Real-Time, Automatic Vehicle-Potential Determination from ESA Measurements: The Count-Ratio Algorithm

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Data from the P78-2 satellite has been used to develop a technique utilizing electrostatic analyzer (ESA) ion count measurements to provide a real-time determination of satellite vehicle potential. The algorithm, which was developed for real-time implementation by space vehicle microprocessors, is based on a comparison of ion counts in adjacent ESA channels and has proved highly successful in detecting vehicle charging.

Introduction

THE problem of spacecraft charging at high altitudes is an important one for Air Force applications; indeed, a major effort (SCATHA project) has been undertaken to understand this phenomenon.[1] Quite simply, when a space vehicle at geosynchronous orbit, interacting with its plasma environment, acquires a high negative potential (on the order of ½ kV), it is possible that onboard instrumentation will be damaged by electrical discharge between differentially charged surfaces of the spacecraft. Thus, it is important to activate a discharge mechanism as soon as a dangerously high potential develops. This means that it is necessary to have a reliable method of determining the real-time vehicle potential, or more specifically, distinguishing between whether or not the potential has reached or exceeded critical levels. An algorithm incorporating an onboard microprocessor to analyze data obtained by the vehicle and to determine the extent of charging is desirable. Computational simplicity and speed are important considerations in the design of such an algorithm. Examination of data from the P78-2 satellite has indicated that electrostatic analyzer (ESA) ion count data could serve as input to an algorithm designed to fulfill the aforementioned objectives. The development and testing of one such algorithm, referred to as the count-ratio algorithm, are described below. Results have been highly encouraging: the potential estimates obtained are in good agreement with carefully determined values based on informed analysis of relevant data.

Received Oct. 23, 1986; revision received March 10, 1987.

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ESA Ion Count Data as an Indicator of Vehicle Charging

One of the instruments aboard the P78-2 satellite, a component of the SC9 experiment (which was designed, built, and operated by the University of California at San Diego), is a high resolution electrostatic analyzer mounted parallel to the spin axis.[2] This instrument counts the number of positively and negatively charged particles (protons and electrons) incident upon it in each of 64 exponentially spaced energy channels that span the energy range 0-81 keV, during sequential 250 ms time intervals (so-called north-south or NS counts). The 64 energy channels have midchannel energies given (in electron volts) by[3]

$$E(I) = 16.1 \times (1.145)^I - 21 + 28/(I + 129), \; I = 0,1,\ldots,63$$

and the ratio of channel width to midchannel energy is essentially constant at about 20% over the entire spectrum. The SC9 ESA provides high resolution in particle number flux during each 16 s sweep through its 64 channels.

When the spacecraft is at zero potential with respect to the ambient plasma, the ESA channel spacing design is such that the number of positive ion counts per channel shows a modest increase with energy up to an energy level corresponding to about twice the plasma temperature (around 10 keV at geosynchronous altitude) and decreases thereafter. But when the spacecraft has acquired a negative potential with respect to the plasma, positive ions approaching the instrument will be accelerated by this potential difference.[4] As a result, the number of ion counts in energy channels below the level of charging would ideally drop to zero and there would be an increase in the number of counts in channels at and just above the level of charging. Examination of SC9 ion count data shows this effect quite clearly: while, for various reasons, the zero count rate is not exactly achieved, the presence of spacecraft charging is characterized by a very low count rate in all channels up to a certain energy followed by a sharp increase in counts in the next few channels. A graph of counts vs energy exhibits a sharp peak during vehicle charging, in contrast to the slow rise associated with the uncharged state. This phenomenon is shown clearly in Fig. 1, a "three-dimensional" graph in which counts (plotted vertically) are shown as a function of time and energy. The qualitative change in the appearance of the plotted surface, from being relatively smooth to noticeably spiked, is associated with vehicle charging. The count-ratio algorithm exploits this phenomenon to determine spacecraft potential.

Description of the Count-Ratio Algorithm

The count-ratio algorithm consists of examining the counts in adjacent energy channels to determine if the upper-to-lower energy count rate has reached or exceeded some empirically determined critical value that will distinguish between a charged and uncharged spacecraft. It is necessary to require that some minimal number of counts be obtained in order to diagnose charging. Otherwise, random fluctuations at low count rates can greatly affect the interchannel count ratio and thereby cause spurious reports of charging. This minimal number of counts is also empirically determined. Based on data from several days during which the spacecraft was negatively charged part of the time, a critical count ratio of 4.5 with a threshold requirement of at least 90 counts in the upper energy ("test") channel was found to give good results. Since channel separation is not perfect, it can happen that a high count rate at a given energy will cause a substantial count increase in the adjacent lower-energy channel, causing the algorithm to underestimate the level of charging. Hence, the results are improved by the following refinement: if the aforementioned criteria are satisfied (indicating vehicle charging), the next higher-energy channel is examined to see whether there is a substantial further increase in counts (by a factor of 1.5 or more). If so, the level of charging is taken to be at this higher-energy level, rather than the level of the initial precipitous increase. Tests of the method never indicated that it was necessary to examine still higher channels to find the charging level. A flow chart of the algorithm is shown in Fig. 2.

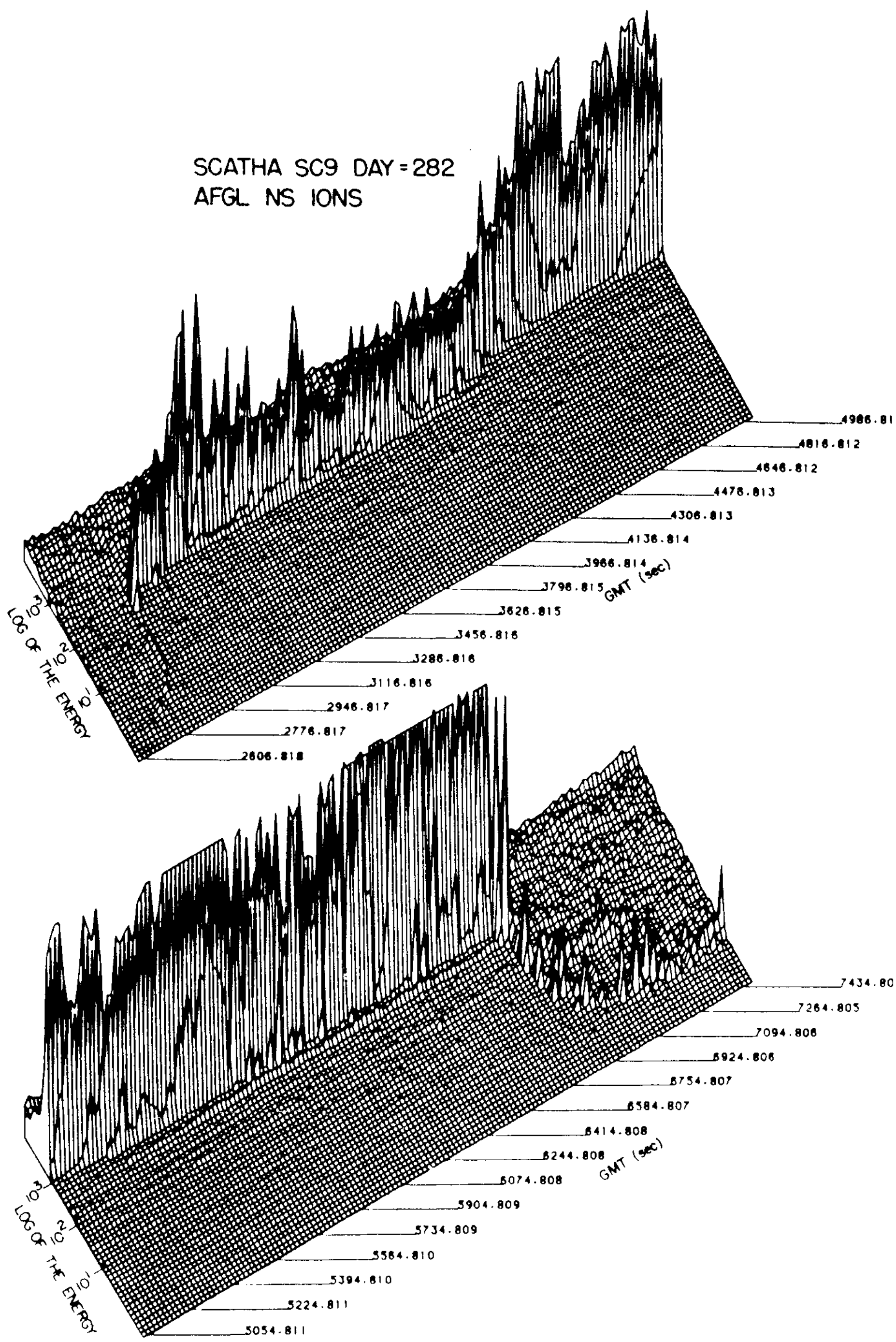

Fig. 1 SC9 NS positive ion counts as a function of time and energy during a period of natural charging on day 79282. Upper graph shows the onset of charging at about 2800 s UT. Negative charge grows in magnitude, attaining values in the range −2 to −3 kV during the time interval 4200–6800 s UT whereupon, as shown in the lower graph, the level of charging rapidly diminishes to about −10 V.

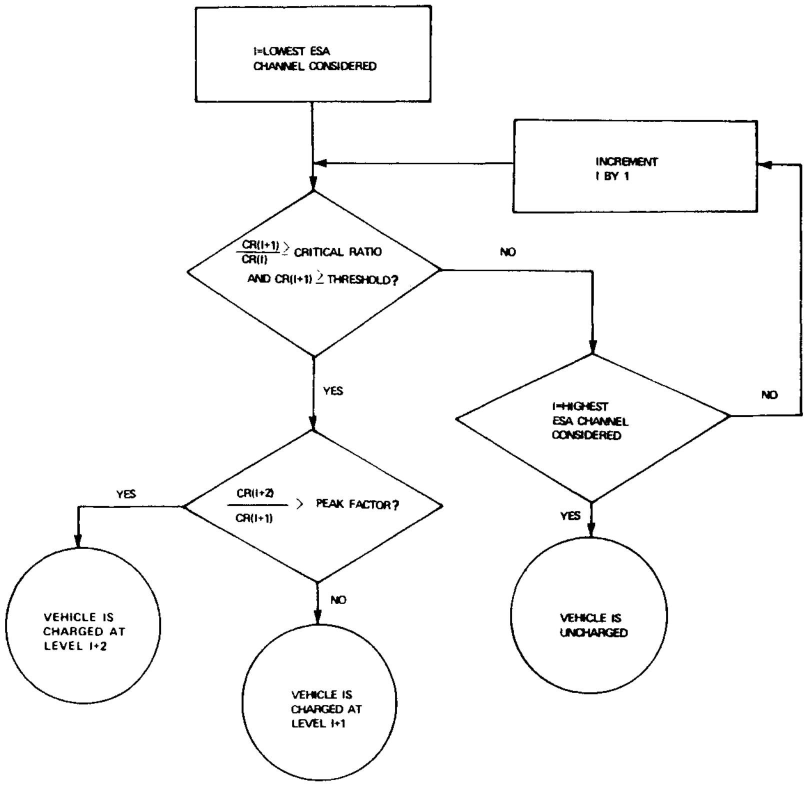

Fig. 2 Flow chart of the count-ratio (CR) algorithm, based on comparisons of ion count rates in adjacent energy channels [CR(I) and CR(I + 1)].

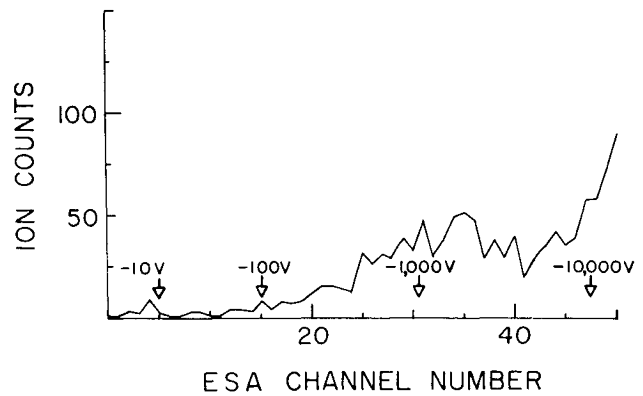

Fig. 3 Positive ion counts as a function of SC9 high-energy ESA channel for day 79105, time 36128 s UT. Count spectrum exhibits no precipitous adjacent channel increase and is typical for the case of an uncharged spacecraft.

The algorithm was originally designed with various options as to the way in which the test channel counts would be compared with those at lower energy. Instead of a simple comparison with counts in the lower adjacent energy channel, an average of two or more consecutive lower-channel counts could be used. Also, the comparison channel(s) could be separated from the test channel by a gap of one or more channels if desired. The objective was to help circumvent difficulties arising from random fluctuations in count rates and overlapping energy response curves. However, it was found that, for SC9 NS ion count data, the use of an adjacent channel critical count ratio with a test channel count minimum gave best results. For the sake of computational simplicity, it was decided to utilize only data from the current count spectrum in the potential determination process, rather than incorporating data from previous spectra. This decision can be changed in future versions of the algorithm if desired.

Tests of the Algorithm Using SC9 Data

In order to evaluate the performance of the count-ratio algorithm, a data base was established consisting of 9925 SC9 NS ion count spectra from 30 time intervals on 30 different days. These intervals contained known periods of natural vehicle charging, all but two of which occurred during satellite eclipse. For each of these 9925 spectra, informed estimates of the vehicle potential were made by visual inspection of both high- and low-energy electron and ion count spectra from the SC9 instrument onboard P78-2. Spectra from neighboring time periods were utilized to assist in estimating the true charge at a given time.

The algorithm was then tested on this data base. Typical count spectra for day 79105 are shown in Fig. 3 (uncharged vehicle) and Fig. 4 (charged vehicle). For these cases, the algorithm estimate coincides with the visually read spectrogram (VRS) potential. A comparison of the algorithm estimates with the VRS potential for the period of vehicle charging on day 79105 is shown in Fig. 5. These results are representative of the algorithm performance for the entire data base, with somewhat better performance on some of the days and somewhat poorer on others. The algorithm's performance was measured in several ways. One measure was the fraction of time the algorithm potential was within 20% (i.e., within one SC9 energy channel) of VRS potential. Another measure, more important from the standpoint of the algorithm's objective, was its success rate at correctly determining whether or not a given critical potential had been reached. This has been calculated for critical potentials of -250 and -500 V; the results for these measures of algorithm performance are given in Table 1.

The results generally show a high level of accuracy, although the success rate is distinctly poorer for a few days. These cases must be studied in more detail to determine whether adjustments in the algorithm parameters or procedure might lead to improved results. A re-examination of the comparison VRS potentials is also necessary, since, in at least a few cases of algorithm "failure," the algorithm's estimate appeared to be equally well supported by the data. In any event, the count-ratio algorithm as described is seen to perform well in its tests with SC9 NS ion count data.

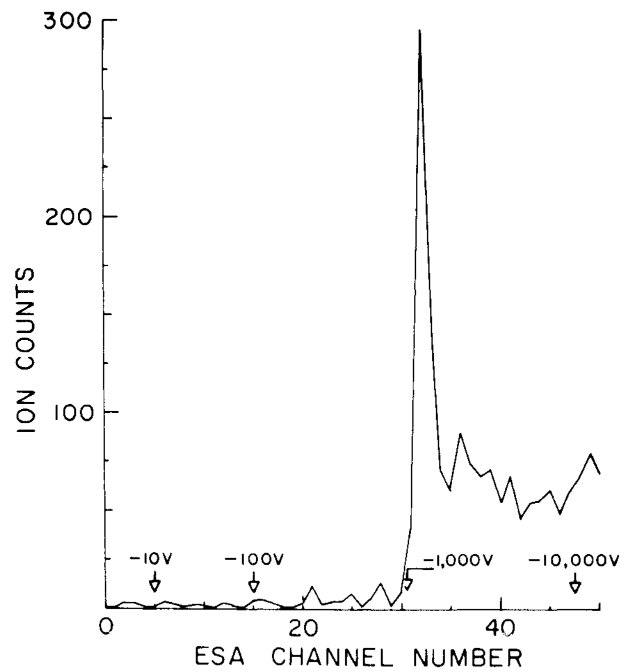

Fig. 4 Same as in Fig. 3, but for time 36408 s UT. The sharp peak in the count spectrum indicates spacecraft charging to the level of ESA channel 32 (−1205 V).

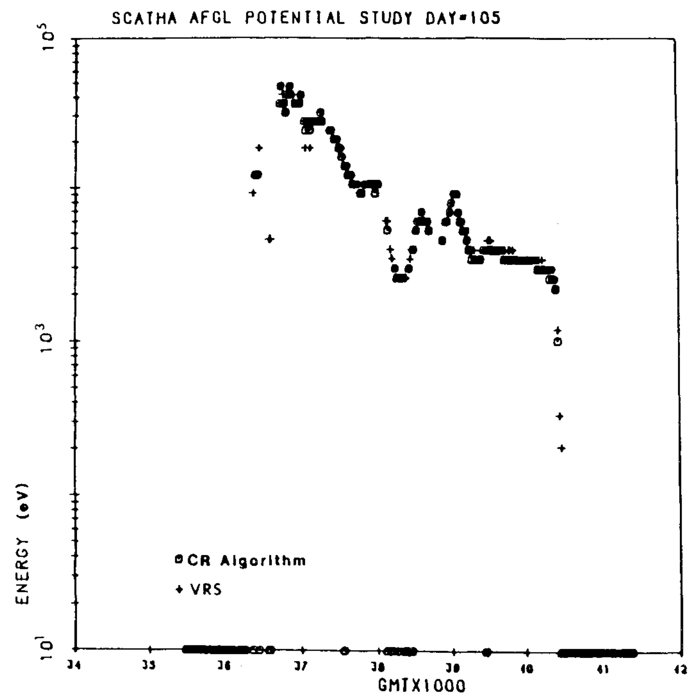

Fig. 5 Comparison of count-ratio algorithm estimates with visually read spectrogram potential estimates for period of vehicle charging on day 79105.

Table 1 Performance of Count-ratio algorithm with SC9 data, %

Day	Correct to within 20%	Correctly determines whether given critical potential is exceeded[a] 250 V	500 V
79086	92	96	98
79087	86	86	86
79098	95	95	95
79100	93	94	94
79104	96	96	96
79105	92	93	98
79106	97	99	99
79108	86	88	88
79114	71	85	87
79117	72	73	98
79118	92	99	100
79120	91	98	98
79172	91	100	100
79241	72	81	93
79267	80	96	100
79270	98	100	100
79271	85	92	93
79272	98	99	97
79273	80	81	81
79274	95	96	99
79276	97	100	100
79277	95	96	97
79282	99	99	99
79283	90	90	94
79285/6	97	97	97
79286	93	94	100
79294	100	100	100
79302	99	100	99
79305	98	99	99
80164	100	100	100
Overall	92.0	94.8	96.5

[a]In data base, VRS potential exceeded 250 V 29.4% of the time and 500 V 23.6% of the time.

Table 2 Parallel ion midchannel energies for SC5 ESA

Low-energy channel	Energy, keV	High-energy channel	Energy, keV
1	0.145	1	4.5
2	0.353	2	10.4
3	0.782	3	25.0
4	1.706	4	59.9

Tests Using Low-Energy Resolution ESA Data

The count-ratio algorithm has also been tested with ion count data recorded by the ESA of the SC5 experiment of the P78-2 satellite.[2] This is a rapid-response, low-energy resolution instrument ($\Delta E/E \sim 1$), spanning an energy interval of 0–50 keV in eight channels. The midchannel parallel ion energies are given in Table 2.[5] These eight channels, plus two background channels, record counts during 200 ms intervals two at a time; a full sweep of the instrument takes 1 s. An instrument with rapid response time is desirable for use as a charge detector, since it can more quickly signal the need for discharging the vehicle. However, the count rates of the SC5 ESA were so low, and hence erratic, that it was found necessary to average over several sweeps of the instrument to obtain suitably smooth data. Thus, the rapid-response-time advantage was lost. To be able to compare results with the true vehicle potentials established for the data base described above, the SC5 data were averaged over 16 s time intervals coinciding with the 16 s SC9 sweeps. Counts influenced by the sun pulse were deleted from the averaging process. With this averaged data, it was found that a critical count ratio of 3.5 and an upper channel count minimum of 11 were suitable parameter choices for the count-ratio algorithm.

The results of testing the algorithm with SC5 parallel ion count data are shown in Table 3. Overall algorithm success rates are shown in the following categories: 1) algorithm agrees with VRS potential to within 20%; 2) algorithm correctly determines whether or not critical potential is exceeded; 3) algorithm gives correct response when VRS potential is

Table 3 Comparison of algorithm performance with various ESA data for 30 day data base, %

Performance	SC5 data	SC9 summed data	SC9 data
Correct to within 20%	56.5	90.3	92.0
Correct determination for 250 V critical potential	78.8	85.7	94.8
Correct when potential exceeds 250 V	65.1	80.3	82.6
Correct when potential less than 250 V	84.5	94.4	99.9
Correct determination for 500 V critical potential	78.1	88.2	96.5
Correct when potential exceeds 500 V	54.5	63.9	85.6
Correct when potential less than 500 V	85.4	95.7	99.9

less than critical; and 4) algorithm gives correct response when VRS potential exceeds critical. Also included in Table 3 are the results for the SC9 high-resolution data and for a test in which the SC9 data were summed into eight "bins" corresponding approximately to the eight SC5 channels.

The results show that the count-ratio algorithm performs poorly with SC5 data. In cases where the critical potential is exceeded, the algorithm detects this barely more than half the time. One reason for this is that the data are known to need further processing, due to problems with the upper energy background channel that prevented its use in correcting the ion counts in the four higher-energy channels. A particular consequence of this is that the count ratio is unreliable in the important 1.7-4 keV range. It appears that another important problem results from the relatively high degree of overlap in the response curves of adjacent SC5 channels.[6] Abrupt increases in count rates typical of vehicle charging are harder to detect when such effects may be smeared over adjacent channels. In contrast, the algorithm is much more successful with the SC9 summed data—which have comparable energy resolution to the SC5 spectra, but much better channel separation (the envelope of the response curves of the summed SC9 channels has less overlap than the SC5 channel response curves). Good separation is clearly necessary for an algorithm based on adjacent channel comparisons.

Conclusion

The count-ratio algorithm has proved to serve as a reasonably accurate voltmeter in its present form, especially with regard to the high-resolution, low-overlap SC9 data. It is quite suitable for real-time implementation on a spacecraft microprocessor, requiring relatively little computation and data storage. One drawback is the ad hoc way in which the parameters are determined. It seems clear that algorithm performance can be improved in some cases by having the critical count-ratio parameter vary with the channel pair being compared. (This would probably help the results with SC5 data.) Since the count rate per channel of itself has no direct physical significance (being a function of ESA design as well as plasma properties), it is difficult to establish count-ratio and threshold requirements in a physically and statistically meaningful way. Still, the count-ratio algorithm has shown considerable success in determining space vehicle potential and is capable of further development and improvement. We expect to report in the near future on the development and testing of a second, related algorithm, based on properties of the plasma distribution function as computed from ion count data.

Acknowledgment

The first author wishes to acknowledge the support of the Air Force Office of Scientific Research/AFSC, United States Air Force under Contract F49620-79-C-0038 and Grant AFOSR-85-0015. We wish to thank Mr. William Huber of AFGL/PHP and Capt. Allen Chesley, USAF, for several helpful discussions regarding this research. We are appreciative of the valuable programming assistance provided by Mr. Curtis Cronin of Tri-Con Associates.

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