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Minimizing Drift in Electrical Conductivity Measurements in High Temperature Environments using the EM-38

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ABSTRACT

The EM-38 is a noninvasive instrument, commonly used for monitoring salinity, mapping bulk soil properties, and evaluating soil nutrient status. Users in the Southwest USA have observed as much as 20% "drift" in the measurement of bulk soil electrical conductivity (EC_a) with this instrument. This drift has usually been ignored or compensated for by statistical procedures. We performed laboratory and field experiments to determine if the drift is due to calibration instability of the instrument or to heating of the instrument by the sun. In laboratory experiments, after a warm-up period, the instrument provided constant readings in the range 25 to 40°C; above 40°C the response of the instrument was unpredictable. In field experiments, where we placed the EM-38 in a fixed location we observed an unexpected response at air temperatures below 40°C. Temperature sensors in different locations on the instrument demonstrated that temperature differences between the instrument's transmitting and receiving coils and the control panel (CP) were as great as 20°C. As the instrument is temperature compensated from this CP, erroneous compensation occurred when the instrument was placed in direct sunlight. In this study, we demonstrate that differential heating of the EM-38 is one cause of drift and erroneous bulk electrical conductivity measurement; shading the instrument substantially reduced this problem, effectively extending the reliable working temperature range by minimizing drift.

THE CONCEPT OF USING induced electromagnetic fields to measure ground conductivity has been applied in the geosciences for more than 50 yr (Belluigi, 1948; Wait 1954, 1955, 1982). Induction methods were used extensively for ore prospecting as metallic ore bodies can have substantial electrical conductivity (Keller and Frischknecht, 1966). They were also used for well logging in the petroleum exploration industry (Keller and Frischknecht, 1966). Noninvasive instruments were first considered for use in agriculture by De Jong et al. (1979). Since then the technique has been used to map a variety of physical quantities with which EC_a correlates (e.g., salinity, moisture, and clay content). Water content has been estimated from measurements of EC_a by Kachanoski et al. (1988) and Sheets and Hendrickx (1995), salinity by a number of authors (Corwin and Rhoades, 1982; Wollenhaupt et al., 1986; Hendrickx et al., 1992; Rhoades, 1993; Lesch et al., 1995a, 1995b; Rhoades et al., 1999), and inferring differences in mineralogy by Triantafilis et al. (2000). Increasingly, applications are being identified in precision agriculture for determining nutrient status and potential yield (Corwin and Lesch, 2003; Corwin et al., 2003).

The EM-38 has been adapted for general mapping in agriculture, an example is the Lower Colorado Region Salinity Assessment Program. This is a network of people and organizations that are committed to improving the assessment of soil salinity in agricultural fields in the Southern Colorado region to guide management decisions (http://www.ussl.ars.usda.gov/lcrsan/LCRhome.htm; verified 7 Oct. 2003). Soil mapping survey units consisting of converted spray rigs, mounted with dual dipole EM-38 units and GPS, have been used to map agricultural fields (Rhoades, 1993; Lesch et al., 1995a, 1995b; Triantafillis et al., 2002). Data has been analyzed using ESAP computer software to produce maps and statistical sampling plans (http://www.ussl.ars.usda.gov/MODELS/esap-95.htm; verified 7 Oct. 2003). As this network of users has developed, large amounts of data have been collected and some anomalous results have been observed.

The term drift has been used to describe disparate values in EM-38 data, collected at different times from the same location, that cannot be accounted for by changes in water content or soil temperature. The causes

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Abbreviations: CP, control panel; EC_a, bulk soil electrical conductivity; H_i, induced magnetic field; H_p, primary magnetic field; Rx, receiving coil; Tx, transmitting coil.

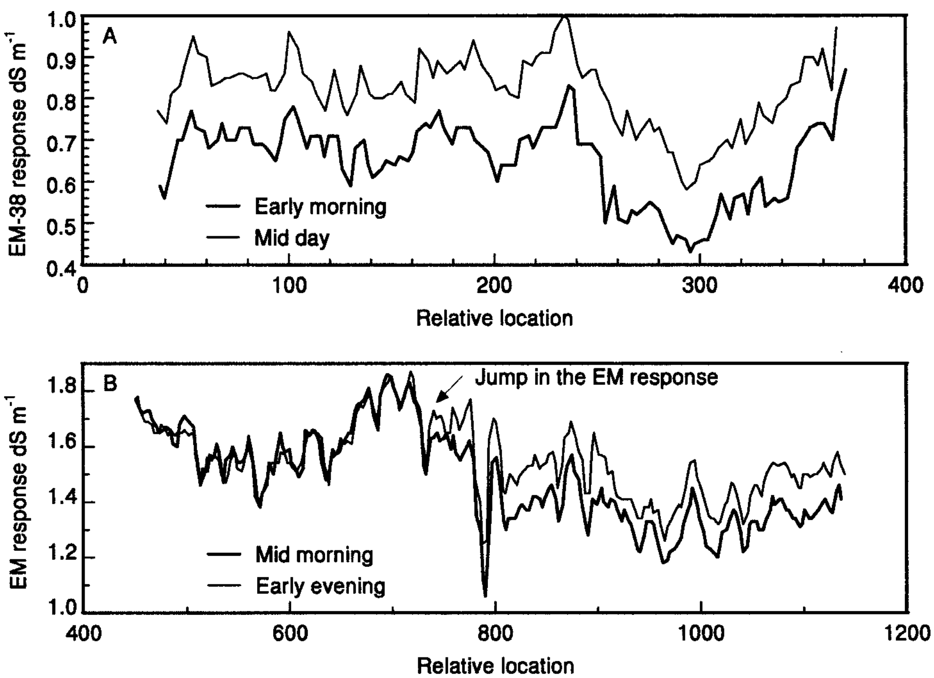

Fig. 1. (A) Data from field mapping where the same row was run in the morning and again later in the day showing responses that follow each other with an offset. (B) A similar data set from another field site run in the morning and again later in the day, where the response jumps at point 730.

of drift are considered to be two-fold, the first arising from the coil spacing and the second due to thermal distortion of the coils. In the case of the EM-38 the spacing between the coils is fixed, the second forms the subject of this piece of work. In an experiment with a static EM-38 Sudduth et al. (2001) noted that as temperature increased, the in-phase I/P reading of the EM-38, which should be zero decreased and as a result the measured EC_a was observed to increase. It is common practice to take measurements along a plough row in a field and then later in the day return to that row to repeat the measurements (Sudduth et al., 2001). This operation is known as running a drift row. Figure 1A shows the values of EC_a along a row where measurements were collected early in the morning and later in the day. The readings correspond to the instrument in the vertical orientation. In Fig. 1A, the readings of the later run are offset by an increase of about 20%. Given the depth of EC_a measurement, this could not be accounted for by changes in soil temperature.

Figure 1B shows another anomaly between EC_a data collected in the morning and in the evening. The data from the evening initially coincides with the data from the morning, then unexpectedly a jump occurs wherein the data follows the same pattern but is shifted upwards by 10%. The cause of these anomalies is unknown and users have suggested that the calibration of the instrument is unstable. If this is the case, maps of soil properties, such as nutrient status, can potentially contain substantial errors.

Our impression from working with the instrument was that drift effects appeared more pronounced on hot sunny days. The Geonics manual suggests that the working range of the instrument is 5 to 50°C. However, in a personal communication with Geonics, we were informed that the instrument is only temperature compensated up to 40°C. Each probe then has its own systematic temperature response characteristic above this temperature. With this information in mind, we designed a set of experiments to determine the effect of environmental temperature on the repeatability of EM-38 measurements. Our objective was to determine the source of drift by: (i) evaluating the stability of EM-38 calibration and (ii) determining the impact of heating on the EM-38 response. These experiments were performed in the laboratory and under field conditions to find a solution for instrument drift and to reduce measurement error.

MATERIALS AND METHODS

Instrument Background

A schematic diagram of the EM-38 is presented in Fig. 2 showing the location of induced magnetic fields during operation. A transmitting coil (Tx) in one end of the instrument creates a primary magnetic field (H_p). This field creates current loops in the ground below and the current loops induce their own magnetic field (H_i). The induced field is superimposed on the primary field and both H_p and H_i are measured in a receiving coil (Rx) at the other end of the instrument (McNeill, 1980). The measured response is a function of ground conductivity, which is linear in the range of soil conductivity of 0 to 10 dS m^{-1}. Measurements of ground conductivity can be made with the instrument in either the vertical or horizontal orientation. In the horizontal orientation the instrument measures to a depth of about 0.75 m with the greatest sensitivity just under the instrument. With the instrument in the vertical orientation it measures to a depth of about 1.5 m with the greatest sensitivity at about 0.4 m.

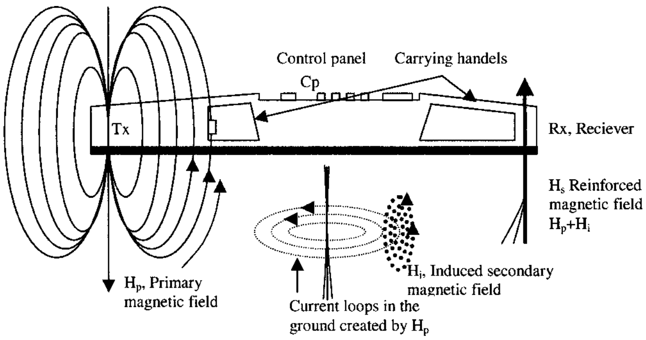

Fig. 2. Schematic diagram of the EM-38, which is 1 m in length. Tx is the transmitting coil and Rx is the receiving coil. Locations CP and Rx are where the temperature sensors were placed.

A standard single dipole EM-38 was used throughout the experiments. A second single dipole EM-38 was used to replicate both the indoor and outdoor experiments. The instruments were calibrated using the described standard method. The probe was placed 1.5 m above the ground on a wooden support; the vertical and horizontal readings were adjusted until the vertical read twice the value of the horizontal. The instruments were calibrated after a warm-up period of 2 h. The calibration was checked for consistency after each experimental run.

During the experiments we measured the temperature of the air, soil, and two parts of the instrument, the CP under which the instrument circuit is located, and at the receiving coil Rx (Fig. 2). Thermocouples, connected to a Campbell CR10x data logger (Campbell Scientific Inc., Logan, UT) were used to record the temperature every minute.

Controlled Experimental Setup Indoors

Indoor experiments were conducted with the EM-38 so that the temperature of the surroundings could be controlled. The first objective was to verify the reliability of EM-38 calibration. The EM-38 was calibrated and placed in a large room where temperature was maintained at 22 ± 1°C. The instrument was placed on a plastic drum, 1 m above the ground and kept in the vertical orientation for all experiments. By doing so the instrument response to the ground, primarily the rebar (iron rods) in the concrete could be evaluated. EM-38 measurements were taken every minute and recorded on a Polycorder located several meters from the instrument.

The second objective was to determine the reliability of the instruments temperature compensation. This was performed by warming the instrument with an electric blanket. Preliminary tests were conducted to ensure that the blanket did not interfere with the response of the EM-38. The response was measured without the blanket, with the blanket wrapped around the central 50 cm of the instrument and with the instrument completely covered. No effect was observed, the same conditions were repeated, but this time with the blanket switched on. Finally, the blanket was switched on and off repeatedly to see if this had any impact on the EM-38 response, again no effect was observed.

We conducted two experiments using the blanket to heat the instrument. The first determined the effect of differential instrument heating and the second determined the effect of uniform instrument heating. In the first of these experiments localized heat was applied to the EM-38 circuit (CP, Fig. 2) in the central 50 cm of the instrument while maintaining the rest of the instrument and the environment at constant temperature and constant electrical conductivity.

The second experiment was used to determine the response of the instrument to uniform warming. This time the entire instrument was wrapped in the blanket and heated. In both experiments the temperature of the instrument was raised to a maximum of 55°C. This is a temperature commonly experienced during summer in the Southern USA.

Outdoor Experiments

Outdoor experiments at the U.S. Salinity Laboratory were conducted on bare soil (Arlington, sandy loam) that was irrigated once per day at 0600 h. Measurements were made on a series of warm sunny days in June and July of 2002 when the weather was similar to that commonly experienced during typical fieldwork. The EM-38 response was recorded continuously over a 10-h period beginning at 0900 h using a Polycorder located several meters from the instrument under shade. High temperatures did not affect the performance of the Polycorder. The experiments were run with the EM-38 in the vertical orientation. This allowed measurements of EC_a to be obtained from a depth where soil is least subject to changes in temperature or water content. The EM-38 was positioned on a 2.5-cm thick piece of wood placed on the ground to prevent heating from the soil and to ensure the same daily location. Soil temperature (10-cm depth) was also monitored at the beginning of each experiment. This was performed around mid-day and in the late afternoon, using a handheld temperature probe. The calibration of the instrument was checked periodically and found to be consistent. A final experiment on an asphalt surface was performed by placing the EM-38 in the vertical position on a 2.5-cm thick wood on top of asphalt. During the first 160 min the instrument was shaded, after that time the shade was removed and EC_a and temperatures at CP and Rx were recorded for 600 min.

RESULTS AND DISCUSSION

Controlled Experiments Indoors

Experiments were conducted indoors in a controlled environment to best define EM-38 response to constant temperatures, differential heating, and elevated temperatures. In the first experiment the instrument was switched on and run continuously at a constant air temperature of 22°C. The readings of the EM-38 were constant during a 12-h uninterrupted time period. This simple experiment was necessary to test the stability of the calibration of the EM-38. Since no jumps or sudden changes in EC_a were recorded and the readings remained constant this demonstrated that the cause of the drift was not unstable calibration.

In the next experiment the central section of the EM-38 containing the instrument circuit board was warmed using an electric blanket, while the transmitting and receiving coils were maintained at the ambient room temperature. The temperature of the receiving coil, floor, and air were monitored and remained constant at 22°C. The response, which was replicated by another single dipole EM-38 (data not shown), showed that as the instrument panel and circuitry warmed up, the instrument electrical conductivity response decreased (Fig. 3). This suggested that the instrument temperature compensation was located at, and controlled by, the instrument circuit board under the black CP (Fig. 2). This also suggests that the temperature compensation is provided for the coils and not the circuit. If the circuit were

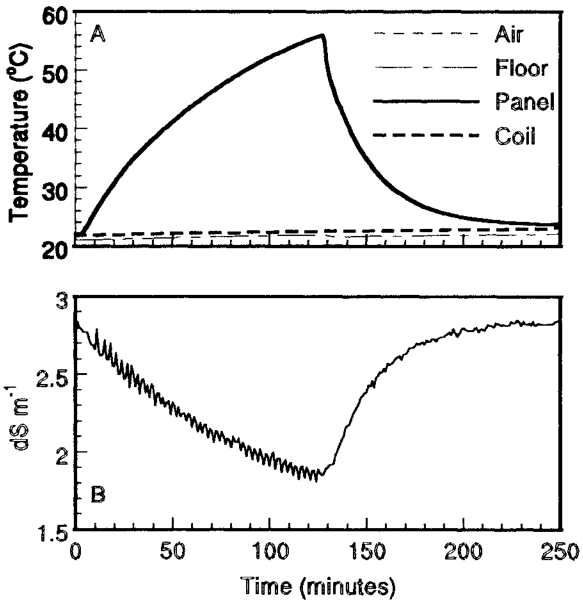

Fig. 3. (A) Temperature response for control panel (CP) and receiving coils (Rx) of the EM-38 with the central 50 cm of the instrument wrapped in an electric blanket and warmed. (B) The soil bulk electrical conductivity (EC_a) response, which reduces as the instrument panel is warmed.

temperature compensated, a constant EC_a value would be expected. The temperature compensation design assumes that the instrument is at a uniform temperature, and that the coils (Rx in Fig. 2) are at the same temperature as the circuit. These findings were corroborated by the third experiment.

The results from the third experiment with the instrument completely wrapped in the blanket and heated uniformly are presented in Fig. 4. This experiment demonstrates more clearly the temperature compensation of the instrument. For the first 120 min, while the temperature is below 40°C, the instrument effectively compensates for temperature changes and provides a constant reading. Above 40°C, when the increase in temperature is more abrupt, the EC_a value measured by the EM-38 increased. The EC_a reading rose from 2.8 dS m^{-1} to a maximum value of 3.2 dS m^{-1} occurring at 46°C (Fig. 4B). As the temperature continued to rise the EC_a reading began to decline (Fig. 4C). When the instrument was allowed to cool down the EC_a response dropped below the initial value. By the time we checked the probe the following day the reading was back to normal and the instrument was in calibration. It is interesting to observe that the temperature of the circuit, under the CP, was slightly higher than the temperature of the receiver (dashed line in Fig. 4). This higher temperature may be due to differing thermal properties of the materials used to construct the instrument.

Outdoor Experiments on Bare Soil Surface

Experiments were conducted on bare soil during a 2-wk period at the end of June and beginning of July 2002, which showed a range of shade temperature. Results for the CP temperature, temperature difference between CP and Rx, and EM-38 response for the five experimental runs are presented in Fig. 5. All the experiments started at 0900 h and finished at 1900 h. The scale in Fig. 5 is relative, showing the time from the beginning of the experiment, when the instrument was switched on, to the end of the experiment. The experiment was designed to mimic a typical data collection day where the instrument had been stored overnight at 20°C, taken outside, and used immediately.

The first four experiments were run with the instrument directly exposed to the sunshine. The EM-38 response for these 4 d is presented in Fig 5C. Day 1 was an extremely hot day with shade temperatures reaching

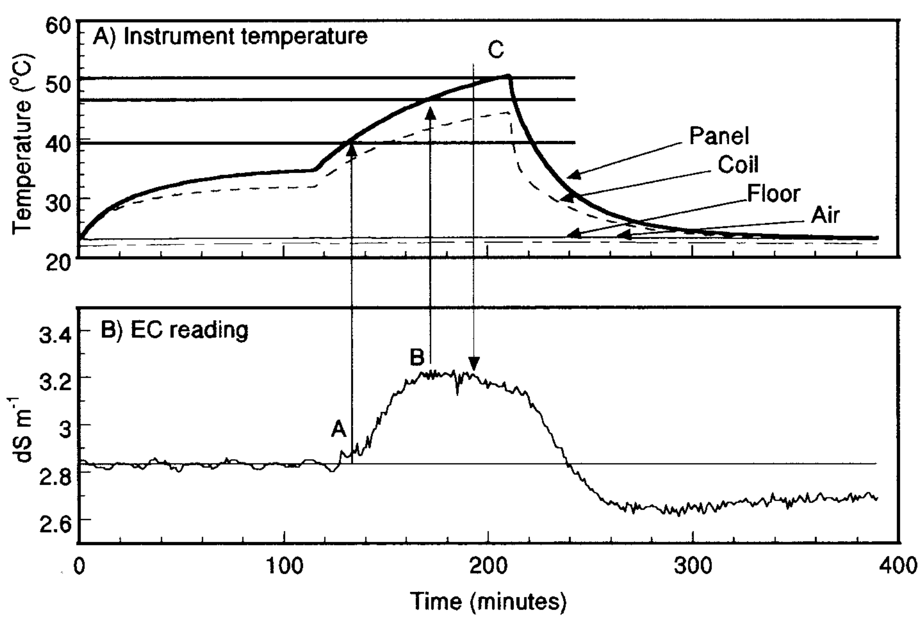

Fig. 4. (A) Temperature response for control panel (CP) and receiving coil (Rx) of the EM-38 with the whole instrument wrapped in an electric blanket and warmed. (B) The soil bulk electrical conductivity (EC_a) response, which demonstrates the temperature compensation up to 140 min and then an unpredictable response as temperature increased above 40°C.

45°C; Days 2 to 4 were progressively cooler. During Days 2 to 4, (i) EC_a data was observed to increase slowly in the first 120 min of the experiment. (ii) A plateau was reached for about 30 min, then (iii) values dropped as temperatures continued to increase. This was similar to the pattern of measured EC_a, increasing, stabilizing and then dropping as the temperature increased observed during the indoor experiments (Fig. 4) The temperatures at which these events occurred (40, 48, and 52°C) were also identical (Fig. 4 and 5). On all days the instrument response showed jumps of increasing EC_a as the instrument began to cool. This occurred between 430 and 550 min, on Days 1 through 4 and showed no consistent pattern.

On Day 1, the temperature of the CP of the instrument at 0900 h was already 40°C. The response of the instrument on this day was displaced with respect to Days 2, 3, and 4 (Fig. 5C). The increase, plateau, and decrease in response observed, when the CP temperature reached 40, 48, and 52°C, occurred at the beginning of the experiment. In fact, by the time we started recording a plateau could be observed which subsequently decreased soon after. This decrease reached a 20% drop below 0.5 dS m^{-1} at the warmest part of the day.

Figure 5B shows the difference in temperature between the instrument CP and the receiver coil during the experiment. In the middle of the day, the temperature of the Rx was 20°C lower than in the CP. It appears that the instrument is temperature compensating the coils for temperatures they are not experiencing. This difference in temperature between the CP, where the temperature sensor and compensation is located, and the receiver coil, for which it compensates, is in part due to the black metallic CP cover. The overestimation of receiver coil temperatures places the instrument out of operational range for most of the day, when it is in direct sun light, resulting in erroneously low values of EC_a.

The last experiment was performed on a day with temperatures equivalent to Day 3. This time the instrument was entirely shaded using a white PVC plastic

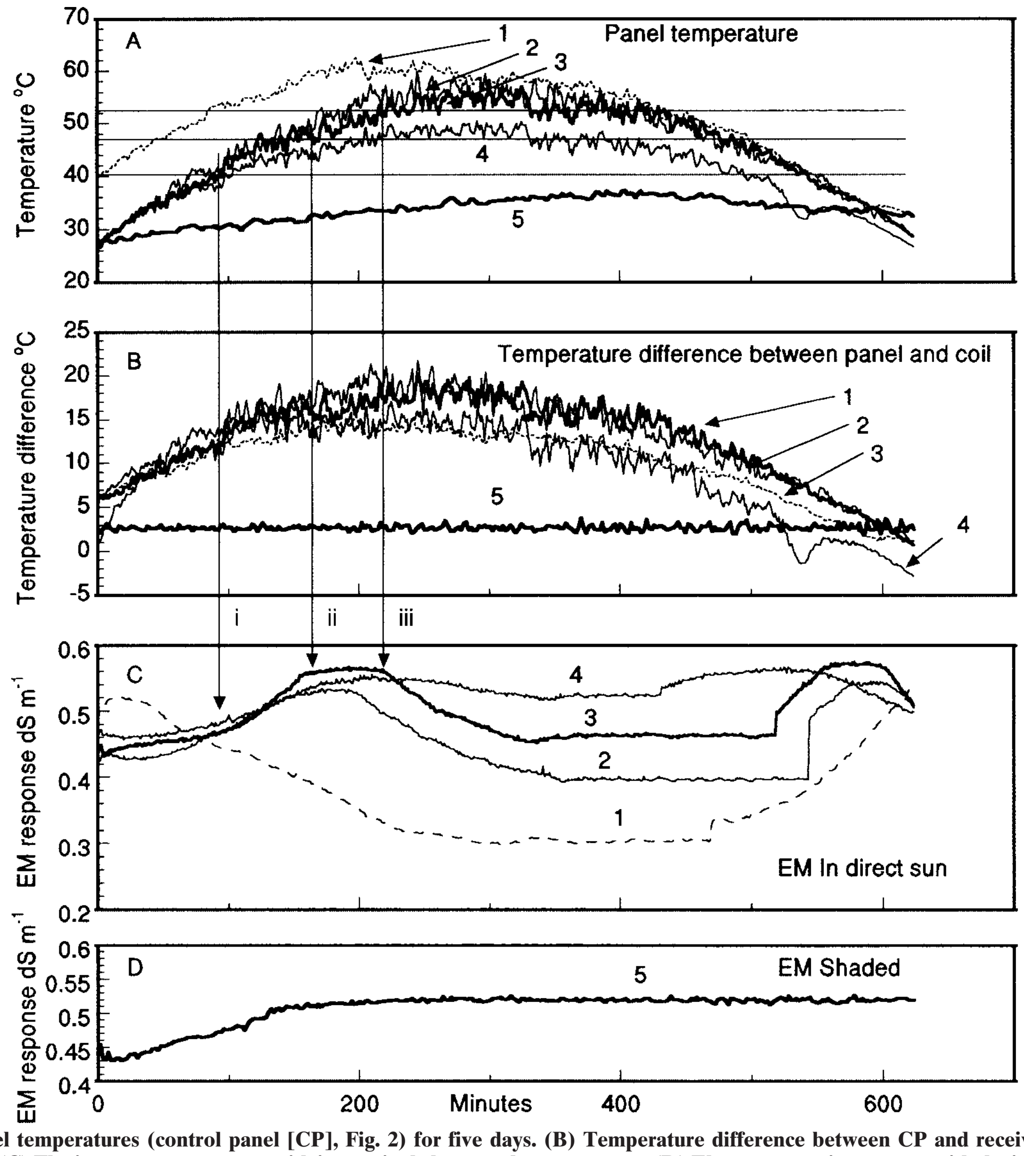

Fig. 5. (A) Panel temperatures (control panel [CP], Fig. 2) for five days. (B) Temperature difference between CP and receiving coil (Rx) for the five days. (C) The instrument responses with increasingly hot panel temperatures. (D) Electromagnetic response with the instrument shaded.

cover. The results for this experimental run became relatively consistent after 120 min, indicating constant soil EC_a, as was expected (Fig. 5D). In the first 120 min of this experiment a 14% increase in measured EC_a was observed coincident with a 2 to 3°C increase in soil temperature (10-cm depth). However, the instrument had been placed in the vertical orientation to avoid response to surface soil heating or water loss. Even if the instrument had responded to a change in soil temperature, it was not sufficient to account for the 14% increase in measured EC_a. This slow increase in instrument response was likely due to a required warm up period. The instrument was stored in the laboratory over night at 20°C and took time to re-equilibrate to the outdoor temperature. We found that the instrument typically required at least 2 h to adjust when the difference between instrument storage temperature and outdoor temperature was 10°C or more. Though not shown these measurements were replicated with a different EM-38 borrowed from colleagues and similar results were observed.

There is always a concern when making measurements on soils that the responses observed are due to changes in water content, or due to changes in the soil temperature and thus EC_a. We have suggested in our argument that the changes in these factors would not be consistent with the observed EM-38 response. However, we conducted a further experiment using the previously described setup but with the instrument located on an impervious asphalt surface. By so doing we could completely rule out a change of water content influencing the results. The heating of the asphalt might be predicted to cause a small if noticeable increase in bulk electrical conductivity measured. Results from this experiment are presented in Fig. 6. During the first 160

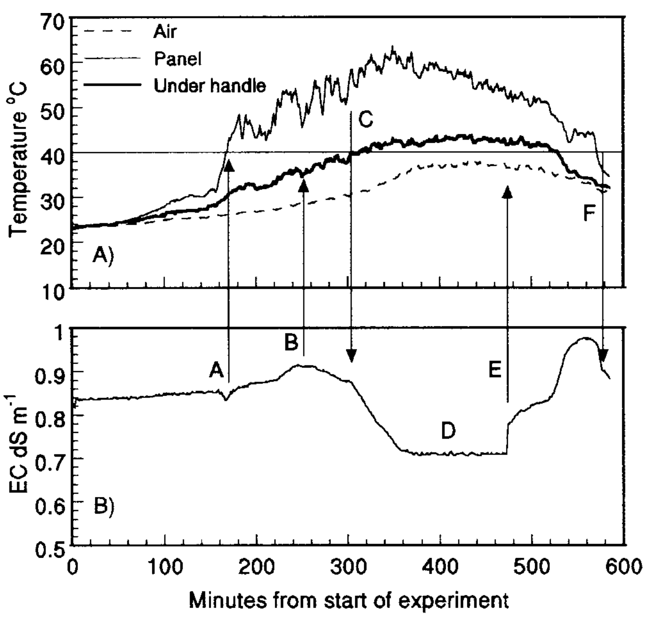

Fig. 6. (A) Temperature of the EM-38 corresponding to the locations under the handle (receiving coil [Rx], Fig. 2) and on the panel (control panel [CP], Fig. 2) of the instrument. (B) The soil bulk density of electrical conductivity (EC_a) response on the asphalt in the vertical orientation without being moved, Points A-E are described in the text.

min the instrument was covered with a shade and as expected there was a marginal increase in the measured bulk electrical conductivity. The shade was removed at the time denoted by Line A and the panel temperature rose rapidly. The EC_a response showed a small fluctuation rising and reaching a peak value with the panel at 48°C (Fig. 6, Point B). As the temperature continued to rise the EC_a response declined slightly. This decline became steeper once the temperature in the panel reached 52°C. Notice that the temperature under the handle, next to the coil reached 40°C (Fig. 6, Point C). This behavior was identical to the indoor experiment shown in Fig. 3 in which we increased the temperature abruptly in the central part of the EM-38. The signal bottomed out at a value 17% lower than the initial value measured in the morning (Fig. 6, Point D). At Point E the instrument response increased abruptly as temperatures were declining. Although the response increased, it didn't reach an EC_a level similar to the morning until all the temperatures dropped below 40°C (Fig. 6, Point F). The response of the instrument on the asphalt confirmed the instrument sensitivity to heating in direct sunlight.

Drift Observed in Field Mapping Data

Our data indicated that differential heating of the instrument and CP temperatures over 40°C were one of the causes of drift. The cause of this drift comes primarily from the elevated instrument CP temperature (40+°C), or lack of instrument warm up time when taken to a new environment with differing temperature. Our findings appear to be in good agreement with those of Sudduth et al. (2001) who found a strong correlation between temperature increase and EC_a decline for field measurements using a vertically oriented EM-38. We agree with the comments of Sudduth et al. (2001) who suggested that an I/P compensation in the instrument was required. There is only a limited amount that can be achieved by producing field compensations. It appears that the drift is a combination of instrument factors that come down to circuit design, placement of temperature compensation sensors, and coil performance under heating. If the circuit cannot be improved it would be of great use to users in hot areas if information such as I/P and coil temperature could be recorded on the data logger. This means that potentially inaccurate data could be removed from survey data.

In a personal communication with Geonics, we were informed that the effect of temperature on the instrument above 40°C is an absolute value. As an example a 0.05-dS m^{-1} absolute change for a ground conductivity of 0.5 dS m^{-1} is a 10% change. However, at 5 dS m^{-1} this is only a 1% change. The drift highlighted in Fig. 1A can be explained by an insufficient warm-up period of time with the instrument having been taken from an air-conditioned lab or truck before use in the field. This may also explain why some users have trouble calibrating the instrument when arriving at field sites. Calibrating the instrument when it has not been given time to equilibrate with outdoor temperatures and warm-up will give a false calibration, as the instrument subsequently warms it may go out of calibration. We recommend as for many electronic instruments a 1-h warm up for the electronics (instrument switched on), and time to equilibrate with ambient temperatures before checking instrument calibration (total of 2 h).

The jump observed in the data in Fig. 1B is consistent with jumps in recorded EC_a at around 550 min in Fig. 5C, these jumps happened again toward the end of the day as the instrument cooled down. We suggest that many of these problems might be avoided by shading the instrument as demonstrated in Fig. 5D. Since data collected with clear skies and temperatures above 40°C are likely to cause erroneous measurements, this simple solution of shading the instrument should extend the working range of the EM-38; giving more accurate EC_a responses. Surveys conducted at air temperatures above 40°C are likely to result in erroneous underestimation of EC_a.

CONCLUSIONS

Results presented in this work demonstrate that drift observed in field data collected with the EM-38 is in part due to elevated temperature conditions. When the CP temperature rises above 40°C spurious EC_a measurements occur with EC_a being increasingly underestimated as temperature rises. Results suggest that shading the instrument and keeping its operating temperature below 40°C can substantially improve results. This can reduce the instrument panel temperature by as much as 20°C. This is where the temperature compensation circuitry is located and this can effectively extend the working range of the instrument. We recommend allowing 2 h for instrument warm up before calibration. We suggest that this lack of warm-up time could be one cause of drift often observed when rows are duplicated as a check on readings during a survey. Following these simple steps could improve measurement accuracy by as much as 20% at low conductivity values.

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