**AFRL-RD-PS-
TR-2021-0008**

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Efficient Simulation of High Power, Ultra-Short Laser Pulse Propagation Through Atmosphere

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8 March 2021

Final Report

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Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776**

NOTICE AND SIGNATURE PAGE

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 08 MAR 2021	**2. REPORT TYPE** Final Report	**3. DATES COVERED** *(From - To)* 17 Oct 2018 - 16 Jan 2021

4. TITLE AND SUBTITLE
Efficient Simulation of High Power, Ultra-Short Laser Pulse Propagation Through Atmosphere

5a. CONTRACT NUMBER
FA9451-19-1-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Shermineh Rostami-Fairchild

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
D0EE

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

Florida Institute of Technology
150 W University Blvd
Melbourne, FL 32901

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RDHP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RD-PS-TR-2021-0008

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES

AFRL/PA Approval #: AFRL-2021-1371

14. ABSTRACT

The goal of the research is to develop a computationally efficient atmospheric propagation simulation suitable for use by both experimental and theoretical scientists. The simulation will aid in the characterization of high peak power laser pulses propagating long distances through atmosphere, and will contribute to the assessment of these pulses in directed energy applications, including EMP and remote radiation generation, LIDAR, and laser-induced breakdown spectroscopy (LIBS).

15. SUBJECT TERMS

Nonlinear Optics Extreme Field Laser, Extreme Field Laser Propagation Modeling, Ultrashort Pulse Laser

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Andreas Schmitt-Sody
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	13	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

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1. SUMMARY

The objective of this project is to design and write a modular, three-dimensional propagation simulation of a femtosecond laser filament in atmospheric conditions. The results from our simulations in conjunction with our experimental data will help providing answers to many questions among the community from the fundamentals to long range applications of atmospheric filaments. These include ionization/conductivity, integrity of atmospheric plasma waveguides and the polarization evolution along propagation. This code is being adapted from an existing two-dimensional code written by Dr. John Palastro.

During the first quarter of this project, the Florida Institute of Technology (FIT) graduate student working on this project became familiar with the fundamental concepts involved in laser filamentation. Before moving forward with the expansion of the code, he tried reproducing the results of the original two-dimensional simulation and verify their accuracy. The original simulation was written in FORTRAN, which is a highly efficient programming language for solving systems of equations. However, due to the lack of familiarity with the language and lack of support with most compilers we chose to convert the existing two-dimensional code to MATLAB. This provided the opportunity for us to begin comparing our experimental results with the simulated results before the full three-dimensional code was finished.

The theoretical simulation results will be supported by experimental data obtained at University of Central Florida (UCF). The initial step was for the graduate student to become familiar with the necessary physics of filamentation to be utilized by the simulation. A large amount of time was spent becoming familiar with the original two-dimensional code, learning the language (FORTRAN), and verifying against already published results. The next step was to begin solving the three-dimensional case. This process was also broken down into three main steps: the initial laser pulse, the atmospheric response, and the ionization and plasma response.

Multiple experiments have been conducted this year at the UCF and the Townes Institute Science and Technology Experimentation Facility (TISTEF). These experiments have provided us with valuable data to compare with our simulation results, in particular the effects of polarization on the filament after the final stage, completing and debugging the three-dimensional code.

2. INTRODUCTION

The goal of the proposed research is to develop a computationally efficient atmospheric propagation simulation suitable for use by both experimental and theoretical scientists. The simulation will aid in the characterization of high peak power laser pulses propagating long distances through atmosphere, and will contribute to the assessment of these pulses in directed energy applications, including electromagnetic pulse (EMP) and remote radiation generation, light detection and ranging (LIDAR), and laser-induced breakdown spectroscopy (LIBS). Short, high power laser pulses can propagate over extended distances in atmosphere while maintaining high intensity [1]. Consequently, these pulses have numerous potential applications of interest to DoD, including EMP and remote radiation generation for electronic warfare, breakdown initiation, and LIDAR and LIBS for remote detection of aerosols, trace gases and biocontaminants [2,3]. A key phenomenon associated with the extended propagation is the polarization density of the atmospheric constituents. The polarization density provides a dynamic, intensity dependent index of refraction responsible for a number of important physical effects. These include self-focusing, supercontinuum generation, nonlinear birefringence, and pulse splitting. All potential applications rely crucially on the understanding, characterizing, and modeling of the feedback between the laser pulse and the refractive index of the air. Because of the nonlinear interaction between the laser pulse and atmosphere, numerical simulation is crucial for developing intuition and predictive capability. However, the disparity in time scales between the laser pulse evolution and atmospheric response can present a challenge for numerical simulation. With this in mind, our goal is to develop an efficient simulation for modeling the nonlinear propagation of high peak power laser pulses through atmosphere that would be freely available to the research community.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

Accurate modeling of the propagation of ultra-short laser pulses requires modeling a dynamic, intensity-dependent refractive index composed of the following contributions [4]: the instantaneous electronic response, the delayed rotational response, the linear and nonlinear plasma responses including ionization, and ionization energy damping, turbulence, and thermal rarefaction. The instantaneous electronic response arises from the time dependent displacement of the bound electron cloud in the presence of a laser pulse. The delayed rotational response results from the alignment of nitrogen or oxygen molecules along the polarization axis of the laser pulse. The plasma response includes a contribution from free electrons oscillating at the laser frequency and a contribution from the ponderomotive displacement of electrons. The plasma polarization density can be highly nonlinear due to the strong intensity dependence of the ionization rate. Ionization energy damping represents the loss of laser pulse energy in freeing an electron from the atomic binding potential. Turbulent fluctuations in the atmosphere contribute a random refractive index modification that can result in beam wander, spreading, and scintillation, that can seed filamentation. Finally, at high repetition rates, multiple laser pulses can significantly heat the air and launch a sound wave. The density depression left behind by the sound wave can result in thermal blooming. Because of the complex interaction between the laser pulse and atmosphere, numerical simulation is crucial for developing intuition and predictive capability. However, three-dimensional simulations of laser pulse propagation over long distances present a computational challenge due to the multiple time and spatial scales involved. Our previously developed two-dimensional cylindrical propagation code was designed for use on a serial processor, and lacks much of the three-dimensional physics important for atmospheric propagation (i.e. flying focus physics or turbulence). Nonetheless, the two-dimensional code was used in a collaborative work by the PIs to explain experiments that measured an unexpected broadening of the supercontinuum generated by elliptically polarized infrared filaments in molecular gases [5]. We propose to use our experience in writing propagation codes and with programming graphic processing units on desktop computers to write an efficient, modular program to solve the combined laser propagation-dynamic polarization system in three-dimensional. The algorithm would use the familiar split-step technique, in which the operators in the nonlinear wave equation are applied sequentially, instead of all at once. For parallelization, we would employ the alternating dimension implicit (ADI) technique, which allows for nonlocal operators, such as diffraction, to be done simultaneously (i.e. in parallel) along each spatial dimension [6]. The code will be written in C++ and make use of object oriented programming to make it as modular as possible. Only freely available libraries will be used. The development goal for the code is to let the user specify an arbitrary number of laser pulses, the properties of these pulses (such as frequency, duration, polarization, etc.), and the wave equation they wish to solve (e.g. the paraxial, modified paraxial, or unidirectional propagation equation). Scientific research will be ongoing with the three-dimensional code development.

4. RESULTS AND DISCUSSION

The initial step to tackle this complicated three-dimensional code was for the graduate student to become familiar with the fundamentals of laser filamentation. These include the nonlinear optics leading to self-focusing of the laser beam, the plasma interaction leading to defocusing, and additional considerations affecting the beam profile such as group velocity dispersion (GVD). In the presence of a highly intense electromagnetic field, the refractive index of air may increase due to the optical Kerr effect, which is directly related to the intensity of the field. This will lead to the self-focusing of the laser:

$$n = n_0 + n_2 I(r,t)$$

Equation 1. Refractive index including Kerr effect

If the input power of the beam exceeds the critical point, then ionization can occur in air. Once ionization occurs, there will be a decrease in the refractive index in the region where plasma is present. This will lead to the defocusing of the beam:

$$n \cong n_0 - \frac{\rho\,(r,t)}{2\,\rho_c}$$

Equation 2. Refractive index including plasma defocusing

For a single pulse, the effects on the field were modeled according to well defined equations for the change in refractive index and the intensity of the beam itself. A running integral for the power of the beam is maintained throughout each iteration of the simulation to easily allow for additional gains/losses that may be added or omitted due to the parameters of this simulation.

Initially only a gaussian beam with wavelength of 800nm was considered, propagating over a distance of 30m and a simplified atmosphere model consisting of 80 percent nitrogen and 20 percent oxygen was used.

Once the basic focusing/defocusing mechanisms were in place, the next step was to consider the effects of subsequent pulses and additional losses due to absorption and dispersion. A main source of energy loss in filamentation process is multi-photon absorption. When an electromagnetic field causes ionization, the field itself will lose energy as the photons from the field are absorbed by the excited electrons. For a field with a specific wavelength and initial intensity, the factor by which the intensity is attenuated over a characteristic length can be calculated.

The main outcome of the first quarter was understanding the driving mechanism of Filamentation and its diffraction-balanced propagation. Converting the existing code to MATLAB, expanding to three-dimensions, and finally testing the simulation and comparing against experimental results are the next steps to follow.

Several statements from the original simulation had also become deprecated and lead to multiple compiler errors. However, after a couple months of debugging the code could compile and was ready for initial analyzing the initial testing.

The equation for the laser pulse came from solving the nonlinear wave equation for the vector potential of the field, and simplifying due to the cylindrical symmetry of the system. The atmospheric susceptibility was expressed in terms of three factors: the instantaneous response of the electron clouds of the nitrogen and oxygen molecules in the presence of an electric field, the rotational response of the molecules described by their rotational quantum eigenfrequencies, and the free-electron susceptibility which is a result of both the ionization and the free-electron-plasma susceptibility.

Next, the ionization rates and energy losses due to plasma interactions were calculated numerically. The model originally was taken from S.V. Poruzhenko, V.D. Mur, V.S. Popov, and D. Bauer, 2008 for individual atoms however, A. Talebpour et al. 1999 showed that the method can be applied to molecules as well. Many of the parameters needed for the simulation were based on an experiment by (F. Calegari, C. Vozzi, and S. Stagira, Phys. Rev A 79, 2009 with a few differences. Pulse lengths of 30fs were modeled with a focal length of 300cm.

After successfully compiling the original version of the two-dimensional code and verifying the results with already published sources, the code was converted to MATLAB. This step was taken in order to make the code more user- friendly and easier to expand to 3 dimensions.
The main drawback to this conversion was that compiling and running the code takes a significantly longer amount of time than in FORTRAN. At the end of this quarter compiling in FORTRAN became more reliable and more time efficient for expanding to three-dimensions. However, since MATLAB is still more commonly used in the community we will continue the expansion in both languages in order to make the final three-dimensinal code more reliable and user- friendly.

The beginning of the simulation remained largely unchanged. In three-dimensions the procedure for initializing the laser began the same way. Starting with a wave equation a three-dimensional field was defined,

$$\nabla \times \nabla \times \vec{A} + \frac{1}{c^2}\frac{\partial \vec{A}}{\partial t^2} = \frac{4\pi}{c}\frac{\partial \vec{P}}{\partial t}$$

Equation 3. three-dimensional wave equation

Where A is the vector potential, and P is the polarization vector.

The atmospheric component was also very similar to the two-dimensional case, however more work was required to solve for the rotational quantum eigenfrequencies and the effect on subsequent pulses.

Finally, the rate equations were expanded into three-dimensions. We had to determine if the previous model would still apply in the three-dimensional case. Additional effects on the laser such as multi-photon absorption, group velocity dispersion, and self-phase modulation also had to be reconsidered when expanding to three-dimensions.

Our next goal was to determine the best algorithm to calculate the desired values. We decided to proceed with ADI method to find numerical solutions for our simulation due to the large degree of symmetry. The ADI method is regarded as a memory efficient way of solving large matrix systems (R. Li, J. White, 2002). This method will help minimizing the length of the simulation while still providing a large degree of accuracy.

The two-dimensional case has been analyzed and run. The output was compared with other published results to verify it's accuracy. A large amount of time has been spent on researching the physics of filamentation and the FORTRAN language itself. The original two-dimensional code was converted to MATLAB as well and a tentative plan for the three-dimensional simulation has been laid out.

This three-dimensional code is currently being developed. The simulation is still in its infancy, but some progress has been made. The main parameter files, constants, and initialization of integration parameters have been written. A three-dimensional electric field, energy calculations, and running integrals of laser power are currently being added with the next step being the atmospheric response model.

The parameter file is run first by the pre-compiler before the rest of the code is compiled. This allows us to define only the desired quantities for our simulation and the computer to save valuable memory. This file defines all of the laser parameters, atmospheric properties, integration parameters, and other necessary variables to be used throughout the simulation. Once the simulation is complete, changes to the laser pulse profile can be easily made by adjusting the values of different parameters in this file without having to rewrite the rest of the code.

Additional useful constants and some frequently used expressions were then written in the constants and init files. Most of these values were taken directly from the two-dimensional code as they are fundamental constants such as pi, Planck's constant, Boltzman's constant, etc. These files use values from the parameter file to define parameters such as the step size for integration, normalization factors for energy, and the wave number for the field. The geometry of the simulation was also established in the arrays file, which defines the volume over which the simulation will take place using the boundary conditions determined in the parameter file and the initial file.

Currently, the initial electric field, energy, and power for the laser are being written. Initially we are considering only a gaussian profile for the laser in order to reduce our timeline for completing the simulation. However, after initial testing of the completed simulation, alternative cases will be supported in the parameter file such as the addition of an aperture. The electric field itself comes from the solution of the nonlinear wave equation for the laser. The total energy can be defined in the parameter file for different experimental cases. The power of the laser will then be calculated directly from the electric field and the integration area.

5. CONCLUSION

In summary, we attempted design and write a modular, three-dimensioanl propagation simulation adapted from our current two-dimensional simulation, develop the code from the ground up for use on graphic processing units and multi-threaded processors and Test against ongoing experiments performed at the University of Rochester, the University of Central Florida, Florida institute of Technology and Air Force Research Laboratory. We succeeded in only part of our goals and more work is required.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

FIT	Florida Institute of Technology
UCF	University of Central Florida
TISTEF	Townes Institute Science and Technology Experimentation Facility
EMP	electromagnetic pulse
LIDAR	light detection and ranging
LIBS	laser-induced breakdown spectroscopy
ADI	alternating dimension implicit
GVD	group velocity dispersion
n	refractive index
A	vector potential
P	polarization vector

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