Neural Networks for Computed Tomography Imaging Spectroscopy of the Solar Atmosphere

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Abstract

Explosive events are a prominent feature in spectrographic observations of the solar transition region. A wide range of phenomena in the solar atmosphere have been found to be associated with explosive events, but are these really all examples of the same underlying mechanism, or are multiple mechanisms responsible for the spectral signature of explosive events? We propose to confront this question by performing snapshot imaging spectroscopy of the transition region. This measurement will provide cotemporal EUV emission line profiles over the full spatial extent of explosive events, permitting further characterization of these events through analysis of their spatial structure. A more complete understanding of the mechanisms responsible for explosive events is directly applicable to the NASA Heliophysics Division's objective of "Exploring the physical processes in the space environment from the Sun to the Earth and throughout the solar system" because the dynamics of explosive events are applicable to other regions of the solar atmosphere and may provide insight into long-standing questions about energy transport within the Sun.

Snapshot imaging spectroscopy of the transition region will be achieved through computed tomography imaging spectroscopy (CTIS) of bright EUV emission lines. CTIS relies on the development of computed tomography algorithms to process data from such an instrument. To help answer the questions proposed above, we intend to develop a new algorithm for CTIS data analysis which is adapted to the environment of the transition region using neural networks. The development of such an algorithm will help to advance the method of CTIS and allow more complete investigations into the structure of the solar atmosphere.

1 Problem Statement

1.1 Background

The solar transition region (TR) forms the boundary between the dense, cool plasma of the chromosphere and the intense environment of the million-degree corona. It is through this region that the plasma composing the solar atmosphere undergoes a rapid temperature increase, rising from 20,000 K to 1 MK over a distance of just tens of kilometers. The processes through which energy is transmitted through this region and its influence on the rest of the solar atmosphere have remained the subject of considerable debate (Innes et al. 2015).

The dynamic environment of the TR is demonstrated by the observation of so-called explosive events (EEs), discovered by Brueckner and Bartoe 1983 using the *High-Resolution Telescope and Spectrograph* (HRTS) and further investigated by Dere, Bartoe, and Brueckner 1989 and Dere 1994. Explosive events are spectral features present in TR emission lines, which are defined by non-Gaussian line profiles showing Doppler shifts between 50–150 km/s (Brueckner and Bartoe 1983). These events have been shown to occur on spatial scales of 2" – 5", last approximately 600s (Dere, Bartoe, and Brueckner 1989), and are consistent with a bi-directional flow through the TR (Dere et al. 1991; Innes et al. 1997).

While the properties of explosive events have been well studied, investigators have been unable to reach a consensus on the cause of these events. It has been postulated that EEs are the signature of siphon flows within small-scale loops (Teriaca et al. 2004), flows along spicules and macrospicules (Wilhelm 2000), plasma ejection and retraction (Huang et al. 2014), and evidence of magnetic reconnection through the plasmoid instability (Innes et al. 2015). Furthermore, EEs have been associated with other events in the solar atmosphere such as coronal microflares (Krucker and Benz 2000), reconnection in the photosphere (Tarbell et al. 1999), and the chromospheric jets observed by De Pontieu et al. 2011.

While the literature describes a extensive list of properties and phenomena associated with explosive events, it remains unclear if all of these properties can be reproduced by a single mechanism, such as the plasmoid instability. From the wide variety of phenomena associated with explosive events listed above, it seems possible that a model of explosive events considering multiple mechanisms may be needed. **If these events do arise from multiple mechanisms, can we distinguish different types of explosive events by considering their spatial structure?**

Measuring the spatial structure of explosive events relies on imaging spectroscopy, a technique that aims to spectrally resolve each pixel of an image. Unfortunately, the capabilities of current imaging spectrographs may be inadequate for a thorough exploration of explosive events. This is because current imaging spectrographs, such as the *Interface Region Imaging Spectrograph* (IRIS) (DePontieu et al. 2014), can only view the sun through a thin slit, and must raster this slit across the sun to build up a spectrally-resolved image. This limited view prevents a complete characterization of explosive events, since only a small portion of the event can be observed at any one time.

The limited observational capabilities of imaging spectroscopy through rastering have prompted the development of snapshot imaging spectroscopy (also known as snapshot hyperspectral imaging or simultaneous spectroscopic imaging), where every pixel in a scene is spectrally resolved in a single exposure. An observation of this type, if achieved using large spatial, spectral, and temporal resolution, allows the spectrum of an explosive event to measured across its entire spatial extent. A snapshot imaging spectroscopy technique known as computed tomography imaging spectroscopy (CTIS) (Okamoto and Yamaguchi 1991; Bulygin and Vishnyakov 1992; Descour and Dereniak 1995) has been used by a mission known as MOSES developed by Kankelborg and Thomas 2001 to image the solar transition region.

1.2 Computed Tomography Imaging Spectroscopy

Computed tomography imaging spectroscopy is an efficient method to perform snapshot imaging spectroscopy (Kankelborg and Thomas 2001). It achieves this measurement by eliminating the slit of a conventional spectrograph, allowing a diffractive element to multiplex the spatial-spectral content of a scene into an image (Hagen and Kudenov 2013). This design is similar in spirit to observing a fireworks display through a diffracting pair of glasses; a scene observed by the detector will have its spectrum dispersed across the image in the outboard orders. To recover a spectrally-resolved image CTIS relies on forming mulitplexed images at multiple diffraction orders and using computational techniques to invert the mulitplexing operation and recover a spectrally-resolved image.

Since a spectrally-resolved image can be represented by a 3D volume, we will refer to this sort of image as a spatial-spectral cube (SSC). Computing this spatial spectral cube using images formed at multiple diffraction orders can be interpreted as a classic 3D tomography problem where N projections are taken through a translucent 3D object in x, y and λ space (Bulygin and Levin 2005). Using this representation, we can write the intensity in each order, I_m, of an object $v(x, y, \lambda)$ viewed by a computed tomography (CT) imaging spectrograph in terms of the intergral equation provided by Fox, Kankelborg, and Thomas 2010

$$I_m(x', y') = \int_B v(x' - \lambda \tan\theta_m \cos\phi,\ y' - \lambda \tan\theta_m \sin\phi,\ \lambda)\, d\lambda, \tag{1}$$

where x' and y' are image coordinates and B is the passband of the instrument. Equation 1 is a Fredholm integral equation of the first kind (Riley, Hobson, and Bence 2006) with a projection kernel. Our goal is then to invert Equation 1 to recover the object $v(x, y, \lambda)$. This problem will be referred to as the "inversion problem" or just simply an "inversion" for the remainder of this proposal.

The CT imaging spectrographs developed by Charles Kankelborg and his research group only take between $N = 3$ and $N = 6$ projections through the spatial-spectral cube. This limited number of projections does not provide enough information to uniquely reconstruct the SSC, i.e. in the case of the CT imaging spectrographs discussed below (MOSES and ESIS), inverting Equation 1 is an *ill-posed problem* (Fox, Kankelborg, and Metcalf 2003). This means that there are multiple solutions to the inversion problem that satisfy a particular set of projections. To uniquely solve the inversion problem a CTIS inversion algorithm (CIA) must find a way to eliminate incorrect solutions to the inversion problem. We can show that many of the solutions to the inversion problem are unphysical, that is, they are inconsistent with physical law and previous solar observations.

Therefore, an inversion algorithm must use physical constraints to trim possible solutions to the inversion problem and accurately reconstruct the spatial-spectral cube (Fox, Kankelborg, and Metcalf 2003). In Section 1.4 we will briefly explore advantages and disadvantages of the physical constraints used by current inversion algorithms, and in Section 2 we will propose to use machine learning algorithms to approximate these physical constraints and solve the inversion problem.

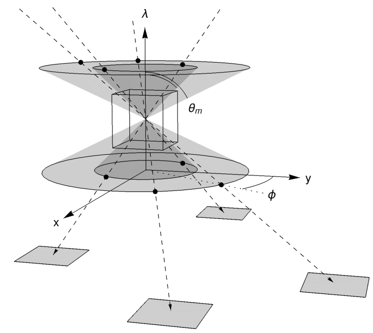


Figure 1: Geometry of the inversion problem for CTIS interpreted as a 3D tomography problem. θ_m describes the angle of the tomographic projection at each diffraction order and takes on discrete values, visualized by the nested cones. ϕ describes the dispersion direction and accepts continuous values. The four dotted lines are examples of particular projections through the spatial-spectal cube. Figure adapted from Bulygin and Levin 2005

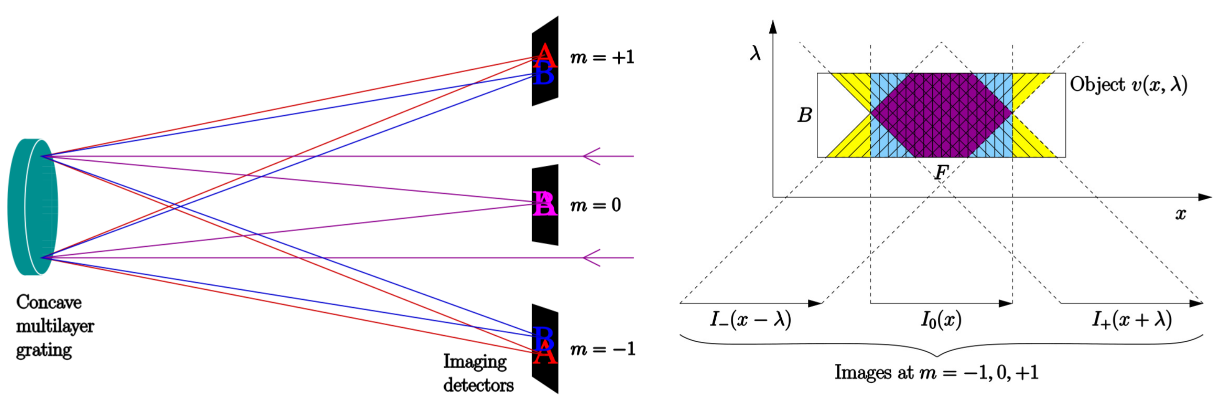
1.3 Current and Planned CT Imaging Spectrographs

In the sections below, we will conduct a limited overview of the current and planned CT imaging spectrographs designed and built by Charles Kankelborg and his research group. A brief understanding of the optical system of each instrument will be helpful to understanding the goals of this proposal.

Each of the instuments in the succeeding sections is designed to fly on a Black Brant IX sounding rocket launched from White Sands Missile Range. Additionally, each instrument is constructed with a narrow passband in EUV dominated by a bright emission line to alleviate intractability of the inversion process.

1.3.1 MOSES

The Multi-Order Solar EUV Spectrograph (MOSES) has successfully undertaken two flights. The first flight occurred in 2005 and observed the Sun in He II 304 Å(Fox, Kankelborg, and Thomas 2010) while the second flight was just recently completed in 2015 and observed the Sun in He VII 465 Å(Smart, Courrier, and Kankelborg 2016).



(a) Sketch of the optical system of MOSES

(b) The analogue of Figure 1 for the MOSES instrument.

Figure 2: Two diagrams used to visualize the imaging system of the MOSES instrument. Figure 2a demonstrates how a bimodal spectral signal represented by a red 'A' and a blue 'B' are imaged by the MOSES optical system. Figure 2b imagines the MOSES optical system as a 2D tomographic projection through a spatial-spectral cube. Figures courtesy of Fox, Kankelborg, and Thomas 2010

MOSES is a CT imaging spectrograph that uses a single concave diffraction grating to produce images in three spectral orders, $m = -1, 0, 1$, as in Figure 2a (Kankelborg and Thomas 2001). This instrument is designed with dispersion in only one plane. Therefore, in the parlance of Figure 1, ϕ is restricted to the values of 0 and π and then, without loss of generality, we can represent the 3D projections of Figure 1 as 2D projections through a plane, as in Figure 2b.

MOSES presents several challenges against achieving an accurate inversion. The most prevalent of these is the large astigmatism present in the outboard orders, which must be accommodated in any inversion process.

1.3.2 ESIS

The EUV Snapshot Imaging Spectrograph (ESIS) is the next generation of a CT imaging spectrograph developed by Kankelborg and his research group. This instrument will be equipped with one large focusing primary mirror, and small, dedicated diffraction gratings for each detector. The first flight is planned for 2019 and the instrument will be equipped with four detectors to image the $m = 1$ order in four separate dispersion directions. After the first flight has been completed, the system will undergo upgrades to install two additional gratings and detectors for a total of six tomographic projections.

The tomographic projections of the ESIS instrument can be visualized in terms of Figure 1. The dedicated diffraction gratings are arranged in an octagonal pattern, producing projections at $\phi = 0$, $\pi/8$, $\pi/4$, $3\pi/8$, $\pi/2$, $5\pi/8$, and $3\pi/4$. Since these projections are not all in the same plane (unlike the MOSES arrangement), the inversion problem cannot be reduced to two dimensions and must be solved in 3D.

1.4 Related Work

The task of inverting MOSES data has already been undertaken by several research projects (Fox, Kankelborg, and Metcalf 2003; Fox, Kankelborg, and Thomas 2010). The most effective inversion algorithm developed by these efforts is known as the *smooth multiplicative algebraic reconstruction technique* (SMART) developed by Kankelborg 2008 based off of earlier algebraic reconstruction techniques invented by Gordon, Bender, and Herman 1970 and refined by Okamoto and Yamaguchi 1991. As discussed in Section 1.2, any CTIS inversion algorithm must use physical constraints to find unique solutions. In the case of SMART, it uses the property that its solutions to the inversion problem must satisfy positivity and definitions of average line profiles to enforce physicality.

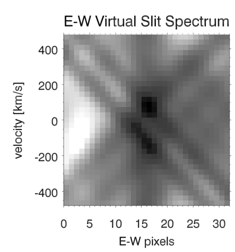


Figure 3: An example of plaid produced by SMART. The vertical dimension is the spectral dimension in units of relative doppler shift from line center, and the horizontal axis is position measured in pixels. Image courtesy of Thomas Rust.

The result is a very efficient algorithm that has been successfully used to determine doppler shifts and line profiles of explosive events in He II (Rust and Kankelborg 2016). Unfortunately, it has proven difficult to convince SMART to produce physical inversions across the entire MOSES dataset. This unphysicality is mainly produced by an artifacts known colloquially as *plaid*. As an example, in Figure 3 we can see that the bright object in the center has been blurred at the angles: $\theta = -\pi/4$, 0, and $\pi/4$ (with respect to the vertical) resulting in plaid.

Plaid occurs whenever SMART attempts to invert a set of CTIS images with a background signal. Therefore, to yield plausible results using SMART, the background must be manually subtracted to isolate and successfully invert the area of interest. This operation prevents the creation of an automated, global inversion process for MOSES data.

1.5 Project Goals

Snapshot imaging spectroscopy using CTIS is a promising method for resolving the spatial-spectral structure of explosive events. However, data analysis for these types of instruments is a challenging problem. Therefore, to approach our goal of determining the spatial structure of explosive events, we propose to conduct this investigation in two phases. In the first phase, we will develop a new algorithm to solve the inversion problem using neural networks. Our goals for this algorithm are speed and supression of plaid artifacts. During the second phase, we will apply our inversion techniques to MOSES and ESIS to explore the spatial scale of explosive events. The remainder of this proposal will be devoted to a discussion of the first phase due to space constraints. We hope to further develop ideas for analyzing the spatial-spectral cubes produced by MOSES and ESIS in later proposals.

2 Proposed Solution

So far, all CIAs have utilized physical constraints derived from first principles (such as positivity). This is not the only way however, instead an inversion algorithm could build physicality constraints based off of direct observation of the solar spectrum. For example, IRIS has been measuring the spectrum of the Sun since 2013 (DePontieu et al. 2014), and has amassed a large dataset composed of observations of the solar spectrum. An inversion algorithm that incorporates these observations has the potential to calculate inversions with greater accuracy because it has an appreciation for typical structures seen in solar EUV emission lines.

One possible way to appy a set of solar spectroscopic observations to an algorithm is by using machine learning. Machine learning is a problem solving technique that allows a computer to learn a relationship between a set of problems and their associated solutions. Artificial Neural Networks (ANNs) are possibly the most popular type of machine learning algorithms, and they have been used successfully to solve a wide variety of problems such as classification, function approximation, and data compression. Recently, it has been shown that ANNs have the capability to solve problems critical to solar data analysis such as denoising (Du et al. 2016) and PSF deconvolution (Xu et al. 2014). ANNs have even been successful in solving ill-posed problems (Kruglov and Mishulina 2013), inversion problems (Jafarian, Measoomy, and Abbasbandy 2015) and computed tomography problems (Boublil et al. 2015). Due to the success of ANNs at solving these types of problems we hypothesize that a CIA represented by a neural network and trained using real solar spectroscopic data would be able to form reasonable solutions to the inversion problem.

2.1 A Brief Introduction to Neural Networks

For the purposes of this proposal, we will view the neural network as a black box, with the capability to approximate any function (Russel and Norvig 2010). Neural networks can approximate any function, if they are provided enough free parameters known as *weights*. These weights are learned through a process known as training, where a neural network is presented with a large number of example inputs to the function to be approximated. The network is then asked to compute the value of the function, and it is given feedbaack based on the error between its value and a known value. Algorithms are used to minimize the error by adjusting the weights of the network.

2.2 Inversion Using Neural Networks

With the basic description provided in the previous section, we can begin to discuss how we one would build a CIA using neural networks, which we will call a *CTIS inversion neural network* (CINN). To summarize Section 1.2, a CIA solves a computed tomography problem, which reconstructs a 3D object using a set of 2D projections. Thus, a CINN's input layer will be a set of neurons representing each pixel in each 2D projection and a CINN's output layer will be a set of neurons representing each voxel of the SSC. These layers will be connected by an unknown number neurons to be determined during training.

To create the training dataset, we start by constructing a spatial-spectral model of the Sun. Since MOSES and ESIS are designed with a narrow passband, the spectral range of this model need not be immense, but it should be representative of the Sun as observed by MOSES and ESIS. As indicated above, this model will be composed of direct spectroscopic observations of the Sun from existing instruments. However, there are no spectrographs that observe the Sun in the same passband as ESIS and MOSES, so we will use observations of emission lines with comparable formation temperatures to that of the emission lines in the passband of MOSES and ESIS.

This spatial-spectral model forms what we will call the "truth dataset". From the truth dataset, we will generate the "input dataset" by using a forward model of the optical system of each instrument. MOSES and ESIS have different optical systems, so to solve the inversion problem for each instrument, we will be required to train two neural networks. The input and truth datasets taken together form the training dataset. During training, data from the input set will be fed into the CINN, and data from the truth dataset will be compared to the output of the CINN to direct the learning process.

2.2.1 MOSES Inversion

MOSES is the simplest instrument to implement a CINN because it can be represented as a 2D tomography problem (Section 1.3.1). As such, the training data for MOSES may be constructed out of simple slices of the SSC. Using the Si IV 1403 Å IRIS dataset to construct the truth dataset for this instrument is an obvious choice, as both the Si IV 1403 Å and He II 304 Å are both low transition region lines, and we simply want to inform our network of common features seen in these lines.

2.2.2 ESIS Inversion

Unlike MOSES, recovering the SSC from ESIS data requires a 3D solution to the inversion problem (Section 1.3.2). Therefore, the truth dataset of an ESIS CINN takes the form of an array of SSCs, which are most easily acquired by using IRIS in raster mode. Unfortunately, few of the rasters produced by IRIS are taken at a high enough spatial resolution to provide a realistic SSCs, and we will need a large number of SSCs to effectively train a CINN. There are several approaches to circumventing this problem, the easiest of which is to naively stacking spectral images to form a psuedo-realistic SSC to be inserted into the truth dataset.

2.3 Preliminary Results

To test if a CINN could be a useful inversion tool, we trained a CINN to invert a simplified forward model of MOSES. This CINN used a input dataset that did not incorporate elements of the MOSES forward model such as the PSF, shot noise or readout noise. While this simplification is certainly unrealistic, this CINN serves to illustrate a proof-of-concept and to justify additional research into this method.

This CINN was trained using approximately 500k truth images with a size of 21×21 pixels. These images were extracted from the IRIS Si IV 1403 Å dataset, and were background subtracted to further simplify the inversion problem for this test. This CINN was trained on an Nvidia 980 consumer GPU using the Caffe (Jia et al. 2014) neural network library.

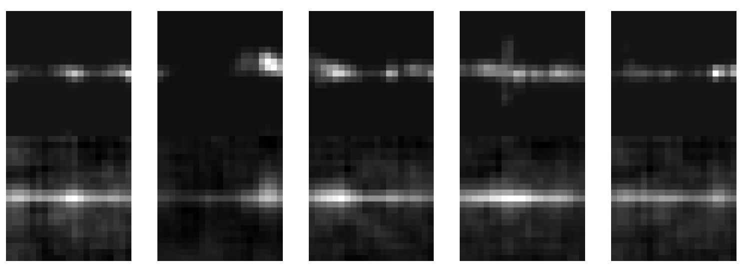


Figure 4: A visualization of the inversions produced by a simple implementation of a MOSES CINN. The top image is the truth image and the bottom images is the output of the CINN.

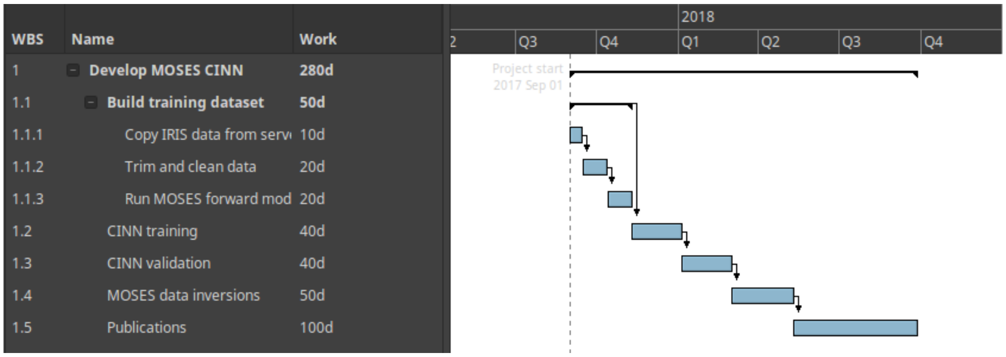
This test provides exciting verification to the efficacy of this method. The quality of the inversions show that the neural network is learning concepts such as: line center, mean line width and the correct distribution of intensity through the inversion. We can see that this neural network isn't always able to produce the exact line profiles of the more energetic events, and often overestimates the intensity of the line core. We hope to train later neural networks with much more data, and many more neurons, allowing the creation of more accurate CINNs.

3 Relevance to Heliophysics

The NASA Heliophysics Division has the goal of "Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system". We believe that the study of transition region explosive events fulfills the desired intent of that goal because these explosive events are thought to be direct evidence of reconnection. Reconnection is thought to be an important process in the dynamics of the solar atmosphere and further insight into these processes has many wide-reaching implications for heliophysics.

4 Project Timeline

The schedule for the first year of this proposal is described by the figure below.



We propose to use the CINN developed during the first year of this proposal to perform data analysis on data from ESIS, MOSES and orbital spacecraft during subsequent years. Defining a schedule for the last two years of this proposal is difficult due to the tenuous nature of spaceflight using sounding rockets. Therefore, we intend for the schedule of the second phase of this proposal to be the discussion of future proposals.

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Teriaca, L. et al. (2004). "Transition region small-scale dynamics as seen by SUMER on SOHO". In: *Astronomy & Astrophysics* 427, pp. 1065–1074. DOI: `10.1051/0004-6361:20040503`.

Wilhelm, K. (2000). "Solar spicules and macrospicules observed by SUMER". In: *Astronomy & Astrophysics* 360, pp. 351–362.

Xu, Li et al. (2014). "Deep Convolutional Neural Network for Image Deconvolution". In: URL: `http://papers.nips.cc/paper/5485-deep-convolutional-neural-network-for-image-deconvolution.pdf`.

Charles C. Kankelborg
Department of Physics
Montana State University
Bozeman, MT 59717-3840
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kankel@montana.edu

Education

Ph.D., September 1996 Department of physics, Stanford University, Stanford, CA. Dissertation: "Multispectral observations of coronal X-ray bright points"

B.S. (summa cum laude, Phi Beta Kappa, Sigma Pi Sigma, Phi Kappa Phi), June 1989 Department of Physics, University of Puget Sound, Tacoma, WA Honors thesis: "Instabilities of turbulent vortex wakes"

Research Interests

Solar magnetic activity; Coronal loops; X-ray bright points; Image analysis; EUV optics and instrument design; space instrumentation, control and telemetry.

Relevant Experience

2015 - present: Principal Investigator, *EUV Snapshot Imaging Spectrograph* (*ESIS*) sounding rocket investigation, NASA Heliophysics LCAS.

2014 - present: Professor, Department of Physics, Montana State University

2008 - present: Co-Investigator, *Inerface Region Imaging Spectrograph*, NASA Heliophysics Small Explorer mission. Responsible for spectrograph optics.

2001 - 2015: Principal Investigator, *Multi-Order Solar EUV Spectrograph* (*MOSES*) sounding rocket investigation, NASA Heliophysics LCAS.

2007 - 2014: Associate Professor, Department of Physics, Montana State University

2001 - 2007: Assistant Professor, Department of Physics, Montana State University

April 2001 - August 2001: Research Scientist, Department of Physics, Montana State University, Bozeman, MT.

Service

2012-present: NASA Sounding Rocket Working Group.

2011-2013, Judge for the National Solar Spectrograph Competition. This is part of the public outreach program for the NASA *IRIS* mission.

2009-2012: NASA Heliophysics Subcommittee.

April 2012 - present: Montana Space Grant Consortium Advisory Board

Served on a variety of NASA review panels, including the Solar Probe Plus Standing Review Board (Aug 2009 - Sep 2010), TMC reviews for two major space missions, SR& T, LCAS, and MIDEX science review.

Referee for The Astrophysical Journal, Solar Physics, and others. Chaired poster and oral sessions at AAS/SPD meetings.
Member, American Geophysical Union
Associate Member, Solar Physics Division of the American Astronomical Society
Member, American Scientific Affiliation

Awards

Spring, 2012: MSU Society of Physics Students Undergraduate Level Instructor Award.
2012: Kavli Frontiers of Science meeting, invited participant.
2011 and 2006: George Tuthill award (outstanding graduate level instructor, selected by the physics graduate students).
2010: Charles & Nora Wiley Faculty Award for Meritorious Research.
Presidential Early Career Award for Scientists & Engineers (PECASE), awarded December 19, 2008 at the White House, "for the development of novel instrumentation for imaging spectroscopy in Solar Physics; and for mentoring undergraduate and graduate students involved in experiments on sounding rockets."

Selected Publications

Dr. Kankelborg is author or co-author of 35 refereed and 144 total publications.

1. "Fast Differential Emission Measure Inversion of Solar Coronal Data", J. Plowman, C. Kankelborg, and P. Martens, *ApJ*, **771**, 2, (2013).

2. "Exploring the Interface Between the Sun's Surface and Corona", Charles Kankelborg, *Physics Today*, **65**, 72-73, (2012).

3. "Data inversion for the Multi-Order Solar Extreme-Ultraviolet Spectrograph", J. L. Fox, C. C. Kankelborg, and T. R. Metcalf, In *Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research V., Larar, Allen M.; Shaw, Joseph A.; Sun, Zhaobo., eds. Proc. SPIE*, volume 5157, pages 124–132, (2003).

4. "Evidence of Separator Reconnection in a Survey of X-Ray Bright Points", D. W. Longcope, C. C. Kankelborg, J. L. Nelson, and A. A. Pevtsov, *ApJ*, **553**, 429–439, (2001).

5. "Simultaneous imaging and spectroscopy of the solar atmosphere: advantages and challenges of a 3-order slitless spectrograph", C. C. Kankelborg and R. J. Thomas, In *Visible Space Instrumentation for Astronomy and Solar Physics, Oswald H. Siegmund; Silvano Fineschi; Mark A. Gummin; Eds., Proc. SPIE*, volume 4498, pages 16–26, (2001).

6. "Forward modeling of the coronal response to reconnection in an X-ray bright point", C. Kankelborg and D. Longcope, *Sol. Phys.*, **190**, 59–77, (1999).

Roy T. Smart

226 Barnard Hall
Bozeman, Montana 59717
(801) 906-1539
roy.smart@montana.edu

EDUCATION

Ph.D., Physics, Expected May 2020
Montana State University, Bozeman, MT

B.S., Physics, May 2015
Montana State University, Bozeman, MT

RESEARCH INTERESTS

Solar Physics: Solar transition region, explosive events, coronal heating.
Optics: Computed tomography imaging spectroscopy, photon sieves.
Scientific Computing: Neural networks, evolutionary algorithms, deconvolution.

EXPERIENCE

Graduate Research Assistant **Fall 2015 - Present**
Montana State University, Kankelborg Research Group, Bozeman, MT
Associated with MOSES III/ESIS solar sounding rocket:

- Data processing.
- Modeling CCD temperature bias.
- Performing optical alignment.
- Developing ground station software.

Graduate Teaching Assistant **Spring 2016**
Montana State University, Bozeman, MT
Lab TA for PHSX 220, Instructor: Dr. Nick Childs

Research Assistant **Spring 2013 - Spring 2015**
Montana State University, Kankelborg Research Group, Bozeman, MT
Associated with MOSES II solar sounding rocket:

- Performed thermal analysis of optical mount.
- Developed software used on embedded system for command and control of MOSES instrument during flight.
- Supported launch operations.

SELECTED POSTERS

Smart, R., Courrier, H., and Kankelborg, C. (2016), "Preliminary Results of the MOSES II 2015 Flight", AAS/Solar Physics Division Meeting, volume 47, page 309

Department of Physics

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January 31, 2017

To: NESSF Selection Committee

Dear Colleagues,

I am writing to recommend my PhD student, Roy Smart, for the 2017 NASA Earth and Space Science Fellowship program. Roy is a highly creative young scientist with a diverse set of talents and a strong work ethic.

Roy began working in my lab as an undergraduate student in Spring of 2013. At that time he made many contributions to our sounding rocket effort, including testing of optical mounts to thermal vac, flight computer hardware, telemetry interface testing, and software for flight and ground support.

Roy developed entirely new control and data handling software for our MOSES sounding rocket payload, which flew successfully in 2015. The requirements for this code included many interfaces, including real time camera commanding, camera data through a custom FPGA interface, shutter control, subsystem power control, science data handling to both SSD and telemetry, discrete uplinks, a two-way serial communications protocol, and implementation of a virtual shell. He did not have the advantage of a real time operating system, but used multithreading and messaging concepts adeptly. By this approach, he improved upon the performance and usability of our original flight software. Most importantly, he eliminated more than 1 second of unnecessary dead time between exposures, which increased the science output of the mission. Roy's code performed flawlessly during integration and testing, and in flight. He was also a key member of my small operations team at White Sands Missile Range that year. Roy and three others carried the ball and solved a multitude of problems to keep the integration and testing on schedule while I returned to Montana for several weeks to deal with a family emergency. Roy impressed everyone at the range with his keen technical ability, presence of mind, and dedication to the mission.

As a graduate student, beginning in Fall of 2015, Roy has become a key player in the development of our new instrument, the EUV Snapshot Imaging Spectrograph (ESIS). He is picking up optics quickly, working on the alignment of the MOSES instrument for reflight and becoming an expert with the interferometer. He is also a great team member, and works very effectively with undergrads, grad students, professional engineers, and our colleagues at MSFC who are providing the detector system for ESIS.

Roy came to me about a year ago with a crazy idea. He wanted to develop a neural network to invert the MOSES and ESIS rocket data.[1] I explained that this looked like a very challenging project, that I didn't know a thing about neural networks, and I would not be able to advise him on the implementation. That didn't seem to worry Roy. He attacked a scaled-down version of the problem as a project for my computational physics course, sought out expertise from the applied mathematicians across campus, took an artificial intelligence class, read a lot of literature, and kept attacking the problem with a combination of creativity and dogged persistence. Although I have been skeptical from the start, Roy has finally convinced me that his neural network approach is truly promising, and likely to result in a more realistic reconstruction of spectra. His success will make it possible to generate high fidelity 2D maps of doppler shift and line width from single exposures with our instruments, and that will have many implications for the kinds of solar science we can do in the future.

Roy completed the PhD written comprehensive exam last summer, passing on the first try. Now that he is finished with the comp and his coursework is nearly complete, he will be able to devote his attention to research. Meanwhile, Roy's interest in solar physics has been growing apace. Like all of my students, he participates actively in our solar journal club. He's also been coming to me, asking a lot of questions about the corona, transition region, chromosphere and photosphere. So, his ideas of how to apply MOSES data to solving scientific problems are developing rapidly at this point. I think that within another year he will be deeper in the scientific literature than many of his peers.

In 20 years, I have not seen a graduate student as creative and persistent as Roy Smart. And though he shows respect and deference to professors and other experienced people, he possesses sufficient initiative and self-confidence to explore his own unique ideas. He is an imaginative problem solver, an effective team member, and a good-spirited person who is bound to make his mark on the field of solar physics. I recommend him highly for the NESSF Fellowship.

Sincerely,

Charles C Kankelborg

Charles C. Kankelborg
Professor of Physics

[1] Both of our rocket instruments, MOSES and ESIS, rely on solving a tomographic inverse problem to turn a series of EUV images into spatial and spectral data cube. We have several working algorithms to perform this inversion, but all are susceptible to similar artifacts.

Department of Physics

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http://solar.physics.montana.edu/kankel/

January 27, 2017

To: NASA/NESSF Program

We affirm that this proposal is the work of the graduate student, Roy Smart, and not that of any other team member.

Sincerely,

Charles C. Kankelborg
Professor of Physics

Roy Smart
Graduate Student

Display Transcript

This is NOT an official transcript. Courses which are in progress may also be included on this transcript.

Transfer Credit Institution Credit Transcript Totals Courses in Progress

Transcript Data

STUDENT INFORMA TION

Name :	Roy T. Smart

Curriculum Information

Current Program

College:	College of Letters & Science
Major and Department:	Physics, Physics

***Transcript type:WEB is NOT Of ficial ***

DEGREES A WARDED:

Awarded:	Bachelor of Science	**Degree Date:**	May 08, 2015
Institutional Honors:	Honors		

Curriculum Information

College:	College of Letters & Science
Major:	Physics
Major Concentration:	Professional
Minor:	Computer Science

Sought:	Doctor of Philosophy	**Degree Date:**	

Curriculum Information

College:	College of Letters & Science
Major:	Physics

TRANSFER CREDIT ACCEPTED BY INSTITUTION -Top-

spr08-spr11: Advanced Placement Program

Subject	Course	Title	Grade	Credit Hours	Quality Points	R
GPHY	121D	Human Geography	TP	3.000	0.00	
M	171Q	Calculus I	TP	4.000	0.00	
PHSX	220	Physics I (w/ calculus)	TP	4.000	0.00	
PHSX	222	Physics II (w/ calculus)	TP	4.000	0.00	
STAT	216Q	Elementary Statistics	TP	3.000	0.00	

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	18.000	18.000	18.000	0.000	0.00	0.00

Unofficial Transcript

INSTITUTION CREDIT -Top-

Term: 2011 Fall Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
ANTY	215IS	UG	Human Prehistory	C+	3.000	6.90			
PHSX	240	UG	Honors Gen & Mod Phys I	A	4.000	16.00			
UH	201US	UG	Texts & Critics:Knowledge	B+	4.000	13.20			
WRIT	101W	UG	College W riting I	B+	3.000	9.90			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	14.000	14.000	14.000	14.000	46.00	3.28
Cumulative:	14.000	14.000	14.000	14.000	46.00	3.28

Unofficial Transcript

Term: 2012 Spring Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CHIN	211D	UG	Chinese Culture & Civilization	W	3.000	0.00			
CSCI	111	UG	Programming with Java I	B	4.000	12.00			
EELE	101	UG	Intro Electrical Fundamentals	A-	2.000	7.40			
M	172Q	UG	Calculus II	C	4.000	8.00			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	13.000	10.000	10.000	10.000	27.40	2.74
Cumulative:	27.000	24.000	24.000	24.000	73.40	3.05

Unofficial Transcript

Term: 2012 Fall Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CHMY	141	UG	College Chemistry I	B+	4.000	13.20			
CSCI	132	UG	Bsc Data Structures/Algorithms	C+	4.000	9.20			
M	273Q	UG	Multivariable Calculus	B	4.000	12.00			
PHSX	200	UG	Research Programs in Physics	P	1.000	0.00			
PHSX	224	UG	Physics III	B+	4.000	13.20			
PHSX	261	UG	Laboratory Electronics I	B	2.000	6.00			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	19.000	19.000	19.000	18.000	53.60	2.97
Cumulative:	46.000	43.000	43.000	42.000	127.00	3.02

Unofficial Transcript

Term: 2013 Spring Semester	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
M	274	UG	Intro to Differential Equation	D	4.000	0.00		E	
PHSX	262	UG	Laboratory Electronics II	B	2.000	6.00			
PHSX	301	UG	Intro Theoretical Physics	B	3.000	9.00			
PHSX	305RN	UG	Art & Science of Holography	C	3.000	6.00			
PHSX	490R	UG	Undergraduate Research	A	2.000	8.00			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	14.000	10.000	10.000	10.000	29.00	2.90
Cumulative:	60.000	53.000	53.000	52.000	156.00	3.00

Unofficial Transcript

Term: 2013 Fall Semester	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
M	221	UG	Introduction to Linear Algebra	A-	3.000	11.10			
M	274	UG	Intro to Differential Equation	A	4.000	16.00		I	
PHSX	320	UG	Classical Mechanics	A-	4.000	14.80			
PHSX	331	UG	Meth of Computational Physics	A	1.000	4.00			
PHSX	343	UG	Intermediate Physics	A	3.000	12.00			
PHSX	441	UG	Solid State Physics	B+	3.000	9.90			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	18.000	18.000	18.000	18.000	67.80	3.76
Cumulative:	78.000	71.000	71.000	70.000	223.80	3.19

Unofficial Transcript

Term: 2014 Spring Semester	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CSCI	232	UG	Data Structures and Algorithms	B	4.000	12.00			
M	386R	UG	Software Appl in Mathematics	A	3.000	12.00			
PHSX	423	UG	Electricity and Magnetism I	A	3.000	12.00			
PHSX	435	UG	Astrophysics	A	3.000	12.00			

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
PHSX	446	UG	Thermodynamics & Stat Mech	B+	3.000	9.90			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	16.000	16.000	16.000	16.000	57.90	3.61
Cumulative:	94.000	87.000	87.000	86.000	281.70	3.27

Unofficial Transcript

Term: 2014 Summer Session

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CSCI	112	UG	Programming with C I	A	3.000	12.00			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	3.000	3.000	3.000	3.000	12.00	4.00
Cumulative:	97.000	90.000	90.000	89.000	293.70	3.30

Unofficial Transcript

Term: 2014 Fall Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CSCI	361	UG	Computer Architecture	A	3.000	12.00			
M	333	UG	Linear Algebra	C-	3.000	5.10			
MUSI	203IA	UG	American Popular Music	A	3.000	12.00			
PHSX	425	UG	Electricity and Magnetism II	B	3.000	9.00			
PHSX	444	UG	Advanced Physics Lab	A-	4.000	14.80			
PHSX	461	UG	Quantum Mechanics I	A	3.000	12.00			
PHSX	494	UG	Seminar/W orkshop	P	1.000	0.00			

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	20.000	20.000	20.000	19.000	64.90	3.41
Cumulative:	117.000	110.000	110.000	108.000	358.60	3.32

Unofficial Transcript

Term: 2015 Spring Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CSCI	305	UG	Concepts/Programming Languages	A	3.000	12.00			
CSCI	442	UG	Comp V ision: Robot Vision	A	3.000	12.00			
CSCI	476	UG	Computer Security	A	3.000	12.00			
CSCI	492	UG	Independent Study	A	1.000	4.00			
					3.000	9.00			

PHL	101IH	UG	Intro Phil:Reason and Reality	B		
PHSX	451	UG	Elem Particle Physics	B	3.000	9.00
PHSX	462	UG	Quantum Mechanics II	B	3.000	9.00
PHSX	499R	UG	Senior Capstone Seminar	A	1.000	4.00

Term Totals (Undergraduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	20.000	20.000	20.000	20.000	71.00	3.55
Cumulative:	137.000	130.000	130.000	128.000	429.60	3.35

Unofficial Transcript

Term: 2015 Fall Semester	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
PHSX	501	GR	Advanced Classical Mechanics	A-	3.000	11.10			
PHSX	506	GR	Quantum Mechanics I	A	3.000	12.00			
PHSX	566	GR	Mathematical Physics I	A-	3.000	11.10			
PHSX	594	GR	Sem: Teaching	P	1.000	0.00			

Term Totals (Graduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	10.000	10.000	10.000	9.000	34.20	3.80
Cumulative:	10.000	10.000	10.000	9.000	34.20	3.80

Unofficial Transcript

Term: 2016 Spring Semester	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
PHSX	507	GR	Quantum Mechanics II	A	3.000	12.00			
PHSX	519	GR	Electromagnetic Theory I	B+	3.000	9.90			
PHSX	567	GR	Mathematical Physics II	A	3.000	12.00			
PHSX	594	GR	Sem: Intro to Rsch	P	1.000	0.00			

Term Totals (Graduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	10.000	10.000	10.000	9.000	33.90	3.76
Cumulative:	20.000	20.000	20.000	18.000	68.10	3.78

Unofficial Transcript

Term: 2016 Summer Session	
College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
PHSX	592	GR	Independent Study	A	1.000	4.00			

Term Totals (Graduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	1.000	1.000	1.000	1.000	4.00	4.00
Cumulative:	21.000	21.000	21.000	19.000	72.10	3.79

Unofficial Transcript

Term: 2016 Fall Semester

College:	College of Letters & Science
Major:	Physics
Academic Standing:	Good Standing

Subject	Course	Level	Title	Grade	Credit Hours	Quality Points	Start and End Dates	R	CEU Contact Hours
CSCI	446	GR	Artificial Intelligence	B+	3.000	9.90			
PHSX	520	GR	Electromagnetic Theory II	A-	3.000	11.10			

Term Totals (Graduate - Semester)

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Current Term:	6.000	6.000	6.000	6.000	21.00	3.50
Cumulative:	27.000	27.000	27.000	25.000	93.10	3.72

Unofficial Transcript

TRANSCRIPT T OTALS (GRADUA TE - SEMESTER) **-Top-**

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Total Institution:	27.000	27.000	27.000	25.000	93.10	3.72
Total Transfer:	0.000	0.000	0.000	0.000	0.00	0.00
Overall:	27.000	27.000	27.000	25.000	93.10	3.72

Unofficial Transcript

TRANSCRIPT T OTALS (UNDERGRADUA TE - SEMESTER) **-Top-**

	Attempt Hours	Passed Hours	Earned Hours	GPA Hours	Quality Points	GPA
Total Institution:	137.000	130.000	130.000	128.000	429.60	3.35
Total Transfer:	18.000	18.000	18.000	0.000	0.00	0.00
Overall:	155.000	148.000	148.000	128.000	429.60	3.35

Unofficial Transcript

COURSES IN PROGRESS **-Top-**

Term: 2017 Spring Semester

College:	College of Letters & Science
Major:	Physics

Subject	Course	Level	Title	Credit Hours
EELE	582	GR	Optical Design	3.000
PHSX	535	GR	Statistical Mechanics	3.000
PHSX	591	GR	Sp: Solar flares and CMEs	3.000

Unofficial Transcript

RELEASE: 8.7.1