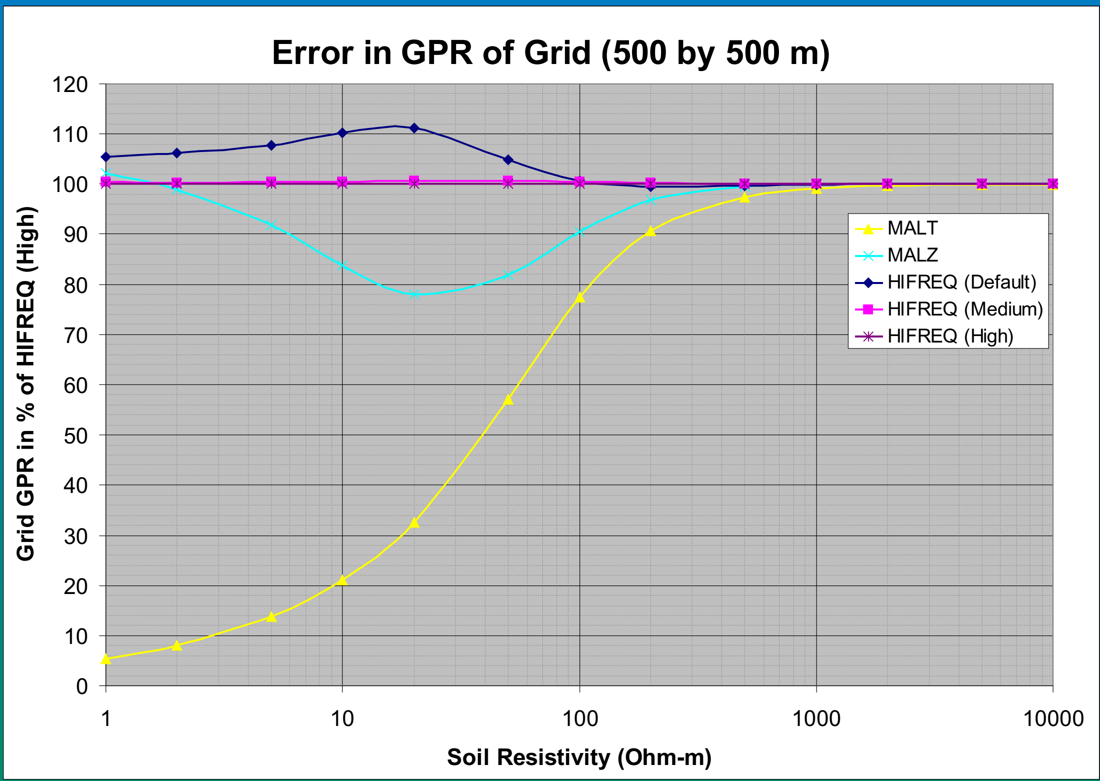
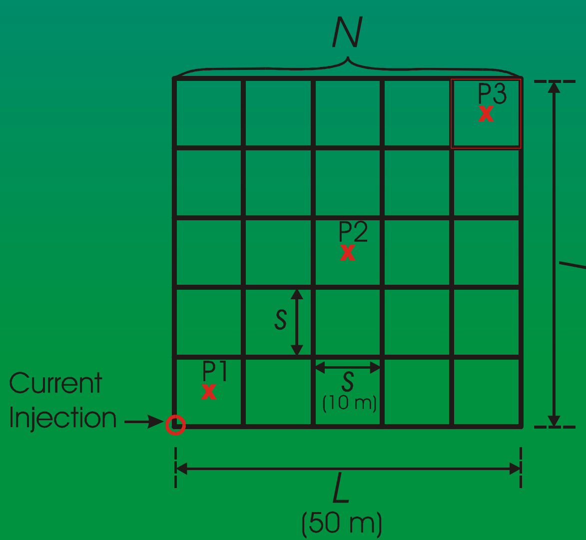
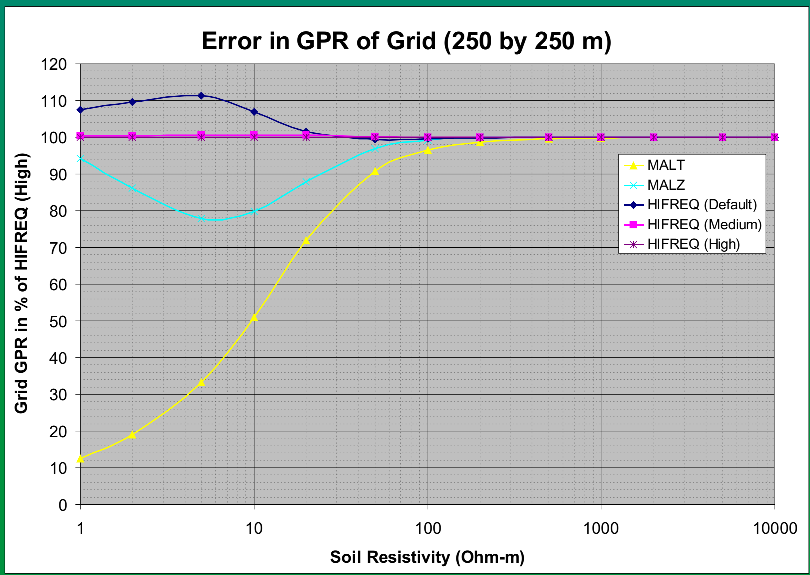
Comparisons of Low-Frequency and High-Frequency Grounding Software Package Capabilities







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Comparisons of Low-Frequency and High-Frequency Grounding Software Package Capabilities

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1 Introduction

The range of applications that can be handled by the low frequency grounding analysis software packages (such as Autogrid Pro, AutoGround, MultiGround and AutoGridDesign) that use the MALT computation program module and the other software packages that support higher frequencies (such as MultiGroundZ or MultiFields) that use the MALZ or HIFREQ computation program modules overlap: they can all be used to compute the touch and step voltages around a grounding grid buried in a uniform or arbitrary soil structures (MALT and MALZ can handle multilayered or arbitrary soil structures, as we all know) as well as the GPR and impedance of the grid.

This raises the following questions:

1. **What are the comparative advantages of each program?**
2. **Which program should be used to model any given problem accurately?**

This article discusses those questions both qualitatively and quantitatively, using buried grids of various sizes as an example. Section 2 describes the assumptions and limitations of the various programs in general terms. Section 3 then describes the physical system that was studied to compare the three programs quantitatively. Finally, Section 4 presents some numerical results.

2 General Considerations

2.1 Basic Assumptions

The MALT, MALZ, and HIFREQ programs are based on different physical assumptions, which determine their range of validity.

The fundamental assumption made in the MALT program is that all conductors belonging to a given electrode are at the same potential. This means that the conductors modelled in MALT are assumed to be lossless. In general, there can be several electrodes held at different potential (we will use only a single electrode in this article). Also, the electric potential is assumed to obey Coulomb's Law perfectly, i.e. the potential varies as 1/r when moving away from the source.

The MALZ program removes the first of these assumptions. It accounts for the potential drop along conductors due to their self-impedance. However, MALZ does not take the mutual inductance of conductors into account. Also, just as MALT does, it assumes that Coulomb's Law holds.

HIFREQ eliminates all of the assumptions mentioned above for MALT and MALZ. It accounts for the self-impedance of conductors, and for their mutual impedances. It accounts for attenuation and phase-shift effects in the electric potential when moving away from the current source. Moreover, HIFREQ is the only program that allows the presence of overhead conductors.

2.2 Advantages of Each Program

The previous discussion would seem to indicate that HIFREQ is the program of choice to model anything, since it does not suffer from the limitations inherent to MALT and MALZ. This is not the case, however. First, HIFREQ is currently restricted to uniform and two-layer soil models, while MALT and MALZ both can handle several useful soil models. Furthermore, the programs differ markedly with respect to ease of use, speed, and memory consumption.

Table 2-1 compares the three programs with respect to those categories. The advantage given to MALT from the point of view of ease of use comes from the assumption that conductors are lossless. In this case, the current flowing into the conductors (as opposed to leaking out of the conductors) is irrelevant, since it does not contribute to the potential of the electrode. Therefore, it is unnecessary to specify the conductors in such a way as to guarantee normal current flow between them. In other words, it is unnecessary to connect the conductors properly at network nodes. While we are constantly trying to improve this aspect of the programs, experienced MALZ and HIFREQ users know a substantial part of the data specification process can be spent verifying the integrity of the connections in the network.

Also, MALT boasts other time saving features, such as its Fall-Of-Potential simulation module. It is possible to simulate a Fall-Of-Potential measurement using MALZ and HIFREQ, but as a rule, setting up the model and analyzing the results is more time-consuming with those programs.

Table 2-1: Comparison of Ease of Use, Memory Use and Speed for MALT, MALZ, and HIFREQ.

Program	Ease of Use	Memory Use for N Segments (MB)	Run-Time (as Multiple of MALT)
MALT	Higher	$4*(N/1000)^2 + 10$	1
MALZ	Lower	$16*(N/1000)^2 + 10$	1.5-2
HIFREQ	Lower	$24*(N/1000)^2 + 5$	150-200

The difference in memory use between MALT and MALZ is due to the use of complex, double precision numbers in MALZ (MALT uses single precision, real numbers). The complex numbers are required for MALZ to account for the self impedances of conductors. The difference in memory use between MALZ and HIFREQ reflects the different techniques used by those programs to compute the distribution of the current in the conductors.

This difference can be quite important. For 5000 segments, for example, MALT requires only 110 MB, which is normally not a problem on a modern workstation. MALZ, on the other hand requires about 400 MB, and HIFREQ 600 MB. When the required memory is not available on the system, the program can slow down tremendously.

The main impediment to the use of HIFREQ is its larger run-time. Keep in mind that the values quoted in the table apply only when there is sufficient memory available; when memory is in short supply, the run-time can be even larger.

2.3 Limitations of MALT

As mentioned above, the main simplifying assumption made in program MALT is that the grid conductors are taken to be lossless. For this approximation to be valid in practice the self-impedance of the conductor should be much smaller than its leakage impedance; if this condition is not met, most of the current would leak out close to the injection point rather than traveling down the conductor, resulting in a shorter effective length for the conductor and a larger GPR.

Therefore, we would expect the GPR computed with MALT to be smaller than that computed with HIFREQ or MALZ. The point at which the values computed with MALT and MALZ start to diverge should correspond roughly to a conductor length for which the self-impedance has about the same value as the leakage impedance.

As a rule, the leakage impedance is proportional to the soil resistivity and inversely proportional to the conductor length.

$$Z_{Leak} \propto \rho / L$$

When the internal impedance of the conductor can be neglected when compared to its external self-impedance (a good approximation for copper at 60 Hz), the self-impedance of the conductor can be approximated by its self-inductance, which is proportional to the length of the conductor and to the frequency.

$$Z_{Self} \propto Lf$$

The condition $Z_{Self} << Z_{Leak}$ gives $L << A\sqrt{\rho / f}$, where A is some unknown constant. A more careful analysis shows that the constant is 3160, i.e.

$$L << 3160\sqrt{\rho / f} \text{ (in meters)}$$

In this last inequality, the right hand side represents the wavelength of propagation in the soil. It may seem strange to have an expression involving the propagation wavelength play any significant role at 60 Hz. Nevertheless, evaluation of the above expression for a resistivity of 4 Ohm-m (admittedly, a pretty low value) and a frequency of 60 Hz gives a limit length of about 750 meters, which is a dimension that can be encountered in practice.

2.4 Limitations of MALZ

The limitations of MALZ are more subtle and are mainly due the fact that MALZ does not take mutual induction effects between conductors into account. As a rule, this tends to underestimate somewhat the longitudinal impedance of the grid. The effect is most striking when the connections between two grids are very sparse, and consist of long, parallel conductors.

This limitation will not be investigated explicitly in this article.

3 System Modelled in Comparisons

3.1 Grounding Grid and Observation Points

Grounding grids of several different sizes were modelled to investigate the effect of grid size on the accuracy of the computations with the three programs. All grounding grids are square grids with equal size meshes, buried at 0.5 m.

For practical reasons, it was impossible to maintain a fixed mesh size for all different grid sizes: this would have generated too many conductor segments for the larger grids. Therefore, the size of the grids and the number of meshes were varied simultaneously, as per Table 3-1. As a result, the larger grids are not simply scaled-up versions of the smaller grids. This should be kept in mind when examining the computation results in the next section.

Table 3-1: Size and Number of Meshes of Modeled Grids.

Size *L* (Side of the square) – m	Number of Conductors *N* per Side	Mesh Size *s* (m)
50	6	10
100	11	10
150	16	10
250	21	12.5
350	21	17.5
500	21	25

Figure 3-1 shows the first grid in the table (the 50 m grid). For the MALZ and HIFREQ cases, a short segment was added at the bottom-left corner of the grid to act as energization segment. This segment is vertical, and goes from Z = 0.1 to Z = 0.5. It is identified as a small circle in the bottom-left part of the grid in the figure. The location of this segment was chosen to maximize the expected difference between the three programs.

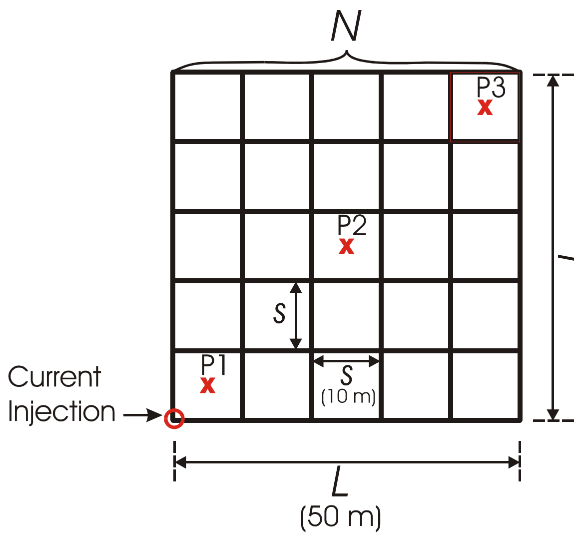

Figure 3-1: 50m Grid with 5 Meshes.

The earth potential (and touch voltages) were computed at three observation points above the grid. These points are identified with an x in the picture. All points are located in the center of a mesh, at the earth surface level. Point 1 is located above the mesh closest to the energization segment, in the bottom-left corner. Point 3 is located above the mesh in the opposite corner. Point 2 is located above the geometrical center of the grid (if the number of meshes is odd), or else above the mesh located next to the center of the grid, in the north-east direction.

All grid conductors are 4/0 copper AWG.

3.2 Soil Models

Two types of soil models were examined: a uniform soil and a two-layer soil.

For the uniform soil model, the following resistivities (in Ohm-m) were used: {1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000}.

Several configurations were studied for the two-layer soil model. The resistivity of both the top and the bottom soil layer was varied, as was the thickness of the top soil layer. The following combinations were studied.

Table 3-2: Two Layer Soil Models.

Top Layer Resistivity (Ohm-m)	Bottom Layer Resistivity (Ohm-m)	Top Layer Thickness (m)
100	1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000	1
1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000	1000	1
100	1000	1, 2, 5, 10, 20, 50
1000	100	1, 2, 5, 10, 20, 50

3.3 Energization

In all cases, the grid was energized with a 1000 Amp injection. In the MALZ and HIFREQ runs, the computation frequency was 60 Hz.

For HIFREQ, the runs were carried out using three different sets of accuracy settings, both to ascertain the validity of the approximations made when using the various accuracy settings and to compare the required run-time:

Table 3-3: Accuracy Settings for HIFREQ.

Name	Accuracy Settings
DEFAULT	**Low-Frequency Approximation**
MEDIUM	**Double-Integration Method; N = 6, M= 8**
HIGH	**Double-Integration Method; N = 32, M= 15**

4 Numerical Results

4.1 Results for Uniform Soil

Figure 4-1 shows the variation of the GPR of the various modelled grids as a function of resistivity. The calculations were carried out using HIFREQ, with the HIGH accuracy settings.

For large resistivities, the GPR is proportional to the resistivity for any grid size. Moreover, the smaller grids have a larger GPR, as expected. For low resistivities, however, the GPR is no longer proportional to the resistivity. Intriguingly, for small enough resistivities, the larger grids have a *larger* GPR.

The point at which the GPR ceases to be proportional to the resistivity varies as a function of the size of the grid: the larger the grid, the larger the resistivity for which the proportionality doesn't apply. This is consistent with the discussion of Section 0.

When the resistivity is small, the GPR curves once more become straight and parallel; the GPR is proportional to $\rho^{0.4}$. The reason behind this is being investigated.

Figure 4-2 shows the same quantity computed with MALZ. The behaviour is very similar.

With the MALT program, the GPR of a grid located in a uniform soil is always proportional to the soil resistivity, as shown in Figure 4-3. Therefore, the resistivity value in Figure 4-1 and Figure 4-2 for which the GPR curve stops being proportional to the resistivity indicates where the MALT approximations are beginning to fail.

This can be seen more clearly in Figure 4-4 to Figure 4-9, which show the grid GPR computed with MALT, MALZ and HIFREQ (for the three accuracy settings of Table 3-3) for all grids defined in Table 3-1. The GPR is plotted as a percentage of the value obtained with the HIGH accuracy settings mode of HIFREQ.

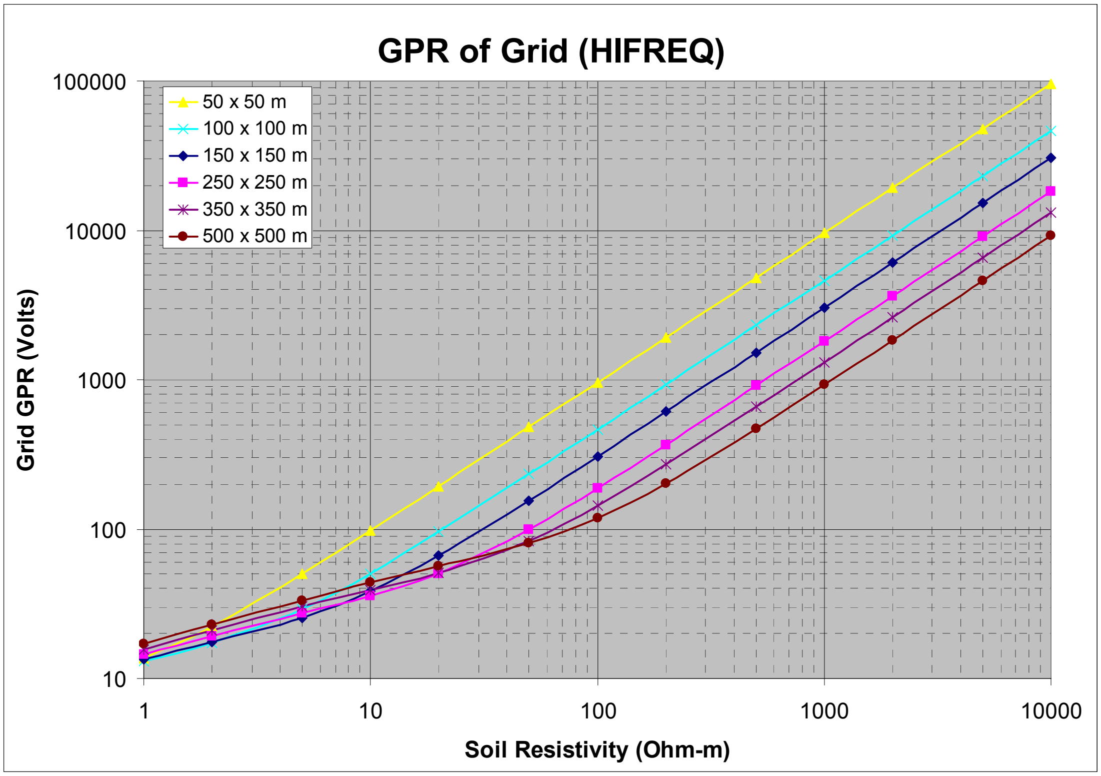

Figure 4-1: Grid GPR Computed by HIFREQ (HIGH Accuracy Settings) as a Function of Resistivity.

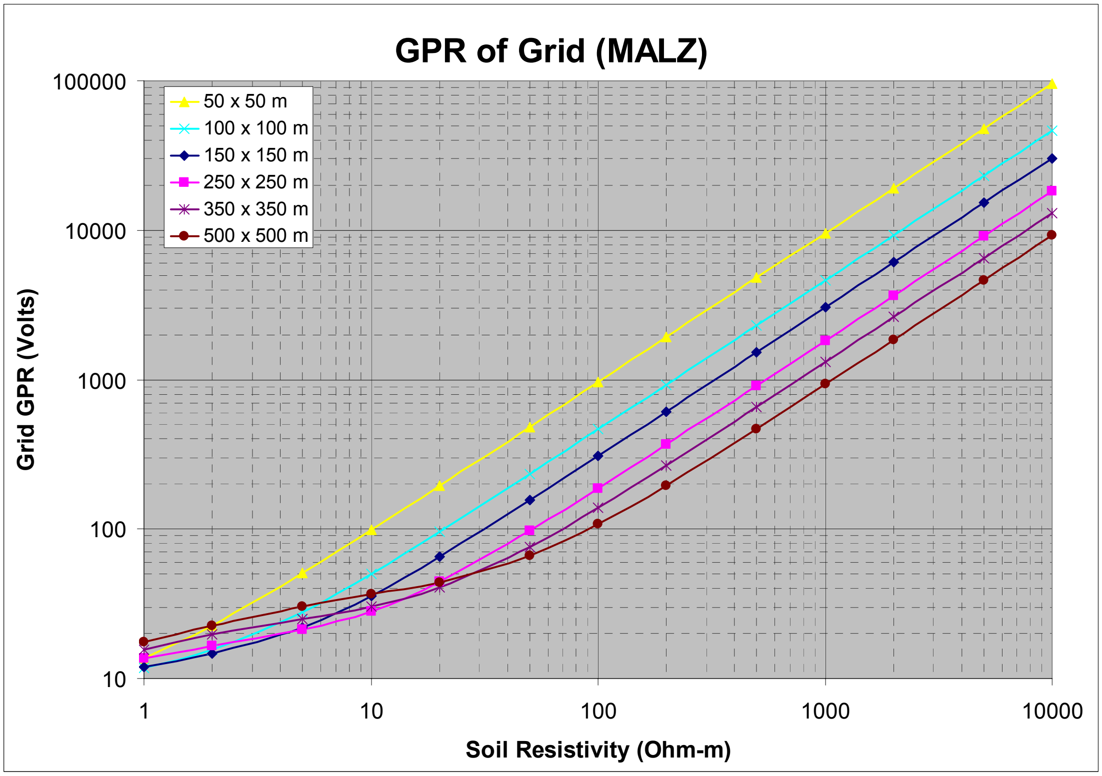

Figure 4-2: Grid GPR Computed by MALZ as a Function of Resistivity.

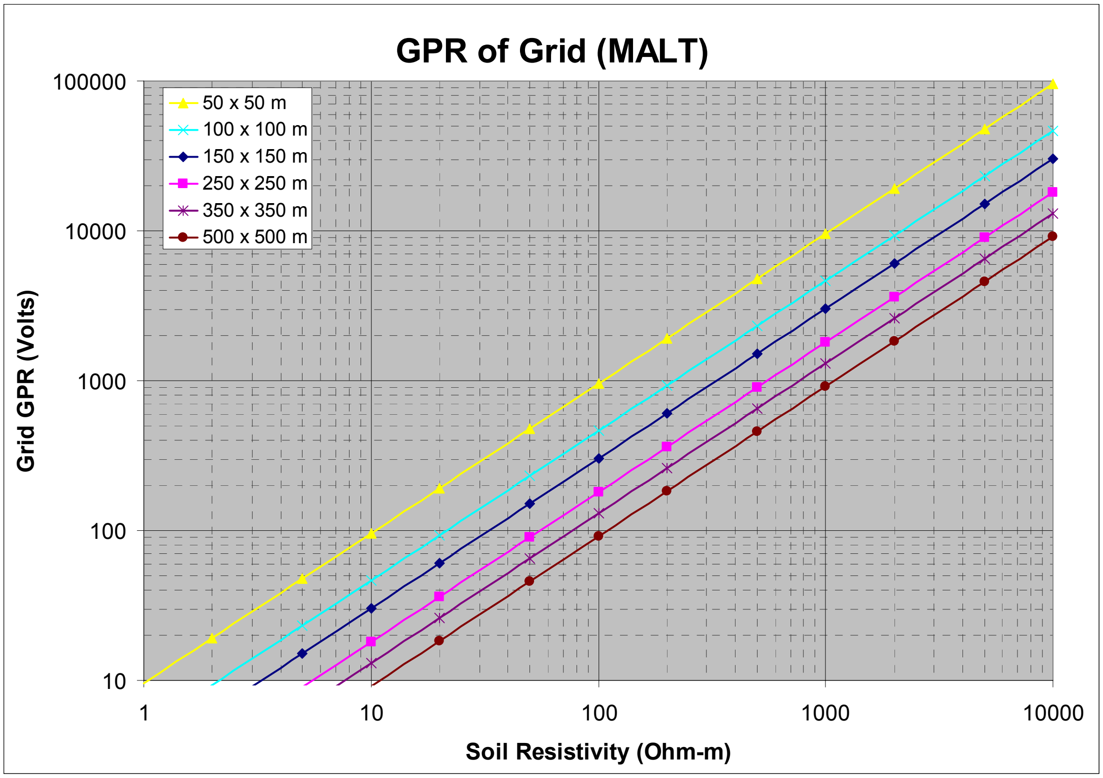

Figure 4-3: Grid GPR Computed by MALT as a Function of Resistivity.

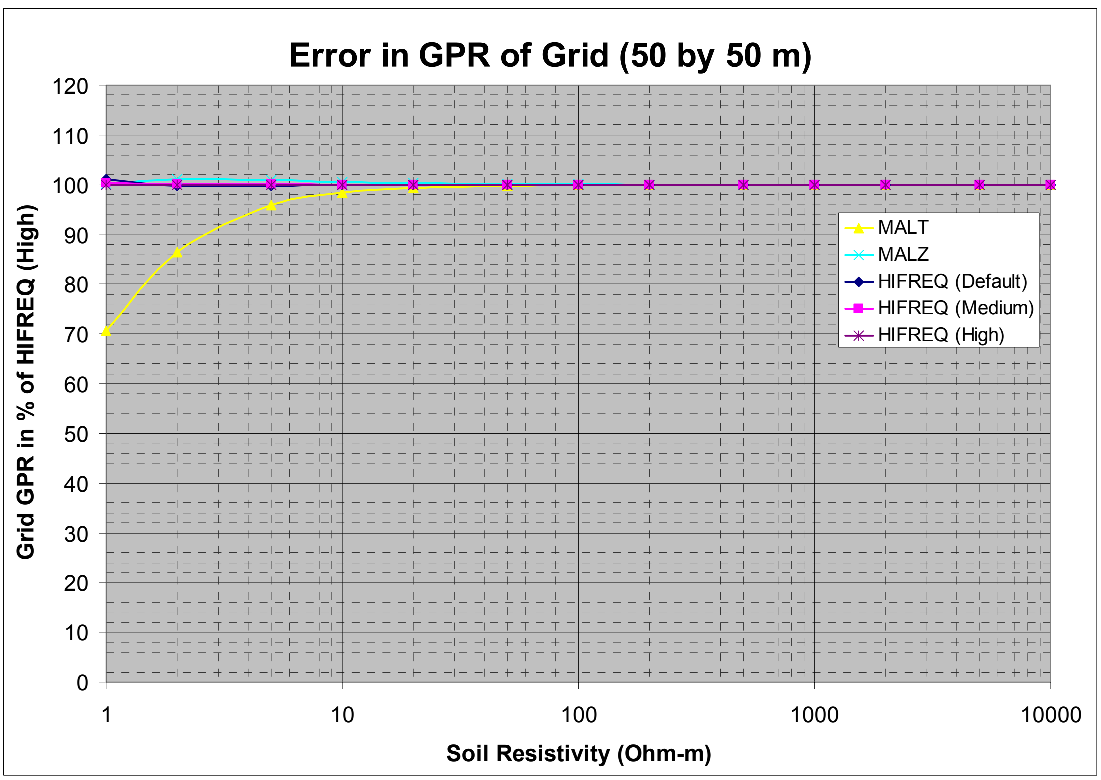

Figure 4-4: Error in GPR for 50 m Grid Compared to High Accuracy HIFREQ.

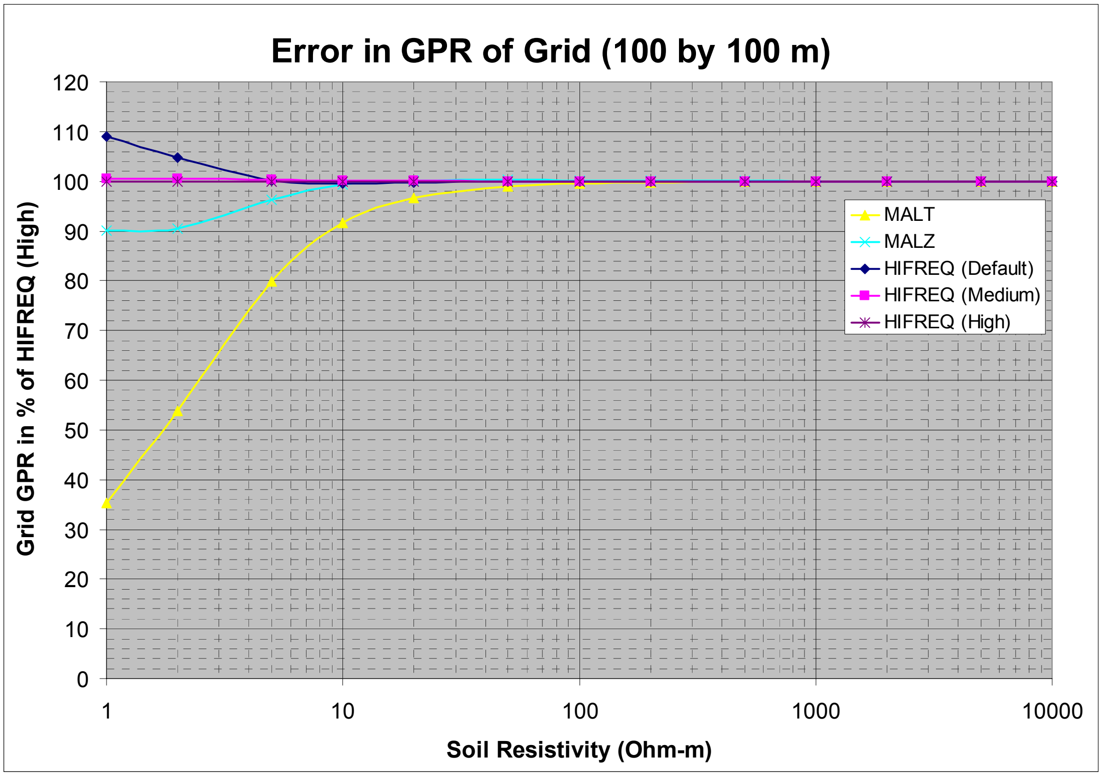

Figure 4-5: Error in GPR for 100 m Grid Compared to High Accuracy HIFREQ.

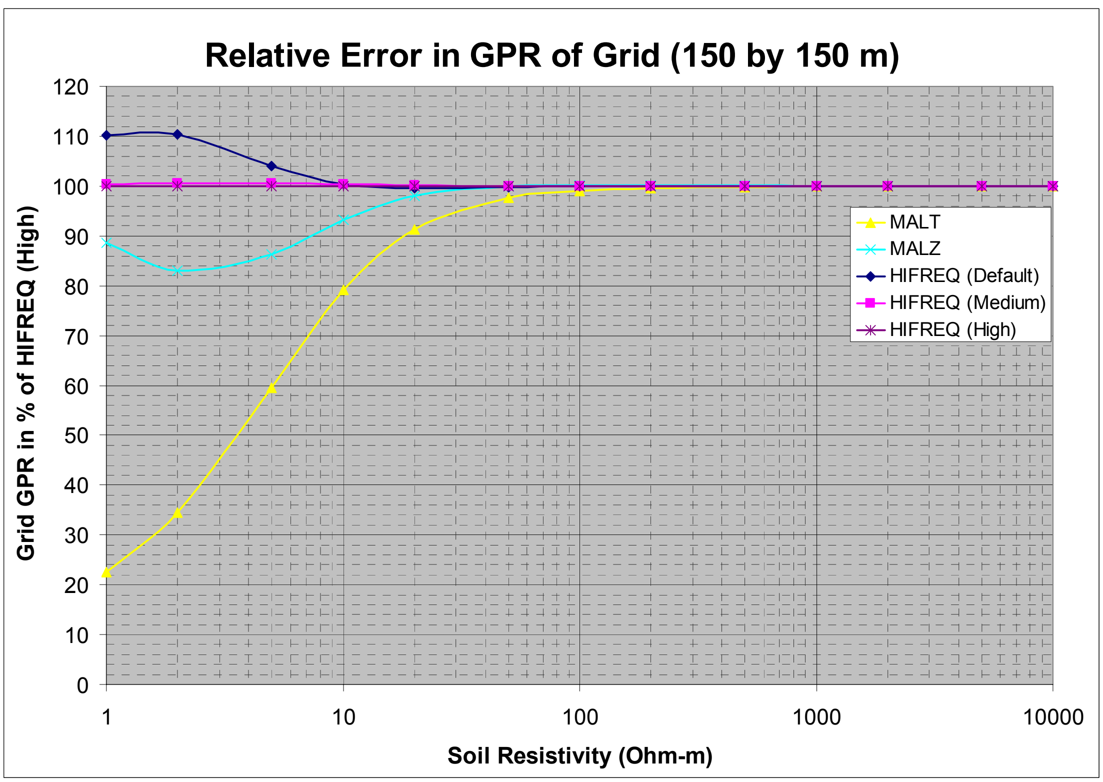

Figure 4-6: Error in GPR for 150 m Grid Compared to High Accuracy HIFREQ.

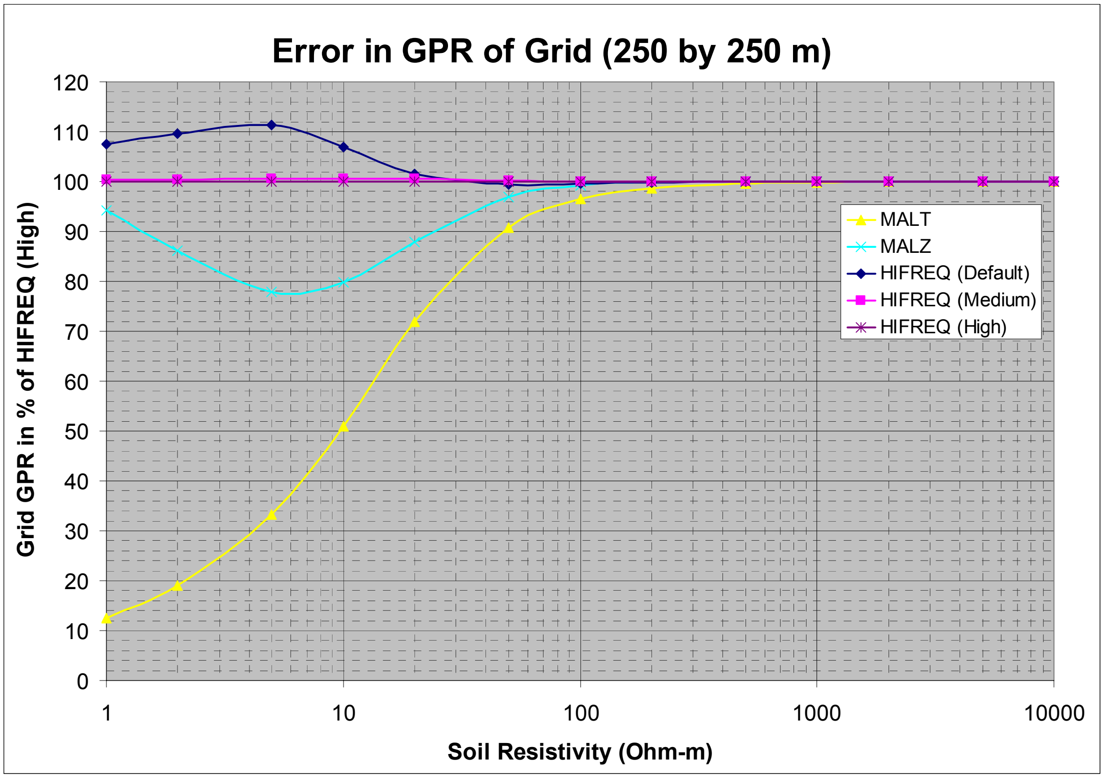

Figure 4-7: Error in GPR for 250 m Grid Compared to High Accuracy HIFREQ.

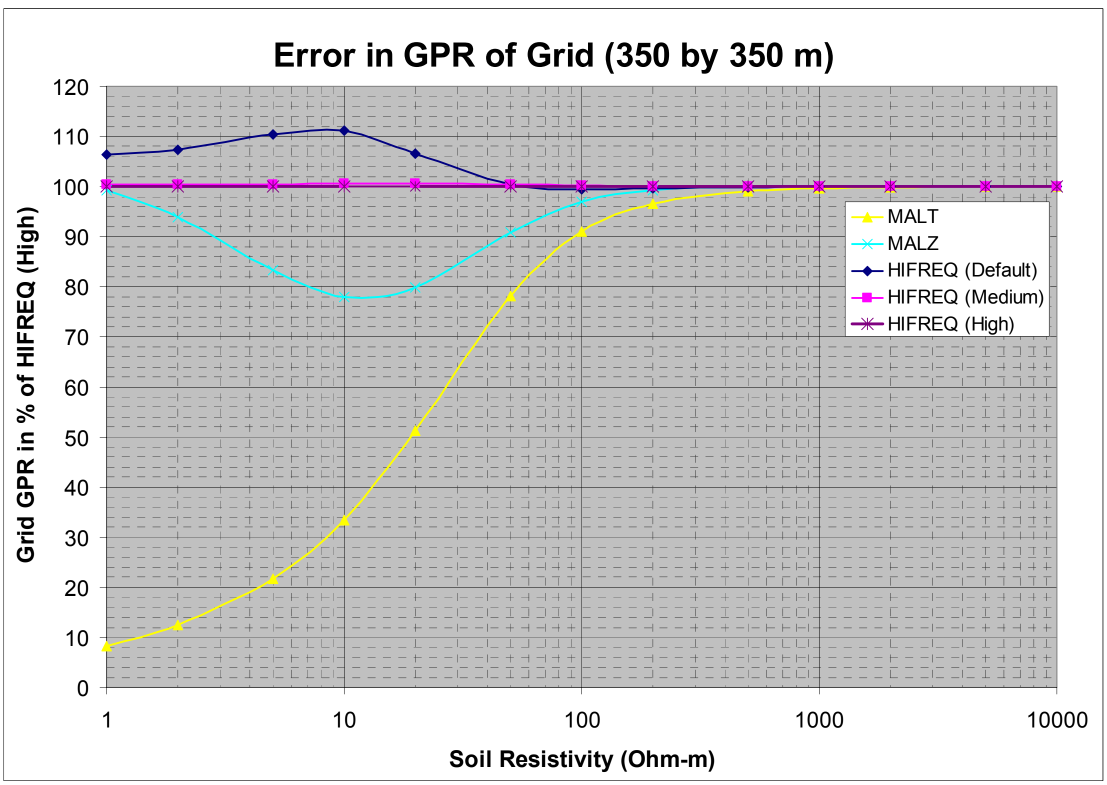

Figure 4-8: Error in GPR for 350 m Grid Compared to High Accuracy HIFREQ.

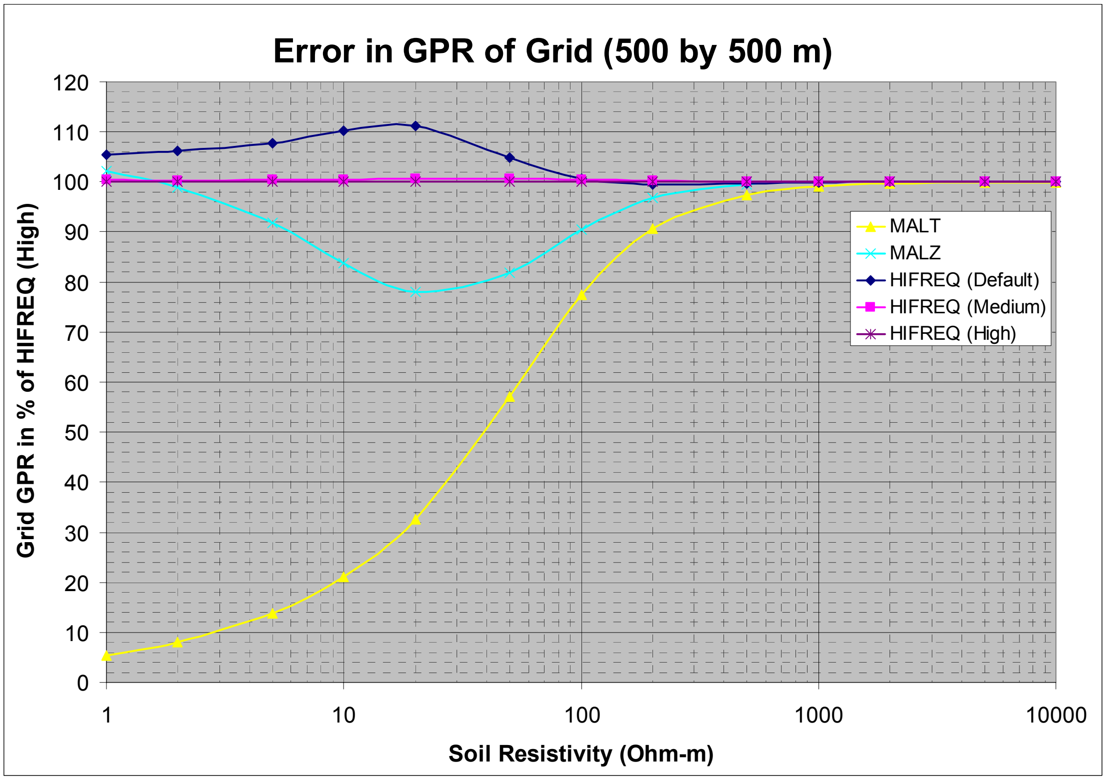

Figure 4-9: Error in GPR for 500 m Grid Compared to High Accuracy HIFREQ.

Several observations can be made with respect to those plots:

- The error made when using the DEFAULT accuracy settings in HIFREQ never exceeds 12%. The values computed with this method are larger than the correct value, which means that the results tend to be conservative. Given that this method is considerably faster than either the MEDIUM or HIGH accuracy settings in HIFREQ, this represents an interesting method for all grid sizes.
- The error made with the MEDIUM accuracy settings in HIFREQ is negligible. Therefore, there is no need to use the more computationally expensive HIGH accuracy settings when dealing with buried conductors at power frequency. Note that this conclusion doesn't necessarily apply to high frequency studies.
- The error made when using MALZ doesn't exceed 22%; however, MALZ underestimates the GPR.
- The error made with MALT can be very large: as much as a factor of 20. As expected, the error is important only for large grids and low resistivity soils.

In practice, it is often more important to obtain accurate values of the touch voltage rather than of the GPR. Figure 4-10 to Figure 4-15 show the touch voltage computed at Point 1 in all cases explored above. The error follows the same trend, although it is smaller for HIFREQ (DEFAULT) and MALZ and considerably larger for MALT.

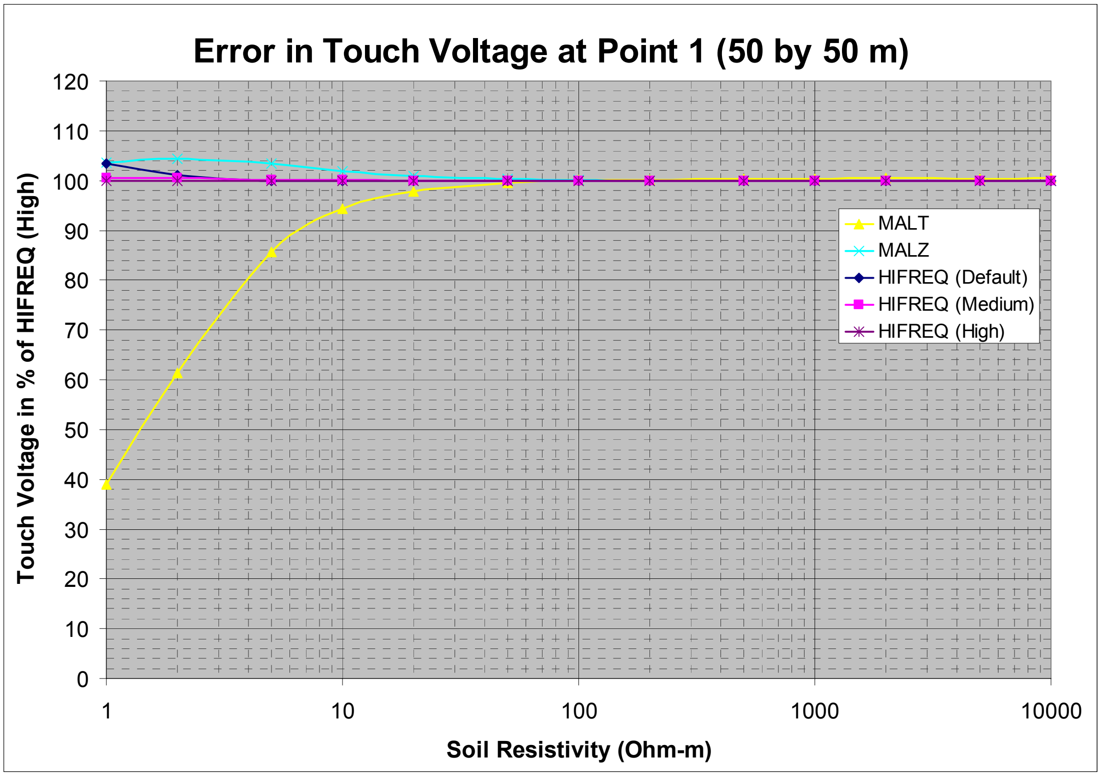

Figure 4-10: Error in Touch Voltage at Point 1 for 50 m Grid Compared to High Accuracy HIFREQ.

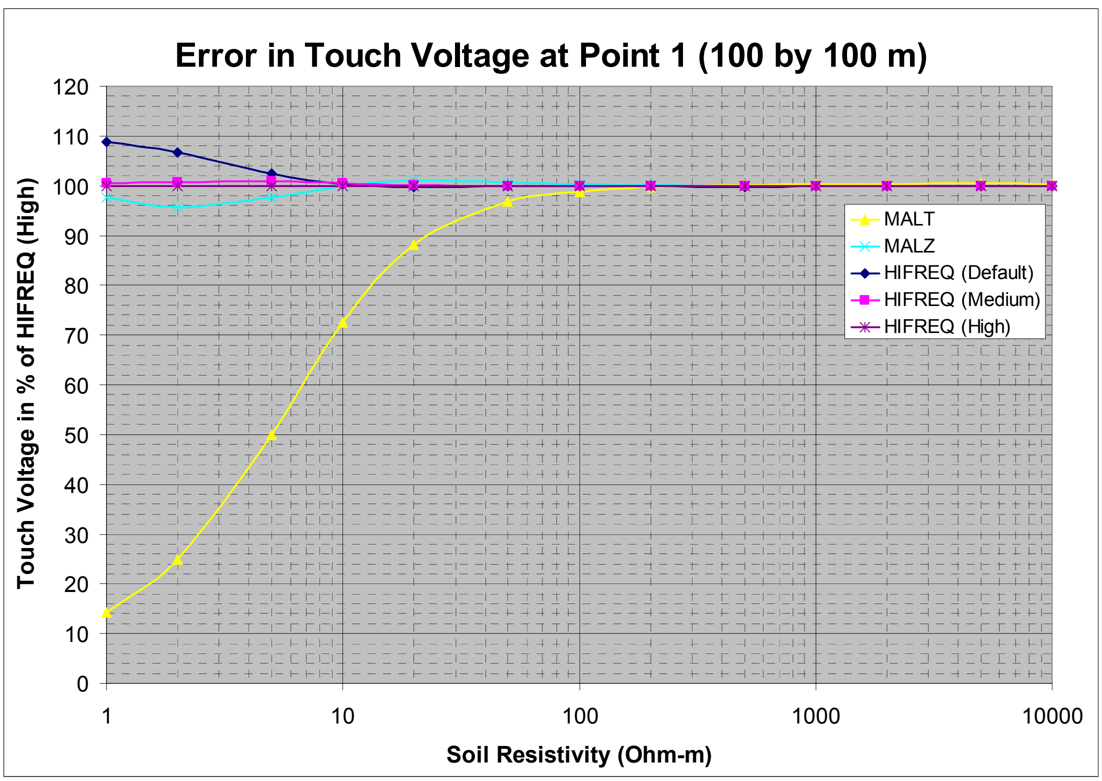

Figure 4-11: Error in Touch Voltage at Point 1 for 100 m Grid Compared to High Accuracy HIFREQ.

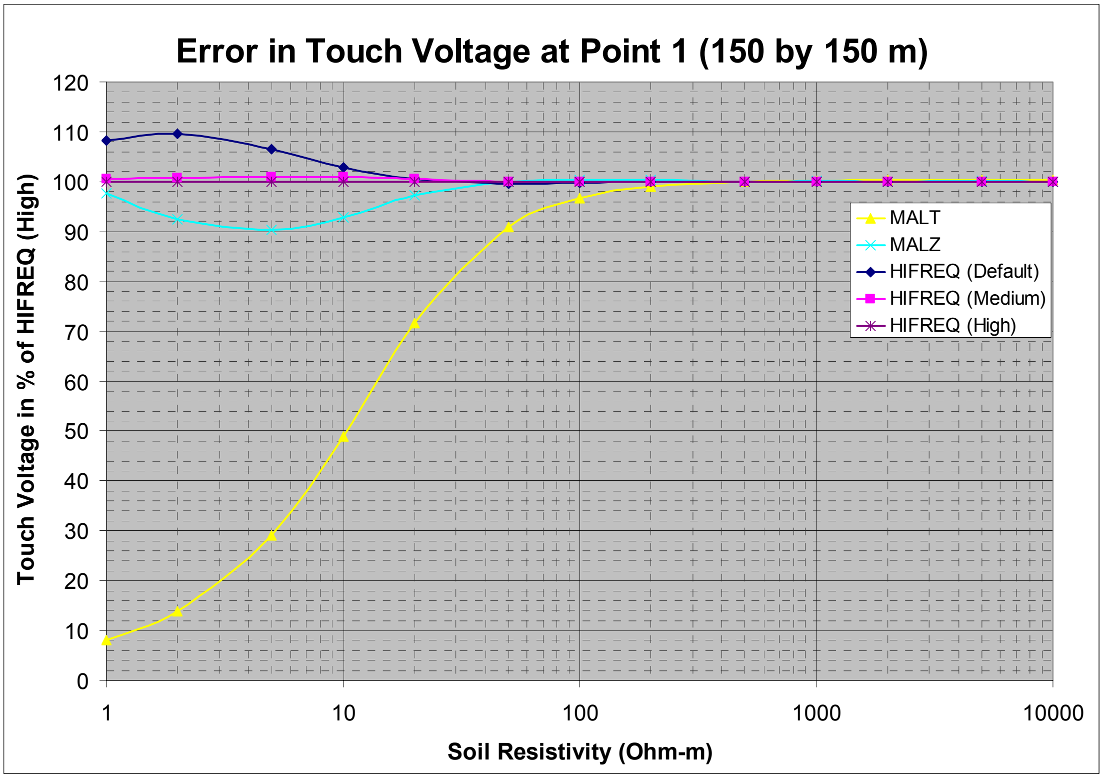

Figure 4-12: Error in Touch Voltage at Point 1 for 150 m Grid Compared to High Accuracy HIFREQ.

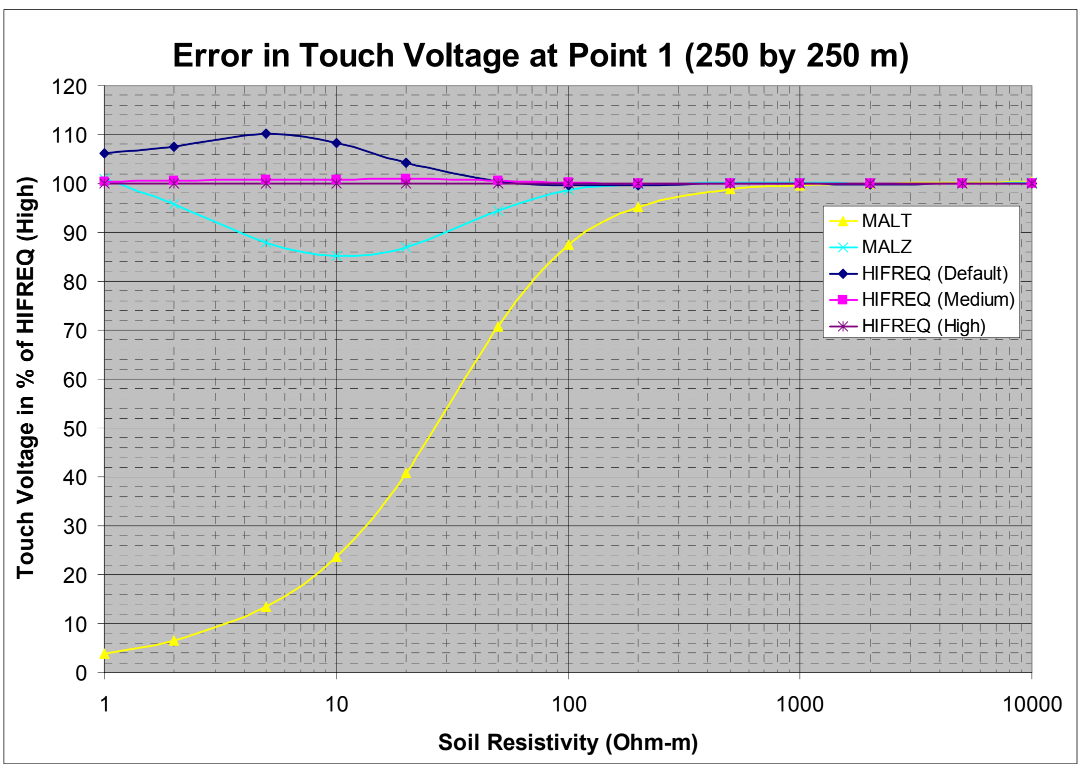

Figure 4-13: Error in Touch Voltage at Point 1 for 250 m Grid Compared to High Accuracy HIFREQ.

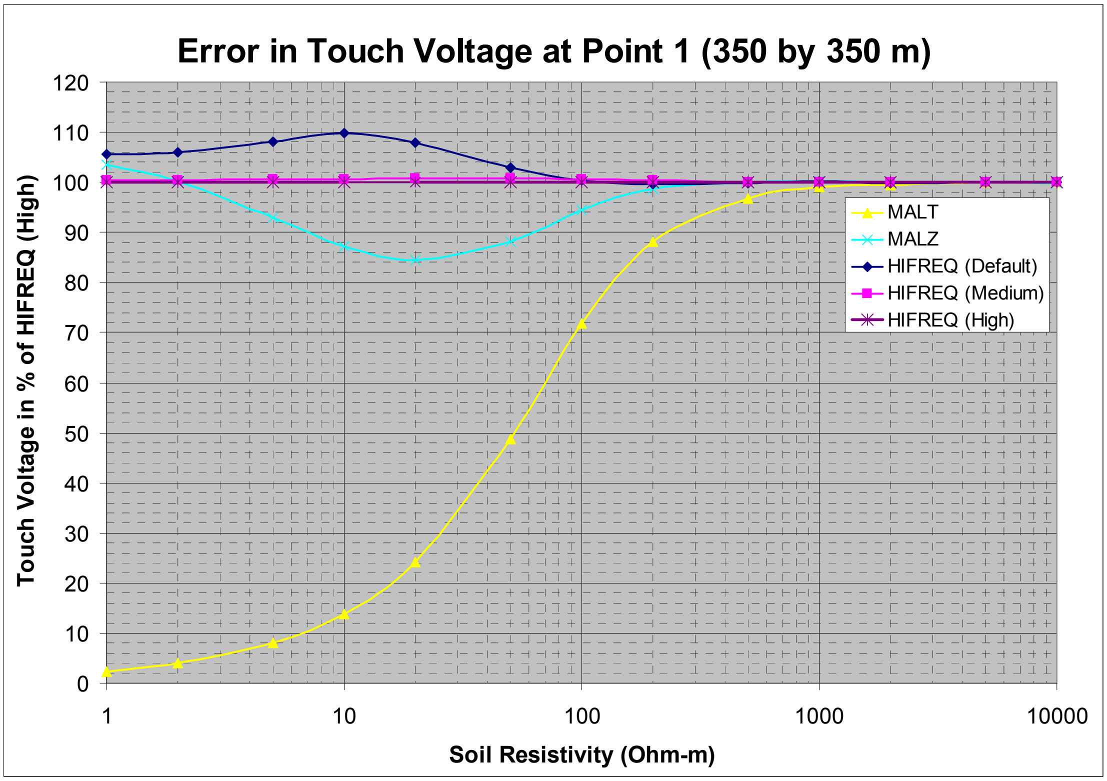

Figure 4-14: Error in Touch Voltage at Point 1 for 350 m Grid Compared to High Accuracy HIFREQ.

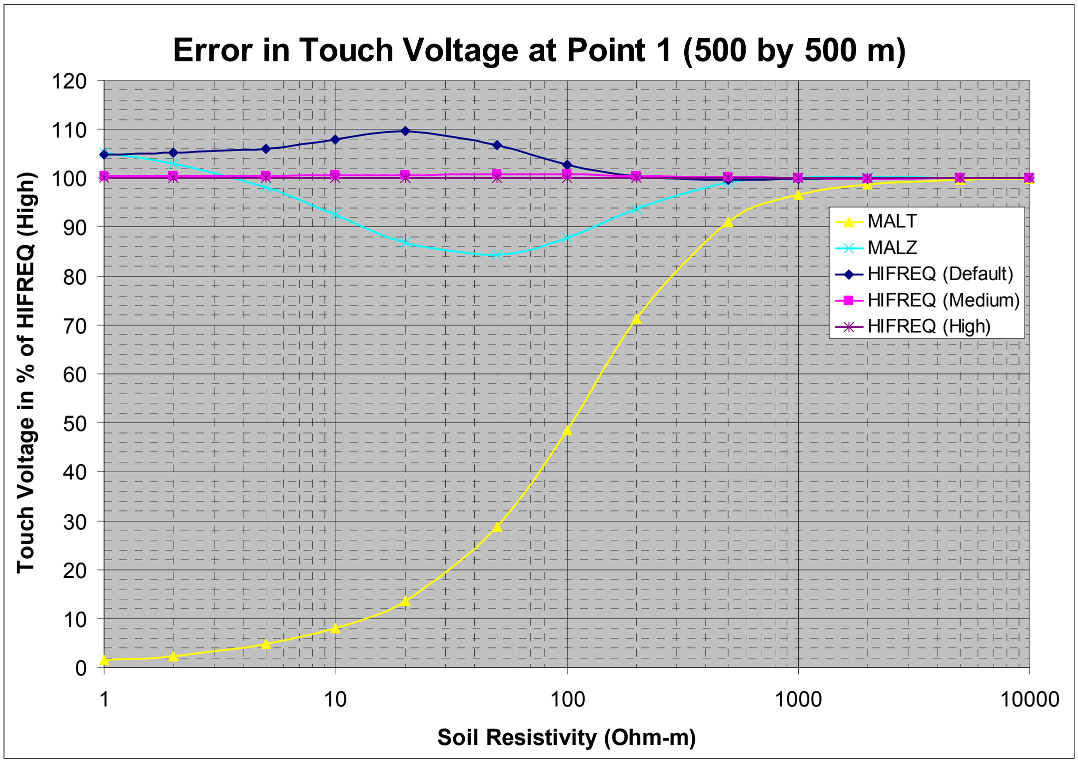

Figure 4-15: Error in Touch Voltage at Point 1 for 500 m Grid Compared to High Accuracy HIFREQ.

The error on the touch voltage at other locations can follow a different pattern. Figure 4-16 shows the error on the touch voltage at Point 3, for the case of the 500 m grid. In this case, all methods overestimate the touch voltage when the resistivity is small.

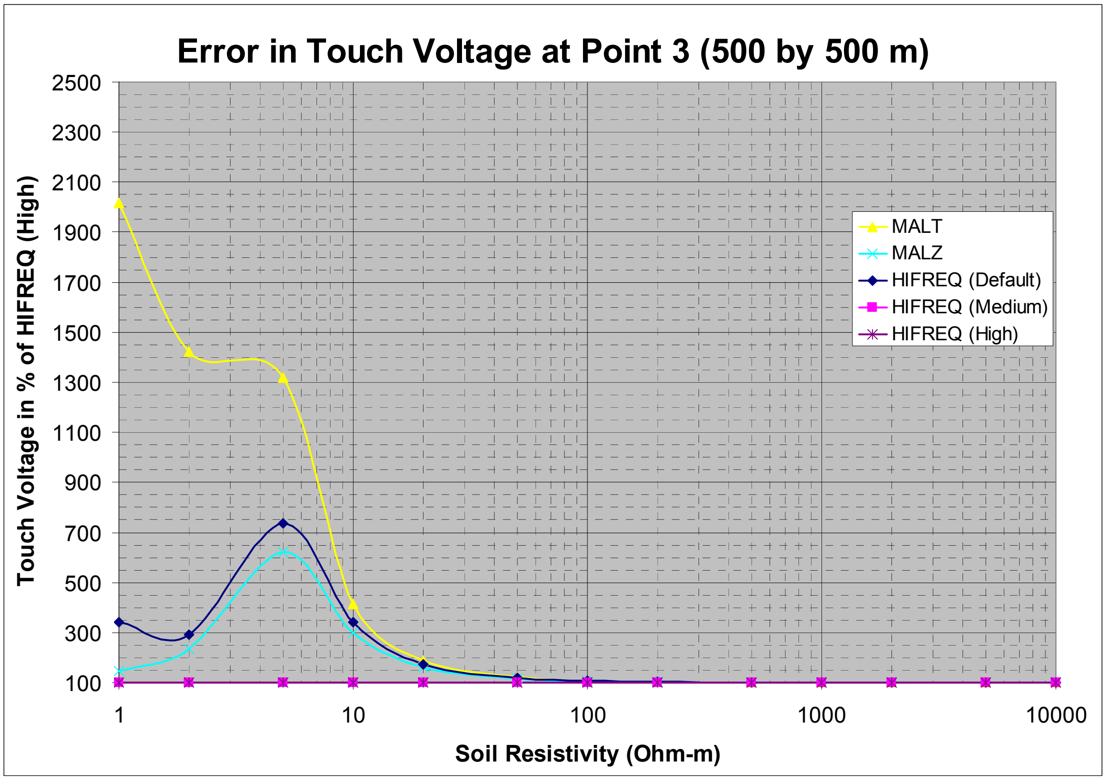

Figure 4-16: Error in Touch Voltage at Point 3 for 500 m Grid Compared to High Accuracy HIFREQ.

The results for the touch voltages at Point 1 can be used to obtain more precise criteria regarding the maximum size of a square grid that can be modeled accurately with MALT.

Figure 4-17 shows the maximum size of a grid that can be modeled with MALT in order for the computed touch voltages (at Point 1) to be within a specified percentage of the true value computed with HIFREQ (HIGH accuracy settings). The various curves in the figure correspond to different target accuracy, from 10% to 50%.

The procedure used to obtain the data was to fit the data in Figure 4-10 to Figure 4-15 with polynomial functions, then to find the root of the polynomial that gives the specified accuracy. Some points on the curves correspond to grids smaller than 50 m, or larger than 500 m. These points were obtained by extrapolation, and are therefore not as reliable as those in the 50 to 500 meter range.

The curves are roughly parallel straight lines, with a slope of 0.5. This means that the maximum size varies as $\sqrt{\rho}$, confirming the discussion of Section 0. The curves for the larger error are completely located above those for smaller errors; this means that if we are satisfied with a larger uncertainty in the calculations, then we can model a larger grid with MALT.

The curves stop for a soil resistivity between 500 and 1000 Ohm-m. This means that for resistivities higher than this, the maximum size of the grid that can be modeled with MALT is larger than 500 meter, but could not be determined more precisely due to lack of data.

The results show that for a 10 Ohm-m soil (which can be encountered in practice), the maximum size of a grid that can be modeled with MALT is 60 meters (if 10% error can be tolerated), and no larger than about 130 meters if 50% error (a full factor of 2) is allowed.

For a 100 Ohm-m soil, the maximum size has already increased a lot, to about 210 meters for a 10% error.

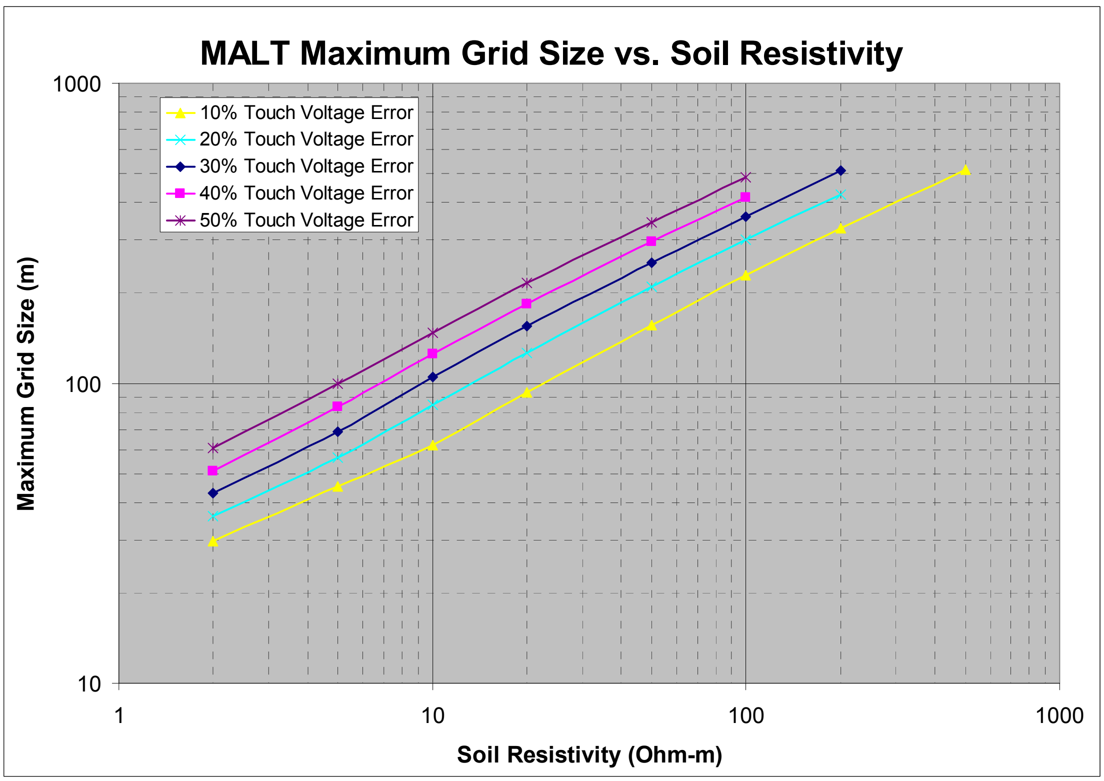

Figure 4-17: Maximum Grid Size that Can Be Modeled with MALT to Reach a Specified Accuracy.

As mentioned in Section 0, one of the main problems with using HIFREQ when compared to MALT is the increased run-time required. Figure 4-18 shows the time required to run MALT, MALZ and HIFREQ for grids of different sizes. The results for a soil resistivity of 10,000 Ohm-m are shown.

From the figure, it can be seen that the run-time required for HIFREQ HIGH accuracy can be about 200 times larger than the corresponding run-time for MALT. The run time for the MEDIUM accuracy HIFREQ case is about 60% smaller than that for the HIGH accuracy. As we saw previously, there is no appreciable loss of accuracy for this case. The DEFAULT accuracy settings case in HIFREQ runs about ten times faster than the MEDIUM accuracy case, but ten times slower than MALT.

The dependence of the run-time on the grid size simply reflects the different number of segments used for the various grid sizes. This explains why the run time remains essentially constant when the size of the grid varies between 250 m and 500 m: these cases all use the same number of segments.

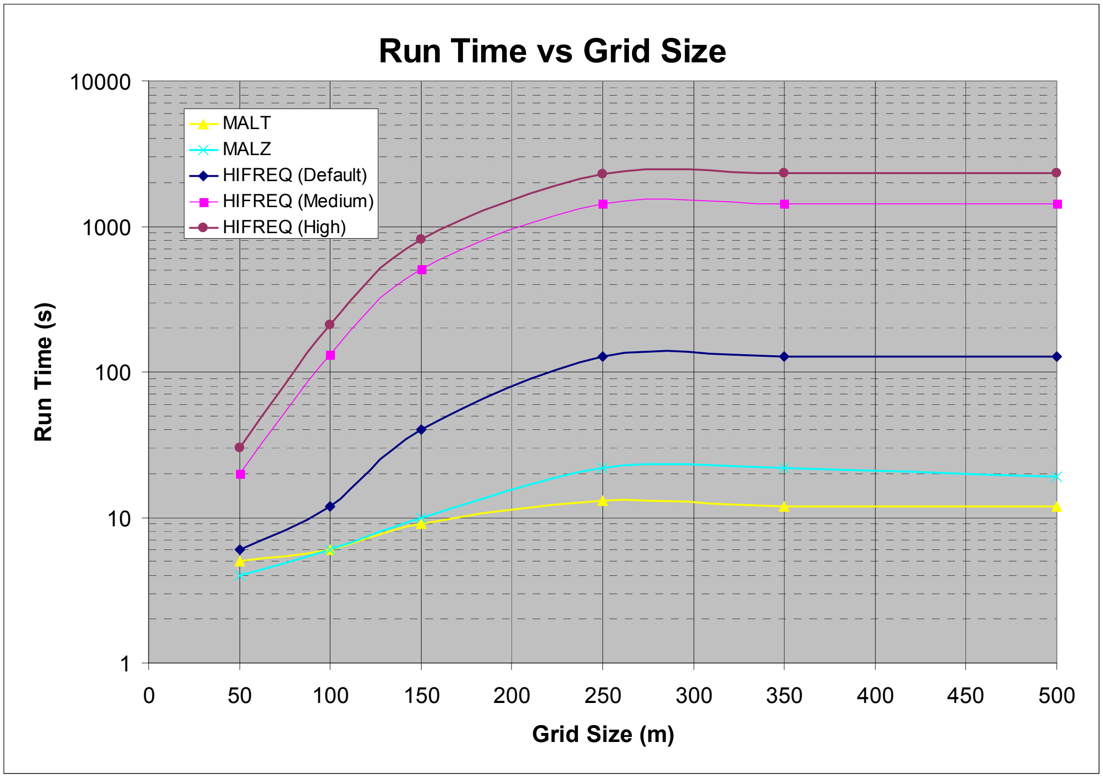

Figure 4-18: Required Run Time for MALT, MALZ and HIFREQ as a Function of Grid Size.

4.2 Results for Two-Layer Soils

The above results are valid for a uniform soil only. To investigate the effects of horizontal soil layers on the computation accuracy of MALT, the GPR of the grids was computed for the soil models shown in Table 3-2.

Figure 4-19 to Figure 4-23 summarize the results. As a rule, the error on the GPR computed with MALT for a two layer soil with layer resistivities ρ_1 and ρ_2 lies between the values of the error on the GPR computed with uniform soils of resistivities ρ_1 and ρ_2. There is one exception, shown in Figure 4-19, where the GPR of a small grid located in a 1/100 Ohm-m is *larger* than that computed with HIFREQ. This is contrary to expectations. The reason behind this phenomenon is still being studied. Note, however, that the difference is very small, and may be due to insufficient segmentation, or other sources of uncertainty.

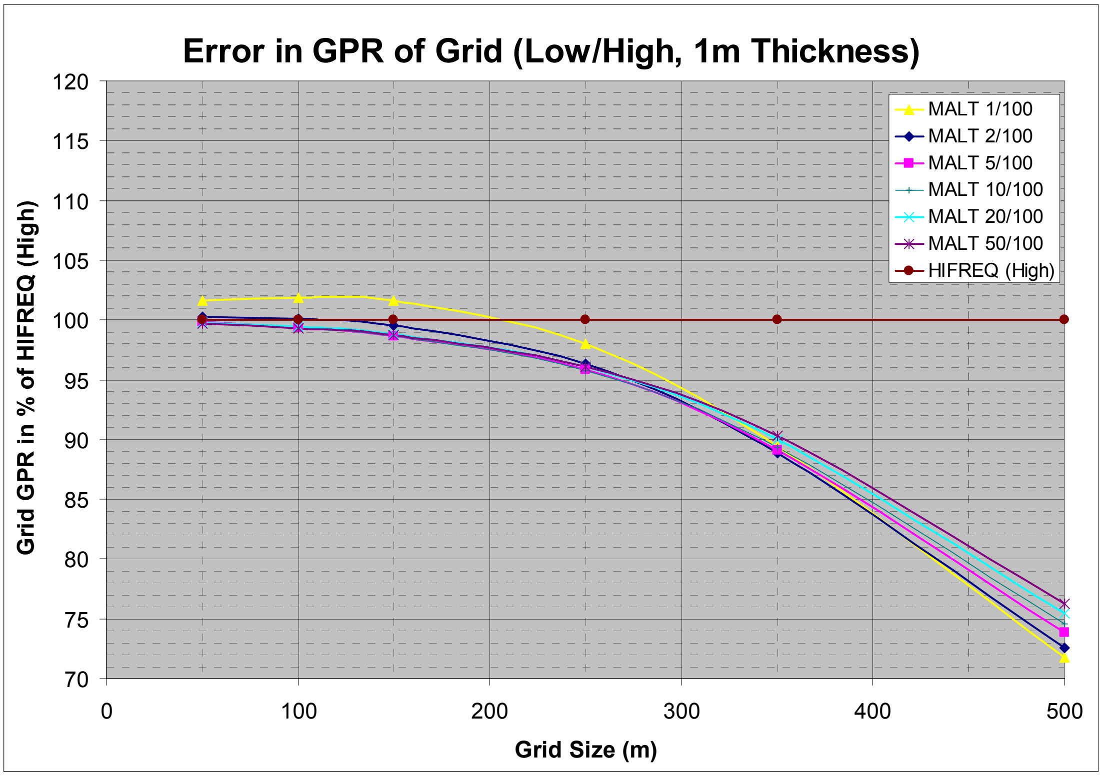

Figure 4-19: GPR Computed with MALT - Bottom Layer of 100 Ohm-m – Top Layer Low.

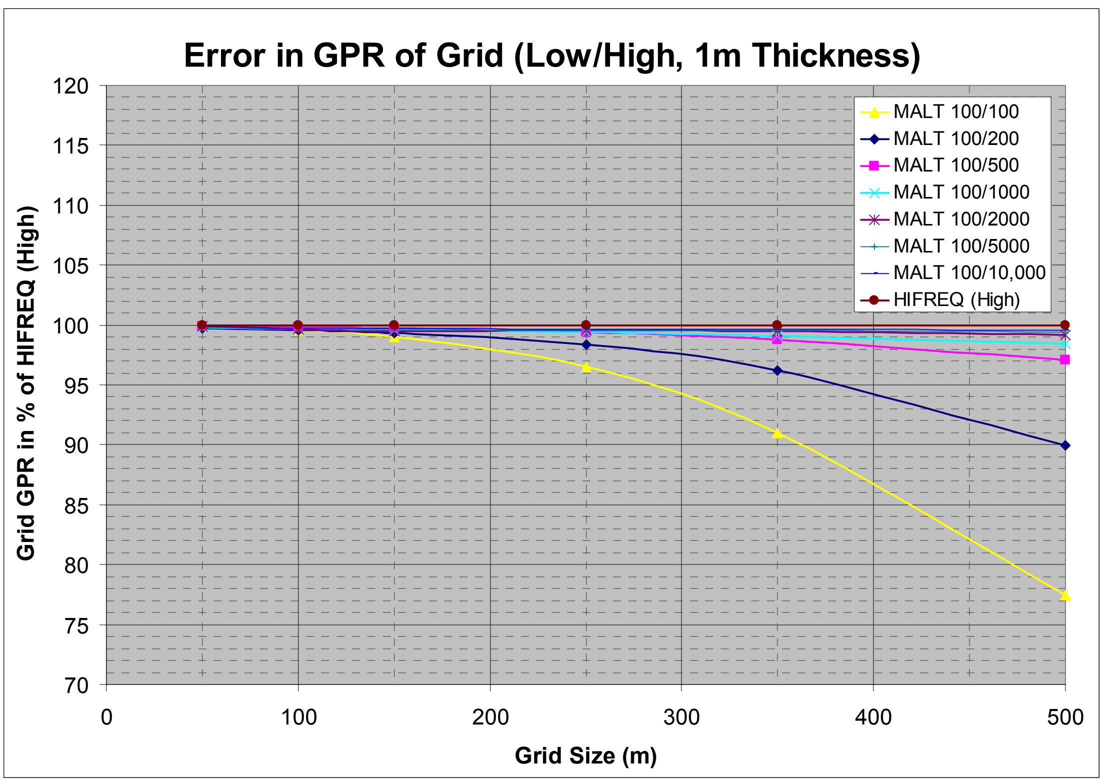

Figure 4-20: GPR Computed with MALT - Top Layer of 100 Ohm-m – Bottom Layer High.

Figure 4-19 shows the error on the grid GPR computed with MALT for several soil models, all having a bottom layer resistivity of 100 Ohm-m, and a top layer resistivity smaller than 100 Ohm-m. The error in this case is quite insensitive to the resistivity of the top layer; therefore, the results of the previous section can be used to estimate the error for this type of soil model, using the resistivity of the bottom as the effective resistivity of the equivalent uniform soil.

Similarly, Figure 4-20 shows the error on the grid GPR computed with MALT for a fixed top layer resistivity (100 Ohm-m) and several values of the resistivity of the bottom layer, all greater than or equal to 100 Ohm-m. The error decreases very sharply as the resistivity of the bottom layer increases. This confirms that for such soil models (low over high resistivity) the error is mainly determined by the resistivity of the bottom layer.

Figure 4-21 and Figure 4-22 show the error in the case of high over low soil models. Figure 4-21 shows how the error varies when the top soil layer has a fixed resistivity of 100 Ohm-m, for various values of the bottom layer resistivity (all less than 100 Ohm-m). Again, the error depends very strongly on the bottom layer resistivity.

Figure 4-22 shows how the error varies when the bottom layer has a fixed resistivity of 100 Ohm-m, and the resistivity of the top soil layer is allowed to vary from 100 Ohm-m to 10000 Ohm-m. Again, the error varies considerably. This means that for a high over low soil, the resistivity of both layers must be taken into account when estimating the error committed by using MALT instead of a more accurate program.

In all cases, the computation error decreases as the resistivity of a soil layer increases, in agreement with the previous observations for a uniform soil.

The above results were based on soil models having a thin (1 m) top layer. Figure 4-23 shows the variation of the error when the thickness of the top layer is varied, in the case of a high over low soil model. The error decreases as the thickness of the top layer increases. This is the expected behaviour, since in the case of a high over low soil, increasing the thickness of the top layer of soil amounts to increasing the effective uniform resistivity of the soil, which is known to improve the accuracy of the GPR computed with MALT. Again, the variation as a function of the thickness is substantial.

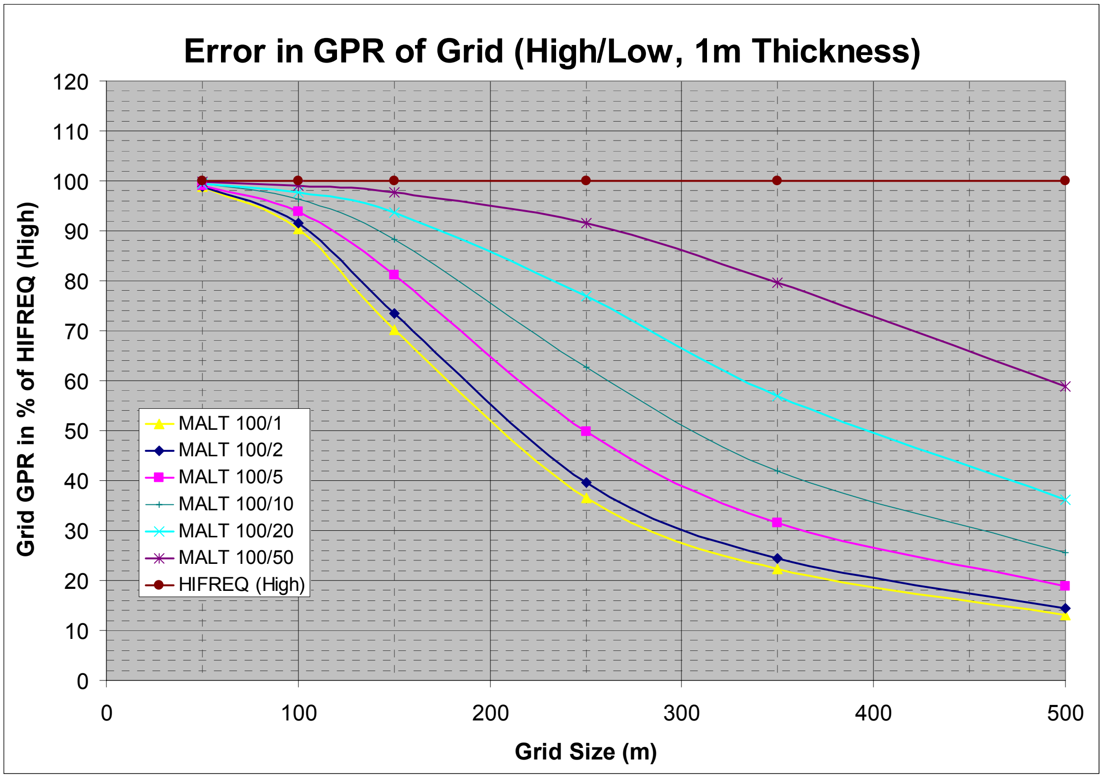

Figure 4-21: GPR Computed with MALT - Top Layer of 100 Ohm-m – Bottom Layer Low.

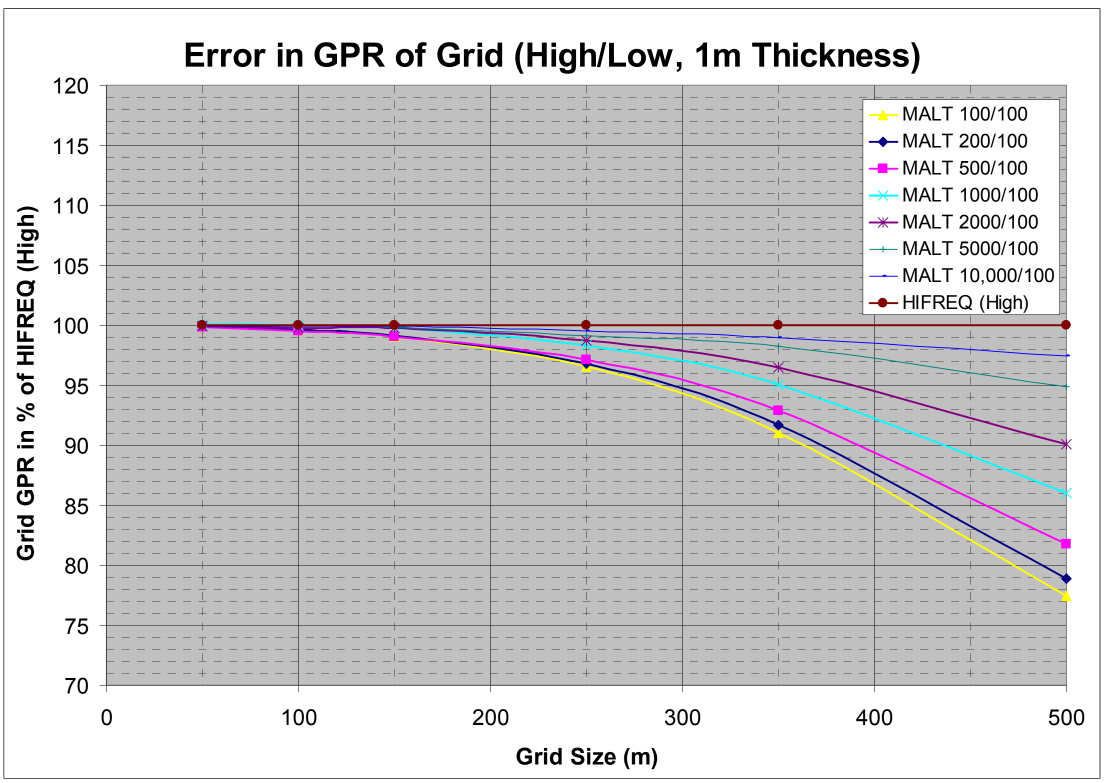

Figure 4-22: GPR Computed with MALT - Bottom Layer of 100 Ohm-m – Top Layer High.

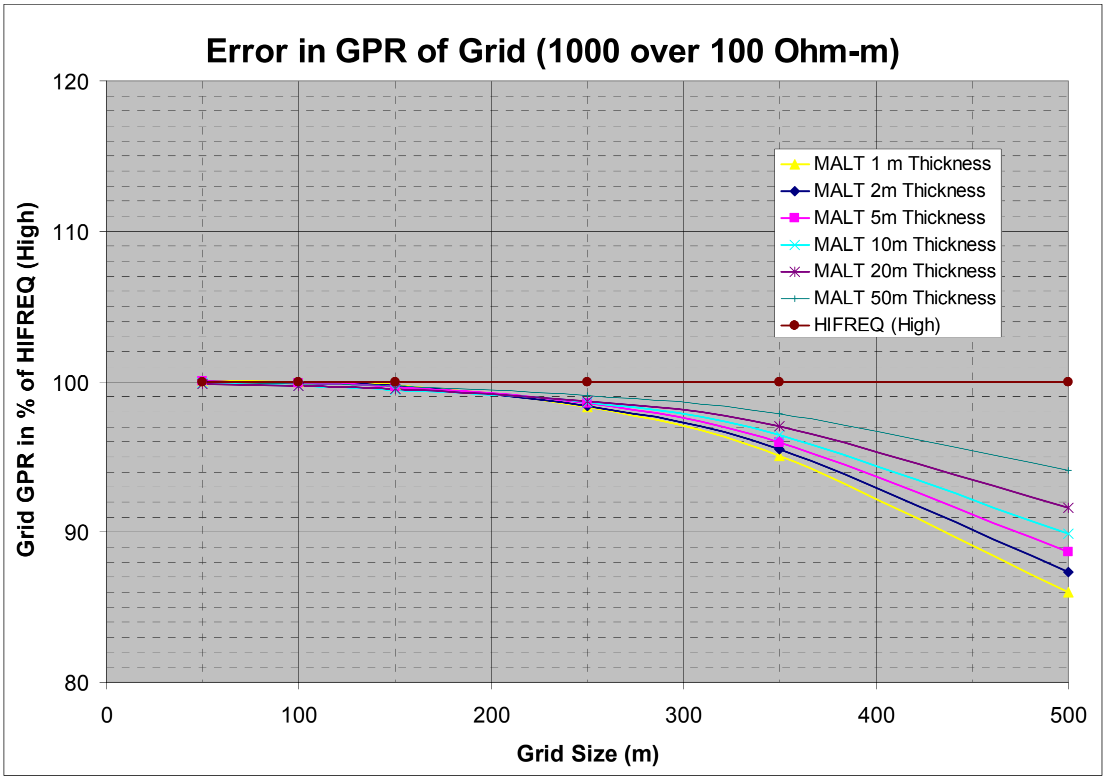

Figure 4-23: GPR Computed with MALT - Top Layer of 1000 Ohm-m over Bottom Layer of 100 Ohm-m. Top Layer Thickness Varies.

5 Discussion and Conclusions

This article compared the computation accuracy and the performance of the three SES programs (MALT, MALZ, and HIFREQ) that can be used to perform grounding studies. The results presented here can help determine which program should be used to solve a given grounding problem.

The comparisons were carried out using grounding grids of various sizes, at power frequency. The main findings are:

- As long as induction effects are not expected to play a significant role, the MALZ program can be used to perform essentially any grounding study. However, MALZ does underestimate the GPR and the maximum touch voltages somewhat (by up to about 20%). Under the same conditions, the DEFAULT accuracy settings of HIFREQ can be used, with about the same accuracy. On the other hand, the run-time of HIFREQ (DEFAULT settings) is at least 5 times longer than MALZ.

- If induction is expected to play a role (such as when there are long parallel conductors joining different parts of a grid) and/or when there are overhead conductors, then HIFREQ must be used. It was found that the MEDIUM accuracy settings are sufficient in all cases at power frequency, and are about twice as fast as the HIGH accuracy settings.

- The MALT program is sufficiently accurate for most cases encountered in practice. However, combinations of large grid size and low resistivities can cause MALT to seriously underestimate the GPR and the touch voltages. For uniform soils, curves were obtained that relate the error made with MALT to the grid size and the soil resistivity. These curves can be used to check if MALT can be used without too much of a risk of error for a given grid size and soil resistivity. It was shown, however, that the error in the MALT result can vary strongly as a function of the soil structure; it is also expected to depend somewhat on the geometry of the grid, and on the characteristics of the grid conductors. Therefore, the curves shown in Section 4 should always be used with caution.

- For a two-layer soil, the error committed when using the MALT program for a large grid is influenced mainly by the bottom layer resistivity when the top layer is thin, except that in the case of a high/low soil where both resistivities play a role.

