Soil salinity mapping with electromagnetic induction and satellite-based navigation methods

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Cannon, M. E., McKenzie, R. C. and Lachapelle, G. 1994. **Soil salinity mapping with electromagnetic induction and satellite-based navigation methods.** Can. J. Soil Sci. **74**: 335–343. This project was undertaken to develop a system to map salinity with a towed **electromagnetic induction meter (EM)** and to position the meter with the **Global Positioning System (GPS).** The characteristics of the GPS are reviewed and the **differential GPS (DGPS)** mode of positioning, as applied to the EM meter positioning case, is explained. An EM38 salinity meter was time synchronized to GPS through a field portable **personal computer (PC)** and mounted on a non-magnetic toboggan for this purpose. The PC was also used to record all data for post-processing and analysis. The system was towed at velocities of up to 25 km h^{-1} during the field measurements. Continuous positioning of the system was achieved with an accuracy of 1–3 m. Salinity and GPS measurements were integrated and recorded on a field portable PC laptop. The results from a 30-ha site near Brooks are presented as well as those from a 100-ha site near Stettler, AB, which was surveyed in 3 h yielding 6000 salinity measurements. In order to test the repeatable accuracy of the system, the survey at Stettler was repeated the following day. The agreement is of the order of 1 dS m^{-1} which is satisfactory for most applications. The effect of measurement spacing on accuracy is also analysed using various scenarios.

Key words: Soil electrical conductivity, salinity, satellite navigation, Global Positioning System, positioning, precision farming

Cannon, M. E., McKenzie, R. C. et Lachapelle, G. 1994. **Cartographie de la salinité du sol au moyen des methodes d'induction électromagnetique et de navigation par satellite.** Can. J. Soil Sci.**74**: 335–343. Le projet ci-décrit a pour but de développer un système pour la détermination de la salinité du sol à l'aide d'un compteur électromagnétique remorqué. Le système est positionné à l'aide d'un récepteur GPS. Les caractéristiques de ce système sont présentées et le mode de positionnement différentiel utilisé dans ce cas est décrit. Un compteur de salinité EM38 est réglé sur le temps GPS à l'aide d'un ordinateur portatif et l'ensemble est installé à bord d'un traîneau démagnétisé. L'ordinateur sert également à l'enregistrement des données pour le traitement et l'analyse en mode différé. Pendant les mesures, le système est remorqué à des vitesses allant jusqu'à 25 km h^{-1} et une précision de 1 à 3 m est obtenue. Les positions et mesures de salinité sont emmagasinées sur l'ordinateur portatif. Les résultats d'un levé de 30 ha, situé près de Brooks, et d'un levé de 100 ha, accompli en trois heures, près de Stettler, Alberta, sont présentés. Quelques 6000 mesures de salinité ont été obtenues lors du levé de 100 ha. La précision répétitive du système a été vérifiée en refaisant le levé de Stettler le lendemain. La concordance des mesures est de l'ordre de 1 dS m^{-1}, ce qui suffisant la plupart du temps. L'effet de l'espacement des mesures est également analysé pour plusieurs cas.

Mots clés: Conductivité electrique du sol, salinité, navigation par satellite, Global Positioning System, positionnement, aviculture de précision

Soil salinity is a major cause of reduced crop production on many soils, especially in western Canada. Authors disagree as to how much land is affected by salinity. In Alberta, estimates vary from 0.32 million ha of secondary salinity (Pettapiece and Eilers 1990) to 1.57 million ha due to saline seepage (Vander Pluym 1982). In Saskatchewan, Anderson and Knapik (1984) estimated the amount of salinity on improved land to be 0.6 million ha but cite other reports with estimates of 1.2, 1.6, 1.7 and 2.0 million ha. Published estimates are based on insufficient data due to the high costs of labour and laboratory analyses associated with traditional mapping of salinity. Estimates based on remote sensing of salinity of large areas are subjected to errors unless extensive ground truthing is conducted.

Anderson and Knapik (1984) report various estimates of the annual rate of the increase of soil salinity which range from 10 to 16% by McCracken (1973), 10% by Vander Plym (1982), to 0.8% by the authors themselves. This lack of consensus on the rate of increase has developed because too few detailed measurements such as done by Ballantyne (1978) have been made to determine the seasonal and annual variations in the extent and severity of salinity.

Electromagnetic Induction Method

A relatively recent method for rapid measurement of soil salinity uses the electromagnetic induction meter (McNeil 1986). Experiments conducted by the Alberta Special Crops and Horticultural Research Center (ASCHRC) during recent years with the EM38 have demonstrated the capability and effectiveness of the method (McKenzie et al. 1988). The apparent soil salinity measurements (EC_a) obtained with an electromagnetic induction meter, such as the EM38, change with soil temperature, texture and moisture and can be converted to saturated paste extract equivalents (EC_e) (McKenzie et al. 1989). A weighted salinity value (EC_e) for the profile is then determined according to Wallenhaupt et al. (1986).

Because modern equipment, such as the EM38 meter, does not require direct soil contact, a large number of salinity

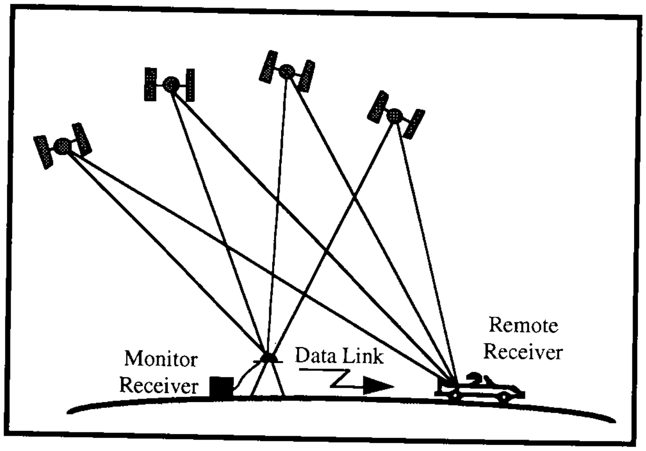

Fig. 1. GPS in the differential mode of operation. The data link is required when DGPS is used in real time.

measurements can be obtained at a lower cost than by conventional salinity mapping techniques (McNeil 1986). Digital data logging equipment and computer drafting technology have also been used to allow the preparation of salinity maps on the basis of detailed EM38 grid surveys (McKenzie et al. 1988). Conventional EM salinity measurements are carried out either by an operator carrying the unit or with the unit mounted on a non-magnetic toboggan towed by a vehicle such as an **all-terrain vehicle (ATV)** at operating speeds of 10–20 km h^{-1}. The latter method allows for some 20–40 ha per day to be surveyed when mapping on a 10 m × 40 m (33′ × 130′) grid. This grid survey method is, however, still restricted by the ATV positioning limitations as follows:

(i) a time-consuming survey is first required to establish a grid pattern prior to the salinity measurements,
(ii) the ATV moves along presurveyed lines, which are usually straight,
(iii) many position errors occur, which often make it difficult to correlate the soil salinity measurements with existing maps,
(iv) irregular topography and brush can severely limit the ATV-based straight line technique,
(v) where the salinity varies rapidly, such as adjacent to saline seeps along an irrigation canal, it may be difficult and/or not cost-effective to conduct more dense measurements to map salinity with the required accuracy, and
(vi) adequate and cost-effective quality control of the salinity measurements may be difficult to achieve due to the above limitations.

The use of GPS in differential mode, removes the above limitations and substantially increases the cost-effectiveness of vehicle-borne EM salinity measurements.

Fundamentals of GPS

GPS is being deployed by the US Department of Defense. The signals are transmitted on two carrier frequencies, namely L1 at 1575.42 MHz and L2 at 1227.6 MHz. At these frequencies, signal attenuation due to rain or other weather phenomena is minimal, making GPS an all-weather system. Line-of-sight between the satellites and the user's antenna is, however, required because waves at these frequencies travel along a straight line which is important to measure accurate ranges and range differences to the satellites but, at the same time, it limits the usefulness of GPS in tree-covered, mountainous and built-up areas.

Over 20 of the projected 24 satellites were operational when these tests were carried out. The configuration was adopted to provide practically continuous worldwide coverage. A ground control network consisting of five stations continuously track the satellites to determine their satellite clock behaviour and orbits. Each satellite is equipped with cesium clocks to keep precise GPS atomic time which is common to all satellites. The receiver time is not synchronized to GPS time and this bias is determined as part of the position estimation process. Pseudo-ranges are therefore the ranges plus a range bias caused by the receiver time bias.

The most effective method to eliminate or reduce many of the error sources associated with GPS is to use the differential mode of operation (Fig. 1). Differential pseudo-range corrections are formed at the monitor and transmitted via a telemetry link to the remote if the enhanced accuracy provided by DGPS is required in real-time. Since the errors are strongly correlated between the monitor and the remote, the differentially corrected positions at the remote are relatively accurate with respect to the position of the monitor. For distances of up to a few hundred kilometres between the monitor and the vehicle, the accuracy of DGPS, using standard C/A code receivers, is of the order of 1–3 m. The accuracy degrades as the separation between monitor and remote increases due to the gradual decorrelation of errors (Lachapelle 1991).

The equipment required to use GPS has evolved rapidly since the early 1980s. Size, power requirements, complexity of operation and costs have decreased dramatically. The initial cost of the post-mission DGPS system used here was approximately $20 000, including software and PCs.

The objective of this project is to develop and demonstrate a low-cost and accurate method of measuring and mapping soil salinity using DGPS and EM technology.

METHODS

A DGPS system and EM38 meter with analog output were assembled using field portable PCs (a 386 PC with a 150 megabyte hard drive). The GPS receivers used consisted of Magnavox 4200D units outputting code and carrier phase measurements every 1 s. These measurements were processed using the software package C^3NAV^{TM} (Cannon and Lachapelle 1992).

The GPS system was mounted on an ATV. The EM38 meter was placed in a non-magnetic toboggan which was towed about 2.5 m behind the ATV to avoid interference from metal in the ATV. The EM38 meter was operated in the vertical mode which measures ECa to approximately 1.2 m (McNeil 1986). The monitor GPS station was located

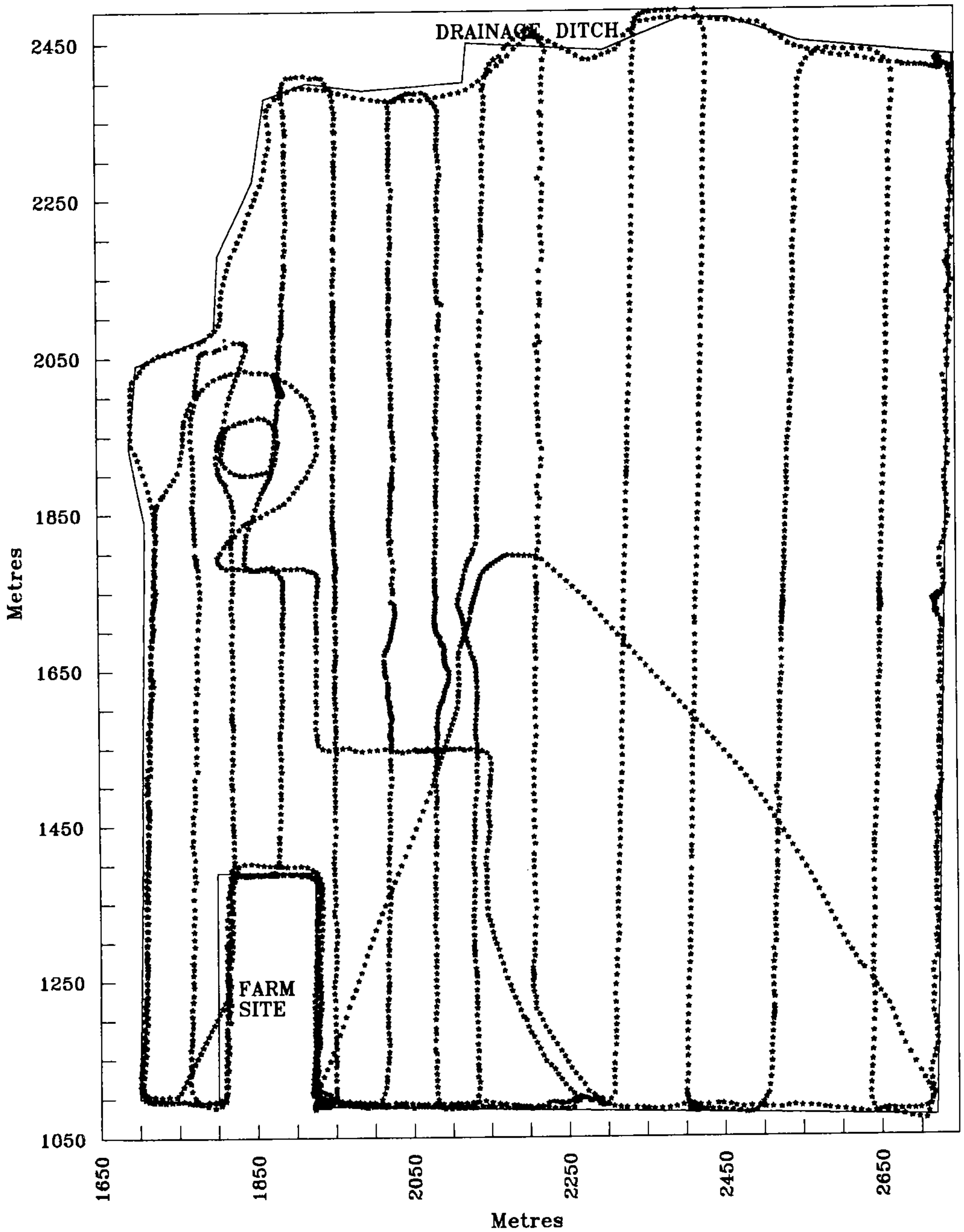

Fig. 2. EM-DGPS survey pattern, Stettler, 23 September 1992.

in one of the field corners in an identifiable location for future surveys.

In May of 1992 a survey was conducted near Brooks, AB, on the SE 3 20 14 W of 4. The surficial material was medium-textured glacio-lacustrine overlying Bearpaw Cretacious marine shales. The soils were Orthic Brown Chernozemic Brown Solonetz (Kjearsgaard et al. 1982) which had become partially salinized from irrigation. The purpose of this survey was to illustrate the use of crossover points to verify the internal consistency of the survey by analyzing the measurement agreement at the crossover points.

In September of 1992 a survey was conducted near Stettler, AB on 25 37 21 W of 4 on shallow glacio-fluvial material overlying Bearpaw marine shales (Bowser et al. 1951). The soils were Orthic Black Chernozemic and Black Solonetz sandy loams which had naturally occurring soil salinity and salinity from oil industry brine spills. A 120-ha field was surveyed on consecutive days, namely 23 and 24 September to analyze the overall repeatability of the mapping technique used. The line spacing on 24 September was half of that used on 23 September to assess the effect of this parameter on the results. In order to obtain a qualitative estimate of

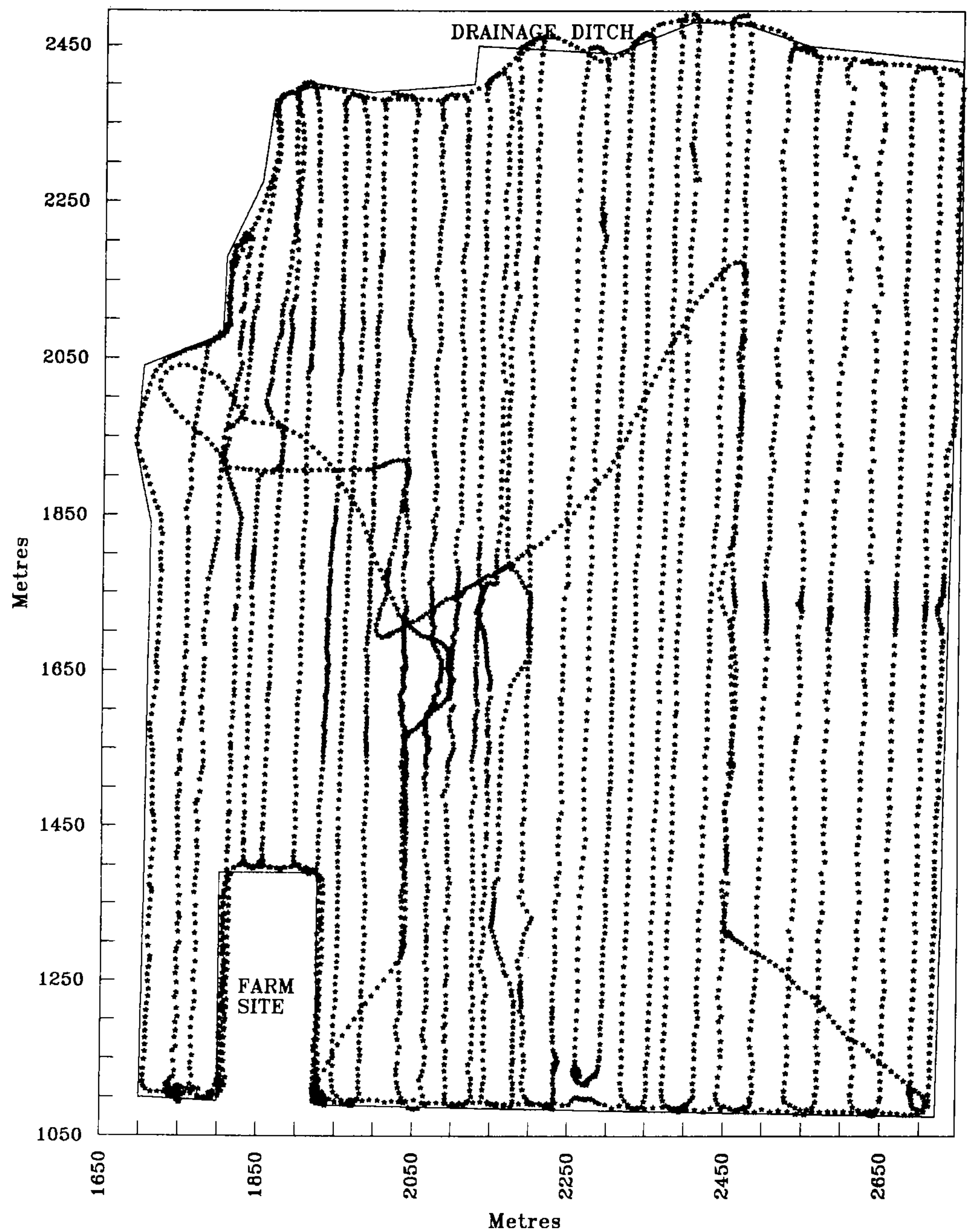

Fig. 3. EM-DGPS survey pattern, Stettler, 24 September 1992.

the interpolation errors, the 24 September survey was re-processed using approximately the same lines as used in the 23 September survey. Half the lines were therefore deleted. The conductivity values using the entire and decimated data sets were intercompared on a regularized interpolation grid. At the Stettler site salinity was determined by the saturated paste extract on soil samples taken at 12 locations. These locations were flagged and the ATV slowed momentarily when the EM38 was adjacent which permitted the locations to be identified on the map and provided a means of comparing the two methods of measuring salinity. Random trajectories zigzagging the parallel runs were made intentionally at the end of each survey to obtain crossover measurements (Figs. 2 and 3). The reason for the regularity of the line spacing is the presence of wheat swaths.

ANALYSIS OF RESULTS AND DISCUSSION

The pattern used near Brooks in May 1992 (Fig. 4) illustrates the use of crossover points to verify the internal consistency. The conductivity over the area ranged from 1 to 15 dS m^{-1} which is typical in a saline area (Fig. 5). The **root mean squared (rms)** error at the crossover points was

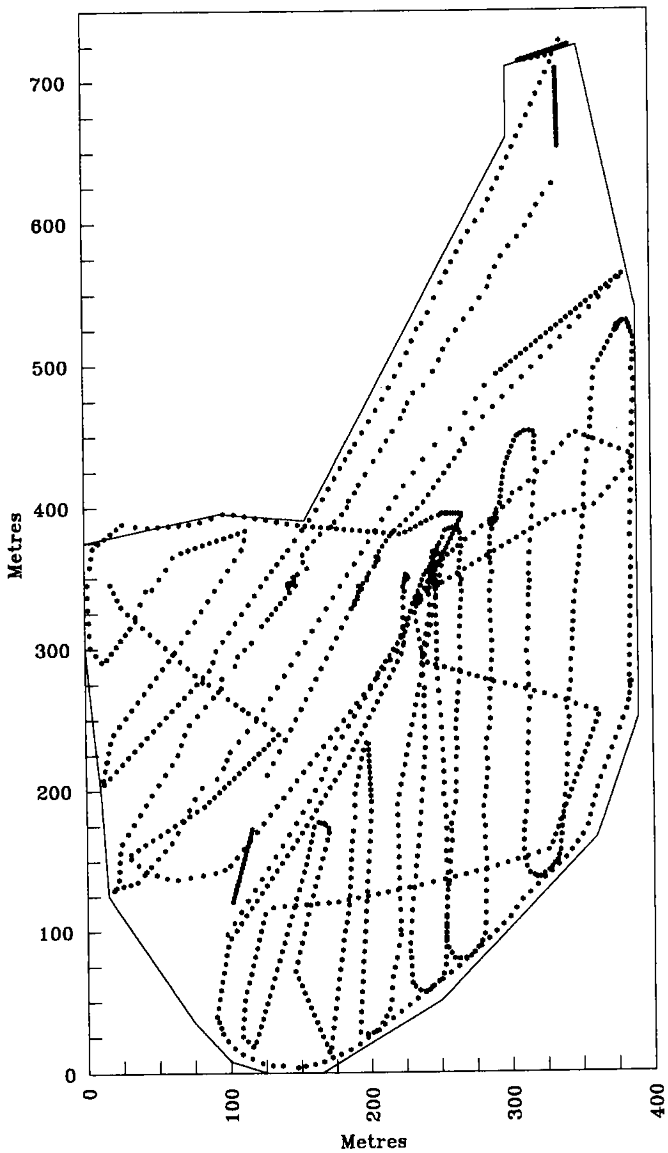

Fig. 4. EM-DGPS survey pattern, Brooks, May, 1992.

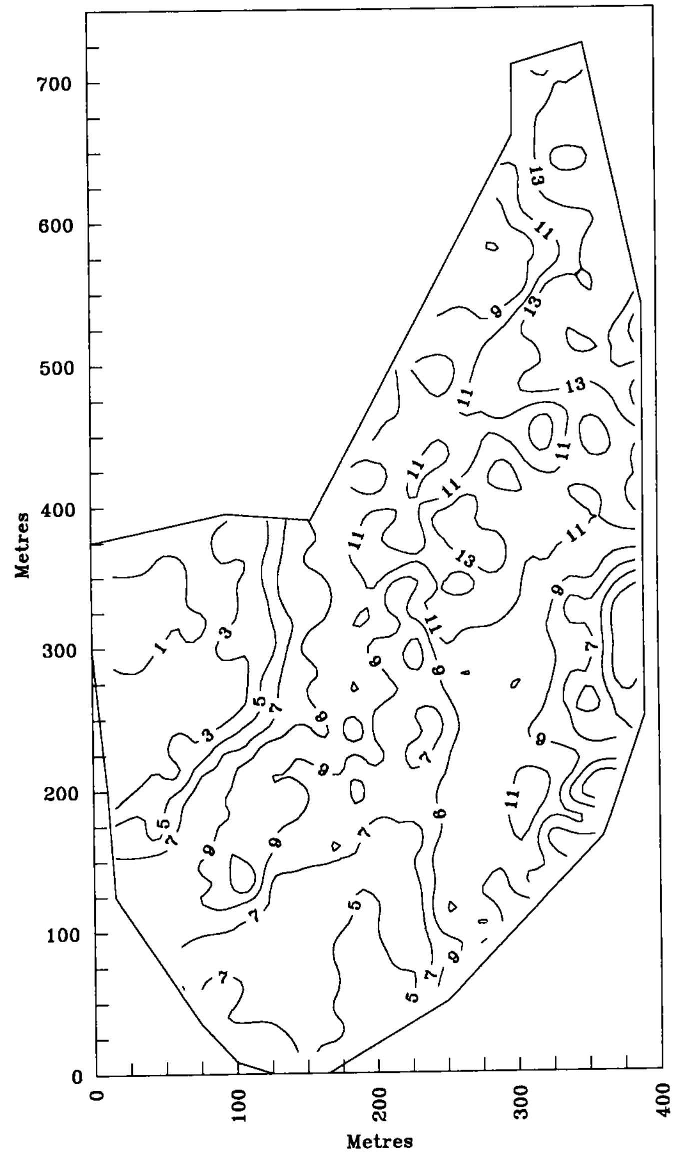

Fig. 5. Soil conductivity dS m^{-1}, Brooks, May, 1992.

of the order of 5%, which is within the accuracy range of the EM38 meter itself. The error contribution of DGPS was therefore negligible in this case.

At the Stettler site the 6000 data points shown in Fig. 3 were acquired in 3 h, confirming the high productivity of the EM-DGPS system. The measurements obtained at some 51 crossover points on 24 September yielded a mean EC_e difference of 0.3 dS m^{-1} and a rms difference of 1.1 dS m^{-1} (Table 1). These statistics were obtained using crossover points located within 1 m and are considered excellent since they take into account the EM38 measuring errors, the GPS positioning errors and the interpolation error over distances of up to 1 m. The same type of analysis was performed between the 23 and 24 September surveys. The mean and rms differences, based on 2744 sample points, were found to be 0.2 dS m^{-1} and 1.0 dS m^{-1}, respectively (Table 1). This confirms the 1 dS m^{-1} repeatable accuracy of the EM-DGPS method along the survey lines. These statistical comparisons are valid for the measurements along the survey lines. Interpolation errors are to be added quadratically to the above. These interpolation errors will depend on the horizontal conductivity gradients which are area dependent.

Figures 6 and 7 show the conductivity contour maps corresponding to the 23 and 24 September survey, respectively. The conductivity variations within each map range from 1 to 21 dS m^{-1}. Since the overall accuracy of the EM-DGPS system is estimated to be of the order of 1 dS m^{-1}, these measured variations are significant and reflect real salinity variations. In certain parts of the field, the variations exceed 10 dS m^{-1} within 100 m, which is considered high. The differences between the two maps reach 3 dS m^{-1} in places where the salinity variations are high,

Table 1. Consistency of EM-DGPS soil salinity mapping method (Based on 100-ha field, Stettler, Alberta)

Comparison type	Number of sample points	Mean difference ($dS\ m^{-1}$)	RMS[z] difference ($dS\ m^{-1}$)
Crossover points (same survey)	51	0.3	1.1
Day 1 vs. day 2	2744	0.2	1.0

[z]Root mean square.

indicating that the use of the denser survey yields a significantly more accurate salinity map.

In order to obtain a qualitative estimate of the interpolation errors, the 24 September survey was re-processed using approximately the same lines as used in the 23 September survey. Half of the lines were therefore neglected. The conductivity values using both the entire and the decimated data sets were intercompared on a regularized interpolation grid. Some 10% of the grid points showed differences in excess of 2 $dS\ m^{-1}$ as shown in Fig. 8.

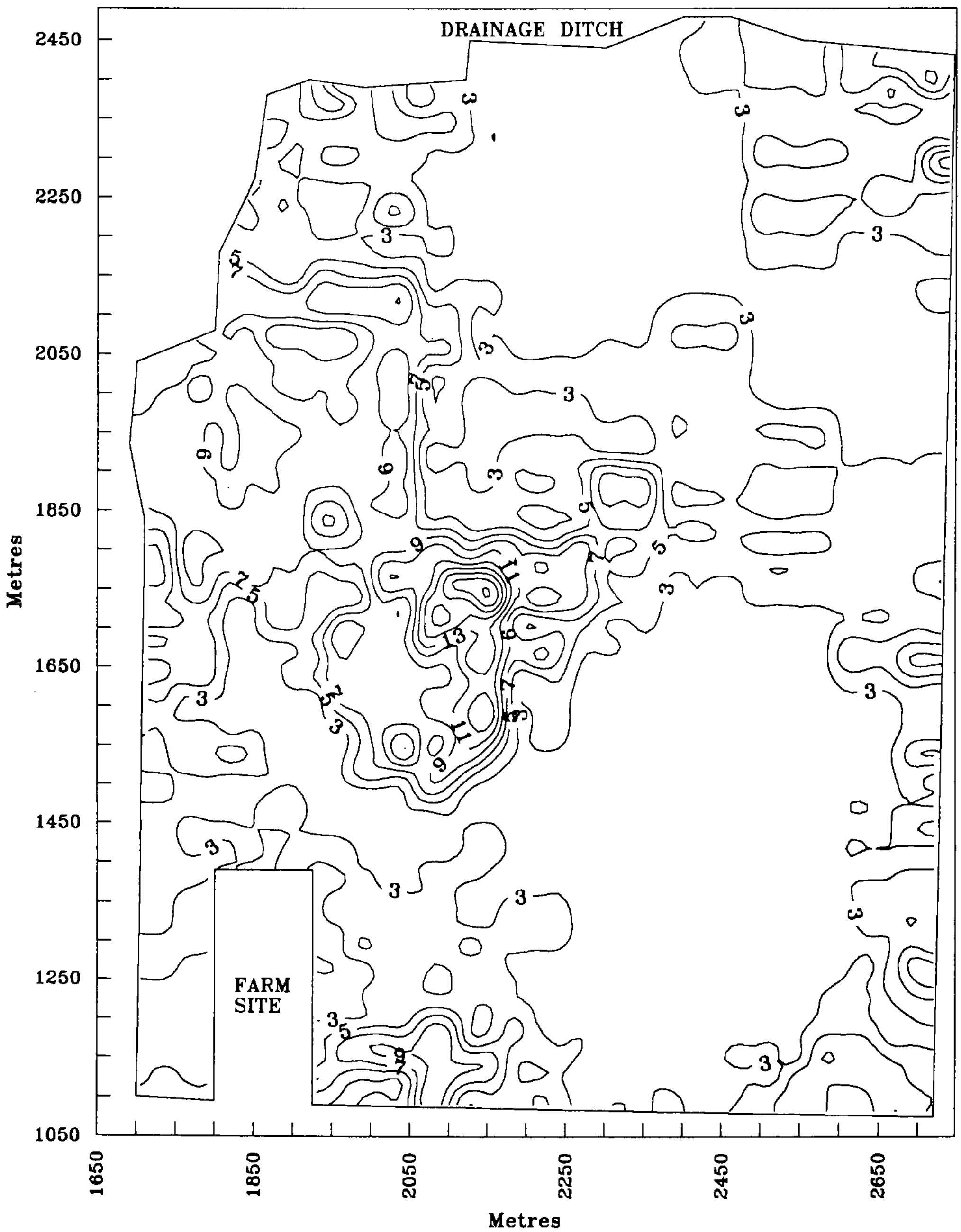

Fig. 6. Soil conductivity $dS\ m^{-1}$, Stettler survey, 23 September 1992.

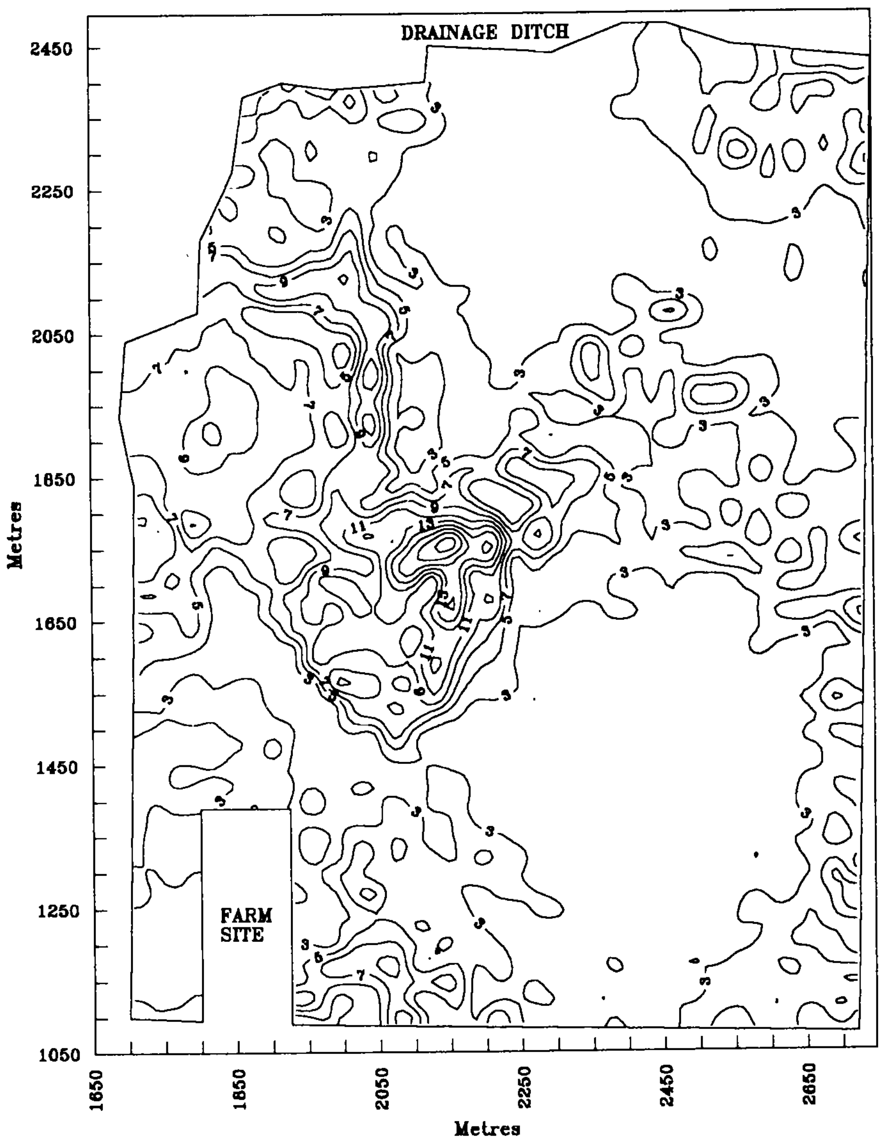

Fig. 7. Soil conductivity dS m^{-1}, Stettler survey, 24 September 1992.

The points are concentrated in areas of steep conductivity gradients as can be seen by analyzing Fig. 7. The mapping accuracy of the survey will ultimately depend on the density of the survey lines which in turn is a function of the horizontal gradients of conductivity.

A weighted EC_e according to Wallenhaupt et al. (1986) was developed for the locations at Stettler where soil samples were taken. This gave a good agreement ($r^2 = 0.95$) with the EC_e values derived from EC_a readings collected in the survey (Fig. 9). Therefore it was not necessary to do a specific calibration of the EM38 for the site.

As the above tests demonstrate, DGPS has a number of advantages over the conventional grid mapping system. It permits large areas to be mapped without the labour and expense of establishing a grid. The survey line spacing can easily be adjusted to account for zones of rapidly changing salinity. An experienced operator can decrease the spacing during parts of the survey where high salinity variations are suspected. At the end of a survey, additional lines can be observed in an irregular pattern to provide crossover points with the other lines and verify the internal consistency of the survey by analyzing the measurement agreement at the crossover points.

CONCLUSIONS AND FUTURE PROSPECTS

An EM-DGPS method for soil salinity mapping has been described and tested with positive results and shown to be highly productive. Field tests have demonstrated that a repeatability of 1 dS m^{-1} can be achieved along the survey lines. The flexibility of the method allows the user to verify the survey accuracy and reliability through an analysis of crossover points. The method can be used on large or irregular shaped areas where rough topography, trees and buildings restrict the line of sight to ground targets. Under

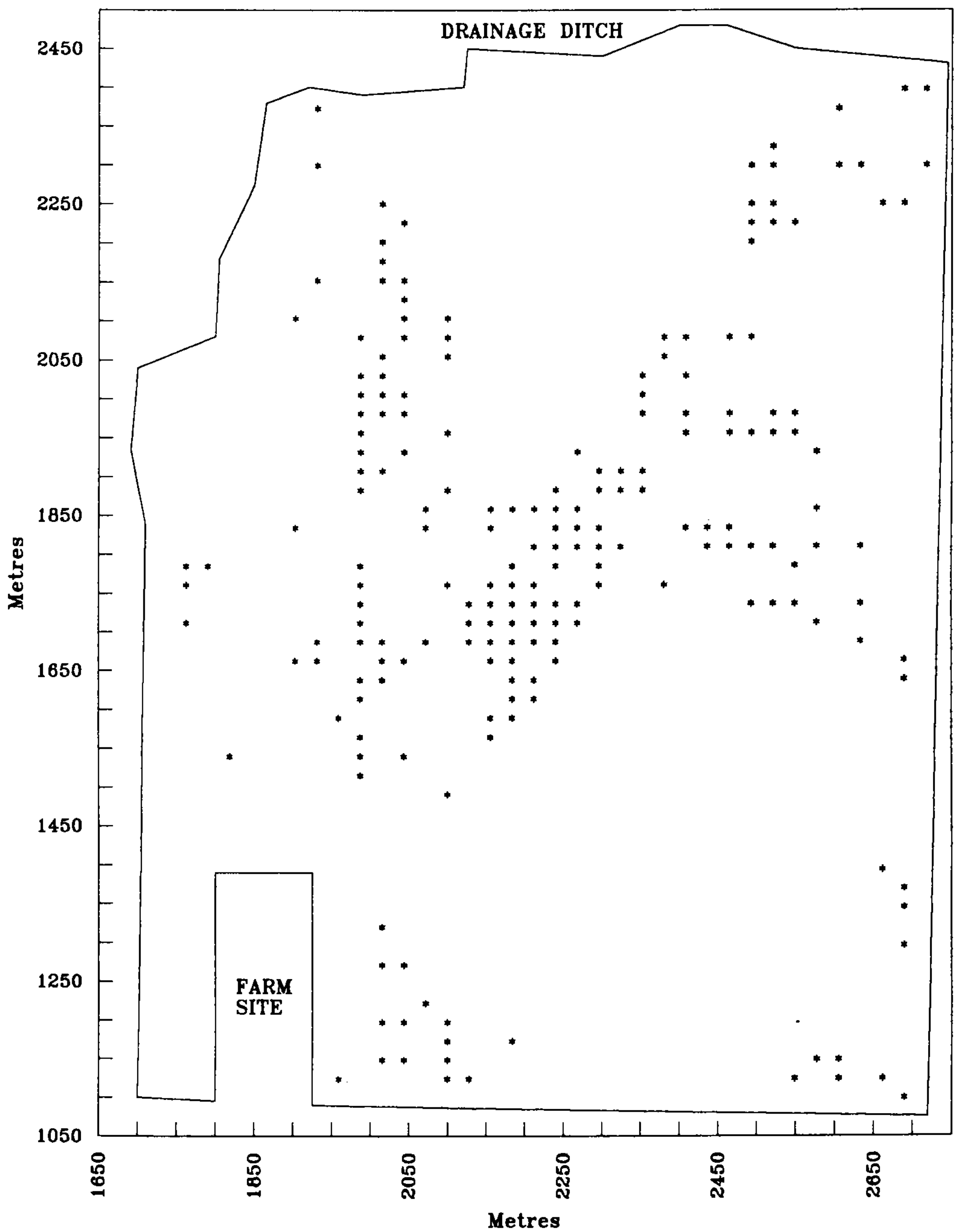

Fig. 8. Differences between EM surveys at 25 and 50 m line spacings. Points where the difference exceeds 2 dS m^{-1} are shown. Stettler survey, 23 and 24 September 1992.

normal operating conditions, up to a few hundred ha per day can be surveyed, which is a productivity increase of five-fold compared with the use of grid EM survey methods. The EM DGPS system makes it feasible to do detailed mapping of soil salinity of a drainage basin.

The investigators are currently testing the use of real-time DGPS to pre-plan a survey along specific routes which will be useful to obtain specific patterns and line spacings in addition to repeating a previous survey along identical lines, thereby eliminating interpolation errors. In future tests, narrow correlator spacing C/A code GPS receivers will be used to improve the DGPS accuracy to the sub-metre level (Cannon and Lachapelle 1992), thereby improving further the accuracy performance of the system for detailed soil salinity studies.

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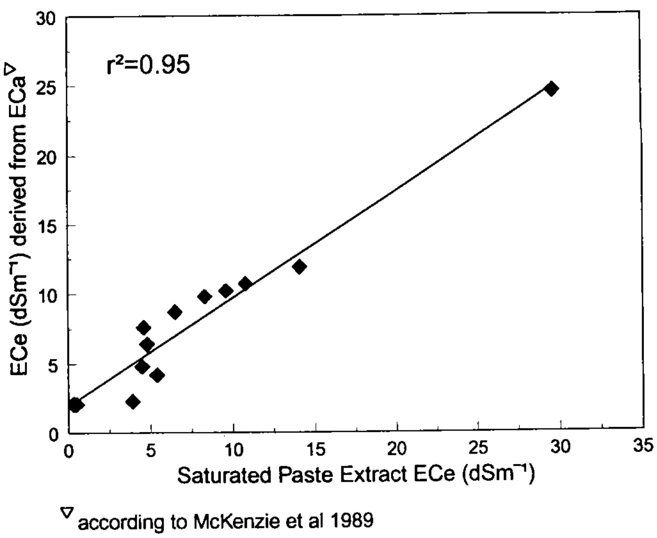

Fig. 9. Comparison of EC_e values from soil sample analysis and EM38 measurements, Stettler survey, September 1992.

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