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MAPPING OF ELECTRICAL POTENTIAL DISTRIBUTIONS WITH CHARGED PARTICLE BEAMS

November 1977-April 1978
Semiannual Report

National Aeronautics and Space Administration

Grant NSG-3166

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ABSTRACT

Progress is reported on the mapping of electrostatic potentials using data from charged-particle trajectories. Experimentally, ions having negligible velocity are formed in the region of interest and detected as they leave the system. Energy, position, and trajectory angle are obtained from a specially designed sensor designed around a continuous-dynode electron multiplier. Work will be extended to include the injection of electron beams into the region of interest. Routines for calculating charged particle trajectories have been programmed and iterative schemes for refining estimated potential functions are under development.

INTRODUCTION

Spacecraft charging simulations, to be meaningful, require some estimate of electrical potential contours in regions of interest. Probing with low-current charged-particle beams will only slightly perturb the potentials yet provide data for calculating the contours. This research deals with general considerations of how one can map nonsymmetric potentials from such data, yet it still relates to the specific need. The work is in two parts, experimental measurement and simulation, where the simulation is to lead to systematic methods of data processing.

Because of a lack of personnel, the rates of progress and expense have been less than initially proposed; significant results are not yet available. Thus, this report describes work in progress and is relatively brief. The experimental section describes work with an ion sensor which detects ions created in a precisely defined test region and ejected by the electrostatic forces. The work will be extended to include measurements of electron trajectories. In the section on simulation are described various approaches for generating potential functions which satisfy certain criteria such as boundary conditions, or more pertinently, particle trajectories. As a necessary prelude to the problem, we have developed subroutines which generate particle trajectories in a region having known potential contours.

EXPERIMENT

Acknowledging that practical application to physical systems is a goal of this research, we feel that experimented measurements are needed to verify methods, to establish limits of resolution, and to reveal unsuspected complications. Consequently, we have constructed a testing apparatus consisting of an electron beam which ionizes background gas in the test chamber, a biased wedge-shaped structure which produces a known potential distribution, an ion detector which discriminates against particles having less than some threshold energy, and mechanical linkages for adjusting the orientation and location of all of the system elements. The system is fully operational and is currently in use. Measurements to date have dealt mainly with the characteristics of the system elements, especially as related to resolution. Furthermore, a set of trajectories has been recorded as the first attempt to correlate trajectory data with the predictions for the wedge geometry. A separate report on these measurements will be issued shortly.

Of critical concern is the resolution achieved by the ion detector. Four parameters are of interest, the energy resolution, the translational resolution, the angular resolution, and the sensitivity. The design of the detector system includes a pair of apertures that admit ions from a narrow cone only. As expected, the response to a highly collimated ion beam is a function of the orientation of the detector system. For a reasonable choice of hole size the angular resolution is less than 1^{o}. The detector system is on a screw-driven carriage that locates the aperture position to within an aperture hole diameter of .05 cm. When ions enter the detector system they pass through a retarding potential which provides energy discrimination to within approximately 1 volt. Ions meeting all of the conditions strike the detector which is a continuous-dynode electron multiplier. Because of the high gain available, individual ions are detected as pulses which are displayed on an oscilloscope and counted.

The ions are created by collision of electrons with background gas, the ions having essentially zero energy at the point of creation. However, the location of this point is not precisely known. The ionizing electron beam itself follows a curved trajectory because of potential gradients and magnetic fields. As beam energy is raised, the trajectory becomes straigher and more definite but the probability of ionization drops. Further uncertainty arises from the finite diameter of the electron beam, though in principle a beam can be focussed to as fine a point as would be desired for this work. Because the ion source points cannot be precisely determined from the electron beam parameters, data processing schemes should not depend upon a prior knowledge of those points but should generate them as a natural output of the process. However, approximate source point data can initialize the computations more efficiently than uninformed guesses. One problem revealed by measurements is the effect of magnetic field on particle trajectories. The low-energy particles used as probes will deflect noticably in the earth's field and compensation must be made for that effect.

Extensions of experimental work are to include more measurements of ion trajectories and the eventual processing of that data when the computer routines become operational. However, a second experimental technique is also to be implemented. A steerable electron source can be mounted on the carriage which presently holds the ion detector and the electron beam it generates can be detected by a stationary grid of wires connected to an electrometer. Such a system will speed data collection and adapt more readily to typical applications, though it will not be effective in regions of positive potential.

The use of beam injection allows a number of options not available from the other method. The revised system will yield values of entry position, entry angle, energy, and exit position of the beam where entry and exit positions do not necessarily coincide. The electrons will not, in general, be associated with some point of zero energy as in the case of the ions, but for selected parameters, they may be. When this happens the entry and exit positions will coincide and the data will be similar to that collected for ions. However, not being restricted to that special case allows quick data collection by the sweeping of the electron beam through an angle as shown in Fig. 1. As the beam is swept it intercepts the detector grid at points in time which can be correlated with the sweep positions at those times.

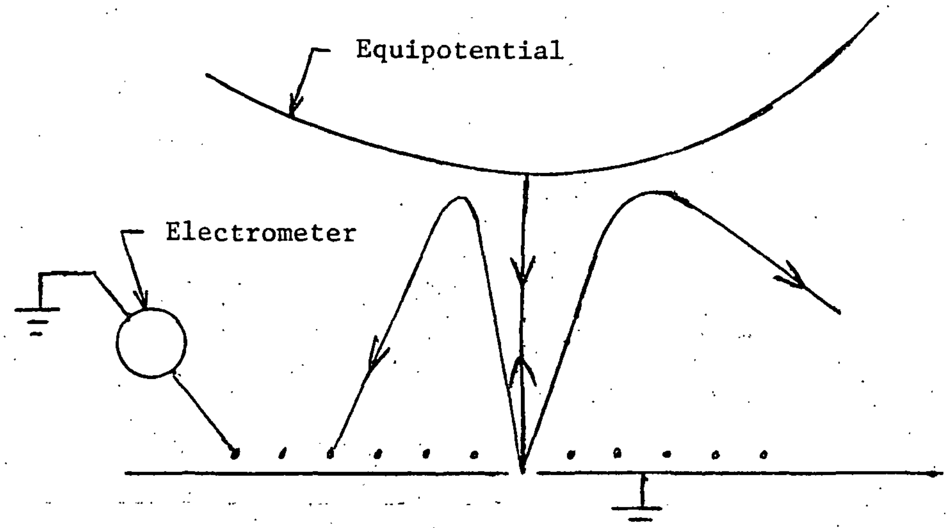

Fig. 1. - Use of a swept electron beam and detector grid to probe regions of unknown potential

SIMULATION

The first step in computing a potential function is to generate a subroutine for calculating trajectories when a potential is specified. Two such routines are now operating, one based on an assumption that the time derivative of acceleration is constant over an interval and the other based on the method of De Vogelaere [1]. The latter has been tested by generating an elliptical orbit in a coulomb potential and noting the accuracy with which the particle returns to the starting point. Still more elaborate methods exist, such as that of Bashford/Adams [2], but sufficient accuracy is attained without them.

Simulated trajectories show expected experimental results for ions generated near a biased wedge-shaped electrode. The fields are calculated by a combination of conformal mapping and the use of a Green's function as done previously by Nguyen [3]. A set of subroutines to generate fields is called by the trajectory-tracing routine which produces results as shown in Fig. 2. Note that this illustrates the case of ions formed with zero energy though the routines can handle the case of ions injected with arbitrary velocity and position.

Generally, trajectories calculated from an assumed potential function are to be compared with measured trajectories such that the assumed function can be modified to more accurately represent the physical system. The objective of computational efforts is thus to generate a potential function which meets certain criteria, perhaps matching boundary conditions or, more specific to this research, matching measured particle trajectories. One approach is to build up the potential function in layers by using first the data for trajectories originating near the boundary of the region and then by using particles coming from deeper in the region. Black and Robinson [4] describe this

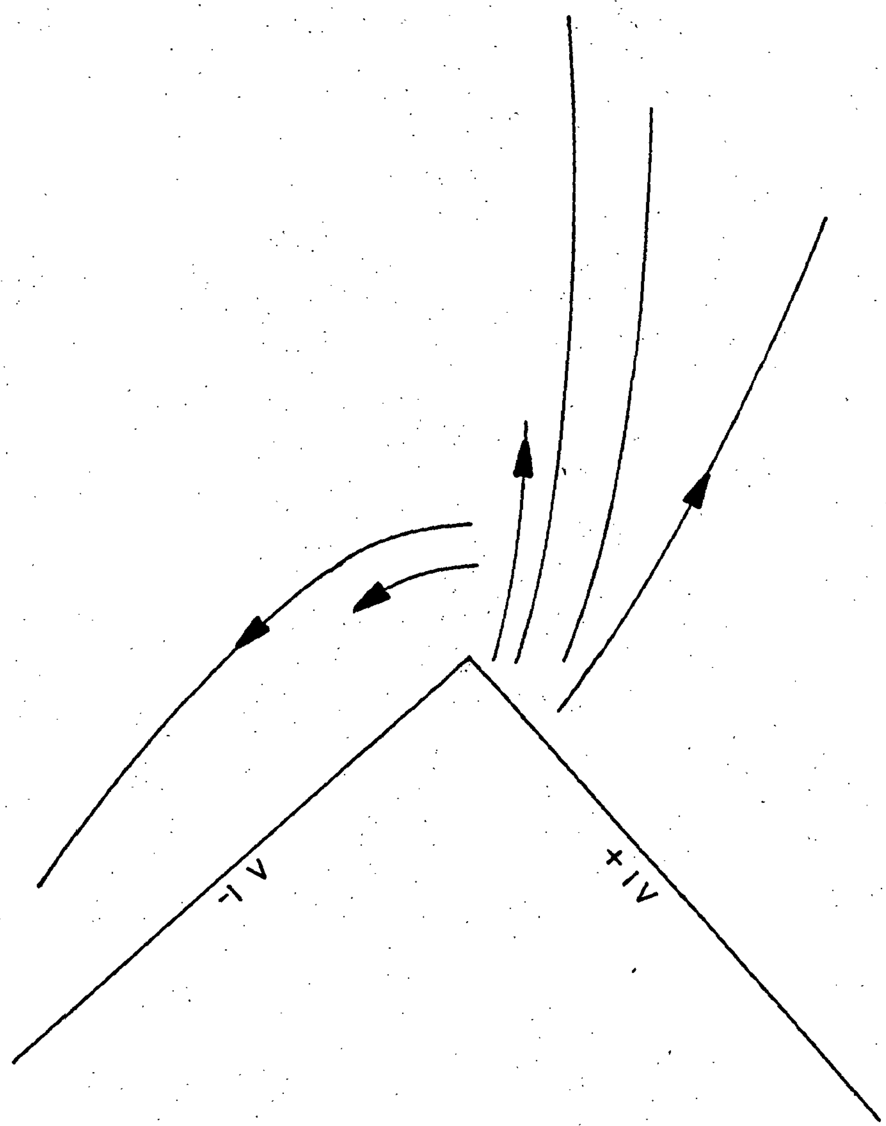

Fig. 2. - Trajectories of ions starting from rest near a biased wedge. The two planes are biased at equal but opposite potentials.

approach for a symmetic potential. Another way is to assume an approximate potential function and to progressively improve the function through a series of perturbations. The work to date in this grant has concentrated on this latter method.

Both before and after a perturbation a potential function must satisfy Laplace's equation if space charge can be neglected. One way of perturbing a function is to add a second function which itself satisfies Laplace's equation. By the principle of superposition, the combination is then satisfactory. One thus looks for some combination of additive functions and the elementary operations of shifting, rotating, and scaling which will converge to the desired result.

The particular perturbation to be implemented should be discernable from a measure of how the estimated potential deviates from the criteria established in a certain region. Because the potential and the particle trajectories depend uniquely on boundary conditions, attention has been focussed so far on using boundary conditions as the criteria. If a certain discrepancy exists over a portion of the boundary, then a perturbation should either "pull" or "push" the potential contours to improve the fit as shown in Fig. 3. A sequence of pulling and pushing operations having a localized range can in concept force a match at the boundary and consequently establish a valid function throughout the region of interest. The problem is to properly identify these functions.

The need for convergence implies that the perturbations should be localized and leads to the consideration of dipole potentials as the perturbations. The dipole function has a singularity where the dipole is centered so that one cannot consider a dipole to be placed in the region of interest. Rather the perturbations are to be thought of as the placement of dipoles outside the region and near to those portions of the boundary which require better matching. The concept of using dipoles applies for either two or three dimensional systems with the potentials varying as either $\frac{\cos\phi}{r}$ or $\frac{\cos\phi}{r^2}$. Here ϕ is the angle measured from the axis of the dipole and r is the distance from it. In two dimensions the addition of the dipole field is equivalent to the conformal mapping, $w = z + 1/z$. This mapping, illustrated in Fig. 4 can be considered either a pull along the v axis or a push along the u axis.

Our present work focuses on how perturbations might be systematically incorporated into a computational scheme. Whe dipoles are used, the strength, location, and orientation must all be sepcified in some optimum manner if rapid convergence is to be attained. Ultimate use requires the specification of perturbations in terms of particle trajectory data instead of boundary conditions. For a given calculation, accuracy will depend on the number and location of trajectories.

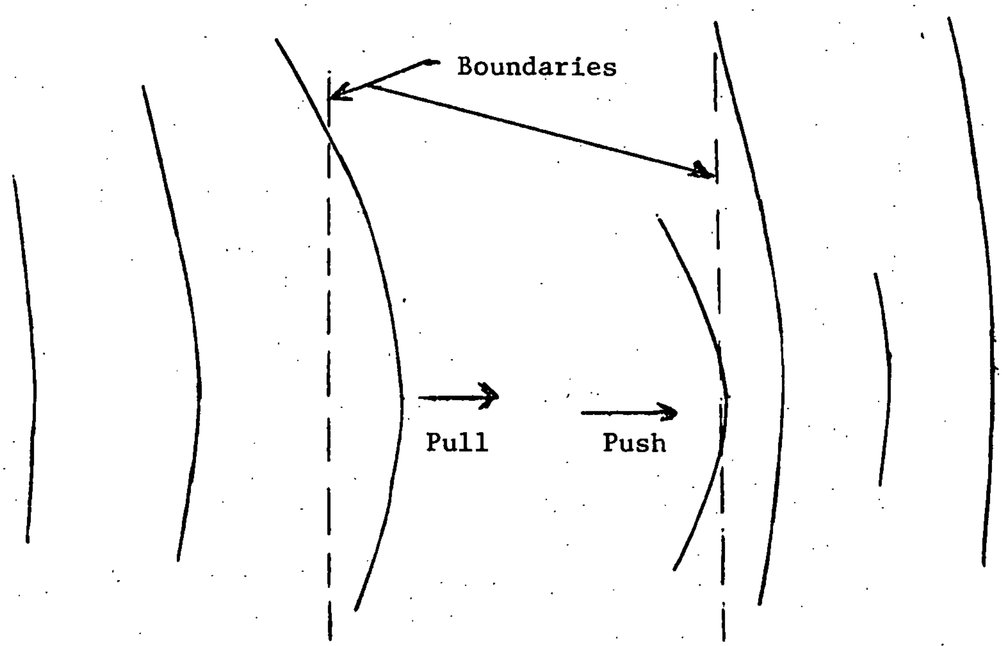

Fig. 3. - Perturbations of potential contours which can improve the matching with boundary conditions in a localized region.

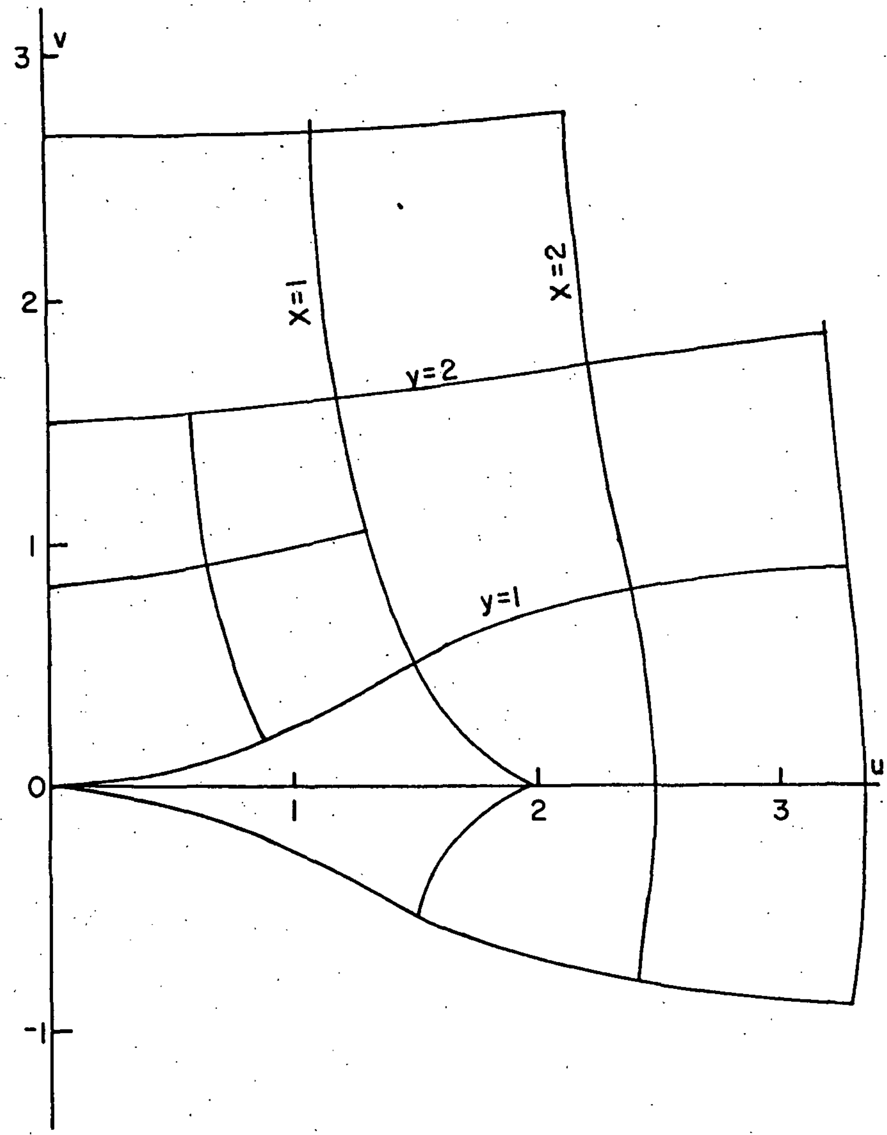

Fig. 4. - The conformal mapping $w = z + 1/z$ which illustrates localized perturbations. The line segment $-2 \leq u \leq 2$ must lie outside the region of interest.

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The contributions of David Ross to the experimental work and David Tilley to the simulation are gratefully acknowledged.

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