Evaluating the Validity of 1D-CARS Using a Single Laser

(Technical Topic)

Evaluating Uncertainty and Public Perception of Developments in Climate Change Modeling

(STS Topic)

A Thesis Project Prospectus Submitted to the

Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree

Bachelor of Science, School of Engineering

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Fall, 2019

On my honor as a student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Since the rise of the information revolution, the complexity of computer models has increased dramatically. The field of climate science has been influenced enormously by the advent of huge computer models. However, it is important for people and scientists to understand the limitations of such models before drawing conclusions. From large-scale climate models to small-scale combustion models, the underlying mechanisms, assumptions, and uncertainties must be thoroughly examined and understood.

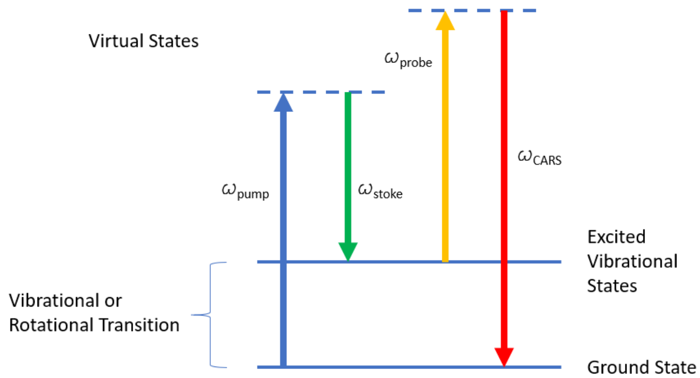
The technical project will validate a simplified laser diagnostic system in order to better understand combustion processes. Analysis will be performed prior to constructing the laser system to determine its feasibility. The technical project will culminate in a validated laser diagnostic system.

The STS prospectus explores the uncertainty inherent in climate change models and the political and scientific consensus in the field. By examining the flaws of current climate change models and developments in the past, this topic aims to shed light onto the current state of the climate controversy and determine the best path forward for policy makers and scientists.

Technical Topic: Evaluating the Validity of 1D-CARS using a Single Laser

The objective of this project is to determine if it is possible to produce 1-dimensional hybrid femtosecond/picosecond coherent anti-Stokes Raman scattering (1D fs/ps CARS) with a single femtosecond (fs) laser rather than using two separate laser systems (Bohlin, Patterson, & Kliewer, 2013). The deliverables for the technical project are (1) experimental data and analysis to determine the feasibility of a simplified 1D-CARS setup and (2) preliminary data collected using the 1D-CARS system to evaluate if the system is effective for use in a combustion environment. A technical report will be completed detailing the methods and results of this research.

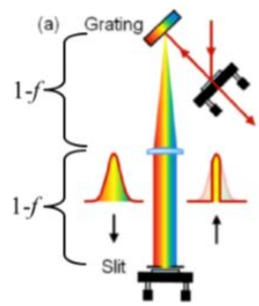
Spectroscopy is the study of the absorption and emission of electromagnetic radiation by matter (Graybeal, Hurst, Stoner, & Chu, 2018). Spectroscopy is used heavily in the fields of biology, chemistry, and physics to help gain insight into the processes and matter surrounding us. Advances in technology have allowed spectroscopy to be utilized to understand phenomena ranging from the micron scale up to the macroscale, such as the study of our solar system (NASA). Coherent Anti-Stokes Raman Spectroscopy (CARS) is a specific spectroscopy technique that provides excellent spatial and temporal resolution in the identification of chemical species and temperatures (Eckbreth, 1996). CARS was first developed in the 1970s and owes its existence to enhancements in high power nanosecond (ns) lasers, as well as compact picosecond (ps) and femtosecond (fs) lasers (Roy, Gord, & Patnaik, 2010). The CARS method uses three lasers focused at a common point, commonly referred to as the pump beam, Stokes beam, and probe beam (Eckbreth, 1996). The frequencies of the pump and Stokes laser beams are chosen so that their difference matches the frequency of the target molecule (Roy, Gord, & Patnaik, 2010). The probe beam then scatters off the induced resonance and, through the conservation of momentum and energy, produces a fourth laser-like signal, referred to as the CARS signal. The generated signal is directed to a spectrometer where the spectral lines reveal information about the concentration and temperature of the target species (Eckbreth, 1996). Since the CARS spectra produced is temperature dependent, it has become a particularly useful technique in the study of combustion and reacting flows (Oxford Instruments).



Interaction of Pump, Stokes, and Probe Beam to Produce CARS Signal

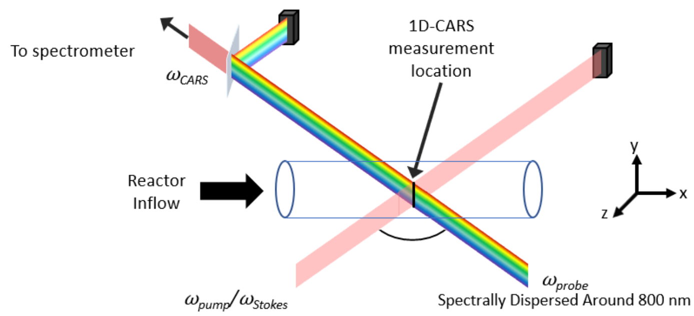
The CARS method has been applied to measure multiple species in reacting flows, measure species in typically difficult to access flow environments, high pressure environments, and in transient environments where high bandwidth and many measurements are necessary (Roy, Gord, & Patnaik, 2010). CARS can therefore provide insight into reacting flow environments that are conventionally difficult to measurable. CARS allows for "in-situ" measurements that do not affect the chemistry or flow of the species being observed. Traditional temperature measurement techniques could involve inserting a thermocouple into the flow or taking a gas sample from the reactor, causing unwanted chemical and fluid reactions; some flows can even be too hot and melt these thermocouples. Extensive research is being done using CARS to understand the process of soot formation and oxidation, which will be necessary to reduce these pollutants (Geigle, et al., 2005). CARS is also being used to help understand the complicated interactions that take place during combustion close to metal surfaces, fundamental interactions that are present in internal combustion engines and gas turbines (Bohlin, Jainski, Patterson, Dreizler, & Kliewer, 2017). Increased efficiency and decreased pollution are possible if the fundamental mechanisms of combustion are better understood through CARS.

Fs/ps CARS setups use an optical grating to disperse the fs laser pulse into its component wavelengths, then the desired wavelength is selected using a slit (Miller, 2012). This generates a frequency-narrow, ps duration laser pulse. Unwanted wavelengths terminate around the edges of the slit and the smaller range of desired wavelengths travels through the slit. Selecting a small range of wavelengths correlates to a desired temporal bandwidth as specified by the Time Bandwidth Product (TBP). This phenomenon is a property of the Fourier transform and defines how wide temporally or spectrally a pulse can be when it is approaching this transform limit.



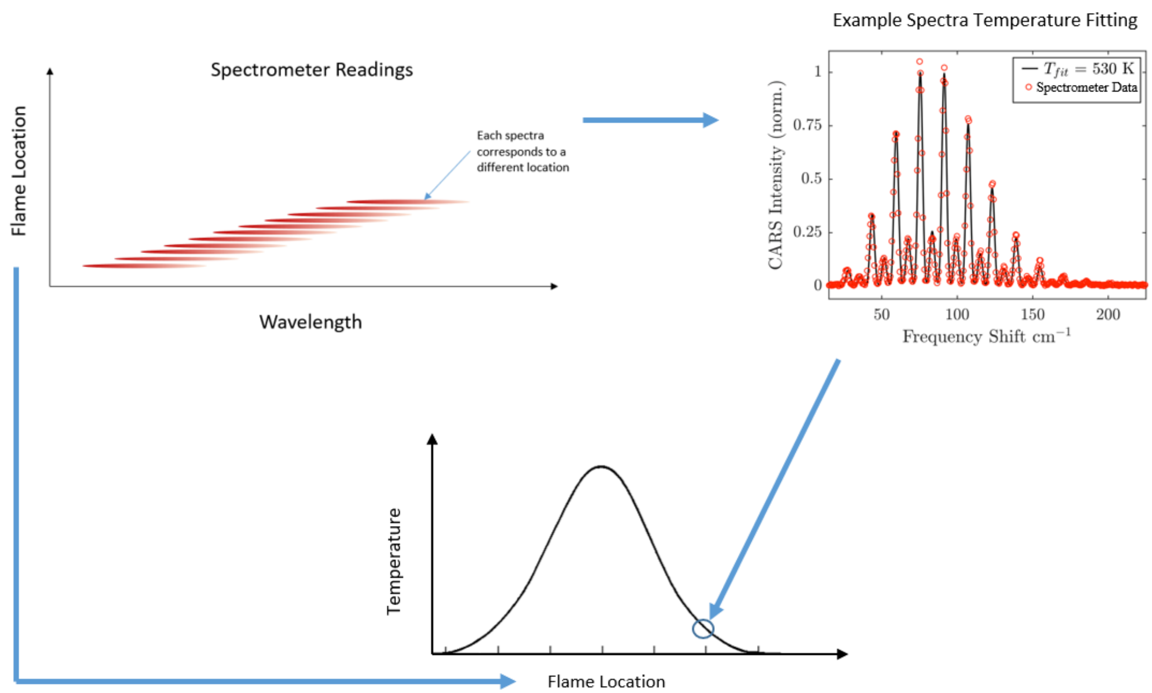
Typical CARS Grating Setup Filtering Out a Small Range of Wavelengths (Miller, 2012)

By using a similar grating, but not filtering out wavelengths, the goal is to create a larger spectrum that is spatially expanded over a line rather than focused to a single point, each spectral unit will then be of the desired temporal bandwidth. If the original beam is tuned to the correct wavelength, then it is possible that the entire dispersed beam will be capable of creating the correct CARS frequency when combined with a pump and stokes beam. The pump beam will be uniform in wavelength and dispersed and focused to a sheet by various lenses. The Stokes beam will also have to be spatially dispersed in order to combine with the stoke and pump beams and relay into a spectrometer.



1D CARS Setup

Typically, a small range of wavelengths is desired in order to produce the CARS signal relevant to the species in question. By tuning the central wavelength of the laser, it may be possible to produce a measurable CARS signal along the entire line of intersecting pump, stokes, and probe beams. Points along the line can then be imaged by a spectrometer in increments of about 50 microns, yielding many points where valuable data can be collected at the same time.



Schematic of Temperature Determination from Spectrometer Data

The temperature of each flame location will be determined by fitting spectral data with a Boltzmann distribution. Each peak in the intensity versus frequency shift graph shown above represents different electronic energy transitions. Based on the intensity of each transition and the overall distribution, the temperature of the reacting species can be determined. The following equation calculates the total intensity of electronic transitions between states *i* and *f* which makes up one peak of the entire Boltzmann distribution used for determining temperature (Eckbreth, 1996).

$$\Delta\rho_{i\rightarrow f} = \frac{g_f}{\sum_m g_m \frac{-E_m}{k_B T}} \left[e^{\frac{-E_i}{k_B T}} - e^{\frac{-E_f}{k_B T}} \right]$$

Intensity of Electronic Transitions Between States *i* and *f* (Eckbreth, 1996)

By investigating and validating a simplified line-CARS setup, researchers will be able perform 1D fs/ps CARS with a single fs laser, instead of using separate fs and ps lasers synchronized in time. The point-CARS method which is more commonly applied can then be transformed into line-CARS without having to buy additional expensive lasers and other equipment.

The fall semester will focus on numerical validation of the simplified line-CARS method and subsequent testing to determine if the dispersion of wavelengths in the probe beam will be within the range to produce a sufficient line-CARS signal energy. Since beams are already dispersed in a point-CARS configuration, it is plausible that the dispersed laser will have enough energy between each 50 micron imageable point to produce a detectable CARS signal. Research will be focused on determining the characteristics of the dispersed probe beam.

The spring semester will focus on incorporating the characterized probe beam into a fully operation 1D-CARS system. If the hypotheses are correct, then testing will commence to characterize the spatial resolution of the 1D-CARS system and use the system to measure temperature within a spatially-varying reacting flow for comparisons to a standard 1D-CARS system. The technical report will be completed in the spring and will describe the viability of this simplified line-CARS system once it is better understood.

STS Research Topic: Evaluating Uncertainty and Public Perception of Developments in Climate Change Modeling

“All models are wrong, but some are useful” is the common aphorism generally attributed to George Box (Curry & Webster, 2011). As the technological revolution rages on and large quantities of data become more common, the search for “useful” models is paramount. Computer models are used across many scientific fields ranging from basic weather forecasting to computational fluid dynamics to facilitate the development of safer, more efficient aircraft (Lamont, 2019). Complex models are built off of basic ideas or theories and make predictions by applying these ideas numerous times to larger systems or collections of data (Coghill, 2015). In the study of climate change, powerful computer models are generated based on physical equations that predict the behavior of the components of the earth, including the atmosphere, oceans, land, and ice. Climate science is a controversial topic and the future of our planet and the human species may ultimately rely on our ability to understand and make decisions based on these inherently flawed but possibly useful climate models. The point of this STS research is to examine how social factors have influenced people’s notions about climate change and to critically evaluate relevant scientific evidence.

Discussion of the widespread adoption of climate science models fits well into the Sociology of Scientific Knowledge (SSK) Science, Technology, and Society (STS) framework. The SSK framework states that social factors can play an even more significant role in scientific development than rational or empirical factors (STS Wiki, 2009). Since climate science has such widespread social impacts and is subject to particularly strong social forces in its development and adoption, the topic lends itself well to an in-depth analysis of social factors. Examining the history and current state of the climate change controversy through the lens of SSK will shed light on why industry, politics, and society in general have become so affected and polarized by the issue.

The goal of climatology is to determine how the energy balance of the earth is changing. Climatologists need to understand where energy resides and how it circulates around the world (Edwards, 2010). Since the system is so large and changes happen over long periods of time, studying the climate based on experimental methods alone is impossible (Edwards, 2010). Scientists must rely on complex models that combine multiple different phenomena to fully understand changes in the earth's climate. Some primary factors to the global climate include, but are not limited to, carbon dioxide concentrations, water vapor concentrations, solar variations, wind patterns, ocean current patterns, volcanic eruptions, and changes in vegetation (Weart & American Institute of Physics, 2017). It would be impossible for one person to compose a truly accurate model that included all of these factors. As a result, many scientifically validated models are combined in order to produce comprehensive Earth System Models (ESMs) (Edwards, 2010).

Advances have not brought a true consensus within the scientific community, and perhaps even exacerbated the problem. The Intergovernmental Panel on Climate Change (IPCC) is the United Nations panel for assessing climate change related science (IPCC). It compiles research on climate change and produces major assessment reports every 5 to 7 years (Clark, 2011). The last report, Assessment Report 5 (AR5), was completed in 2014 and concludes that "human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC, 2014). NASA states that 97 percent of actively publishing climate scientists agree with the IPCC's 2014 findings (NASA Global Climate Change, 2019). How is and how should consensus be evaluated? According to these two agencies, the climate is in fact changing, and humans are responsible. However, there is a small, but vocal minority questioning the science behind these assertions. Judith Curry, once the head of the Department of Earth and Atmospheric Sciences at Georgia Tech, is now part of that minority (Sorman & City Journal, 2019). Curry says that "independence of mind and climatology have become incompatible," and as such decided to give up on academia in the middle of what she calls "CRAZINESS" in the field of climate science (Harris, 2013) (Curry, 2017). She believes that climate science and policy need take full account of the uncertainty related to it. Curry went against the established orthodoxy by expressing her true opinions about climate science, inadvertently driving herself out of academia in the process.

Climate model imperfection can be broken down into two categories according to Judith Curry: model inadequacy and model uncertainty. Model inadequacy reflects our inability to fully understand the climate system. There will always be aspects of the climate system that are not yet discovered or understood well enough to be incorporated into comprehensive models. According to Curry, model uncertainty can then be broken down into three main categories: parameter uncertainty, sub-grid parameter uncertainty, and initial condition uncertainty.

Parameter uncertainty reflects general uncertainty in the constants used in climate models. Many parameters are well established, but even slight errors in the accuracy of parameters can have unintended effects on a large model undergoing thousands if not millions of iterations. Sub-grid uncertainty reflects uncertainty in phenomena that are too small to be captured specifically in climate models. The sub-grid phenomena are accounted for by being incorporated into the grid size of the model, thereby simplifying small phenomena like boundary layer turbulence or cloud microphysics in units the size of many square or cubic miles of space. These grid sizes are chosen so that the model can be solved in a reasonable amount of time. Until there is exponential improvement in computing technology, it will be impossible to directly account for such small-scale phenomena. Initial condition uncertainty encompasses errors in the initial conditions given to the models. Small errors in these, similar to small parameter errors, could have enormous effects on the outcomes of a climate forecast. It is important to understand the structure of and uncertainty in climate models before conclusions can be drawn. The uncertainties outlined make up what Judith Curry calls the “Uncertainty Monster”, something she believes plagues even the best Earth System Models. (Curry & Webster, 2011)

Advances in computing power have allowed scientists to build upon simple relationships and construct increasingly complex computer models to analyze the earth’s climate. Despite scientific consensus that the earth’s temperature is rising due to human factors, there is still a lot of uncertainty in the models that needs to be examined critically without bias from popular media, politics, and industry. Many scientists and academics who disagree with the assertions of governmental bodies like the IPCC claim that we “just don’t know”, which seems neither reassuring nor helpful. Whether the models are strong enough to make these conclusions needs to be further analyzed. It would be dangerous not to act upon the results of the climate models if the evidence is compelling, but it could be equally damaging to incorrectly draw conclusions and create regulations based upon incomplete science.

Conclusion

By examining climate change science and models through the lens of SSK since the industrial revolution, the limitations and uses of the existing climate models can be deduced and applied to better understand the current state of the climate controversy. The technical project will aim to validate a simpler, more cost-effective laser diagnostic technic for combustion with similar capabilities to those already employed. Understanding the limitations of climate science, and the necessary areas of improvement will help highlight the need for better understanding of the processes, combustion specifically, which may contribute to it.

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