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COMPARISON OF SCALE-MODEL RESULTS WITH FIELD SURVEYS CONDUCTED OVER THE NIGHT HAWK TEST RANGE USING FIXED-LOOP AND MOVING-SOURCE ELECTROMAGNETIC SYSTEMS[1]

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ABSTRACT

Physical scale-modelling of the behaviour of a fixed-loop electromagnetic prospecting system when operated over closely spaced, vertically dipping conductors located in a conductive host, strongly suggests that the Night Hawk test range conductor located near Timmins, Ontario, Canada, is not a single wide conductor but two separate conductors. Comparison of model results with the results of surveys conducted over the Night Hawk test range show that the two-conductor character of the response is present in the high-frequency responses provided by TURAM and GENIE and in the early-time responses provided by EM-37 and PROTEM. The model responses show that two closely spaced conductors can behave as a single wide conductor at low frequencies while the responses obtained over the test range for low frequency and late time indicate that this may also be the case at Night Hawk.

The model results also suggest that the response of the Night Hawk conductor to fixed-loop systems is strongly influenced by the gathering of current from the host environment. The host resistivity at Night Hawk can be estimated on the basis of the model results to be approximately 2000 ohm-m.

INTRODUCTION

The Night Hawk conductor located in the Thomas Township of Ontario (Figure 1) has been used throughout the past decade as a standard test target for electromagnetic exploration systems. The most extensive tests on this site were conducted by the Ontario Geological Survey (Barlow et al., 1982; Pitcher, 1985). The site has also been used in the development of new electromagnetic devices (Macnae and Walker, 1981; West et al., 1984; Johnson and Doborzynski, 1988).

The conductor at the Night Hawk site is a graphitic schist located at a depth of 87 to 90 m beneath glaciofluvial sands and gravels. The host for the conductor is a rhyolite tuff which appears to have been treated as being nonconductive in most of the interpretation of surveys conducted at this site.

In previous work reported for the Night Hawk test range, the conductor has been shown to respond as a horizontal plate to frequency-domain, horizontal coplanar-coil, Slingram-type surveys conducted with the Apex MAX-MIN device and to moving-source transient electromagnetic surveys conducted with the Crone PEM system (MacNae and Walker, 1981). It has also been found to behave as a dipping plate in fixed-loop transient electromagnetic surveys conducted with the Lamontagne UTEM system (MacNae and Walker, 1981; West et al., 1984). Its response to the Androtex ELFAST-TURAM and to the fixed-loop version of the Scintrex GENIE — both of which are frequency-domain systems — suggests two conductors (Pitcher, 1985; Johnson and Doborzynski, 1988).

COMPARISON OF SCALE-MODEL AND FIELD RESULTS

TURAM profiles

In a scale-model study of the response of the TURAM system, Duckworth and O'Neill (1989) considered the case of closely spaced, parallel, vertically dipping, thick conductors located in a conductive host environment. This study demonstrated the pronounced anomaly enhancement that can result from current gathering as predicted by Lajoie and West (1976). It also demonstrated the anomaly enhancement that can come from the interaction of closely spaced pairs of identical conductors in a conductive host. The results for one such model, presented in the form of TURAM-reduced field strength ratio and phase difference profiles, are shown in Figure 2. This study of closely spaced, vertically dipping, parallel conductors was not undertaken specifically to match the responses found at the Night Hawk test range, yet the strong similarity between the model responses of Figure 2 and responses measured along line 100E at Night Hawk, which are shown in Figure 3 (after Pitcher, 1985), is clear.

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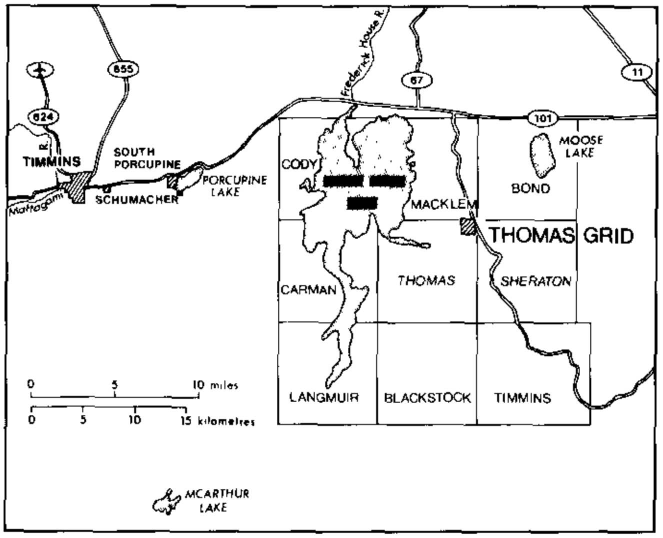

Fig. 1. The Night Hawk test range is located 20 miles east of Timmins, Ontario, in the northeast corner of the Thomas township.

The outstanding feature common to both the scale-model and field results is the strong enhancement of the part of the anomaly which, in the model, is located over the conductor which is most distant from the transmitter. In the low-frequency scale-model profiles, this anomaly becomes so weak that the response could be interpreted as being due to a single conductor with a width equal to the combined width of the two conductors. It is also notable that the anomaly associated with this second conductor in Figure 2 migrates away from the transmitter as the frequency rises, until at 200 kHz the anomaly peak is displaced off the conductor. A very similar migration is also present in the Night Hawk profiles of Figure 3. These similarities suggest that the Night Hawk conductor also consists of two closely spaced conductors located in a conductive host rock.

Drilling, which only penetrated a short distance into the centre of the conductive zone indicated by the geophysical results, found nonconductive material (Barlow, pers. comm.). This led to an interpretation of the conductor as a tightly folded synclinal structure. We did not conduct tests of a synclinal model because the modelling project that produced these results did not set out to simulate the responses from the Night Hawk test range. The strong similarity between the model responses and the field responses from Night Hawk became evident after the model study had been completed.

The enhancement effects shown by the scale-model results in Figure 2 can be compared with the responses for the same conductors located in free space, which are shown in Figure 4. The free-space scale-model profiles show almost identical field strength ratio (FSR) anomalies for all frequencies, with little phase difference anomaly above 10 kHz. This shows that in free space these conductors responded at the inductive limit for all frequencies above 10 kHz. Also notable is the lack of a phase inversion in the free-space model profiles of Figure 4 of the type shown in Figure 2 at 400 kHz.

The similarity between the model profiles of Figure 2 and the Night Hawk profiles of Figure 3 is lacking only in that the Night Hawk profiles do not show phase inversion. It appears that the frequencies used in the field surveys conducted at Night Hawk were not high enough to cause phase inversion.

Table 1, which was constructed from the modelling responses obtained by Duckworth and O'Neill (1989), shows the host resistivities which, in the field, will give the same current-gathering effects that were seen in the model. This table was constructed for a linear scaling factor of 1 to 1000. The column of resistivities below the model frequency of 400 kHz would produce a condition well beyond the point of transition to phase-inverted response. The resistivities in the column below the model frequency of 100 kHz will give responses which are close to phase inversion. The apparent approach to phase inversion shown by the 2025-Hz profiles

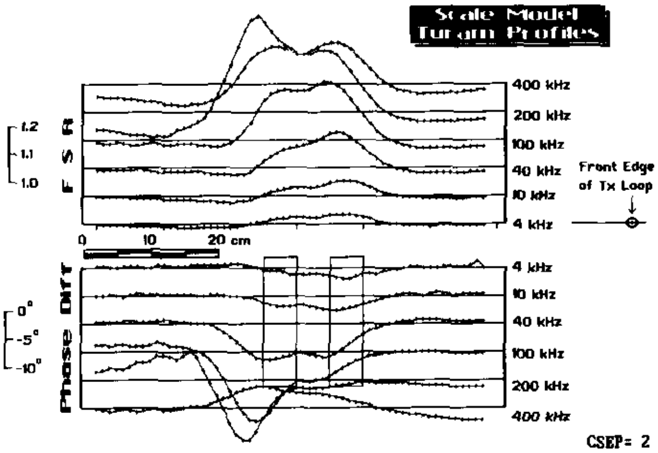

Fig. 2. Scale-model TURAM profiles over closely spaced identical graphite slab conductors in a conductive host show pronounced enhancement and phase inversion at high frequencies due to current gathering. The selective enhancement of the anomaly over the conductor most distant from the transmitter is also notable.

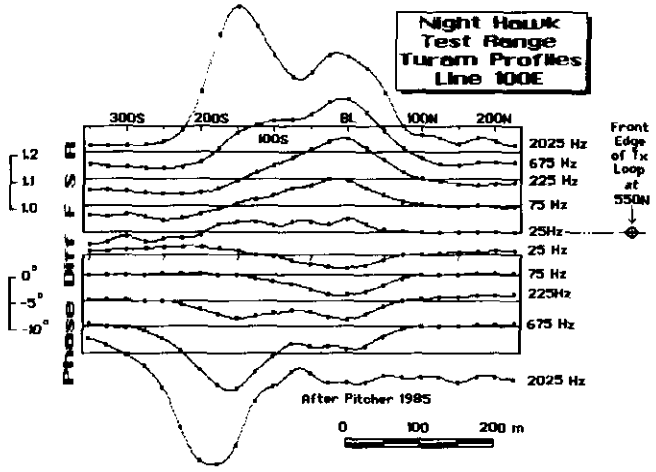

Fig. 3. TURAM anomalies recorded over the Night Hawk test range display strong similarity with the scale-model profiles of Figure 2 in terms of enhancement at higher frequencies and selective enhancement of the anomaly over the possible second conductor.

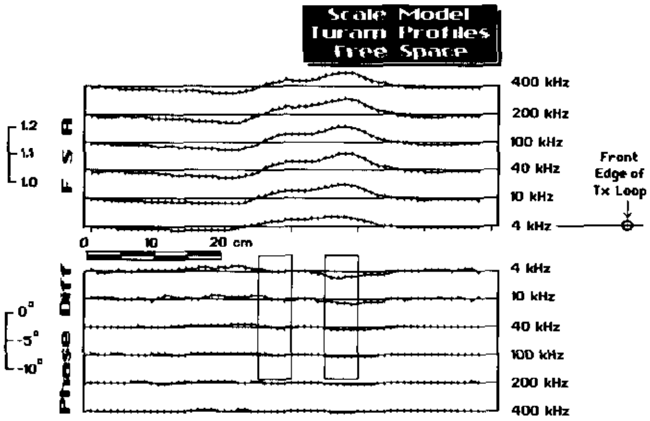

Fig. 4. Scale-model tests over the same graphite conductors used in Figure 2 but located in a free-space host. The uniform response throughout the frequency range indicates inductive limit response. The lack of enhancement and phase inversion at higher frequencies are notable.

in Figure 3 suggests that an estimate of the resistivity of the host for the conductor at Night Hawk can be found in the 100-kHz model frequency column of Table 1 for the field frequency of 2000 Hz. This shows that if the very similar effects observed at Night Hawk and in the scale model are both caused by current-gathering effects due to conductivity within the respective host environments, then the resistivity of the host at Night Hawk is of the order of 2000 ohm-m.

In the scale model, the increase of frequency from 100 kHz to 400 kHz gave phase inversion, so that as the full-scale system appears to have closely followed the model system, an increase in the frequency above the maximum frequency of 2025 Hz used in the full-scale system should also produce phase inversion. The exact frequency at which this transition will take place can not be predicted, but a full-scale frequency of 8000 Hz would give responses well beyond the point of phase inversion for a host resistivity of 2000 ohm-m. This leads us to predict that if operating frequencies of the order of 4000 Hz to 6000 Hz are used at Night Hawk, an inversion of the phase response will be observed.

Table 1. The host resistivities shown within the main box will generate responses in the full scale which were seen in the model for the frequencies listed. All the resistivities in the column below the model frequency of 400 kHz would cause phase inversion at the corresponding full-scale frequency (or any higher frequency).

Linear Scale Factor 1:1000

1 m in the model = 1 km in the field

* Phase Inverted

Field Frequencies	Model Frequencies 400 kHz	100 kHz	40 kHz	10 kHz
4 kHz	1000 *	4000	10000	40000
2 kHz	500 *	2000	5000	20000
1 kHz	250 *	1000	2500	10000
400 Hz	100 *	400	1000	4000
100 Hz	25 *	100	250	1000

← INCREASING CONDUCTIVITY

INCREASING CONDUCTIVITY ↓

Host Resistivities for Equivalent Response (Ohm—metres)

It is possible that geological configurations other than the model we propose could cause the Night Hawk conductor to display the behaviour shown in Figure 3. However, we believe that the reader will agree that the unusually good match between the scale model and full-scale results is compelling evidence that the response of the Night Hawk conductor (or conductors) is a good example of current gathering in operation.

GENIE profiles

In the scale-model experiments the measured parameters were the amplitude and phase of the signal detected by a single receiving coil. The wide frequency range from 4 to 400 kHz used in the model allowed the amplitude data to be converted to the form of amplitude ratios between selected pairs of frequencies as employed by the GENIE system. Exact correspondence between the frequency pairs used in GENIE and the pairs available in the model was not attempted.

GENIE-type response profiles generated from the model data are shown in Figure 5, while the corresponding profiles obtained over Night Hawk as presented by Johnson and Doborzynski (1988) are shown in Figure 6. Again, the two-conductor character of the response at high frequency and the enhancement of the response as frequency increases are evident in both the model and field data. The 3037.5/37.5 raw GENIE profile shows the two-conductor response by a mild change of the slope of the anomaly which causes the profile to display two inflexions located at 125S and at the base line. The clear indication of the two conductors produced by the Fraser-type filtering of the raw profiles, which emphasises inflexions in the profile as described by Johnson and Doborzynski (1988), shows the benefit of the differential type of data display that the filtering provides and which TURAM generates directly. In that GENIE depends on the difference in response between frequencies, it can be seen that

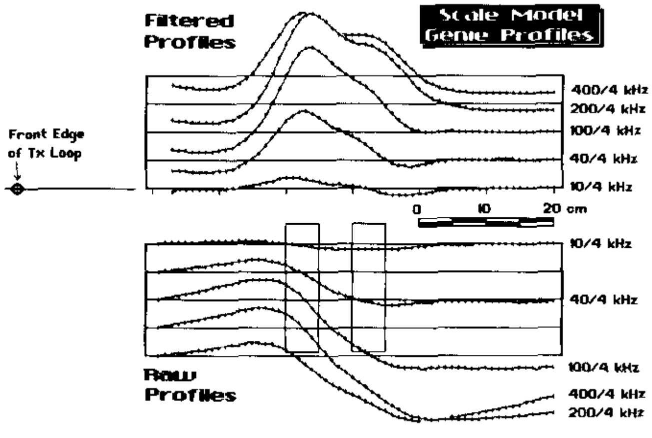

Fig. 5. Scale-model responses over identical conductors presented in the format used by the GENIE exploration system.

this device appears to benefit considerably from the enhancement of these differences that current gathering provides.

EM-37 profiles

Profiles obtained with the transient electromagnetic EM-37 system over the Night Hawk test range were published by Barlow et al. (1982) and are shown in Figure 7. At late time these responses are very similar to the response of a thin plate dipping away from the transmitter, as shown by West et al. (1984). However, at early time these profiles show a pronounced change in slope located very close to the location of the base line. This change of slope is similar to the effect seen in the raw GENIE profiles of Figures 5 and 6. Examination of the early-time UTEM profiles provided by West et al. (1984) suggests that a similar break in slope is also present in the UTEM data for this test range.

PROTEM profiles

Some of the most recent tests at Night Hawk have been conducted with the moving-source PROTEM transient electromagnetic device. Figure 8 displays vertical-component profiles obtained with PROTEM along the same traverse used in all the surveys discussed above. These profiles were published in a case study of the operational characteristics of this new system by McNeill (1989). It was the conclusion of this study that the response shown by PROTEM over Night Hawk was the response of a single wide conductor and that the small anomaly on the left shoulder of the main anomaly was geologically insignificant even though the PROTEM device was designed to achieve high spatial resolution of anomalies.

The scale-model profile displayed in Figure 9 was conducted for a simulated target depth of 90 m with a coil separation of 40 m. The graphite slab model conductors simulated full-scale conductors of 50 m and 30 m width with separations of 0 and 25 m. This test was conducted in the frequency domain using horizontal coplanar coils. The weak anomaly on the flank of the main peak, seen when the conductors were separated, became imperceptible when the separation was reduced to zero, so that there appears to be no other reasonable conclusion than that the weak anomaly on the flank was caused by the presence of the two separate conductors. The character of this weak-shoulder anomaly in the scale-model data of Figure 9 appears to be very similar to the weak anomaly centred at 125S on the PROTEM profiles in Figure 8. This suggests that the PROTEM data did in fact indicate the two-conductor character of the target at the Night Hawk site. This response over Night Hawk appears to verify that the aim of providing better spatial resolution than other moving-source systems has been achieved.

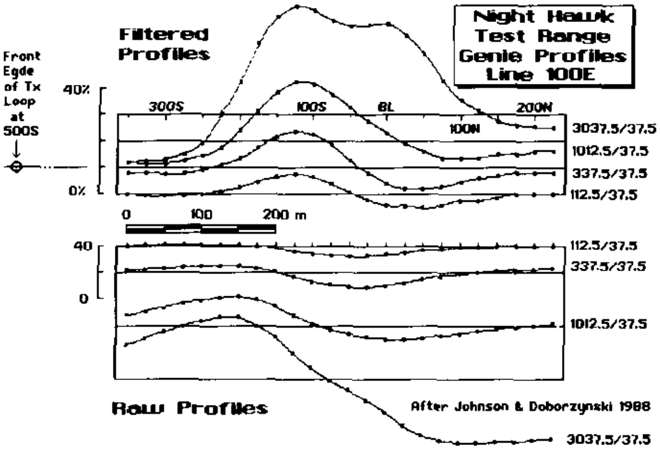

Fig. 6. GENIE responses obtained over the Night Hawk test range show a strong similarity to the scale-model profiles of Figure 5.

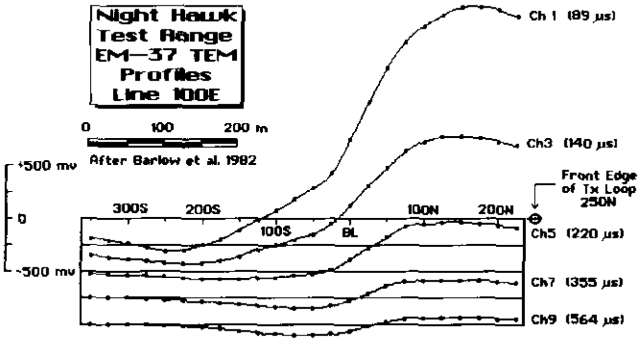

Fig. 7. Transient electromagnetic profiles obtained over the Night Hawk test range with the Geonics EM-37 indicate the presence of two conductors in the early time responses.

DISCUSSION

It appears that both frequency-domain and transient electromagnetic (TEM) profiles indicate the two-conductor interpretation which has been presented above. When fixed-loop systems are employed, the effect of the second conductor, as seen in the secondary-field profiles of TEM systems, is much weaker than that of the conductor nearest to the transmitter. This contrasts with the tendency of TURAM or filtered GENIE data to emphasize the anomaly over the second conductor. It

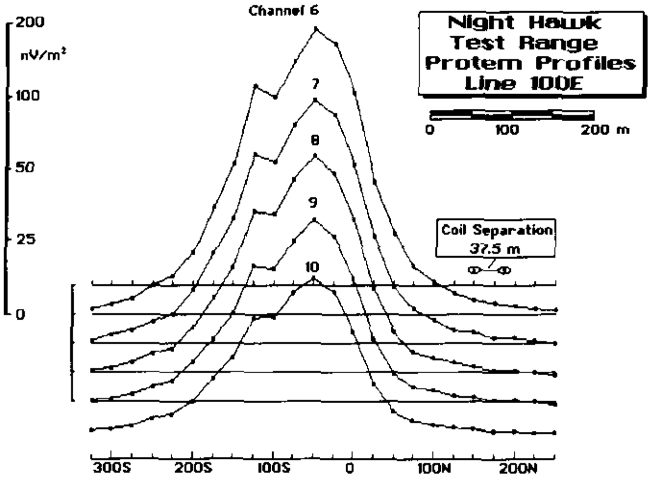

Fig. 8. Geonics PROTEM transient system profiles obtained over the Night Hawk test range display a weak anomaly on the south flank of the main anomaly which could be regarded as geologically insignificant.

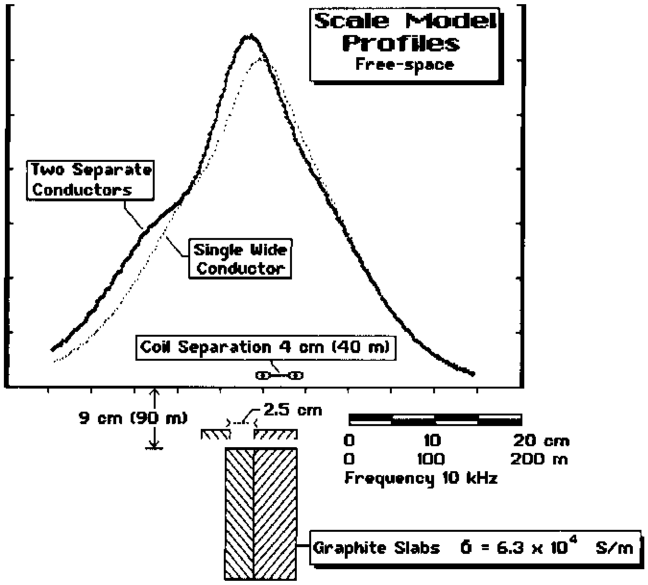

Fig. 9. Scale-model profiles which simulate the geometry of the PROTEM system as used at Night Hawk show that a weak anomaly developed on the flank of the main anomaly when the two conductors were separated.

is clear that the effects of the second conductor can be all too easily overlooked in TEM profiles. This suggests that fixed-loop TEM data might benefit from being presented in a differential form of the type produced automatically by TURAM.

The enigmatic behaviour of the Night Hawk conductor can be explained in terms of the target consisting of two closely spaced steeply dipping conductors. The gap between these conductors does not appear to be large so that it is not detected by moving-source in-line systems which use large coil separations, and its influence becomes negligible at low frequency or late time. The two conductors do not have to be connected other than by their mildly conductive host.

The responses observed in the scale model were due to the gathering of current into the target conductors from the host. The notable similarity between the field data and the scale-model data leads to the conclusion that it is probable that the responses detected over the Night Hawk test range are also due to current gathering.

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SIMULATED ANNEALING EXPERIMENTS IN STATICS COMPUTATION: SYNTHETIC AND REAL DATA EXAMPLES[1]

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ABSTRACT

Removal of residual statics, commonly referred to as surface-consistent statics, is crucial in seismic data processing for refining subtle and complex structures in seismic sections. Methods using simulated annealing search techniques to compute statics are becoming common. Application of simulated annealing statics corrections to both synthetic and field data shows that the coherency of seismic events is enhanced. Preliminary study of the dependency of the simulated annealing search method on cooling schedules in this work suggests the use of slow cooling.

INTRODUCTION

Direct search methods are routinely used to solve residual statics problem (Taner et al., 1974; Wiggins et al., 1976; Russell, 1989; Bancroft, 1990; Kirchheimer, 1990). However, in some extreme cases, they can be expected to have little hope of resolving the optimization problems presented by the residual statics estimation. This is largely because the optimization function defined in the statics parameter space generates an extremely complex surface with many local minima and even a "degenerate" global minimum where the degeneracy refers to the multiple minima having the same value for the optimization function (Ronen and Claerbout, 1985). The complexity of the surface in most cases is so extreme that trapping in a local minimum seems inevitable!

There are two steps which can be undertaken to increase the efficiency of the search. The first step is to "clean up" the surface by removing as many of the irrelevant minima as possible. The second step would be to employ a search technique which reduces the likelihood of terminating in any of the remaining local minima. These goals can be addressed by the use of a "stack power" to define the surface and by the use of the simulated annealing technique which avoids trapping in local minima through the use of a tunable "temperature" parameter (Kirkpatrick et al., 1983; Rothman, 1985, 1986; Paulson, 1986). Variations of this method were applied to improve the field data from the Wyoming Overthrust belt by Rothman (1986). However, stack power optimization still presents difficulties in that the ground state statics solution remains highly degenerate. Partial removal of this degeneracy has been accomplished by introducing a constraint on the difference between neighbouring shot and receiver statics (Dahl-Jensen, 1989) and this has led to some success.

The approach proposed recently by Vasudevan et al. (1991) abandoned the stack power as the "coherence function" and instead introduced a cross-correlation between two stacks. Although some degeneracies in the ground state remain, the degenerate solutions that most severely corrupt the overall coherence are seriously reduced. A search for the optimum set of statics parameters can then be carried out using the steepest descent, the iterative improvement, or the simulated annealing technique, depending on the remaining complexity of this cleaned-up surface. However, even after the use of the cross-correlation between two stacks, there are many situations where the complexity of the surface still requires the use of the simulated annealing technique to ensure that the global minimum or near-global minimum solution is reached.

This paper is divided into two sections. In the first section, the simulated annealing approach is discussed in terms of a physical annealing process as well as the specific application to processing seismic data where residual statics must be removed. A detailed general description of the simulated annealing technique can be found in literature (Rothman, 1985, 1986; Aarts and van Laarhoven, 1987). Only a brief overview is presented here. Three characteristically-different "cooling" schedules and their effects on the data are outlined.

In the second section, results obtained with synthetic and field data are presented. The field data are typified by a

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