1. Different Methods for Electric Field Measurements

The present attempts and plans to measure electric fields in the magnetosphere can in a natural way be divided into three main categories, each of them having its special advantages and disadvantages.

The first class consists of experiments where a potential difference between two points in the plasma is measured (AGGSON and HEPPNER, 1965a, b, c; JOHNSON and KAVADAS, 1963; KAVADAS and JOHNSON, 1964; DOLEZALEK, 1964, 1966; HIRAO and MIYAZAKI, 1965). The theory and methods for such probe measurements in laboratory plasmas are well developed. When applied to space conditions some complications arise, but by careful design most of the difficulties can be avoided. The following analysis will show that reliable probe measurements can easily be made in the ionosphere and the inner magnetosphere, and with larger efforts probably also in the outer magnetosphere and in interplanetary space.

The second class of devices (WILDMAN, 1965; CURRIE and KREIELSHEIMER, 1960; GDALEVICH, 1963; GDALEVICH et al., 1965; GUREVICH, 1964) measures the charge on a metal surface placed in the field. The charge is found by measuring the current flowing to a surface element that is intermittently screened off from the outer field, e.g. by a rotating metal shutter. These devices, usually called 'field mills', work perfectly well in a uniform atmosphere, but when immersed in a plasma serious difficulties appear. One of these is that the field mill will be covered by a plasma sheath that may change the field strength at the surface by orders of magnitude. Another difficulty is that electrical currents will flow from the plasma to the field mill. Reliable quantitative corrections based on theoretical calculations are not available at present, because too little is known about plasma-boundary layers and too little data exist about interactions of charged particles with surfaces. Several of these difficulties can be at least partly avoided by simultaneous operation of several field mills, situated at different sides of the spacecraft and rotating with different frequencies. However, there are also technological difficulties with moving parts in vacuum and electrical noise. It is the author's impression that field mills may be of great future importance particularly in very dilute plasmas, but at present no reliable method based on field mills has been described.

The third class of methods consists of indirect measurements where the electric field is deduced theoretically from other measurements, e.g. from the observed motion of charged particles and magnetic fields. Energy and pitch-angle distributions of
particles in the ionosphere, deduced from spectral measurements or satellite-borne collectors, may enable calculations of electric fields in and above the ionosphere (Johansen and Omholt, 1963). According to a formula derived by Persson (1966) the electric-field component along the magnetic-field lines can be calculated from particle measurements. If the space and velocity derivatives of the phase-space distribution function are known at a point, the electric field is uniquely determined at that point. It is sufficient to know the derivatives for a single type of particles (protons or electrons) for arbitrarily chosen values of the velocity components. Experiments can be made by studying particles injected from chemical (Haerending, 1965) or nuclear explosions (Christofilos, 1959; O'Brien et al., 1962; Burrows and McDiarmid, 1964) or satellite-borne gas sources or accelerators. Experiments may also be designed to study the motion of particles emitted from one part of a satellite and collected by another part.

For a general survey of electric fields in the magnetosphere, however, probe measurements seem at present to be best suited. In the following sections some of the necessary considerations behind a successful probe experiment will be discussed. This problem has also been considered by Aggson and Heppner (1965a, b, c), Boyd (1967), and Dolezalek (1966).

2. Field Measurements with Electric Probes

The electric field can in principle be calculated from any measurement of the voltage between two or more arbitrarily shaped metal electrodes in contact with the plasma, when the distance and geometry of the electrodes are known. However, each of the probes will be surrounded by a plasma sheath and will acquire a potential different from that of the plasma. The voltage drop in a sheath is very difficult to determine theoretically, and there is no reason to believe that it should be equal for differently shaped or differently oriented electrodes. A reliable field measurement with electrodes that are different in some respect will then, because of the weak fields to be measured, necessitate a very, often unrealistically, large probe distance. The fundamental rule for probe measurements is then that equally shaped electrodes should be used. Further the electrodes must be equally oriented since the magnetospheric plasma is always anisotropic when seen from the moving spacecraft. The probes must be far away from each other and all other obstacles that may disturb the symmetry by screening off different parts of the incoming particle flux from the different probes. Finally the electrodes should be of the same material, and their electrical connections must present the same electrical loading to them. If all these requirements are fulfilled, a true value of the electric field can easily be obtained from a measurement of the potential difference and knowledge of the distance between the probes.

In practice none of the rules stated above can be strictly fulfilled, and it is the aim of the present article to get estimates of the limiting requirements for a satisfactory probe measurement. These requirements will be different in different parts of the magnetosphere and for different experimental conditions. For this reason a number