AFRL-RH-FS-TR-2020-0009

General Dynamics Information Technology Directed Energy Bioeffects Research II Task Order 5 Final Report

Contract No. FA8650-13-D-6368

(b) (6)

General Dynamics Information Technology

February 2020

Final Report for October 2015 – February 2020

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Air Force Research Laboratory
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"General Dynamics Information Technology Directed Energy Bioeffects Research II Task Order 5 Final Report Contract No. FA8650-13-D-6368 (Final Report for October 2015 - February 2020)"

(AFRL-RH-FS-TR- 2020 - 0009) has been reviewed and is approved for publication in accordance with assigned distribution statement.

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Contract Monitor

Radio Frequency Bioeffects Branch

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
13-02-2020	Final	1 Oct 2015 – 13 Feb 2020

4. TITLE AND SUBTITLE

General Dynamics Information Technology Directed Energy Bioeffects Research II Task Order 5 Final Report Contract No. FA8650-13-D-6368 (Final Report for October 2015 – February 2020)

5a. CONTRACT NUMBER
FA8650-13-D-6368-0005

5b. GRANT NUMBER
N/A

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)

(b) (6)

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
HOEB

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

General Dynamics Information Technology
(b) (6)

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command, Air Force Research Laboratory
711th Human Performance Wing, Airman Systems Directorate,
Bioeffects Division, Radio Frequency Bioeffects Branch
(b) (6)

10. SPONSOR/MONITOR'S ACRONYM(S)
711 HPW/RHDR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RH-FS-TR-2020-0009

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution B: Distribution authorized to U.S. Government agencies only (proprietary information, February 2020). Other requests for this document shall be referred to 711 HPW/RHDR, (b) (6).

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Understanding the biological effects of directed energy is a primary goal of the Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (711 HPW/RHDR) at JBSA Fort Sam Houston, Texas. General Dynamics Information Technology (GDIT) scientists, with specialized expertise in biological and biophysical research, conducted mathematical, statistical, and theoretical analyses necessary for the development of modeling and simulation products. These models led to capabilities including predictive and decision-making software that allowed futuristic views of the bioeffects from exposure to radio frequency (RF)/high-power microwave energy. We completed research efforts directly aimed at identifying any biological impact from RF exposures ranging from RF to millimeter-wave (MMW) frequencies, and pulse durations down to nanoseconds. This body of research focused upon the modeling and simulation of continuous-wave RF/MMW and high-power pulsed microwave bioeffects. This report describes in detail the different research efforts and associated deliverables generated for each project assigned to GDIT under the Directed Energy Bioeffects Research II program for Task Order 5 (Modeling & Simulation of Radio Frequency Bioeffects).

15. SUBJECT TERMS
RF exposure, FDTD, simulation, modeling, millimeter wave, bioeffects

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			(b) (6)
Unclassified	Unclassified	Unclassified	SAR	12	19b. TELEPHONE NUMBER *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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LIST OF ACRONYMS

711 HPW/RHDO	Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate (formerly Human Effectiveness Directorate), Bioeffects Division, Optical Radiation Bioeffects Branch
711 HPW/RHDR	Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate (formerly Human Effectiveness Directorate), Bioeffects Division, Radio Frequency Bioeffects Branch
AFRL	Air Force Research Laboratory
CHIRP	Cranial High pressure from RF Pulses
DEWDST	Directed Energy Weapon Decision Support Tool
DTM	Dynamic Thermal Model
DST	Decision Support Tool
EM	Electromagnetic
FEM	Finite Element Model
FCC	Federal Communications Commission
FDTD	Finite-Difference Time Domain
GDIT	General Dynamics Information Technology
GPUs	Graphics Processing Units
GUI	Graphical User Interface
HCTM	Human Common Target Model
IEEE	Institute of Electrical and Electronics Engineers
IVIS	In Vivo Imaging System
IWEA	Integrated Weapons Environment for Analysis
JREM	Joint Radio-Frequency Effectiveness Model
M&S	Modeling & Simulation
MMW	Millimeter Wave
PIRE	Probability of Injury from RF Exposure
RDT&E	Research, Development, Test, & Evaluation
RF	Radio Frequency
SAIC	Science Applications International Corporation
SAR	Specific Absorption Rate
SME	Statistical Multipath Exposure
STING	Superficial Thermal INjuries from GHz
TASC	Total Administration Services Corporation
TO	Task Order
1D	1-Dimensional
3D	3-Dimensional

EXECUTIVE SUMMARY

Understanding the biological effects of directed energy is a primary goal of the Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch (711 HPW/RHDR) at JBSA Fort Sam Houston, Texas. General Dynamics Information Technology (GDIT) scientists, with specialized expertise in biological and biophysical research, conducted mathematical, statistical, and theoretical analyses necessary for the development of modeling and simulation products. These models led to capabilities including predictive and decision-making software that allowed futuristic views of the bioeffects from exposure to radio frequency (RF)/high-power microwave energy. We completed research efforts directly aimed at identifying any biological impact from RF exposures ranging from RF to millimeter-wave (MMW) frequencies, and pulse durations down to nanoseconds. This body of research focused upon the modeling and simulation of continuous-wave RF/MMW and high-power pulsed microwave bioeffects. This report describes in detail the different research efforts and associated deliverables generated for each project assigned to GDIT under the Directed Energy Bioeffects Research II program for Task Order 5 (Modeling & Simulation of Radio Frequency Bioeffects).

1.0 INTRODUCTION

The objective of this contract was to conduct exploratory and developmental research and provide support relating to health and safety standards for human exposure to directed energies and human vulnerabilities to such exposures. It included the impact of exposures to human performance. These studies assessed the physiological, behavioral, and long-term effects of radio frequency (RF) emitting technologies.

2.0 TASK ORDER 5: MODELING & SIMULATION OF RADIO FREQUENCY BIOEFFECTS

Experiments on living cells and organisms are expensive and time consuming, which drives the need for modeling and simulation (M&S) computer programs to predict energy absorption and cellular and physiological responses quickly and accurately. Team General Dynamics Information Technology (GDIT) used state-of-the-art M&S techniques to produce high-fidelity models that accurately simulate the dynamic environments encountered by the military during directed energy (DE) engagements. This technology area is highly dependent on the rapid changes in M&S technologies. Teammates Engility Corporation, Science Applications International Corporation (SAIC), ThermoAnalytics, Stellar Science, Total Administrative Services Corporation (TASC), Kitware, Inc., and REMCOM Inc. enabled us to tap into emerging techniques and technologies to keep the M&S tasks on the cutting edge.

GDIT scientists designed and conducted basic research on the bioeffects of RF energy, and on direct-contact electronic control devices. They also supported the development of standards. The research performed encompasses the following areas:

2.1 Decision Support Tool (DST)

The Directed Energy Weapon Decision Support Tool (DEWDST) is a suite of engagement-level support tools for radiofrequency (RF) and microwave exposures. DEWDST is the result of work from previous contracts and was being finalized at the start of this Task Order (TO), TO5. The Engility Corporation, as a subcontractor of GDIT, worked on documentation and graphical user interface (GUI) capabilities for the final versions of DEWDST. DEWDST serves as a prototype for future engagement- and mission-level support tools with the transition point being software libraries for the Integrated Weapons Environment for Analysis (IWEA). GDIT collaborated with 711 HPW/RHDO colleagues to develop the Human Common Target Model (HCTM), an IWEA plugin. The GDIT contributions to the IWEA plugins are located on the AFRL's GitLab server within the following repositories: AFRL-RHD/RFHAZ_Library, AFRL-RHD/libDR, AFRL-RHD/HumanCommonTargetModel, AFRL-RHD/GeoMath, AFRL-RHD/libMPE, and AFRL-RHD/SBORDM_Library.

2.2 Validation

Validating DE M&S products with experimental data is essential in establishing reliable products, understanding specific bioeffects and their mechanisms, and exposing gaps in knowledge. Three projects from TO7 - Directed Energy System Effects Optimization (Thermal Validation, Swine Skin Analysis, and Pig Skin Damage) were designed to collect experimental data to validate the M&S products. The Thermal Validation studies collected thermal data on both carcasses and live rats when exposed to RF energy. This data has been and will continue to be used to validate the whole-body thermal response to RF energy models (e.g., ThermoReg) and the Finite-Difference Time-Domain (FDTD) models (i.e., REMCOM XFdtd® 3D Electromagnetic

Simulation Software and the in-house CFDTD, a C-language FDTD) used to calculate the specific absorption rate (SAR) as input for the thermal response models.

ThermoAnalytics originally developed the ThermoReg computer code to aid in the study of the potential health hazards of electronic devices that emit RF energy. ThermoReg was enhanced through a subcontract with GDIT to support a broader range of use cases. Most notable, the current version of the software now includes an analytic steady-state solution, which greatly reduces the computational burden when performing trade space studies across a range of parameter values. A final report and software code were submitted to 711 HPW/RHDR. The software code is found on the Research, Development, Test, & Evaluation (RDT&E) computing cluster, STARLA, in the module directory /share/apps/modules/ThermoReg/5.1.

(b) (6) (2017, June). *ThermoReg Steady State Solution – Final Report.* Calumet, MI: ThermoAnalytics, Inc. Also submitted software, ThermoReg v5.1. Submitted to 711 HPW/RHDR.

The Swine Skin Analysis and Pig Skin Damage studies have collected data on the swine thermal response and damage to RF energy, where excised skin and live subjects are exposed to GHz sources. At GHz frequencies, the thermal response is primarily superficial and may be modeled with a RF source incident on a one-dimensional (1D) multi-layered description of the body (e.g., skin, fat, and muscle). This data will allow for the validation of the whole-body and 1D thermal response M&S approaches. The collected data is located on RDT&E's TSRL-Server1.

2.3 Project Support

The M&S group provided support for the projects in the TO6 - Novel Direct Energy Weapon Effects and TO7 - Directed Energy System Effects Optimization groups. The support resulted in a variety of products such as novel models, simulation data, figures, tools, presentation materials, and reports.

2.4 CFDTD

Electromagnetic dosimetry is the cornerstone for the majority of RF studies—almost every project at 711 HPW/RHDR involves electromagnetic (EM) dosimetry. For many of these projects, the M&S group uses in-house software (CFDTD) to calculate SAR and provide dosimetry estimates. Over the time of this contract, improvements have been made to CFDTD. The improvements worth noting are listed below:

- The refactorization of the code while fixing several bugs and improving runtime performance by 50%
- The support of digital phantoms that demand more memory
- Allows exposures from an arbitrary number of plane wave incident fields that are incident on an object from any direction
- The ability to export steady-state electric and magnetic fields
- The ability to model incident fields with a Gaussian beam shape

- An improved work-load distribution of reading in the digital phantoms across multiple computational nodes
- The ability to provide, as input, the percentage of the Courant limit
- The ability to monitor the fields of user specified voxels

The most recent version of CFDTD is located on RDT&E's STARLA in the module directory at /share/apps/modules/FDTD.

2.5 Peak Spatial-Averaging

To report maximum SAR values, the RF community typically reports the peak spatial-averaged SAR values. One such method for calculating the peak spatial-average SAR is defined in IEEE Std.C95.3-2002. This method is a computationally expensive process. A GDIT scientist created a program called NGram that significantly reduces the computational burden in calculating mass-averaged SAR values. The optimization enables calculations to be performed 10-100x faster compared to other 711 HPW/RHDR peak spatial-averaging tools used. The scientist also included the ability to spread the calculation over multiple computational nodes. This capability allows the user to perform peak spatial-averaging on digital phantoms with a larger voxel count. NGram is located on RDT&E's STARLA at /share/apps/modules/NGram.

2.6 ThermoAcoustic Time-Domain Solver

Pulsed microwave exposure incident on a head can cause microwave hearing—an audible clicking/buzzing that appears to originate within one's head or immediately behind the head. This effect is induced when the head absorbs the pulsed microwave energy, causing a thermoelastic expansion that generates pressure waves. To model these thermoelastic pressure waves, a novel tool (ThermoAcoustic Time-Domain Solver) has been created by the M&S group. ThermoAcoustic Time-Domain Solver implements a FDTD approach to model the thermoacoustic effects from RF exposure. This software has been created and used in support of the Cranial High Pressure from RF Pulses (CHIRP) project. The software is located on RDT&E's STARLA at /share/apps/modules/ThermoAcoustic-Time-Domain-Solver. It has been used to investigate the thermoelastic pressure waves inside a variety of objects and species.

2.7 Mie Software

GDIT and Engility collaborated to produce MieQt, software with a GUI that provides the Mie solution to Maxwell's equations for a multi-layered sphere of a given radius. The analytical solution benefits the M&S group by providing close to real-time results and the solution acts as a reference to verify numerical approaches (e.g., FDTD methods).

2.8 Modeling of Thermal Effect Thresholds

The RF exposure safety limits defined by standards committees, such as the Federal Communications Commission (FCC) and Institute of Electrical and Electronics Engineers (IEEE), are set to ensure individuals do not experience any adverse health effects. These limits are set with

a safety factor between the actual exposure conditions that cause adverse effects and the provided safety limits. Understanding the actual limits that lead to adverse effects is important. It allows informed decisions to be made about the acceptable levels of risk for warfighters (i.e., health and safety), the development of Directed Energy systems, and the development of RF bioeffects models. GDIT utilizes high-fidelity, multi-physics models (e.g., a combination of CFDTD and ThermoReg) to explore the microwave and MMW portions of the RF spectrum. These models can be computationally expensive.

To use resources more efficiently, GDIT scientists have created an automated system (Probability of Injury from RF Exposure, or PIRE) to perform high-fidelity, multi-physics simulation sweeps, to search for thermal effect thresholds, to store the results in a database, and to visualize the results. The database allows users to query results quickly, recall data for additional post-processing, and collect large samples of data together. The PIRE software suite enables users to explore the RF spectrum as a function of exposure configuration (frequency, polarization, intensity, duration, and digital phantom) and an exposure's resulting SAR, thermal response, and thermal dose – common metrics used to study and quantify adverse health effects. The database is housed on the Tri-Service Research Laboratory's RDT&E network. Versions of the simulation submission software and visualization software are located on the 711 HPW/RHDR's GitLab server saved under the projects widget and PIRE-Viz, respectively. Future work is aimed to continue to fill the database and to develop real-time phenomenological models based on the data.

For RF exposures at MMW frequencies (30 GHz to 300 GHz), the absorption of the EM energy is predominately superficial. This regime enables the use of simpler models that consist of a 1D multi-layer phantom (e.g., epidermis, dermis, fat, and muscle). The M&S group developed a product called Superficial Thermal INjuries from GHz (STING). STING is a collection of analytical and numerical models written in C++ to study MMW RF exposures incident on skin. It will be evaluated against the Swine Skin Analysis and Pig Skin Damage studies discussed in Section 2.2. Additionally, the M&S group studied the non-linear effects of the thermal response to MMW exposures. In particular, the M&S group explored the temperature-dependence of conduction and how the temperature-dependence could be the cause of the non-linear effects.

Two abstracts were submitted to 711 HPW/RHDR for Bioelectromagnetics 2020 Conference scheduled to be held in Oxford, UK on 21-26 Jun 20.

(b) (6) (2020, January). *Simulated RF Exposure of High-Resolution 3D Human Head at 6-300 GHz* (AFRL-RH-FS-AB-2020-120632; P.A. Case No. TSRL-PA-2020-0101, 7 Jan 20). Abstract for BioEM 2020 scheduled to be held in Oxford, UK on 21-26 Jun 2020.

(b) (6) (2020, January). *Parameter-space Sweeps of One-dimensional Multilayered Models at GHz Frequencies: Effects on Damage Thresholds and Comparison to Exposure Guidelines* (AFRL-RH-FS-AB-2020-120633; P.A. Case No. TSRL-PA-2020-0100, 7 Jan 20). Abstract for BioEM 2020 scheduled to be held in Oxford, UK on 21-26 Jun 2020.

2.9 Digital Phantoms

Digital phantoms provide a map of material types and properties that describe a given object/organism. These phantoms are a key resource in the M&S group. GDIT scientists regularly modify, improve, and prepare acquired phantoms for M&S. As the M&S group started to use 3D models at higher frequencies (> 4 GHz), a need for phantoms with a higher fidelity, or finer resolution, was needed. The numerical calculations require the linear resolution of the phantom to be $1/10^{th}$, or finer, of the wavelength of EM emission. GDIT scientists have upscaled phantoms from their lower resolution to finer resolutions. In one case, the linear resolution of the 711 HPW/RHDR Visible Human head was improved from 2 mm to 50 µm. In another case, GDIT scientists have created hybrid phantoms, where the human phantom with a 2 mm resolution is upscaled to a finer resolution and then combined with a digital phantom of the inner ear structure. The insertion of the inner ear phantom provides the hybrid phantom with detailed structures that were missing from the lower resolution phantom. Digital phantoms are also available in the community. The M&S group also regularly prepares acquired phantoms for use in our software. Preparations consist of relabeling the tissue maps, fixing digital artifacts, identifying mischaracterizations of materials, changing data types, and reposing the phantom.

2.10 Vitruvius

EM energy causes heating in human tissues that can be hazardous to human performance and health. The amount of heating – characterized by the SAR – is dependent on the incident EM field, anthropometric parameters, and the posture of the human within the field. Stellar Science developed Vitruvius to predict the effects of EM exposures. Vitruvius is capable of altering the anthropometric parameters, creating postures, and simulating temperature rises in humans. Most of these calculations are executed using graphics processing units (GPUs) so that better-than-real-time results can be obtained. However, until this project, Vitruvius did not have the ability to calculate the localized SAR values from EM exposure characteristics (plane wave amplitude and frequency). A major focus of this effort was to implement such a capability, also using GPUs.

Stellar Science Ltd. Co. (2018, April). *Expanding Vitruvius for Use with Joint Radio-Frequency Effectiveness Model* (JREM). Albuquerque, NM: Stellar Science Ltd. Co. Submitted to 711 HPW/RHDR.

2.11 Statistical Multipath Exposure Technique

GDIT scientists have developed a statistical multipath exposure (SME) method to interpolate between previously generated plane waves that vary over a range of incident polar and azimuthal angles, theta and phi. This allows the user to calculate a large range of plane waves with unique theta and phi values from a small set of previously generated plane waves. Otherwise, the computationally expensive 3D numerical methods (i.e., FDTD) would have to be used to calculate each unique plane wave incident on a digital phantom. To compare results between the SME and in-house CFDTD software, CFDTD has been modified to include the ability to combine multiple incident plane waves.

2.12 Stochastic SAR for Multiple Plane Waves

Depending upon the environment, a person may be exposed to a far-field RF field pattern that follows a given theta and phi distribution. This pattern can be represented by a series of incident plane waves that have been randomly selected to sample the theta and phi distributions. To build the series of incident plane waves and calculate the resulting SAR distribution, the M&S group used the SME method in conjunction with a small set of numerically calculated incident plane waves to reproduce the emission pattern.

2.13 IVIS

Non-invasive imaging of small laboratory animals is made possible by the PerkinElmer In Vivo Imaging System (IVIS®) Spectrum. The IVIS works by recording and mapping the emission from bioluminescence and fluorescence reporters. GDIT employees have been trained to operate the IVIS. It has been used to support both the IVIS and CHIRP projects, and the IVIS is a key device in protocols RHDR-18-03 and RHDR-18-16 to measure the fluorescence from heat shock protein upregulation and bioluminescence from the upregulation of glial fibrillary acidic protein combined with exogenous luciferin D, respectively.