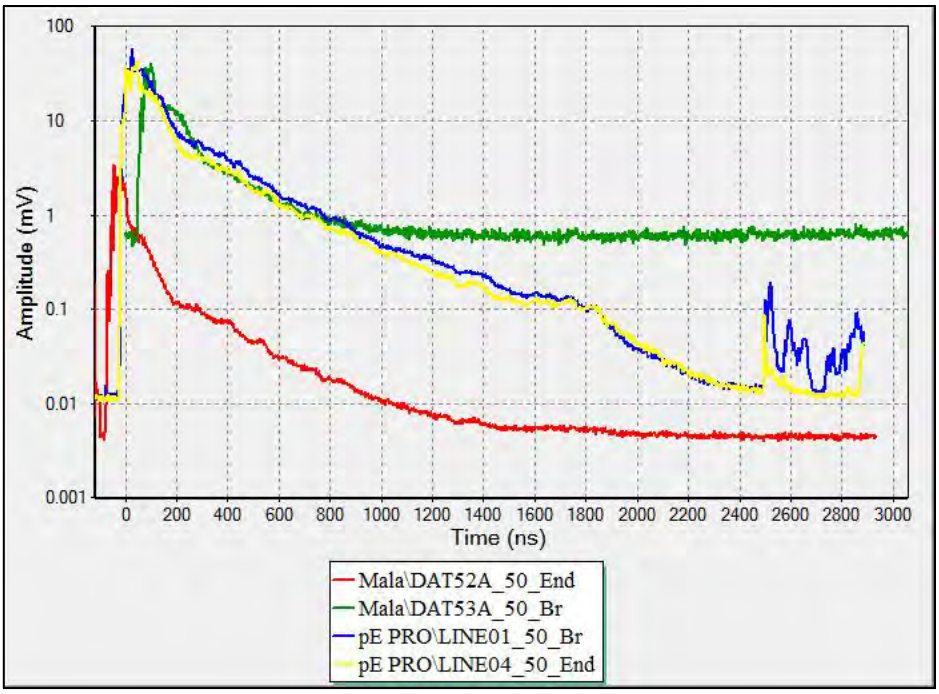

***Figure 10**: Average Trace Amplitude (ATA) plot for all profiles measured with 50 MHz antenna and both for parallel endfire (End) and perpendicular broadside (Br) configuration. (Malå: red/green; PulseEKKO: blue/yellow).*

6.2 Profile images based on 50 MHz antennas

Figures 11 to **14** show results for the profiles measured with 50 MHz antenna using the parallel endfire configuration (**figures 11** and **12**) and perpendicular broadside (**figures 13** and **14**). **Figures 11** and **13** show the processed images obtained with EKKO_project while **figures 12** and **14** the ones obtained with RadExplorer.

In EKKO_project the routine included editing of first break (64 and 118 ns for Malå and S&S respectively), standard dewowing and application of SEC2 gain function (Attenuation = 50 dB/m, Start Gain = 8, Maximum Gain = 5000). The high Attenuation value is aimed at preferentially increasing gain for deeper signals, start gain value indicates that signal amplitudes are reduced after the first break and Maximum Gain value is used to highlight the maximum penetration depth. No filtering was necessary for these datasets.

In RadExplorer DC and Background removal were applied with their default values while Time zero adjustment utilized the same values as in EKKO_project to match the first break with zero level. In this software an AGC gain function has been chosen with an operator length of 20 ns. This small operator window has enhanced deeper reflectors without taking its toll on resolution. A simple bandpass filter was also employed to increase signal to noise ratio. Passband frequencies started at 25 and ended at 75 MHz while low and high stopband frequencies were 0 and 100 MHz respectively.

Figures 11 and **12** immediately reveal an obvious difference in penetration depth. PulseEKKO data acquire information on reflectors from almost 100 meters deep (2500 ns) while the Snake system "sees" down to ~80 meters (2000 ns). However, this penetration depth of 80 meters is not characterized by the same quality as in S&S data. At ~55 meters depth (1400 ns) the noise becomes significant and only strong reflectors are detectable below that point. These limits coincide with the limits obtained by the ATA plot shown in **figure 10**. The Malå signal reaches background noise level faster than S&S equipment regardless of configuration. Therefore, the reason for discrepancies in performance are built-in the equipment itself. This can be explained by higher transmitted energy and/or more efficient antennas.

Figures 13 and **14** indicate first of all that the datasets measured with Malå standard unshielded and perpendicular broadside configuration are problematic. High noise starts occurring at ~40 meters (1000 ns) with only a few strong reflectors 'surviving' below that point. It is also evident that resolution is strongly affected especially in the upper and lower layers of the profile. This effect is probably due to bad connections, electronic noise or malfunctioning antenna. In either case, results could not be obtained from the used Malå equipment for perpendicular broadside configuration. On the contrary, S&S perpendicular broadside data appear to reach the same penetration depth as parallel endfire. Here, the only difference is a slightly better resolution when perpendicular broadside configuration is used. Having used the exact same processing routine, several reflectors appear stronger and clearer with this particular configuration (for example at position 40-55 m and 45 meters depth) while hyperbolic reflections appear more evident in the first 50 meters of the profile in shallow depths, features indicative of boulder presence in these layers. These hyperbolas are not as clear when using parallel endfire configuration. This discrepancy between configurations when using S&S can also be explained in **figure 10**. The signal decay is almost identical leading to similar penetration depths.

However, the perpendicular broadside ATA graph (blue line, **figure 10**) indicates a stronger signal at least down to 1800 ns (72 m). Signals become almost identical below this point leading to comparable resolution. The glitches found at 2500 ns (100 m) are also portrayed in all S&S profiles. The stronger perturbations in perpendicular broadside are translated into strong banding at 100 m while the same effect is milder in parallel endfire on the same depth.

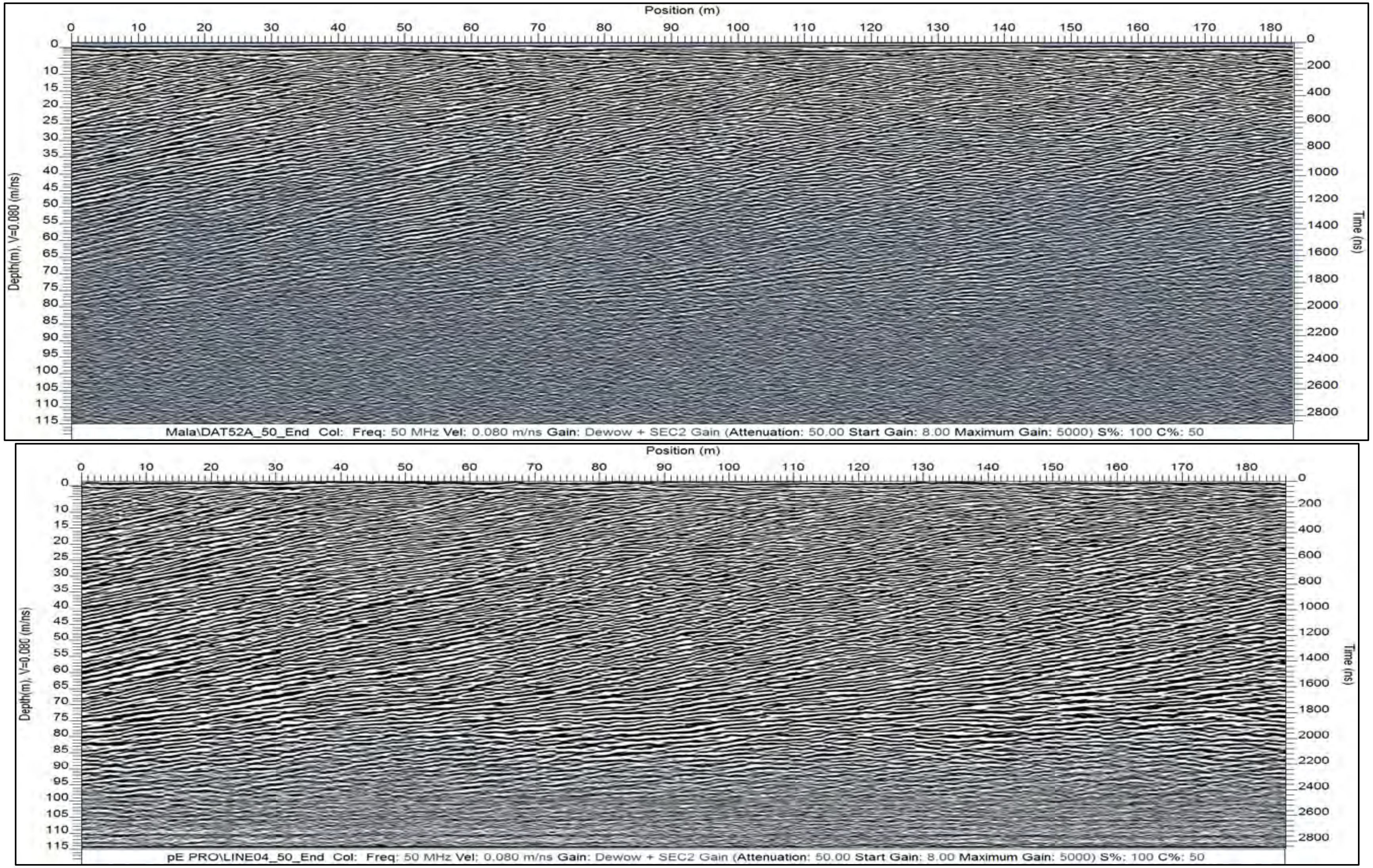

***Figure 11**: Malå RTA (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of EKKO_project. Both profiles were conducted with 50 MHz parallel endfire antenna configuration.*

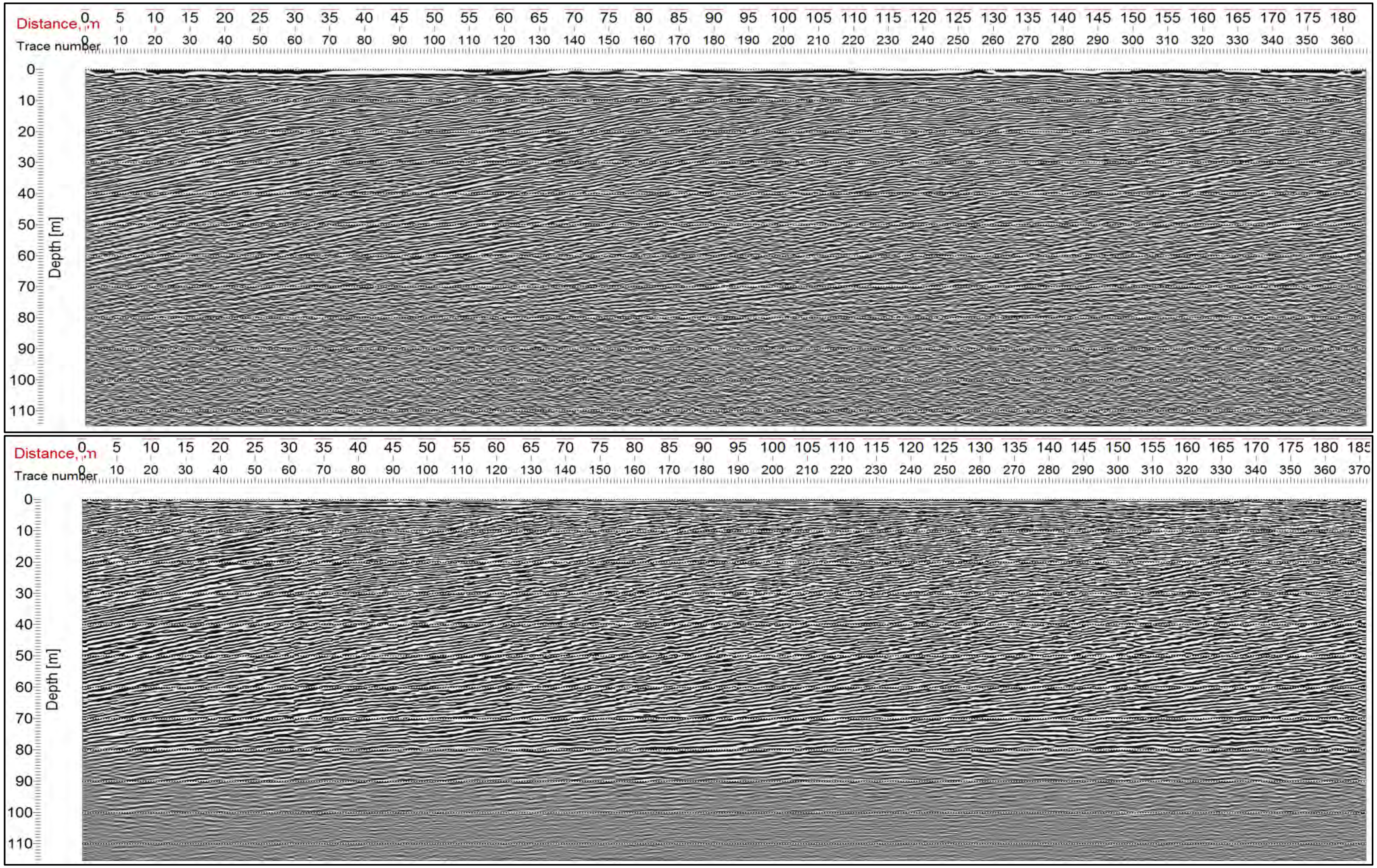

***Figure 12**: Malå RTA (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of RadExplorer. Both profiles were conducted with 50 MHz parallel endfire antenna configuration.*

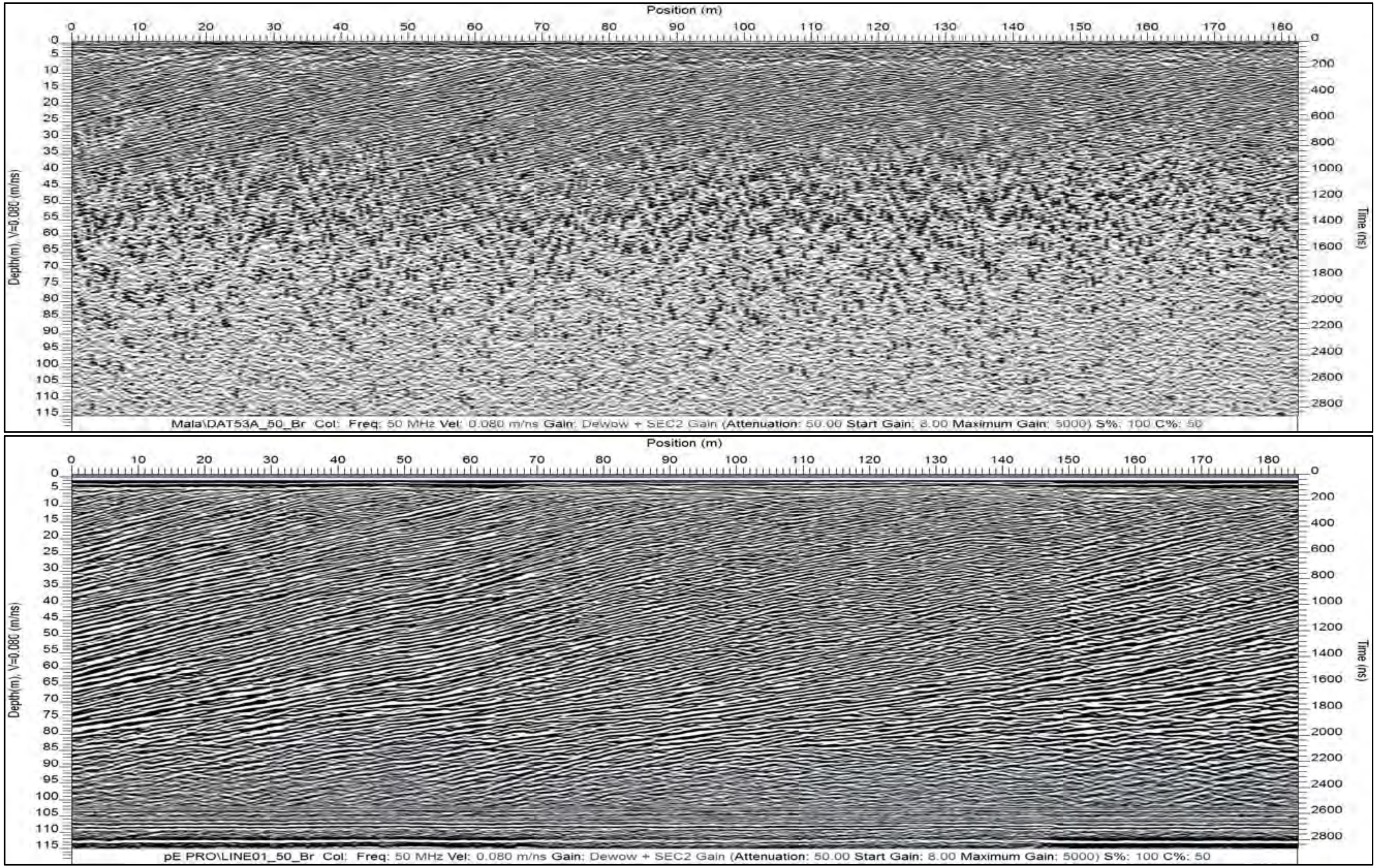

***Figure 13**: Malå Standard Unshielded (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of EKKO_project. Both profiles were conducted with 50 MHz perpendicular broadside antenna configuration.*

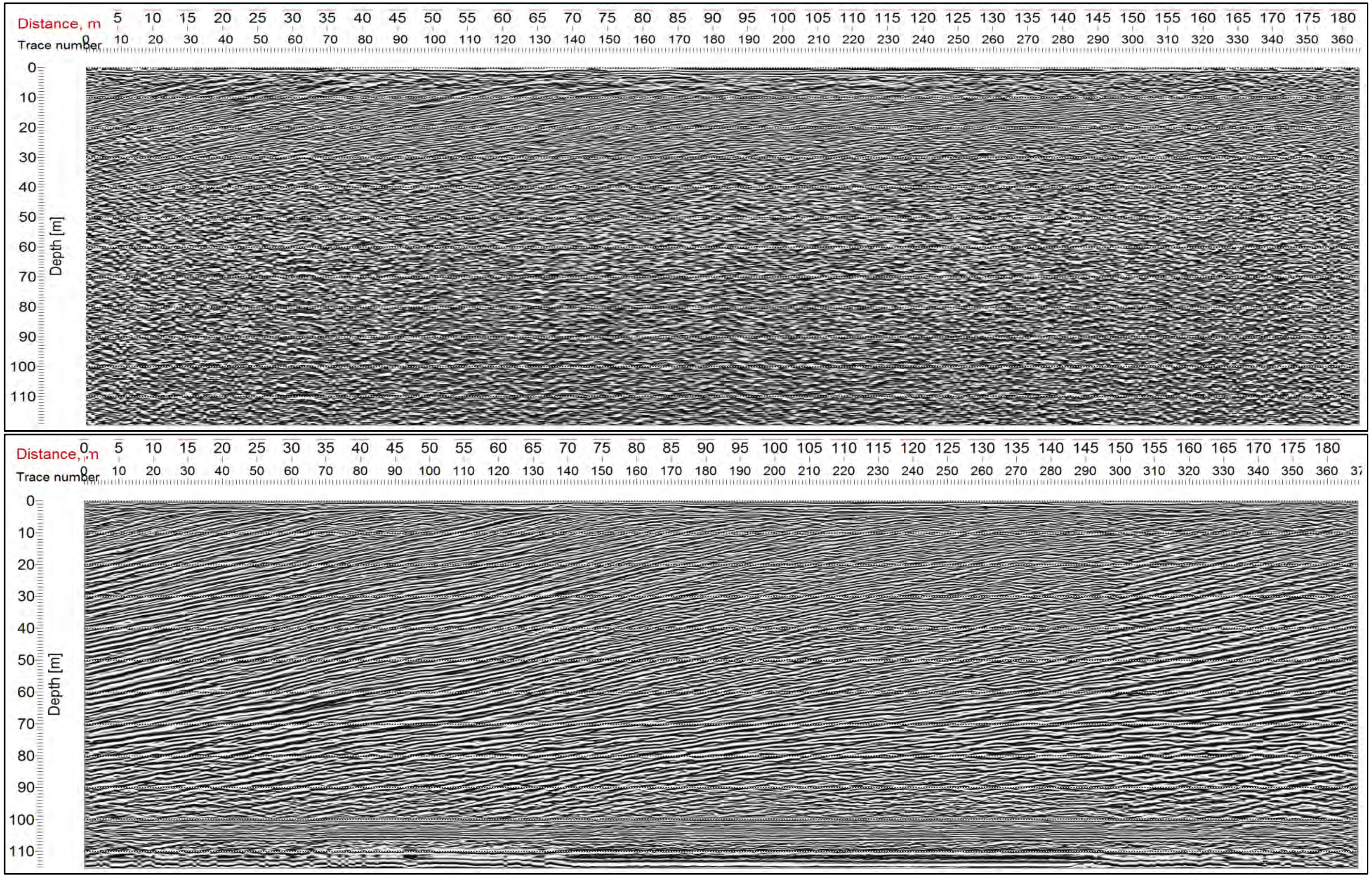

***Figure 14**: Malå Standard Unshielded (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of RadExplorer. Both profiles were conducted with 50 MHz perpendicular broadside antenna configuration.*

6.3 100 MHz antennas, AFS and ATA

Before commenting on the processed images of the profiles measured with the 100 MHz antenna, we should mention again that the time window applied is not the same for both manufacturers. The Sensors & Software data have been measured with 3000 ns while the Malå data with 1500 ns. This essentially means that the RTA/Standard Unshielded registration depth is half the PulseEKKO one (60 and 120 meters respectively). In other words, the Malå time window setting does not allow registrations below that depth, regardless of it being signal or noise. We will comment on whether this option has led the instrument to miss reflectors beneath 60 m later in this section.

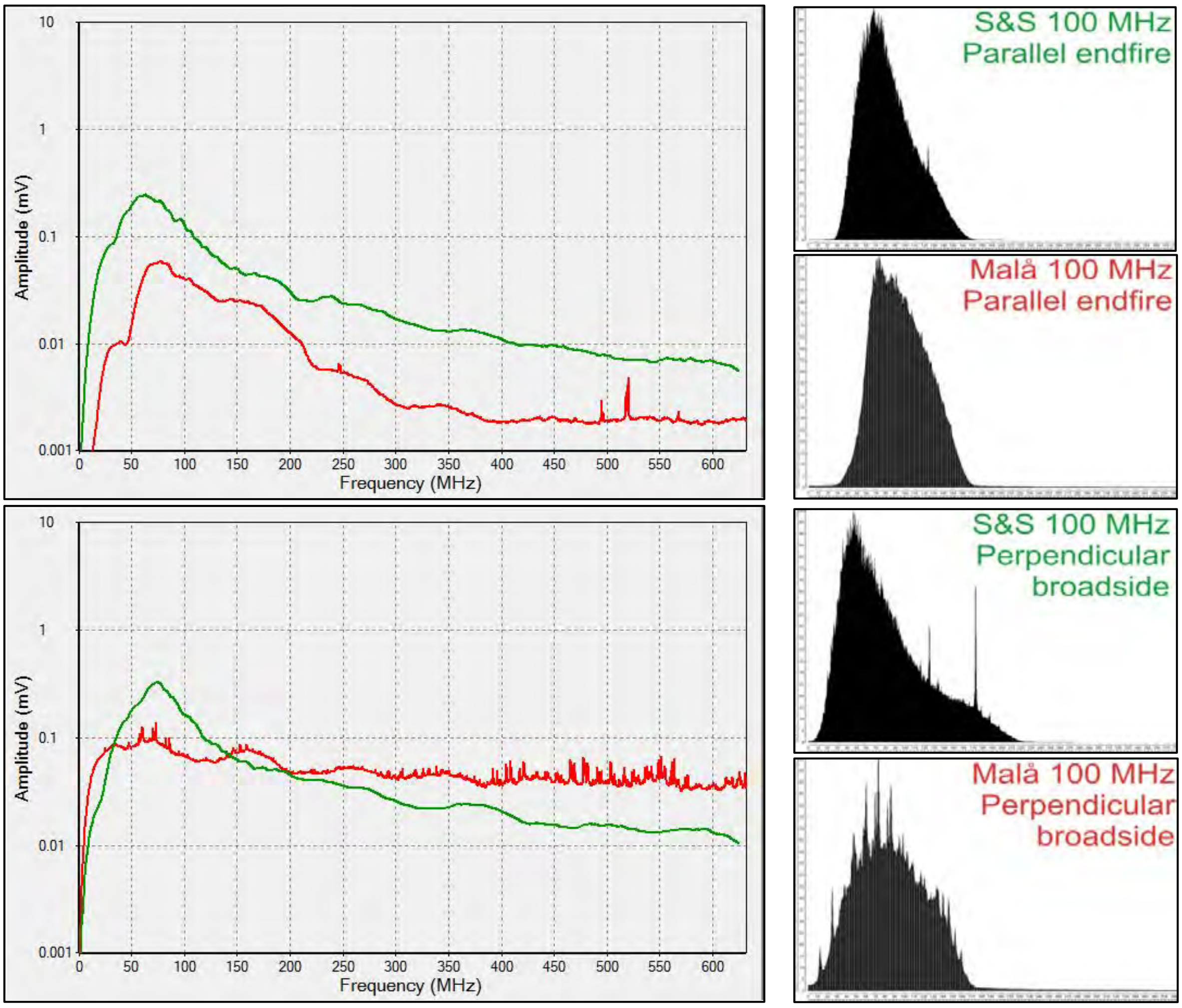

***Figure 15**: Average Frequency Spectrum (AFS) plot of all radagrams measured with the 100 MHz antenna on parallel endfire and perpendicular broadside mode for Malå (red) and Pulse EKKO (green) as extracted from both EKKO_project (left) and RadExplorer (right).*

The AFS plot for each dataset is shown in **figure 15** (for detailed arithmetic estimations check **table IV**). It is obvious that a central frequency which is closer to the 100 MHz antenna specification is better achieved with Malå RTA (~80 MHz). For Sensors & Software equipment the discrepancies are much greater, especially in perpendicular broadside configuration where the central frequency is actually much closer to 50 than 100 MHz (65 MHz). For parallel endfire antenna configuration the central frequency value lies in the middle between 50 and 100 MHz. These graphs indicate that the penetration depth for PulseEKKO is expected to be larger than Malå especially when perpendicular broadside configuration is employed. The resolution on the other hand is expected to be better for Malå data since the actual frequency is higher. Finally, the Malå perpendicular broadside configuration data appear to be plagued by several spiking frequencies and an ambiguous distribution.

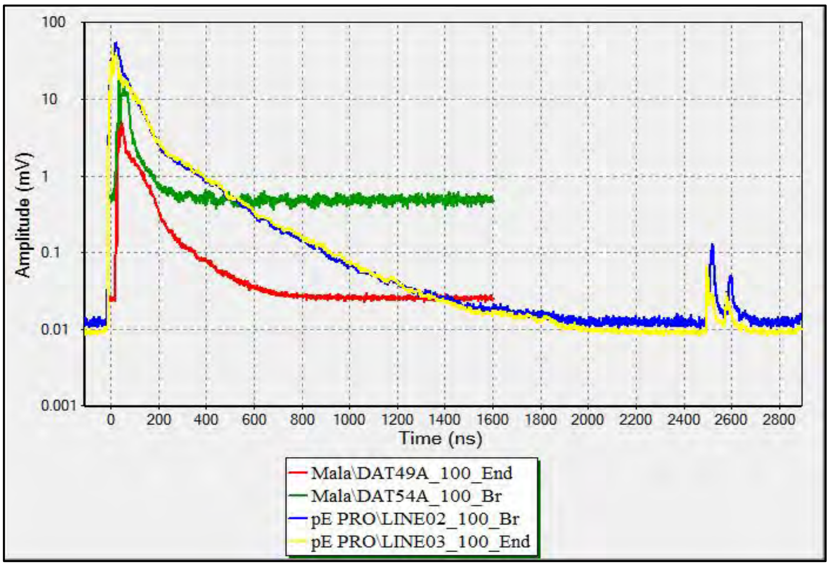

***Figure 16**: Average Trace Amplitude (ATA) plot for all profiles measured with 100 MHz antenna and both for parallel endfire (End) and perpendicular broadside configuration (Br).*

The Average Trace Amplitude (ATA) plot shown in **figure 16** reveals useful information about the performance of both Georadars. The behavior of the signal's amplitude is almost identical for the S&S system as in the case of 50 MHz. The graph pattern is unaffected by configuration utilized and the signal decays relatively slowly to background level after ~2000 ns. On the contrary, configuration or antenna type seems to be a rather important factor for Malå equipment. When RTA antennas with parallel endfire configuration is used, the signal decay time is ~800 ns while with the standard unshielded antennas and perpendicular broadside configuration it is almost the half (~500 ns). The signal amplitude itself on the other hand is much higher with perpendicular broadside but so is the background noise level. In this sense, another remarkable feature is that background noise level for PulseEKKO is lower and the amplitude stronger compared to Malå regardless of configuration.

6.4 Profile images based on 100 MHz antennas

Figures 17 and **18** show the results for parallel endfire while **figures 19** and **20** display the results for perpendicular broadside configuration. To really see the structures in these plots, the figures should be enlarged (images of higher resolution than the ones included in this report are available to any interested party).

Each set of processed images is shown as obtained by EKKO_project first and subsequently by RadExplorer. The processing routines for parallel endfire and S&S perpendicular configuration were the same as for 50 MHz. In EKKO_project the processing required editing of first break (33,7 and 110,2/118,1 ns for Malå and S&S both configurations respectively), standard dewowing and application of SEC2 gain function (Attenuation = 50 dB/m, Start Gain = 8, Maximum Gain = 5000). No filtering was necessary for these datasets.

In RadExplorer we have used DC and Background removal while Time zero adjustment utilized the same values as in EKKO_project. The AGC gain function had an operator length of 20 ns again while a standard filter designed for 100 MHz antennas was applied. Passband frequencies started at 50 and ended at 150 MHz while low and high stopband frequencies were 0 and 200 MHz respectively.

However, the systematic noise that is present within the data measured by Malå Georadar with perpendicular broadside unshielded antenna configuration forced us to modify the processing routine in order to clean the resulting images to the extent possible. These specialized processing steps were not applied on the respective PulseEKKO data since no such noise is present in that dataset. The main difference in processing refers to gain function. In order to clear up the images we had to use an AGC function with a very small operator length (1.5 ns) in both processing programs. In RadExplorer, the filtering was designed with a smoother transition from higher passband until stopband (0-50-150-600). This processing modification has at least managed to reveal the strongest reflectors and in the case of RadExplorer, to almost null the noise. Filtering in EKKO_project proved to be a more demanding task but the strong reflectors are still enhanced above noise levels. All other processing steps were kept constant with time zero adjustment being 25,3 ns for Malå perpendicular broadside antenna configuration.

Comparing the resulting top and bottom images in **figures 17** and **18** we deduce that S&S equipment has performed much better than Malå for 100 MHz parallel endfire configuration. The penetration depth achieved is ~85 m (2100 ns) for PulseEKKO and ~35 m (800 ns) for Malå RTA, which is again directly connected with the qualitative characteristics derived from the ATA plot in **figure 16**. It is also interesting to note that a 15 MHz difference in the central frequency after plotting the average spectrum (77 and 91 MHz respectively - **figure 15**) resulted in twice the depth penetration. In fact, the penetration achieved with PulseEKKO using the 100 MHz antenna is even better than the one achieved with the Malå RTA system with the use of the 50 MHz antenna. In addition to that, higher resolution images were obtained due to higher frequency. Nevertheless, in the case of 100 MHz parallel endfire configuration, the Malå data are characterized by better resolution. The first ~20 m of penetration (450 ns) display a larger variety of reflectors with several possible boulder positions (**figures 17** and **18** - top). Moreover, when perpendicular broadside configuration is used the quality between Malå and S&S equipment is not much different. Bottom panel **figures 17** and **18** indicate that penetration depth is still at ~85 m and the resolution comparable to the results we obtained by parallel endfire for the Malå equipment. On the other hand, it is difficult to compare results obtained by Malå unshielded antenna against any other dataset due to the high noise level which led to a modified processing procedure (**figures 19** and **20**). In any case and regardless of the fact that only the strong reflectors survived the noise filtering, reflectors seem to be detectable down to ~30 meters.

Considering the fact that the time window chosen in Malå equipment has a registration depth of 60 m, the penetration depth achieved has not been cut off by this option for either configuration. Finally, we should note that the vertical banding noise appearing in the bottom profiles (Sensors & Software data) in **figures 19** and **20** between 93 and 105 meters are explained by to cell phone interferences.

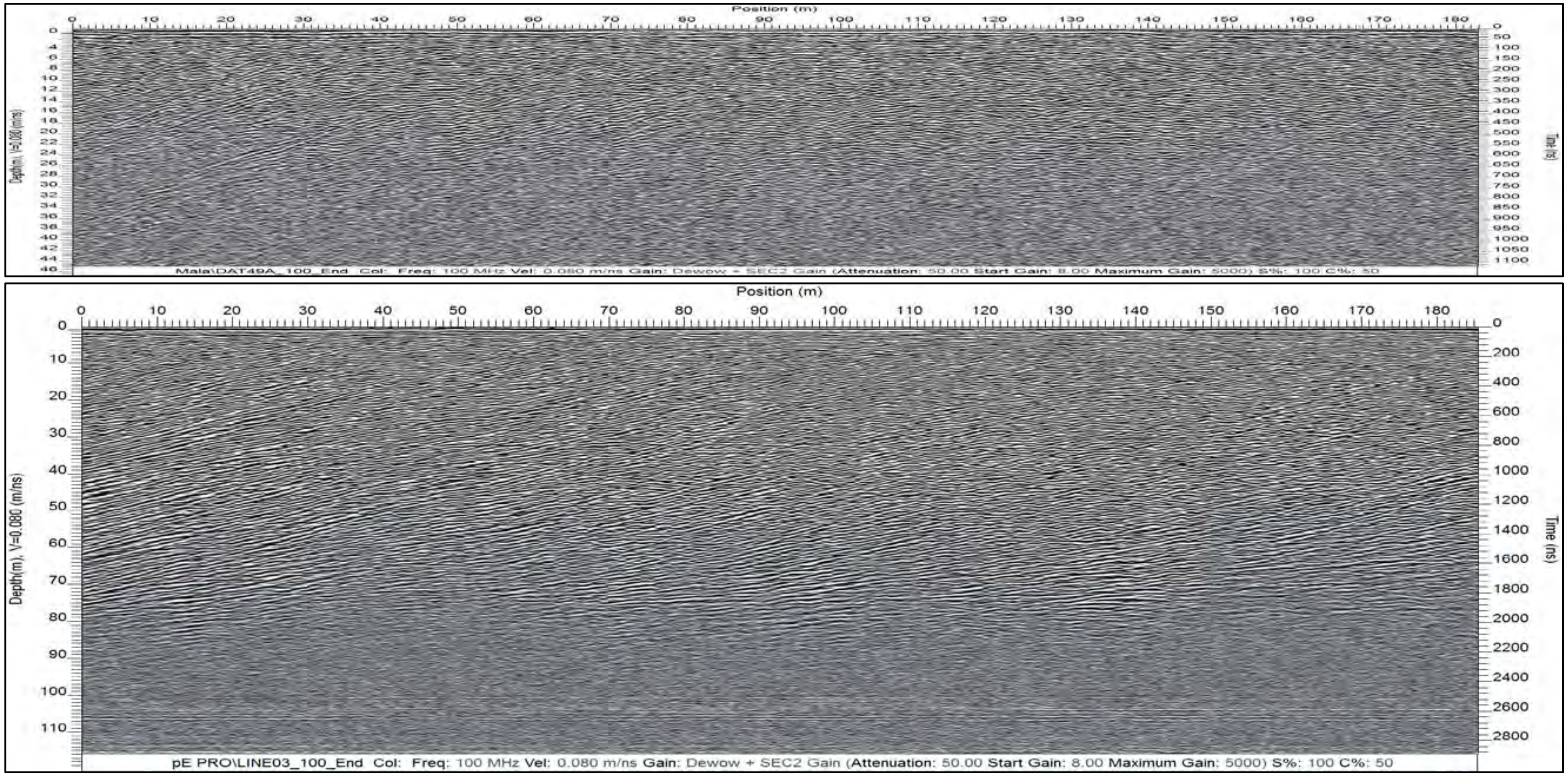

Figure 17*: Malå RTA (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of EKKO_project. Both profiles were conducted with 100 MHz parallel endfire antenna configuration.*

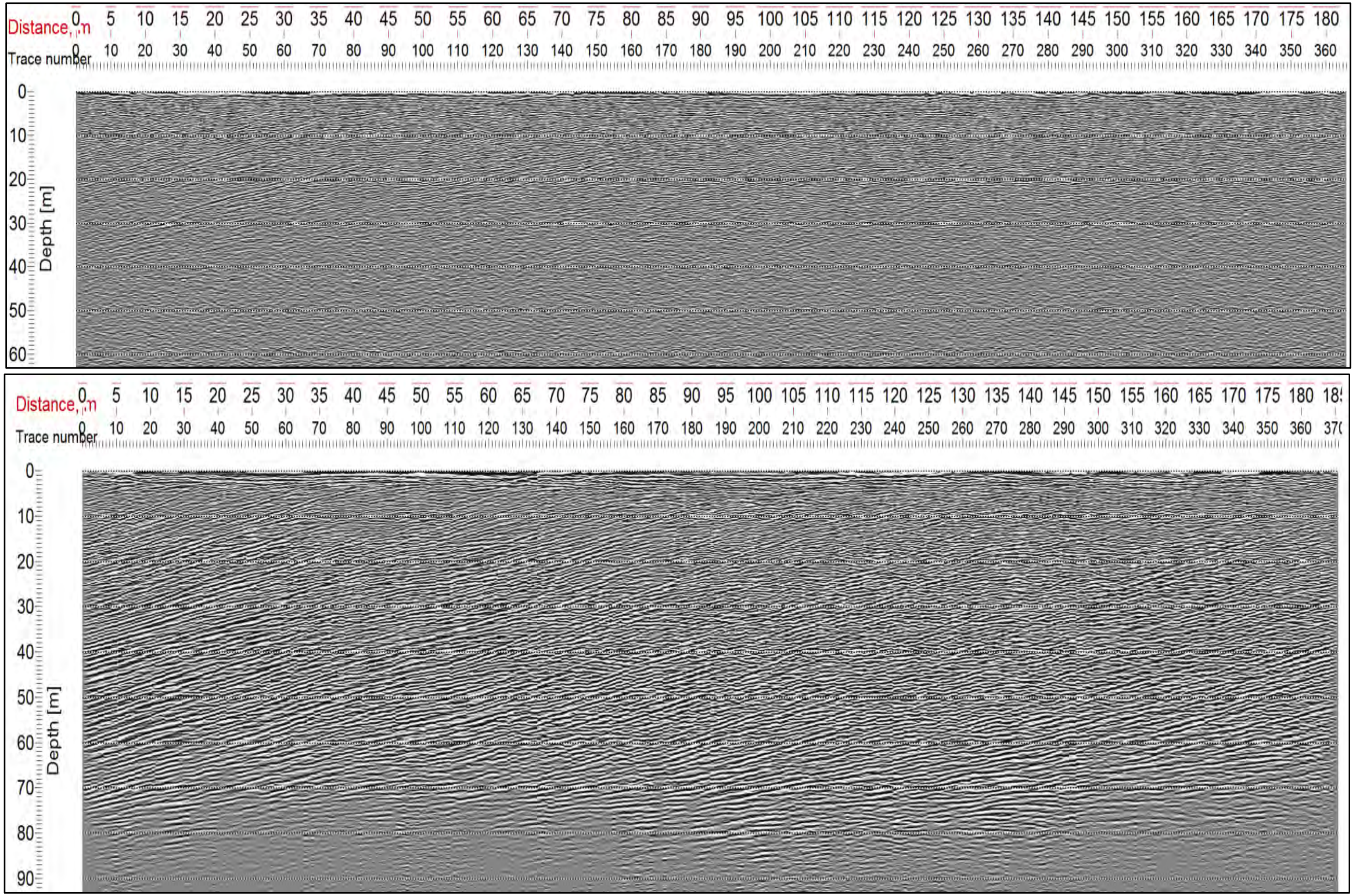

***Figure 18**: Malå RTA (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of RadExplorer. Both profiles were conducted with 100 MHz parallel endfire antenna configuration.*

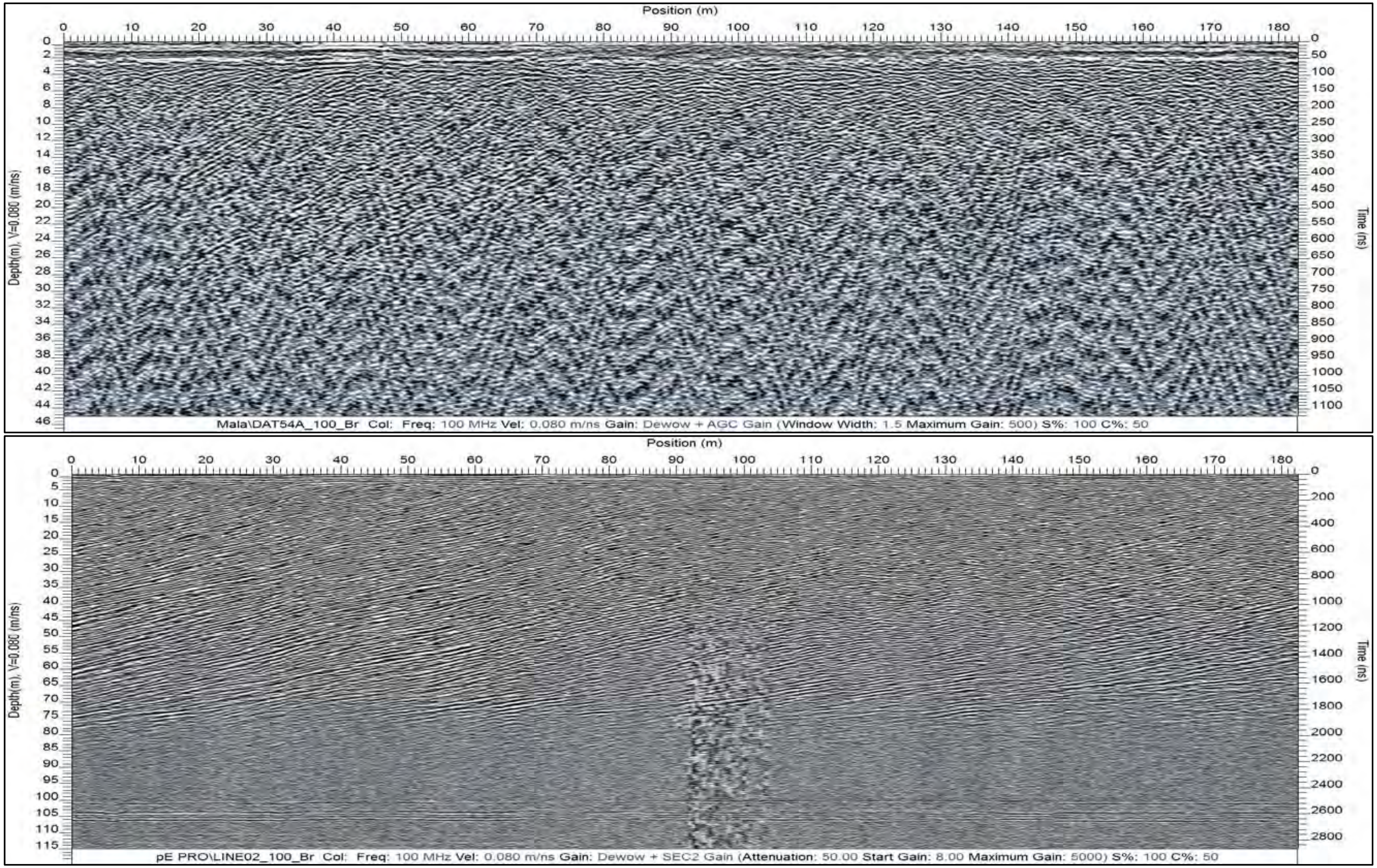

***Figure 19**: Malå Standard Unshielded (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of EKKO_project. Both profiles were conducted with 100 MHz perpendicular broadside antenna configuration.*

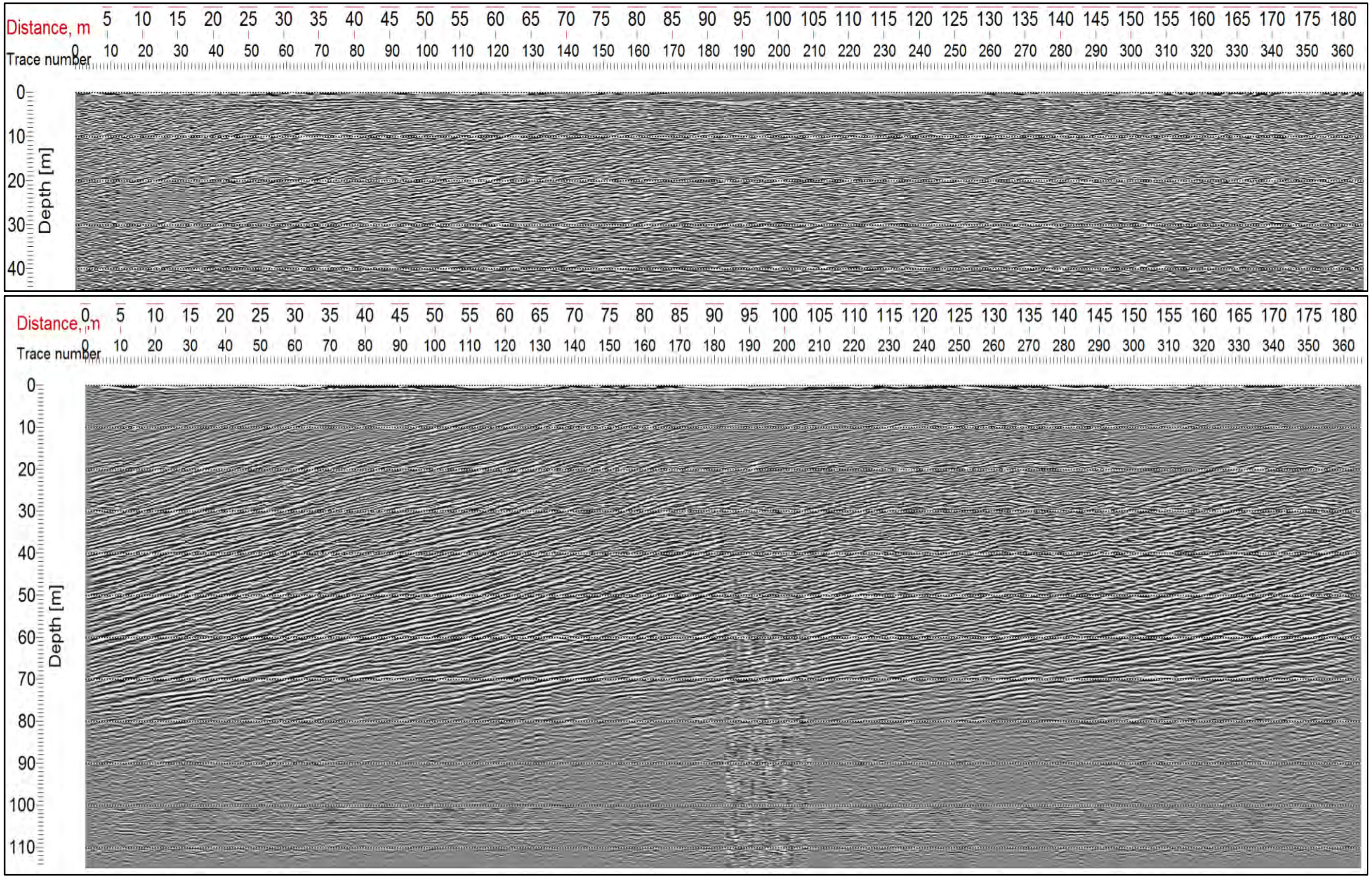

***Figure 20**: Malå Standard Unshielded (top) and PulseEKKO (bottom) Georadar results processed with routines compiled with the use of RadExplorer. Both profiles were conducted with 100 MHz perpendicular broadside antenna configuration.*

6.5 25 MHz antenna, AFS and ATA

This unique profile was measured using the Malå RTA system with the lowest frequency antenna available and parallel endfire configuration only. Since we were not able to produce equivalent data with 25 MHz S&S antennas, neither test more configurations than parallel endfire, this test profile had to be compared with other parallel endfire data which present similar quantitative characteristics and have been already described in previous sections. We will selectively compare the 25 MHz Malå data against the 50 and 100 MHz S&S profiles for parallel endfire configuration.

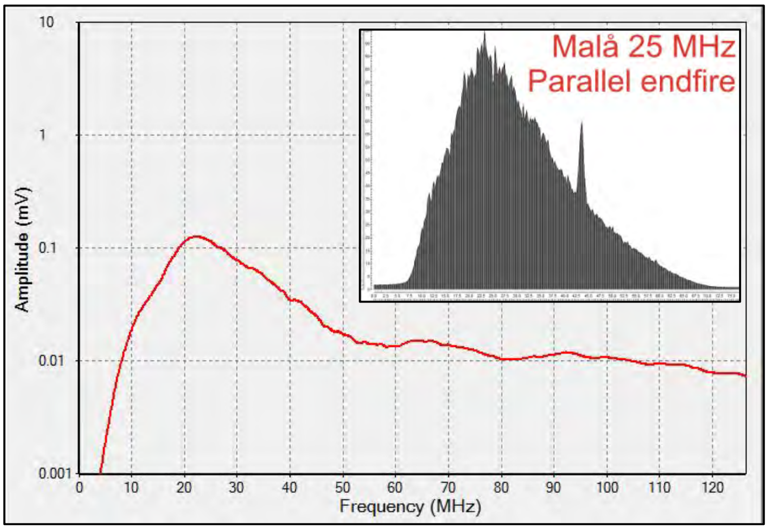

***Figure 21**: Average Frequency Spectrum (AFS) plot of the radagram measured with Malå RTA system using the 25 MHz antenna on parallel endfire configuration as extracted from both EKKO_project (main) and RadExplorer (window).*

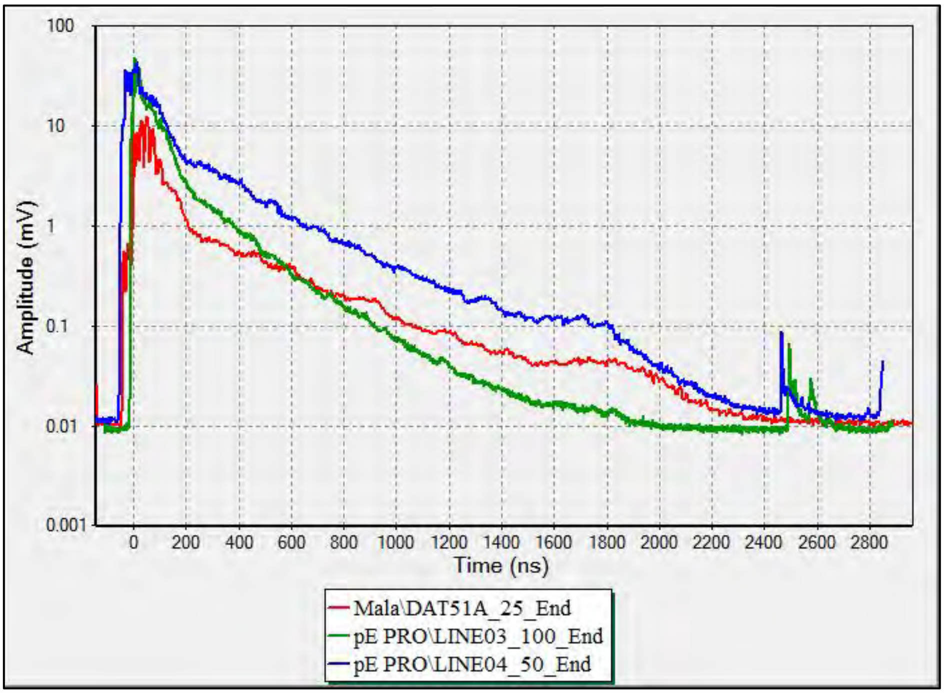

***Figure 22**: Average Trace Amplitude (ATA) plot for the profiles measured with 25 MHz for Malå and 50 and 100 MHz antennas for S&S. All data have been measured with parallel endfire configuration.*

The AFS graph indicates that the 25 MHz antenna specification is fulfilled in our data. As can be seen in **figure 21** (for detailed arithmetic estimations check **table IV**), the central frequency is indeed located at ~25 MHz, a fact dictating that this antenna usage should theoretically yield the largest expected penetration depth but also the lowest resolution from any other radagram produced in this survey. The average trace amplitude plot is the safest way to ascertain whether this claim is satisfied in our data or not.

Figure 22 shows the signal amplitude (ATA) from three radagrams (Malå 25 MHz, S&S 50 and 100 MHz) plotted against time. Foremost, the most important conclusion we may acquire from this graph is that the signal decay time is the same for both the Malå 25 MHz and the S&S 50 MHz antenna (~2500 ns) while the S&S 100 MHz one is shorter but not by far (~2000 ns). This means that the penetration depth for the Malå 25 MHz antenna does not exceed the value obtained by using the S&S 50 MHz one and that it's not as larger than the S&S 100 MHz result as it should. The signal amplitude on the other hand, decays towards the background noise level from a lower value than both the S&S antennas.

6.6 Profile images based on 25 MHz antennas

Figure 23 presents the processed profile images obtained by EKKO_project and RadExplorer. The processing routines are the same as presented above for the other frequencies: in EKKO_project we applied editing of first break (140 ns), standard dewowing and application of SEC2 gain function (Attenuation = 50 dB/m, Start Gain = 8, Maximum Gain = 5000) while in RadExplorer we applied DC removal, Background removal, Time zero adjustment (140 ns), AGC gain function (operator length 20 ns) and a simple bandpass filter (5-15-35-75). The results show a penetration depth of ~100 m, a value directly connected with the signal amplitude decay time (~2500 ns). This depth is the equal to the one we obtained by using the PulseEKKO Georadar with a 50 MHz antenna indicating that the S&S equipment has performed better in terms of depth penetration. Resolution for higher frequency antennas is better by default. Still, the RTA system's convenience and maneuverability in rugged terrains is valuable and cannot be matched by the bulky PulseEKKO system.

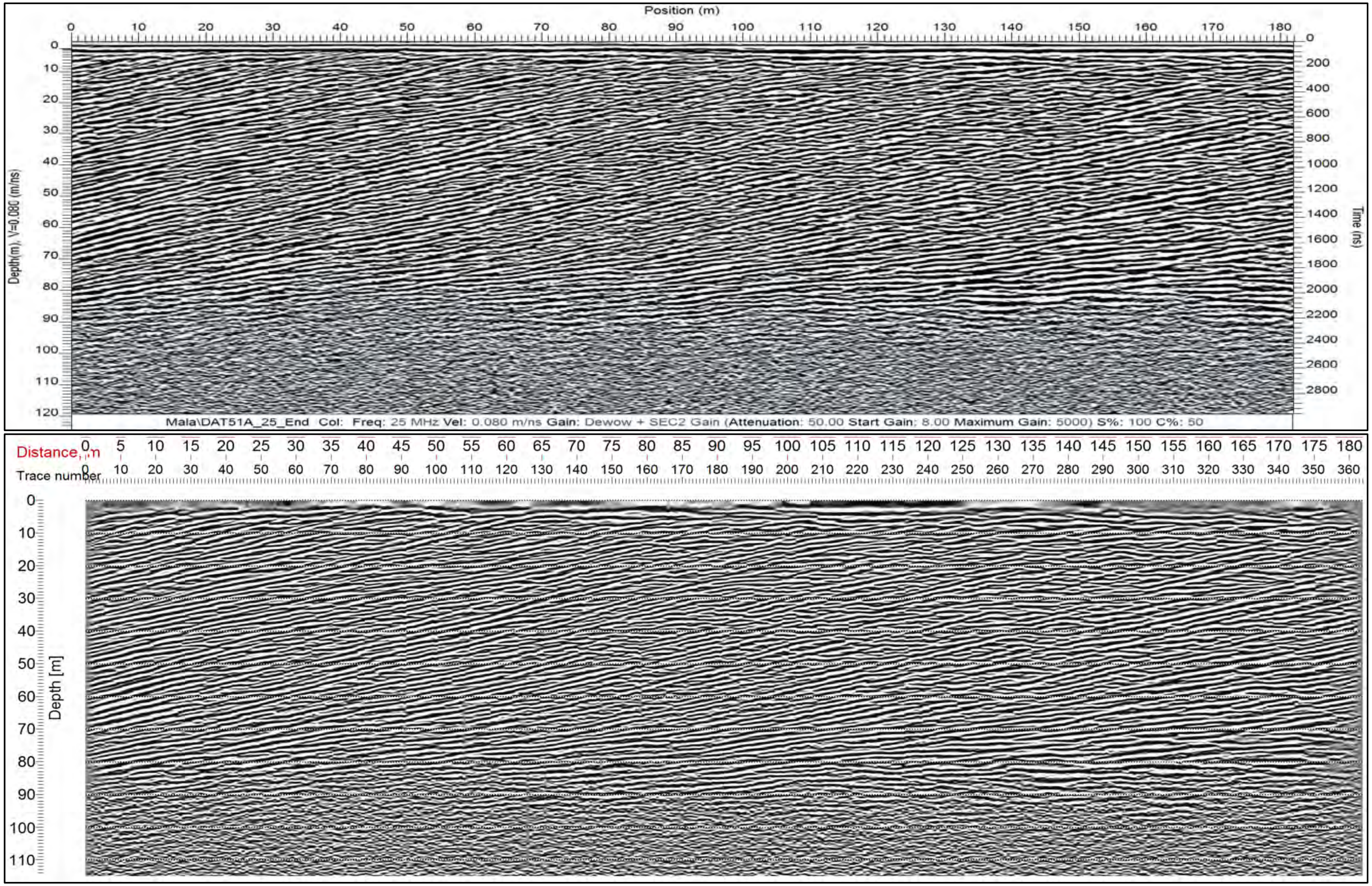

Figure 23: *Malå RTA Georadar results processed with routines compiled with the use of EKKO_project (top) and RadExplorer (bottom). Profile was conducted with 25 MHz parallel endfire antenna configuration.*

6.7 200 MHz antenna, AFS and ATA

This profile conducted with PulseEKKO Pro is also unique since its settings have not been duplicated or tested with a Malå system. These settings incorporated a 200 MHz antenna with perpendicular broadside configuration. Theoretically, the resulting image should be characterized by the highest resolution among all radagrams as well as the lowest penetration depth. However, **figure 24** displays an interesting discrepancy between the specified antenna frequency and the one the instrument actually functioned (for detailed arithmetic estimations check **table IV**). The frequency content is widespread with a notable clustering around 100 MHz (central frequency ~115 MHz) and a smaller one around 300 MHz. Essentially, this means that the system has operated on a dominating frequency (if one may be chosen as shown in **figure 24**) which renders this profile more suitably comparable to the one obtained by the 100 MHz S&S antenna using the same configuration.

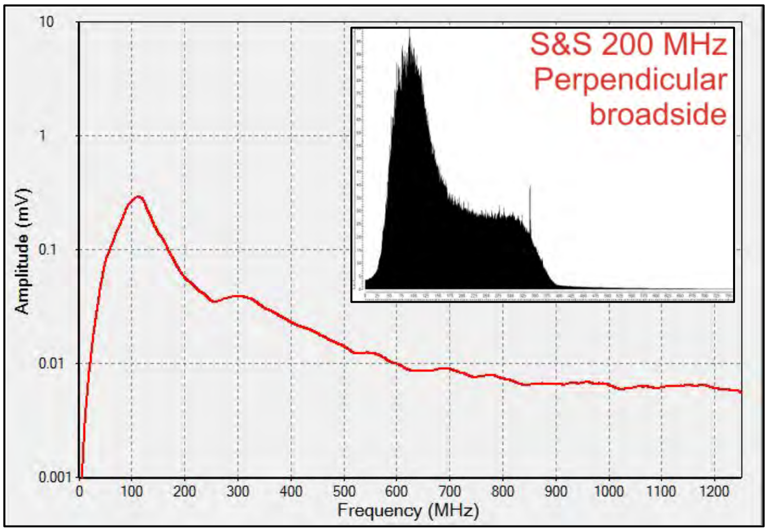

***Figure 24**: Average frequency spectrum of the radagram measured with PulseEKKO system using the 200 MHz antenna on perpendicular broadside configuration as extracted from both EKKO_project (main) and RadExplorer (window).*

Figure 25 displays the Average Trace Amplitude (ATA) plot for three profile repetitions, two done with PulseEKKO Pro using perpendicular broadside configuration and one with Malå RTA using parallel endfire setting. The red line indicates the graph for 100 MHz using Malå equipment and the green and blue lines the graphs for 100 and 200 MHz antennas using PulseEKKO Pro. The signal's amplitude for the 200 MHz antenna appears to be decaying faster than both the 100 MHz antennas but the two latter profiles present similar behavior. The PulseEKKO 200 MHz signal reaches background noise level after ~1000 ns while the Malå 100 MHz reaches noise after ~800 ns regardless of configuration. Therefore, the signal amplitude for 200 MHz S&S perpendicular broadside follows a similar pattern to the signal of 100 MHz Malå parallel endfire data. However, Pulse EKKO Pro have a better penetration due to lower noise level.

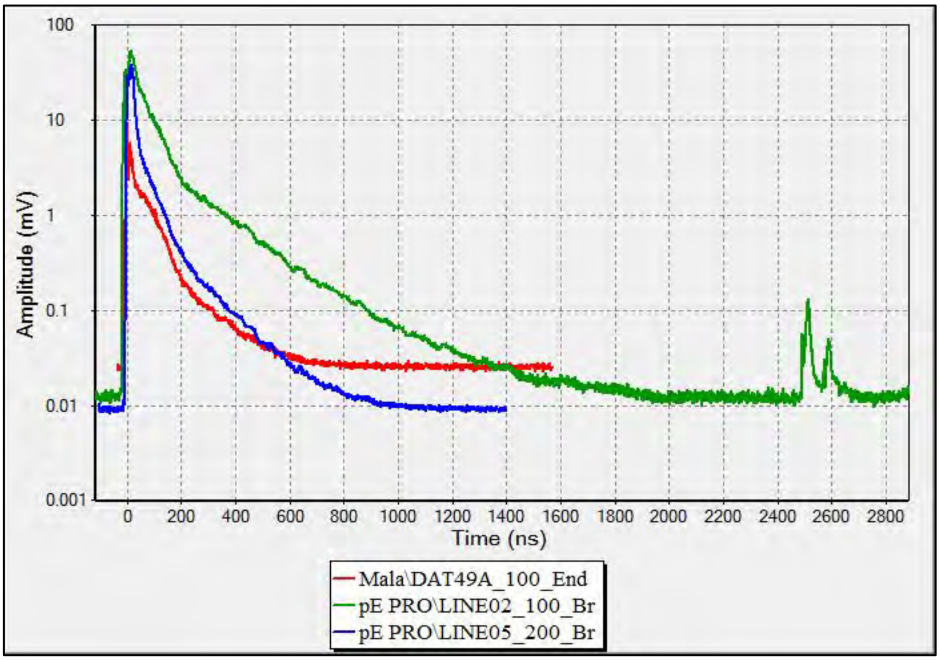

Figure 25*: Average Trace Amplitude (ATA) plot for the profiles measured with 100 and 200 MHz S&S antennas. All data have been measured with perpendicular broadside configuration.*

Processing of data was kept constant as in the previous section, except for the Time zero adjustment/Edit first break option which was set equal to 102.4 ns and the filtering in RadExplorer which was adjusted to fit the 200 MHz antenna frequency (15-120-300-400).

6.8 Profile images based on 200 MHz antennas

Figure 26 shows the images which resulted from both utilized processing programs. First of all it is interesting to note that the penetration depth is probably more than 56 meters which is the maximum registration depth allowed by the chosen time window (1500 ns). There is a shift in resolution at about 40 m (1000 ns) where according to the ATA plot is where the signal reaches the noise level but several strong reflectors are detectable beneath that point. Some of these reflectors are obviously intersected at the bottom of the images which means that a higher time window was more appropriate in this case. Resolution is quite high on the first 35 m revealing many possible boulder positions as in the case of 100 MHz antennas. However, as we have already seen the frequency under which the georadar is functioning is questionable. Although the mean frequency is about 200 MHz, the peak energy is closer to 100 MHz which does not fully correspond to the antenna specifications.

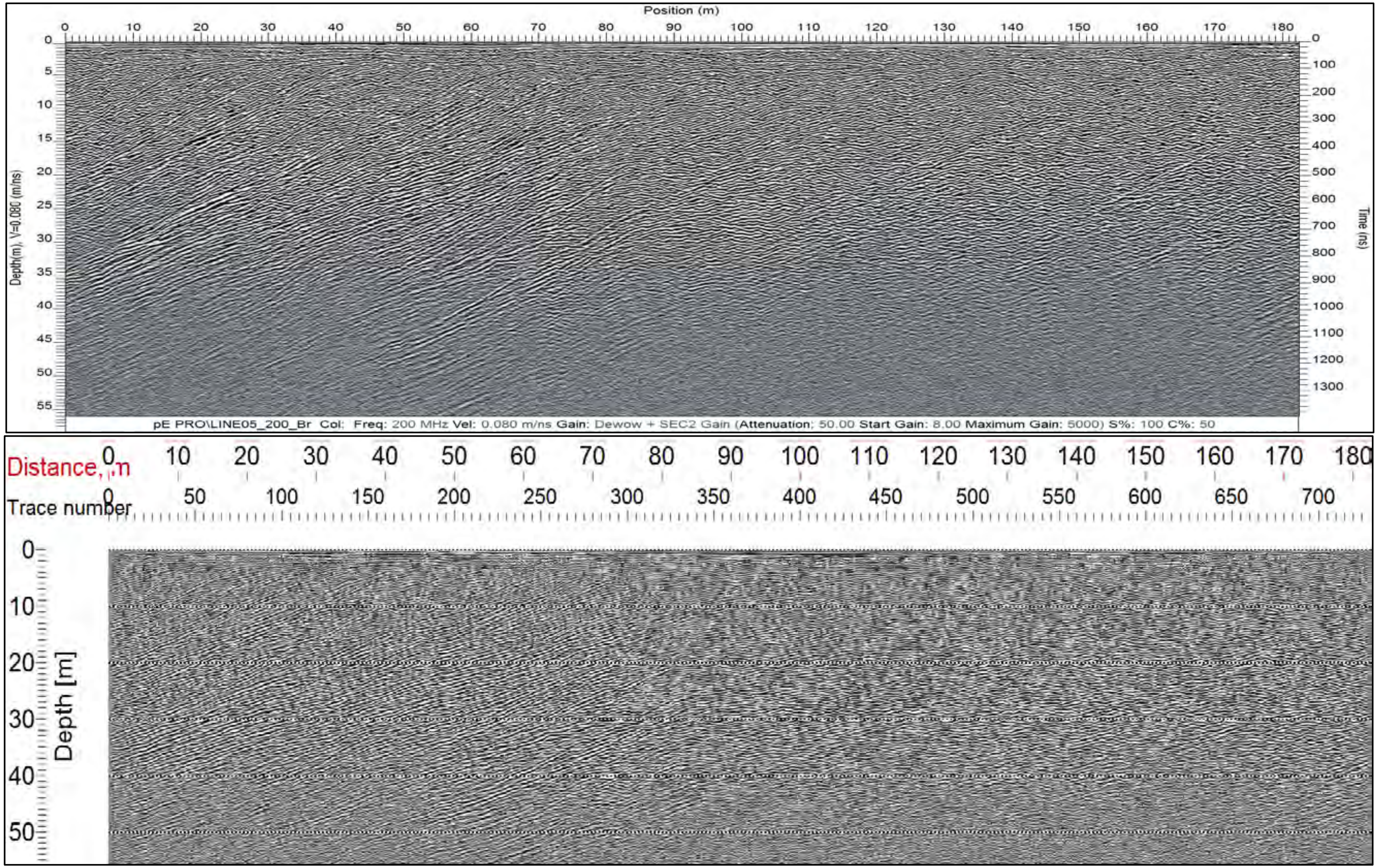

***Figure 26**: PulseEKKO Georadar results processed with routines compiled with the use of EKKO_project (top) and RadExplorer (bottom). Profile was conducted with 200 MHz perpendicular broadside antenna configuration.*

7. CONCLUSIONS

In this study we have systematically compared the performances of GPR systems manufactured by Sensors & Software and Malå Geoscience, respectively. Main conclusions are summarized in **Table III**.

	Malå Geoscience	**Sensors & Software**
Average Frequency Spectrum analysis	Actual and specified frequencies are almost equal	Functioning on lower frequencies than specified
Average Trace Amplitude plot	Lesser quality a. Lower signal and higher noise levels b. Heavily dependent of antenna configuration (perp. broadside is worse)	Better quality a. Higher signal and lower noise levels b. Independent of antenna configuration
Penetration depth (for the same frequencies)	Less penetration	Better penetration
Resolution	Resolution deteriorates with depth but is higher for perp. broadside and superficial layers	Resolution is uniform until noise levels
Processing software (designated software should be used for each dataset)	RadExplorer is easier, faster and more straight forward	EKKO_project requires better knowledge of the method but also offers more processing options and tools
Overall	Snake antenna suitable on rough terrains	Better overall performance and data quality but less suitable in rough terrains

Table III: *Main conclusion summary.*

Considering that Georadar surveys depend on both the instrument and antenna specifications as well as the properties of the ground, we have performed repeated GPR profiling along a single transect at Bøaøyna, Stryn Municipality using a variety of different antennas and configurations. In order for the whole procedure to be systematic, profiles of similar configurations and processing were compared. Therefore, the available data were categorized by antenna frequency and configuration used and were subjected to identical processing routines in two programs, EKKO_project and RadExplorer. For the qualitative and quantitative evaluation of the results we have used the processed images but also additional tools were used such as Average Frequency Spectrum analysis and Average Trace Amplitude plot.

Primarily, the **Average Frequency Spectrum (AFS) analysis** revealed that the Malå antenna's actual frequencies are close to the manufacturer's specifications. Sensors & Software on the other hand, exhibit discrepancies between the central (peak) frequencies employed and the specified one. These actual frequencies vary according to the specified antenna frequency but are always lower. In the case of 200 MHz, for instance, there is a relatively big discrepancy between the antenna specification and the peak frequency used. The central frequency however, is not far from the specified 200 MHz. This strongly affects both the penetration depth and resolution achieved and in some cases renders the comparison between datasets inappropriate. Working on slightly lower frequencies than the central frequency can partly explain better why penetration depth is larger for Sensors & Software equipment compared to identically specified antenna frequencies by Malå. **Table IV** contains a rough central (peak) frequency estimation for all systems and configurations as well as the respective bandwidth as extracted from the respective AFS plots shown in **figures 9**, **15**, **21** and **24**.

System	Configuration	Specified frequency (MHz)	Central (Peak) frequency (MHz)	Bandwidth (MHz)
Malå	PE	50	~40	~25
Malå	PB	50	~47	~78
S&S	PE	50	~35	~28
S&S	PB	50	~34	~63
Malå	PE	100	~80	~68
Malå	PB	100	unsure	unsure
S&S	PE	100	~65	~63
S&S	PB	100	~73	~52
Malå	PE	25	~22	~18
S&S	PB	200	~115	~74

Table IV: *Specified and observed (central) frequency and bandwidth for all systems and configurations employed (PE = Parallel Endfire, PB = Parallel Broadside configuration).*

Using the **Average Trace Amplitude (ATA) plot** we were able to discern the signal quality (see Table V). In all cases, the signal from PulseEKKO is of better quality (higher signal and partly lower noise level) and is almost independent of antenna configuration. Both parallel endfire and perpendicular broadside configurations produce a strong signal which decays relatively slowly to a low background noise level compared to its maximum amplitude. The signal from Malå equipment on the other hand is heavily dependent on antenna type. Parallel endfire RTA is characterized by low noise level but also weaker signal when compared to perpendicular broadside unshielded where a stronger signal is accompanied by higher noise levels. There are reasons to believe that Malå unshielded antennas were not working properly. Due to lower signal to noise level, the Malå antenna signal reaches background noise level faster compared to the one produced by PulseEKKO, which leads to a smaller depth penetration.

The **penetration depth** is of course dependent on the antenna frequency. All processed data indicate that PulseEKKO antennas reach deeper compared to their Malå counterparts (see Table V). This could be due to the fact that regardless of the specified antenna frequency, Sensors & Software equipment is functioning slightly on lower frequencies than Malå. However, Sensors & Software antennas still perform better after comparing their actual frequencies against the Malå antennas of equal functioning characteristics. PulseEKKO profiles reach deeper and in most cases with better resolution than the Malå ones. For an environment consisting of fluviodeltaic sediments with a propagation velocity of 0.08 m/ns the S&S depth penetration is ~100 m for 50 MHz and ~85 m for 100 MHz while for Malå these depths are 80 and 35 m respectively. Moreover, the RTA system by Malå employing the 25 MHz antenna has a penetration depth which is equal to the one obtained by using PulseEKKO with the 50 MHz antenna while the 200 MHz perpendicular broadside configuration for S&S performs slightly better than the 100 MHz parallel endfire Malå setting.

System	Frequency (MHz)	Configuration	Noise level (mV)	Penetration (ns)
S & S	50	PB	0,01	2500
S & S	50	PE	0,01	2500
S & S	100	PB	0,01	1900
S & S	100	PE	0,01	1900
S & S	200	PB	0,01	900
Malå RTA	25	PE	0,01	2400
Malå RTA	50	PE	0,006?	2000
Malå RTA	100	PE	0,04	800
Malå unshield	50	PB	0,8	1000
Malå unshield	100	PB	0,8	400

Table V: *Noise level and and penetration dept (depth where noise level is reached) (PE = Parallel Endfire, PB = Parallel Broadside configuration).*

The resulting **resolution** is dependent on the signal quality. S&S equipment retains an equally good resolution throughout its penetration depth while the profiles conducted with Malå equipment present a resolution which deteriorates with depth. As already described, penetration depth for PulseEKKO is not dependent on configuration however, perpendicular broadside appears to have slightly higher resolution yielding reflectors which in cases are clearer and more pronounced. Moreover, profiles measured with PulseEKKO are more easily and effectively processed in EKKO_project than Malå data in RadExplorer. Unfortunately, some problem in the connections or some power malfunction araised when perpendicular broadside configuration, unshielded Malå antennas were utilized. This prevents us from further commenting on the issue.

Preference over **processing software** should be given accordingly to the user's background. RadExplorer is a software which enables users to handle GPR data in an easy automated way. Therefore, this software is more suitable to either users without any prior GPR processing background or experts who wish to obtain results fast. EKKO_project on the other hand is more sophisticated and requires a higher understanding of the theoretical background of the method. Its processing routines are more detailed and powerful and allow room for modification of several parameters which lead to more intricate solutions. As is expected, pulseEKKO Pro data are better handled by EKKO_project. Furthermore, Malå data also benefit from more sophisticated processing but ReflexW is required in order to convert the RadExplorer data format into a readable one for the EKKO_project software.

In summary, we can say that the Sensors & Software Pulse EKKO Pro gives a better performance because the system works at lower frequencies than stated. In addtion, it has a lower noise level and probably higher transmitted energy. It should be noted that regardless of the slightly inferior performance by the Malå radar, the snake (RTA) system has yielded satisfying results. Essentially this means that rough terrain can be surveyed satisfactorily with this particular system. In contrast the PulseEKKO system is bulky and less applicable in rugged areas. Wherever possible though, the Pulse EKKO Pro system should be preferred.

8. AKNOWLEDGEMENTS

The data measured with Malå georadar with RTA antennas from Eikesdal (Figure 1) were provided by Isabelle Lecompte from NORSAR / University of Oslo.

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