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Determining the photocurrent of spherical probes from one-sonde-shading electric field data

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ABSTRACT

We propose a method for determining the saturation photoelectron current density of spherical probes, designed for measuring the electric field by the double-probe technique. Shading of only one of the probes causes specific changes in the electric field, and using the potential difference ΔV between the two probes created by the shading we obtain an analytical expression for the photocurrent density. We derive this expression in two different ways: directly, from the potential difference; and after calculating the resistance of the plasma layer around the probe. In both cases the value of the photocurrent is determined from the ion current. Data for the concentration and the plasma temperature is needed to determine the ion current. We considered two limiting forms of its collection: (1) SAL-sheath area limited case (thin layer); (2) OML-orbital motion limited case (thick layer). We validate the method using data from Intercosmos Bulgaria - 1300 satellite. The photocurrent density is calculated for two shading-of-the-probe instances. The values we obtain are significantly larger than the ones from laboratory measurements, but close to the photocurrent values deduced from other space experiments.

1. Introduction

It is commonly assumed that when measuring the electric field of satellites and rockets by the double probe method it is not necessary to know the photocurrent from each of the probes. This is due to the expected equality of the photocurrents from the two probes and, more generally, to the assumed uniformity of the measurement conditions of the probes. These are not always realistic assumptions, however, as was demonstrated, for example, on Injun 5 (Explorer 40) (Cauffman and Gurnett, 1972), where a difference between the spherical probes saturation photocurrent density - 3.1 nA/cm^2 was observed, due, according to the authors, to a prelaunch probe contamination. Another example of the probes dissimilarity is the measured potential difference ~ 150 mV between the spherical probes on ISEE-1 caused by photocurrent differences (Mozer et al., 1983a). These observations suggest that knowledge of the photocurrent from each probe can be necessary for the accurate determination of the electric field. The photocurrent value can also be used to study the variations in the solar spectrum in the EUV.

Photoemission properties of selected materials used in space exploration are presented in (Feuerbacher and Fitton, 1972). Data from samples at room temperature and vacuum of about 10^{-6} Torr, corresponding, according to the authors, to the conditions on a spacecraft were determined by laboratory measurements. Using the photoyield measurements, combined with a model of the solar intensities (the continuous part of the solar spectrum for the case of a distance of 1 a.u. from the sun and the Lyman-α line), the saturation photoelectron current density from typical satellite surfaces were calculated. Since the electric field measurements were usually done with vitreous carbon (VC) spherical probes, in this section we mostly discuss photocurrent properties of such probes. For one particular type of vitreous carbon (see reference (Mozer et al., 1983b) in (Feuerbacher and Fitton, 1972)) a value for the photocurrent density $I^0ph \sim 2.1$ nA/cm^2 was obtained in (Feuerbacher and Fitton, 1972). From the same laboratory measurement results, but using a different approximation for the spectrum, (which includes more high-energy photons) and a different way of determining the photoemission properties, somewhat smaller value of $I^0ph \sim 1.3$ nA/cm^2 was obtained in (Grard, 1973). Close to these laboratory results is the saturation photocurrent density of the VC spherical probes on GEOS-1 and GEOS-2 satellites determined at the beginning of their operation, and on ISEE-1 satellite (around 3.0 nA/cm^2 and 2.0 nA/cm^2, respectively) (Pedersen et al., 1984). However, many space experiments convincingly demonstrate that photoemission properties of materials in space can significantly differ from those measured in laboratory.

Here are several notable cases. In (Schmidt and Pedersen, 1987) is

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investigated the appearance of a false signal in the electric field measurements, caused by the influence of photoelectrons emitted by the booms. In the analysis of the results these authors used for the saturation photocurrent from the spherical VC probes the value $\sim 6\,\text{nA/cm}^2$. In publications (Pedersen, 1995) and (Escoubet et al., 1997) a method for determining the parameters of the ambient plasma as a function of the difference between the potential of the satellite and the potential of the plasma was proposed. The method was applied to data collected by several satellites, and for the saturation photocurrent density of spherical VC probes the following values were used: 5.0 or $8.0\,\text{nA/cm}^2$ for GEOS-1 and ISEE-1 satellites (Pedersen, 1995); $5.2\,\text{nA/cm}^2$ from the probes and satellite body of ISEE-1 (Escoubet et al., 1997); $4.6 \div 6.8\,\text{nA/cm}^2$ for the Cluster satellites (Pedersen et al., 2008).

One reason for reversible changes of the photocurrent from the probes during their work in space is the dependence of the photocurrent on the solar spectrum. For example, from measurements of the electric field in a rocket experiment the saturation photocurrent density for a VC spherical probe was estimated to be $0.4 \pm 0.2\,\text{nA/cm}^2$ (Fahleson et al., 1974). The authors find this value consistent with the laboratory results, because of the reduction of the solar spectrum with altitude. In (Brace-Noegy and Theis, 1988) the intensity of the solar EUV near Venus was examined, based on data from the cylindrical Langmuir probe. A variation of about 10–15% of the photoemission with a 27-day periodicity was observed. Moreover, the photoemission at solar maximum was shown to be almost two times greater than that at solar minimum.

Photoyield also depends on the conditions of the probe surface. In one already cited work (BraceNoegy and Theis, 1988), it was shown that there is approximately 1.75 factor reduction in the photocurrent of the cylindrical probe with the decrease of the altitude of the periapsis from 900 km to 300 km. An example of similar "dramatic change" of the photoemission from the spherical probes on the satellite ISEE-1 can be found in (Pedersen, 1995). The decrease of the periapsis to 500 km, leads to three-to four-fold reduction of the photoelectron production, which returns to its previous values with the increase of altitude. In both cases the authors attribute these to the changes of the probes' surface properties, caused by operating in the lower and denser atmosphere, where the absorption of a large amount of heavy neutrals and ions takes place.

Long-term changes in the photoemission of the spherical VC probes also have been observed. In (Pedersen et al., 1984) it is stated that the photoyield from VC spherical probes on ISEE-1 satellite has increased by a factor of 2 over the two years of operating in space, while in (Mozer et al., 1983a) for the same probes three years after launch an approximate four-fold increase of the photoyield was found. In (Pedersen, 1995) from the same VC spherical probes when orbiting far from the Earth's atmosphere the value of the photocurrent increased during the first few months to approximately six times the laboratory value. The explanation proposed by the authors is that the layer of adsorbed gases on the probes surface due to prelaunch contamination was gradually reduced when exposed to the solar radiation for an extended period of time, which, in turn, led to higher photoemission.

In (Pedersen et al., 1984) irreversible changes in the surface properties of a spherical probe is mentioned; the appearance of a patchyness structure which manifested itself as a false electric field signal. The authors conjectured that these patches are due to the effects of the sustained significant ion flow from the solar wind, altering the surface properties of the probe.

Schläppi et al. (2010). discussed three different mechanisms responsible for the outgassing process: 1) desorption of water from exposed surfaces of the spacecraft - the most important process during the first 200 days of a mission; 2) diffusion; 3) decomposition of the material - starts to play a role for long missions after several years in space.

All these examples show that the photocurrent from a probe in space can vary due to changes (both short- and long-term) in the probe's intrinsic characteristics (like its surface properties), as well as changes to the environment in which it operates. Thus, it is very desirable to have reliable and convenient method for obtaining the photocurrent from the probe, which can be used to track these changes, and to verify and validate other measurement methods.

Cauffman and Maynard (1974) develop a model for the interactions between the double floating probe systems and the spacecraft at high altitudes, where Debye lengths exceed the probe-spacecraft separation. Floating potential is calculated under the requirement of current balance for each probe and the predictions from the model are found to be in good agreement with the observations from the Explorer 45.

In the present work we propose a method, which uses data collected during intervals of shading of only one of the probes caused by other parts of the satellite. When such shading occurs there is no photocurrent from the shadowed probe, and the equality requirement is violated. Specific changes in the electric field measurements during these instances have been observed already in some early rocket (Fahleson and Kelley, 1970) and satellite (Cauffman and Gurnett, 1971) experiments.

In the Injun 5 spacecraft the electric field probes impedance at frequency 30 Hz was measured (Cauffman and Gurnett, 1972). In reference (Cauffman, 1971) the author, using the impedances of the illuminated probe Z_0 and the shaded probe Z_s, the change of the potential difference between the probes $\triangle V_M$ caused by the shading, and utilizing the block diagram of an electric field device, derived an analytic expression for the photoelectron current for spherical probe at negative potential:

$$I_P = \frac{(Z_S - Z_0)\Delta V_M}{Z_0(2Z_S - Z_0)\ln\frac{2Z_S - Z_0}{Z_0}}. \tag{1}$$

However, when the resistance of the plasma layer of the probe is not measured this expression cannot be applied. An alternative method, utilizing ambient plasma characteristic and the same potential difference between the probes ΔV, was proposed in (Fahleson and Kelley, 1970). No explicit expression for the photocurrent was derived in that work, but some values obtained for the photoelectric emission from carbon-coated probes were given.

In this work we extend these earlier proposals, and present a general method for determining the photocurrent density of spherical probes at a negative floating potential. It relies on the data of the electric field measurements when one of the probes is shaded, as well as measurements of the plasma density and the temperature of the ambient plasma.

The paper has the following structure. In section "**Determination of photocurrent**" we present the essence of our method, and derive a general expression for the saturation photocurrent density as a function of the ion current, bias current and potential difference caused by shading. Two limiting cases for the ion current are considered: sheath area limited case - SAL (thin layer) for moving and static probe; orbital motion limited case - OML (thick layer). In the next section - "**Verification using experimental data**" - instances of shading during two orbits are described. By comparing electric field measurements with other concurrent measurements we demonstrate that the variation in the electric field are caused by the shading. We use the data collected during the shading to obtain numerical values of the photocurrent density. We discuss the advantages and the limitations of the proposed method for determining the photocurrent in "**Conclusion and discussion**". In the Appendix we present a way to obtain an approximate solution for the floating potential for the OML case.

2. Determining the photocurrent

2.1. Determining the photocurrent

The general conditions necessary for accurate electric field measurements using a double probe are discussed in (Fahleson, 1967). When measuring the electric field by the double probe method, each probe is in a quasi-equilibrium state, i.e. there is a balance of the currents $\Sigma i = 0$ and this condition determines the probe potential. Shading of only one of the probes creates additional potential difference between the probes, due to the difference in the measurement conditions. We propose a method