Plasma Analyzer for Measuring Spacecraft Floating Potential in LEO and GEO

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***Abstract*— A design for a plasma analyzer for measuring spacecraft floating potential is described. The proposed Plasma Analyzer for Space Science (PASS) would use two methods simultaneously to determine spacecraft charge. Floating potential to kilovolts negative may be determined by the energy analysis of positively charged particles (ions) through the low energy ion cutoff method. Floating potentials from a few tens of volts negative to the highest positive potentials expected may be measured though the electron-spectroscopic method. The use of two charge sensing techniques should allow a large range of both positive and negative floating potentials to be measured. The simultaneous use of two dissimilar methods enables the refinement of both methods and should improve the reliability of spacecraft floating potential measurement. PASS should be able to determine spacecraft floating potential in both LEO and GEO from -10 kV to the largest positive floating potential expected. Based on what was learned from the development of the Spacecraft Charge Monitor, PASS should have superior performance in energy resolution, geometric factor, and data gathering efficiency compared to charged particle energy analyzers that have been used in the past.**

***Index Terms*—Space technology, Spectroscopy, Electron optics.**

I. INTRODUCTION

THE Plasma Analyzer for Space Science (PASS) is a proposed spacecraft charging monitor that would have the ability to simultaneously determine spacecraft floating potential using two independent charged particle energy analysis techniques. The device would be an improvement over its predecessor, the Spacecraft Charge Monitor (SCM), which was developed to flight readiness in 2006 [1]. The SCM was designed for use on the International Space Station (ISS) and the National Polar-orbiting Operational Environmental Satelite System (NPOESS). The SCM is a hemispherical electrostatic electron energy analyzer that has been optimized to determine spacecraft floating potential through the electron spectroscopic method [2].

The electron spectroscopic method of spacecraft floating potential determination works as follows. Since ambient electrons are accelerated by a positive spacecraft chassis floating potential (or they are decelerated by a negative floating potential) then features in spectra collected by a spacecraft mounted electron energy analyzer will be shifted in energy compared to spectra collected when the spacecraft is at the same potential as that of the ambient space plasma.

The shift observed in the energy of the features will be the same magnitude (in eV) as the spacecraft floating potential (in volts). The data reduction to determine floating potential is straightforward if two conditions are met. First, the spacecraft chassis potential and the electron energy analyzer chassis potential must be the same (or at a known difference). This condition can be satisfied in practice by clamping the instrument chassis potential to that of the spacecraft. Second, an identifiable energy-spectral feature (or features) that can be used to determine the energy scale of the ambient electrons must be observed in the spectrum. Past research has shown that there are often identifiable energy features in the electron energy spectra collected from space, as will be discussed in Section IV. Advantages expected for the electron spectroscopic method include a straightforward derivation of floating potential and the promise of great accuracy and precision in measurement. Additionally, electron-spectroscopic charge monitoring could be performed by a compact spacecraft surface mounted instrument (with no boom or probe required) that would experience no drift in calibration over time. However, the electron-spectroscopic method requires the collection of electron spectra in an unusually low energy range with unusually high energy-resolution. Such qualities were not available in an off-the-shelf flight instrument until the SCM was built.

The SCM was built to determine spacecraft chassis potential (relative to space plasma) from -145 to +45 volts at daylit local times (as would be useful on the ISS). It was designed to determine floating potential with 0.1 volt accuracy (as was desired for NPOESS). The SCM was built as a proof of concept flight experiment for low earth orbit (LEO), low radiation environment, demonstration of the electron spectroscopic method of charge determination. The

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650-gram, flight-ready SCM that was delivered to NASA in 2006 is shown in Fig. 1.

Fig. 1. The flight-ready SCM that was delivered to NASA in 2006. This is the direct predecessor of the proposed PASS instrument. The complete SCM weighs 650 grams.

The SCM was designed to compensate for negative floating potentials by charging a plate at the front of the hemispherical analyzer to positive potentials. After the SCM was constructed, analysis of laboratory data [3] and charged particle trajectory modeling indicated that the SCM negative floating potential range would be limited to less than a few tens of volts negative unless it were mounted on a boom and/or the positively charged plate at the front of the SCM were enlarged. Due to the demand for a device that would measure large negative floating potential, especially in geosynchronous earth orbit (GEO) where large negative floating potentials are common, an effort was undertaken to improve upon the SCM. The PASS design is the SCM design modified to determine large negative floating potentials in both LEO and GEO. The PASS design was at one time referred to as the "SCM2" [4], [5].

II. OBJECTIVE

The PASS sensor is designed to detect charging through analysis of ambient charged particles. In 2007 work began on the next generation SCM that would be included in a space weather suite on the Transformational Satellite Communications System (TSAT), a spacecraft that was to fly in GEO. It was determined that the modification of the SCM by the addition of an ion energy analyzer, the addition of a second data channel, and the substitution of its current scanning power supply for one that would produce higher voltages would yield a more versatile spacecraft charge monitor.

The resulting Plasma Analyzer for Space Science (PASS) design will yield an instrument that should be able to measure floating potential in LEO or GEO to negative potentials as great as -10 kV through the 'low energy ion cutoff' method. The low energy ion cutoff method evolved from the instrumental effect that first indicated negative spacecraft floating potential [6] and has been used in GEO or LEO for decades [7]-[11].

Slightly (a few tens of volts) negative to positive floating potentials will be measured by the electron spectroscopic method by retaining the negative charged particle analyzing ability of the SCM. The use of two charge-sensing methods simultaneously at slightly negative spacecraft floating potentials should enable in-flight refinement of both methods. It was determined that a compact charged particle optics design will enable the simultaneous use of both charge detection methods with little increase in instrument size or mass.

Although charged particle energy analyzers have been used to measure spacecraft floating potential for decades, the design of PASS is unique: it has been optimized for spacecraft charge sensing. Charged particle energy analyzers that have flown in the past have not had the energy resolution, geometric factor, pointing direction, or data gathering (scanning) method that would enable the efficient and accurate determination of spacecraft floating potential. Furthermore, the PASS device would require fewer resources (power and mass) than charged particle energy analyzers currently being used to determine charge. The objective of this paper is to describe a device that can readily be built which should improve the state-of-the-art of spacecraft floating potential determination.

III. DESCRIPTION

The PASS design includes two hemispherical-shell energy-analyzing regions. Three nested hemispherical electrodes would be arranged as shown on the right side of Fig. 2. Fig. 2 illustrates the modification of the SCM charged particle optics (left side) to produce the charged particle optics of PASS.

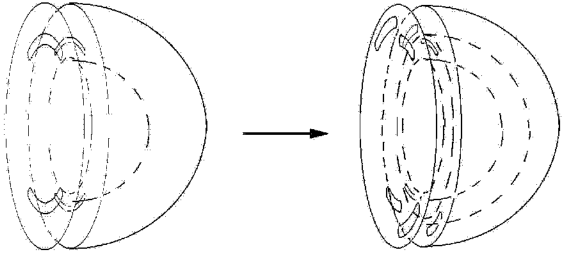

Fig. 2. Nested hemispheres would allow ions and electrons to be energy analyzed simultaneously in a compact device. The SCM design (with one hemispherical analysis region) is shown on the left and the PASS design (with two hemispherical analysis regions) is shown on the right.

Fig. 3 shows the electrostatic configuration planned for PASS. A positive potential is applied to the outermost and innermost electrostatic surfaces. A negative potential is applied to the hemispherical conductor that is between the inner and outer hemispherical conductor. The electrical arrangement shown in Fig. 3 is a simplification of the actual arrangement that will be used. The application of electrostatic potentials of the polarities shown should allow the simultaneous energy analysis of electrons (negatively charged particles) and ions (positively charged particles).

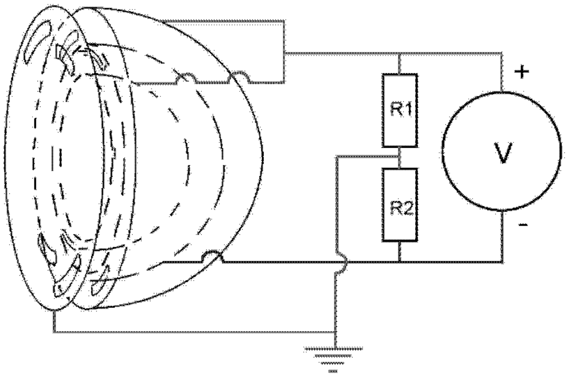

Fig. 3. The electrode polarities for simultaneous electron and ion energy analysis.

The electron optical configuration shown in Fig. 2 and Fig. 3 includes the large geometric factor collimator and aperture arrangement that is a unique feature of the SCM and will be included in PASS. The collimator and aperture arrangement is described in detail in [12].

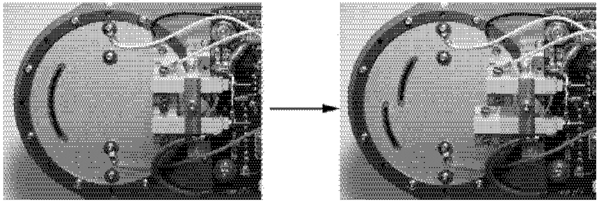

Fig. 4. Proposed modification of the SCM (left) to produce PASS (right). Note that there are two entrance apertures included in the PASS design and the channel electron multipliers are shifted in location slightly to capture the charged particles that exit the analyzer. One CEM is for ions, the other is for electrons.

Fig. 4 illustrates the expected appearance of PASS (right) compared to the already constructed SCM (left). The arrangement of the two entrance apertures and the two channel electron multipliers can be seen. The SCM is equipped with two custom designed ceramic-bodied channel electron multipliers (CEMs). By shifting the locations of the entrances of the channel electron multipliers slightly (as shown in Fig. 4), much of the construction of the SCM can be retained. The electronics would be modified to include a second data channel (for positively charge particles), a second CEM power supply, and a higher voltage scanning power supply.

Three 7.6 cm by 7.6 cm printed circuit boards contain the electronics for the SCM. The division of function between the three boards is illustrated in Fig. 5. The addition of a fourth board (or the enlargement of the high voltage board) will be required to accommodate the second data channel, an additional high voltage channel electron multiplier supply, and the higher voltage scanning power supply.

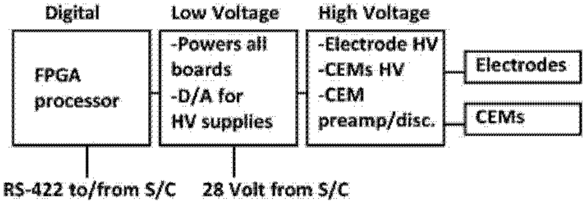

Fig. 5. The electronics of the predecessor to PASS are contained on three printed circuit boards designated “Digital”, “Low Voltage”, and “High Voltage”.

Fig. 6 illustrates the three-board arrangement of the SCM. There are a number of advantages to having the electronics in close proximity to the hemispherical analyzers. Advantages include the minimization of mass and the minimization of CEM signal loss or corruption.

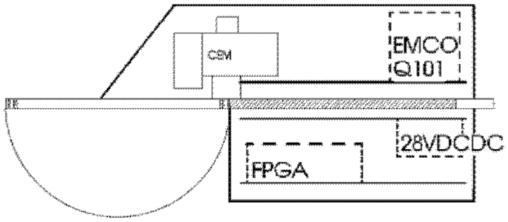

Fig. 6. The arrangement of the three printed circuit boards within the chassis of the predecessor to PASS.

Housing the electronics in a separate enclosure, located remotely from the sensor head, has been considered as an option for PASS where it appears that doing so would provide advantages. Advantages include more efficient thermal control and more efficient radiation shielding for the electronics.

Communication between the spacecraft and the SCM is illustrated in Fig. 7. This function of the SCM’s electronics could be retained for PASS.

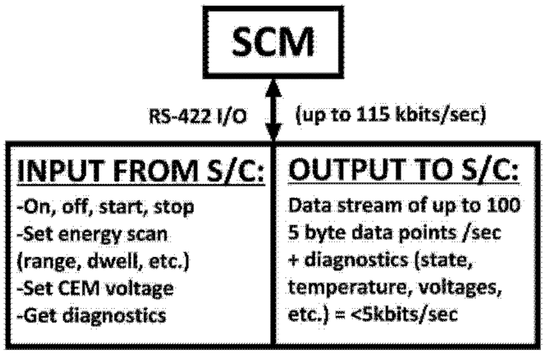

Fig. 7. The input/output scheme for the predecessor of PASS.

The SCM can be commanded to gather electron energy spectra with as little as 0.05 eV separation in energy bins with accumulation times for each bin as short as 0.005 seconds. A typical spectrum collected during thermal vacuum testing of the SCM was of 200 evenly spaced energy bins over a 10 eV energy range. One 200-point spectrum was collected each second. PASS can be built with the same capabilities.

The SCM has been vibration tested (shown in Fig. 8) and qualified for vibration to 14.5 Gs. The SCM has passed vacuum testing over six cycles from -24°C to 61°C and has passed an electromagnetic interference test. All of the components of the SCM are either radiation tolerant or available in radiation tolerant equivalents. Detailed results of the tests of the SCM are reported in [1]. It is expected that the modification of the SCM to produce PASS should be straightforward and that the flightworthiness of PASS, if built, should meet or exceed that of the SCM.

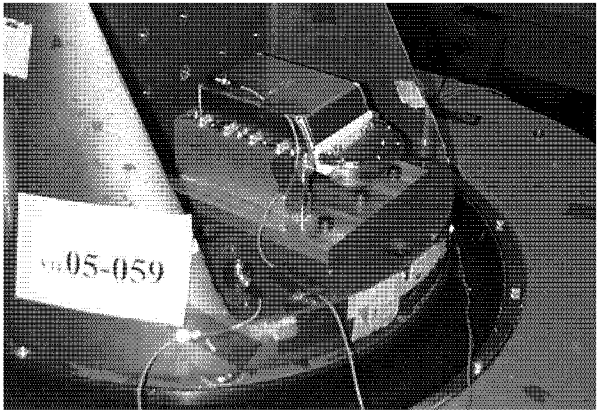

Fig. 8. Vibration test of the predecessor of PASS.

IV. MEASUREMENT TECHNIQUE

Spacecraft floating potential can be determined by measuring the acceleration of the otherwise undisturbed space plasma that impinges upon the spacecraft. Either the electron spectroscopic or the low energy ion cutoff method can be used (in both LEO and GEO) depending on spacecraft charge, as illustrated in Fig. 9. The ability to use either method depends on the ability to collect charged particle energy spectra with the features required to measure the acceleration induced by the spacecraft's floating potential.

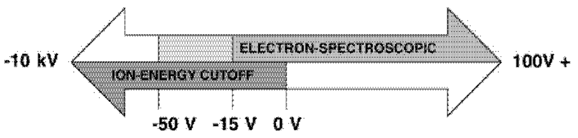

Fig. 9. Dual methods should enable floating potential measurement from -10 kV to the largest positive potentials expected. The electron-spectroscopic method may be used to determine positive potentials or negative potentials as low as -15 volts (when the 20-30 eV atmospheric photoelectron peaks are visible) or as low as -50 volts (when the 60 eV drop-off in atmospheric photoelectrons is visible). The low energy ion cutoff method may be used for negative floating potentials to -10 kV (a maximum limited by the electronics proposed for the PASS instrument).

The electron spectroscopic method, which was discussed briefly in the Introduction, will now be discussed in detail. Almost half of the solar energy deposited in the atmosphere above 120 km is given to electrons of energies of less than 100 eV which are produced by the photoionization of N_2 and O [13]. The electron spectroscopic method [2] utilizes the sharp electron-spectral peaks that can be seen in the atmospheric photoelectron spectrum due to the solar He II line that is an order of magnitude more intense than any other ionizing line [14]. Photoionization by other solar lines and scattering between electrons produces electrons with other energies as well. The resulting photoelectron spectrum thus appears as an exponentially sloped 'background' from 0 to 60 eV with peaks due to the He II (304 Å) line superimposed. Photoelectrons with energies greater than 60 eV are generally not produced. Thus, three features in the photoelectron spectrum can be used to determine spacecraft floating potential. The first feature is the characteristic sloping background in the flux of electrons, which appears as a maximum in flux at 0 eV that is reduced several orders of magnitude to 60 eV. The second is the characteristic set of peaks at 20-30 eV. The third is the steep 'cut off' in photoelectrons at 60 eV. These features are evident in the photoelectron spectra presented in Fig.10, from [15]. Note that the flux that appears at energies above 60 eV is attributed to stray photons and cosmic rays, not photoelectrons.

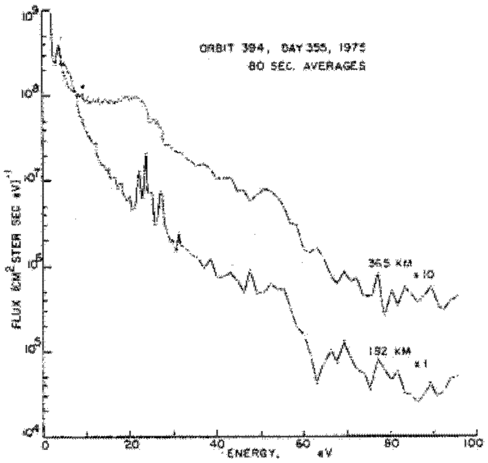

Fig. 10. Characteristic atmospheric photoelectron spectra from the PES instrument of the Atmosphere Explorer-E satellite. Note the features that can be used to determine spacecraft floating potential: the largest flux of electrons at 0 eV that diminish exponentially to 60 eV, the peaks near 25 eV (which may be broadened through transport), and a sharp drop in photoelectron flux above 60 eV. The flux above 60 eV in these spectra has been attributed to stray photons and cosmic ray radiation within the PES instrument. From [15], reproduced with permission.

The electrons used to determine spacecraft floating potential through electron spectroscopy have been created in the 'photoelectron production region', the sunlit atmosphere from about 150 to 300 km altitude. Atmospheric photoelectrons are found at a great distance from the production region because they travel along field lines. The electron may move directly up or down the field line (with a pitch angle of 180° or 0°), or it may move along the field line in a helical path with an intermediate pitch angle. The energy of the electron is distributed between along-field-line motion and circular motion. Photoelectrons that have traveled along geomagnetic field lines from their origin to the other end of the field line (conjugate photoelectrons) have been found in the electron energy spectra gathered by satellite [16], [17]. In fact, electrons that originate from the sunlit side of the Earth are even detected on the night side of the Earth [18]. At altitudes above 250 to 300 km the photoelectrons detected are no longer locally produced and the photoelectron lines in the spectrum may be broadened and shifted (by less than 0.5 eV) because of scattering by the ambient thermal plasma [18]. In general, the spectra collected after the photoelectrons have traveled great distances have the same features expected in a spectrum that that has been collected at the top of the production region. If electrons have passed through a region of high plasma density, the spectrum may exhibit peak broadening and a slight reduction in the energy of the peaks [19], [20], but at least some evidence of the peaks at 20-30 eV is visible in the vast majority of spectra presented in [18] regardless of the altitude at which they were collected. Photoelectron transport has been investigated through theoretical modeling [21] and some work has been done to compare theory with what has been found experimentally [22].

It is unfortunate that spectra from altitudes above 1000 km have not yet been collected with instruments with the energy resolution needed to reveal the peaks at 20-30 eV. However, atmospheric photoelectrons at GEO altitudes are evident in spectra such as the one shown in Fig. 11. Fig. 11 is an electron spectrograph from the Los Alamos National Laboratory (LANL) Magnetospheric Plasma Analyzer (MPA) [23]. The MPA instruments have been deployed on spacecraft with international designators of 1989-046, 1990-095, and 1991-080. The narrow bands of intensity at look angles of approximately 360° and 180° (spacecraft North and South) from local time (LT) 6 to LT 16 are thought to be atmospheric photoelectrons [24]. The flux of the electrons, their predominance at low energies (0-15 eV), and their directionality is consistent with what would be expected for atmospheric photoelectrons transported along geomagnetic field lines. More about the electron spectroscopic method can be found in [2].

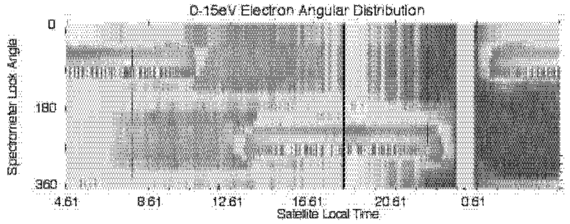

Fig. 11. MPA spectrogram for electrons for one full 24-hour geosynchronous orbit, March 21, 2007. Note the horizontal band of a lighter shade at about 360 and 180 degrees look angle. It is thought that this data is evidence of 0-15 eV atmospheric photoelectrons that have been transported to GEO altitude.

The electron spectroscopic method is limited to positive charge or minor negative charge. The steep reduction in flux at 60 eV marks the end of the atmospheric photoelectron population. If the spacecraft is floating at more than 60 volts negative then atmospheric photoelectrons will not reach the spacecraft. There is also a large flux of photoelectrons of energies of 10 eV or less that originate from spacecraft surfaces that may interfere with the electron spectroscopic method. By assuming that any spectrum may be contaminated by 0-10 eV spacecraft generated photoelectrons, a maximum negative spacecraft charge of approximately -15 volts can be estimated for the limit of charge determination based on the identification of the 20-30 eV atmospheric photoelectron peaks. Likewise, a floating potential of approximately -50 volts can be estimated for the maximum negative floating potential determination based on the identification of the steep reduction in atmospheric photoelectrons at -60 eV. A method other than the electron-spectroscopic method must be used to determine large negative floating potentials. The method that PASS will use is the low energy ion cutoff method.

The low energy ion cutoff method works as follows. It is assumed that there are ambient ions around the spacecraft that would have very little kinetic energy if the spacecraft were not present. For a negatively charged spacecraft the differential energy spectrum of ions will exhibit a ‘low energy cutoff’, the minimum energy at which ions can be detected. Since the ion energy analyzer reference potential is that of the spacecraft frame, then the apparent minimum in ion energy (in eV) is taken to be the spacecraft’s floating potential in volts (negative) relative to space plasma. Fig. 12 is an example of an ion energy spectrum from which spacecraft floating potential can be derived. The figure contains three ion energy-spectra collected by the ATS 6 spacecraft on day 59, 1976 [7]. The dashed lines in Fig. 12 give the energy distribution of ions when the spacecraft does not have a highly negative floating potential. The solid line is the distribution when the spacecraft is in eclipse and is highly charged (charged to kilovolts negative). Other examples of low energy ion spectra, and the floating potential derived from them, are given in [8], [9]. Low level as well as high level charging can be detected with this method. The low energy ion cutoff method has been used in LEO as well as GEO [11].

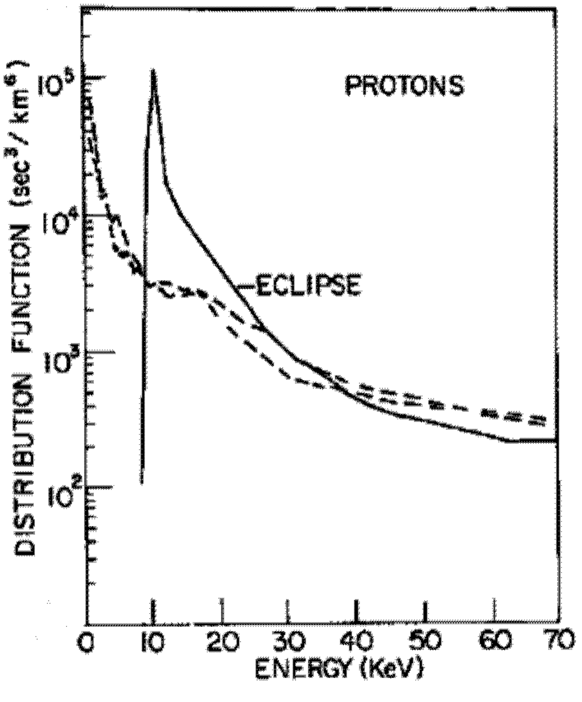

Fig. 12. An example of an ion (proton) energy spectrum from which spacecraft floating potential can be derived. The spectra shown are from when the geosynchronous orbiting ATS 6 spacecraft was in eclipse (solid line) and before and after eclipse (dashed lines). The solid-line spectrum contains the feature used to derive negative floating potentials. Note the absence of ions at below approximately 10 keV. Adapted from Fig. 2b of [7], with permission.

Many ion spectrograms from the MPA show the low ion energy cutoff clearly and have been used to determine spacecraft charge [25] in GEO. Fig. 13 is an ion spectrogram from the MPA instrument. The spectrogram is not an individual ion energy spectrum, but a series of spectra plotted versus time. The ion density at a given energy is plotted on a color scale. Identification of the lowest energy of ion detection yields the spacecraft’s negative floating potential. In Fig. 13 one can observe how the Los Alamos satellite’s floating potential varied as the spacecraft went through a 24-hour (local time) orbit at GEO. Both Fig. 11 and Fig. 13 are plots of data for one full 24-hour geosynchronous orbit for the date March 21, 2007. The exact method used to determine spacecraft floating potential from MPA data is given in [26]. At times when the low energy ion cutoff is not clear, an analysis based on electron spectroscopy is used, but the MPA is not capable of using the electron spectroscopic method presented in [2] and described earlier in this section.

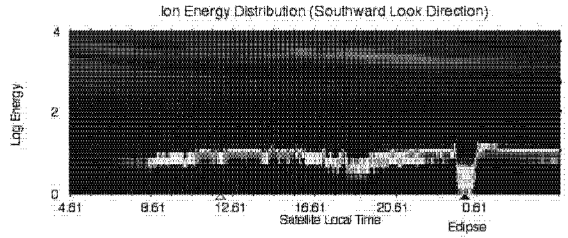

Fig. 13. MPA spectrogram for ions for one full 24-hour geosynchronous orbit, March 21, 2007. The floating potential of the spacecraft (in volts negative) is taken to be the lowest energy (in eV) at which ions can be reliably detected. This is the same 24 hours local time orbit as for the electron spectrogram shown in Fig. 11.

V. PERFORMANCE

A. Overview

In order to determine floating potential through charged particle energy analysis with unprecedented speed, accuracy, and versatility, PASS will need extraordinary energy resolution, geometric factor, and data-gathering efficiency. The geometric factor and energy resolution of a charged particle energy analyzer is analogous to the light gathering power and resolving power of an optical telescope. Energy resolution and geometric factor are fundamental performance metrics for charged particle energy analyzers. The data-gathering scheme of PASS (the instrument pointing direction and energy scan) can be optimized to determine spacecraft charge with speed and precision.

B.Energy Resolution

It has been stated that designing and constructing space-borne hemispherical analyzers with an energy resolution of 1% (ΔE/E) is significantly more difficult than designing and constructing one with an energy resolution of 10% [27]. For instance, the designers of the Cassini spacecraft Ion Beam Spectrometer (IBS) designed the device to have an energy resolution of 1.3% and were only able to achieve an energy resolution of 2.0%, just 65% of their stated goal [28]. Difficulty in designing and building high energy-resolution devices may be part of the reason why lower energy resolution devices are flown. 5%, 10%, or even 40% energy resolution devices appear to be the norm. However, there are compelling reasons to build, and fly, high energy-resolution charged particle analyzers.

Higher energy resolution not only helps separate closely spaced peaks in a charged particle energy spectrum, it aids in the detection of weak sources of discrete energies when superimposed on a broad continuum by enabling the emergence of a tall peak above the statistical noise of the continuum [29]. An advantage of high energy-resolution is illustrated in Fig 14. In the two superimposed hypothetical spectra shown, all of the fundamental properties of the spectrometer except energy resolution are held constant. A triangular instrument function has been chosen for this example. The peak for 100 eV particles gathered with 2% ΔE/E full width at half maximum (FWHM) energy resolution measures 2 eV across at half its height. For the same flux of charged particles and the same dwell time at each energy bin, the 40% energy resolution peak measures 40 eV across at half its height. The 40% energy resolution peak has a height of 10 counts and the 2% resolution peak has a height of 200 counts. In practice, a spectral feature that is easily seen in the spectrum from the 2% resolution instrument might be obscured by statistical noise in a spectrum from the 40% resolution instrument.

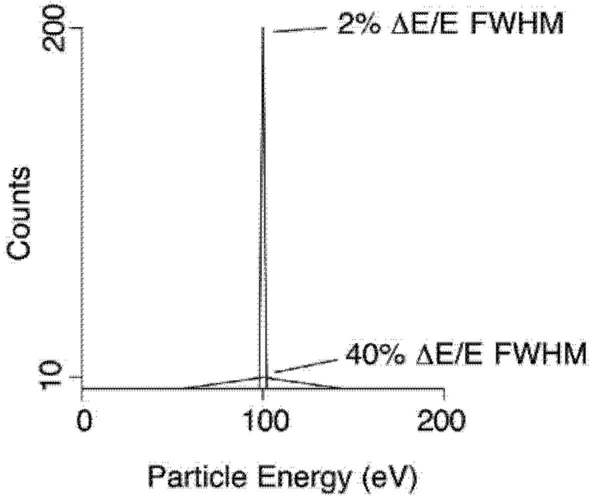

Fig 14. Higher energy resolution reveals more about the observed charged particle energy distribution. In this example, 2% energy resolution produces a peak of 200 counts for 100 eV electrons whereas 40% energy resolution produces a peak of 10 counts when gathering a spectrum of the same source. In practice, at 40% resolution the signal may be obscured by noise.

As a historical example of the benefit of higher energy resolution, the 2.5% energy resolution of an electron spectrometer that was flown in the 1970s (PES) enabled the collection of the first spectra that showed structure in the photoelectron energy distribution in the daytime ionosphere at between 20 and 30 eV [30]. Lower energy resolution instruments would not have revealed such structure. It is hard to imagine circumstances where higher energy resolution would not be desired over lower energy resolution. So why don't all charged particle energy analyzers have high energy-resolution? Higher energy resolution comes at a cost. Not only are such devices more difficult to design and build, there is generally a trade-off between energy resolution and geometric factor, as will be discussed in the next subsection.

PASS is designed to have an energy resolution of 2.0%. This is the same energy resolution as its predecessor, the SCM. The spectrum in Fig. 15 was collected with the SCM in an electron beam gas scattering experiment in the laboratory. The SCM prepared to gather a scattering spectrum is shown Fig. 16.

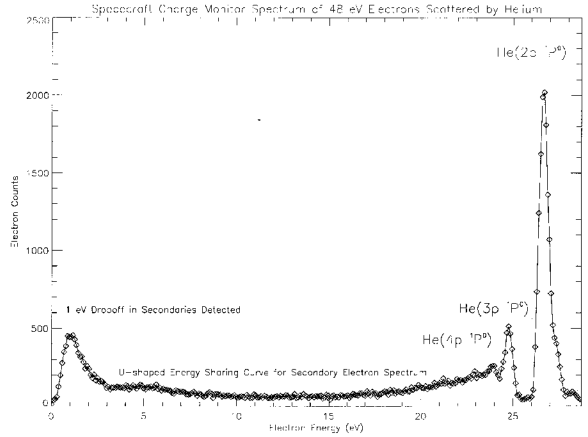

Fig. 15. A helium scattering spectrum that demonstrates the extraordinary energy resolution of the predecessor of PASS.

The scattering spectrum in Fig. 15 demonstrates the 2% energy resolution expected for PASS. Details about the method used to collect the spectrum in Fig 15, and a more complete analysis of the spectrum, are included in [1]. The SCM modified to produce PASS should have the resolution needed to excel at determining spacecraft floating potential through the electron spectroscopic and low energy ion cutoff methods.

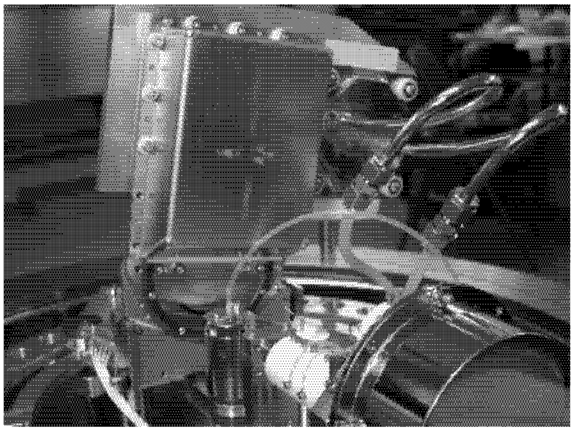

Fig. 16. Apparatus used to produce a helium scattering spectrum with the flight-ready SCM. The exit optics housing of the electron monochromator is shown at the right (white tube), and a collision center is seen in front of the entrance aperture of the SCM. Differential pumping was used in the vacuum chamber to keep the helium density high in the collision center.

C. Geometric Factor

Geometric factor is the other key performance metric for charged particle energy analyzers. If one assumes the detection efficiency for a class of instruments (e.g., the class of channel electron multiplier equipped instruments) is the same, geometric factors can be compared to determine which instrument in that class will be more sensitive to a given particle flux. Instruments with a larger geometric factor will be able to collect spectra more rapidly. Increased geometric factor can be an enabling technology for certain studies. Increased geometric factor allows the collection of spectra with better-defined features, or, alternatively, the collection of useful data over more energy, spatial, or temporal bins.

The geometric factor of a charged particle energy analyzer gives the 'particle gathering power' of the device. It is a product of the instrument's field of view and its entrance aperture area, as illustrated in Fig. 17.

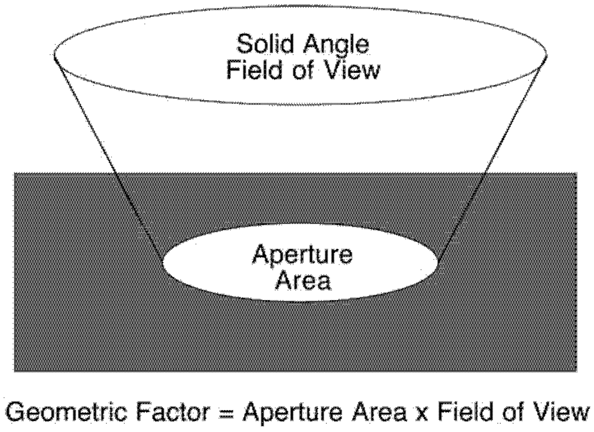

Fig. 17. How geometric factor is calculated.

A trade-off between a charged particle spectrometer's energy resolution and its geometric factor may arise due to the practice of reducing slit width (and area) to increase energy resolution [31]. Geometric factor is thereby reduced when resolution is increased. The features of interest in a charged particle spectrum may be easier to discern above the background if resolution is increased, but it may then take too long to gather a spectrum due to the reduced geometric factor. Long accumulation times are especially problematic in the dynamic, low particle flux environment of space.

The 180° spherical sector curved plate electrostatic charged particle energy analyzer ("hemispherical analyzer") has been deployed in space since at least the 1960s. Hemispherical analyzers are also used for high energy-resolution work in the laboratory due to their high particle throughput 'focusing' charged particle optics. Traditionally, the aperture for a hemispherical analyzer has been circular, as it was for the PES instrument of the Atmosphere Explorer Satellites [32]. Fig. 18 illustrates how the aperture area of a hemispherical analyzer can be increased without increasing the slit width. It has been shown in practice that using a curved aperture and collimator arrangement increases the aperture area without a decrease in energy resolution. Curved apertures have been used for decades in laboratory instruments and on at least one space-borne instrument [27]. PASS is designed to benefit from the unique curved collimator and aperture arrangement that has been proven to work in the SCM. The advantages of the unique design are discussed in [12] and [1].

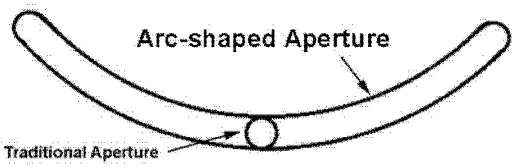

Fig. 18. A traditional aperture is smaller than the arc-shaped apertures used on the SCM and planned for use on PASS.

Based on a 20-fold increase in aperture area and a 3-fold increase in field of view, the SCM has 60-fold the geometric factor of its predecessor, the PES instrument. The geometric factor of the PES instrument was determined to be $3.0 \pm 0.5 \times 10^{-4}$ cm^2·sr [33]. Since the SCM has a nearly identical electron optical design to PES (with the exception of its curved aperture and collimator), the geometric factor of the SCM can be estimated at 60 times that of PES: 1.8×10^{-2} cm^2·sr.

For the SCM modified as shown in Fig 4, one can assume the geometric factor of each of its two channels will be about half that of the single channel SCM. A geometric factor of ~9 x 10^{-3} $cm^2 \cdot sr$ is estimated for each channel (one for ions, one for electrons) of PASS if it is built as shown on the right-hand side of Fig.4.

D.Data Gathering Scheme

The SCM may be the first charged particle energy analyzer designed exclusively to measure spacecraft floating potential. Charged particle energy analyzers have not been placed on satellites with the detection of vehicle charging as their prime objective [34]. The charged particle energy analyzers that have been deployed have not been efficient floating potential monitors in part because the instrument's data gathering scheme (the instrument pointing direction and energy scan) has been inappropriate for that purpose.

Although the low energy ion cutoff method has been used for decades, it has never been done with a device having the performance characteristics of PASS. Furthermore, experience has shown that unless the charged particle analyzer is pointed in the direction of the geomagnetic field and is configured to collect spectra in the appropriate energy range "a charging peak will not be observed in the data" [34].

The electron spectroscopic and the ion energy cutoff methods both benefit from the largest signal when the instrument field of view is aligned with the geomagnetic field [34], [35]. There is some tolerance for pointing direction, at least for the electron spectroscopic method. Of the six PES instruments that were deployed in LEO (two each on three satellites), the instrument that was mounted on the ram-side of the satellite that orbited at a 19.7 degree inclination observed the highest fluxes of atmospheric photoelectrons. That instrument pointed along the de-spun spacecraft's polar-aligned axis and was able to gather atmospheric photoelectron spectra that did not suffer from attenuation of the atmospheric photoelectron flux due to 'shadowing' by the spacecraft and had a look direction that was always less than 55 degrees from the geomagnetic field direction [35]. Fig. 19 is a photograph PES sensor 1 in position the AE-E satellite, the sensor that gathered the highest quality spectra of the six deployed. Other electron spectrometer placement recommendations are discussed in Appendix 1 of [35], in [2], and in Section VI of this work.

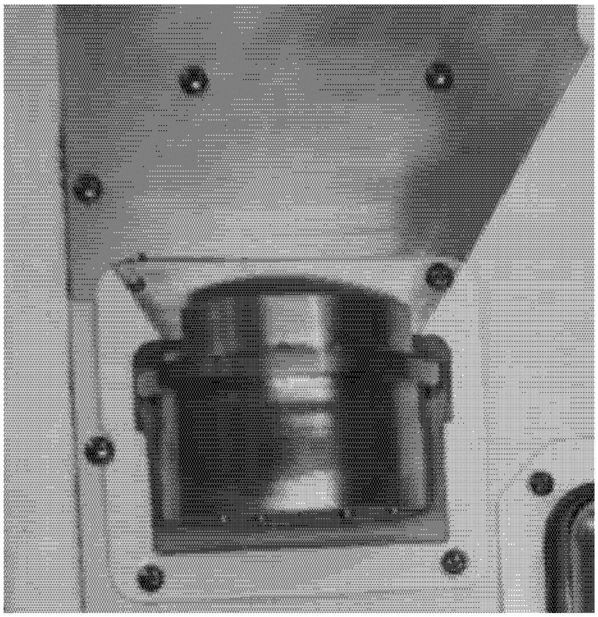

Fig. 19. Of the six PES sensors that flew, the sensor shown in this photograph collected atmospheric photoelectron spectra with the least attenuation due to pointing direction. It was mounted on the ram side of the LEO orbiting Atmosphere Explorer-E spacecraft that flew at an inclination of 19.7 degrees and had its field of view approximately pole-aligned so that its look direction was always less than 55 degrees from the geomagnetic field direction. This same instrument is shown in a broader view of the satellite in Fig. 22.

The SCM was designed to determine spacecraft floating potential with great precision over a narrow energy range. The SCM modified to produce PASS will have the precision needed to enable the measurement of low-level charge (from approximately -50 volts to approximately 0 volts) through two methods simultaneously. This should enable the refinement of both methods and improve the state of the art in charged-particle-analyzer-based floating potential determination.

The following is a demonstration of the precision of the direct predecessor to PASS. Fig. 20 is a plot of the apparent pass energy of a 20 eV, 24 eV, and 30 eV electron beam as energy analyzed by the SCM under simulated spacecraft charging conditions. The test was performed by the Electrostatics and Surface Physics Laboratory at NASA's Kennedy Space Center (KSC) [3]. Fig. 21 shows the test apparatus with the SCM installed. The plot in Fig. 20 demonstrates the shift in energy location of the electron spectral peak detected by the SCM due to the shift in the chassis potential (floating potential) of the SCM. The SCM chassis potential (the spectrometer reference potential) was varied from laboratory ground potential (0 volts) to about 40 volts negative. The three energies of the incident beam were selected to represent the energy range of the solar He II atmospheric photoelectron peaks (20, 24, and 30 eV). The results demonstrate that the SCM can determine negative floating potential (under simulated conditions) and that the correlation between floating potential (in volts) and the shift in the apparent energy of the spectral peak (in eV) is 1:1. The precision of the SCM was vital to this study. Such precision is planned for both the ion and electron channels of PASS that, in turn, should enable unprecedented precision in floating potential determination through the electron-spectroscopic and low energy ion cutoff methods.

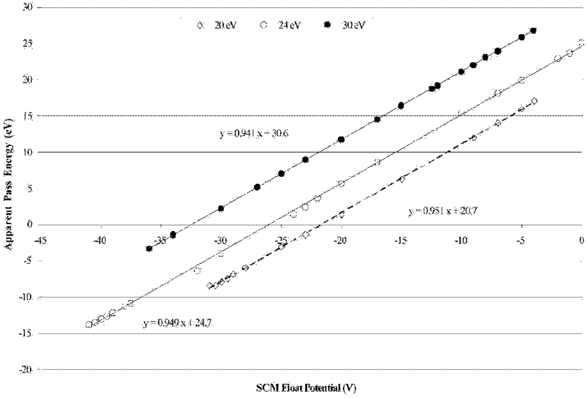

Fig. 20. Data that demonstrates the electron-spectroscopic method under simulated spacecraft charging conditions. The chassis potential (and electronics ground potential) of the SCM was lowered in increments to approximately -35 volts and the shift in the electron spectroscopic peak detected by the SCM was plotted versus floating potential.

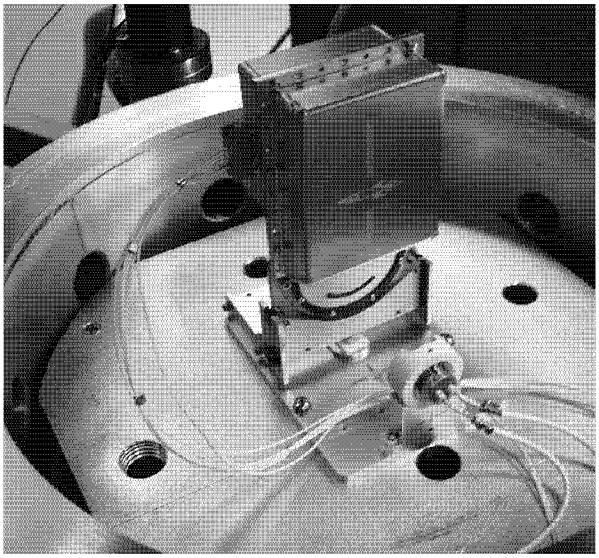

Fig. 21. The apparatus that was used to test the predecessor of PASS under simulated charging conditions at NASA KSC in 2005. A bare filament electron gun (enclosed in the short white tube in front of the SCM entrance aperture) was used.

PASS could also benefit from in-flight programmable data collection. The microprocessor equipped SCM can be commanded to collect data through adjustable parameters such as first energy in scan, total energy range scanned, energy separation between bins, and dwell time per bin. For PASS, which will scan over a much larger energy range, a logarithmic scan could be considered to enable the rapid collection of spectra over a large energy range. The option of programming PASS to adjust the energy scan of the of the electron and ion energy analyzers in real time in response to the data being collected could provide even more timely floating potential determinations.

E. Comparison to LANL MPA

In order to illustrate the advantages that PASS should offer compared to other charged particle energy analyzers that have measured floating potential, PASS will now be compared to the LANL MPA.

The MPA was not deployed with the detection of vehicle charging as its primary use. It is a 'survey type' instrument. It gathers data from many directions over a broad range of energies in a short amount of time. Such instruments are not ideal for charge determination. The MPA has a mass of 3.6 kg, a geometric factor of 5×10^{-4} $cm^2 \cdot sr$ per detector for each of six detectors, an energy resolution of 40% ($\Delta E/E$ FWHM), and requires 3.5 W to power [36], [37]. It gathers data in 40 logarithmically spaced energy bins from 1 eV to 40 keV once every 0.42 seconds [37], [38]. The instrument alternates between collecting ion data and electron data by reversing the polarity of its analyzer electrodes and its CEMs [37].

It is estimated that the mass of the modified sensor head and the modified electronics may result in a PASS instrument that is double or triple the 0.65 kg mass of the SCM. Therefore it is estimated that PASS will weigh approximately 2 kg. PASS may require somewhat more power than the <2 Watts required for the SCM due to the inclusion of a higher voltage power supply and circuitry for an additional data channel. Based on the electronics required for the SCM and research into higher voltage power supplies, it appears that PASS can be built to require less than 3 Watts to power. Therefore it appears that fewer spacecraft resources (mass and power) will be required for PASS than are required for the MPA. Now major performance metrics for PASS will be compared to those of the MPA.

If one takes the sum of the geometric factors of all six channels of the MPA, the resulting geometric factor of the device is 3×10^{-3} $cm^2 \cdot sr$ [37]. At 9×10^{-3} $cm^2 \cdot sr$ for each channel (one for ions, one for electrons, as described in Section V.*C*), each channel of PASS could have three times the geometric factor of all of the MPA channels combined. Furthermore, the MPA devotes half of its time to collecting data for negatively charged particles and half of its time to collecting data for positively charged particles, whereas PASS is designed to collect ion and electron data simultaneously. The MPA also devotes its time to looking in many directions in space (it surveys a complete 4π steradian of viewing angles each ten seconds) rather than looking mainly in the direction of geomagnetic field. Most notably, the 2% energy resolution that has been demonstrated in the SCM (and is expected for PASS) is 20 times that of the MPA.

When it comes to determining spacecraft floating potential as described in this work, the MPA's poor energy resolution, its relatively low geometric factor, its inability to collect ion data and electron data simultaneously, and its inflexible data collecting scheme (constantly scanning at all angles in space, gathering data over 40 keV in only 40 fixed energy bins) all compare unfavorably to the performance that might be achieved with PASS. Comparisons of the performance metrics of the proposed PASS instrument to the MPA are summarized in Table I.

Comparisons of the proposed PASS instrument, or the SCM, to other flight instruments yield similar results: no instruments with such high energy-resolution combined with a large geometric factor have yet been flown.

VI. SPACECRAFT ACCOMMODATION

The accommodation of PASS on a spacecraft is now discussed. We are fortunate that six PES instruments have flown. Since PES had about the same energy resolution (2.5% for PES, 2.0% for PASS) and gathered electron energy spectra at low energies (1 to 500 eV), much can be learned from PES that will aid in the deployment of PASS.

The PES instruments were mounted so that the entrance aperture protruded slightly from the surface of the spacecraft, as shown in Fig. 19, Fig. 22, and Fig. 23. Fig. 22 shows PES sensor 1 as it was mounted on the AE-E satellite. The fan-shaped 9 degree by 20 degree field of view was aimed approximately pole-ward for the entire orbit of this low inclination LEO spacecraft. The field of view was thereby kept within 55 degrees of the geomagnetic field. PASS would also benefit from being mounted so that it is pointed to within 55 degrees of the geomagnetic field. The field of view of the PES instrument was unobstructed by solar arrays, antennas, etc. An unobstructed field of view would be required for PASS as well. In order to avoid the blocking of the charged particles of interest by the spacecraft ('shadowing') and in order to avoid contamination of the charged particle spectra by ions and electrons that originate from spacecraft surfaces, ideally PASS would be mounted with the center of its field of view pointing toward the geomagnetic field line and the center of its field of view normal to the spacecraft surface. This was the preferred arrangement for PES as well, but the ideal configuration was not possible on the AE satellites, as can be seen in Fig. 22 and Fig. 23. It is evident from the success of the deployment of PES that there is flexibility in positioning instruments such as the proposed PASS instrument.

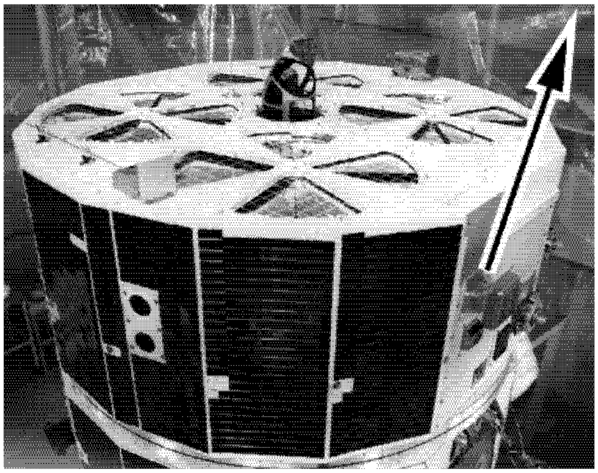

Fig. 22. PES sensor 1 on AE-E. Arrow shows the pointing direction of the sensor. This is the same sensor that is shown in close-up in Fig. 19 and considered the best positioned of the six AE satellite PES instruments. Placement on the top of the satellite would be even better at excluding spacecraft generated photoelectrons and decreasing the possibility of spacecraft 'shadowing' as discussed in [35]. An unobstructed field of view of approximately 120 degrees by 10 degrees would be required for PASS.

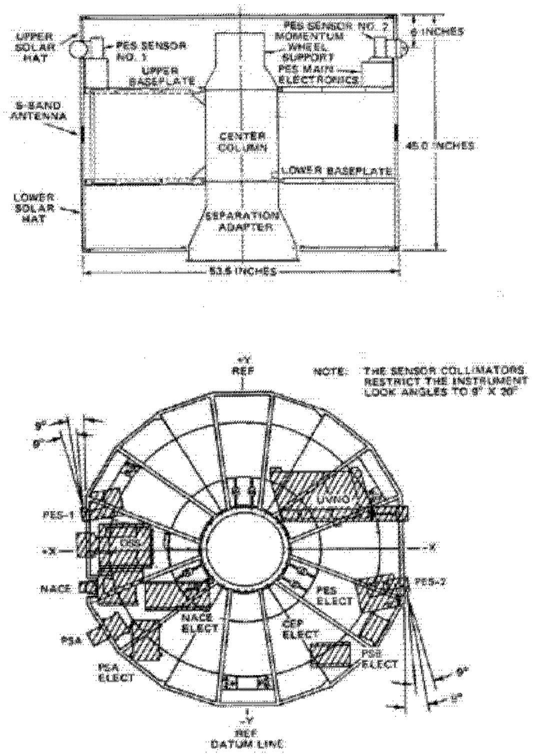

Fig. 23. This diagram shows how the PES instruments were mounted on AE-C. Note that the PES instruments on AE-C were mounted in a different orientation than the PES instruments on AE-E. From [39].

Fig. 24 is a schematic diagram that shows the shape of the SCM and its ~120 degree by 10 degree field of view. The SCM can be mounted to the spacecraft frame by means of bolts through 13 bolt holes in the same way it was mounted for vibration tests as shown in Fig. 8 and Fig. 25. A similar arrangement could be chosen for attaching PASS to a spacecraft.

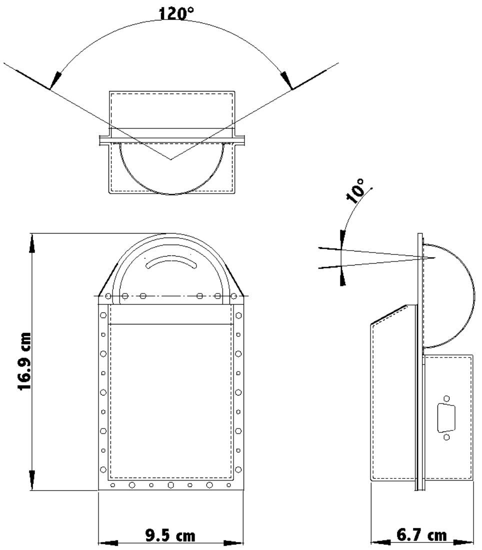

Fig. 24. Drawings of SCM. The approximately 120 by 10 degree field of view of the hemispherical analyzer is shown. This is the same field of view that is planned for PASS.

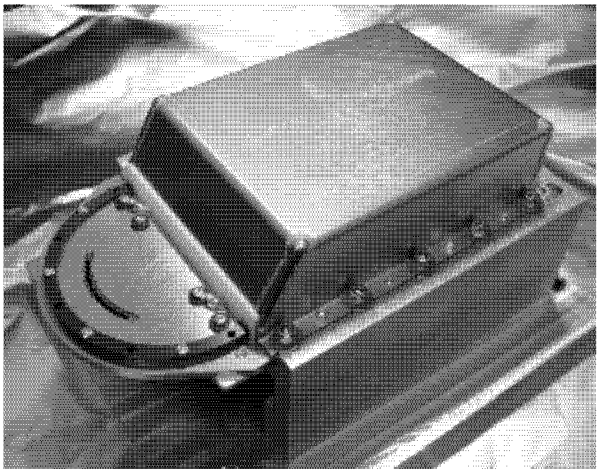

Fig. 25. SCM mounted on a vibration test stand adaptor. Same mounting holes in SCM chassis can be used to mount to spacecraft. The same arrangement could be used for PASS.

Since PASS would be equipped with channel electron multipliers that cannot distinguish between charged particles and ultraviolet light, it is possible that spectra will be contaminated when the sun is in the field of view of the instrument. In practice, for the PES instruments, when the count rate increased dramatically at all energies to very high levels it was assumed the sun was in the field of view. Such spectra were disregarded. An advantage of the full 180-degree hemispherical analyzing space of the PES, SCM, and PASS instruments is that it takes multiple reflections for a photon to reach a channel electron multiplier. A collimator also appears at the analyzer entrance of the SCM, as is planned for PASS as well. A gold black coating could be used on PASS's hemispherical surfaces (as has been done for charged particle energy analyzers that point toward the sun to monitor the solar wind) to further reduce the possibility of interference by photons.

One of the difficulties in gathering low-energy charged particle spectra with electrostatic analyzers is the exclusion of magnetic fields from the space between the electrodes. The PES and SCM instruments were equipped with magnetic shields that have been shown to exclude interference from magnetic fields of as large as 7 gauss [39]. The PASS instrument would be similarly equipped.

An electrical interface like that designed for the SCM could be used for PASS. The SCM is equipped with a DB-9 connector to supply instrument power and communication between the SCM's microprocessor and the spacecraft. The SCM is operated in the laboratory through its RS-422 interface by a laptop computer equipped with a USB to RS-422 converter and a control program written in Tcl. In operation, the SCM sends data to the host at a rate of 8 kbits/sec. The SCM electronics ground is isolated from its chassis ground to minimize electromagnetic interference.

The PES and SCM instruments both contained electron multipliers. The SCM contains two glass-ceramic channel electron multipliers of the same manufacture that has been used on numerous flight instruments (including instruments on HOPE, Ulysses, Cassini, and the ISS). No deployable protective covers should be needed for the SCM or PASS. However, it would be recommended to store the instruments in as clean and dry an environment as is typically found in a laboratory. The engineering unit SCM had been exposed to the laboratory atmosphere for over two and a half years between performance tests with no evidence of CEM (or any other) degradation. The channel electron multipliers are contained deep within the SCM instrument and contamination from outgassing during deployment is not expected to degrade performance. The same environmental hardiness of the SCM is expected for the PASS instrument.

VII. DISCUSSION

In the field of spacecraft charging technology, spacecraft charge is often discussed but rarely measured. Actual measurements of spacecraft charge are useful for validating and/or improving charging models, assessing the effectiveness of charge reduction or mitigation techniques, correcting biases to plasma measurements, warning of dangerous spacecraft charge, and determining the cause of spacecraft anomalies.

To date, there is no all-purpose spacecraft charge monitor. Langmuir probes, often used in LEO, won't work in GEO. Simple devices that measure internal (dielectric) charge or detect spacecraft arcing don't measure spacecraft chassis floating potential. All charge monitors have limitations.

A limitation for charged particle energy analyzers is that floating potential can only be determined if the spectra collected exhibit the required feature(s). Unfortunately, it is not yet possible to predict exactly where and when the proposed PASS instrument would be able to determine charge. Spectra of a quality comparable to those that PASS might be able to collect are only available from PES, and the PES data set is very limited. PES collected no ion spectra and we have no PES spectrum from above 1000 km. Furthermore, the PES instrument had only 1/60th the geometric factor of the SCM and the proposed PASS instrument. It may take the flight of an instrument like the SCM or PASS to determine where and when floating potential can be determined by such devices.

The potential for the proposed PASS instrument to use two dissimilar methods (by analyzing ions and electrons simultaneously) is unique and worth noting: such comparisons could significantly improve the accuracy and reliability of floating potential determinations.

In the field of spectroscopy, it is often an improvement to spectrometer performance that brings a breakthrough in science. Experience has shown that as the geometric factor and/or energy resolution of a charged particle spectrometer is improved, details in spectra that were once faint, or even absent, may be revealed. As a result, useful measurements might then be made. As instruments improve, science advances.

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