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Comparative Fractal Analysis of 2013 November 5 Multiple Solar Eruptions with Fokker-Planck Equation Using Solar Dynamics Observatory Digital Images

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***Abstract*—Digital solar images are available to users with access to standard, mass-market software. This project examines the advantages of using ImageJ, a popular free software from NIH, for comparative fractal analysis of the 2013 November 5 multiple solar eruption images in the Solar Dynamics Observatory Database. The Fokker-Planck equation based description of brightness fractal dimension probability density function has been shown to be important to the understanding of the brightness fluctuation. The project results suggest observable trends in box-counting fractal dimension of the brightness signal before an eruption in the AIA-13.1 nm hot channel. The project has been valuable in giving community college pre-engineering students some hands-on experience in research projects. The proposed algorithm would help to establish a publicly smartphone accessible, computing network that could assist in exploratory studies of FITS data in community college science and pre-engineering classes including outreach programs.**

Keywords*— *fractal dimension; brightness statistics; probability density function, ImageJ free download

I. Introduction

Community college pre-engineering students sometime need extra counseling on which career path such as professional engineers, research engineers, information technology engineer, etc. Hands-on experience gained in doing a research project in a laboratory and presenting the results in conferences would enhance motivation and improve retention. The Sun provides us with energy but its eruption effect on space weather has been observed to disrupt and damage power grids on Earth. NASA, NOAA, ESA etc has been funding spacecraft missions for solar observations. Digital solar images are available to users with access to standard, mass-market software such as ImageJ, Photoshop, etc. Many scientific projects utilize the Flexible Image Transport System (FITS) format, which requires specialized software typically used in astrophysical research. Data in the FITS format includes photometric and spatial calibration information, which may not be readily useable to researchers having little time to invest their effort to read FITS files with dedicated programs, especially when the researchers are working with self-calibrated comparative approaches. This project examines the advantages of using mass-market software with readily downloadable coronal image data in multiple wavelengths from the Solar Dynamics Observatory SDO AIA instrument for comparative analysis as compared to the use of specialized software capable of reading data in the FITS format. The free software ImageJ from NIH had been updated to read FITS files. Usually FITS file could be read and processed by FV-tool Visualizer available from NASA High Energy Astrophysics Division [1]Comparative analyses of brightness statistics that describe the solar using algorithms included in mass-market free software on images in JPEG, GIF, etc give results similar to analyses using FITS data. The statistical histogram feature in Photoshop works well but lacks advanced features such as fractal dimension analysis. This paper focuses on the details of using ImageJ algorithms on MPEG-JEPG files as compared to FITS files. The proposed algorithm would help to establish a publicly smartphone accessible, computing network that could assist in exploratory studies of all FITS data. ImageJ is considered as simple mass-market software since our experience in teaching ImageJ to community college students majoring in liberal arts has been very successfully over the years. Other authors have found success in teaching ImageJ algorithms in astronomy projects [2] and in classes as well [3]. The advances in computer, smartphone and tablet technology could incorporate such an approach readily for the enhancement of high school and first-year college space weather education on a global scale. The importance of solar irradiance forcing in climate model has been recognized [4].

II. MATERIALS AND METHODS

The Solar Dynamics Observatory (SDO) AIA FITS files are documented [5]. The FITS data, and the MPEG movies intended for the general public are also available [6]. ImageJ is downloadable from NIH website [7]. The frames in a SDO movie can be captured by Quick Time for example, and can be stored as images in JPEG, GIF, etc. SDO also put up individual images in JPEG, GIF, etc for interesting events such as solar flare, coronal mass ejection, etc. on their website for popular viewing. These static images have been studied and compared to their counterpart FITS files. Testing statistical parameters include coefficient of variation (standard deviation divided by average) and box counting image fractal dimension (explained in ImageJ online help website).

III. RESULTS OF IMAGE DATA ANALYSIS

A typical solar coronal image is shown in Figure 1. The data was copied onto the clipboard from a MPEG movie by using Quick Time. The data has been stored as JPEG format. The box counting fractal dimension values of the JPEG file and FITS file agree well. The given example is used for illustration.

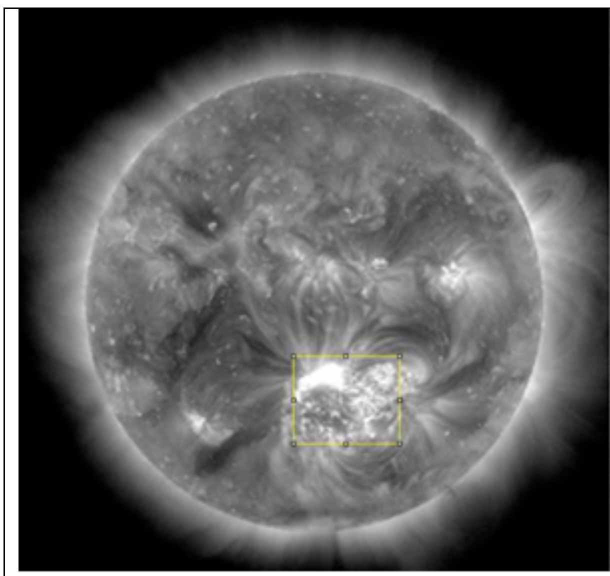

Figure 1: The JPEG file of the SDO 2012 July 12 17:15:21 observed at 19.3 nm. The box fractal dimension was found to be ~ 1.7189 by ImageJ box counting fractal dimension algorithm. Note that Microsoft Word might have distorted the aspect ratio upon pasting.

The ImageJ image fractal dimension algorithm was applied to the JPEG box region and the result is displayed in Figure 2.

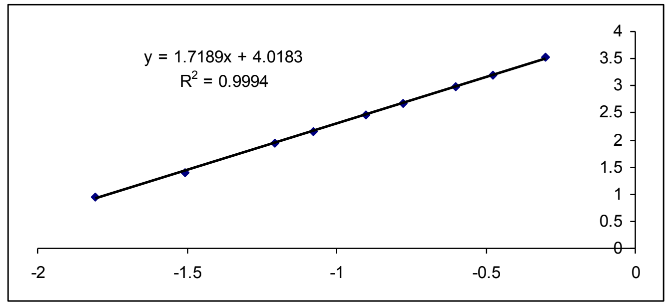

Figure 2: Logarithm of L(k) (y-axis) versus logarithm of 1/k for the SDO 2012 July 12 17:15:21 19.3 nm JPEG data box region.

The FITS data directly from SDO is displayed below in Figure 3.

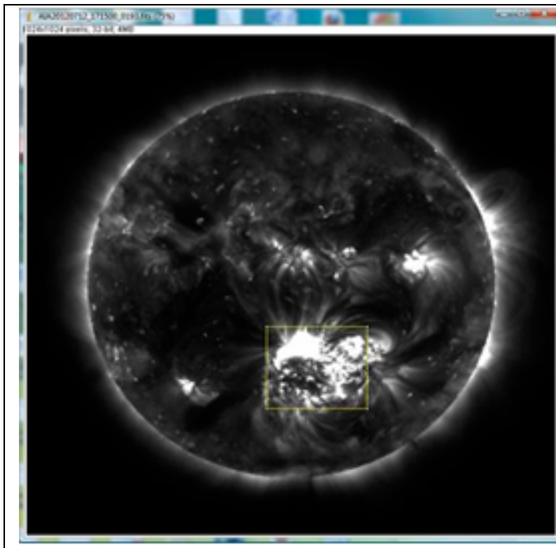

Figure 3: The FITS file of the SDO 2012 July 12 17:15:00 image observed at 19.3 nm. The box fractal dimension was found to be ~ 1.73 by ImageJ box counting fractal dimension algorithm. Note that Microsoft Word might have distorted the aspect ratio upon pasting.

The ImageJ image fractal dimension algorithm was applied to the FITS box region and the result is displayed in Figure 6. The JPEG and FITS image fractal dimension values agree well.

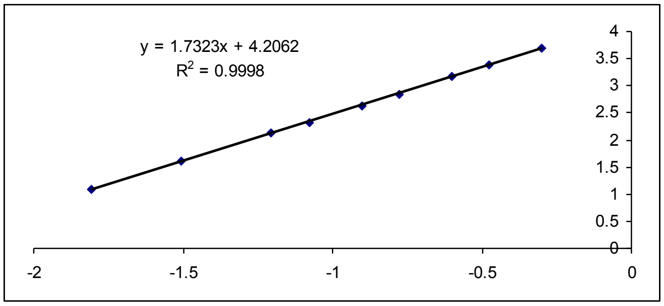

Figure 4: Logarithm of L(k) (y-axis) versus logarithm of 1/k for the SDO July 12 17:15:00 19.3 nm FITS data box region.

The coefficient of variation CV (standard deviation divided by average) values also agrees well within a few percent between JPEG and FITS files for self-calibrated comparative studies. Photoshop Elements software also gives histogram statistics with deviation and average information for CV calculation, providing values consistent with ImageJ's pixel counting algorithm.

The 2013 Nov 5 SDO images show multiple eruptions including a solar flare class of X3.3 at the end of the day. The Nov 5 13.1 nm video starts from frame-0 and ends at frame-95. The Sunspot AR1890 source provided a Class X3.3 flare at 22:15:34 UT in the 13.1-nm wavelength 15-min time gap video, while the X3.3 flare eruption peaked ~ 22:12 UT on Nov 5 with another X1.1 flare eruption on Nov 7, according to NASA [8].

The brightness statistics of solar active region, represented by the area 76 width by 63 height pixels with an upper left coordinate at (151, 589) at frame-0,.is shown below in Figure 5. The JPEG CV (coefficient of variation) has a value of 0.263 while the FITS CV has a value from 0.255 (with 3.96 background subtraction in ImageJ) to 0.266 (with a background subtraction of 4.08 in Image J). The FITS data processing subtraction also affects the fractal dimension. The JPEG box counting fractal dimension has a value of 1.672 while the FITS fractal dimension has a value from 1.682 (with 3.96 background subtraction in ImageJ) to 1.678 (with a background subtraction of 4.08 in Image J). The FITS file would require subtraction since it contains all photons including noise signals that are processed already by NASA in their movie clips.

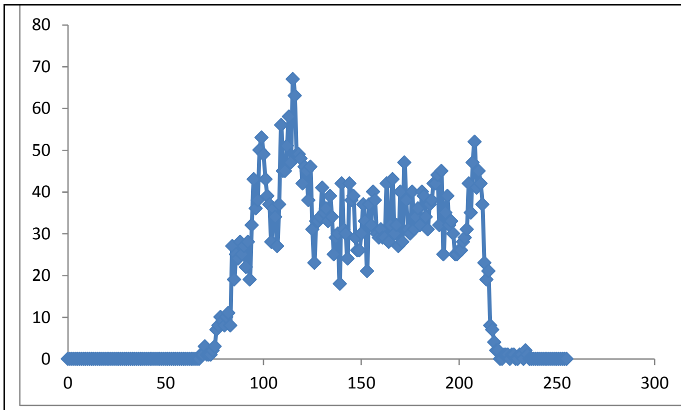

Figure 5: Brightness statistics: Number (y-axis) versus brightness (x-axis) at 2013 Nov 5 00:01:10 UT. The area represents the solar active region 76 width by 63 height pixels with an upper left coordinate at (151, 589) at frame-0.

In order to focus on the bright pixel variation in space and time, the box counting fractal dimension was computed after subtracting out the low valued pixel. Using figure 7 as a guide, a subtraction value of 200 was used. Similarly, a value of 130 was used for the comparative region, an area of 76 width by 63 height pixels with an upper left coordinate at (151, 519) at frame-0. The box-counting fractal dimension results are displayed in Figure 6. The upper curve shows periodic dip before eruptions in contrast to the comparative region. Eruption would eliminate brightness fluctuation correlation across pixels and thus would suppress the fractal dimension in both JPEG and FITS data analysis.

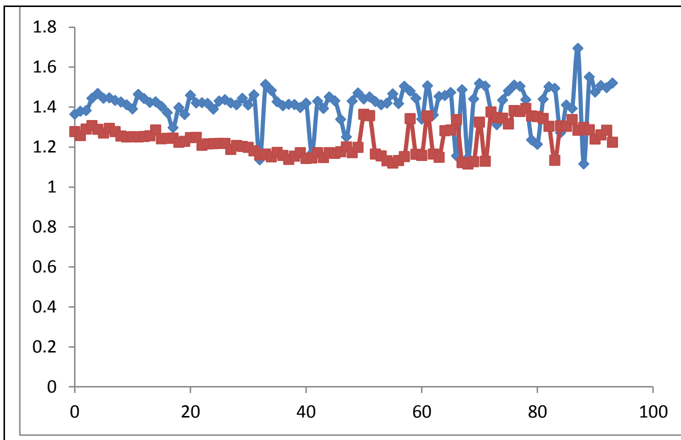

Figure 6: Box counting fractal dimension (y-axis) versus time in 15 min resolution (x-axis). X-axis starts at 2013 Nov 5 00:01:10 UT and ends at 23:46:31 UT in the JPEG data. The upper curve data (diamonds) represent the solar active region 76 width by 63 height pixels with an upper left coordinate at (151, 589) at frame-0, and the lower curve data (square) represent the solar regular region 76 width by 63 height pixels with an upper left coordinate at (151, 519) at frame-0; in the 1024 by 1024 pixels image. The algorithm includes coordinate compensation for the solar rotation while keeping the same area size of interest.

IV. DISCUSSION

Comparative analyses of brightness statistics that describe the solar disk brightness variation using ImageJ algorithms on JPEG-MPEG files have been shown to give results similar to analyses using FITS data. Intensity increment datasets, (I2-I1)/I1 or d (log I)/ d (pixel), have been used for the study of volatility in Hubble ultra-deep field data, another measure of correlated randomness [9]. The movie clip JPEG data already include the log function in contrast to FITS data. The box-counting fractal dimension in the log brightness is a measure of correlation in log mass with accepted creditability from the stellar theory on the proportionality between luminosity and mass-cubed. The AIA Fe-(XXI) 13.1 nm hot channel image data of the corona (about 10 million Kelvin) has been used to study magnetic flux rope in side-loop images [10]. Sunspot probability density function (pdf) modeled with Fokker-Plank equation (Figure 7) on star-spot cycle has been published [11].

$$\frac{\partial f}{\partial t} = \frac{1}{2}\sigma^2(s_0, t_0)\frac{\partial^2 f}{\partial s^2} - \mu(s_0, t_0)\frac{\partial f}{\partial s}.$$

Figure 7: Fokker Planck equation tracks the development of the sunspot number probability density function $f(s, t)$ with s_0 for the initial sunspot number and t_0 as the initial time. The right hand side contains the diffusion term with coefficient σ , and the advection term with coefficient μ.

Basically the sunspot number pdf evolution in time has been modeled with the Fokker-Planck equation, which was shown to represent an unknown stellar cycle driver function in terms of advection and diffusion, with the extracted coefficient values using the Wolf Number dataset over 200 years. Similar to sunspot number pdf, bright area fractal dimension pdf distribution can be modeled as extraordinary spot pdf, driven by an unknown magnetic reconnection function; and thus the bright area fractal dimension pdf would follow similar Fokker-Plank description where the s variable in Figure 7 would stand for the bright area fractal dimension. In fact the Fokker-Planck description of a pdf could be interpreted as a model on a stochastic variable in the Ornstein–Uhlenbeck process in mathematics. The box counting fractal dimension would include spatial variation, a more useful number in developing a space and time model that can track the magnetic reconnection. The analytical sunspot number pdf solution to the Fokker-Planck equation with constant advection and diffusion coefficients has been given in and would be valid in short time frames [11]. Using the fractal dimension data in the upper curve in Figure 6, and excluding the fractal dimension values during explosions, three histograms of fractal dimension in three different time periods can be built. In other words the overall histogram for the entire studied duration shown in Figure 8 can be separated into three time periods. In a first order approximation approach, the histogram average in time would track the advection term in the Fokker-Planck equation of fractal dimension pdf, and the histogram standard deviation would track the diffusion term. For the three time periods, histogram average changes as 1.412, 1.434, and 1.439 respectively; and the standard deviation changes as 0.036, 0.037, and 0.068 respectively. The change or growth of the histogram represents the pdf changes and would be describable by a Fokker-Planck equation model.

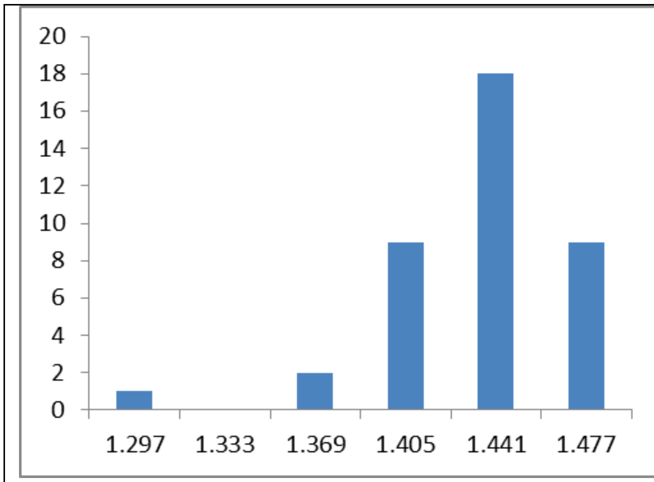

Figure 8: Bright area fractal dimension histogram for the entire studied duration.

The speculation whether the standard deviation in the third period would be unreliable, due to the X3.3 flare, would need more data analysis from other wavelengths and solar eruptions. The possibility that solar eruption could have be driven by the advection term in the AR1890 Nov-5-data is interesting for future studies. Furthermore the traditional use of Fokker-Planck equation for the studying of stochastic variable distribution evolution in time, for example, the energy and angular momentum variables in rotating stellar cluster investigation [12], can also be incorporated in a Fokker-Planck approach in the study of magnetic flux rope energy.

In general ImageJ is suitable for teaching community college pre-engineering students and high school STEM students about digital solar image analysis with application to space weather research in regular classes and outreach programs. The advances in computer, smartphone and tablet technology could incorporate such an approach readily for teaching space weather education with relationship to climate model on a global scale. Of course, the background subtraction in the FITS format would affect the numerical values but comparative approach would be more robust to background subtraction in data processing in principle. The compression scheme used by NASA in the JPEG-video is acceptable for comparative studies especially for community college students. In fact NASA continues to include some science information on solar eruptions in general news releases such as using the SDO AIA-13.1 nm data at about 10 million Kelvin as the magnetic flux rope maker in contrast to the 19.3 nm data at about 1.6 million Kelvin in the 2012 July 18 eruption with side-loop feature [13]. It has been pointed out by Polsterer in the Heidelberg Institute for Theoretical Studies Astro-informatics Group that the amount of astronomy data are increasing exponentially with new detectors and instrument innovation in engineering while the number of astronomers does not [14. 15]. Therefore there is an important need for machine learning in the automation of data handling and pipeline with informative numbers beyond just posting fascinating images in the public domain. The above approach would be amenable for machine learning and deployable in smartphone apps used in mobile technology, in FITS and/or JPEG formats.

V. CONCLUSIONS

This project examines the utilization advantages of using mass-market software ImageJ with readily downloadable image data in JPEG-MPEG from the Solar Dynamics Observatory for comparative analysis. The box counting fractal dimension in ImageJ has been shown to be able to track the Sunspot AR1890 responsible for the 2013 Nov 5 solar eruptions ending with a X3.3 flare on that day. The fractal dimension histogram changes could be modeled in a Fokker-Planck equation approach yielding informative features for space weather research. The analysis is amenable for machine learning environment adaption and deployable in apps used in mobile technology for digital learners. The project has been valuable in giving community college pre-engineering students some hands-on experience in research projects.

ACKNOWLEDGMENT

The authors thank the research groups cited in this paper for posting their data and programs in the public domain.

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