Experimental Validation of the Relativistic Runaway Electron Avalanche (RREA) Model using an Array of Cosmic Ray Muon Detectors

E. R. Benton[1*], A. N. Ruse[1], N. C. Lindy[1], D. Petersen[2], and W. Beasley[2]
[1]Radiation Physics Laboratory, Oklahoma State University
[2]School of Meteorology, University of Oklahoma

ABSTRACT: Despite the fact that some version of the Relativistic Runaway Electron Avalanche (RREA) model is considered by many to be the most likely explanation of lightning initiation, there have been few efforts at experimental validation of this model. We are attempting to experimentally validate the RREA model by correlating time- and location-resolved lightning initiation data from the Oklahoma Lightning Mapping Array (OKLMA) with time- and location-resolved cosmic ray muon count rate data. Secondary cosmic ray muons are used as a proxy for relativistic seed electrons produced in cosmic ray extensive air showers (CREAS) since few secondary cosmic ray electrons make it to the ground before ranging out. An array of four ground-based cosmic ray muon detectors have been designed, fabricated, and deployed in the shape of a 200 m square within the central area of coverage of the OKLMA. Each detector consists of a pair of plastic scintillators separated by a 3 cm layer of Pb in order to discriminate between relativistic muons and lower energy electrons and γ-rays, including those of terrestrial origin. Each detector measures the muon count rate with sub-millisecond resolution and data from the four detectors are combined to identify large CREAS. Data from the cosmic ray muon detectors obtained while thunderstorms pass over the array are then compared to OKLMA data. We present preliminary results from this experiment and describe how the cosmic ray muon detector array can be expanded to obtain higher resolution data over a wider area of coverage.

INTRODUCTION

One of the major unanswered questions in lightning research is how lightning discharges are initiated. According to Marshall et al. [2005], the peak electric fields within a thunderstorm are an order of magnitude weaker than is needed to achieve conventional, dielectric breakdown of the atmosphere [Bazelyan and Raizer 1998]. Several theories have been developed to achieve electric breakdown at measured thunderstorm electric field strengths [Latham and Roxburgh 1966; Gurevich et al. 1992; Petersen, et al. 2008]. The Relativistic Runaway Electron Avalanche (RRBA) model proposed by Gurevich et al. [1992] is currently considered one of the most likely explanations for lightning initiation [Dwyer et al. 2003; Dorman 2004], despite the lack of experimental verification.

The RREA model theorizes that a population of high energy seed electrons traveling through a strong electric field region of a thunderstorm produces enough secondary electrons to initiate a lightning discharge. In fair weather electric fields, high energy secondary electrons from CREAS lose energy via ionization and bremsstrahlung while traveling through the atmosphere. The amount of energy lost by the high energy electrons to both types of interactions per unit path length is called the stopping power [ICRU 1984]. Figure 1 displays electron stopping power at an altitude of 6 km in typical thunderstorm conditions [Burning et al. 2007].

* Corresponding Author: Dr. Eric Benton, Radiation Physics Laboratory, Oklahoma State University, 1110 Innovation Way Dr. #100, Stillwater, OK, USA, Email: eric.benton@okstate.edu

High energy electrons can be accelerated by the strong electric fields found within active thunderstorms. For a specific range of electron energies, the energy gained from being accelerated in the electric field can be greater than the energy lost to ionization and bremsstrahlung and these electrons are called runaway electrons [Gurevich et. al. 1992]. In Figure 1, electrons with a stopping power below the red line will become runaway electrons in a 300 kV m^{-1} vertical electric field. Runaway electrons do not range out in the atmosphere (i.e. lose all their kinetic energy and stop) and instead continuously produce secondaries via ionization and bremsstrahlung. Depending on the energy of secondary electrons produced by runaway electrons, these secondary electrons can also become runaway electrons. The number of runaway electrons and their secondaries increase exponentially with distance and are collectively called a RREA. In the RREA model, multiple RREAs create a dense electron plasma to breakdown the atmosphere and generate an electric discharge [Gurevich et al. 1992].

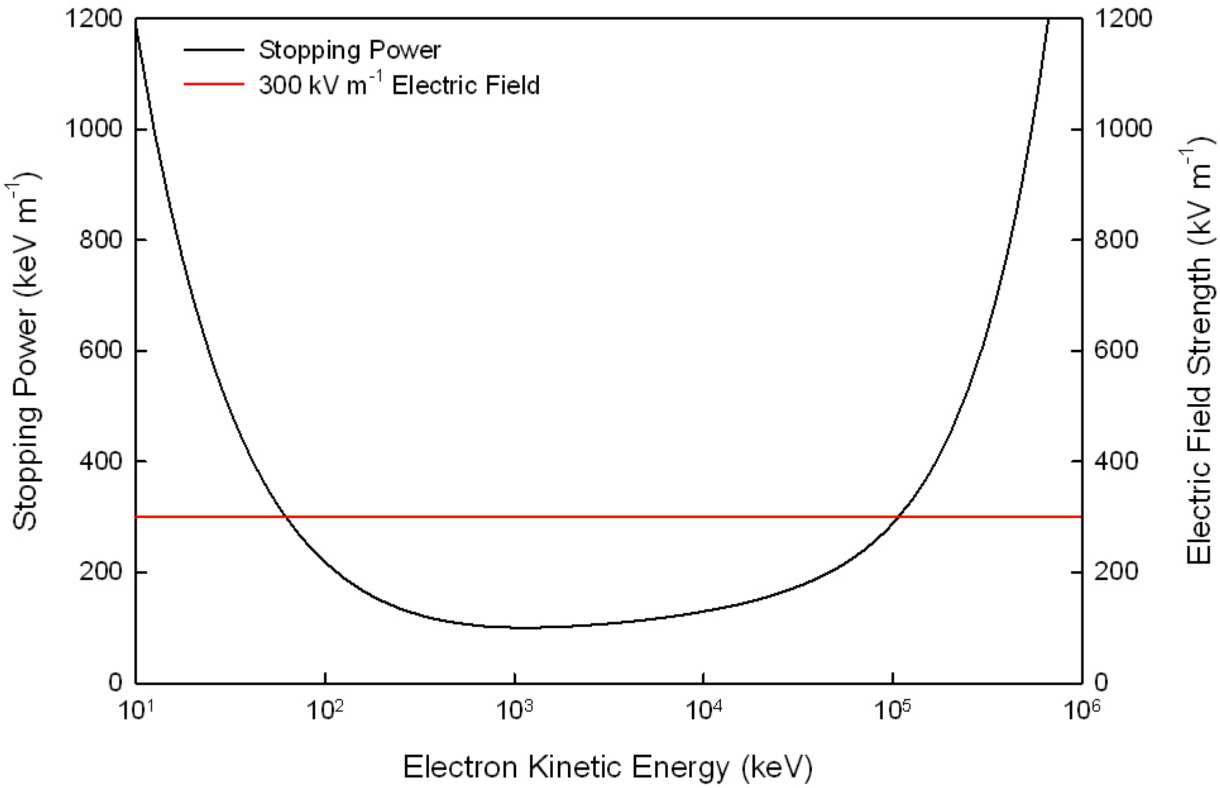

Figure 1: Electron stopping power as a function of electron kinetic energy at an altitude of 6 km in thunderstorm conditions (black curve). The red line represents a 300 kV m^{-1} electric field [Burning et al. 2007; NIST 2014].

The initial high energy, seed electrons are thought to be created by cosmic ray extensive air shower (CREAS). CREAS are initiated in nuclear interactions between primary cosmic rays and atmospheric nuclei. Primary cosmic rays are made up of protons, electrons, photons, and heavy ions of energies between 10^8 to 10^{20} eV [Grieder 2010]. When cosmic rays enter the atmosphere, they undergo nuclear interactions with atmospheric nuclei, usually N or O, producing many types of secondary particles including charged and neutral pions. Neutral pions have a half-life ~10^{-14} s and decay into two high energy gamma photons [Beringer et al. 2012].

The two high energy gamma photons undergo pair production in the atmosphere and initiate an electromagnetic cascade [Rossi 1952]. Electromagnetic cascades are responsible for creating the high energy seed electrons needed for the RREA model.

Outside the strong electric field region of a thunderstorm, electrons do not gain enough energy by being accelerated in the electric field to overcome their energy losses via ionization and bremsstrahlung. These electrons slow down and eventually stop in the atmosphere, i.e. range out.

Secondary muons are produced via the decay of the charged pions produced in a CREAS. Muons are leptons like electrons, except they have ~200 times the mass. Due to their large mass, muons lose the majority of their energy via ionization [Rossi & Greisen 1941] and can be measured deep underground [Grieder 2001; Dorman 2004]. Secondary muons are produced at approximately the same time as the electromagnetic cascades are initiated [Grieder 2010]. For this reason, secondary muons measured on the ground can be used as a proxy for high energy secondary electrons higher in the atmosphere.

We are attempting to experimentally validate the RREA model by correlating time- and location-resolved lightning initiation data from the Oklahoma Lightning Mapping Array (OKLMA) with time- and location-resolved cosmic ray muon count rate data from an array of four cosmic ray muon detectors located in Norman, OK. Details of the design and operation of the OKLMA can be found in Krehbiel et al. [2000]. The construction design of the muon detector array is discussed in Methods section. Preliminary results of correlating lightning initiations with CREASs are also shown.

METHODS

Cosmic Ray Muon Detector Design

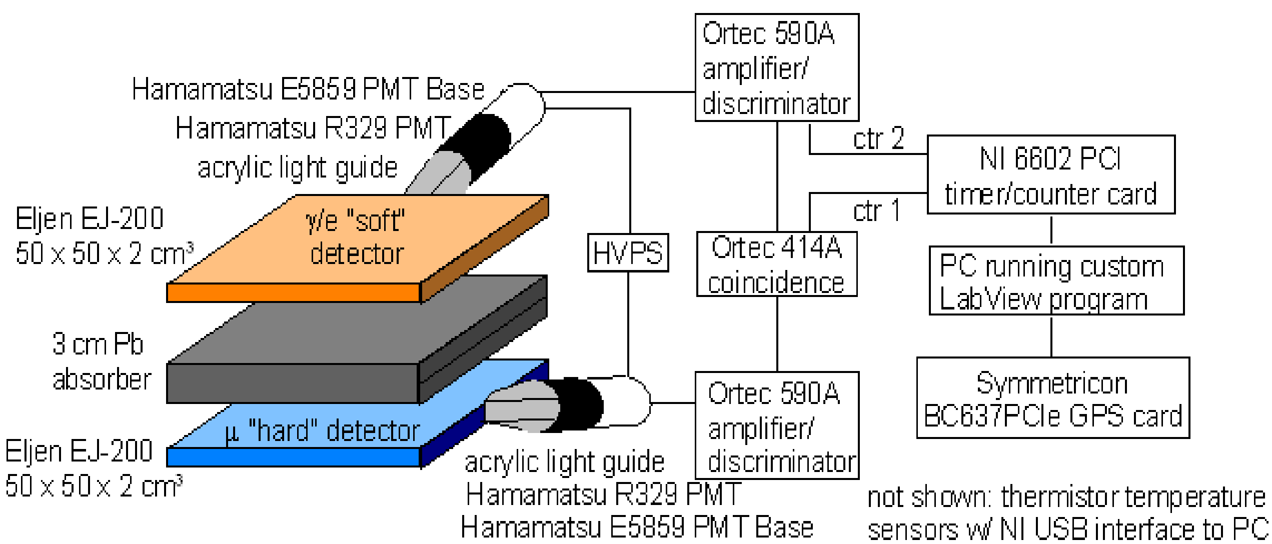

Figure 2: Diagram of the ground-based cosmic ray muon detector.

Each ground-based cosmic ray muon detector contains two plastic scintillator paddles optically coupled, via acrylic light guides, to photomultiplier tubes (PMT). Each plastic scintillator paddle consists of a 50 cm x 50 cm x 2 cm sheet of Eljen EJ-200 plastic scintillator having a fluorescence decay time of 2.1 ns and maximum emission intensity at 425 nm [Eljen

Technology 2014]. Hamamatsu R329-02 PMTs with E5859 bases are optically coupled to the plastic scintillator paddles. To separate the “hard” muon component, from the “soft” electron and photon component, a 3 cm thick sheet of lead absorber is placed between the two scintillator paddles. A diagram of the cosmic ray muon detector is shown in Figure 2.

The electric signals from the PMTs pass to Ortec 590A amplifer discriminator modules for amplification and discrimination to remove noise in the signal. The filtered signals from both the top and bottom scintillator paddles are then passed to an Ortec 414A coincidence module. Cosmic ray secondary muons are highly penetrating and will travel through both plastic scintillator paddles and the lead absorber, so the Ortec 414A coincidence module only sends out a pulse if a signal arrives from within a few nanoseconds of each of the PMTs. Pulses from the Ortec 414A coincidence module are sent to a computer with a NI 6602 PCI counting card and are collected in 100 μs time bins and output to a text file via custom Labview code. The binned output data is timestamped from the output signal of a Symmetricon BC637PCIe GPS time card also located in the computer.

Ground-Based Cosmic Ray Muon Detector Array Design

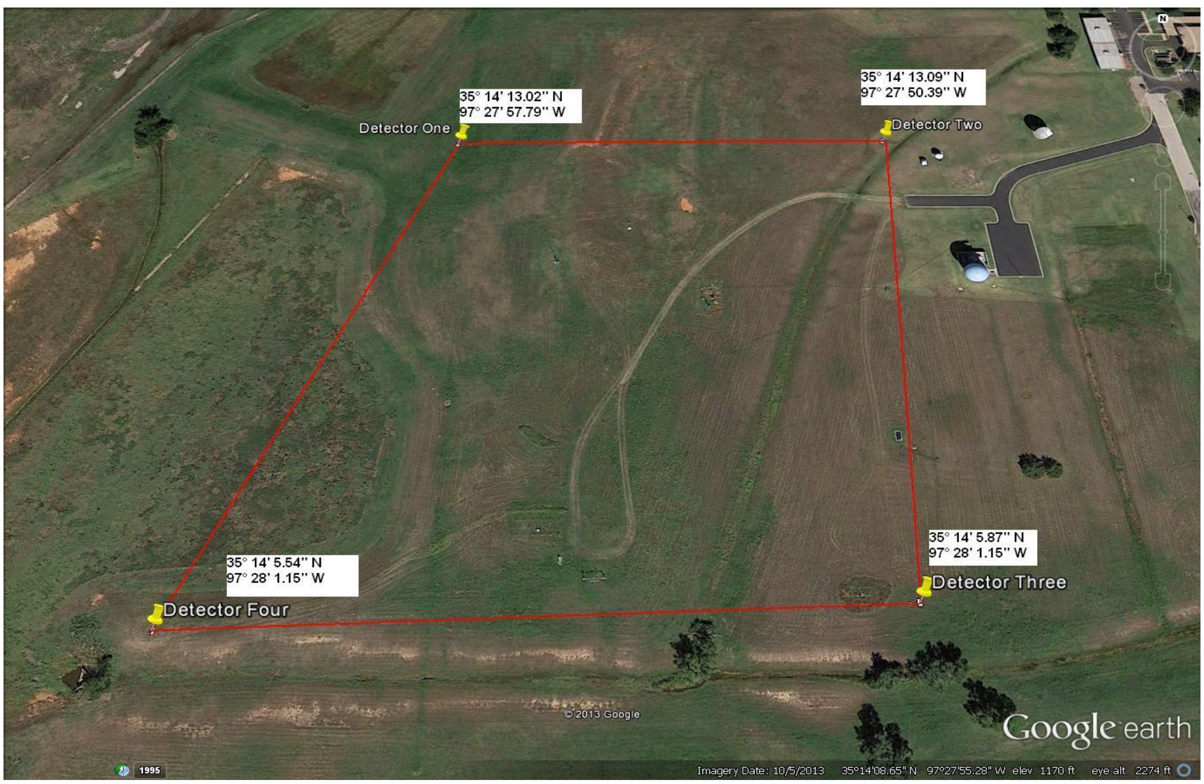

Figure 3: Image of the four cosmic ray muon detector array developed in Norman, OK [Google 2014].

The ground-based cosmic ray muon detector array is made up of four cosmic ray muon detectors deployed at the OU’s School of Meteorology Test Field in Norman, OK (35° 14' 9.38"

N 97° 27' 55.10" W). The four detectors are arranged in a ~200 m square, with a detector in each of the corners. Due to the geography of the test field, the array is not quite a square as shown in Figure 3.To protect the cosmic ray muon detectors from the environment, each detector is housed in a wooden enclosure covered by vinyl siding and includes electric fans to circulate air to cool the detectors and electronics.

Correlating CREASs with lightning initiations.

According to Gurevich and Zybin [2005], only CREASs initiated by >10^{16} eV cosmic ray primaries are able to generate enough high energy seed electrons to initiate lightning. However, the majority of CREAS in the atmosphere are initiated by lower energy cosmic ray primaries, which produce fewer secondary muons. Figure 4 shows the average density of cosmic ray secondary muons on the ground from 10^{14} and 10^{16} eV proton initiated CREASs. The average secondary muon density shown in Figure 4 was determined from CREAS simulated in the Monte Carlo cosmic ray code CORSIKA (COsmic Ray SImulations for Kascade) 6.790 [Heck at al. 1998]. The U.S. Standard Atmosphere [NOAA, et al. 1976], magnetic field for Norman, OK [IAGA 2010], and fair weather electric fields were assumed in the CREAS simulations. The results are from vertical CREAS primaries and the secondary muon density was assumed to be cylindrically symmetric on the ground.

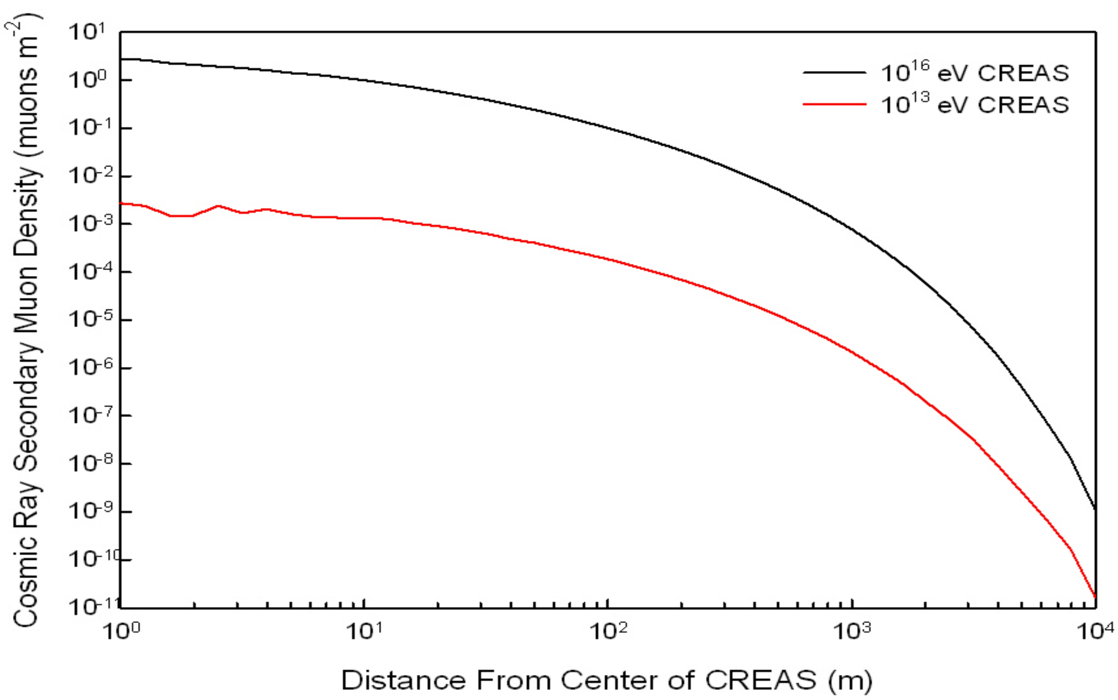

Figure 4: Simulated average of the cosmic ray secondary muon density on the ground from a 10^{14} and 10^{16} eV proton initiated CREASs. This result was obtained via using CORSIKA 6.790 simulations [Heck at al. 1998].

Secondary muons can be measured hundreds of meters from the center and core of the CREAS, especially in higher energy CREAS. One method to differentiate high energy from low energy CREAS is to measure in coincidence secondary muons in multiple cosmic ray secondary muon detectors spread over a large geographic area [Riggi 2012; Budnev et al. 2013; Chiavassa et al. 2014; Tinyakov 2014]. This experiment requires that three or more of the detectors to register muon counts within the same 100 μs time bin before an event is considered a CREAS. CREAS events are determined in post processing of the cosmic ray muon detector data.

The CREAS events are compared to OKLMA data for the geographic region near the cosmic ray muon detector array. In order to compare the OKLMA and CREAS data sets, the OKLMA data was binned in the same 100 μs time bins that were used for the CREAS data set. This experiment uses the first LMA source from a lightning discharge to be the lightning initiation location. The binned OKLMA and CREAS data sets are then analyzed to determine difference in the time between the CREAS events and lightning discharges.

PRELIMINARY RESULTS

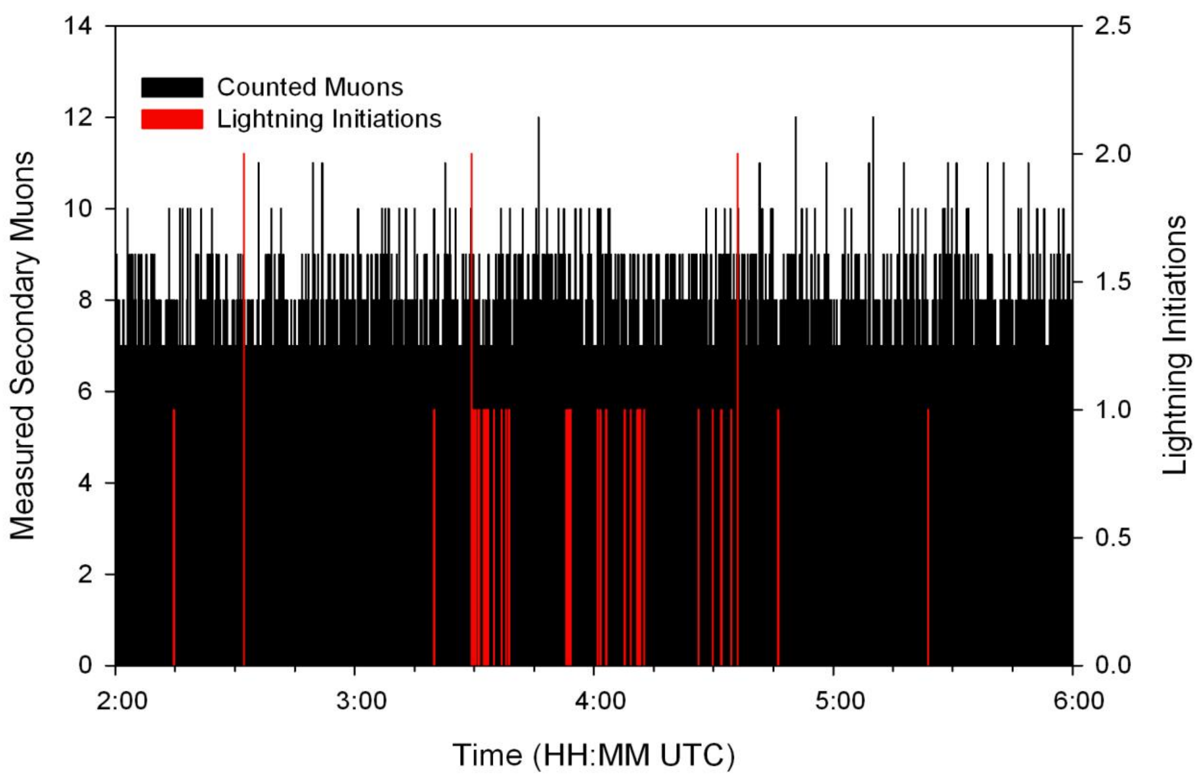

Figure 5: The distribution of CREAS events and lightning initiation events within 1 km of the cosmic ray muon detector array for a thunderstorm on 5/19/2013. Each black line represents a single CREAS event and the red lines are the number of lightning initiations within a single 10 ms time bin.

The cosmic ray muon detector array was upgraded in November 2013 to 100 μs time bins. Before the upgrade, the cosmic ray detector array used 10 ms time bins, which requires that at least three of the four cosmic ray muon detectors to trigger within 10 ms to be considered a CREAS event. The lightning initiation data from the OKLMA was also convert to the same 10 ms time bins. A representative sample for the 10 ms binned muon and lightning initiation data is shown in Figure 5. Figure 5 shows the total number of muons detected in each CREAS event (black) and the number of lightning initiations within 1 km of the center of the cosmic ray muon detector array (red) for a thunderstorm on 5/19/2013.

The number of CREAS events far outnumbers the number of lightning initiations during an active thunderstorm. CREAS events are seen to occur at a constant rate regardless of the atmospheric weather conditions, whereas the lightning discharges occur in shorter 15 to 30 minute periods for the duration of the thunderstorm. To correlate CREAS events with lightning initiations, the data must be compared at a smaller time scale than an entire thunderstorm. Figure 6 shows CREAS events and lightning initiations on a 500 ms time scale, using data from the same thunderstorm shown in Figure 5. The CREAS events still outnumber lightning initiations, but on this 500 ms time scale, the separate CREAS events can be observed. CREAS events are stochastic in nature, so the time between CREAS events is not constant. The pair of lightning initiations in Figure 6 occurred 40 ms after a pair of CREAS events. From discharge observation, there is <1 ms between electric breakdown and leader formation [Rakov and Uman 2003], so the above CREAS events are unlikely to be correlated with the lightning initiation.

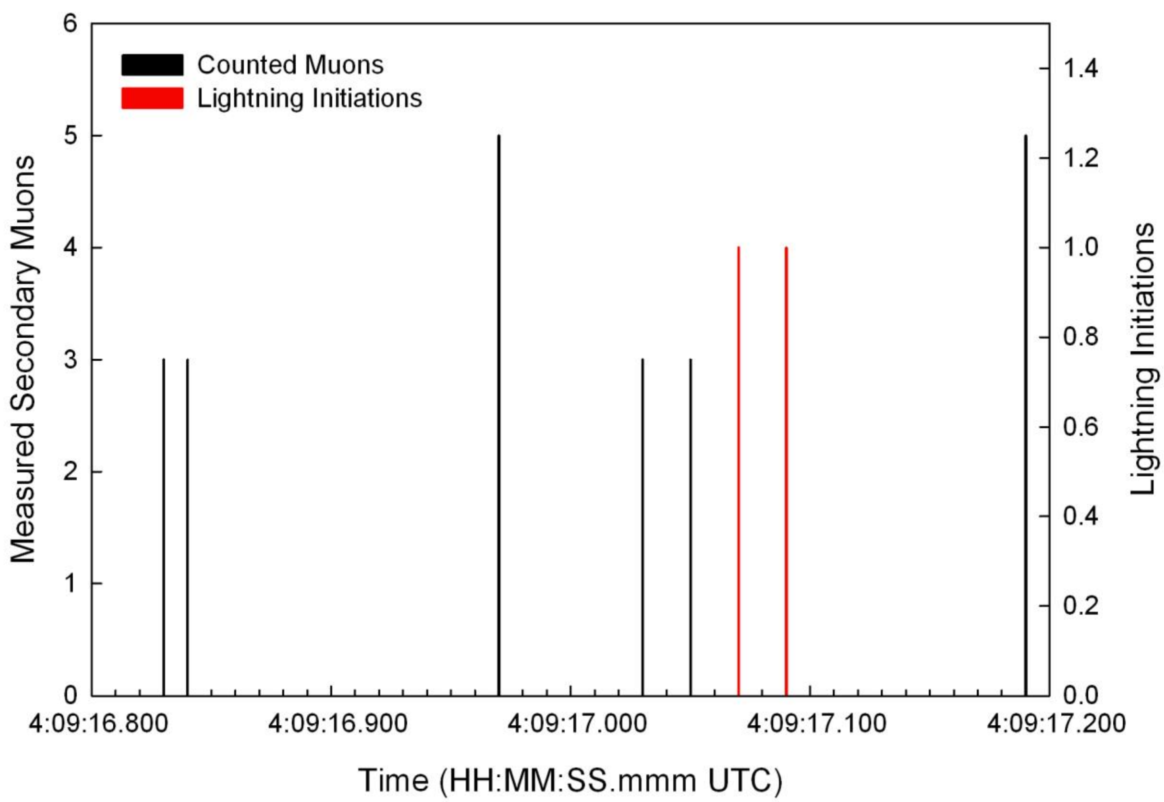

Figure 6: Plot of the CREAS events and lightning initiation events within 1 km of the cosmic ray muon detector array for a thunderstorm on 5/19/2013. Each black line represents a single CREAS event and the red lines are the number of lightning initiations within a single 10 ms time bin.

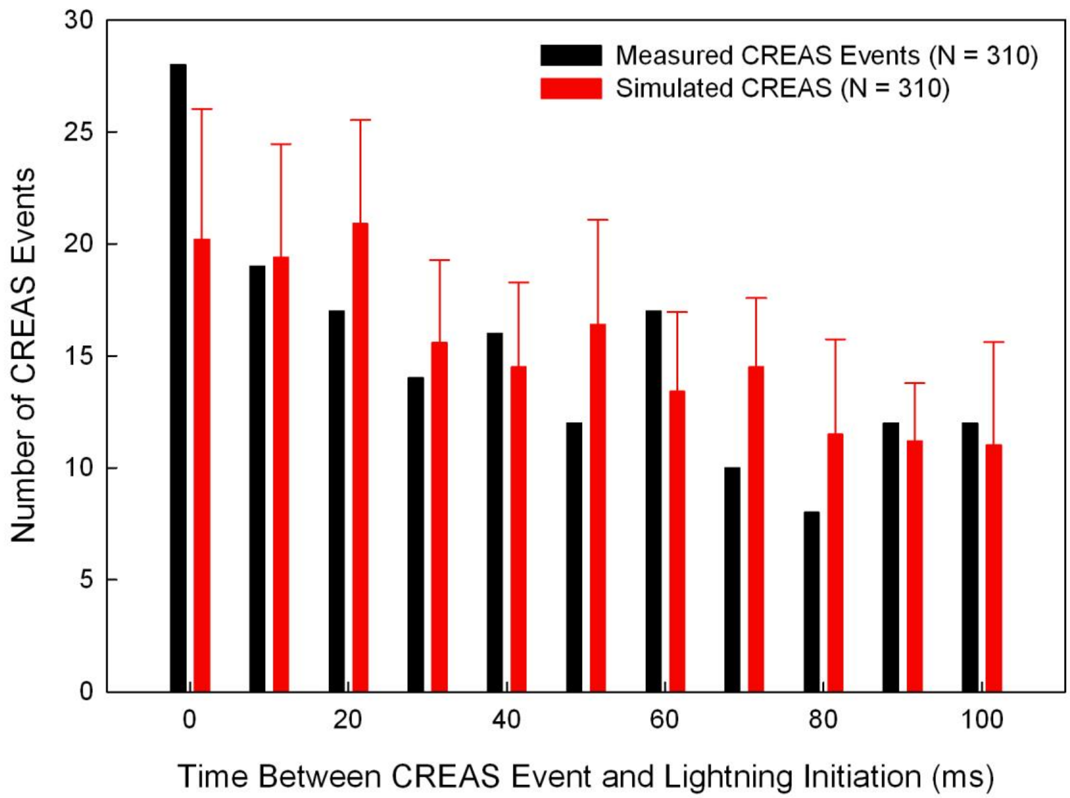

Figure 7: Plot of the time between CREAS events and lightning initiation within 1 km of the cosmic ray muon detector array. The black bars represent actual CREAS events measured by the cosmic ray muon detector array and the red bars represent randomly generated CREAS events at the same average frequency. The error bars on the simulated CREAS events represent 1σ. Data is from thunderstorms on 4/26/2013-4/27/2013, 5/16/2013-5/17/2013, and 5/18/2013-5/19/2013.

Figure 7 shows the distribution of the time between CREAS events and lightning initiations that occurred within 1 km of the cosmic ray muon detector array. The data for Figure 7 was acquired from thunderstorms on 4/26/2013-4/27/2013, 5/16/2013-5/17/2013, and 5/18/2013-5/19/2013, which had a total of 310 lightning initiations within 1 km of the detector array. Approximately 15% of all lightning initiations occurred within 10 ms following a CREAS event as detected by the cosmic ray muon detector array. The statistical significance of this result was compared to an average of 10 sets of simulated CREAS events over the same time period. The simulated CREAS occurred at the same frequency as the measured CREAS events but the exact time bin was randomly determined. For the first eleven time bins (0-100 ms between the CREAS event and a lightning initiation), χ^2 = 8.82 (ten degrees of freedom), which means there is little significant difference between the measured and simulated CREAS event data. For the first two time bins (0-10 ms between a CREAS event and a lightning initiation), χ^2 = 3.02 (one degree of freedom), which is statistically significant at the >90% confidence level. Therefore, it appears that the cosmic ray muon detector array is measuring statistically more CREAS events coincident with lightning initiations than from an assumed random distribution of CREAS events.

Conclusions

The goal of this project is to attempt to experimentally verify the RREA model of lightning initiation. Experimental data is being collected from the OKLMA and a cosmic ray muon detector array. The current time resolution of the detector array is 100 μs.

Preliminary data from the cosmic ray muon detector array, with a time resolution of 10 ms, has been collected from thunderstorms on 4/26/2013-4/27/2013, 5/16/2013-5/17/2013, and 5/18/2013-5/19/2013. The thunderstorms produced a total of 310 lightning initiations within 1 km of the detector. Approximately 15% of all lightning initiations were preceded within 10 ms by a CREAS event. Also, at >90% confidence level, the cosmic ray muon detector array measured statistically more CREAS events than an assumed random CREAS distribution of events in the 0-10 ms time bins. These preliminary results show that there may well be a correlation between CREAS and lightning initiations. Since CREASs generate the high energy electrons required by the RREA model, so the preliminary results appear to support the RREA model for lightning initiation.

The cosmic ray muon detector array can upgraded with additional detectors. Figure 8 shows a proposed expansion that would require an additional 4 detectors. Having additional detectors inside the original array serves two purposes: increase the overall detection efficiency of CREASs and the ability to detect non-vertical CREASs. Currently, three of the four detectors must trigger in order to be considered a CREAS event. The secondary muon density on the ground is ~1 muon m^{-2} at 100 m distance from the center of a 10^{16} eV CREAS, so there is a probability that a CREAS of sufficient size does not trigger enough detectors to be counted as a CREAS event. The additional detectors will decrease the average distance between the detectors and lower the fraction of the total number of detectors that must trigger to be considered a CREAS event (to three or four out of eight), which will increase the probability of detecting CREAS events.

Increasing the number of detectors in the cosmic ray muon detector array will also allow for non-vertical CREAS to be accurately measured. Currently, near vertical CREASs with centers within the area of the array can be accurately detected. This limits the range of lightning initiations that could have been created by measured CREAS to just over two kilometers. CREAS from further distances are much more inclined and have a lower secondary muon density on the ground, making it harder to accurately measure as a CREAS event by the detector array. Additional detectors inside the existing array will increase the likelihood of accurately detecting these inclined CREAS, thus increasing the range of influencing lightning initiations. An additional benefit of detecting non-vertical CREAS is that it will be possible to estimate the direction from which the CREAS originated from. The directional information of CREAS will then be compared to the location of the lightning initiation, for a direct correlation between CREAS and a lightning initiation. These direct correlations between CREAS and lightning initiation locations will improve experimental verification of the RREA model of lightning initiation.

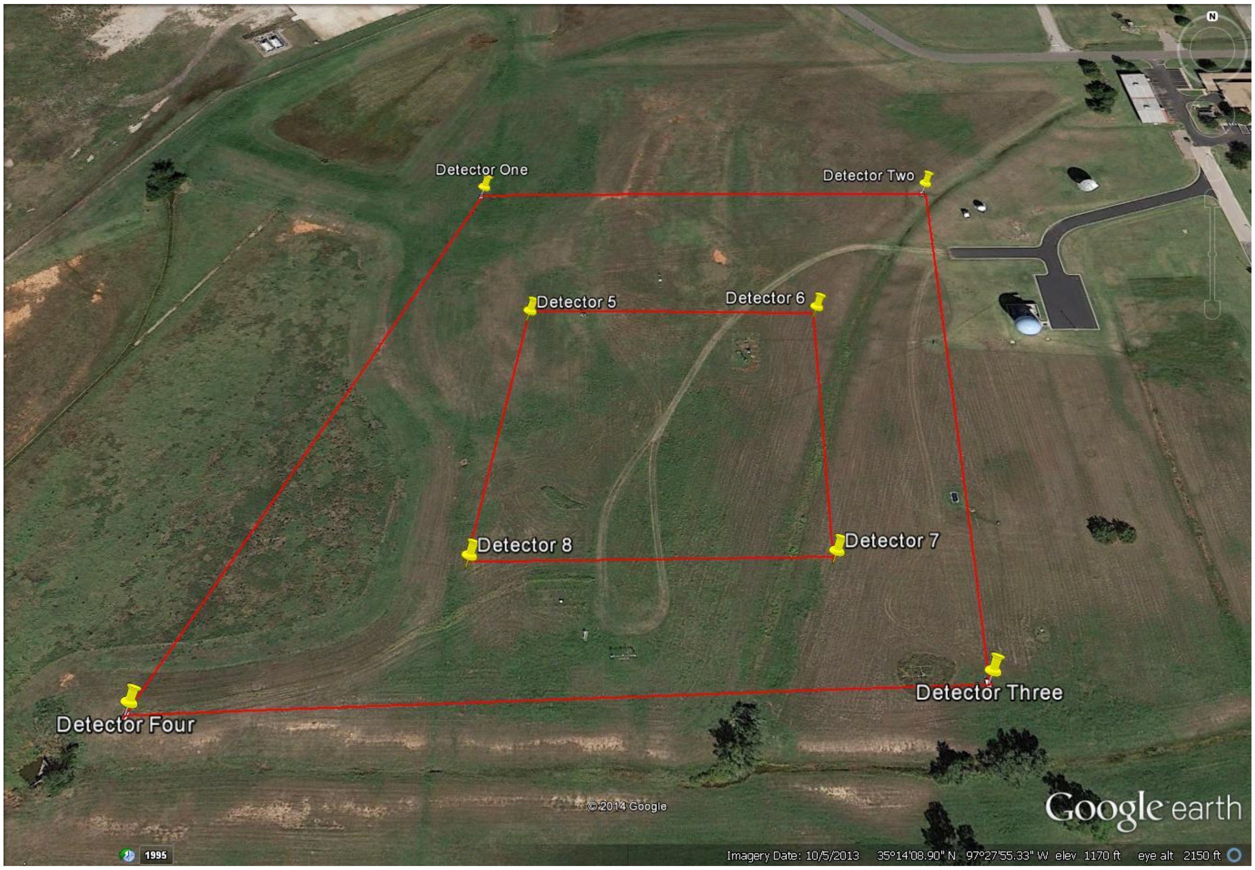

Figure 8: An image of a proposed expansion of the ground-based cosmic ray muon detector array. This expansion adds four additional detectors arranged in a ~100 m square in the center of the existing array [Google 2014].

Acknowledgements

The authors wish to thank Robert Honeyman of the Oklahoma State University Radiation Physics Laboratory for his assistance in deploying the analysis software and Dr. Arthur Lucas for his insightful advice for this project. This project is funded through the DARPA Nimbus program.

REFERENCES

Bazelyan, E. M. and Y. P. Raizer, 1998: *Spark Discharge*. CRC Press, Boca Raton, Florida, USA, 294pp.

Beringer, J. et al. (Particle Data Group), 2012: Mesons. *Phys. Rev*. D**86**, 010001.

N. Budnev, N., D. Chernov, O. Gress, E. Korosteleva , L. Kuzmichev, B. Lubsandorzhiev, G. Navarra, L. Pankov , V. Prosin, Yu. Semeney, C. Spiering, R. Wischnewski, and I. Yashin, 2013: Tunka-25 Air Shower Cherenkov Array: The main results. *Astropart.*

Phys., **50-52**, 18-25.

Bruning, E. C., W. D. Rust, T. J. Schuur, D. R. MacGorman, P. R. Krehbiel, a W. Rison, 2007: Electrical and Polarimetric Radar Observations of a Multicell Storm in TELEX. *Mon. Wea. Rev.*, **135**, 2525-2544.

Chiavassa, A., W. D. Apel, J. C.Arteaga-Velázquez, K. Bekk, M. Bertaina, J. Blümer, H. Bozdog, I. M.Brancus, E. Cantoni, F. Cossavella, C. Curcio, K. Daumiller, V. de Souza, F. Di Pierro, P. Doll, R. Engel, J. Engler, B. Fuchs, D. Fuhrmann, H. J. Gils, R. Glasstetter, C. Grupen, A. Haungs, D. Heck, J. R. Hörandel, D. Huber, T. Huege, K. H. Kampert, D. Kang, H. O. Klages, K. Link, P. Łuczak, M. Ludwig, H. J. Mathes, H. J. Mayer, M. Melissas, J. Milke, B. Mitrica, C. Morello, J. Oehlschläger, S. Ostapchenko, N. Palmieri, M. Petcu, T. Pierog, H. Rebel, M. Roth, H. Schieler, S. Schoo, F. G. Schröder, O. Sima, G. Tomae, G. C. Trinchero, H. Ulrich, A. Weindl, J. Wochele, and J. Zabierowski, 2014: Latest results from the KASCADE-Grande experiment. *Nuc. Instrum. Methods A*, **742**, 10-15.

Dorman, L. I., 2004: *Cosmic Rays in the Earth's Atmosphere and Underground*. Kluwer Academic Publishers, Dordrecht, Netherlands, 855pp.

Dwyer, J. R., M. A. Uman, H. K. Rassoul, M. Al-Dayeh, L. Caraway, J. Jerauld, V. A. Rakov, D. M. Jordan, K. J. Rambo, V. Corbin, B. Wright, 2003: Energetic Radiation Produced During Rocket-Triggered Lightning. *Science*, **299**, 694-697.

Eljen Technology, 2014: EJ-200 Plastic Scintillator. www.eljentechnology.com.

Google, 2014: Google Earth. http://www.google.com/earth/.

Gurevich, A. V., G. M. Milikh, and R. Roussel-Dupre, 1992: Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. *Phys. Lett. A*, **165**, 463-468.

Gurevich, A. V. and K. P. Zybin, 2005: Runaway Breakdown and the Mysteries of Lightning. *Physics Today*, 37-43.

Grieder, P. K. F., 2001: *Cosmic Rays at Earth: Researcher's Reference Manual and Data Book*. Elsevier, Amsterdam, Netherlands, 1093pp.

Grieder, P. K. F., 2010: Extensive Air Showers: High Energy Phenomena and Astrophysical Aspects-A Tutorial, Reference Manual and Data Book. Springer, Heidelberg, Germany, 1113pp.

Heck, D., J. Knapp, J. N. Capdevielle, G. Schatz and T. Thouw, 1998: Report FZKA 6019. Forschungszentrum Karlsruhe, <https://web.ikp.kit.edu/corsika/physics_description/corsika_phys.html>, 90pp.

International Association of Geomagnetism and Aeronomy (IAGA), Working Group V-MOD, “International Geomagnetic Reference Field: the eleventh generation”, Geophy. J. Int., 183, 2010.

International Commission on Radiation Units and Measurements (ICRU), 1984: Stopping Powers for Electrons and Positrons. ICRU Report 37, 271pp.

Krehbiel, P. R., R. J. Thomas, W. Rison, T. Hamlin, J. Harlin, and M. Davis: GPS-based Mapping System Reveals Lightning Inside Storms. *EOS Transactions of American Geophys. Union,* **81**, 3, 21-32.

Latham, J. and I. W. Roxburgh, 1966: Disintegration of Pairs of Water Drops in an Electric Field. *Proc. R. Soc A,* **295**, 84-97.

Marshall, T. C., M. Stolzenburg, C. R. Maggio, L. M. Coleman, P. R. Krehbiel, T. Hamlin, R. J. Thomas, and W. Rison, 2005: Observed electric fields associated with lightning initiation. *Geophys. Res. Lett.,* **32**, L03813.

National Institute of Standards and Technology (NIST), 2014: ESTAR: Stopping Power and Range Tables for Electrons. <http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>

National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and United States Air Force, 1976: *U.S. Standard Atmosphere, 1976*. U.S. Government Printing Office, Washington D.C., USA.

Petersen, D., M. Bailey, W. H. Beasley, and J. Hallett, 2008: A brief review of the problem of lightning initiation and a hypothesis of initial lightning leader formation. *J. Geophys. Res,* **113**, D17205.

Rakov, V. A. and M. A. Uman, 2003: *Lightning: Physics and Effects*. Cambride University Press, Cambridge, UK, 687pp.

Riggi, S., A. Insolia, G. Medina-Tanco, and E. Trovato, 2012: Reconstruction of muon tracks in a buried plastic scintillator muon telescope (BATATA). *Nuc. Instrum. Methods A*, **688**, 22-31.

Rossi, B., 1952: *High-Energy Particles*. Prentice-Hall, Inc., Englewood Cliffs, NJ, USA, 569pp.

Rossi B. and K. Greisen, 1941: Cosmic-Ray Theory. *Rev. Modern Phys.*, **13**, 246-309.

Tinyakov, P., 2014: Latest results from the telescope array. *Nuc. Instrum. Methods A,* **742,** 29-34.