Influence of Reflected Electrons on Multipactor Prediction for Rectangular Waveguides

Akoma Henry E.C.A, Adediran Y.A

Abstract—**An important design consideration in systems utilizing hollow waveguides operating at low gas pressures and high RF power levels is the prevention of the multipactor (MP) breakdown phenomenon. This work makes use of a proposed multipactor prediction algorithm designed with proper consideration for reflected electrons to predict possible multipactor breakdown power levels for rectangular waveguide geometries operating at the TE_{10} propagation mode. The results of analysis using the algorithm suggest that it is crucial to account properly for reflection electrons during a multipacting process investigation in order not to overlook subtle breakdown powers.**

Index Terms—: **multipactor breakdown, multipactor prediction algorithm, reflected electrons, rectangular waveguide, secondary emission**

I. Introduction

Satellite-borne rectangular waveguides operate in a high vacuum space environment and also under high RF power. Both these conditions favour the initiation of multipactor breakdown. Multipaction (MP) is the resonant growth of secondary electron population in RF components. It is a phenomenon that leads to damage and degradation in payload performance and, therefore, limits greatly the output power of any communication satellite. Various research efforts in the field of multipaction have been devoted to better understand the phenomenon including the combination of physical processes leading to it. A number of researches have focused on the study of the higher order resonant modes, the analysis of steady stable trajectories, the radiated power spectrum of a multipactor discharge in parallel-plate regions, and multipactor detection and suppression methods [1][2]. The phenomenon of secondary electron emission which is the primary contributing physical process that leads to multipactor has also received its share of research endeavors, resulting to a further understanding of secondary electron yield (SEY) of various materials vis-a-vis emission of true secondary and reflected electrons [3][4]. Studies have also shown that for accurate multipacting analysis to be done on RF components, it is expedient to determine the electromagnetic (EM) field distribution within the component of interest [5]. The outcomes of these researches have led to the development of models and algorithms for multipactor detection and suppression within microwave components, RF devices and Superconducting RF (SRF) equipment. Conventional multipactor suppression techniques, such as surface treatments, require that a good percentage of the inner surface of the geometry of interest be coated or sputtered with a material with low secondary electron yield. Similarly, surface geometry modification techniques may require that the geometry surface modification be extensive. The application of a magnetic field has been proven to completely extinguish multipactor in a rectangular waveguide. However, since the risk of placing magnetic fields close to satellite-borne equipment is too great, the cutting of grooves on the waveguide centre-line and full metal surface coating have received support as acceptable suppression techniques [6][7]. The disadvantage of just cutting grooves at the center-line of the waveguide geometry is that the center-line may not be the point of emission of multipactor-initiating electron. Also, applying full coating on the metal surface may just be financially wasteful as only the portion of the waveguide surface emitting the multipactor initiating electrons need be coated. Therefore, given these challenges, the European Space Agency (ESA) awarded a contract titled "Multipactor and Corona Discharge: Simulation and Design in Microwave Components", which was essentially devoted to the investigation of multipactor and corona effects in rectangular waveguide components through the development of multipactor prediction software tools. The multipactor predictor was required to possess the capability to analyze not only the electromagnetic response of microwave components but also to determine (predict) the breakdown power of such structures with reasonable accuracy [8]. Essentially, this incorporated multipactor prediction into the design and manufacturing process of RF and microwave hardware. In an effort to meet the ESA requirement, researchers adopted various assumptions, applied a range of engineering and scientific techniques and came up with a variety of algorithms, some of which have translated to software tools useful enough to predict the multipactor threshold voltage. Data generated from these prediction software have guided RF and microwave components designers on the geometry modifications needed to eliminate or suppress multipaction altogether. Geometry modification results in electromagnetic field pattern changes which lead to electrons trajectories

Manuscript received July 16, 2012. This work was supported in part by the National Space Research and Development Agency (NASRDA), Abuja, Nigeria and the University of Ilorin, Ilorin, Nigeria

Akoma Henry E.C.A is with the National Space Research and Development Agency (NASRDA), Abuja, Nigeria (phone: +234 809 6496 859, +234 805 896 1660; e-mail: akomahenry@gmail.com).

Adediran Y.A is a professor of Electrical and Electronics Engineering presently is the head of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Ilorin (e-mail: yinusaade@yahoo.com).

distortion that breaks resonant conditions for multipactor discharge. In line with the ESA contract award, this research work sought to design a multipactor prediction algorithm capable of optimizing current suppression techniques by predicting the possible multipactor initiating RF power levels for rectangular waveguide geometries operating at the TE_{10} mode.

II. THE MULTIPACTOR PREDICTION ALGORITHM

A. Design Considerations and Assumptions

Some works on the subject of MP prediction did not consider elastic and inelastic electrons (often referred to as reflected or backscattered electrons) in their design [8]. Ordinarily, this omission is capable of undermining the actual quantities and types of "emitted" electrons present in a system after consecutive electron-wall impact events. Some researchers whose algorithm accounted for reflected electrons adopted the PIC approach which does not allow for a comprehensive modeling and tracking of individual electrons since a single "super electron" was representative of as many as a thousand "micro-electrons" [9]. To address this lapse, the design process for the algorithm presented in this article took proper account of all the various types of electron "emissions" that were probable during a multipacting process - true secondaries and reflected electrons. The technique employed allowed for a comprehensive modeling and tracking of individual electrons.

A few of the assumptions guiding the development of the algorithm included the following:

a. all the primary electrons were created during the first period of the EM field
b. the initial primary electron population size was a minimum of 1000 electrons
c. emitted primary electrons possessed non-zero energy levels
d. since only the onset of the multipactor discharge is to be predicted, electron dynamics were influenced only by the EM field but not affected by the presence of other electrons (space charge)
e. the collision of an electron with a plate could rip zero (absorption), one, or more electrons from the wall, and,
f. the total kinetic energy of the emitted electron(s) is equal to or less than the kinetic energy of the impacting electron.

B. The MP Prediction Algorithm

The MP process begins with the generation of primary electrons from the bottom plate of the rectangular waveguide during the first period of the EM field following a uniform distribution. Uniform distribution is implemented here because there is no immediate reason to give unequal likelihoods to the possible emission positions within the waveguide. Each electron is emitted with an energy distribution of 2 eV at a velocity perpendicular to the emission surface. The EM field distribution for the TE_{10} dominant mode rectangular waveguide structure was computed using the equations

$$E_y = E_0 \sin\frac{\pi x}{a}\cos(\omega t - \beta z) \quad (1)$$

$$H_x = -\frac{E_0}{Z_{TE}}\sin\frac{\pi x}{a}\cos(\omega t - \beta z) \quad (2)$$

$$H_z = \frac{jE_0}{\eta}\left(\frac{\lambda}{2a}\right)\cos\frac{\pi x}{a}\cos(\omega t - \beta z) \quad (3)$$

Fig. 1 shows a typical TE_{10} mode configured rectangular waveguide indicating also the directions of the electric field, magnetic field and EM wave propagation. *a* and *b* are the *a*-side and *b*-side dimensions of the waveguide respectively. E_y, B_x and B_z represent the electric field component in the *y*-axis, magnetic field component in the *x*-axis and magnetic field component in the *z*-axis respectively. Other EM field components such as E_x, E_z, and B_y are not represented because for the TE_{10} mode they have values of zero (0) and so do not affect the electron dynamics.

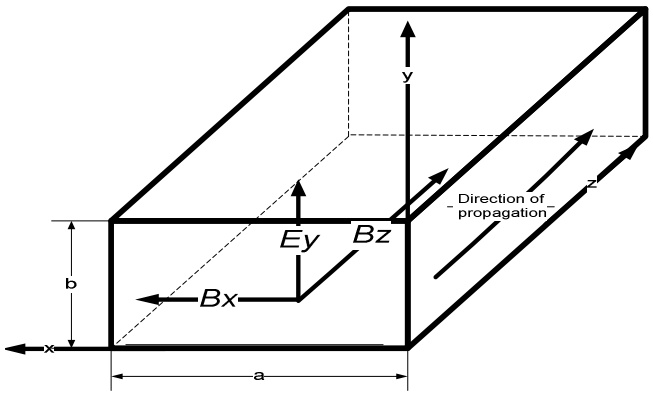

Fig. 1. TE_{10} mode EM field configurations in a rectangular waveguide indicating the directions of the electric field, magnetic field and EM wave propagation

To compute and analyze the electron trajectory, the 4th Order Runge-Kutta method was used to solve the non-relativistic Lorentz force equation which is expressed as

$$\boldsymbol{F} = m_e\frac{d\boldsymbol{v}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}) \quad (4)$$

$$\begin{cases}\frac{d\boldsymbol{v}}{dt} = \frac{-e}{m_e}(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}) \\ \boldsymbol{v} = \frac{d\boldsymbol{R}}{dt}\end{cases} \quad (5)$$

The 4th Order Runge-Kutta and the Adam-Bashforth and Adam-Moulton (AB-AM) predictor-corrector methods provide the best accuracy though at the expense of computational speed which was not a priority consideration in the research. However, because the AB-AM predictor-corrector method possesses the disadvantage of not being self-starting and also more tedious to program, the 4th Order Runge Kutta method was selected as the preferred technique for computing and analyzing the electron trajectory.

Fig. 2 shows the trajectory of an electron just before impact with a wall surface. The pre-impact position, *k*, is given as (X_p-

$_{l}$, Y_{p-l}, Z_{p-l}) and the impact position, *f*, is given as (X_p, Y_p, Z_p). The electron trajectory is both vertical and horizontal. The vertical distance covered from the pre-impact position to the impact position is the change in *y*-coordinate. The difference between the *y* coordinates is extremely small and so may be assumed to be a straight line. Therefore, the angle of impact, Φi, is computed as

$$\Phi_i = \tan\left[\frac{hypot(X_p - X_{p-1}, Z_p - Z_{p-1})}{Y_p - Y_{p-1}}\right] \quad (6)$$

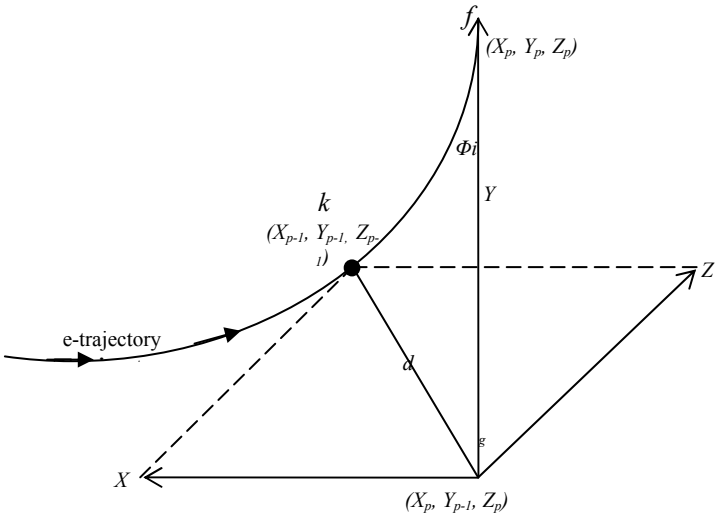

Fig. 2 Determination of angle of impact Φi

To compute the total SEY, this work combined the Geng SEY model [10] shown in eqn. (7) with Poisson distribution in order to determine the proper average number of true secondary electrons generated per impacting electron. This modified approach is preferred because due consideration is given to the probability that a collision does produce true secondary electrons and also to the probability for this collision to produce a certain number of true secondary electrons.

$$\delta(u) = \delta_m\left(\frac{1-\exp[-\mathrm{A}(\mathrm{u}/u_m)^{\mathrm{B}}]}{C(\mathrm{u}/u_m)^D}\right) \quad (7)$$

Parameter u is the impacting energy (in eV) of the primary electron, δ_m is the maximum SEY corresponding to an impacting energy of u_m and the curved fitted *ABCD* parameters are A = 1.55, B = 0.9, C = 0.79, and D = 0.35. In addition, this modified Geng model is combined with a secondary emission probability distribution proposed by [11] in order to properly account for reflected (elastic and inelastic) electrons in the multipacting process. Both elastic and inelastic collisions produce one emitted electron. In the first case, the incoming electron is perfectly reflected. In the second case, the electron penetrates into the material, one electron scatters from atoms inside the material, and is reflected out with energy loss.

Because the emissions considered in this work take consideration of true secondary and reflected electrons, different models were used for computing their emission energy distributions making use of the principles of conservation of energy and material work function. References [8] and [12] explain that the distribution of the true secondary electron emission energies is largely independent of the primary electron energy. The first of the *n* secondaries is assigned the maximum possible energy [13],

$$E_{s,max} = \frac{wkfn}{3} \quad (8)$$

and for the following ones computed by

$$E_s(next) = E_s(previous) - E_s(previous) * random\ value \quad (9)$$

where parameter E_s is the emission energy of the secondary electron and $wkfn$ is the work function of the coating material on the wall surface; the *random value* is generated using a Gaussian probability distribution. The elastically reflected secondary electron retains the same energy as that of the primary electron that generated it. Thus,

$$E_s = E_p \quad (10)$$

An inelastic collision with a wall surface result in a percentage of the impact electron energy being transferred (lost) to the impacted atom [12]. Because the atom is massive with respect to the electron, it barely recoils and the electron reflects with a velocity nearly equal in magnitude to its incident velocity. The transferred energy is a function of the ratio of the masses of the electron and impacted atom, and the velocity of the impacting electron [14][15]. This is given as

$$E_{transferred}(eV) = \left(4 * \left(\frac{m_e}{m_{atom}}\right) * \frac{1}{2} m_e {v_e}^2\right)/e \quad (11)$$

Hence, on reflection, the energy of the emitted electron is computed as

$$E_s = E_{impact} - E_{transferred} \quad (12)$$

This model provides a better approach to determining the emission energy of an inelastically reflected electron when compared to other approaches offered by some researchers which neither takes into consideration the ratio of masses of the electron and the impacted atom nor the velocity of the impacting electron.

III. THE ALGORITHM CODE IMPLEMENTATION

Simulation scenarios in this research work were run on an Intel Core 2 Duo CPU with a maximum computational/processing speed of 1.6 GHz with a 2GB memory size. This computational resource is inadequate when compared to high power, high speed and large volume memory computing systems used in advanced laboratories for running MP simulation scenarios. Because of this limitation, iterations were limited to only 10-gap crossings in some

simulations. Though, some researchers recommend 20-gap crossings [16], 10-gap crossing is still acceptable [10].

The simulation code was implemented using the MATLAB software. Electron gap crossings were limited to 10-gap crossings, given the limited computational resource. In spite of this limited number of crossings implemented, the quantity of emitted virtual electrons was so large at certain power levels that the computer memory could no longer handle the computation involved. Consequently, the computer system would display an "inadequate memory" error message and then stall further computation. Under this circumstance it was difficult to predict what the quantity of emitted virtual secondary electrons would be at the 10^{th} iteration. To overcome this particular challenge, an extrapolation technique was applied to enable the determination of what could be the possible population size of the emitted virtual electrons at the end of the 10^{th} iteration. The extrapolation technique employed used a growth function which uses existing data to calculate predicted exponential growth. The growth function was preferred to other extrapolation function types such as forecast function, trend function, linest function, longest function and slope function because, similar to the growth of emitted electrons, its implementation used an exponential model. MS Excel Spreadsheet has an implementation of this function and so was used for the extrapolation process.

Validation

The result obtained by [10] during an experimental research on MP prediction and suppression on a niobium (*Nb*) coated rectangular waveguide surface is shown in fig. 3. The result shows the values of the normalized enhanced counter function (*Nen*) for power levels from 0 kW to 500 kW at 500 MHz operating frequency for 10-gap crossings. The results generated by the proposed MP prediction algorithm in this article were compared with those obtained by [10] for both 10- and 20-gap crossings; they were found to be in agreement. Figs. 3 and 4 show the plots of normalized enhanced counter values (*Nen*) against the forward power levels (kW) for 10-gap crossings.

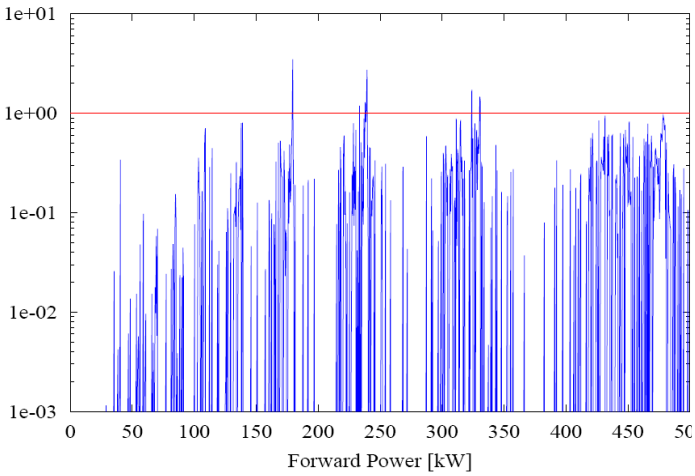

Fig. 3. The normalized enhanced counter function Nen_{10} for the TW mode. The Nen_{10} = 1 line is indicated. Ref: [10].

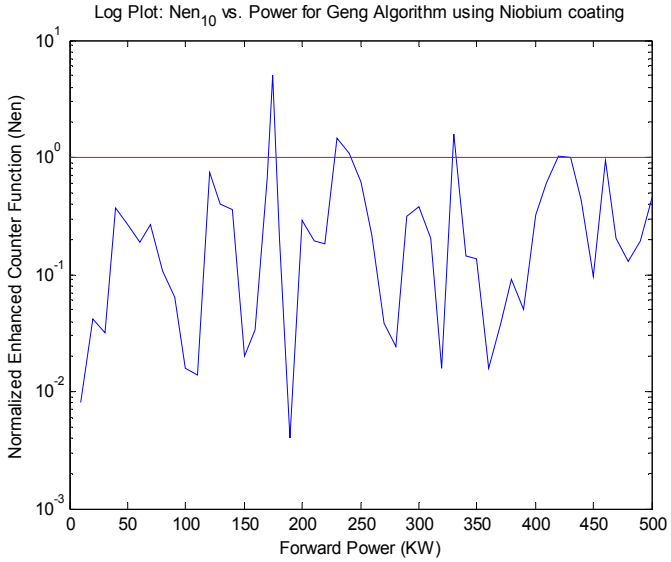

Fig. 4. The relative enhanced counter function Nen_{10} for the TW mode. The Nen_{10} = 1 line is indicated.

IV. RESULTS AND ANALYSIS

Following the validation of the proposed MP algorithm, two simulation scenarios were implemented for 0 kW to 500 kW at 500 MHz operating frequency: (i) Silver coating with the ***exclusion*** of Reflection electrons, and (ii) Silver coating with the ***inclusion*** of Reflection electrons.

The first scenario involved the use of silver coating with the exclusion of reflection electrons, meaning that inelastic and elastic electrons were not accounted for. So, only true secondary electrons were assumed to be emitted from the metal surface. The result obtained from this simulation is shown in fig. 5.

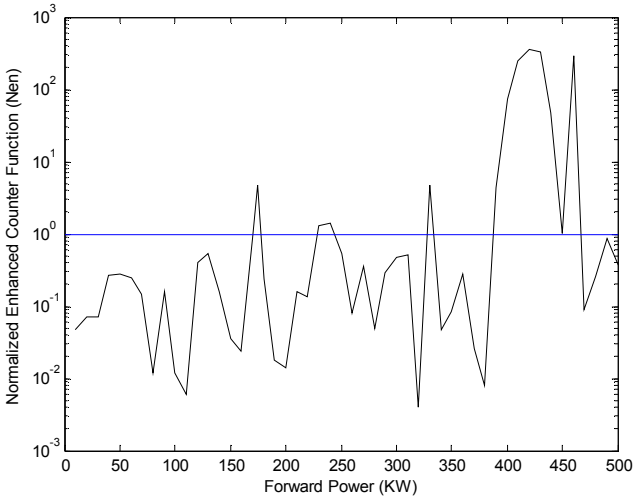

Fig. 5. Plot of *Nen* vs. Transmit power level without consideration for reflected electrons

The second scenario also involved the use of silver coating but with the inclusion of reflection electrons; that is, in addition to the true secondary electrons, inelastic and elastic electrons were also accounted for. The result obtained from this

simulation is shown in fig. 6. It was observed that, in addition to all the possible MP initiating power levels obtained from the first simulation scenario, one additional power level, 120 kW, also indicated the possibility of MP initiation. The only explanation for this is that the reflected electrons which had not been considered in the first simulation scenario contributed to this MP initiation process. This shows that it is possible to overlook a subtle breakdown power (such as 120 kW in this case) if reflected electrons are not properly accounted for.

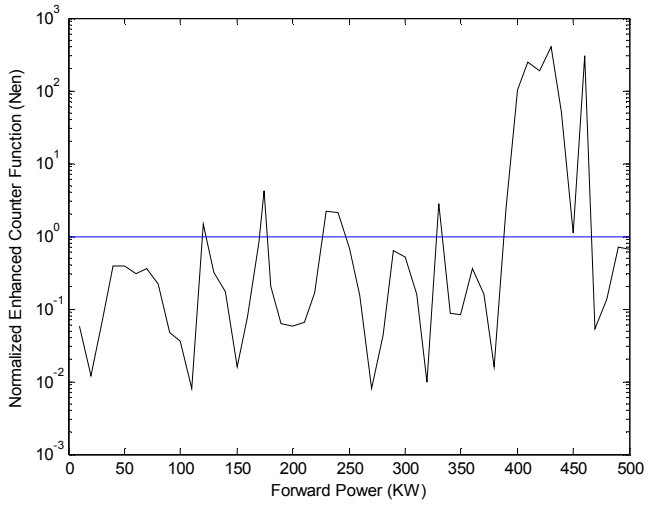

Fig. 6. Plot of *Nen* vs. Transmit power level with consideration for reflected electrons

V. CONCLUSION

This work implemented an MP prediction algorithm which considered reflected electrons during the design process. Results of simulation scenarios ran using the algorithm suggests that it is absolutely crucial to account properly for reflected electrons during a multipacting process investigation in order to avoid undermining the actual quantities and types of "emitted" electrons present in a system after consecutive electron-wall impact events in addition to overlooking subtle breakdown powers. These points are critical as they guarantee improved reliability against MP initiation within rectangular waveguides that work under multiple power operations.

Future work on the subject of multipactor prediction should develop retrace algorithms with the capability to predict (identify) critical points of electron emission which can result in MP initiation and possibly system breakdown or failure. This information is important as it may be used to optimize the suppression procedures on the geometries of interest, hence reducing the manufacturing resource requirement for space-borne waveguides.

ACKNOWLEDGMENT

We acknowledge and appreciate the National Space Research and Development Agency (NASRDA), Abuja, Nigeria, for providing the opportunity to engage in this research.

REFERENCES

[1] E. Sorolla, A. Sergio, G. Benito, M.P. Antonio, C. Vicente, J. Gil, F. J. Pérez-Soler, F.D. Quesada, A. Álvarez, and V.E. Boria, "An Analytical Model to Evaluate the Radiated Power Spectrum of a Multipactor Discharge in a Parallel-Plate Region", Departamento de Comunicaciones, Instituto de Telecomunicaciones y Aplicaciones Multimedia, Universidad Politécnica de Valencia, 46022 Valencia, Spain, 2008.

[2] R. Udiljak, D. Anderson, P. Ingvarson, U. Jordan, U. Jostell, L. Lapierre, G. Li, M. Lisak, J. Puech and J. Sombrin, "New method for detection of multipaction", *IEEE Trans. Plasma Sci.*, vol. 31, no. 3, pp. 396–404, Jun. 2003.

[3] H.M. Li and Z.J. Ding, "A Monte Carlo Simulation of Secondary Electron and Backscatrered Electron Images in Scanning Electron Microscopy", Acta Metallurgica Sinica, Vo1. 1 8 No. 3, pp 351-355, 2005.

[4] L. Yinghong and D.C. Joy, "A New Examination of Secondary Electron Yield Data", Surface and Interface Analysis, Surf. Interface Anal., Published online inWiley InterScience (www.interscience.wiley.com), vol. 37: pp. 895–900, 2005

[5] European Cooperation for Space Standardization, *Multipaction Design and Test*, ESA Publications Division, pp. 39-50., 2003.

[6] R.L. Geng, S. Belomestnykh, H. Padamsee, P. Goudket, D.M. Dykes, R.G. Carter, *Studies of Electron Multipacting in CESR Type Rectangular Waveguide Couplers*, Proceedings of EPAC, pp. 1057-1059, 2004.

[7] Crossed-Field Amplifier with Multipactor Suppression", World Intellectual Property Organization (WIPO), http://www.wipo.int/pctdb/en/wo.jsp, 2011.

[8] C. Vicente, M. Mattes, D. Wolk, H.L. Hartnagel, J.R. Mosig and D. Raboso, "FEST3D-A Simulation Tool for Multipactor Prediction", *Proc. MULCOPIM 2005*, ESTEC-ESA, Noordwijk, The Netherlands, 2005, pp. 11-17, 2005.

[9] C. Nieter, C.M. Roark, P.H. Stoltz and K. Tian, "Benchmarking Multipacting Simulations in Vorpal", Proceedings of PAC09, Vancouver, BC, Canada, 2009, pp. 1-3., 2009

[10] R.L. Geng and H.S. Padamsee, "Exploring Multipacting Characteristics of a Rectangular Waveguide", Proceedings of Particle Accelerator Conference, New York, NY., Vol. 05, pp. 429, 1999

[11] L. Juan, P. Francisco, A. Manuel, G. Luis, M. Isabel, R Elisa and R.G. David, "Multipactor Prediction for On-Board Spacecraft RF Equipment with the MEST Software Tool", IEEE Transactions on Plasma Science, Vol. 34, No. 2, 2006.

[12] R. Seviour, "The Role of Elastic and Inelastic Electron Reflection in Multipactor Discharges", IEEE Transactions on Electron Devices, VOL. 52, NO. 8, AUGUST 2005 1927, pp. 1927-1930, 2005.

[13] G. E. Becerra, *Studies of Coaxial Multipactor in the Presence of a Magnetic Field*, U.S. Department of Energy Report, Plasma Science and Fusion, Vol. 99, pp 26-41, 2007.

[14] L.D. Landau and E.M. Lifshitz, *Mechanics: Course of Theoretical physics*, 3rd Ed., vol. 1, Butterworth and Heinemann Publication, pp. 41-53, 2000.

[15] P. M. Bellan, *Fundamentals of Plasma Physics*, pp. 14-16, 2004

[16] S. Anza, M. Mattes, J. Armendariz, J. Gil, C. Vicente, B. Gimeno, V. E. Boria, J.R. Mosig, D. Raboso, "RF breakdown prediction for microwave passive components in multicarrier operation", Ultra-Wideband, Short Pulse Electromagnetics 9, ISBN 978-0-387-77844-0. Springer Science Business Media, LLC, p. 375, 2010

AKOMA Henry E.C.A is a research engineer with the National Space Research and Development Agency (NASRDA), Abuja, Nigeria, and is currently engaged in his doctoral degree program at the University of Ilorin, Ilorin, Nigeria. He obtained a Master of Engineering (MEng) degree in Electrical Engineering (Communications Option) with Distinction from the Federal University of Technology, Minna, Nigeria. . He has published a book on the Fundamentals of Space Systems Engineering and has published several journal and conference papers particularly in the field of multipaction. Engr Akoma Henry E.C.A is a Registered Engineer, Council for the Regulation of Engineering in Nigeria (COREN). He is also a member of the Nigerian Society of Engineers (MNSE).

ADEDIRAN Yinusa Ademola is a professor of Electrical and Electronics Engineering presently is the head of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Ilorin. He Obtained

Doctor of Philosophy, Federal University of Technology, Minna, Nigeria , Master of Science (M.Sc.) in Industrial Engineering University of Ibadan and Master of Science (M.Sc.) in Electrical Engineering (Telecommunications Option) with Distinction, Technical University of Budapest, Hungary. He has published seven (7) books including Reliability Engineering, Telecommunications: Principles and Systems (First Edition), Fundamentals of Electric Circuits, Introduction to Engineering Economics, Applied Electricity, and Telecommunications: Principles and Systems (Second Edition) and Fundamentals of Electric Circuits. The author has published over 70 journals, Conferences and manuscripts in Electrical & Electronics Engineering. Professor Yinusa Ademola Adediran is a Registered Engineer, Council for the Regulation of Engineering in Nigeria (COREN). He is a member of several professional society including Fellow, Nigerian Society of Engineers (FNSE),Member, Institute of Electrical & Electronic Engineers, USA (MIEEE), Corporate Member, Nigerian Institute of Management, Chartered (MNIM),Member, Quality Control Society of Nigeria (MQCSN).