Electrostatic Charging of Balloons and Gondolas in the Earth Atmosphere

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ELECTROSTATIC CHARGING OF BALLOONS AND GONDOLAS IN THE EARTH ATMOSPHERE

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ABSTRACT

Electrostatic charging of balloons and gondolas is frequently observed, especially during ascents in the atmosphere. Charge build up modifies the potential distribution of the environment and perturbs the measurements of quasistatic fields with electric antennas and of atmospheric conductivity with Langmuir probes and relaxation probes. The magnitude of the surface charging is a function of altitude, vertical velocity and body size and geometry; the polarity of the potential may differ during ascent and descent. An explanation is proposed for the mechanism responsible for this complex phenomenon, where the loss of negative ions and the existence of aerosol and a downward fair weather electric field play critical roles. This model is supported by experimental results collected during balloon flights dedicated to the investigation of atmospheric electricity. The possible consequences for the measurements to be performed during the descent of the Huygens Probe in the atmosphere of Titan are briefly discussed.

1. INTRODUCTION

The performance of the instruments which measure electric field and conductivity on balloons are frequently impaired by the electrostatic charges which develop on their outer surfaces, due to their vertical motion through the atmosphere. The potential difference between the gondola and the sensor: electric antenna, relaxation probe, Langmuir probe or Gerdien condenser, may reach such high levels that it brings into saturation the input stage of the electronic circuitry to which this charge collector is electrically connected.

This phenomenon is frequently observed during ascents and has been reported in the literature [Ref. 1,2]; the potential of the gondola is generally positive and as high as a few tens of volts above that of the sensors. It has been proposed, not surprisingly, that these potentials were associated with electrostatic charging and that more than one process were probably at work, but no clear explanation has ever been put forward.

Several questions call for answers, namely:

(1) Does the event observed during the ascent takes also place during the descent?
(2) Does the charge builds up on the balloon, on the gondola or on the sensor?
(3) Are the observed potentials always positive?
(4) What is the nature of the subjacent mechanism(s) responsible for this differential charging?

The results collected during earlier flights are first recapitulated. The additional data which are presented do not only corroborate the previous observations but also bring new experimental evidences about this phenomenon. An explanation based on these experimental facts is then proposed. Finally the possible occurrence of a similar interaction during the parachute descent of the ESA Probe, Huygens, through the atmosphere of Titan, the largest satellite of Saturn, in 2004, is tentatively taken in consideration

2. EXPERIMENTAL OBSERVATIONS

The potential of the gondola was measured by Garg and John with respect to reference electrodes, at distances of 15-30 cm from the surface, during two balloon flights [Ref. 1]. The data shown in Figure 1 were presumably recorded during the ascents; below the altitude of 10 km, the potential fluctuations were such that no reliable estimate could be made.

Similar potential measurements are reported in Figure 2; they have been obtained during the flight of a balloon which carried a mock up of the Huygens Probe and a development model of the instrument which will measure the electric properties of the atmosphere of Titan [Ref. 3]. The surface of the gondola is conductive; its symmetry axis is vertical and its height and maximum radius are about 60 cm. The reference electrode consists of a flat disk, 3.5 cm in radius, mounted sideways at a distance of 20 cm from the surface.

As in Figure 1, the relative potential of the gondola is positive and sometimes exceeds +10 V; it decreases with height above a certain altitude, here 13 km. Below this level, the potential is smaller but

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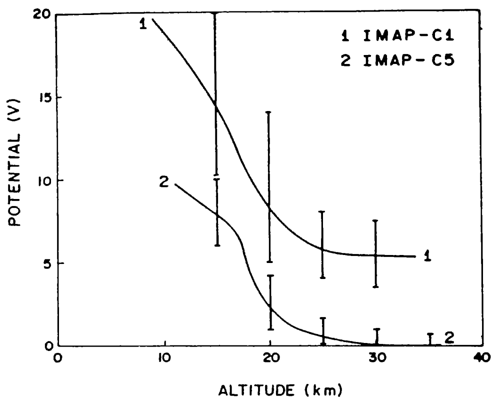

Figure 1. Potential difference between the gondola and a Langmuir probe during the ascents of two balloons [Ref. 2].

the measurements are much more scattered. However, during the descent from the float altitude, between 30 and 19 km, the potential is remarkably constant at about + 0.5 V. At 19 km the payload is jettisoned and, following a free fall of a few seconds, a parachute is opened. It is observed that the potential decreases immediately to a value less than -12 V, the lower limit of the instrument measuring range, and then returns progressively to its former level. The potential keeps a small positive value down to 12 km, where the parachute and the payload disappear behind the horizon and the telemetry link is lost.

3. THEORETICAL APPROACH

3.1. Atmospheric Electricity

The problem is unidimensional and the space variable, the altitude, is measured from the Earth surface along the z-axis oriented positively upwards.

The fair weather electric field E, oriented downwards, is a negative quantity which is due to the separation between the negative charges carried by the surface of the Earth and the net positive charge distributed within the atmosphere. This field is associated with a downward electric current density,

$$j=\sigma E, \qquad (1)$$

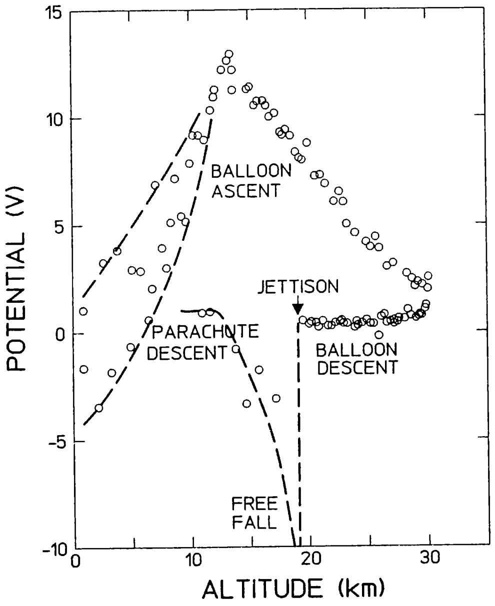

Figure 2. Potential difference between the Huygens Probe and a reference electrode during the flight of the Comas Solà balloon.

approximately equal to - 2.5 x 10^{-12} A m^{-2} (Ref. 4), and a conductivity

$$\sigma=\sigma_0\exp(z/z_0), \qquad (2)$$

where σ_0, the conductivity at the surface of the earth, equals 2.7 x 10^{-13} mho m^{-1} and z_0 is a scale length of the order of 8 x 10^3 m [Ref. 6].

The current density can also be written

$$j=(n_+v_+-n_-v_-)e, \qquad (3)$$

where v_+ and v_- are the velocities, and n_+ and n_- are the volume density numbers, of the positive and negative ions, respectively; e is the electron charge. It is shown experimentally that the current densities carried upward by the negative ions ($v_- > 0$) and downward by the positive ions ($v_+ <$o) are equal [Ref. 4], so that

$$n_+v_+ + n_-v_- = 0. \qquad (4)$$

It is derived from theory and confirmed by experiment [Ref. 5] that

$$\frac{n_+}{n_-}=\frac{v_-}{v_+}=\frac{\mu_-}{\mu_+}\approx 1.25, \tag{5}$$

where

$$\mu_-=v_- /E, \tag{6}$$

$$\mu_+=v_+ /E, \tag{7}$$

the mobilities of the negative and positive ions, lie in the range 1.5 - 2 x 10^{-4} m^2 V^{-2} s^{-1} between 10 and 30 km [Ref. 7].

Combining (1) and (2) gives the electric field

$$E=\frac{j}{\sigma_0}\exp(-z/z_0), \tag{8}$$

which is maximum and equal to about 10 V m^{-1} at the Earth surface. Replacing E by (8) in (6) and (7) shows that the drift velocities of the positive and negative ions are always less than 10^{-2} m s^{-1} at altitudes less than 30 km.

The gradient of the electric field is derived from Poisson's equation,

$$\frac{dE}{dz}=\frac{n_+-n_-}{\epsilon_0}e, \tag{9}$$

where ϵ_0 is the permittivity of vacuum; it can be combined with the derivative of (8) to yield

$$n_+-n_-=\frac{\epsilon_0\, j}{ez_0\sigma} \tag{10}$$

3.2. Collected Current

The net ram current collected by a body is

$$I_c=(n_+|v_+-V|)-n_-|v_--V|)eA_c, \tag{11}$$

where V is the vertical velocity, measured positively upwards, and A_c is the body area projected on the horizontal plane. Equation (9) can be expressed under the forms:

$$v_-<V,\quad I_c=[(n_+-n_-)V-(n_+v_+-n_-v_-)]eA_c; \tag{12}$$

$$v_+<V<v_-,\quad I_c=[(n_++n_-)V-(n_+v_++n_-v_-)]eA_c; \tag{13}$$

$$V<v_+,\quad I_c=[-(n_+-n_-)V+(n_+v_+-n_-v_-)]eA_c; \tag{14}$$

or, taking equations (6)-(8) into account:

$$v_-<V,\ I_c=-j(1+\frac{\epsilon_0V}{\sigma z_0})A_c; \tag{15}$$

$$v_+<V<v_-,\ I_c=(n_++n_-)VeA_c; \tag{16}$$

$$V<v_+,\ I_c=j(1+\frac{\epsilon_0V}{\sigma z_0})A_c. \tag{17}$$

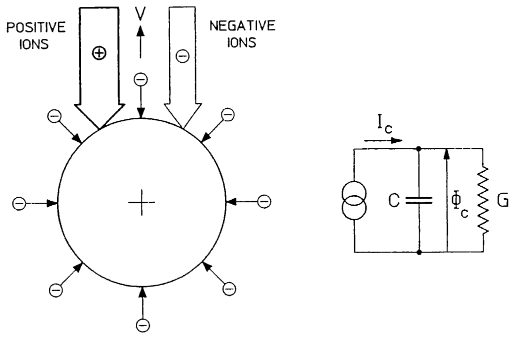

Figure 3. Schematic representation of the collection of positive and negative ions by a conductive body in ascending motion in the Earth atmosphere.

Being given the orders of magnitude v_+, v_-, σ_0 and z_0 and considering that 10^{-2} m s $^{-1} << |V| <$ 10 m s $^{-1}$, except at the float altitude and possibly during free fall, the quantity

$$\left|\frac{\epsilon_0 V}{\sigma_0 z_0}\right|$$

is estimated to be less than 4 x 10^{-2}. Then, equations (15) and (17) reduce to

$$I_c = \mp jA_c, \tag{18}$$

where the minus and plus sign apply to the ascent and descent, respectively.

3.3. Equilibrium Potential

The electric potential Φ_c of a conductive body moving in the atmosphere is in equilibrium when the net ram current is balanced by the relaxation current

$$I_c = \Phi_c G, \tag{19}$$

as illustrated in Figure 3; the conductance

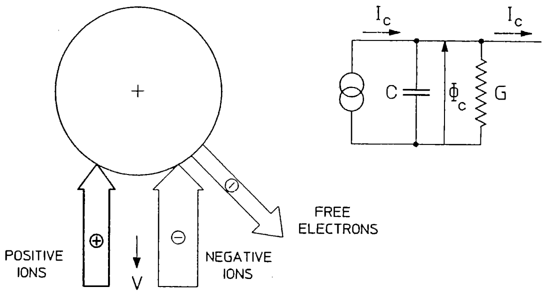

Figure 4. Schematic representation of the exchange between a conductive body and its atmospheric environment during the descent.

$$G = C\frac{\sigma}{2\epsilon_0} \tag{20}$$

is derived from the capacitance C assuming that (1) the medium homogeneity is not perturbed by the air flow, (2) the surface of the body is equipotential and (3) the positive and negative ion conductivities are both equal to $\sigma/2$, as observed experimentally.

The floating potential is obtained by combining equations (18-20), i.e.:

$$\Phi_c = \mp 2A_c \frac{j}{\sigma}\frac{\epsilon_0}{C}. \tag{21}$$

In the case of a spherical body of radius r, for example, equation (21) takes the simplified form

$$\Phi_c = \mp\frac{jr}{2\sigma} = \mp\frac{r}{2}E. \tag{22}$$

This implies that, since the equilibrium potential is proportional to the radius of the body, a small electrode mounted on a sufficiently long boom can serve as a reference for measuring the potential of a much larger gondola.

Replacing σ by equation (2) in equation (22), one finally obtains:

$$\Phi_c = \mp \frac{jr}{2\sigma_0}\exp(-z/z_0), \qquad (23)$$

which corresponds to potentials of +10 mV for an electrode with a radius of 1 cm, + 10V for a gondola with a radius of 1 m and + 100 V for a balloon with a radius of 10 m, during the early phase of the ascent.

4. DISCUSSION

4.1. Validity of the Theoretical Model

Equation (23) summarizes the theoretical treatment carried out in the preceeding section; it explains that: (1) differential charging occurs on conductive bodies with various sizes and geometries; (2) the potential of the gondola is larger in magnitude than that of the electrode; (3) the potential of the gondola relative to that of the reference electrode is positive during the ascent; (4) the equilibrium potential decreases with altitude, as observed in Figure 1 and, above 13 km, during the ascent, in Figure 2.

In practice, a potential Φ is measured with respect to a reference electrode which stands at a distance l from the surface of the gondola. In the case of a spherical body of radius r, the surface potential is consequently

$$\Phi_c = \frac{r+l}{l}\Phi. \qquad (24)$$

It is estimated that a corrective factor of the order of 3 should be applied to the measurements shown in Figure 2. For example, a floating potential of about 40 V corresponds to the relative potential Φ = 13V, measured at the altitude of 13 km during the ascent. This equilibrium potential is therefore significantly larger than the value of a few volts predicted by equation (23) at the same altitude.

Other features cannot be explained by the theoretical model, namely:

(1) the variation of the measured potential when the altitude increases from 0 to 13 km; (2) the asymmetry of the potential profiles recorded on the up-leg and down-leg of the balloon flight; (3) the large negative potential which develops during free fall.

We shall now attempt to explain these discrepancies in terms of additional effects induced by (1) the input admittance of the electronic device which measures the gondola potential, (2) the concentration of large ions in the low altitude range and (3) the loss of negative ions.

4.2. Input Conductance of the Amplifier

The potential difference between the gondola and the reference electrode Φ is related to the measured voltage Φ' by the equation:

$$\Phi' = \Phi\frac{G_e}{G_e+G_i}, \qquad (25)$$

where $G_i \approx 10^{-13}$ mho is the input conductance of the amplifier, and

$$G_e = 4\sigma r' \qquad (26)$$

is the conductance of the electrode, which consists of a flat disk of radius $r' = 3.5$ cm, in a medium where the positive or negative ion conductivity is $\sigma/2$. The conductances G_e and G_i are comparable when σ is of the order of 5 x 10^{-13} mho m^{-1} , which equals approximately the atmospheric conductivity near the Earth surface given by equation (2). It is therefore concluded that the condition $G_i << G_e$ is certainly fulfilled in the upper altitude range where $\Phi' \approx \Phi$, but it is not applicable in the earlier part of the ascent where the gondola potential is probably underestimated.

4.3. Effect of Large Ions

The atmospheric conductivity represented by equation (2) characterizes the mobility of the small ions: air molecules having lost or gained one electron. This formula is not valid below an altitude of about 5 km, due to the high concentration of large ions, which result from the attachment of small ions to aerosol particles [Ref. 6]. The mobility of the large ions is several orders of magnitude smaller than that of the small ions, which entails a drastic reduction of the atmospheric conductivity.

Assuming that $G_e << G_i$ and combining equations (23)-(26) gives

$$\Phi' = \mp\ 2\frac{rr'l}{r+l}\ \frac{j}{G_i}\ , \tag{27}$$

that is a potential of about 0.25V in magnitude.

4.4. Loss of Negative Ions

Using the theoretical model represented by equation (23) and taking into account the limitation imposed by the measuring technique (conductance of the preamplifier and presence of large ions), one may explain in a semiquantitative way the potential profile observed during the ascent, but not during the descent.

We shall now propose a qualitative argument which may help understanding why the differential charging is strongly reduced during the balloon and parachute descent, except during the time interval which immediately follows the jettison.

The situations observed during the ascent and the descent are compared in Figures 3 and 4. In both cases, the positive and negative ions are collisionally bound to the neutral flow ($|v_+|$, $|v_-| << |V|$); the source of the current I_c is therefore represented by a current generator with a large internal impedance.

The net current I_c is positive during the ascent; the body, which is characterized by a capacitance C, develops a positive potential and attracts additional negative ions to keep the potential at a fixed level Φ_c. In other words, the capacitance is continously discharging through a conductance G which is directly proportional to the atmospheric conductivity (Figure 2).

One would expect a symmetric situation during the descent, with negative values for I_c and Φ_c, but it is observed that a body falling in the atmosphere with a velocity of the order 5 ms $^{-1}$ develops only a very moderate potential.

Unlike positive ions, negative ions can be lost through mechanisms other than recombination or attachment to aerosols. Negative ions can indeed be destroyed through collisional and associative detachments, with release of energy, or by photodetachment due to the exposure to IR radiation [Ref. 8]. We tentatively assume that electron detachment is induced by impact with the body, whereas positive ions are adsorbed at the surface.

Electron and ion collisions frequencies are comparable in the atmosphere but the electron drift velocity, v_e, which is inversely proportional to the mass of the particle, is several orders of magnitude larger than that of the ions. We therefore make the hypothesis that v_e is comparable or larger than $|V|$, except momentarily during the free fall. As long as $v_e > |V|$, the electrons are free to escape and prevent the body from developing a negative potential; in fact a small positive potential is required to limit the electron outflow and keep the current balance (Figure 3).

When $v_e < |V|$, during the free fall, the electrons are bound within the neutral flow; one observes a situation similar to that encountered during the ascent, but with an opposite polarity.

5. THE DESCENT OF HUYGENS IN THE ATMOSPHERE OF TITAN

The conditions encountered in the atmosphere of Titan should, according to current models, differ drastically from those encountered on Earth: (1) the energy dissipated in electric processes is 10^3-10^4 times lower [Ref. 9]; (2) the atmosphere of Titan contains no electrophilic species and the negative charges are carried by free electrons [Ref. 10]; (3) the conductivity is about two orders of magnitude larger than on Earth, at altitudes less than 30 km [Ref. 3]. Considering that the velocity of the gondola will be less than 10 ms^{-1} during the last phase of the Huygens mission, which is comparable to that experienced during the parachute descent in the Earth atmosphere, it is predicted that electrostatic charging is quite unlikely below 30 km. However, during the earlier part of the descent, in the altitude range 80-170 km, the velocity will be of the order of 60-100 ms^{-1} and the situation may be similar to that met during free fall in the Earth atmosphere. This problem deserves a detailed investigation which lies outside the scope of the present study.

6. CONCLUSION

The electrostatic charging of a gondola in an atmospheric environment is a complex phenemenon. Several mechanisms are required to explain the variation of the surface potential with altitude and the dissimilarity between the ascent and descent profiles. It is hoped that the present investigation is only a first attempt to be followed by additional theoretical and experimental works.

It will be difficult to quantify the role of triboelectricity, but numerical simulation might prove useful in exploring the effects of (1) the gondola geometry, (2) the transition from laminar to turbulent flow, (3) the charge depletion in the trail of the balloon during the ascent. A systematic experimental programme should also be undertaken with gondolas of various shapes carrying electrodes mounted on booms of different lengths. Finally, flight campaigns should be carried out under the most diversified conditions, namely during day and night, in fair and stormy weathers.

ACKNOWLEDGEMENTS

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REFERENCES

1. Garg S.C. and John T. 1996, Balloon gondola charging and its estimation, *Adv. Space Res.*, 17, 1199-11102.

2. John T. and Garg S.C. 1996, Results of balloon-borne ion conductivity intercomparison measurements from Hyderabad, *Adv. Space Res.*, 17, 11103-11106.

3. Grard R., Svedhem H., Brown V., Falkner P. and Hamelin M. 1995, An experimental investigation of atmospheric electricity and lightning activity to be performed during the descent of the Huygens Probe on Titan, *J.Atmos. Terr. Phys.*, 57, 575-585.

4. Volland H. 1982, Quasi-electrostatic fields within the atmosphere, in *CRC Handbook of Atmospherics*, H. Volland (ed.), Vol. 1, pp. 65-109, CRC Press, Boca Raton, Florida.

5. Malan D.J. 1965, The theory of lightning, in *Problems of Atmospheric and Space Electricity*, S.C. Coroniti (ed.), pp. 323-331, Elsevier Publish. Co., Amsterdam, The Netherlands.

6. Bricard J. 1965, Action of radioactivity and of pollution upon parameters of atmospheric electricity, in *Problems of Atmospheric and Space Electricity*, S.C. Coroniti (ed.), pp. 82-117, Elsevier Publish. Co., Amsterdam, the Netherlands.

7. Rosen J.M. and Hofmann D.J. 1986, Balloon-born measurements of electrical conductivity, mobility, and the recombination coefficient, *J. Geophys. Res.*, 86, 7406-7410.

8. Banks P.M. and Kockarts G. 1973, *Aeronomy*, Academic Press, New York.

9. Desh M.D. and Kaiser M.L. 1990, Upper limit set for lightning activity on Titan, *Nature*, 343, 442-443.

10. Borucki W.J., Levin Z., Whitten R.C., Keezee R.G., Capone L.A., Summers A.L., Ton O.B. and Dubach J. 1987, Predictions of the electrical conductivity and charging of the aerosols in Titan's atmosphere, *Icarus*, 72, 604-622.

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