Measuring Spacecraft Potential with an Electron Spectrometer

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Abstract. A high energy-resolution electron spectrometer can be deployed on rockets or low Earth orbit satellites to measure absolute spacecraft floating potential with an accuracy of up to ±.05 volt. Peaks due to the photoionization of nitrogen and atomic oxygen appear in high resolution electron-energy spectra that have been collected by satellite. Each peak can be identified as due to a given photoionization reaction. The spacecraft floating potential is determined by measuring the apparent shift in the energy location of the photoelectron peaks in spectra gathered by a spacecraft. We have developed the technique by analyzing spectra from a high energy-resolution electron spectrometer that flew in 1976. Features in the spectra exhibit an altitude-dependent shift in energy location that is consistent with the altitude-dependent change in the spacecraft floating potential. Since the technique shows promise, we are developing an instrument to determine spacecraft floating potential through high energy-resolution electron spectroscopy. The instrument will be able to determine spacecraft potential with great accuracy at all locations in the sunlit atmosphere at altitudes between 150 and 250 km and at certain sunlit locations at higher altitudes. The accurate measure of spacecraft floating potential will be useful for gauging the efficacy of and controlling charge mitigation devices, improving the accuracy of plasma energy analyzers, and investigating the spacecraft charging phenomenon in low Earth orbit.

1. Introduction

Over the decades, various methods have been used to determine spacecraft floating potential. However, the determination of spacecraft potential with accuracy and precision has proven very difficult. Multiple techniques used on a single spacecraft have yielded widely differing results. We present here a powerful new method for the determination of spacecraft floating potential above absolute ground for spacecraft that orbit at altitudes from 150 and 900 km.

The method promises an accurate and precise measure of spacecraft potential based on the analysis of high energy-resolution electron spectra from space. Sharp peaks appear between 20-40 eV in high energy-resolution (2.5% $\Delta E/E$) electron spectra gathered at altitudes from 150 to 900 km. The photo-electrons responsible for the peaks are produced in the atmosphere at well known energies. Electrons are decelerated (if the spacecraft potential is negative) as they enter the electron spectrometer on the spacecraft. The amount of kinetic energy lost by the electrons (in eV) is exactly equal to the spacecraft floating potential below the space plasma potential (in volts). The phenomenon can be exploited to measure what is sometimes referred to as "absolute spacecraft potential".

The spacecraft's floating potential can be determined accurately wherever spectra can be gathered that show clear photoionization peaks. Such spectra can be gathered at all locations in the daylit atmosphere between 150 and 250 km. Spectra that exhibit the sharp photoionization peaks can also be gathered at altitudes to 900 km if thermal plasma conditions permit.

We are developing a compact, lightweight, low power high energy-resolution electron spectrometer for use in determining spacecraft floating potential. We are striving to keep the instrument weight below 500 grams and power requirements below one Watt so that it will be useful on a variety of platforms that fly between 150 and 900 km.

Uses for accurate floating potential measurements include: determinations of the efficacy of and control of charge mitigation devices, improving the accuracy of measurements from plasma energy analyzers (e.g. those from retarding potential analyzers), and investigations into the spacecraft charging phenomenon in low-Earth orbit.

2. Sharp Peaks in Photoelectron Spectra

Extreme ultraviolet light (EUV) spectra of the Sun exhibit a sharp maximum in intensity at 304Å (the He II line). 304Å radiation is the most intense ionizing radiation from the Sun [*Hinteregger et al*., 1981]. Figure 1 illustrates the production of photoelectrons in the Earth's upper atmosphere. The peak production region for photoelectrons is from about 150 to 250 km altitude. At altitudes below about 150 km the EUV radiation has been attenuated enough that photoelectron production is very small. At altitudes above 250 km or so the density of the neutral atmosphere is not great enough to produce large quantities of photoelectrons. Even though the production region for photoelectrons is at about 150 to 250 km, photoelectrons travel from the region of production to higher altitudes. The transport of photoelectrons to higher altitudes becomes important in determining spacecraft potential above 250 km, as will be discussed in Section 5.

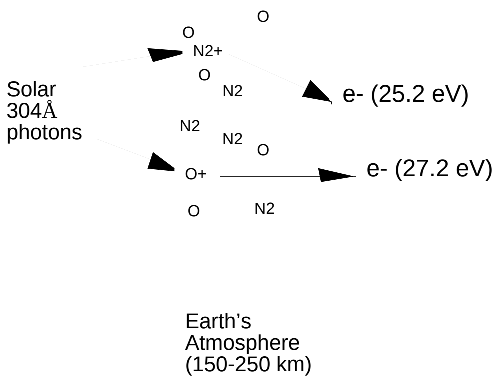

Figure 1. Photoionization in the upper atmosphere.

The 304Å photons supplied by the Sun provide 40.8 eV of energy for photoionization. The energy needed to ionize atomic oxygen or nitrogen to a given final electronic energy state of O^+ or N_2^+ is well known. It is the ionization potential for the transition, which is well known and is readily available from the literature. In a photoionization reaction, the energy in excess of the ionization potential is converted to the kinetic energy of the ejected electron. Therefore, in the model of the atmosphere shown in Figure 1 electrons of 25.2 eV will be ejected as $N_2^+(X^2\Sigma_u^+)$ is produced, electrons of 27.2 eV will be ejected as $O^+(^4S)$ is produced, and so on, for all the major photoionization reactions of nitrogen and oxygen. The energy spectrum of ejected electrons (photoelectrons) that results is shown in Figure 2, an actual photoelectron spectrum of the Earth's atmosphere at about 200 km.

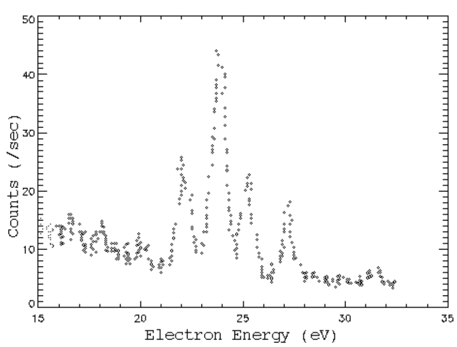

Figure 2. A photoelectron spectrum from AE-E.

The spectrum in Figure 2 was gathered by the high resolution electron spectrometer (PES) that flew on the AE-E (Atmosphere Explorer-E) satellite in 1976. The four peaks that stand out clearly at the center of the spectrum are due to the photoionization of atomic oxygen and molecular nitrogen by the sharp 304Å line. The great relative intensity of the 304Å line is responsible for the prominence of the peaks at the central region of the spectrum. We can also see evidence of photoionization by 386Å and 256Å solar radiation. The small peaks to the right and to the left of the four prominent peaks are due to the production of photoelectrons by those two EUV lines. All of the peaks in Figure 2 are identified in Table 1.

Table 1. Assignment of peaks in Figure 2

Peak	Energy (Centroid of Peak)
368.07Å MG IX.	
O^+ (^2P) and N_2^+ ($B^2\Sigma_u{}^+$)	15.1 eV
O^+ (^2D) and N_2^+ ($A^2\Pi_u$)	16.8 eV
N_2^+ ($X^2\Sigma_u{}^+$)	18.1 eV
O^+ (^4S)	20.1 eV
303.78Å HE II.	
O^+ (^2P) and N_2^+ ($B^2\Sigma_u{}^+$)	22.2 eV
O^+ (^2D) and N_2^+ ($A^2\Pi_u$)	23.9 eV
N_2^+ ($X^2\Sigma_u{}^+$)	25.2 eV
O^+ (^4S)	27.2 eV
256.32Å HE II.	
O^+ (^2P) and N_2^+ ($B^2\Sigma_u{}^+$)	29.8 eV
O^+ (^2D) and N_2^+ ($A^2\Pi_u$)	31.5 eV
N_2^+ ($X^2\Sigma_u{}^+$)	33.1 eV
O^+ (^4S)	34.8 eV

3. Floating Potential from Spectra

The spectrometer that gathered the spectrum in Figure (PES) was based on a hemispherical electrostatic charged particle analyzer (hemispherical analyzer). Details about hemispherical analyzers are given in *Goembel and Doering* [1998] and the references listed in that work. Figure 3 is a cut-away drawing of a spectrometer that contains a hemispherical analyzer. PES was configured so that the reference potential of the spectrometer was held at spacecraft ground (spacecraft chassis potential). For an electron spectrometer configured as PES was, if the spacecraft chassis was negatively charged, the electrons would be decelerated before energy analysis. Alternately, for a positively charged spacecraft (positive instrument reference potential) the electrons would be accelerated as they entered the analyzer. The phenomenon is such that electrons are accelerated or decelerated (in eV) by exactly the spacecraft floating potential (in volts) [*Goembel and Doering*, 1998].

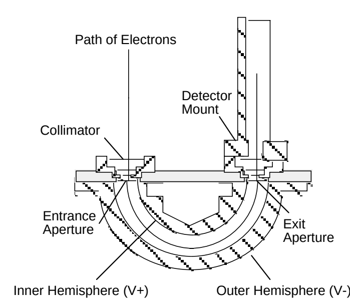

Figure 3. A cut-away drawing of a hemispherical electrostatic charged particle analyzer.

Figure 4 includes three idealized photoelectron spectra that illustrate the method by which spacecraft floating potential can be determined. The spectra differ from actual spectra from PES in that PES scanned in energy at

0.5 eV increments, too coarse to show the photoionization peaks as clearly as illustrated in Figure 4. The top spectrum is what we would expect to collect with the instrument's reference potential held at the surrounding bulk space plasma potential ("ground" in outer space). Each peak appears at the energy expected for the photoionization of N_2 and O by 304Å radiation (as tabulated in Table 1). We have labeled this the "source spectrum". The bottom two spectra are those expected from a spectrometer mounted on a spacecraft that is at an electrical potential that is negative relative to the space plasma. The two lower spectra contain peaks that are shifted to lower energies than those of the source spectrum. The observed shift in the energy location of the peaks indicates that the satellite was at -0.9 volts floating potential at 250 km and at -0.4 volts floating potential at 150 km. Note the 1:1 correlation between spacecraft potential and peak shift. The idealized spectra shown below are consistent with the data from PES [*Goembel and Doering*, 1998].

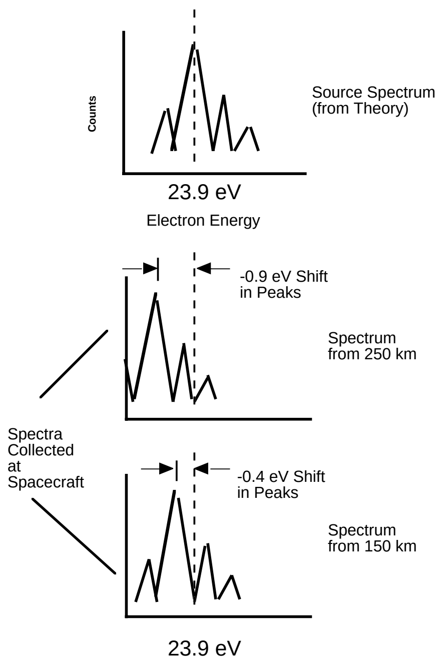

Figure 4. Three different cases of photoelectron detection.

4. A New High Resolution Spectrometer

The spectrometer that flew on AE-E was not well suited to measure spacecraft floating potential. PES was designed to make a broad survey of photoelectron fluxes from 1 eV to 500 eV in at altitudes from 150-1000 km. The instrument's finest energy scan produced a spectrum that spanned 0-34 eV with 0.5 eV between energy channels. The spectrum in Figure 2, which has much finer energy spacing than 0.5 eV, was composed from many orbits of data [*Goembel and Doering*, 1998]. The coarse energy sampling of PES made it impossible to determine spacecraft floating potential with better than 0.5 eV precision.

The instrument we are developing will be vastly improved over PES. Foremost among the planned improvements: an innovative electron-optical design that offers greater sensitivity and smaller size while retaining the 2.5% energy resolution needed to determine spacecraft potential. The increased sensitivity will allow higher frequency and/or more accurate spacecraft floating potential measurements than would have been possible with PES. The sampling mode of the instrument under development will be optimized for spacecraft potential determinations.

The instrument under development will also take advantage of advances that have been made in electronics since PES was designed. The use of channeltron electron multipliers or microchannel plates will improve performance and reduce weight. The spectrometer will also contain smaller, higher performance control and signal processing electronics. The electronics will be designed to oversample the 2.5% energy resolution of the hemispherical analyzer. One design under consideration would collect a 128-point spectrum over a 22 eV range in one second. Such an instrument could be used to determine spacecraft potential with an accuracy of 0.2 volt and a precision of 0.1 volt every five seconds in flight [*Goembel and Doering*, 1998]. The accuracy of the floating potential measurement in the photoelectron production region is ultimately limited by the in-lab calibration of the instrument, which is ±0.05 volt for the helium resonance technique [*Goembel and Doering*, 1998]. Looking farther ahead, we believe we can increase the performance of the instrument by an order of magnitude (or more) through advances in its electron optical design. We also expect to incorporate on-board processing of spectra for autonomous spacecraft potential determinations in future models.

The spectrometer we will produce will be compact and lightweight, low power, and have a low data rate. We intend to keep the instrument weight ≤ 500 grams and keep the power consumption ≤ 1 Watt.

5. Determinations above 250 km Altitude

Spacecraft potential can be determined very accurately from any spectra that include photoionization peaks (as shown in Figures 2 and 4). Such spectra can be collected from all locations in the daylit atmosphere from 150-250 km (the production region for photoelectrons). In that region, photoelectrons are produced and lost locally and the distribution is isotropic. However, the method used to determine spacecraft floating potential from spectra gathered in the photoelectron production region can be extended to higher altitudes.

An upper bound of 250 km has arbitrarily been chosen for the photoelectron production region. It can extend to 300 km if the density of neutrals (mostly atomic oxygen at those altitudes) is great enough. Above 250-300 km the density of neutrals is so low that the photoelectrons observed at those altitudes are almost exclusively escaped photoelectrons from the top of the production region (from 250-300 depending on atmospheric density). The photoelectrons travel from the region of production to higher altitudes along geomagnetic field lines. Fluxes of photoelectrons to higher altitudes are great enough that high energy-resolution spectra can readily be obtained with the spectrometer described in this paper. If the photoelectrons pass through a region of low thermal plasma density, the spectra will be little changed from spectra collected at lower altitudes [*Lee et al*., 1980], and it will be possible to make accurate spacecraft potential determinations at that location. If the photoelectrons have passed through a region of high thermal plasma density, the peaks will be broadened due to coulomb scattering, and it will not be possible to determine spacecraft potential as accurately as at lower altitudes. Data from PES of AE-E indicate that it should be possible to make accurate spacecraft potential determinations by an examination of the photoionization peaks at altitudes higher than 250 km (up to 900 km) at local times from 6 to 9 under most circumstances. It may be possible to make accurate floating potential determinations at altitudes up to 900 km at other local times as well, depending on thermal plasma density. We would like to develop techniques for gauging spacecraft floating potential at even higher altitudes (perhaps with less accuracy) and other local times by examining other features in high energy-resolution electron spectra. Unfortunately, there are very few high energy-resolution electron spectra in the energy range of 1-100 eV in existence, and it may require the collection of more spectra to perfect a higher altitude technique.

6. Other Uses for the Spectrometer

Three pairs of high energy-resolution electron spectrometers have orbited the Earth in the past: the very successful PES instruments of Atmosphere Explorer -C, -D, and -E (launched in the 1970's). Their flight led to many important firsts, including the discovery of photoelectron peaks at 21-18 eV.

The survey of low energy electron fluxes that was made by PES in the 70's was by no means exhaustive (for instance, the spectrometers collected data only for a fraction of a solar cycle). The flight of another high-energy resolution electron spectrometer to increase our knowledge of the low energy electron environment in space is important enough to justify the development of such an instrument. However, compelling new uses for high energy-resolution electron spectra have been found since PES was flown.

Foremost among them is the determination of spacecraft floating potential, the focus of this paper. Spectra in the same energy range and at the same resolution used to determine spacecraft potential could also be gathered at altitudes above ~250 km to gauge thermal electron plasma conditions. It has been found that the same effect that can reduce the accuracy of spacecraft floating potential measurements at higher altitudes (the broadening of the four peaks at 21-28 eV) can be observed to gauge the thermal plasma density between the photoelectron production region and the location of the spacecraft. The transparency of the thermal plasma changes in response to solar activity, and its measurement can serve as an important indicator of plasma conditions.

Spectra collected within the photoelectron production region can also be used to determine O/N_2 ratios. Atmospheric O/N_2 ratios change in response to energy input to the atmosphere (e.g. during geomagnetic storms). O/N_2 ratios can be determined by examining the relative heights of the spectral peaks [*Goembel et al.*, 1997]. Spectra collected at altitudes greater than 250 km may be useful for gauging the O/N_2 ratios at the top of the production region. The spectra collected by the instrument will be valuable to those who wish to investigate atmospheric dynamics and the Sun-Earth connection.

7. Conclusion

It is possible to measure spacecraft floating potential with a high energy-resolution electron spectrometer. Very accurate measurements of spacecraft potential can be made in all locations the daylit atmosphere at altitudes of 150-250 km. Very accurate measurements can also be made where thermal plasma conditions permit (generally at local times of 6 to 9) at altitudes up to 900 km. It may also be possible to make electron-spectrometric determinations of spacecraft floating potential with somewhat less accuracy other local times or at higher altitudes. More high energy-resolution spectra in the 1 eV to 100 eV range need to be collected to investigate the possibility of extending our technique to other regions of space.

The method is novel, and, so far, has only been evaluated with the small amount of applicable data from PES. The instrument we are developing, a compact (500 gram) low power (1 Watt) instrument designed specifically to determine spacecraft floating potential, could set a new standard for the measurement of spacecraft floating potential.

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