AEROSPACE REPORT NO.
TOR-2015-02540

RF Breakdown Prevention, Part 2 Product Overview

May 7, 2015

Preston T. Partridge
Antenna Systems Department
Communication Systems Implementation Subdivision

Prepared for:

National Reconnaissance Office
14675 Lee Road
Chantilly, VA 20151-1715

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 Program Mission Assurance Improvement Workshop.

AEROSPACE
Assuring Space Mission Success

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
07 MAY 2015	**Final**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
RF Breakdown Prevention, Part 2 Product Overview	**FA8802-14-C-0001**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Preston T. Partridge	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Aerospace Corporation 2310 E. El Segundo Blvd. El Segundo, CA 90245-4609	**TOR-2015-02540**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
National Reconnaissance Office 14675 Lee Road Chantilly, VA 20151-1715	**NRC**
	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

Refrigeration tests were performed on the Sunpower CryoTelÂ® CT cryocooler to provide design inputs prior to a contractorâs payload critical design review. The primary performance matrix was obtained at cold tip temperatures of 60 K, 65 K, and 70 K at heat loads of 3.75 W and 4.5 W. Forced convective air cooling was used to maintain the cryocooler heat rejection temperature at 45Â°C. The cooler required 129.5 W of electrical input power to the thermo-mechanical unit (TMU) to remove 4.5 W from the cold tip at 65 K and 112 W of input power to remove 3.75 W at 65 K. By lowering the heat rejection temperature to 30Â°C, the required TMU power consumption to remove 4.5 W @ 65 K was reduced to 120.3 W. Independent voltage and current measurements were taken to verify the inputs to the vendorâs controller and showed good agreement with the commanded power levels.

15. SUBJECT TERMS
Cryocoolers, Performance Testing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**20**	

Acknowledgments

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.

The other members of the team came from the government and the aerospace industry. For their contributions, we thank the following contributing authors for making this collaborative effort possible:

Rick Bennett	Flight Microwave Corporation
Larry Capots	Lockheed Martin Corporation
Will Caven	Space Systems/Loral
Douglas Dawson	Jet Propulsion Laboratory
James Farrell	The Boeing Company
Bruce Flanick	Northrop Grumman
Aimee Hubble	The Aerospace Corporation
Thomas Musselman	The Boeing Company
Preston Partridge	The Aerospace Corporation
Rostislav Spektor	The Aerospace Corporation
Jeffrey Tate	Raytheon Space and Airborne Systems

Acknowledgments (cont.)

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

Ryan Bentley	Ball Aerospace
Larry Epp	Jet Propulsion Laboratory
Paul Giuliano	The Boeing Company
Steven Gold	Naval Research Lab
Timothy Graves	The Aerospace Corporation
Eric Holzman	Northrop Grumman
Kurt Ketola	Raytheon Space and Airborne Systems
Rolf Kich	Flight Microwave Corporation
Rami Kishek	University of Maryland
Kevin Lim	Flight Microwave Corporation
Jared Lucey	NASA GSFC
Jerry Michaelson	The Aerospace Corporation
Raul Perez	Jet Propulsion Laboratory
Stu Quade	Northrop Grumman
Joseph Roubal	Aeroflex, a Cobham Company
Norman Strampach	Lockheed Martin Corporation
Ghislain Turgeon	Space Systems/Loral
Jian Xu	Aeroflex, a Cobham Company

RF Breakdown Prevention, Part 2

Product Overview

James Farrell, Boeing Satellite Systems
Dr. Jeffrey P. Tate, Raytheon Space and Airborne Systems
Preston Partridge, The Aerospace Corporation

May 7, 2015

Agenda

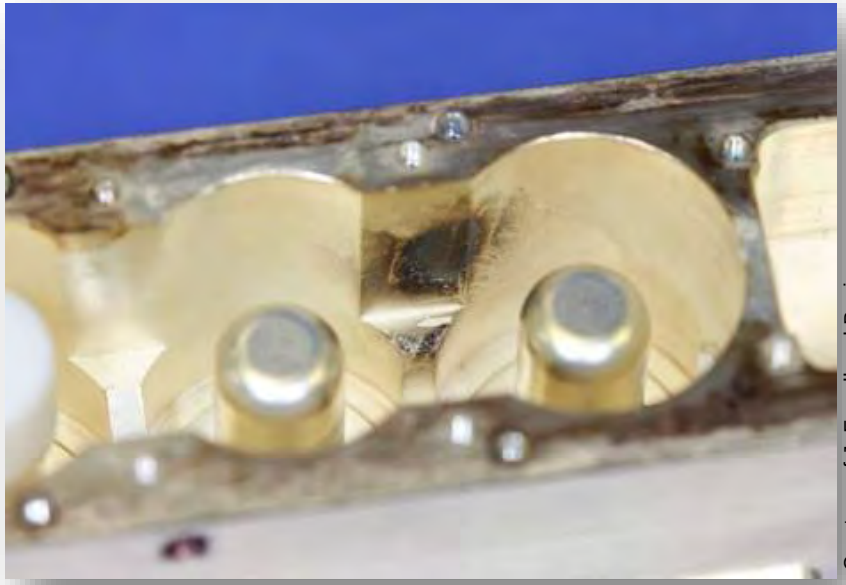
- Issue definition
- Examples
- Motivation for product
- Team charter
- Product overview
- Workshop results
- Topic follow-on recommendations
- Team membership and recognition

RF Breakdown Remains an Issue

- Ionization breakdown (IB) and multipactor have caused multiple failures in RF components
  - *Increasing satellite powers and bandwidth requirements will continue to increase risk*
  - *Consequence of failure ranges from degraded mission capability to complete loss of satellite*
- Significant ground/on-orbit failures on current government and commercial programs
  - *High power filters, isolators, circulators, antenna feeds, switches, etc.*
- Issues currently handled by a few industry experts (many of whom are on the team) and each organization's general guidelines

Courtesy of J. Farrell and Boeing

IB plasma discharge in isolator

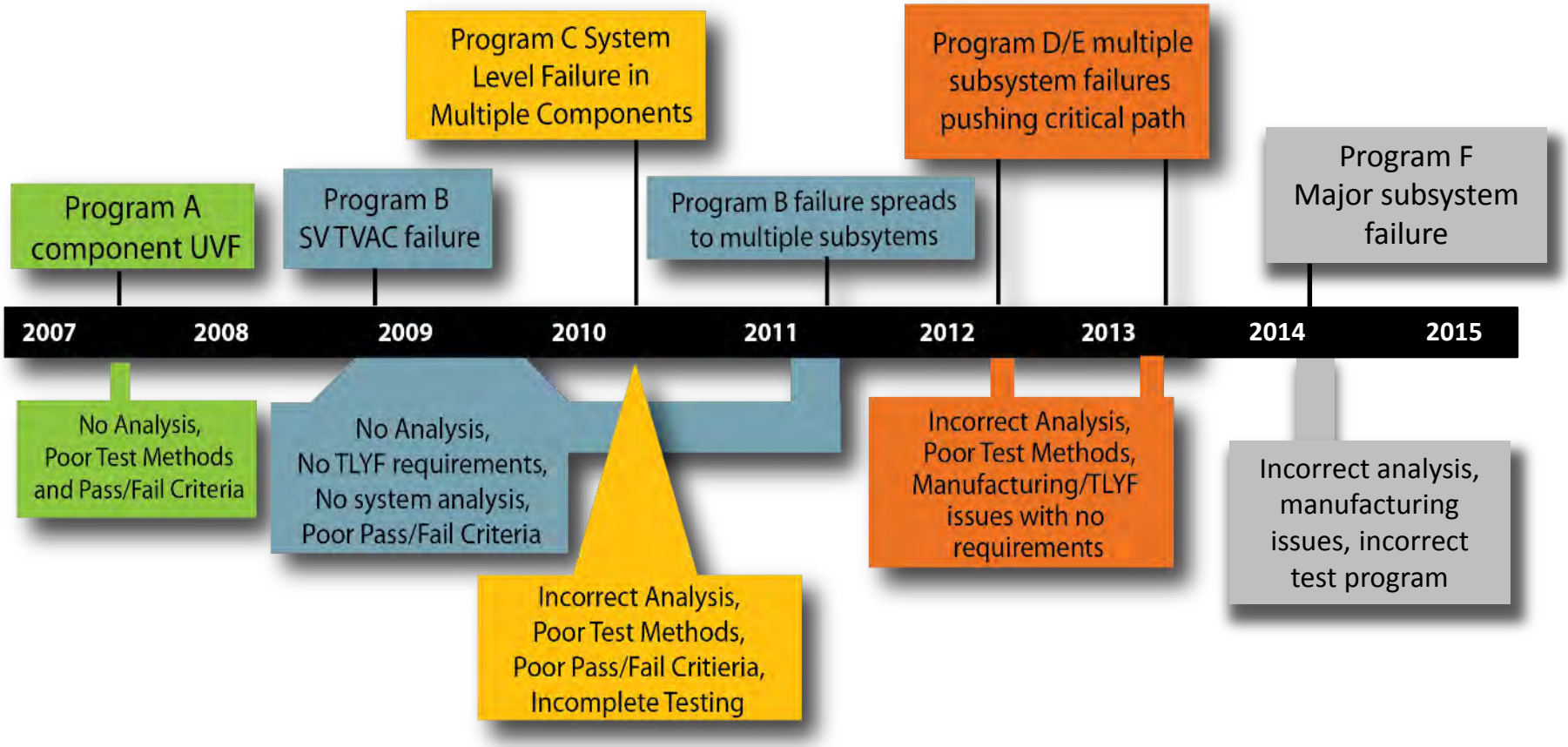


Courtesy of J. Farrell and Boeing

IB damage in cavity filter from test

Timeline of RF Breakdown Issues

- Recall timeline from Year 1 presentation
- Problems continue to arise, requiring deployment of experts



Major program delays and loss of functionality caused by RF breakdown

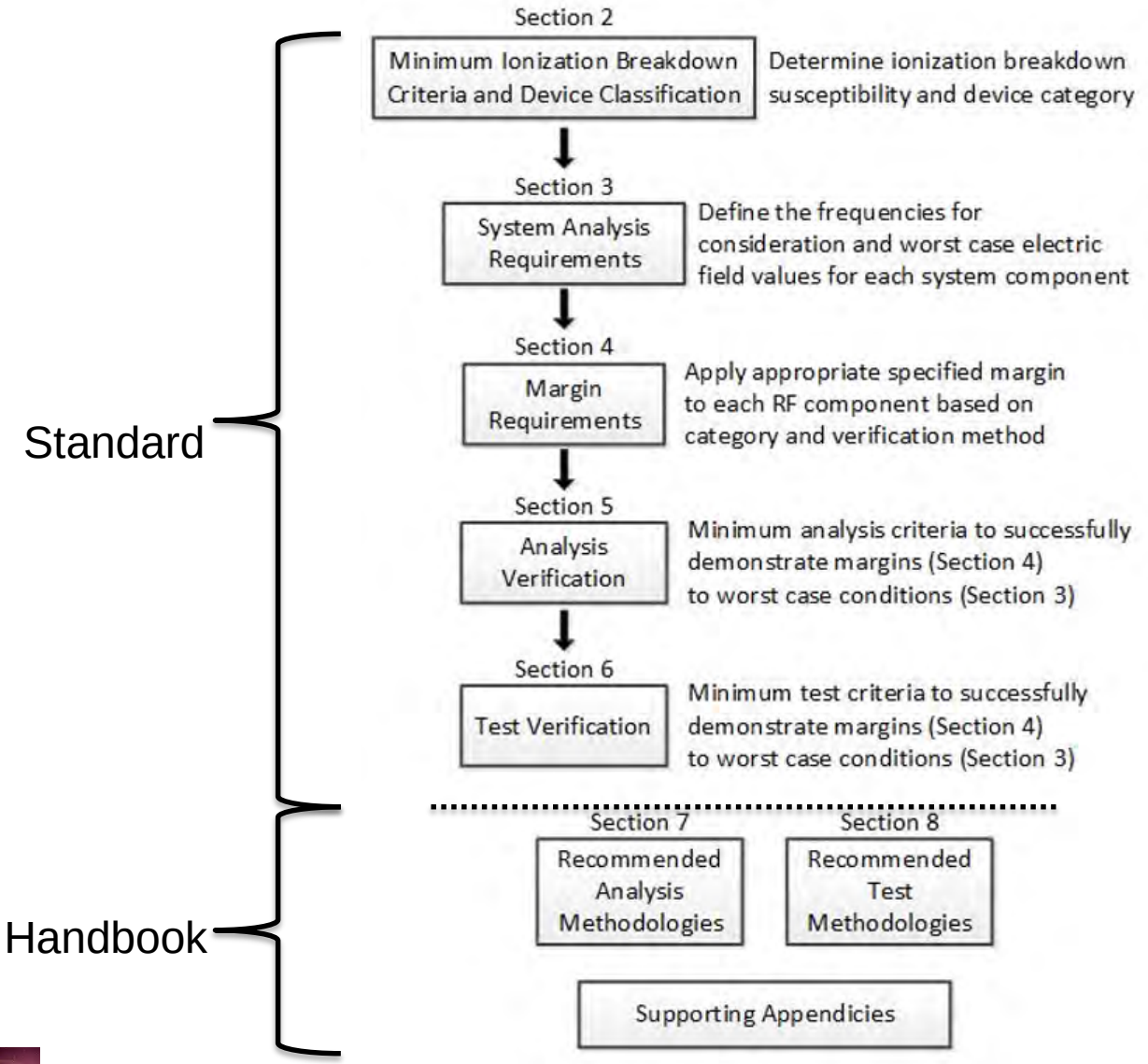
Motivation for RF Breakdown Prevention Standard

- **Ionization breakdown failures on programs affecting mission success**
- Lack of ionization breakdown prevention standard in industry
  - *Best practices for ionization breakdown issues vary widely across the industry*
  - *Standardization of testing, analysis, and requirements development methods needed*
  - *No standard currently exists at the domestic or international levels*
- Existing multicarrier multipactor best practices held by each prime contractor
  - *No scientific consensus on best practices*
  - *However, several widely used methods require clear explanation and documentation in multipactor standard*
- Need to establish forum for ongoing updates and reviews of document after MAIW
  - *Creation of AIAA committee for RF spacecraft components and adoption of TORs into AIAA standards*

RF Breakdown Part 2 Team Charter

- Create draft standard for ionization breakdown prevention
  - *Follow format of Year 1 multipactor document*
  - *Provide analysis and test minimum requirements and guidelines*
- Address multicarrier multipactor by documenting current industry best practices
  - *Provide summary of survey in a TOR*
- Work with AIAA to create RF breakdown committee
  - *Stand up RF spacecraft components committee for enduring maintenance of documents*
  - *Committee to be made up of MAIW team members with additional members form government and academia*

Ionizing Breakdown (IB) Document Overview



IB Device Verification Flow Chart

- Flow charts used for demonstration of processes to qualify/accept a device for ionization breakdown
- References to sections in document in each box

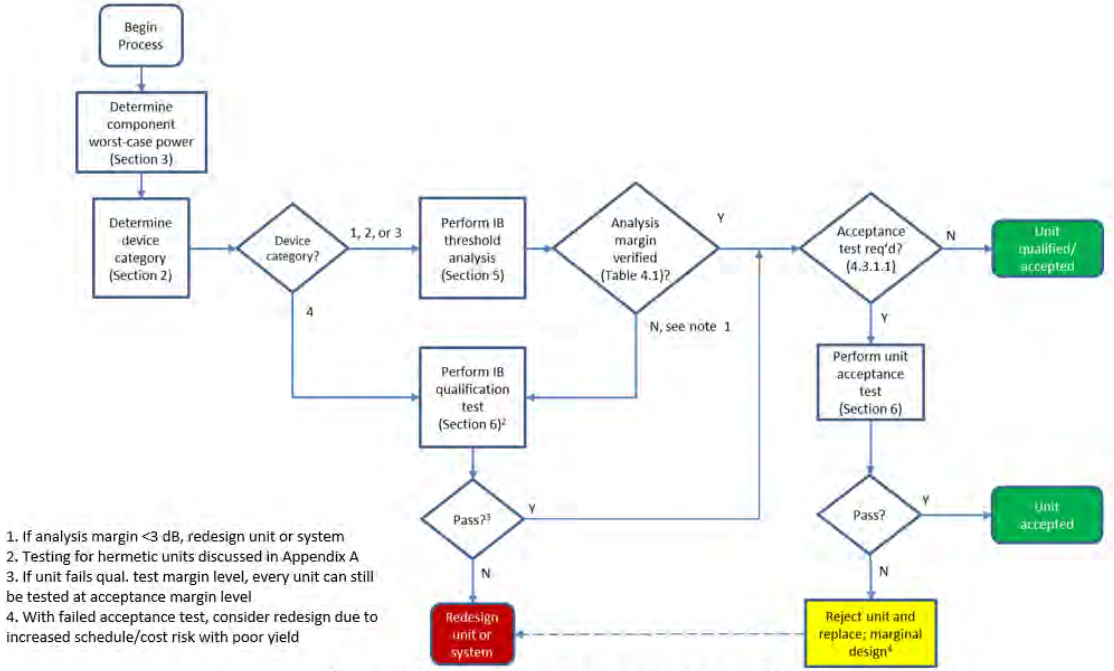


Figure 2.2: Flow chart for margin determination and verification process

IB Device Categories and Margins

- Different methods presented for analyzing different device categories
- Margins to qualification by analysis, qualification by test, and acceptance provided

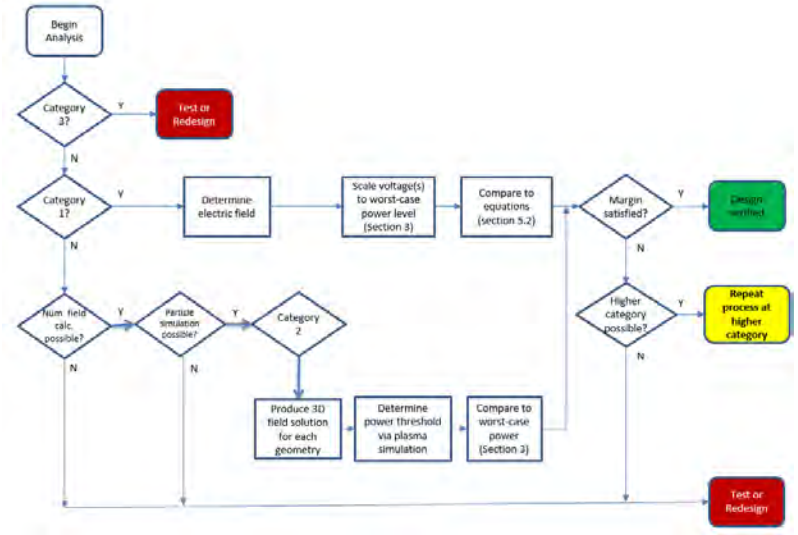
Category	Definition	Device Features or Examples	Analytical RF Breakdown Level Determination (Section 5)
1	Simple geometries. Bounding diffusion length can be determined	Resonator Cavity, Transmission Lines	Require Analytical Curve (Section 5)
2	Diffusion length cannot be directly determined	Impedance transitions, filters, multiplexers, isolators	Require appropriate numerical multidimensional plasma breakdown simulator
3	Uncontrolled geometries or workmanship variability	Potted device, tuning screws in critical areas	N/A

Test (dB)		Analysis (dB)
Qualification	Acceptance	Qualification
6	3	10*

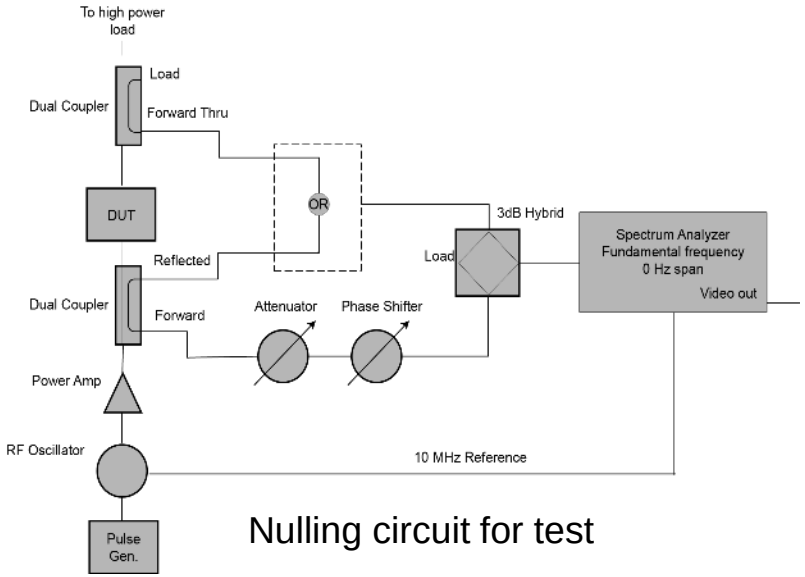
*Category 3 cannot be qualified by analysis

IB Recommended Methods

- Provide industry best practices in guidance sections (7 and 8) of document for analysis and test



Analysis process flow chart



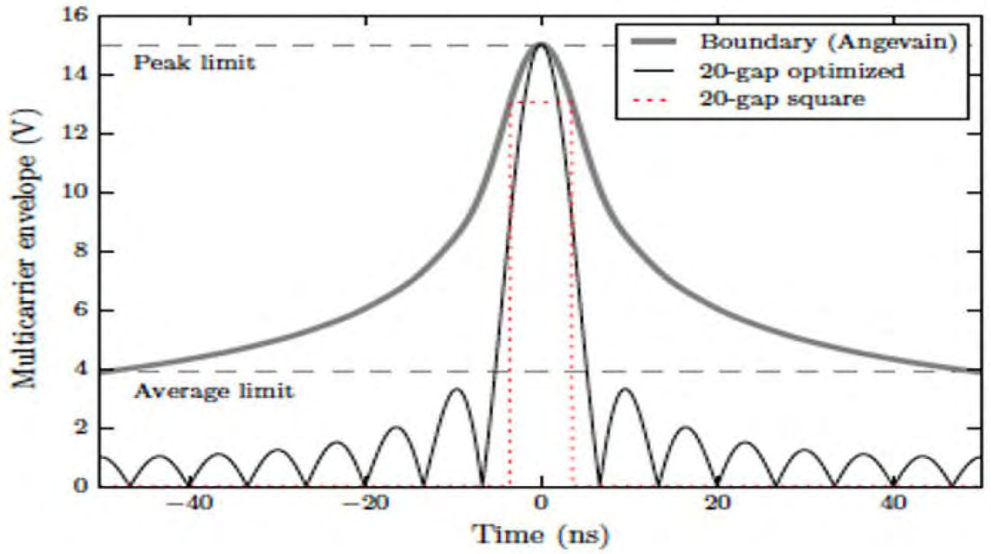
Nulling circuit for test

Multicarrier Multipactor Outline

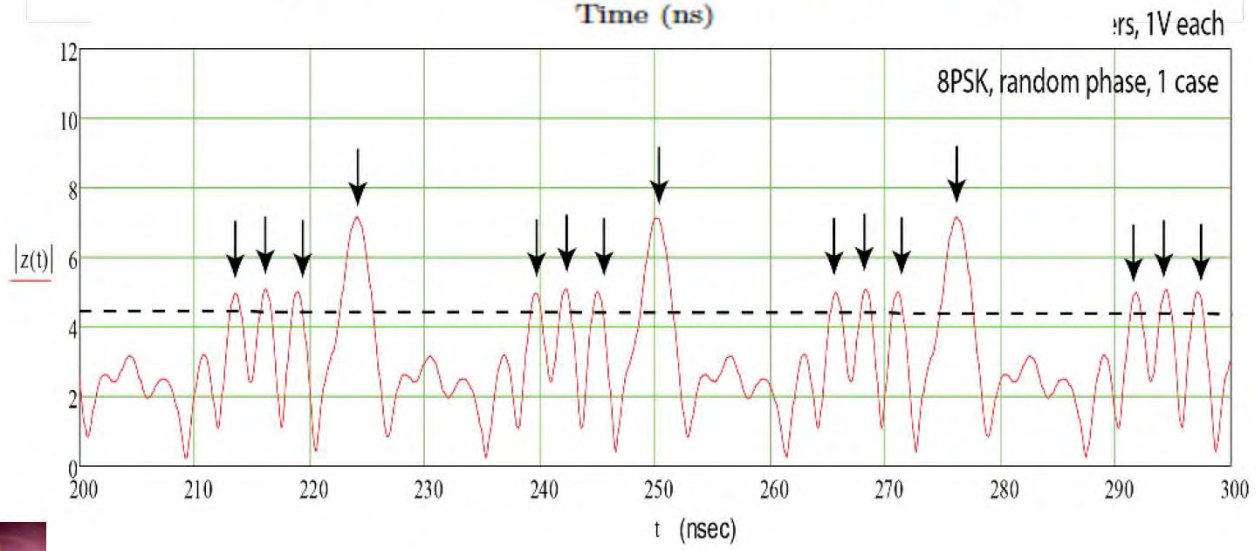
- Detailed explanation of industry best practices used by different organizations
  - *How to calculate*
  - *Applicability and limitations of each*
- Methods discussed
  - *n^2P (square of number of carriers times power of each carrier)*
  - *Gap crossing rules (i.e., P20)*
  - *Total average power*
  - *Statistical methods*

Multicarrier Multipactor Example Charts

P20 method



Statistical method



Intended Product Use

- Ionization breakdown document
  - *Use by prime contractors, suppliers, commercial satellite operators, government agencies*
    - Standard set of requirements for IB test and analysis verification
    - Provide guidance for test and analysis methods
  - *Deliver to new AIAA committee for conversion to formal standard*
  - *Share with ESA to attempt for unified international standard*
- Multicarrier TOR
  - *Use by prime contractors, suppliers, commercial satellite operators, government agencies as a reference document for existing methods*

Leveraging Expertise to Meet Future Challenges

- *Supporting funded efforts by researchers with relevant high-power expertise*
  - MAIW Year 1 released TOR in use
  - Year 2 AFOSR MURI: Transformational Electromagnetics
    - *Lead PI: University of New Mexico*
  - Serving on the Industrial Advisory Board (Tate)
  - Graduate student teleseminars
  - 2014+ year-end reviews
  - MURI Year 3 and 4 recommendations
- *Supporting future AFOSR MURI BAA development*
- *Upcoming discussions with other customer and government communities*

RF Breakdown Prevention, Part 2 Team Membership

Core Team

First Name	Last Name	Organization
Preston	**Partridge**	**The Aerospace Corporation**
James	**Farrell**	**Boeing**
Jeff	**Tate**	**Raytheon**
Aimee	Hubble	The Aerospace Corporation
Rostislav	Spektor	The Aerospace Corporation
Larry	Capots	Lockheed Martin
Will	Caven	SSL
Thomas	Musselman	Boeing
Rick	Bennett	Flight Microwave
Douglas	Dawson	NASA (JPL)
Bruce	Flanick	Northrop Grumman

Bold – co-leads

SME Team

First Name	Last Name	Organization
Ryan	Bentley	Ball Aerospace
Larry	Epp	JPL
Paul	Giuliano	Boeing
Steven	**Gold**	**Naval Research Lab**
Tim	**Graves**	**The Aerospace Corporation**
Eric	**Holzman**	**Northrop Grumman**
Kurt	**Ketola**	**Raytheon**
Rolf	**Kich**	**FMC**
Rami	Kishek	University of Maryland
Kevin	Lim	FMC
Jared	Lucey	GSFC
Jerry	**Michaelson**	**The Aerospace Corporation**
Raul	Perez	JPL
Stu	Quade	Northrop Grumman
Joseph	**Roubal**	**Aeroflex**
Norman	**Strampach**	**Lockheed Martin**
Alex	Thompson	Intelsat
Ghislain	Turgeon	SSL
Jian	Xu	Aeroflex

Bold – attended workshop

AEROSPACE REPORT NO.
TOR-2015-02540

RF Breakdown Prevention Part 2 Product Overview

Approved Electronically by:

Todd M. Nygren, GENERAL MANAGER
SYSTEMS ENGINEERING DIVISION
ENGINEERING & TECHNOLOGY GROUP

Jacqueline M. Wyrwitzke, PRINC DIRECTOR
MISSION ASSURANCE SUBDIVISION
SYSTEMS ENGINEERING DIVISION
ENGINEERING & TECHNOLOGY GROUP

Diana M. Johnson, PRINC DIRECTOR
COMMUNICATION SYS IMPLEMENTATION SUBDIV
COMMUNICATIONS & CYBER DIVISION
ENGINEERING & TECHNOLOGY GROUP

Catherine J. Steele, SR VP NATL SYS
NATIONAL SYSTEMS GROUP

Jackie M. Webb-Larkin, SECURITY SPECIALIST III
GOVERNMENT SECURITY
SECURITY OPERATIONS
OPERATIONS & SUPPORT GROUP

SY0026

AEROSPACE REPORT NO.
TOR-2015-02540

RF Breakdown Prevention Part 2 Product Overview

Technical Peer Review Performed by:

Jacqueline M. Wyrwitzke, PRINC DIRECTOR
MISSION ASSURANCE SUBDIVISION
SYSTEMS ENGINEERING DIVISION
ENGINEERING & TECHNOLOGY GROUP

Catherine A. Allen, DIRECTOR DEPT
ANTENNA SYSTEMS DEPT
COMMUNICATION SYS IMPLEMENTATION SUBDIV
ENGINEERING & TECHNOLOGY GROUP

Preston Partridge, ENGRG SPECIALIST
ANTENNA & PHASED ARRAY EVALUATION
ANTENNA SYSTEMS DEPT
ENGINEERING & TECHNOLOGY GROUP

Cheryl L. Sakaizawa, ADMINISTRATIVE SPEC III
MISSION ASSURANCE SUBDIVISION
SYSTEMS ENGINEERING DIVISION
ENGINEERING & TECHNOLOGY GROUP

SY0026