

White Paper on Multicarrier Excitation of Multipactor Breakdown: A Survey of Current Methods and Research Opportunities

June 18, 2015

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Prepared for:

National Reconnaissance Office
14675 Lee Road
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Contract No. FA8802-14-C-0001

Authorized by: Engineering and Technology Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement Workshop.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 18 JUN 2015		2. REPORT TYPE Final		3. DATES COVERED -	
4. TITLE AND SUBTITLE White Paper on Multicarrier Excitation of Multipactor Breakdown: A Survey of Current Methods and Research Opportunities				5a. CONTRACT NUMBER FA8802-14-C-0001	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Preston T. Partridge				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation 2310 E. El Segundo Blvd. El Segundo, CA 90245-4609				8. PERFORMING ORGANIZATION REPORT NUMBER TOR-2015-02548	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Reconnaissance Office 14675 Lee Road Chantilly, VA 20151-1715				10. SPONSOR/MONITOR'S ACRONYM(S) NRO	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT 2015 MAIW Product					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Executive Summary

Multipactor breakdown is a failure mode that occurs in RF systems and system components that operate in a vacuum. For component and system verification, multipactor is treated as a peak field and voltage phenomena where the verification power level is chosen such that the maximum instantaneous operational voltage in the component is excited. In a single carrier system, this power level is fairly straightforward to determine. However, for RF components exposed to multiple distinct signals simultaneously, there are a variety of methods used to address multipactor breakdown verification.

This white paper describes methods of assessment and possibly to mitigate multipactor for spacecraft components in multiple carrier systems [1]–[3]. The methods described in this paper highlight existing approaches used in the U.S. space industry. This paper serves as a survey of current practice and is not meant to be used as a set of requirements. This document will also highlight the advantages and limitations of the various methods currently in use.

This document will also reference new analysis methods under investigation for multicarrier excitation threshold prediction based on a survey of the research literature. In general, this topic is in need of additional basic and applied research and validation in order to further improve industry understanding prior to application.

Acknowledgements

The creators of this document were part of the Mission Assurance Improvement Workshop (MAIW). The team was co-led by James Farrell, The Boeing Company; Preston Partridge, The Aerospace Corporation; and Dr. Jeffrey Tate, Raytheon Space and Airborne Systems.

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The topic team would also like to acknowledge the contributions and feedback from the subject matter experts who reviewed the document prior to publication:

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1. Criteria for Evaluation of Definitions

The following criteria have been agreed upon as reasonable measures when establishing which methods to apply in a given set of analytical and/or test conditions. These criteria are by definition somewhat objective and discretion is advised in their application. The (proposed) basic criteria for establishing the applicability of a particular multi-carrier multipactor excitation method are:

- Ability to establish reasonable threshold definitions for power, transit time, and frequency of operation for the situation under investigation as appropriate to the method (e.g., P_{20} , T_{20} , mean frequency)
- Is the method readily amenable to analysis/test for the structure under investigation (e.g., availability of tools, simplicity of analysis...)?
- Can valid inputs be established for use of the method (e.g., number of carriers, carrier phasing, and method for carrier combination)?
- Consistency of results obtained
- Ability to understand and interpret results obtained
- Are results too restrictive or too lenient?

2. System Engineering Definitions and Guidelines

2.1 System Frequency and Power Definitions – Current Industry Practices

2.1.1 N²P Method

2.1.1.1 Description

The N²P method assumes that all carriers will phase such that the maximum instantaneous peak voltage is created. This peak voltage is converted to an equivalent CW power level, which is used as the verification threshold. Realizing this effective power level in the device is of extremely low probability given that generally the carriers start with random phases.

The advantage of this method is that it is understood across the industry to be a bounding condition.

2.1.1.2 Limitations

- Conservative: N²P only occurs for an instant in time, not enough electron crossings to develop sufficient electron density
- As the number of carrier signals increases, the power thresholds grows quadratically resulting in unreasonable test configurations and potentially unattainable power levels.

2.1.2 PX/TX Methods

2.1.2.1 Description

These power definitions are based on the multipactor gap rule. In general this rule states that the power level threshold (P_x , e.g., P_4 or P_{20}) for multipactor is determined by the transit time required (T_x , T_4 or T_{20}) for an electron (bunch) to cross the structure gap. It is typically assumed that the

geometry of the structure consists of two parallel surfaces (e.g., in a parallel plate waveguide or coaxial structure). The basic formula for the transit time is provided below,

$$T_x = \frac{Xn}{2f}$$

Where X = number of gap crossings (e.g., 4 or 20), n = the multipactor order and f is the signal operating frequency. The value for the operating frequency typically used can depend on the application but is typically the mean or average frequency of the multi-carrier signals being transmitted. In some cases, according to the literature [1], the lowest frequency of the operating bandwidth is used. For the special case of equally-spaced carrier frequencies the formula for the transit time takes the form,

$$\frac{T_x}{T_e} = \frac{Xn}{2} \left(\frac{\Delta f}{f} \right)$$

Where Δf is the carrier frequency separation and T_e is the time period for the modulation envelope. The basic form of the power threshold definition is then derived by an analysis of the carrier envelope in the time domain. This determines the amount of time the envelope exceeds the desired signal power or voltage threshold. An example of this situation for a five-carrier signal is provided below in Figure 1 from Anza et al., [1]

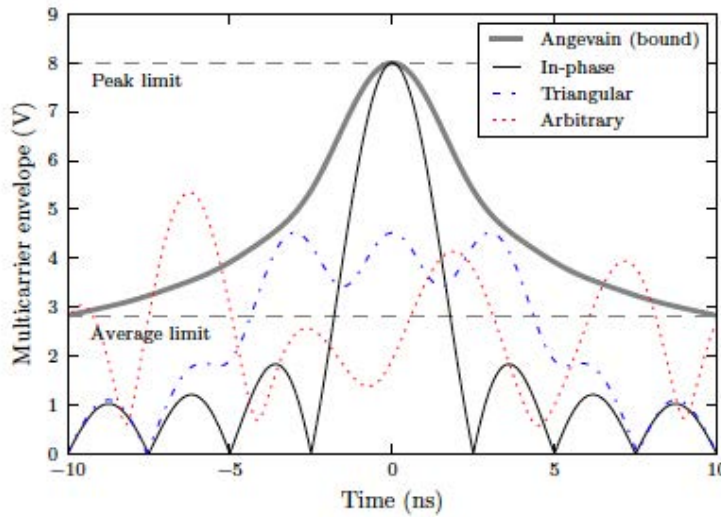


Figure 1

The threshold level for multipactor excitation is determined by aligning the peak limit line to the maximum level on the main lobe of the signal envelope. In the case above in Figure 1, the peak and average power limits are shown. The modulation envelope will of course depend on the method of combination for the carrier phases. Typically, an optimization method is used for phase combining which results in a particular modulation envelope in the time domain. Several example phase combinations are shown in Figure 1. The user will need to determine the method or algorithm for phase combination most consistent with their application. Figure 2 shows examples for a fifteen-carrier case with two different frequency separations to demonstrate this impact this parameter can have on the carrier envelope.

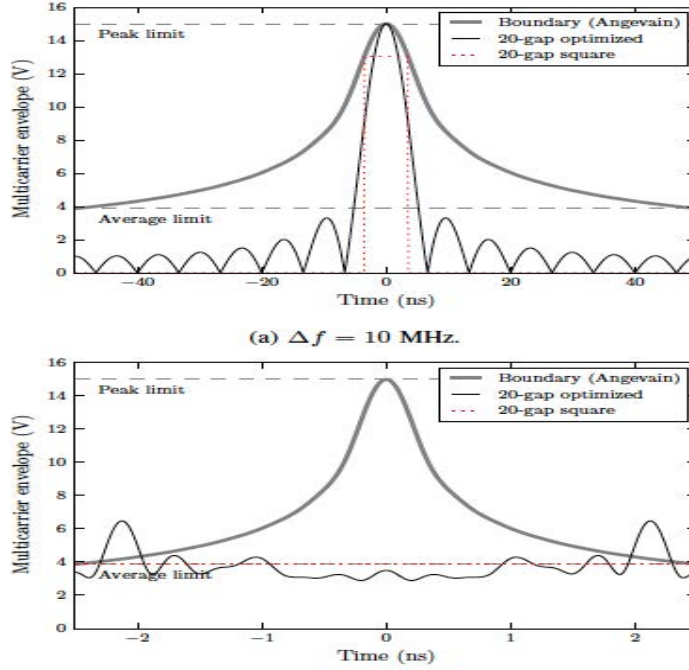


Figure 2

In Figure 2, we see how the carrier separation will impact the amount of time above the signal threshold [1]. This example also demonstrates the relationship between the transit time for gap crossings and the envelope period. The magnitude of the ratio T_x/T_e from reference [1] depends on the carrier separation. This condition will determine whether the gap rule will produce a result with positive or zero multipactor margin.

The advantages of the gap crossing rules include:

- Well established method
- Defines a criterion for a single multi-carrier peak power threshold

2.1.2.2 Limitations

- Requires knowledge of the critical gap size to establish the required breakdown threshold
- These rules only consider electron growth over a single period
- They do not account for inter-period charge growth
- The results are dependent on the main lobe level of the modulation envelope (time to exceed threshold)
- The results depend on the carrier separation, leading to very conservative (extreme positive margin) or very lenient performance (zero margin) against multipactor excitation

2.1.3 Total Average Power

2.1.3.1 Description

The total average power definition for multicarrier excitation of multipactor is based on the number of carriers N multiplied by the peak power level for each carrier P . For example, in the case of 12 carriers with 60 W peak power for each carrier the total average power threshold would be 720 W. The other parameters in the definition include,

- Frequency: worst-case in band
- Same calculation regardless of frequency band, carrier spacing, or modulation
- 3 dB multicarrier derating to account for phasing, independent of margin

The applicability of this method is covered by the following criteria

- The number of carriers is greater than or equal to 5 ($N \geq 5$)
- The carriers are assumed to be randomly phased
- This method does not necessarily apply to closely spaced channels

The advantages of this method include:

- Simple to apply and use
- Decades of heritage in its use
- Based on a statistical analysis of randomly phased peaks

2.1.3.2 Limitations

The disadvantage of this method is that it is not a fully generalized approach based on the limited guidance for carriers greater than 5. This limits the potential applicability (increases risk) for frequency plans that require a larger number of carriers.

2.2 Future Approaches and Methods

Our current understanding of the methods for analyzing multicarrier excitation of multipactor requires new research. Future work in this area is needed to address the open questions that remain about the optimal usage of existing approaches. Recommendations for such application will not be possible without new research into physical mechanisms, the impact of signal modulation design, methods for carrier phase combination as well as materials properties. In this section we outline the current efforts in some of these areas. The reader is referred to the literature for a more comprehensive review on this topic.

2.2.1 Statistical Methods

2.2.1.1 Description

For the statistical approach, the goal is to apply a mathematical method for a more realistic phase combination of the carriers in a multicarrier signal. This accounts for the statistical nature in which

phased carriers will combine in actual operation. This method is not directly or solely dependent on a transit time rule and is not limited in the number of carriers that can be considered.

The basic statistical approach involves running a large number of cases with the carrier starting phases treated as a random variable. This is similar to the development of a digital symbol sequence.

Using this method, the durations that the modulation peaks exceed a chosen threshold would determine the likelihood of multipactor excitation. The use of complex multicarrier signals with arbitrary random phase to simulate the excitation of multipactor requires proper modeling of the excitation process physics to address the statistical impact of the waveforms on electron population growth and dynamics. Research to develop these modeling approaches is still very active [1][4][7] and [8].

Advantages include:

- A realistic accounting for carrier phase combinations
- The method is based on a mathematical approach that is amenable to scientific verification
- Leads to more applicable, realistic bounding cases
- Bounding curves can be easily generated

2.2.1.2 Limitations

- Requires anchoring to an existing method where margins are not consistent (i.e., the T_x rule outlined in Section 2.1.2)
- Additional research is required in order to generalize this method for arbitrary modulation schemes and for test validation.

2.2.2 New Research in Quasi-stationary Methods

Research to increase our understanding of the impact of multicarrier signals on electron dynamics has been carried out in recent years [6]–[9]. This includes the development of a non-stationary theory to provide a more general model of the electron dynamics. Recent work also includes a framework for the analysis of multipactor excitation under non-resonant polyphase conditions. This approach works to overcome some of the limitations of earlier methods which simulate the multi-carrier signal as a single-carrier signal with a modulated pulse signal envelope. The previous method results in questions about the proper modeling of electronic charge accumulation during inter-pulse periods (pulse-off/dwell times).

Recent work in the area of quasi-stationary signal characterization has been undertaken as another alternative to the gap crossing approaches mentioned above in Section 2.1.2. These methods involve the use of a non-stationary approach to model the multipactor electron dynamics as well as characterizing the electron-surface absorption processes. Both resonant and non-resonant multipactor processes can be modeled using this technique. A key element of the new theory is to model the secondary electron velocity as a random variable. A probability distribution function (e.g., a Maxwellian distribution) is used to model the electron emission velocities during the initiation and duration of the multipactor processes. This results in a distribution of electron phases, impact energies and multipactor orders as described in Anza, et al. [8]. The new methods of Anza et al. introduce random variables for additional parameters that directly model the electron dynamics to model the physics of the multipactor process. This is distinct from solely modeling the signal characteristics of

the multipactor process by assigning only the signal phase as a random variable. Additional research (analytical and experimental) is required to determine the validity and applicability of these various approaches.

3. Risk Profile

Based on the results of a tailoring exercise and agreement from the engineering and customer communities, a risk profile should be developed that carefully outlines the impacts to the system and program based on the choice of a particular multicarrier definition. This should include an assessment of the inputs and results of the tailoring process and fully account for the impact of both advantages and disadvantages of the method chosen.

4. References

1. Anza, S. et al., Multipactor Prediction with Multicarrier Signals: Experimental Results and Discussions on the 20-gap-crossing Rule, 8th European Conference on Antennas and Propagation (EuCAP), 2014, pp. 1638 – 1642.
2. Geissler, K. H., and D. Wolk, Multipactor Testing of Multiplexer and Waveguide Components Exposed to Multicarrier Loading, pp. 194 – 198.
3. Marrison, A., et al., A Study of Multipaction in Multicarrier RF Components, ESTEC, January 1997.
4. Rasch J., and J. F. Johansson, Non-resonant Multipactor – A Statistical Model, Physics of Plasmas, v. 19, p. 123505, 2012.
5. Agilent Technologies, Characterizing Digitally Modulated Signals With CCDF Curves, Application Note 5968-6875E.
6. Anza, S., C. Vicente, J. Gil, M. Mattes, D. Wolk, U. Wochler, V. E. Boria, B. Gimeno, and D. Raboso, Prediction of Multipactor Breakdown for Multicarrier Applications: The Quasi-Stationary Method, IEEE Transactions on Microwave Theory and Techniques, v. 60, n. 7, July 2012
7. Anza, S., M. Mattes, C. Vicente, J. Gil, D. Raboso, V. E. Boria, and B. Gimeno, Nonstationary Statistical Theory of Multipactor, Physics of Plasmas, v. 18, p. 032105, 2011.
8. Anza, S., C. Vicente, J. Gil, V. E. Boria, B. Gimeno, and D. Raboso, Nonstationary Statistical Theory of Multipactor, Physics of Plasmas, v. 17, p. 062110, 2010.
9. Anza, S., C. Vicente, B. Gimeno, V. E. Boria, and V. E. Boria, Long-term Multipactor Discharge In Multicarrier Systems, Physics of Plasmas, v. 14, p. 082112, 2007.

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External Distribution

REPORT TITLE

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REPORT NO.	PUBLICATION DATE	SECURITY CLASSIFICATION
TOR-2015-02548	July 31, 2015	UNCLASSIFIED

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