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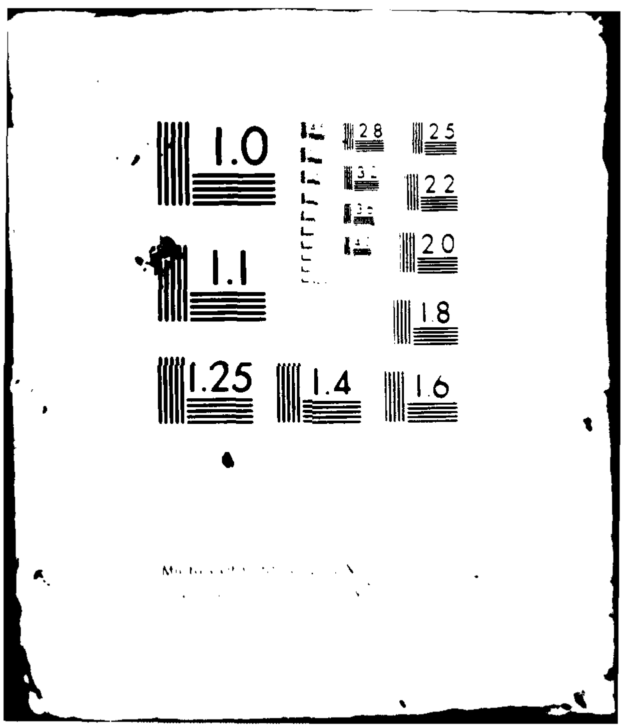
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VALIDATION OF THE NASCAP MODEL USING SPACEFLIGHT DATA*

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Abstract

The NASA Charging Analyzer Program (NASCAP) has been validated in a space environment. Data collected by the SCATHA spacecraft has been used with NASCAP to simulate the charging response of the spacecraft ground conductor and dielectric surfaces with considerable success. Charging of the spacecraft ground observed in eclipse, during moderate and severe substorm environments, and in sunlight has been reproduced using the code. Close agreement between both the currents and potentials measured by the SSPM's, and the NASCAP simulated response, has been obtained for differential charging. These comparisons with experiment and other independent tests of the features of the NASCAP physical model all support the conclusion that NASCAP is able to predict spacecraft charging behavior in a space environment.

Introduction

The NASA Charging Analyzer Program is a computer code designed to model spacecraft charging in a plasma environment of the type encountered at geosynchronous altitudes. The SCATHA (Spacecraft Charging AT High Altitude) (P78-2) satellite was launched in early 1979, specifically to monitor charging activity, material response and to observe the plasma environment in this region. The wealth of data collected by SCATHA has provided an opportunity to validate the NASCAP model by comparing the observed response of the satellite to NASCAP's numerical simulations.

In order for a computer model of spacecraft charging to accurately reproduce experimental results at least two conditions must be satisfied:

1. The physical model on which the computer code is based must contain all of the essential processes and mechanisms responsible for spacecraft charging and the outcome of the particular experiment of interest.
2. The values of the input parameters that characterize these physical processes must accurately reflect the situation observed experimentally.

In this paper we provide an overview of the validation of NASCAP using data collected by SCATHA. We briefly describe the physical model employed by the NASCAP code and then go on to describe in detail the standard techniques used in numerical simulations. We enumerate and discuss each of the simulations carried out, and what conclusions we can draw from them. Finally we summarize the present status of the validation effort and discuss the insights that have been gained into the mechanisms of spacecraft charging as a result of this study.

The NASCAP Physical Model

NASCAP and its physical basis have been described at length elsewhere.[1] Briefly the model provides for a three-dimensional, finite element representation of a spacecraft within a 16 x 16 x 32 grid. The spacecraft is assumed to charge due to the accumulation of electrons and ions from the surrounding plasma, with energies in the 0-50 keV range on its surface. Fluxes of particles with energies greater than ~50 keV that are able to penetrate the materials are assumed to be negligible by comparison, and the deposition of charge within spacecraft materials is neglected. Collection is assumed to be orbit-limited. This is a very good approximation for sufficiently convex objects with dimensions much smaller than the Debye length of the ambient plasma.[2] (A typical geosynchronous orbit plasma with a density of 10^6 m^{-3} and a temperature of 1 keV has a Debye length of ~235 m.) In addition to the collection of primary electron and ion currents other surface mechanisms, namely secondary electron emission, backscatter and photoemission are also included. State of the art descriptions for the variation of these processes with incident particle energy and angular distribution are incorporated into the model. The most recent set of values for the parameters characterizing these descriptions has been compiled from the literature for many different materials. This same standard set of so-called "Material Properties" is used in all the simulations. The distribution of incident particle enrgies and angles may be specified by choosing from a number of possible representations of the surrounding

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plasma's spectrum and its angular distribution function. The spectrum may be Maxwellian, double Maxwellian, or described by a set of tabulated spectral data points. The angular distribution function may be isotropic, or a loss-cone/gain-cone type of anisotropic form.

NASCAP translates this charge collection algorithm into potentials via a resistive-capacitive electrical model of the satellite. In addition, due mainly to experience and understanding gained in developing the code, NASCAP takes into account the three-dimensional character of the satellite's electric field and the role it can play in limiting the emission of low energy secondary and photoelectrons. Space charge effects within the sheath are neglected however, since the fields due to this effect are negligible by comparison to those due to surface charging.

NASCAP does adequately represent this description of the physical processes responsible for spacecraft charging. This has been confirmed by numerous comparisons with laboratory experiments.[3,4] The question that still remains to be answered is whether the mechanisms incorporated into NASCAP are sufficient to explain charging phenomena observed in space. In the remainder of this paper we describe the NASCAP simulations of SCATHA results that have been made and ask what they tell us about the validity of the assumptions built into the NASCAP model for the conditions encountered in space.

Simulation Methodology

Each of the simulations described below was carried out using the standard set of material properties tabulated in Ref. 5. This set represents the best estimates available of quantities such as secondary emission yields drawn from the literature.

For simulations involving a full model of the SCATHA spacecraft, the so-called "One-grid" model, also described in Ref. 5, was used (Figure 1).

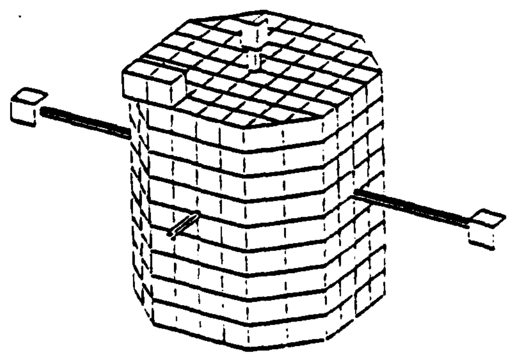


Fig. 1 SCATHA "One-Grid" NASCAP representation.

Representations of plasma spectra measured on board SCATHA by the SC9 detector were used in all simulations. These were constructed using the same standard fitting procedures in each case. Both single and double Maxwellian fits were made.

Double Maxwellian fits to SC9 spectra are noticeably better than the single Maxwellian fits. This reflects the deviation of the observed spectra from pure Maxwellian forms. Experimentally observed values and both fits are compared in Figure 2 for a Day 87 environment. Moment fitting becomes rather involved for a double Maxwellian when the cutoff and spacecraft potential are non-zero. When the spacecraft is charged, repelled particles with energies at infinity less than the spacecraft potential in eV, never reach the detector and so are not measured. For a negative spacecraft this creates an information "gap" in the electron spectrum observed between zero and the spacecraft potential in eV. Much better fits are obtained using a simple least squares procedure. A range of choices for densities and temperatures, within physically reasonable bounds, are tested until the best fit (in a least squares sense) is found. Representations found in this way have usually been remarkably close fits to experiment. The information gap is filled in simply by extrapolating the fit made to the data actually measured. In many cases (particularly for ions) noise in the low energy channels forced us to ignore data below a cutoff of several hundred volts. A standard value of 500 eV above the energy of the lowest energy particles arriving at the surface was finally chosen as the minimum possible to guarantee physically reasonable parameters in the resulting fits. (Using all of the data sometimes lead to components of the double Maxwellian with densities in the range typical of liquid metals!).

Both single and double Maxwellian fits made using these procedures suffer from a deficiency derived from the original data. The electron densities tend to be as much as a factor of ten higher than the ion densities. This unphysical result is thought to be due to a systematic error in the calibration of the SC9 electron detector.[6] To correct for this the electron densities are normalized to the overall ion density so that the plasma is neutral. This would be a trivial operation if all the ions were actually protons but as shown by Kaye, et al.,[7] O^+ often dominates the ion composition.

If all the incident ions were O^+, the count rate would be reduced by a factor of $(m_O/m_H)^{1/2}$ compared to a proton plasma at the same temperature. The processing of raw SC9 data assumes that all ions are protons and so the ion density is underestimated by the same factor. This does not affect the calculation of ion fluxes by NASCAP because in translating from

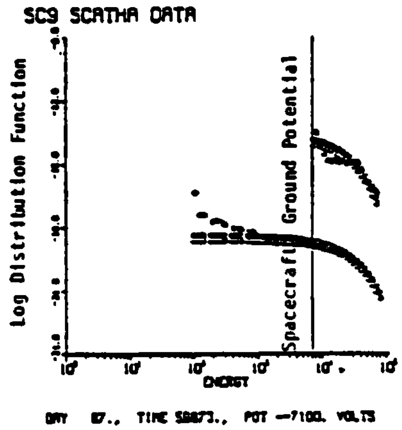


Fig. 2(a) Comparison of single Maxwellian fit (S) with observed ion (Δ) and electron (◇) distribution functions.

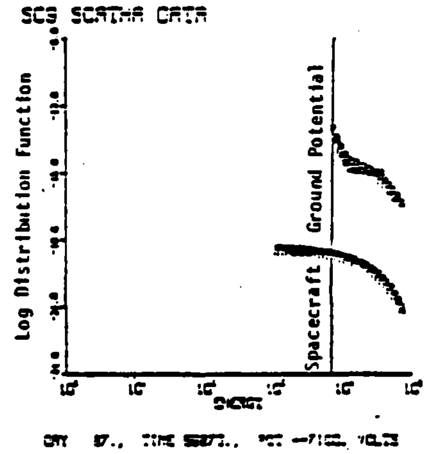


Fig. 2(b) Comparison of double Maxwellian fit (P) with observed ion (Δ) and electron (◇) distribution functions.

distribution functions it too assumes an all proton plasma (i.e., the errors cancel out). However in normalizing the electron densities the underestimation of ion density must be taken into account. If α is the fraction of O^+ in the plasma then the electron densities are normalized by multiplying the initial (large values) by the fraction g

$$g = \frac{N_{total}^{ion}}{N_{total}^{electron}(1-0.75\alpha)}$$

The values of α for the relevant SC9 collection period are estimated from data provided by SC8,[7] which are accurate only to within a factor of two. For periods where no SC8 data has been supplied α is assumed to be 0.5 (a typical value).

The angular distribution of the plasma velocities was assumed to be isotropic in all cases except for the simulation made specifically to test the NASCAP anisotropic formulation, described below.

Using these established techniques for obtaining the NASCAP input parameters a number of comparisons between simulations and observed behavior have been made. We now discuss each of these in detail.

Simulations of Spacecraft Ground Potential

The SC9 detector on board SCATHA is a high resolution device. It is capable of resolving incoming particles with energies of up to 80 keV, differing in energy by 13 percent or less. A plot of the measured incoming ion spectrum shows a distinct discontinuity at the minimum energy for positively charged particles to reach a negatively charged spacecraft. This minimum is the "structure" potential and is assumed to represent the overall potential of the spacecraft. It is known only to within the resolution of the instrument (±13 percent).

A series of simulations have been carried out to compare NASCAP predictions for the satellite underlying ground conductor potential with the observed SC9 structure potential. The standard procedure described above was used in all cases. We discuss these in turn.

Day 146, 1979: Sunlight Charging

The period 1797-3600 UT on Day 146 of the SCATHA mission has been simulated to test the ability of the NASCAP code to predict spacecraft ground potentials in sunlight. During this time the satellite was illuminated by the sun only on the sides, leaving the top and bottom in shadow (Figure 1). SC9 data collected were fit to a double Maxwellian form using the procedure described above. Table 1 shows that the environment was very stable during the entire period, and so just one set of typical parameters (at 179[illegible]) were chosen for the simulation.

The abundant emission of photoelectrons will prevent sunlit surfaces from acquiring a negative charge unless positive fields, due to highly negative neighboring surfaces, inhibit their escape. Surfaces in shadow with an effective secondary yield smaller than unity will begin to charge negatively, however. As the spacecraft rotates such surfaces will charge and discharge as they move periodically in and out of the sunlight. NASCAP is able to model this behavior successfully. If the timescale for charging is much longer than the period, for the purposes of a ground potential calculation, we can average the illumination of each cell over a rotation. For most SCATHA surfaces this is true at one rotation per minute.

Table 1 Double Maxwellian fits to plasma spectra observed by SC9 on day 146, 1979, 1797-3600 UT

Time	NE1	TE1	NE2	TE2	NI1	TI1	NI2	TI2
1797	1.8+05	1.4	2.5+05	8.0	1.6+04	0.8	2.2+05	16.0
1828	1.6+05	1.2	3.0+05	8.0	4.8+04	1.4	2.1+05	18.0
1859	1.5+05	0.9	2.5+05	8.0	3.4+04	1.3	1.8+05	16.0
2045	1.2+05	0.7	4.3+05	8.0	1.1+05	2.7	2.0+05	17.0
2510	2.0+05	0.9	2.6+05	8.0	6.3+04	1.9	2.2+05	16.0
2882	1.1+05	0.8	3.2+05	7.0	7.5+04	1.5	2.3+05	15.0
3130	1.0+05	0.9	4.0+05	7.0	8.0+04	2.9	2.3+05	16.0
3378	1.5+05	1.1	6.1+05	8.0	2.6+04	1.3	3.4+05	13.0
3595	1.2+05	0.8	5.6+05	9.0	2.6+04	1.0	3.0+05	14.0

NE1, NE2, NI1, NI2 - First and second component electron and ion densities respectively in m^{-3}.

TE1, TE2, TI1, TI1 - First and second component electron and ion temperatures respectively in kV.

With these factors in mind the numerical simulation of ground charging was carried out using the so-called "SPIN" option, which averages the illumination in the way described above. This caused all of the cells on the side of the spacecraft initially to remain neutral. However, the kapton SSPM on the top and the white paint on the bottom remained in shadow and began to charge. As their potentials decreased their associated electric fields became sufficiently strong to limit the photoemission from the side cells and they, along with the spacecraft ground, gradually acquired small negative potentials. This mechanism for sunlight charging has been discussed by Mandell. [8] A ground potential of -22 V is predicted. The SC9 ion spectra and SC10 measurements [9] both indicate a ground potential in the -100 V range.

The simulation clearly shows that the NASCAP model is capable of predicting a negative ground potential for the satellite in sunlight, as observed. No free parameters were involved in this comparison. Quantitative agreement is reasonable given the considerable uncertainty in the particle densities measured by SC9. The calculation also shows that the photocurrent in the absence of field limiting exceeds the incident electron current by an order of magnitude (6×10^{-6} A m^{-2} versus 8×10^{-7} A m^{-2}). Hence negative charging in sunlight is a purely three-dimensional electric field related phenomenon. [10] Our understanding of this type of charging behavior is derived primarily from NASCAP studies.

Simulation of Day 87, 1979

In this, and the remaining examples, charging takes place in eclipse. The period chosen on Day 87, 1979 was the eclipse that began at ∿59800 sec UT. Some of the double Maxwellian fits to the SC9 data made using the standard procedure are shown in Table 3. The entry into eclipse preceded the onset of a magnetic substorm and, as can be seen to some extent from Table 2, the environment fluctuated wildly during this time. This conclusion is also supported by the rapid changes in ground potential indicated by both the SC9 ion data and the spectrogram of the period. Because of these rapid changes in environment this period is a difficult case for a comparison between calculated ground potentials and those observed experimentally.

SC9 samples the environment over a span of 20 seconds. This is a much longer timescale than that associated with many of the fluctuations in both potential and incident flux. Thus both the potentials indicated by the ion spectra, and the spectra themselves, are only approximate, average impressions of activity over a 20 second period. With this in mind we nevertheless attempted to simulate the dynamic charging behavior of the satellite.

The NASCAP calculation was carried out assuming that all potentials were close to zero upon entry into eclipse. The simulation was begun using the environment observed at 59813 UT, with zero sun intensity. Only after the elapsed time exceeded 40 seconds were the parameters updated to the next environment, measured at 59853 UT. The simulation continued in this way, always looking backwards to the most "recent" environment data measured. The code does this automatically. A comparison of the resulting NASCAP prediction for the spacecraft ground potential and that implied by the ion spectra is shown in Figure 3. The numerical results of this "quick look" reproduce the two major charging pulses detected by SC9 but fail to resolve three smaller pulses due to the coarse-grained timesteps taken. NASCAP predicts a more negative initial pulse than indicated by the ion spectra but there is closer agreement for the second pulse.

The Day 87 simulation shows that given an active substorm environment, both the observed satellite ground potential and the NASCAP predicted response show similar bursts of negative charging and discharging in eclipse. Furthermore there is a definite correlation between the plasma spectrum in

Table 2 Double Maxwellian fits to plasma spectra observed by SC9 on day 87, 1979, 59800-62000 UT

Time	NE1	TE1	NE2	TE2	NI1	TI1	NI2	TI2
59813	8.0+05	1.5	7.4+04	7.0	3.5+05	3.5	1.3+05	28.0
59853	2.2+04	5.1	1.2+05	11.0	2.1+04	0.6	3.7+04	16.0
59873	2.1+04	4.7	2.9+05	12.0	3.7+04	1.0	9.6+04	14.0
59933	6.7+04	1.8	3.5+05	9.0	1.1+05	1.7	3.2+05	10.0
59973	1.0+06	2.9	2.5+05	9.0	0	-	5.5+05	4.0
60013	1.5+05	1.6	2.2+05	10.0	7.6+04	2.0	8.0+04	29.0
60493	1.8+05	1.8	2.7+05	7.0	1.0+05	1.8	1.8+05	16.0
61033	1.8+05	3.9	1.0+05	15.0	7.4+04	1.5	1.0+05	19.0
61513	4.4+05	1.7	3.7+05	9.0	2.0+05	2.2	1.7+05	23.0
62033	3.3+05	3.7	1.5+05	9.0	0	-	3.0+05	4.0

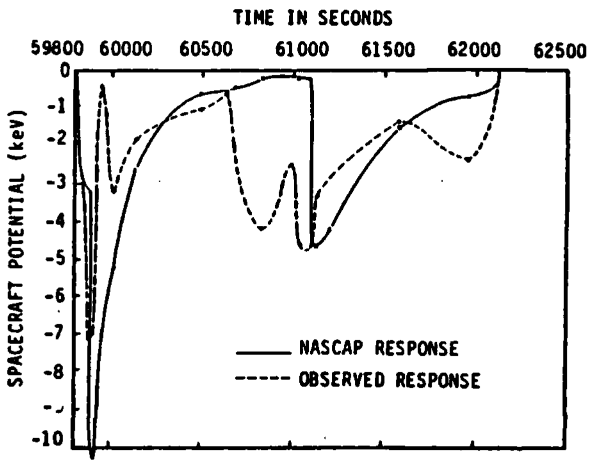


Fig. 3 NASCAP simulated SCATHA charging response for Day 87 eclipse.

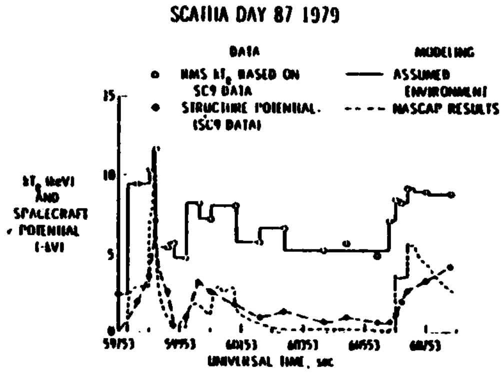


Fig. 4 Simulation of Purvis, et al. (Ref. 11) with single Maxwellian environments.

the 0-50 keV range and the degree of charging. Figure 4 shows a comparison of the SC9 ion spectra potentials and the results of a simulation carried out by Purvis, et al.[11] using standard single Maxwellian fits to the same Day 87 period, and very short computational timesteps. The electron temperatures of these fits correlate quite closely with both the observed and calculated spacecraft potential.

These results are clear evidence supporting the notion that charging is a surface phenomenon, dominated by the collection of non-penetrating plasma particles with energies below ~50 keV. Quantitative accuracy is again acceptable given the limitation in both the measured spectrum and potentials discussed above.

Day 114

The simulation for the period 25944-26104 UT in eclipse on Day 114, 1979 was carried out in the same way as for Day 87. A comparison of NASCAP predicted potentials and SC9 structure potentials is shown in Table 3 and Figure 5. Full umbra eclipse begins at ~25950, as shown by the steep climb in structure potential as the surface photoemission current is cut off. After the steep rise the structure potentials settle down in the -4 to -6 kV range. The NASCAP predictions show close agreement: A rapid rise is followed by oscillation around -5 kV. The oscillation is a result of the unnaturally sudden changes made in the plasma spectrum description every 20 seconds. (Nature has the advantage of being able to change smoothly the plasma spectrum.)

Table 3 Comparison of structure potentials and those simulated by NASCAP for day 114, 1979

Time (sec)	SC9 Structure Potential (kV)	NASCAP Potential (kV)	Time (sec)
25944	-0.5	0	25950
25960	-2.7	-1.8	25951
25976	-5.4	-3.0	25953
29992	-6.2	-4.2	25994
26008	-5.4	-5.2	26009
26024	-5.4	-3.7	26024
26040	-5.4	-6.8	26041
26056	-5.4	-4.3	26056
26072	-5.4	-7.5	26072
26088	-4.1	-4.8	26088
26104	-3.6	-4.3	26097

Charging on both Day 87 and Day 114 shows similar qualitative behavior. Potentials reached are high, typically in the -5

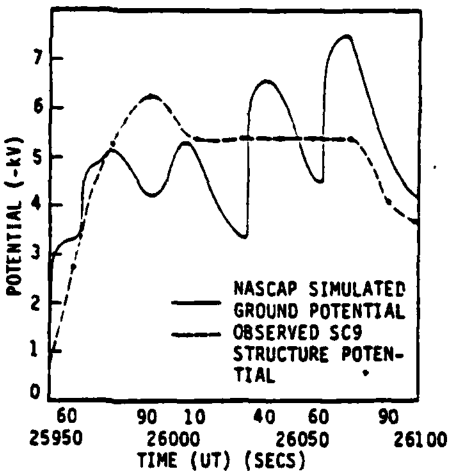


Fig. 5 Comparison of simulated and observed SCATHA ground potentials during eclipse on Day 114, 1979.

to -10 kV range. There are rapid fluctuations: The potential changes by many kV in just a few seconds. We characterize this type of behavior as severe charging. NASCAP successfully models this type of charging.

The remaining two periods simulated using NASCAP show a qualitatively different type of charging. This is characterized by negative potentials less than 2 kV and much longer charging timescales, with fluctuations occurring over hundreds of seconds. NASCAP is also able to model this moderate charging behavior. Furthermore, it is able to offer an explanation as to the difference in charging mechanism responsible for the qualitative and quantitative differences between the two cases.

Days 98 and 272: Moderate Charging

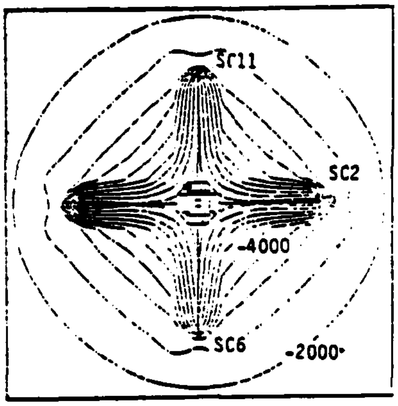
Like the period in sunlight on Day 146, the potentials during eclipse on Days 98 and 272 showed considerable stability. Hence, just as for Day 146, no attempt was made to follow the time dependent behavior of the potentials and only equilibrium potentials at fixed times were simulated. Double Maxwellian fits to plasma spectra measured at 44998 sec on Day 98 and 15603 on Day 272 were chosen as typical of their respective periods. The NASCAP predicted equilibrium ground potentials are compared with experiment in Table 4. The column labeled "one-grid" refers to calculations based on the standard one-grid NASCAP model of SCATHA. Both experiment and calculations agree in indicating moderate charging; however, numerical agreement for the one-grid model is poor. The reason for this, and the reason for the different charging timescales in moderate charging days lies in the mechanism responsible for charging the satellite.

Table 4 Comparison of NASCAP equilibrium potentials and observed values for 44998 on day 98 and 15603 on day 272 (kV)

Day	Observed	One-Grid Ground	Three-Grid Ground
98	-1.4	-0.3	-1.5
272	-1.8	-0.5	-2.7

Unlike the two severe charging days (87 and 114) the plasma spectra on moderate days 98 and 272 were not "hot" enough to give the solar cell coverglass ("SOLAR") covering most of the spacecraft, an initially negative net current. This means that if all of the spacecraft surface was composed of "SOLAR" the spacecraft would not charge negatively at all. The only reason negative ground potentials are obtained is because the small amount of kapton and white paint on the spacecraft do charge in these environments. The NASCAP calculations clearly show that as the kapton charges negatively potential barriers form in front of surrounding "SOLAR" material preventing the escape of the low energy secondary electrons. Hence, the effective secondary yield for "SOLAR" is reduced to almost zero, and the net current collected becomes negative, causing the "SOLAR" (and the whole spacecraft) to begin charging. This "bootstrap" charging mechanism has been described elsewhere. [12] It is a direct result of the differential charging between surfaces and so occurs on a long (differential charging) timescale. This is because differential charging involves the charging of the large inter-surface capacitances, rather than the smaller capacitance of the whole spacecraft with infinity. [12]

The one-grid model of SCATHA omits realistic representations of the four booms perpendicular to each other in the satellite rotation plane. [5] These booms are composed of alternating bands of platinum and kapton. Such regular arrays tend to charge in a way similar to their most charging component (i.e., kapton). [12] Figure 6 shows how important the charging booms are to the electric field structure around the body of the satellite, and hence the "SOLAR" material. Since the potential reached by "SOLAR" (and the whole spacecraft) depends strongly on the electric field in front of its surfaces, omission of the booms will have a serious effect on the numerical accuracy of any attempt to model charging that depends strongly on 3-D electric field effects ("bootstrap" charging). Conversely, omission of the booms is much less important in the "severe" charging case when "SOLAR" (and the whole spacecraft) charge due to an initially negative net incident current, rather than field suppression of low energy emission. To demonstrate this, realistic representations of the booms were added to the standard one-grid model, extending it into three-grids. The booms are assumed



SCATHA charging in eclipse; spacecraft ground = -6200 V; contour steps = 500 V.

Fig. 6 SCATHA potential contours.

covered with kapton. The results for this so-called three-grid model are also shown in Table 4. As expected, the NASCAP predicted potentials are increased compared to the less field-limiting one-grid model. Agreement with experiment is better though not perfect. As discussed in Reference 12, unless the computational mesh is very fine compared to the object dimensions, exact quantitative agreement cannot be expected for situations involving bootstrap charging. Qualitatively, however, NASCAP is successful in predicting only moderate charging on a long timescale for both Days 272 and 98, and severe charging on a short timescale for Days 87 and 114.

Differential Charging of Insulating Surfaces

The SCATHA satellite has on board three Satellite Surface Potential Monitors[13] (SSPM's) designed to measure the differential charging of kapton, teflon and quartz cloth. Two of the SSPM's (SC1-1, SC1-2) are on the sides of the spacecraft 180 degrees apart and the third (SC1-3) is on the top. While most of each sample is backed with aluminum, providing strong capacitive coupling to the ground potential, the spot where the insulated potential is actually measured has no backing, and is much more weakly coupled to spacecraft ground. This allows the differential potential monitored to fluctuate on a much shorter timescale than the rest of the sample, and hence to show much wider variations.

The NASCAP simulation of Days 146, 87, 114, 98 and 272 were all carried out using the correct value of the thickness of the kapton and teflon films and assuming a metalized backing. Thus the numerical predictions of the differential potentials refer to the major portion of the sample rather than the small test spot, and show a much slower variation. In the Day 87 case the kapton sample in SC1-1 is predicted to charge gradually to a potential of -1500 volts with respect to spacecraft ground after 900 seconds of charging. The measured differential potential for kapton (SC1-1) on the other hand shows a more rapid climb to ∿-2000 V[13] after ∿200 seconds.

To simulate properly the SSPM results the value for the thickness of the sample must be increased to reflect the lower capacitance controlling the charging rate of the spot. We have carried out a simulation of the kapton SC1-2 response during the Day 87 eclipse using a model of SC1-2, surrounded by solar cells. A set of material properties for kapton, including effective thickness and dielectric constant, that reproduce laboratory charging experiments were used, along with the same single Maxwellian environments used for the calculation of the ground potential shown in Figure 4. The material properties are given in Table 5. The results for a simulation of SC1-2 are shown in Figure 7. The dynamic charging behavior of the spot is followed very well by the predictions.

Table 5 Material properties used for kapton SSPM study

	Dielectric Constant	3.0
	Thickness of Patch (m)	0.000127[a]
	Conductivity (mho m^{-1})	3×10^{-15}
	Atomic Number	5
Secondary Emission Properties Ref. 1	Delta max	2.1[b]
	E. max (keV)	0.15[b]
	Range 1. (Å)	71.5[b]
	Exponent 1.	0.60[b]
	Range 2. (Å)	312.1[b]
	Exponent 2.	1.77[b]
	Yield for 1 keV Protons	0.455[b]
	Max dE/dx for Protons (keV)	140.0[b]
	Photocurrent (A m^{-2})	2.0×10^{-5}[b]
	Surface Resistivity (ohms)	7.5×10^{12}

Effective Thickness of the Spot[c] = 12.5 x Patch Thickness

NOTES: a. nominal value
b. standard NASCAP value
c. non-NASCAP quantity

Both the electron densities, temperatures and observed spacecraft potentials were "flared" through the existing data points to give a more smoothly varying environment. (These flared electron environments are shown in Figure 8a, b, and c.) The NASCAP predictions for the SSPM currents shown in Figure 7 indicate an interesting anomaly. NASCAP predicts a positive leakage current at 180 seconds. This is absent in the data for SC1-2 but does occur (as predicted) for SC1-1. The absence of this feature for SC1-2 is presently unexplained.

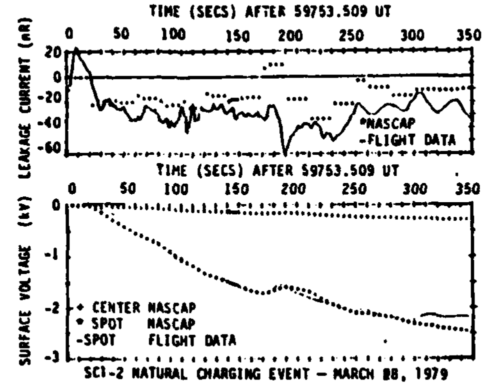


Fig. 7 SC1-2 charging on Day 87.

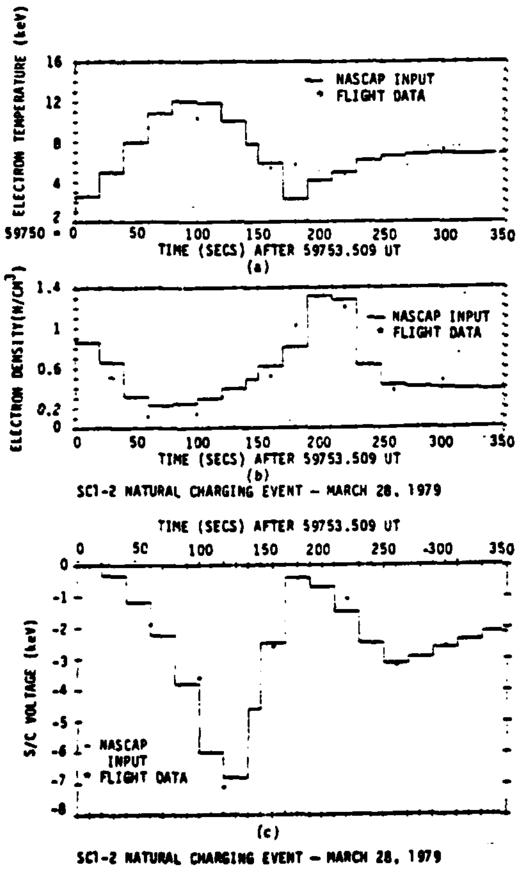


Fig. 8 Flared input data for electron environments and spacecraft potential used in SSPM simulation.

These results indicate that given a model of the experiment, material properties and descriptions of the environment NASCAP can predict differential charging very well, the dynamics as well as the equilibrium values. The behavior of the SSPM's indicated by full SCATHA model simulations are not comparable to the dynamic behavior observed experimentally, but should give accurate estimates of equilibrium potentials. So far NASCAP has been unable to reproduce the anomalous behavior of SC1-3, but its predictions of the remaining SSPM equilibrium potentials have been in reasonable agreement with experiment.

The occurrence of high levels of differential charging in both Day 146 and Day 87 also lends weight to the argument that incident fluxes of high energy particles play only a small part in charge collection. Data from SC3 [14] for fluxes of particles with a range of energies measured on Day 87 and Day 146 is compared in Table 6. While the currents incident on both days due to particles with energies below 50 keV are of similar magnitude ($\sim 10^{-7}$ A m^{-2}) the higher energy penetrating fluxes observed on Day 146 are lower by almost an order of magnitude than those observed on Day 87. This difference in high energy currents is not reflected in a similar difference in observed potentials, suggesting that the lower energy fluxes do indeed dominate the charging behavior.

Table 6 Electron fluxes measured by SC3 (reference 14) on day 87 and day 146, 1979 of the SCATHA mission in electrons cm^{-2} s^{-1} keV^{-1} $steradian^{-1}$

Energy (keV)	Flux At 60000 UT, Day 87	Flux At 2400 UT, Day 146
47-68	1×10^5	5×10^4
66-87	5×10^4	5×10^3
87-129	2×10^4	3×10^3
129-299	2×10^3	7×10^2
269-834	2×10^2	7×10^1

Active Control Simulations

No definitive quantitative simulation of an event involving the operation of the SC4 electron and ion guns has been carried out so far. However, the NASCAP physical model has been successfully used to analyze qualitatively, charging behavior observed during active control experiments. Since these qualitative examples illustrate dramatically the success of the model in explaining results previously poorly understood we include a brief account of one.

During the operation of the SC4-2 electron gun on Day 89, 1979 of the SCATHA mission the sides of the spacecraft were sunlit. As expected on the basis of the ratio of thermal plasma electron current and emitted electron current the satellite ground potential remained close to +1500 V when a 1.5 kV, 1.0 mA electron beam was emitted. During this experiment the differential potential of the kapton SC2-2 SSPM oscillated from -10 V to -80 V respectively as it rotated in and out of the sunlight.[15]

This result can be understood in terms of the onset of field reversal in front of the kapton sample. If the insulating kapton surface is originally at a potential of +1500 V the low energy secondary and photoelectrons are unable to escape and its potential begins to drop towards zero. As the kapton becomes increasingly negative with respect to surrounding surfaces fixed at -1500 V the field in front of it reverses, allowing the low energy electrons to escape to spacecraft ground and halting the decrease in the kapton potential. In darkness, an 80 V differential is required to cause this. In sunlight, photoemission increases the low energy electron yield, and a differential of only 10 V is sufficient to allow enough electrons to escape to balance the incoming current.

When the beam current and voltage were increased to 6 mA and 3 kV, the ground again went to the beam potential (i.e., +3 kV). The kapton surface however now charged to between 1200 and 1400 volts negative with respect to ground (i.e., between +1600 and +1800 volts with respect to the plasma). This much higher differential potential arises because even with all of its photo and secondary electrons escaping to ground the maximum positive potential kapton can achieve lies in this range. This conclusion is supported by a calculation showing that for a neutral plasma with densities and temperatures of 1 cm^{-3} and 1 keV respectively kapton can charge to only ~+2000 V when all of its low energy emitted electrons escape.

Photosheath Effects

To investigate the importance of space charge in the photosheath when the spacecraft is charged to small positive potentials in sunlight, self-consistent space charge calculations were made for the SCATHA satellite fixed at +0.5 volts. Sunlit surfaces were assumed to emit 2 x 10^{-5} A m^{-2} of photoelectrons. The results are shown for the rotation plane of the satellite in Figure 9. A barrier of ~0.75 volts forms ~0.75 m from the emitting surface. Fields due to the space charge of photoelectrons are less than one volt per meter. These predictions are similar to those observed experimentally when the SC10 boom was unfurled for the first time. Aggson [9] observed a dipole moment indicating a barrier of ~1 volt, 4 m from the spacecraft.

These observations and the sample calculations both confirm the validity of NASCAP's assumption that the effect of the photosheath is negligible compared to the 10^4 V m^{-1} fields produced by surface charging.

Helios 1

Finally we look at an example of NASCAP simulation of a satellite other than SCATHA in a plasma environment other than geosynchronous earth orbit. Helios 1 is a solar orbiting satellite whose primary ambient

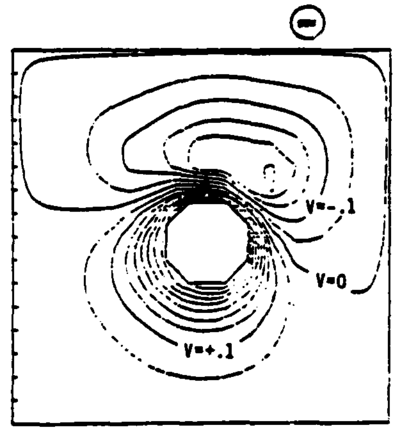


Fig. 9 Self-consistent potential contours around a simplified SCATHA model, vehicle potential = +0.5 volts, top view. Contour spacing = 0.05 volts.

plasma source is the solar wind. [16] The potential of its long antenna has been measured by Kellogg as a function of angle as the satellite rotates in and out the sunlight. The results reproduced from Kellogg's paper [16] are shown in Figure 10. They show the familiar pattern of oscillation between positive and negative potentials as the photocurrent is turned on and off as the antenna moves in and out of shadow.

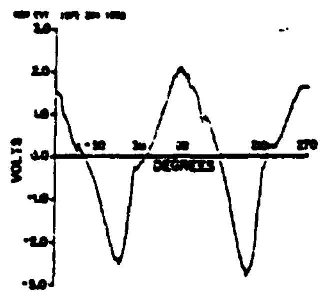


Fig. 10 Relative antenna potential during one revolution at 0.31 AU. (The DC component of potential is not measured.) (From Reference 16.)

To demonstrate that NASCAP predicts the same qualitative behavior even in the solar wind environment a crude model of the spacecraft, shown in Figure 11, was constructed. The spacecraft was assumed to be a simple 2 m cube with a 16 m antenna extending from one side. The surface material was chosen to be kapton. Since this problem is dominated by the incident electron current and the photoemission, the results should be rather insensitive to the material properties. The material properties of the actual spacecraft are not well known. The electron spectrum estimated by Kellogg, a 20 keV Maxwellian plasma with a density of 5 cm^{-3}, was assumed for both species in the NASCAP calculation (ion collection is also of

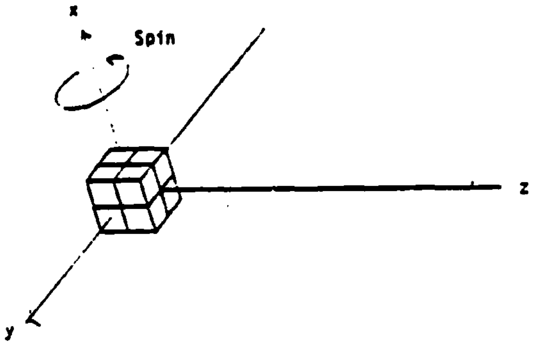


Fig. 11 NASCAP model of HELIOS 1 spacecraft. (Sun direction lies in the y-z plane.)

limited importance in this case.) With these input parameters the potential of the boom as a function of angle was calculated using NASCAP in the "ROTATE" mode[5] with a timestep for each 7.5° of rotation. The results are shown in Figure 12 for both ends of the boom.

They show excellent qualitative agreement with experiment. No serious attempt at quantitative accuracy has been made in this simulation, but nevertheless the predicted amplitude of the potential oscillations is of the same order as those observed. This calculation show that even when knowledge of materials, environments and structural details of the satellite is limited, a qualitative picture of behavior can still be obtained using NASCAP. Hence the physical model and algorithms underpinning the code are not crucially sensitive to exact knowledge of input parameters.

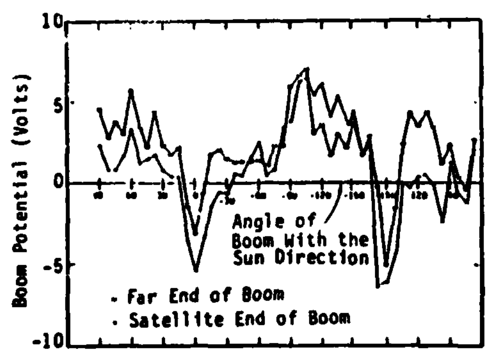


Fig. 12 NASCAP simulated HELIOS 1 boom potential as a function of sun angle.

Conclusions

NASCAP has been validated for charging in a space environment. As in any scientific investigation confidence in a theoretical model grows with the number and diversity of successful tests. The tests carried out so far do consistently support the crucial assumptions in the NASCAP model. We enumerate these as follows.

1. The comparisons show that there is a strong correlation between the collection of particles with energies below 50 keV and the degree of charging. Spectral data for Days 87 and 146 show that this is not true of the higher energy flux. This supports the NASCAP view that charging in space is indeed due to the surface collection of non-penetrating particles.

2. The successful simulation of the charging of spacecraft ground on Day 146 in sunlight, Days 98 and 272 in eclipse, and the explanations of the qualitative behavior of the SSPM's during electron beam emission, support the validity of the description of 3-D electric field effects included in the NASCAP model. However, predictions of phenomena sensitive to these effects should not be regarded as fully quantitative. Computational limitations in both the spatial resolution required to estimate small electric fields and the problem of estimating the change in the field during a timestep can lead to quantitative inaccuracies in potentials. These limitations are not usually severe enough to produce qualitative errors.

3. The SC10 measurements and NASCAP photosheath calculations conclusively show that the neglect of space charge by the code is a valid approximation.

In addition, on the basis of these tests we arrive at the following conclusions regarding the predictive ability of the code.

1. NASCAP is successfully able to distinguish between severe charging, characterized by the following observations:
   - High potentials in the -4 to -10 kV range
   - Rapid fluctuations in potential on a timescale of a few seconds

   and moderate charging characterized by
   - Potentials below about -2 kV
   - Very stable potentials changing on a timescale of hundreds of seconds

   These differences are illustrated dramatically for Days 98 and 114 in Figure 13. NASCAP predicts severe charging on SCATHA, via a conventional mechanism, when the "SOLAR" material has an initially negative net current. Moderate charging is predicted via a "bootstrap" mechanism when "SOLAR" has an initially positive net current, while other parts of the spacecraft like kapton have negative currents.

   Quantitative accuracy is good for severe days. For moderate days, the sensitivity of the bootstrap mechanism to the electric field structure, makes quantitative accuracy dependent upon the representation of the spacecraft. Exact quantitative accuracy cannot

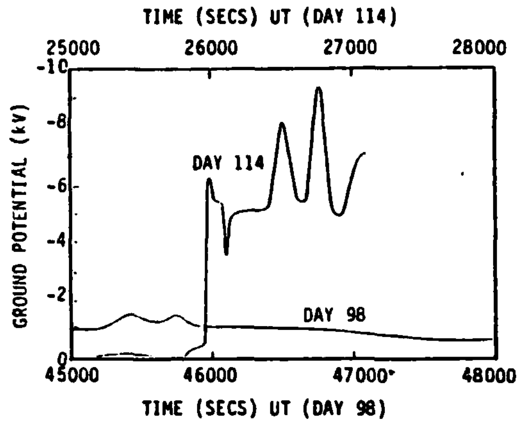


Fig. 13 Comparison of charging activity in eclipse on Days 114 and 98. (From SC9 data.)

always be expected for simple models but results should always be qualitatively correct. Simulations of severe days are much less sensitive to the detail of the spacecraft model.

2. NASCAP successfully predicts negative ground potentials in sunlight (Day 146). The mechanism involved is exactly analogous to "bootstrap" charging in eclipse with low energy photoelectrons playing the role of the secondary emission. The same considerations regarding quantitative accuracy apply.

3. Under conditions that produce considerable differential charging between insulating surfaces in space, the code also predicts the buildup of large differential potentials. In the case of the careful NASCAP simulation of the Day 87 kapton SSPM results, agreement with dynamic behavior was quantitative.

4. Many of the more detailed observations from SCATHA and other spacecraft are successfully reproduced by NASCAP. (These include anisotropy effects, beam emission, and photosheath effects.)

The body of evidence compiled here all lends weight to the conclusion that NASCAP does indeed contain adequate representations of all of the physical processes essential to the understanding of spacecraft charging at geosynchronous altitudes. Furthermore, knowledge of the parameters that characterize these processes is sufficient to allow meaningful predictive calculations of charging effects on real satellites.

The principal quantitative observation that NASCAP has yet to explain is the behavior of SC1-3.[15] Both the anomalously high potentials of the teflon and quartz samples and the anomalously low potentials measured for kapton is not predicted by NASCAP. The failure of the kapton sample to charge is not understood even at a qualitative level at this time. In addition the code is unable to adequately model the space charge dynamics of emitted particle beams. This is due mainly to the three-dimensional character of the beam spreading and the inordinate computational effort required to follow the beam dynamics by conventional particle tracking methods.

In summary we can say that NASCAP has been able to reproduce, with reasonable accuracy, most of the observations it has been used to analyze so far. It has been able to do this using input parameters obtained using standard procedures, without regard to the outcome of any one simulation, and without any "creative" adjustment to insure agreement with experiment. Furthermore the tests successfully carried out have consistently pointed to the validity of the major assumptions included in the model. While there are some observations that the code is unable to predict, they are few in number and as yet, not fully understood at any level. These unexplained events deserve further investigation but we should not allow them to obscure the major successes that have resulted from the validation effort.

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The NASA Charging Analyzer Program (NASCAP) has been validated in a space environment. Data collected by the SCATHA spacecraft has been used with NASCAP to simulate the charging response of the spacecraft ground conductor and dielectric surfaces with considerable success. Charging of the spacecraft ground observed in eclipse, during moderate and severe substorm environments, and in sunlight has been reproduced using the code. Close agreement between both the currents and potentials measured by the SSPM's, and the NASCAP simulated response, has been obtained for differential charging. These comparisons

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) with experiment and other independent tests of the features of the NASCAP physical model all support the conclusion that NASCAP is able to predict spacecraft charging behavior in a space environment.

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