The Worst Case GEO Environment and the Frequency of Arcs in GEO

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Abstract— **Proper spacecraft design and testing depend on a knowledge of the worst case environment and the number of arcs to be endured during the spacecraft lifetime. In this paper, we define the criteria to be used to specify the worst case geosynchronous earth orbit (GEO) charging environment (plasma density and temperature), including the physical constraints on particle and magnetic field energy densities and the relative importance of frame charging and differential charging. A previous estimate of the frequency of arcing (found in the literature and incorporated into an International Standards Organization standard) and the consequent total number of arcs to be encountered in a GEO satellite lifetime are found to be incorrect because they were based on environmental measurements using a faulty algorithm to determine spacecraft charging and plasma density. Using more accurate estimates of the frequency of GEO plasma densities and temperatures, we arrive at a much lower estimate of the total number of arcs during a GEO satellite lifetime. Finally, the worst case GEO charging environment seen to date is determined from *Nascap-2k* simulations. Our estimates of worst case charging environments and arc frequencies may be more confidently used by GEO spacecraft designers and test engineers.**

Index Terms— **GEO, plasmas, spacecraft charging, worst cases.**

I. Importance of Being Realistic

ONE of the most important parameters for design and testing of spacecraft is the worst case environment to be expected. Of course, for every environmental condition (contamination, radiation, and plasma) a worst case can be defined, and spacecraft designers and test engineers use this worst case to guide their designs and tests. In general, some margins are put on the design and test conditions to take care of uncertainties. It is important to try to keep these margins down, as they invariably drive the total cost, weight, volume, and other characteristics of the design. Thus, it is important to keep the worst cases realistic, so as to keep these design constraints at a minimum. That is, one wants to not overdesign or overtest spacecraft components. Just as important is the importance of not underdesigning or testing, for these will lead to failures on orbit. One of the major causes of spacecraft failures in the past has been arcing, due to spacecraft charging in the plasma environment. Many worst case charging environments to be used in designs and testing have been proposed over the years. These worst cases have been incorporated in standards and requirements for spacecraft design and testing [1]–[5]. It is the purpose of this paper to show that there are important physical and historical constraints to worst case spacecraft GEO plasma environments, and applying these constraints, to determine what are, in reality, the worst case spacecraft charging environments that may be encountered in GEO, and to help determine how many arcs are to be expected in these environments during a typical spacecraft lifetime.

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II. Magnetic Versus Plasma Energy Densities

It is commonly supposed that the degree of spacecraft charging in GEO is a function of either the electron flux or the temperature of the plasma [6]. Since the electron flux increases with both temperature and plasma density, this is tantamount to saying that the higher the temperature and/or the density of the plasma, the greater will be the charging. While this may appear obvious, there are physical limits to the density and temperature of GEO charging plasmas. One of the most important is that charging takes several minutes, during which time the plasma must be contained by the magnetic field, or the field will be disrupted [6]. Thus, the plasma kinetic energy density perpendicular to the magnetic field must be less than the magnetic field energy density if charging is to occur.

Since both the electrons and ions contribute to the particle kinetic energy density, and since it is only the perpendicular particle energy density that must be contained by the magnetic field, the formula expressing this constraint (assuming single Maxwellians for electron and ion distribution functions and perpendicular temperatures equal to parallel temperatures) is [8]

$$3/2(N_i kT_i + N_e kT_e)/2 < B^2/8\pi \tag{1}$$

where B is the local magnetic field strength and N_i and N_e are the ion and electron number densities, respectively, in CGS units. To show that this inequality holds even for six of the worst case charging environments [1]–[5], [8], in Fig. 1 is plotted E (electron volts) versus N (m^{-3}) for both ions and electrons, and lines of magnetic field with the equivalent energy density. Here, it can be seen that the highest average plasma kinetic energy densities for these worst cases corresponds to about 1.7×10^{-7} T, about the maximum GEO B-field measured by geostationary operational environmental satellite (GOES) satellites during solar geomagnetic charging events [9]. This corresponds to $NkT = 4.4 \times 10^{10}$ m^{-3} eV, which we propose as a worst case charging perpendicular particle kinetic energy density.

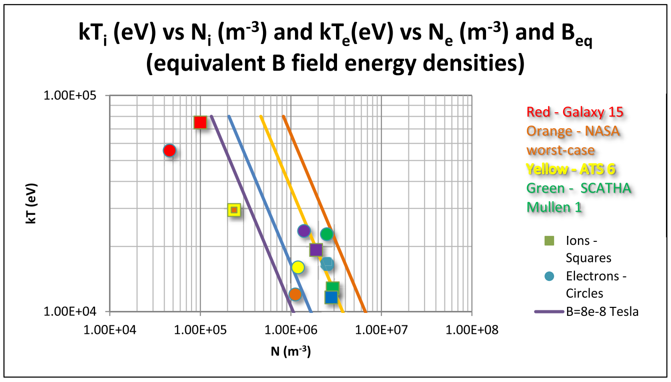

Fig. 1. Magnetic field strengths with equal energy densities to worst case environments.

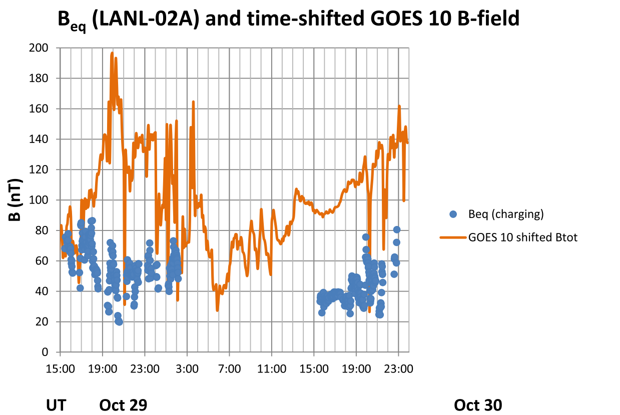

Fig. 2. Equivalent B-field from LANL measurements of electron and ion densities and temperature and GOES 10 B-field time shifted to LANL-02A LT.

One might speculate that this limitation is only coincidental, however, and that the condition might be violated if more environments were considered. To test the hypothesis that the magnetic field must contain the charging plasma by having a magnetic energy density higher than the perpendicular kinetic energy of the plasma, we turn to measured magnetic fields and particle fluxes during one of the most severe geomagnetic storms in recent times, the Halloween events of 2003. The particle flux moments were measured by Los Alamos National Laboratory (LANL)-02A [10], while the magnetic field measurements were taken from GOES 10 [9]. Fig. 2 shows a plot of the LANL-02A Beq (the magnetic field with equal energy density to the particle kinetic energy density) for the Halloween 2003 dates along with the time-shifted magnetic field as measured by GOES 10. The longitude of GOES 10 on the dates in question was 43° less than that of LANL-02A [so the local time (LT) was within 3 h]. The GOES data are accordingly shifted to later times to match the LT of the LANL satellite.

It can be seen that even though the GOES data were taken almost 3 h before the LANL satellite reached the same LT, the inequality was not violated. While it was probably fortuitous that the magnetic field configuration on those days held relatively steady with LT for the 3-h period between when the two satellites occupied the same LT, but when the magnetic field dipped, so did the equivalent magnetic field of the particles. This is strong evidence that even in this severe geomagnetic storm, the energy density inequality still held inside the magnetosphere.

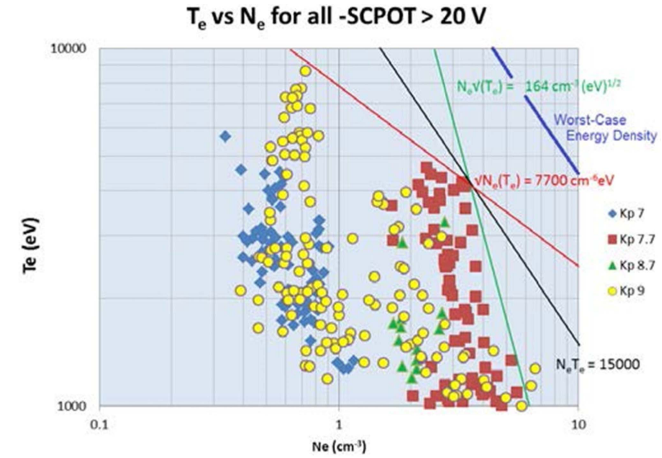

Fig. 3. Electron temperature and density moments for all LANL charging data of October 29 and 30.

Fig. 3 shows all of the electron temperatures and densities for negative frame charging (-spacecraft potential) of >20 V for the published LANL October 29 and 30, 2003 data [10]. Here, it can be seen that there is an absolute limit of about 15 000 cm^{-3} eV for the energy density combo $N_e T_e$. There also seem to be limits on the total electron flux [proportional to $N_e(T_e)^{0.5}$] and on $N_e^{0.5} T_e$. The colors on the data points indicate the geomagnetic activity level at the time (Kp of 7.7 = 8-, etc.). Of interest here is the fact that while the temperature only reached its highest levels at Kp = 9, the density has dropped off from its highest levels reached at about Kp = 8-. At no time are the highest temperatures coincident with the highest densities. This is, of course, what our energy density hypothesis would predict, but also has important implications for the worst case GEO charging environment.

III. Worst Case Conditions Should Be Realistic

Cho *et al.* [11] published a paper using statistics to estimate the total number of arcs to be expected on a GEO satellite in its lifetime. In this paper, they made several assumptions, among which were these.

1) A hypothetical spacecraft would arc whenever its differential voltage was greater than 400 V.
2) The data published on the LANL CDAWeb site for five LANL satellites gave a good statistical representation of the electron and ion densities and temperatures to be expected in GEO, so that probabilities of given density and temperature combinations could be taken from them.
3) The NASA air-force spacecraft charging analysis program (NASCAP) spacecraft charging code gave valid numbers for differential charging.

Cho *et al.* [11] used "…data from five LANL satellites: LANL 1989-046, 1991-080, 1990-095, 1984-04, and 97A. At the CDAWeb site, magnetospheric plasma analyzer (MPA) data are listed for n_e, T_e, n_{iH}, n_{iL}, T_{iH}, and φ_{sat} at

TABLE I

SETS OF PLASMA PARAMETERS WITH THE DIFFERENTIAL VOLTAGE CALCULATED BY THE NASCAP SIMULATION HIGHER THAN 400 V AND THE PROBABILITY OF OCCURRENCE HIGHER THAN 0.01% UNDER THE SUNLIT CONDITION

Plasma parameters				NASCAP result, ΔV				
T_e, keV	n_e, cm^{-3}	T_i, keV	n_i, cm^{-3}	LT0e, V	LT0n, V	LT6, V	LT12, V	LT18, V
13.5	5	5	0.25	16,890	2244	2142	2198	2251
10.5	10	10	0.25	16,440	2931	2836	2884	2940
10.5	5	10	0.25	13,840	1716	1628	1680	1725
10.5	5	5	0.25	13,280	1723	1636	1685	1731
7.5	10	10	0.25	11,630	2012	1935	1976	2017
7.5	10	5	0.25	11,240	2015	1942	1987	2022
7.5	5	10	0.25	9,760	1133	1056	1109	1136
7.5	5	5	0.25	9,480	1141	1064	1117	1145
4.5	10	10	0.25	6,501	925	864	907	928
4.5	10	5	0.25	6,418	931	871	917	934
4.5	5	10	0.25	5,347	419	356	410	421
4.5	5	5	0.25	5,336	429	365	419	430
4.5	5	1.25	0.25	4,850	437	373	427	438

approximately every 90 s.” Using these data, they derived the data in [11, Table 5], which we reprint as Table I.

Reference [11, Table 5] lists the case where the NASCAP simulation result gives $V > 400$ V and the probability of occurrence in any LT zone is higher than 0.01% under the sunlit condition. The combination of high electron temperature (4.5 keV), high electron density (5 cm^{-3}), and low ion density (0.25 cm^{-3}) provides such conditions.

The problem is that these densities are higher than those reported for charging anywhere in the literature (see, for example, the worst case conditions given in [1], [13], reprinted here).

All of the conditions in Table I have $n_e > 3$ cm^{-3}, the highest value found elsewhere in the literature for severe charging conditions.

Cursory inspection of the CDAWeb data shows that these unphysical combinations of high electron temperatures and densities are numerical artifacts of the potential fitting routine. Michelle Thomsen (LANL), who originated the LANL fitting routine, concurs with this assessment. To illustrate that this is the case, we present data used in [11] for a single day, August 16, 2005, in Table I and Fig. 4.

However, an LANL MPA 01A spectrogram (where the intensity of fluxes is color coded, energy is on the vertical axis, and time is on the horizontal axis) does not show charging at 01:00. The reason the website data are in error is that the algorithm used to determine charging there looked for an ion line, which was extremely diffuse at that time. The correct amount of charging is shown in Fig. 5, where it is seen that use of the ion line (red dots) when it is not clearly present leads to wrong values for charging [12]. An e-mail reply from [12] explains the situation thusly, “…the event you have sent me (01a on August 16, 2005) is an example where our algorithm to identify the spacecraft potential from the particle observations goes awry. We are looking for the sharp line in the ion spectrum from the accelerated lower

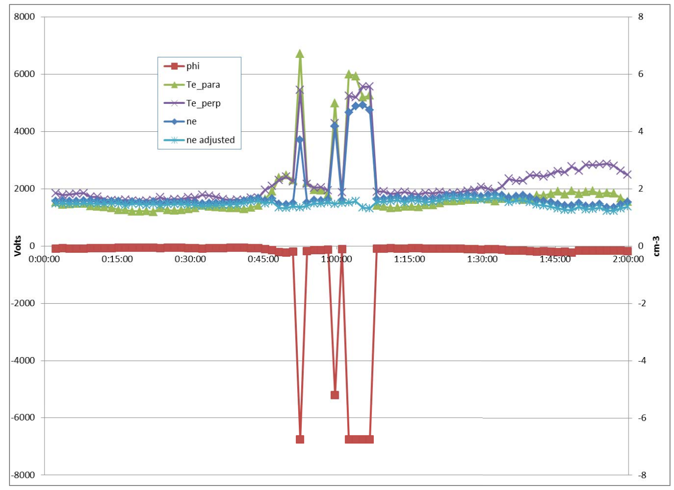

Fig. 4. Data from the CDAWeb site for August 16, 2005. Data points show very high spacecraft charging and electron densities and temperatures near 01:00:00. N_e adjusted is corrected for spacecraft charging.

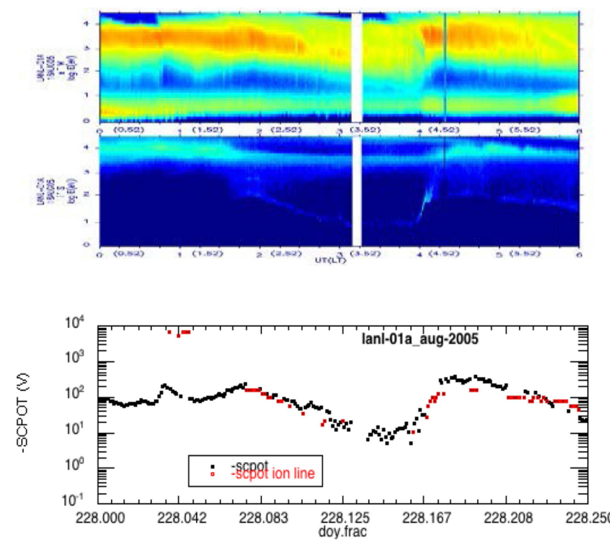

Fig. 5. Top—raw spectrograms. The top spectrogram shows the ion line used for charging estimation. Bottom—derived charging value. Near 228.04, the ion line derives spurious charging.

energy ions. Unfortunately, at times (like the one you have identified), our detection algorithm finds what it thinks is such a line, but it is really just the counts cutoff of the high-energy population… As you note, the other moments (densities, temperatures, and so on) will not be correct if the potential is misidentified.”

When the ion line algorithm used to derive the spacecraft charging gave a great amount of charging, this had a cascading effect on the algorithms used for the density and temperature moments. In effect, the high charging implied that the low-energy electrons were not being sufficiently counted, and correcting for them gave high electron fluxes at low energies, and also influenced the derived temperature moment. That is, all of the moments were affected.

Further perusal of many dates of data used in [11] shows that the only times densities as high as in Table I were seen by LANL satellites were when

		T_e, keV							
		1.5	4.5	7.5	10.5	13.5	16.5	19.5	22.5
n_e cm^{-3}	1.25	7x4	7x4	7x4	7x4	7x4	7x4	7x4	7x4
	5	7x4	6x4	6x4	6x4	6x4	6x4		
	10	7x4	2x4	2x4	2x4	2x4			
	15	7x4	2x4	2x4	2x4				
	25	1x4	1x4	1x4	1x4				
	50	1x4							

Fig. 6. Reprint of [11, Fig. 5]. Parameter matrix considered for the NASCAP simulation. The shaded blocks are ignored. In each block made of n_e and T_e, the numbers of combinations considered for the values of n_i and T_i are shown. Blocks colored pink are considered unphysical in this paper.

the electron temperature was very low, as we have seen in Fig. 4.

Cho *et al.* [11] go on to state that when they did the statistics of occurrence of N_e and T_e, they used the values in [11, Fig. 5], reproduced as our Fig. 6. Now, based on our presumed highest allowed physical particle kinetic energy densities, we can state that all of the probability boxes we have colored pink were unphysical.

When the unphysical charging values are removed from their sample, their total sunlit trigger arcs/year goes from 2434 to 762. This is probably pessimistic, as most are from $N_e = 5$ cm^{-3} and $kT_e = 7.5$ keV, still a rare to nonexistent condition, as shown in Fig. 3. If that density and temperature combination is also thrown out, the number goes down to 105 per year! However, without redoing the entire gargantuan Cho *et al.* analysis, the most we can say about the number of arcs per year is that it is probably at least a factor of three less than the Cho *et al.* estimate, and may be less than 5% of their estimate, even assuming that their differential arcing threshold of 400 V is correct. As Cho *et al*'s argument is repeated verbatim in [3], it must now be corrected. Koons *et al.* [13] show that for spacecraft charging at high altitudes (SCATHA), a differential potential of 300 V on their gold surface charging monitor was associated with arcing, and different values of differential charging to be needed for arcing to occur have been derived in [14] and [15]. It has even been shown [15] that in laboratory simulations, aging can dramatically affect the differential voltage arcing threshold for realistic solar arrays. Before definitive answers can be given for the number of surface arcs to be expected on GEO spacecraft, these issues must be resolved.

IV. Toward a Proper Worst Case Environment for Charging

Cho *et al.* [11] did properly emphasize the fact that differential charging is the most important charging parameter for determining a worst case. We also believe that, to be considered proper, worst case environment combinations of densities and temperatures for a valid worst case condition must be as follows:

1) reported in the literature or published databases;
2) checked to make sure they are valid;
3) physically realistic (do not violate energy density requirements);
4) compared with each other using good spacecraft charging codes (i.e., multi-utility spacecraft charging analysis tool (MUSCAT), spacecraft plasma interactions software, and *Nascap-2k*).

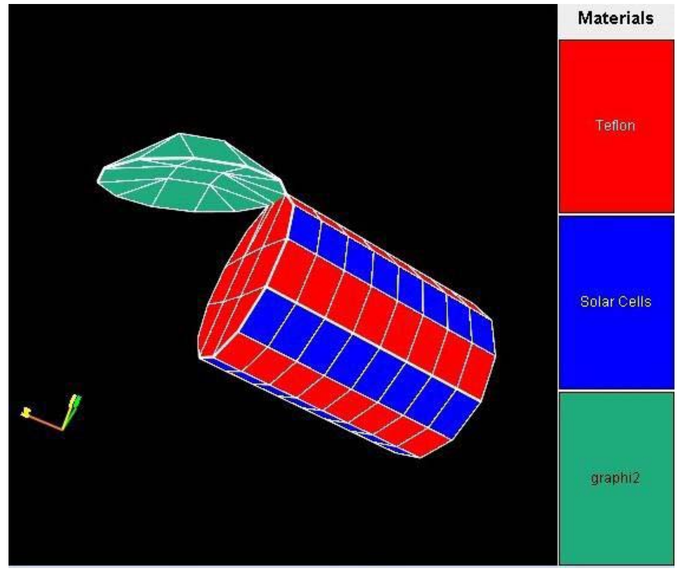

Fig. 7. Model 6. A spinner with its spin axis aligned perpendicular to the Sun.

TABLE II
Worst Case Geosynchronous Plasma Environment

Item	Units	Value	Description
N_E	cm^{-3}	1.12	Electron number density
T_E	eV	1.2×10^4	Electron temperature
N_I	cm^{-3}	0.236	Ion number density
T_I	eV	2.95×10^4	Ion temperature

Another paper in this 13th Spacecraft Charging Technology Conference [16] compares MUSCAT [17] and *Nascap-2k* [18] estimates of charging in an attempt to define a worst case environment. Here, we report *Nascap-2k* results using two other spacecraft models, to see if our worst case charging environment is dependent on spacecraft type. The two other models reported here are of spinning spacecraft, one with its rotation axis perpendicular to the Sun (reminiscent of the old Hughes 376 GEO communication satellites) and one with its rotation axis pointed at the earth (somewhat like the LANL GEO research satellites). *Nascap-2k* representations of these spacecraft are shown below.

In Fig. 7, graphi2 has the *Nascap* properties of graphite. Results of *Nascap* modeling for 2000 s each are given in Tables II–IV.

From Table II, Model 6 not rotating: Frame and (Max–Min)—ATS-6 is the worst case and (Max–Frame)—SCATHA-Mullen1 is the worst case.

From Table III, Model 6 rotating: Frame and (Max–Min)—ATS-6 is the worst case and (Max–Frame)—SCATHA-Mullen1 is the worst case, just like nonrotating.

Thus, from Table VI, for Model 3 not rotating: Frame—SCATHA-Mullen 1 is the worst, (Max–Min)—

TABLE III

LANL DENSITY, TEMPERATURE MOMENTS, 16-08-2005

Date	Time	ne	phi	Te_para	Te_perp
16-08-2005	0:45:20	1.6	-111	1639	1955
16-08-2005	0:46:46	1.7	-138	1905	2104
16-08-2005	0:48:12	1.5	-205	2384	2295
16-08-2005	0:49:38	1.4	-226	2466	2414
16-08-2005	0:51:04	1.5	-190	2309	2254
16-08-2005	0:52:30	3.7	-6760	6715	5447
16-08-2005	0:53:56	1.5	-174	2218	2169
16-08-2005	0:55:22	1.6	-142	1964	2032
16-08-2005	0:56:48	1.6	-141	1946	2048
16-08-2005	0:58:14	1.6	-121	1795	1936
16-08-2005	0:59:40	4.2	-5208	4991	4280
16-08-2005	1:01:06	1.6	-106	1627	1869
16-08-2005	1:02:32	4.7	-6760	5997	5243
16-08-2005	1:03:58	4.9	-6760	5924	5186
16-08-2005	1:05:24	4.9	-6760	5186	5564
16-08-2005	1:06:50	4.8	-6760	5256	5565
16-08-2005	1:08:16	1.6	-94	1414	1899
16-08-2005	1:09:42	1.6	-93	1370	1900
16-08-2005	1:11:08	1.7	-80	1328	1806
16-08-2005	1:12:34	1.7	-87	1343	1849

TABLE IV

MODEL 6—NOT ROTATING, DAYLIGHT

	Min Chg	Max Chg	Frame	-Frame	Max-Min	Max-Frame		Rank Frame	Max-Min	Max-Frame	Avg rank
NASA Worst Case	-12430	-6005	-7803	7803	6425	1798	NASA Worst Case	2	2	3	2.67
ATS-6	-18160	-8757	-11420	11420	9403	2663	ATS-6	1	1	2	1.33
SCATHA-Mullen1	-9945	-4919	-7600	7600	5026	2681	SCATHA-Mullen1	3	3	1	2.67
SCATHA-Mullen2	-9065	-4428	-6149	6149	4637	1721	SCATHA-Mullen2	4	4	4	4
ECSS-E-ST-10-04C (SCATHA 1979)	-9446	-4589	-6023	6023	4587	1434	ECSS-E-ST-10-04C (SCATHA 1979)	5	5	5	5

TABLE V

MODEL 6—ROTATING AT 1 r/min

	Min Chg	Max Chg	Frame	-Frame	Max-Min	Max-Frame		Rank Frame	Max-Min	Max-Frame	Avg rank
NASA Worst Case	-10070	-2883	-3752	3752	7187	869	NASA Worst Case	5	2	5	4
ATS-6	-15620	-4718	-6217	6217	10902	1499	ATS-6	1	1	3	1.67
SCATHA-Mullen1	-10010	-3632	-5800	5800	6378	2168	SCATHA-Mullen1	2	3	1	2
SCATHA-Mullen2	-9194	-3188	-4771	4771	6006	1583	SCATHA-Mullen2	3	5	2	3.33
ECSS-E-ST-10-04C (SCATHA 1979)	-9389	-3124	-4119	4119	6265	995	ECSS-E-ST-10-04C (SCATHA 1979)	4	4	4	4

TABLE VI

MODEL 3—NOT ROTATING (FIG. 8)

	Min Chg	Max Chg	Frame	-Frame	Max-Min	Max-Frame		Rank Frame	Max-Min	Max-Frame	Avg rank
NASA Worst Case	-22990	-5773	-6308	6308	17217	535	NASA Worst Case	5	5	5	5
ATS-6	-32690	-8791	-10020	10020	23899	1229	ATS-6	2	4	4	3.33
SCATHA-Mullen1	-43500	-8707	-11140	11140	34793	2433	SCATHA-Mullen1	1	2	1	1.33
SCATHA-Mullen2	-50060	-7074	-8338	8338	42986	1264	SCATHA-Mullen2	4	1	3	2.67
ECSS-E-ST-10-04C (SCATHA 1979)	-35200	-7520	-8996	8996	27680	1476	ECSS-E-ST-10-04C (SCATHA 1979)	3	3	2	2.67

SCATHA-Mullen 2 is the worst, and (Max–Frame)—SCATHA-Mullen 1 is the worst.

OVERALL—ATS-6 (a single Maxwellian) and SCATHA-Mullen 1 (a double Maxwellian) are the worst worst-cases from these simulations. For the results of other spacecraft configurations, rotating and nonrotating, see [7].

Finally, Ferguson *et al.* [7] have shown that the most accurate GEO daylight spacecraft charging index for differential charging is the electron flux above about 9 keV energy.

TABLE VII

ENVIRONMENTS AND ELECTRON FLUX RANKING

Environment	F > 9 keV (e^-/cm^2sec)	Rank
SCATHA-Mullen1	5.75E+09	1
SCATHA-Mullen2	4.08E+09	2
ECSS-E-ST-10-04C (SCATHA 1979)	3.19E+09	3
ATS-6	2.26E+09	4
MIL STD-1809	2.11E+09	5
ATS-6 day 178, 1974	2.08E+09	6
ATS-6 day 217, 1974	1.98E+09	7
NASA Worst Case	1.70E+09	8
Galaxy15	1.79E+08	9

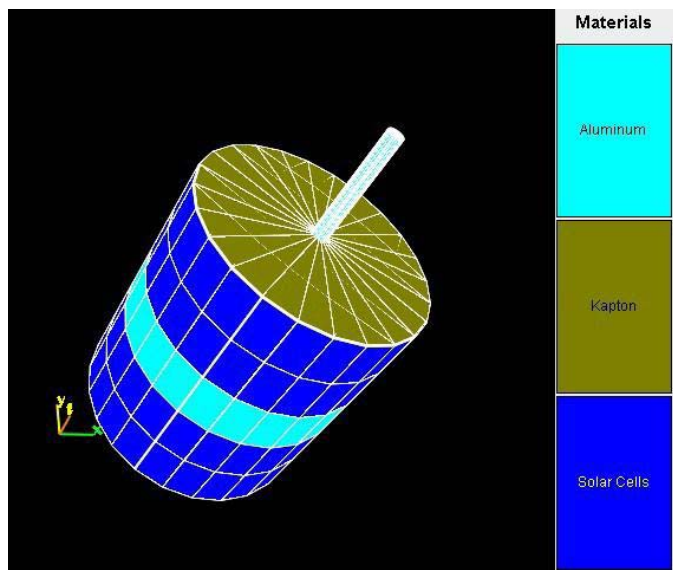

Fig. 8. Model 3. A spinner with its spin axis pointing towards Earth

TABLE VIII

WORST CASE SINGLE MAXWELLIAN SPECTRUM

	N_e (m^{-3})	T_e (eV)	N_i (m^{-3})	T_i (eV)
ATS-6	1200000	16000	236000	29500

Table VII shows the fluxes above 9 keV for several proposed worst case GEO environments.

Combining these results with those in [16], the all-around worst case environment so far reported is: SCATHA-Mullen1. The worst case environments suggested are given in Tables VIII and IX.

Worst case particle energy density

$$NkT = 4.4 \times 10^{10}\ \mathrm{m}^{-3}\ \mathrm{eV}.$$

TABLE IX
WORST CASE DOUBLE MAXWELLIAN SPECTRUM

	Ne1 (m^{-3})	Te1 (eV)	Ne2 (m^{-3})	Te2 (eV)	Ni1 (m^{-3})	Ti1 (eV)	Ni2 (m^{-3})	Ti2 (eV)
SCATHA-Mullen1	200000	400	2300000	24800	1.60E+06	300	1.30E+06	28200

V. CONCLUSION

Proper spacecraft design and testing depend on a knowledge of the worst case environment and the number of arcs to be endured during the spacecraft lifetime. In this paper, we have defined the criteria to be used to specify the worst case GEO charging environment (plasma density and temperature), including the physical constraints on particle and magnetic field energy densities and the relative importance of frame charging and differential charging. A previous estimate of the frequency of arcing (found in the literature and incorporated into an ISO standard) and the consequent total number of arcs to be encountered in a GEO satellite lifetime were found to be incorrect because they were based on environmental measurements using a faulty algorithm to determine spacecraft charging and plasma density. Using more accurate estimates of the frequency of GEO plasma densities and temperatures, one can arrive at a much lower estimate of the total number of arcs during a GEO satellite lifetime if our present estimates of differential voltage thresholds are correct. Thus, at present, it may be that most of the solar arrays tested under ISO 11221 are being overtested by at least a factor of three in the number of arcs, and possibly by a factor of 20. Finally, the worst case GEO charging environment seen to date was determined from *Nascap-2k* simulations. Our estimates of worst case charging environments and limits on arc frequencies may be more confidently used by GEO spacecraft designers and test engineers than those presently in ISO 11221.

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