

A miniature sensor for electrical field measurements in dusty planetary atmospheres

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Abstract. Dusty phenomena such as regular wind-blown dust, dust storms, and dust devils are the most important, currently active, geological processes on Mars. Electric fields larger than 100 kV/m have been measured in terrestrial dusty phenomena. Theoretical calculations predict that, close to the surface, the bulk electric fields in martian dusty phenomena reach the breakdown value of the isolating properties of thin martian air of about a few 10 kV/m. The fact that martian dusty phenomena are electrically active has important implications for dust lifting and atmospheric chemistry. Electric field sensors are usually grounded and distort the electric fields in their vicinity. Grounded sensors also produce large errors when subject to ion currents or impacts from clouds of charged particles. Moreover, they are incapable of providing information about the direction of the electric field, an important quantity. Finally, typical sensors with more than 10 cm of diameter are not capable of measuring electric fields at distances as small as a few cm from the surface. Measurements this close to the surface are necessary for studies of the effects of electric fields on dust lifting. To overcome these shortcomings, we developed the miniature electric-field sensor described in this article.

1. Introduction

Dusty phenomena such as regular wind-blown dust, dust storms, and dust devils play an important role in the Earth's climate and are the most important, currently active, geological processes on Mars. Electric fields larger than 100 kV/m have been measured in terrestrial dusty phenomena [1, 2, 3, 4], while theory predicts that the bulk electric fields in martian dusty phenomena are limited by the breakdown of the thin martian air at about 20 kV/m [5, 6, 7]. Renno *et al.* [8] show theoretical and observational evidence that martian dusty phenomena are electrically active. This has important implications for dust lifting and atmospheric chemistry [9, 10, 11].

The large electric fields produced by dusty phenomena can substantially reduce the critical wind speed necessary to produce saltation, and even directly lift dust particles from the surface [9]. Saltation is the process by which sand particles are forced to move by the wind and bounce on the surface, ejecting the smaller, harder to lift, dust particles into the air [12]. Electric fields might facilitate saltation and dust lifting on Earth, Mars and elsewhere. Both field measurements [2] and theory [13], [14] show that electric field strengths increase rapidly towards the surface [9]. Thus, measurements of

electric fields at a few centimeters from the surface are essential for studies of the role of electric fields in dust lifting. Finally, on Mars ion chemistry driven by these electric fields is predicted to dissociate water vapor and produce large quantities of hydrogen peroxide, a powerful oxidant that can make the surface inhospitable to life [10, 11].

This article describes an innovative electric field (E-field) sensor jointly developed by the Jet Propulsion Laboratory (JPL) and the University of Michigan (UM) to:

1. Make in-situ measurements of E-fields in dusty phenomena to study their electrification;
2. Measure E-fields as close as 2 cm from the surface and study their role on dust lifting;
3. Study the role of electric fields on ion chemistry in planetary atmospheres.

Our prototype sensor is currently being characterized at UM. This sensor could be used to make in-situ measurements where blowing dust or snow might produce electrification such as on Earth, Mars, Venus and Titan. Moreover, it has the potential to shed light on dust lifting, saltation, and the effects of ion chemistry on the habitability of Mars. Finally, our sensor could also be used to measure electric fields near the surface of the Moon and shed light on the levitation of lunar dust [15, 16].

2. Theory

As mentioned above, electric field sensors are usually grounded and distort the fields during measurements. Moreover, they are subject to errors because of currents induced by ions in the atmosphere. In the absence of wind, ions drift along field lines and impinge on an isolated sensor until its charge becomes sufficiently large to distort the field lines far enough so that they no longer terminate on it. Although isolated sensors become charged, the charging process is self-limiting and their potential stays close to that of the unperturbed local space. Self-charging by the collection of atmospheric ions is therefore not a significant error source in isolated sensors, unless they are placed close to a grounded conductor and are affected by the image of their charge on it. Thus, measurements close to the surface require sensors with small cross sections.

Things are different when charged particles are transported by the wind. When charged dust or sand particles are transported by the wind, the shape of the local field lines is immaterial, and considerable amounts of charge might strike the sensors. The potential of grounded sensors remains at zero, but the potential of the isolated sensor may change significantly. In both cases, the current associated with the charge transfer can produce significant errors.

We developed an isolated electric field mill that removes the error caused by wind-borne charge transfer in two steps: (i) In the first step small, sharp points are added to the surface of the field mill to effectively limit its potential with respect to the local ambient field. Since its potential is limited by the rate at which charge leaks from the surface, such as in Van de Graaff generators, the difference between the potential of the sensing surface and that of space can be limited to reasonably small values by corona discharges. However, this does not alter the field mill's charging rate, and the current this charging generates could cause large errors unless another step is taken. (ii) In the second step the current induced by incoming charges is measured using an idea developed by *Smiddy and Chalmers* [17] and *Maruvada et al.* [18]. They used a grounded double field mill, operating at two different rotation rates, to remove the error caused by wind-borne charges. Instead, we use a single isolated field mill operating sequentially at two different rotation rates. Our approach provides the magnitude and direction of the electric field in a plane perpendicular to the sensing cylinder, even in the presence of wind-borne charges. This second step is discussed in detail below.

The output of cylindrical field mills consists of two components; the first component is caused by charges *induced* by the electric field to be measured and is proportional to the field mill rotation rate (rotation-dependent component), while the second component is caused by charges *impacting* on the sensor and is independent of the rotation rate (rotation-independent component). A single measurement cannot distinguish between these two components. However, measurements with a single field mill operating sequentially at two different rotation rates can separate the two components. A sketch of this type of field mill with the relevant parameters is displayed in figure 1.

First we consider the component of the output due to ambient electric field. In a cylindrical field mill, the surface charge density (per unit length) induced by the ambient electric field is

$$\sigma(\theta) = 2r\epsilon_0(E_x \sin\theta + E_y \cos\theta), \quad (1)$$

where r is the radius of the field mill, ϵ_0 the permittivity of the air, E_x and E_y the two components of the ambient electric field in a plane perpendicular to the sensing cylinder, and θ the azimuth angle of the cylinder as indicated in figure 1. Integrating equation (1) over half the cylinder, the total charge on each electrode can be calculated as a function of β , the angle between the electrode and the ambient electric field. Thus, the charge on electrode a is

$$q_a = \int_{\beta}^{\beta+\pi} \sigma(\theta) d\theta. \quad (2)$$

It follows from the above that the total charges on electrodes a and b are

$$q_a = -q_b = 4r\epsilon_0(-E_x \cos\beta + E_y \sin\beta). \quad (3)$$

Taking the angular velocity as constant, so that $\beta = \omega t$, we get

$$q_a(t) = 4r\epsilon_0(-E_x \cos\omega t + E_y \sin\omega t). \quad (4)$$

As the electrodes rotate, induced charges remain fixed with respect to the ambient field and pass from one electrode to the other. Assuming that the change in the ambient electric field over one rotational cycle is small, we have that $i = dq/dt$. Thus, differentiation of equation (4) with respect to time yields the value of the current in the wire connecting the two electrodes

$$i_E(t) = 4r\epsilon_0(E_x \omega \sin\omega t + E_y \omega \cos\omega t), \quad (5)$$

where the subscript E indicates current due to the ambient electric field.

Now we analyze the current caused by the impact of charged dust or sand particles on the sensor. We decompose the wind velocity into two orthogonal components, as indicated in figure 1. Assuming uniform volumetric charge density ρ , and constant wind velocity v , the current per unit area normal to the wind vector is simply

$$I = v\rho. \quad (6)$$

Thus, the current between the electrodes of cylindrical field mills subject to this flux of charged particles is

$$i_D(t) = \frac{1}{2}A(I_x \cos\omega t + I_y \sin\omega t), \quad (7)$$

where A is the “effective area” of the cylinder collecting the charged particles, I_x and I_y are the two components of the flow of charged particles, and where the subscript D indicates that the current is caused by wind-borne dust. The factor $\frac{1}{2}$ appears because wind borne particles collide only with the upwind half of the sensor, and yet their charge is distributed around the whole cylinder. We refer to A as the “effective area” because the efficiency with which charges from dust particles are transferred to the cylindrical field mill is not known. The area A is smaller than the area of the cylinder projected into the normal to the wind, because the properties of the boundary layer and the efficiency to which dust particles are deflected by it depends on their sizes, properties of the air, and the angular velocity of the field mill (e.g., Reynolds, Knudsen, and Taylor numbers). Nevertheless, an approximation based on a constant A is useful and can be corrected after calibration and tests with the prototype sensor. Assuming that this area is linearly proportional to the radius r , we get

$$i_D(t) = \frac{1}{2}kr(I_x \cos\omega t + I_y \sin\omega t), \quad (8)$$

where $k = A/r$ is a constant that depends on the length of the cylinder.

Adding the components due to the ambient electric field and the flow of charged dust particles, we get the total current between the electrodes

$$i(t) = 4r\epsilon_0(E_x\omega \sin \omega t + E_y\omega \cos \omega t) + \frac{1}{2}kr(I_x \cos \omega t + I_y \sin \omega t) \quad (9)$$

$$i(t) = \omega K_1(E_x \sin \omega t_x + E_y \cos \omega t) + K_2(I_x \cos \omega t + I_y \sin \omega t), \quad (10)$$

where $K_1 = 4r\epsilon_0$ and $K_2 = \frac{1}{2}kr$. Equation (10) shows that the radius of the cylinder affects both components equally. The amplitude of the field-induced component depends on the angular velocity ω , while that of the current induced by wind borne particles striking the field mill does not depend on the angular velocity. As described above, this allows us to separate the two components by having the sensor switch sequentially between two rotation rates.

3. Our miniature sensor

We fabricated a prototype isolated cylindrical field mill (E-field sensor) that can rapidly switch between preset angular velocities. The speed-dependent portion of the signal can be used to separate the field-induced from the dust-induced portions of the signal. We are currently testing, optimizing, and calibrating the prototype sensor. In addition, we are fabricating a flight version of the sensor.

3.1. Science requirements

It follows from the studies summarized in the introduction that the top-level requirements for studies of electrification in terrestrial and martian dusty phenomena are:

1. **E-field range:** 50 V/m to 1×10^6 V/m, although 100 V/m to 0.5×10^6 V/m would be enough.
2. **E-field resolution:** 10 V/m in the low end of the scale, 1 kV/m in the high end.
3. **Time resolution:** A typical dust devil would pass over the sensor in ~ 2 s, thus a 1 Hz response would be marginally adequate. A 10 Hz response is adequate for dusty phenomena.
4. **Angular E-field (vector) resolution:** $\pm 10^\circ$ is adequate.
5. **Operation time:** The instrument should be able to collect data at the maximum rate and resolution for at least 1 hour to study dust storms. It would be useful to also have a low-resolution mode that could operate for up to 24 hours. This implies the ability to switch between modes when events of interest occur.
6. **Sensor configuration:** Minimum of 4 sensors, deployed at various heights above ground to measure the near-surface E-field and its vertical profile.
7. **Ground isolation:** Since we are interested in the electric field profile, the field must be unperturbed by the sensors. Therefore, the sensors should be electrically isolated from each other and from the ground, and should equilibrate to the local space potential.
8. **Physical size:** Measurement at ~ 2 cm from the ground is necessary to study the effects of E-fields on dust lifting. A cylindrical sensor can make measurements at about one diameter away from the surface with reasonable accuracy [19, 20], thus it should be smaller than 2 cm.
9. **Charged particles:** A typical dust devil has charge density of approximately 10^{-8} C/m³ [4]. In a typical 20 m/s martian/terrestrial wind, the sensor cross section is struck by up to 2×10^{-7} C/(m² s). In steady state, this current generates a reading equivalent to an electric field of about 11 kV/m. The sensor must therefore be able to separate the signal due to impingement of charged particles from that due to the electric field. This requires measurements of the amplitude of the signal at two rotation rates. Moreover, the sensor must be able to:
 - Measure the ambient E-field over the range stated above with error smaller than 10%.
 - Estimate the current due to the impact of charged particles, so that the atmospheric charge density can be estimated.

In the next section, we describe our prototype sensor. This sensor was designed to meet the requirements summarized above. However, its detailed characterization is still underway.

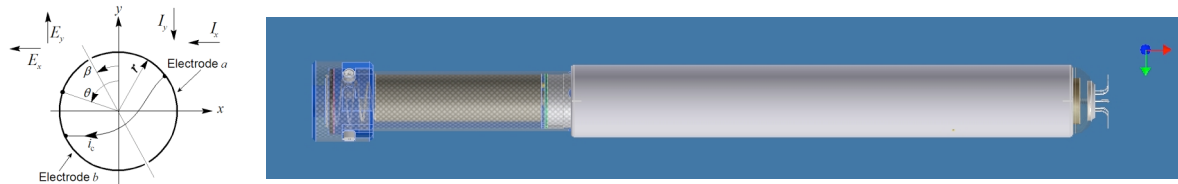


Figure 1. (Left) Sketch of the cross section of the field mill in a two-dimensional electric field (E) and a two-dimensional flow of charged particles (I). The output of the device is the current (i_c) in the wire connecting electrodes a and b . (Right) Sketch of the sensor assembly.

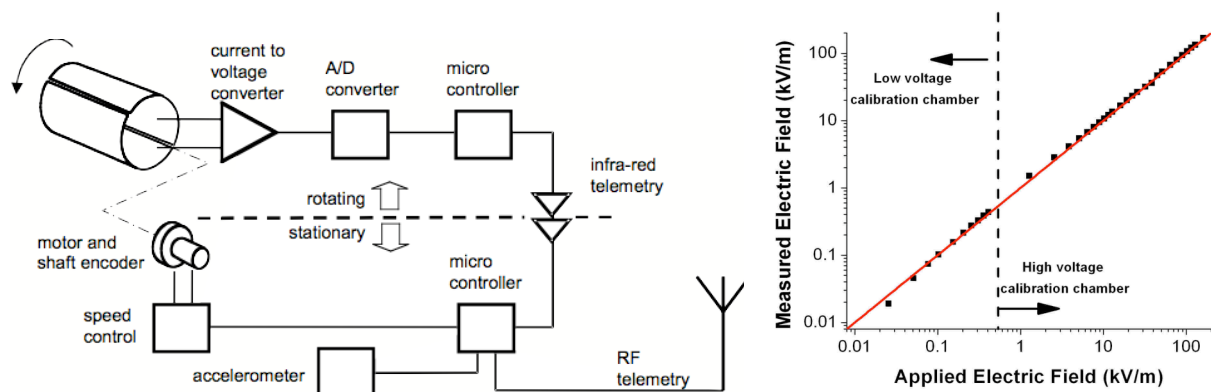


Figure 2. (Left) Block diagram of the prototype E-field sensor indicating rotating and stationary parts. (Right) Results of the sensor calibration in the laboratory.

3.2. The prototype sensor

The sensor electronics is separated into rotating and stationary parts, as indicated in figure 2. The angular velocity of the sensing cylinder is set by a microcontroller, using the feedback of a reference position sensor, and can be adjusted according to operational requirements. A low angular velocity operational mode can be used to conserve power, while high velocity modes can be used to increase the measurement accuracy and to separate the effects of the ambient electric field from that of ion currents or impacts of charged dust/sand particles.

Measurements of the electric field near the ground or any other surface requires a sensor of small cross section as discussed in the science requirements listed above. However, extreme measures to keep the sensor diameter small were avoided in the prototype instrument. The diameter of the motor selected is 16 mm. Smaller motors exist, but we wanted an off-the-shelf solution for position feedback, and this was the smallest motor with encoder and index signal available.

The outer diameter of the sensing cylinder needs to be large enough to accommodate the motor, the electrodes and coupling mechanisms. The diameter of the outer shell of the prototype sensor is 22 mm, and the sensing surface (electrode) has the same diameter and is 150 mm long. The overall sensor length is 208 mm. The outer shell is a thin polycarbonate cylinder, with silver conductive paint applied to the outside. The paint wraps around the inner surface on the end with the rotating electronics so two spring-loaded pins can contact it for the measurement. Results of laboratory (figure 2) and field tests (not shown) indicate that the sensor can accurately measure electric fields ranging almost 5 orders of magnitude and that its time resolution is over 30 Hz (not shown). We plan to commercialize various versions of the sensor suitable for either industrial or scientific applications.

Acknowledgments

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