

USING A FIELD MILL CLIMATOLOGY TO ASSESS ALL LIGHTNING LAUNCH COMMIT CRITERIA

THESIS

Shane C. Gardner, Captain, USAF

AFIT-ENV-MS-20-M-204

DEPARTMENT OF THE AIR FORCE AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. The views expressed in this document are those of the author and do not reflect the official policy or position of the United States Air Force, the United States Department of Defense or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENV-MS-20-M-204

USING A FIELD MILL CLIMATOLOGY TO ASSESS ALL LIGHTNING LAUNCH COMMIT CRITERIA

THESIS

Presented to the Faculty

Department of Mathematics and Statistics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Shane C. Gardner, BA

Captain, USAF

March 2020

DISTRIBUTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-20-M-204

USING A FIELD MILL CLIMATOLOGY TO ASSESS ALL LIGHTNING LAUNCH COMMIT CRITERIA

THESIS

Shane C. Gardner, BA Captain, USAF

Committee Membership:

Dr. Edward D. White Chair

Dr. Brent Langals Member

Todd McNamara, MS Member

> Dr. Alfred Thal Member

Abstract

Due to the danger and cost of lightning striking a space vehicle, the Cape Canaveral Air Force Station (CCAFS) balances between the mission of launching and cessation thereof to minimize the risk of a lightning strike. This process is mediated through a set of rules called the Lightning Launch Commit Criteria (LLCC). To date, no empirical modeling of these rules has been established. To alleviate this shortcoming, this thesis uses the voltage readings of the surrounding CCAFS surface field mills to establish the viability of modeling the entirety of the LLCC rules statistically. Converting approximately 312,000,000 field mill voltage readings into a salient collection of 9,000 green, amber, and red zones for meteorological operators, this thesis demonstrates not only the validity of this modeling process but also produced an easy to understand tool to use hands-on within the CCAFS region; the first of its type. As clients such as SpaceX, Blue Origin, and United Launch Alliance continue to request the use of the Cape Canaveral space port, the tool provided by this research will serve to ensure scheduling around probable lightning violations, thereby maximizing operational capability.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Edward D. White, for his patience, diligence, and mentorship throughout this thesis process. Also, I would like to thank the Weather Subject Matter Experts, Bill Roeder and Todd McNamara for their continuous pursuit of good research. Lastly, I would like to thank my wife, for her constant support as well as my children.

Shane C. Gardner

Abstract	iv
Acknowledgments	v
List of Figures	viii
List of Tables	xi
I. Introduction	1
1.1 Background	1
1.2 Problem Statement	4
1.3 Thesis Organization	5
II. Literature Review	6
2.1 Introduction	6
2.2 The Science of Rocket-triggered Lightning	6
2.3 History of Rocket-Triggered Lightning and Steps to Mitigate	8
2.4 Current Lightning Launch Commit Criteria (LLCC) Rules	9
2.5 Research into the LLCC	16
2.6 Conclusion	19
III. Methodology	_21
3.1 Introduction	
3.2 Raw Data	21
3.3 Condensing the Dataset	28
3.4 Building the GAR database	32
3.5 Conclusion	35
IV. Results and Analysis	37

Table of Contents

4.1 Introduction	
4.2 The Datasets	
4.3 Field Mill Data	39
4.4 Empirical Data Validation	45
4.5 Conclusion	_50
V. Conclusions	_51
5.1 Introduction	51
5.2 Results and Past Research	_51
5.3 Alternative Methodology and Future Research	_52
5.4 Final Remarks	53
Bibliography	55

List of Figures

Figure 1: Rocket-triggered lightning May 2019 (Courtesy of the Russian News Agency, 2019). 1
Figure 2: The field mills in Cape Canaveral, FL, 2019, photo courtesy of Lucas, et al., (2017)3
Figure 3: Physics of triggered lightning. Drawing by J. Schoene. Source: (Uman 2008)
Figure 4: Lightning that led to the destruction of the AC 67 Rocket Photo courtesy of (NASA
1987)9
Figure 5: Display of an anvil cloud photo courtesy of NASA (2008)13
Figure 6: Field mill machine located at the CCAFS/KSC Photo Courtesy of NASA (2006)16
Figure 7: Displays the composition of the raw dataset22
Figure 8: Displays the difference between the amount of data available in 1997 and a normal
calendar year24
Figure 9: Displays the three accuracy processes beginning with datapoints over 19,000 V m-1.
Figure 10:Displays the three accuracy processes beginning with datapoints over 15,000 V m-1.
Figure 11: Displays a datapoint found that indicated an error in the dataset, this datapoint was
eliminated28
Figure 12: Displays the 1-hour means on the left, maxes on the right eigenvectors for the PCA.
Figure 13: Displays the percent of years Field Mill 14 held the highest of the lowest correlations.
Figure 14: Displays the percent of years Field Mill 14 held the second highest of the lowest
correlations34

Figure 15: Displays all the field mill locations and draws particular attention to the central clus	ster
of field mills: 13, 14, 15, 16, 19.	_34
Figure 16: Displays the flowchart and the 10 different databases this thesis analyzed.	.36
Figure 17: Displays the distributions of the three subsets of the maxes, the above displays the	
max of the maxes.	36
Figure 18: Displays the Red percentage distributions, the left displays the maxes, right the	
means.	_38
Figure 19: Displays the Amber percentage distributions, the left displays the maxes, right the	
means.	
Figure 20: Displays the Green percentage distributions, the left displays the maxes, right the	
means.	
Figure 21: Displays the year pattern for the Red criteria.	41
Figure 22: Displays the yearly pattern for the Amber criteria.	.42
Figure 23: Displays the yearly pattern for the Green criteria.	42
Figure 24: Displays the monthly pattern for the Red Criteria.	43
Figure 25: Displays the monthly pattern for the Amber criteria.	43
Figure 26: Displays the monthly pattern for the Green criteria.	43
Figure 27: Displays the diurnal pattern for the amber criteria.	44
Figure 28: Displays the diurnal pattern for the green criteria.	44
Figure 29: Displays the diurnal pattern for the green criteria.	45
Figure 30: First sample distribution in Krider et al. (2006) for comparing to Figure 26 in this	
thesis. DOY = Day of the Year.	46

Figure 31: Second sample distribution in Krider et al. (2006) for comparing to Figure 26 in th	is
thesis. DOY = Day of the Year.	46
Figure 32: Third sample distribution in Krider et al. (2006) for comparing to Figure 26 in this	i
thesis. DOY = Day of the Year.	47
Figure 33: Details the Red % when comparing to successful launches.	_48
Figure 34: Details the Amber % when comparing to successful launches.	49
Figure 35: Details the Green % when comparing to successful launches.	
Figure 36: Details a screenshot of the tool provided by this thesis to the CCAFS/KSC.	

List of Tables

Table 1: General format of the raw data obtained from Lucas, et al. (2017). 22
Table 2: A listing of the days and times showing the storm events checked for data consistency
from years 1998-201223
Table 3: An example of a field mill correlation matrix for detecting possible erroneous values (as
highlighted in pink). This specific example is for year 2000 using 15-minute field mill voltage
max readings25
Table 4: Displays the linear regression model for the 1-hour means, year reveals least predictive.
29
Table 5: Displays the PCA for the means on the left and the maxes on the right, the total
supersedes 100, due to rounding31
Table 6: Displays the eigenvectors for the 1-hour means on the left and maxes on the right
Table 7: Displays the R2 for the Maxes models. 41
Table 8: Displays the R2 for the Means models. 41

USING A FIELD MILL CLIMATOLOGY TO ASSESS ALL LIGHTNING LAUNCH COMMIT CRITERIA

I. Introduction

1.1 Background

Lightning remains one of the biggest concerns for space launches. The Kennedy Space Center neither fuels a rocket if there is greater than a 20 percent chance of a lightning strike within a five-mile radius of the launch site, nor launches if lightning is observed within 10 miles of the flight path (Patel 2018). That radius also includes the presence of the cloud that produced the lightning. Such precautions are warranted given the cost of a space launch scrub. During the era of the Space Shuttles, every cancellation after fuel loading had begun cost somewhere around \$1.2 million—\$500,000 in fuel losses, and another \$700,000 to pay for the extra labor needed to initiate an additional launch (Moskowitz 2009). This concern regarding lightning also entails strikes triggered by the launch itself as shown with the Russian Soyuz rocket displayed in Figure 1 (Japaridze 2019).



Figure 1: Rocket-triggered lightning May 2019 Photo Courtesy of the Japaridze (2019)

The National Advisory Committee for Aeronautics, later becoming the National Air and Space Administration (NASA) (Suckow 2009), first noticed dangerous conditions when *aircraft* flew in and out of clouds. During this period, pilots observed that an aircraft could trigger lightning, even when no natural lightning occurred (Harrison 1946). Upon the establishment of NASA, research into lightning and eventually space launches became paramount. However, it does not appear that NASA fully understood the causes or reasons for triggered lightning during this period. Instead they focused on avoiding natural lightning, which caused issues with the Mercury, Gemini, and early Apollo programs.

Apollo XII initiated NASA's pursuit of understanding rocket triggered lightning. This launch triggered two lightning strikes, which caused a temporary loss of power and controls and almost brought an abrupt end to the mission. Adequate backup systems allowed the flight to proceed without disaster, but that mission brought increased attention to triggered lightning (Pomeroy 2013). Even though rocket triggered lightning almost caused the death of three astronauts in Apollo XII, the watershed moment for rocket triggered lightning occurred in 1987. This rocket triggered lightning event initiated the destruction of the Atlas Centaur (AC) 67 and all of its payload. At the conclusion of this incident, panels, committees and congressional hearings heard evidence that the CCAFS/KSC knew the risks of launching the AC 67 in those weather conditions and chose not to follow their own lightning launch procedures (Merceret, et al. 2010).

NOTE: this thesis mentions or references NASA, the Kennedy Space Center (KSC) or the Cape Canaveral Air Force Station (CCAFS) relatively interchangeably. These three institutions, located at Cape Canaveral Florida, serve as close partners in space exploration and defense. Due to some overlap in these departments, this thesis henceforth refers to either NASA, the KSC, or the CCAFS as simply CCAFS/KSC. Weather resources and other documents from Cape Canaveral frequently mention these as such.

In 1988, the Lightning Review Committee, an independent review board, developed the Lightning Launch Commit Criteria (LLCC), a set of rules that prohibit a space launch if one of ten criteria is violated (discussed in detail in Chapter II). One of these rules, the surface field mill rule, states that if the electric differential inferred using the field mill measurement between the sky and ground exceeds the absolute value of 1500 Volts per meter (V m⁻¹), then a launch is not authorized (NASA 2017). As shown in Figure 2, the CCAFS/KSC maintains 31 working field mills located in and around Cape Canaveral, Florida to observe this differential during a launch. This research acquired data from these field mills during the years of 1997 – 2015 and is referenced in greater detail in Chapter III.



CCAFS/KSC Field Mill

Figure 2: The field mills in Cape Canaveral, FL, 2019, photo courtesy of Lucas, et al., (2017)

1.2 Problem Statement

The Surface Electric Fields rule (henceforth referred to as the field mill rule) serves as one cog in a wheel of rules that allows the CCAFS/KSC to protect all rockets launched from the Cape Canaveral Space port from lightning, both triggered and natural. Because of the importance of the LLCC, our problem statements center around it. First, this research pursues to corroborate that an LLCC climatology can be modeled using only the surface electric field mills. Secondly, we seek to uncover which of the 31 field mills are the most important in building a climatology of the LLCC. Lastly, we seek to know what inputs provide the best predictors of the voltage recorded by the field mills, i.e., year, month, day etc. To build this climatology, our research draws its historical inferences from all 31 field mills. With exceptions to outages of the field mills or instances of missing data, every minute of every day during that time the electrical field mills recorded the inferred atmospheric electricity measurements (inferred measurements of atmospheric electricity are discussed in Chapter II).

After statistical development and analysis, the inferred climatology patterns need to be validated. This validation step includes analyzing other patterned lightning climatologies. Also, the validation evaluated the climatology created by this thesis against successful launches that occurred in Cape Canaveral. The CCAFS/KSC evaluates all LLCC violations during a space launch. All LLCC's must be satisfied for a launch to occur. Therefore, our validation tests our climatology against these times to authenticate if the field mill climatology serves as a proxy for all LLCC violations. Chapter IV discusses these items in further detail.

The importance of building a climatology of these rules appears when considering the cost and frequency of scrubbed launches due to weather. Weather, specifically lightning, results in roughly 30% of scrubbed launches (45th Weather Squadron 2016). The CCAFS/KSC tries to

plan for lightning. However, with the addition of new space companies to the space field i.e., SpaceX, Virgin Galactic, Blue Horizons, and others, the CCAFS/KSC desires a robust climatology that accounts for most, if not all, of the ten rules of the LLCC.

1.3 Thesis Organization

We lay out the thesis as follows. In Chapter II, we document the history of both natural and rocket-triggered lightning strikes of space vehicles, the history of the LLCC to include its inception to current status, and the few attempts to model the LLCC. In Chapter III, we describe the data obtained for this thesis, the statistical methods used for analysis of this data, and the data behind the validation of this analysis. Chapter IV displays the results of the climatological patterns, as well as the results from the descriptive and inferential statistical analysis and findings from testing our climatology with the validation dataset. Chapter V discusses the results as they pertain to the CCAFS/KSC, the past research that further validates our climatology, and further analysis needed in regard to the LLCC.

II. Literature Review

2.1 Introduction

Rocket-triggered lightning, noted first in 1969, creates greater weather restrictions for space vehicles than aircraft. Because of the importance of keeping a space vehicle safe from lightning, Chapter II begins by centering on a summary of the physics of lightning and rocket triggered lighting. Then the chapter communicates the major instances of rocket triggered lightning and how the CCAFS/KSC tries to avoid it. The CCAFS/KSC codified this avoidance into ten criteria referred to as the LLCC. Therefore, this naturally leads to addressing the current LLCC. We finish by focusing on research conducted with field mills and any attempts to create a climatology for this rule.

NOTE: This thesis references the LLCC but will not state them verbatim. Knowing all details of every LLCC supersedes the scope of this thesis. In its place this, chapter provides a summary for each LLCC.

2.2 The Science of Rocket-triggered Lightning

Electricity builds in thunderstorms as negative charges are separated from positive charges. Researchers of lightning normally describe this field as the positive charges sitting on top of the cloud and the negative charges sitting on the bottom or middle. However, habitually the ground holds a positive charge. As the charge difference between the negative and positive charges increase, the electromagnetic field becomes stronger. Air normally acts as a buffer between these opposite charges and staves off a potential lighting strike. However, Eventually, , the built-up electricity reaches a point where the air cannot serve as a buffer and the energy dissipates through a sudden discharge of electricity, or a lightning strike. The lightning flash can either be an intra-cloud or a cloud-to-ground flash. In addition, anything can induce lightning by

reaching high into the sky and producing a conduit which pierces through air buffer. Thus, taller objects get struck by lightning first. Lightning rods work in this fashion.



Figure 3: Physics of triggered lightning. Drawing by J. Schoene. Source: (Uman 2008)

A tall building, a large tree or a rocket all potentially function as objects that create an easier path for lightning (Dwter and Uman 2013). The Space Shuttle sitting on the launch pad in the Kennedy Space Launch Center can be struck by lightning because of its increased height; it bridges the gap between the cloud base and the grounded earth. Equally, a space launch vehicle propelled into space links the ground and the sky with the large exhaust plume produced by the rocket (Mazur 2016). This, triggered lighting is a phenomenon where elements of natural lightning would not normally occur but do because of an easier path for lightning exists. The first documented case of triggered lightning did not occur amid rocket launches. The National Advisory Committee for Aeronautics wrote a document in 1946 warning those in the aeronautical industry about the presence of natural and triggered lightning with aircraft (Harrison 1946).

2.3 History of rocket-triggered lightning and steps to mitigate

The history of rocket-triggered lightning intermingles with that of natural lightning. Any atmosphere electrically charged to the point of natural lightning occurring will also incur the same risk for triggered lightning. However, not all cases that cause triggered lightning will produce natural lightning. In a natural lightning occurrence in the 1960s, the Gemini II launch vehicle experienced a near lightning strike while sitting on the launch pad. Likewise, Apollo I experienced two natural lightning strikes while on the launch pad. These strikes damaged the launch tower and the mobile launcher. This experience caused the CCAFS/KSC to modernize its weather detection equipment in order to prevent natural lightning strikes. However, these events failed to initiate caution in regard to *triggered* lightning. The incident that genuinely changed the CCAFS/KSC's thought process about triggered lightning occurred on November 14, 1969. This event stands apart as the first time a space launch vehicle experienced a lightning strike in the air. Even more disconcerting is that the CCAFS/KSC followed its Lightning Criteria to ensure safety of the mission and crew. Unbeknownst to the CCAFS/KSC, launching a rocket on a cloudy day could initiate lightning due to *rocket-triggered* lightning (Merceret, et al. 2010).

Apollo XII experienced a triggered lightning strike forty-three seconds after lift-off. Sixteen seconds later Apollo XII underwent *another* triggered lightning strike. Notwithstanding this danger, the electrical and environmental systems engineer managed to reboot the system and save Apollo XII's mission and the crew. In the analysis of Apollo XII, lightning avoidance criteria were recommended. Two of the criteria included were: Do not launch into clouds that look like thunderstorms. Do not launch within 5 miles of a thunderstorm or 3 miles of an anvil cloud. These criteria became the basis for the CCAFS/KSC's LLCC until further revised in the late 1980s. Even though triggered lightning almost caused an abrupt end to Apollo XII's mission, the watershed moment for lightning advisory and safety occurred in 1987 when NASA initiated the self-destruction of the AC 67 rocket due to a triggered lightning strike. Figure 4 displays the triggered lightning from that incident. Reports after the fact showed the CCAFS/KSC ignored the adverse weather conditions which consisted of rain, clouds and powerful electrical fields. More specifically a NASA investigation found that launch personnel ignored the violation of the fourth of five LLCCs during the launch. Furthermore, the main finding of this investigation drew upon that the AC 67 rocket launched when the field mills indicated the dangerous nature of that launch. No specific rule for field mills existed for rockets such as the AC 67. These findings and criticism helped spur the creation of the Lightning Advisory Panel (LAP). The LAP in turn created the current Lightning Launch Commit Criteria mostly still intact with minor adjustments today at the CCAFS/KSC (Merceret, et al. 2010).



Figure 4: Lightning that led to the destruction of the AC 67 Rocket Photo courtesy of (NASA 1987)

2.4 Current Lightning Launch Commit Criteria (LLCC) Rules

The LLCC exists to protect the facilities and space launch vehicles, located at any

spaceport in the United States, against lightning strikes. Weather scientists based these rules on

experience, research and experimentation. A prerequisite to launch requires the CCAFS/KSC to prove that no violations are occurring. The violation of any *one* rule obligates a penalty of time. If this penalty of time conflicts with a launch time, then this usually denotes a scrubbed launch. For almost every rule, there exists caveats that if fulfilled can allow a launch weather officer to check other measurements to determine the safety of a launch. Therefore, due to the severity and intensity of lightning strikes the LLCC contains vast details, caveats and explanations for each rule. This thesis, as previously stated, does not regurgitate the LLCC verbatim. Instead we summarize them by first presenting the four rules which do not mention the field mill. Then this chapter mentions the six that do mention the field mill. The rules, and the caveats are drawn from the work of NASA (2017). When this thesis sought other guidance to explain an LLCC we annotated it as such.

2.4.1 Disturbed Weather

Disturbed weather is non-transparent clouds that contain, at the top, temperatures colder than 0°C. When a launch carries a space vehicle through a disturbed cloud it violates this rule. This rule also stipulates that if precipitation or evidence of melting precipitation appears at a distance of 5 nautical miles (nmi) of the flight path this also violates this rule. This rule does not mention a field mill piece.

2.4.2 Thick Cloud Layers

In meteorology thick cloud layers are often referred to as stratus clouds. Even though these clouds produce no natural lightning threat, they pose a threat to rocket triggered lightning. Similar clouds produced the triggered lightning effect on the Apollo XII. This rule provides clarity between the difference of "Thick Clouds" and "Cumulus Clouds." The main difference is verticality. Cumulus clouds build vertically due to the rising of air. Stratus clouds are lower in the atmosphere, sometimes represented as fog, but still pose a threat to triggered lightning. Rarely do stratus clouds produce natural lightning strikes (Willett, et al. 2016). This rule does not contain a field mill reference.

2.4.3 Smoke Plumes

The CCAFS/KSC has not yet violated this rule. However, the LLCC does not only apply to the CCAFS/KSC. It applies to all other spaceports in the United States. This rule tells weather operators that in the event that a launch takes a space vehicle through a cumulus cloud that was produced by a smoke plume, then it mandates a delay of the launch until the cloud detaches from the smoke plume. After the cloud separates from the smoke plume this rule stipulates that a rocket cannot fly through this cloud for up to 60 minutes. This does not contain a field mill piece.

2.4.4 Triboelectrification

Triboelectrification occurs when electrons from one molecule separate and attach themselves to another molecule. This process creates an electrical imbalance and this imbalance can produce electricity (Forward, et al. 2009). Describing a simplified version of this process is much like rubbing shoes on a carpet, which compels electrons from the shoes to fasten to the carpet, creating an electrical imbalance. A rocket flying through a cloud can create this same imbalance except the collision of cloud particles on the rocket causes the buildup of static electricity. This buildup of static electricity on the rocket can discharge and cause a triggered lightning strike. These clouds rarely produce natural lighting but manage to trigger lightning, creating a hazard to a space flight. In order to detect this imbalance, the CCAFS/KSC relies on temperature. This LLCC rule states, that a space vehicle's flight path must not pass through any cloud where the temperature extends below or equal to -10°C. There exists no caveat for this

11

rule. The weather team needs to wait until a cloud, as previously mentioned, no longer remains in the flight path. This rule like the three before it does not mention a field mill piece (Willett, et al. 2016).

2.4.5 Lightning (Natural)

When natural lightning occurs within 10 nmi of the flight path of the rocket, this violates the LLCC and incurs a 30-minute penalty. Caveats for this rule exist if a working field mill exists within 5 nmi of the flight path and the absolute value of the field mill measurement remains below 1000 V m⁻¹ for 15 minutes.

2.4.6 Surface Electric Fields

When a field mill located within 5 nmi of the flight path exceeds an absolute reading of 1500 V m^{-1} this violates the LLCC and incurs a 15-minute penalty; there does not exist a caveat for this violation. However, when the field mill measures between 1499-1000 V m⁻¹, different caveats exist. These caveats however, center on the transparency of the clouds and the temperatures within them.

2.4.7 Cumulus Clouds

When the flight path takes a rocket through a cumulus cloud this violates the LLCC. Unlike the previous rules, no time penalty exists for this rule. This rule contains multiple caveats if this rule is violated. These caveats include cloud temperature, current precipitation, working field mill existing less than 2 nmi of the center of the cloud and all field mill measurements within a 5 nmi of the flightpath have been between -100 V m^{-1} and 500 V m⁻¹.

2.4.8 Anvil Clouds: Attached and Detached Rules (Two Rules)

An anvil cloud grows quickly with convection to such heights until it reaches a stable portion of the upper atmosphere. This stable portion exists because the rising air either becomes colder or at the same temperature of the upper atmosphere. Once it reaches this stable point of the upper atmosphere, the rising air loses its buoyancy and ceases to grow upwards. However, because of the rising air beneath this stable layer the anvil cloud commences to grow horizontally instead of vertically. As the cloud flattens it creates an anvil shape as seen in Figure 5. When the flight path of a rocket takes it within 3 nmi of an attached anvil cloud, it violates this LLCC rule. No field mill caveat exists for an attached anvil cloud. An anvil cloud can lose convection and the bottom portion of the cloud then dissipates. Furthermore, the top portion of an anvil cloud can break off from the bottom piece. In both cases these types of clouds are classified as detached anvil clouds. For a detached anvil cloud one of the caveats states that a working field within the horizontal distance of less than 5 nmi of the detached anvil cloud must measure less than the absolute value of 1000 V m⁻¹.



Figure 5: Display of an anvil cloud photo courtesy of NASA (2008)

2.4.9 Debris Cloud

A debris cloud, unlike anvil clouds, essential are imploding clouds. In some cases, debris clouds are clouds that break off from other thunderstorms. Since it is difficult to tell a cloud's

actions visually, the CCAFS/KSC utilizes temperature to detect this. Because of the dangerous amounts of electric potential created by debris clouds and the time it takes for that energy to dissipate, a space vehicle cannot pass within 3 nmi of a debris cloud. This penalty exists for three hours after the formation of the debris cloud. Two caveats exist for a debris cloud and both must be satisfied to caveat this rule. The first caveat involves reflectivity, which is not discussed in this research. The second, similar to the rules before it, states that the absolute value of the field mill measurements within a 5 nmi of the flight path cannot exceed 1000 V m⁻¹ for 15 minutes.

2.4.10 Justification for the Electric Field Mill Rule

All of the aforementioned rules serve to protect space launch vehicles from lightning strikes. Since the use of these ten LLCCs, the CCAFS/KSC has avoided any incident in regard to lightning strikes. Since this thesis used the data gathered from the electric field mills, we seek to further justify the creation and use of this rule. In that spirit, we will reengage the AC 67 incident when the field mill shifted from a useful tool to an essential part of the LLCC. In the aftermath of the AC 67 destruction, Congress, the USAF and NASA created independent review panels to determine the reason for the mishap. NASA's independent panel dubbed the 'Busse Panel' centered its review around the CCAFS/KSC's use of the electric field mills. They found that after the launch the weather officer observed that the field mill reading indicated ~ 3000 V m⁻¹, signifying a great potential for triggered lightning. This panel also observed that the day after the AC 67 accident, the National Weather Service, which warned against a launch the day before, observed the electric field mill data of the launch day and determined that the readings indicated a dangerous atmospheric electrical environment. In the aftermath this report, the Busse Panel recommended to officially institute electric field mill measurements as a means of

14

examining lightning severity. Because of these panels the LAP officially created the Surface Electric Fields rule (Merceret, et al. 2010).

2.4.11 The CCAFS/KSC Field Mill Maintenance and Verification

The electric field mill, as hitherto stated, operates to measure electricity in the atmosphere. The main piece of the field mill, the cylindrical object on top, as seen in Figure 6, contains a motor that spins a rotor blade at 2,500 revolutions per minute. The term "measures electricity" can be a misnomer. The field mill takes measurements of the ground's electrical activity and records them in 50 hertz (100 readings per minute). It uses these measurements to infer what the electrical potential is in the clouds. Habitually, the ground charge remains opposite of the charges in the clouds above. Therefore, the field mill records these measurements in volts per meter because the field mill stands one meter off the ground and measures the ground's charge there. Rather than receive all 100 readings of the 31 field mills located in Cape Canaveral, the field mill sends these measurements as one-minute means, via land line, to the weather team at the CCAFS/KSC (Range Generation Next 2019).

The CCAFS/KSC maintains the field mills by checking, inspecting, and replacing various sensors and components of the field mill. The CCAFS/KSC runs a system check daily. Monthly, they perform Host Computer Maintenance. Once a quarter, the CCAFS/KSC replaces the sensor heads on all the field mills while simultaneously inspecting the entirety of the field mill including the tripod, back-up battery and the surrounding area of the field mill. As needed, the CCAFS/KSC will remove the field mill and place it in a lab to calibrate it against artificial atmospheric electricity (Kennedy Space Center 2019).

15



Figure 6: Field mill machine located at the CCAFS/KSC Photo Courtesy of NASA (2006).

2.5 Research into the LLCC

The CCAFS/KSC uses the electric field mill along with radar, weather balloons, measurements from aircrafts etc. to determine the safety of a launch in regard to lighting. Because of this the CCAFS/KSC constantly funds research conducted into the LLCC. In this section we discuss the different aspects of research compiled to support the CCAFS/KSC in regard to lightning and specifically the LLCC.

2.5.1 Modeling the Distribution of Lightning Strike Distances

Sanderson (2019) discovered that lightning within 5 nmi could be decreased to 4 nmi when applying the Weibull distribution. This research concluded that with the Weibull distribution, modeled out of 1000 storms, the CCAFS/KSC could have avoided 182 false positive alarms. This resulted while incurring 3 false negative alarms per 1000, saving on average 30%-man hours that would not need to cease activities because of false positive lightning warnings (Sanderson 2019). This research provides interesting insights into how we predict and warn of lightning. It does provide a model to follow to help others measure lightning within 4 nmi correctly. Nevertheless, this study did not provide a means to forecast or build a climatology for the field mill or the LLCC in general.

2.5.2 Identifying an evident difference between the coast and inland field mills

Lucas, et al. (2017) witnessed a consistent difference between the field mill data sites on the coast and those in land located at the CCAFS/KSC. This study proved a median difference of 50 V m⁻¹ between the field mills in land and those on the coast. It demonstrated a statistical difference between the coast and inland in terms of electrical potential with the coast presenting a greater electrical potential. Lucas et al. (2017) aided in the creation of the field mill climatology for this thesis. Using the dataset provided by the researcher of this study, we recreated and demonstrated this same phenomenon. Our research concluded that by executing a correlation matrix of the 15-minute means and max of field mills, no significant difference between the costal field mills and inland field mills exists. However, this requires additional testing to substantiate this claim definitively.

2.5.3 Radar Now casting of Total Lightning over the CCAFS/KSC

Seroka, et al. (2012) collected four years of daytime doppler data (sound data) and analyzed it to build a better predictor for lightning. This study utilized the data to demonstrate that inter-cloud lightning commonly occurred (76% of the time) before cloud to ground lightning. The model revealed that the inter-cloud predictor generated a 2.4 min lead time before cloud to ground lightning. However, this study did not include a climatology for the LLCC.

2.5.4 Developing empirical lightning cessation forecast guidance for the CCAFS/KSC

Stano, et al. (2010) observed 116 storms using the Lightning Detection and Ranging Network. It produced a model based on the empirical data of the study. This model contributed to a five to ten-minute early lightning advisory at the CCAFS/KSC. However, it did not provide a climatology of the LLCCs or the electric field mills.

2.5.5 Cloud Climatology for Rocket Triggered Lightning from Launches at the CCAFS/KSC

Strong (2012) tracked cloudy weather conditions from January 1998 to December 2010. It utilized three databases and determined which databases obtained the best measurements of cloud data for the CCAFS/KSC. It also produced a daily climatological probability of violation in terms of a seven, eleven- and fifteen-day average of violating the cumulous cloud rule at the CCAFS/KSC. It also produced daily, monthly climatological probabilities for violating the Cumulus Cloud rule (LLCC Rule III). Furthermore, this research broke the climatology and probabilities into cloud layer (Strong 2012). This climatology and research did not use or incorporate the field mill rule or hope to combine the LLCC rules in one climatology. However, our field mill research strives to create a climatology for the field mill rule similarly as Strong (2012).

2.5.5 LLCC Climatology by Maier and Lake Nona High School

Lake Nona High School AP Statistics students have been building models for the CCAFS/KSC for three years detailing a climatology based on past LLCC violations. The students unfortunately have not produced a working climatology as of yet, however, the students discovered some interesting trends in the data (Roeder 2019).

2.5.6 Climate Analysis of Lightning Launch Commit Criteria for the CCAFS/KSC

Murray and Krider (2005), taken place in conjunction with the CCAFS/KSC, aimed at understanding the relationship between cloud reflectivity and the electric field mill. A number of the LLCCs use radar to detect the severity of a cloud. A mostly transparent cloud does not pose a severe risk to space launch vehicles in terms of triggered lightning. However, weather scientists refer to clouds in terms of reflectivity instead of transparency when using radar. A more reflective (less transparent) cloud presents greater danger to a space launch vehicle. This study hoped to draw a statistical correlation between cloud transparency and recorded field mill voltage. However, the conclusion of this study demonstrated the need to preserve equally the radar (which detects cloud reflectivity) and the electric field mills as both discern electrical potential of the atmosphere. Murray and Krider (2005) sought to understand how cloud reflectivity and the field mills related to one another. Our research also seeks to draw correlations of triggered lightning events and the electric field mill.

2.5.7 Operational analysis of electric field mills as lightning warning systems in Colombia

Aranguren, et al. (2012) focused on calibrating field mills based on their distance to a thunderstorm. It set about to confirm previous studies about distance and field mills. It confirmed the previous notion that after 10,000 meters the usefulness of a field mill deteriorates quickly. The CCAFS/KSC utilizes a rule of 8047 meters (5 miles) to determine if a field mill should be used to gauge atmospheric V m⁻¹. Although Aranguren, et al. (2012) confirmed a CCAFS/KSC rule in terms of distance a field mills from launches it did not include a climatology or a model to use the field mill to help schedule around lightning strikes.

2.6. Conclusion

These studies, mostly remunerated by the CCAFS/KSC, assist the weather team to improve the tools and measurements of the LLCC. The CCAFS/KSC relies on this LLCC to protect space launch vehicles from destruction of lightning. Although the Surface Electric Fields rule is only one of the ten rules, the LLCC proved the field mills usefulness in the aftermath of

the AC 67 destruction. Since then, six other rules rely on the field mill as a means to confirm violations. As previously shown, no study exists on building a climatology surrounding the Surface Electric Fields rule. Multiple studies built climatologies for different rules in the LLCC, however, no study brings these together into one LLCC climatology. The next chapter examines how we processed the field mill data in order to build the final climatology for the CCAFS/KSC.

III. Methodology

3.1 Introduction

This chapter discusses the raw data gathered to address the research aims of this thesis as well as the statistically methodologies adopted. In the discussion of the database, we lay out the process by which we not only assimilated it but also the steps taken to check for and remove erroneous data. Additionally, we describe the creation of the research specific database that we simply refer to as GAR (Green/Amber/Red) data. The generation of GAR data entails using correlation analysis, principal component analysis, and ordinary least squares. We speak to these statistical techniques and other methodologies embraced in addressing the research questions posed in Chapter I.

3.2 Raw Data

Lucas, et al. (2017) provided the bulk of the raw data and originates with the Global Hydrology Resource Center (GHRC) and the KSC weather archive. The GHRC contains an archive of the CCAFS/KSC's field mill readings from August 1, 1997 to October 13, 2012. The data from the KSC Archive holds an archive of the field mill readings that covers the time from January 24, 2013 – Present. Lucas, et al. (2017) combined these two sources, ceasing on August 2, 2015. In total, this database spans from August 1, 1997 – August 2, 2015, and Table 1 presents its general layout. Both databases provide one minute means for the 50 hertz field mill readings as explained in Chapter II. However, upon visual inspection, the dataset contained several weeks and months of missing data. To address the largest missing portion, October 13, 2012 – January 24, 2013, the CCAFS/KSC Weather Squadron provided *five-minute* mean data. These three data sources provide the composition of the raw data as displayed in Figure 7. To

ensure standardization we verified that all the raw data remained in Greenwich Mean Time Zone (GMT).

Date/Time	Field Mill #
MM/DD/YY	1 Min Mean

Table 1: General format of the raw data obtained from Lucas, et al. (2017).



Figure 7: Displays the composition of the raw dataset.

3.2.1 Data Accuracy

As stated in Chapter II, the CCAFS/KSC focuses on the absolute value of the field mill reading and not its natural value. Therefore, the first action we undertook to the raw data was to convert all field mill readings to absolute values. Afterwards, we sought to verify the accuracy of the dataset. We first accomplished this through visual examination of the online KSC weather archive. This process randomly selected three 12-hour periods between January 24, 2013 – August 2, 2015. In all cases, the data provided by Lucas, et al. (2017) matched exactly with the KSC weather archive. However, as formerly mentioned, the CCAFS/KSC archive does not contain data older than January 24, 2013, and the GHRC dataset ends on Oct 13, 2012.

To verify the GHRC portion of the dataset we turned to the National Center for

Environmental Information (NCEI), which archives previously reported weather events. The data verification process compares the raw field mill readings with a reported storm for every year in the GHRC database. In some rare cases, this process relied on field mill voltage readings an hour prior and an hour after a reported storm. However, in almost all circumstances the storm events coincided precisely with high voltage readings by the field mills. Those values that did not concur exactly, but remain within this two-hour window, are annotated with an (*) in Table 2, which shows the random sampling of days and times chosen. Due to sheer scale of the data, it was infeasible to check all days, times and weather.

Date	Time	Storm Event	FM Max	FM Min
2/17/98	0730	Tornado	6,468	(7,233)
5/8/99	1550	Thunderstorm Wind	1,663	(4,677)
6/11/01	1750	Thunderstorm Wind	740	(1,067)
6/18/02	1510	Thunderstorm Wind	(247)	(7,167)
* 4/25/03	1548	Hail	8,095	(4,470)
10/20/04	1700	Tornado	1,184	(1,809)
4/7/05	1820	Thunderstorm Wind	2,596	(2,148)
7/30/06	2234	Thunderstorm Wind	5,526	(1,235)
7/14/07	1542	Funnel Cloud	201	(3,223)
6/23/08	1745	Hail	824	(3,706)
6/5/09	1430	Funnel Cloud	4,012	(2,003)
9/5/10	1740	Thunderstorm Wind	226	(5,955)
1/25/11	1920	Thunderstorm Wind	5,282	(5,153)
5/17/12	1839	Hail	149	(6,126)

Table 2: A listing of the days and times showing the storm events checked for data consistency from years 1998-2012.

Once we completed the previously mentioned external corroboration of the dataset, the next phase required internal corroboration, that is, ensuring the data points represented correct values. For these forthcoming processes, we used Microsoft Excel 2019 and the statistical software package, JMP Pro 15. First, we sought to standardize each year of the dataset. Five

years in the dataset contained leap years and every year contained missing days and times where no data was provided. In particular, 1997 held an inadequate amount of data. Specifically, 1997 contained field mill voltage readings for only three days in August, eight days in November, and 23 days in December. Due to this extreme data sparsity, we eliminated 1997 from consideration and commenced with 1998. Figure 8 visually displays how atypical 1997 was in comparison to the amount of field mill readings for the remaining years studied.



Figure 8: Displays the difference between the amount of data available in 1997 and a normal calendar year.

3.2.2 Rogue Field Mills

After standardizing the dataset to absolute values and beginning the dataset with 1998, we sought to understand how each field mill correlated to one another. Because of the vast datapoints per year (approximately 16M field mill readings per year), we condensed each year of field mill readings into 15-minute means and 15-minute maxes to accomplish a correlation plot for each year. This process revealed that each year contained field mills that did not correlate highly with each other. As displayed in Table 3, several field mills correlated below 0.5. Due to the location of the field mills and that they share a very similar climate, we suspected that this correlation disclosed that the dataset possibly contained erroneous data points.

In order to discover these possible erroneous field mill data values, we revisited the raw one-minute field mill voltage readings. Specifically, we investigated the pairing of field mills that displayed a correlation below 0.5. Table 3 displays such an example. Upon visual inspection of this data, we noticed a significant amount of field mill readings at or above 19,000 V m⁻¹. This is significant because the CCAFS/KSC reports the highest value of a field mill during a launch at approximately 19,000 V m⁻¹ (Roeder, personal communction, 2019). Using this Subject Matter Expert (SME) logic, we commenced a review of any field mill reading greater than the absolute value of 19,000 V m⁻¹. This review process discovered that in every case, but one, when a field mill reading exceeded 19,000 V m⁻¹ this reading also followed two other distinctions. First, when a field mill superseded 19,000 V m⁻¹, this reading would continue to remain greater than a 10,000 V m⁻¹ per minute reading difference prior to the reading first exceeding 19,000 V m⁻¹. It is as if the field mill voltage suddenly spiked and remained "spiked" and not resetting itself. Secondly, these "spiked" field mill readings maintained a difference of

Table 3: An example of a field mill correlation matrix for detecting possible erroneous values (as highlighted in pink). This specific example is for year 2000 using 15-minute field mill voltage max readings.

	1	2	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	25	26	27	28	29	30	32	33	34
1	1	0.8377	0.8386	0.7851	0.7615	0.7605	0.7856	0.7359	0.7569	0.7459	0.6514	0.707	0.6649	0.6446	0.607	0.6486	0.6349	0.6081	0.6193	0.4592	0.5763	0.545	0.5001	0.5632	0.5251	0.4574	0.4939	0.4981	0.449	0.455	0.4601
2	0.8377	1	0.7831	0.881	0.8046	0.869	0.7765	0.7363	0.8334	0.8004	0.6595	0.687	0.711	0.711	0.63	0.7163	0.7002	0.6646	0.6849	0.5095	0.6442	0.6257	0.559	0.5963	0.581	0.5058	0.55	0.5587	0.4997	0.5172	0.5184
4	0.8386	0.7831	1	0.8129	0.8689	0.7271	0.8924	0.8433	0.8011	0.7948	0.7679	0.79	0.7595	0.7527	0.6993	0.7254	0.7081	0.6953	0.6949	0.512	0.635	0.5991	0.5588	0.6741	0.5988	0.5392	0.5676	0.5752	0.522	0.5203	0.545
5	0.7851	0.881	0.8129	1	0.8881	0.8706	0.7883	0.7435	0.8899	0.8329	0.6842	0.6861	0.7357	0.7496	0.6401	0.7498	0.7464	0.6915	0.6986	0.482	0.6562	0.6217	0.5796	0.5948	0.5636	0.4797	0.5566	0.5494	0.5137	0.5279	0.5204
6	0.7615	0.8046	0.8689	0.8881	1	0.788	0.8486	0.7997	0.8658	0.8493	0.7532	0.7393	0.7728	0.7929	0.7082	0.7795	0.7711	0.7224	0.7284	0.53	0.6681	0.6308	0.5848	0.6547	0.6057	0.5363	0.5952	0.5877	0.544	0.5506	0.5651
7	0.7605	0.869	0.7271	0.8706	0.788	1	0.7328	0.6886	0.8548	0.8055	0.6441	0.6343	0.68	0.6983	0.5903	0.7335	0.7433	0.6516	0.6848	0.4923	0.6556	0.6309	0.5608	0.5547	0.5461	0.4803	0.5414	0.5338	0.4879	0.5154	0.5081
8	0.7856	0.7765	0.8924	0.7883	0.8486	0.7328	1	0.9424	0.8132	0.8628	0.7917	0.8682	0.842	0.8144	0.7708	0.7844	0.7407	0.7714	0.77	0.5696	0.6771	0.6611	0.589	0.7462	0.6757	0.5854	0.6275	0.6348	0.5652	0.5689	0.5905
9	0.7359	0.7363	0.8433	0.7435	0.7997	0.6886	0.9424	1	0.7906	0.8375	0.8048	0.9208	0.8734	0.8353	0.7902	0.793	0.7346	0.7913	0.7865	0.5814	0.6891	0.6712	0.6078	0.7674	0.694	0.6064	0.6507	0.6612	0.592	0.5878	0.6153
10	0.7569	0.8334	0.8011	0.8899	0.8658	0.8548	0.8132	0.7906	1	0.9017	0.7576	0.7365	0.7826	0.8	0.6905	0.8147	0.8009	0.7498	0.7631	0.5556	0.7203	0.6846	0.6227	0.6683	0.6301	0.5551	0.6262	0.6225	0.5744	0.5937	0.5935
11	0.7459	0.8004	0.7948	0.8329	0.8493	0.8055	0.8628	0.8375	0.9017	1	0.791	0.7847	0.8436	0.8816	0.7245	0.8815	0.8438	0.8007	0.8248	0.5934	0.7517	0.7226	0.6328	0.6972	0.6655	0.5659	0.6481	0.6409	0.578	0.5948	0.6
12	0.6514	0.6595	0.7679	0.6842	0.7532	0.6441	0.7917	0.8048	0.7576	0.791	1	0.7748	0.8044	0.8426	0.6454	0.7874	0.7567	0.744	0.7463	0.55	0.6824	0.6161	0.592	0.6663	0.602	0.5382	0.5906	0.5883	0.5628	0.5228	0.567
13	0.707	0.687	0.79	0.6861	0.7393	0.6343	0.8682	0.9208	0.7365	0.7847	0.7748	1	0.8918	0.8207	0.8597	0.779	0.7241	0.8111	0.7903	0.59	0.6906	0.6788	0.6049	0.8199	0.7249	0.6444	0.6762	0.6866	0.6197	0.5899	0.6416
14	0.6649	0.711	0.7595	0.7357	0.7728	0.68	0.842	0.8734	0.7826	0.8436	0.8044	0.8918	1	0.9135	0.8627	0.8805	0.813	0.9135	0.8972	0.6662	0.789	0.7631	0.6793	0.8451	0.7781	0.6655	0.7242	0.7371	0.6598	0.639	0.6892
15	0.6446	0.711	0.7527	0.7496	0.7929	0.6983	0.8144	0.8353	0.8	0.8816	0.8426	0.8207	0.9135	1	0.784	0.9283	0.8551	0.8856	0.9003	0.639	0.792	0.7637	0.6794	0.7858	0.7268	0.6262	0.7026	0.6952	0.6468	0.6398	0.6641
16	0.607	0.63	0.6993	0.6401	0.7082	0.5903	0.7708	0.7902	0.6905	0.7245	0.6454	0.8597	0.8627	0.784	1	0.7749	0.7256	0.8386	0.7915	0.6118	0.6928	0.693	0.6194	0.8878	0.7715	0.6888	0.7028	0.7225	0.6449	0.619	0.6778
17	0.6486	0.7163	0.7254	0.7498	0.7795	0.7335	0.7844	0.793	0.8147	0.8815	0.7874	0.779	0.8805	0.9283	0.7749	1	0.92	0.8835	0.9098	0.6626	0.8387	0.7959	0.6976	0.7613	0.7168	0.6089	0.7046	0.6884	0.6303	0.6342	0.6523
18	0.6349	0.7002	0.7081	0.7464	0.7711	0.7433	0.7407	0.7346	0.8009	0.8438	0.7567	0.7241	0.813	0.8551	0.7256	0.92	1	0.8204	0.8521	0.6167	0.8437	0.7802	0.6799	0.6984	0.6552	0.5471	0.655	0.634	0.5971	0.598	0.602
19	0.6081	0.6646	0.6953	0.6915	0.7224	0.6516	0.7714	0.7913	0.7498	0.8007	0.744	0.8111	0.9135	0.8856	0.8386	0.8835	0.8204	1	0.9459	0.7109	0.8432	0.8282	0.7398	0.8617	0.8159	0.6902	0.7746	0.7747	0.708	0.6896	0.7296
20	0.6193	0.6849	0.6949	0.6986	0.7284	0.6848	0.77	0.7865	0.7631	0.8248	0.7463	0.7903	0.8972	0.9003	0.7915	0.9098	0.8521	0.9459	0.7404	0.7121	0.8/31	0.8568	0.7538	0.8263	0.8011	0.6797	0.7761	0.768	0.7029	0.6896	0.725
21	0.4592	0.5095	0.512	0.482	0.53	0.4923	0.5696	0.5814	0.5556	0.5934	0.55	0.59	0.6662	0.639	0.6118	0.6626	0.6167	0.7109	0.7121	0.0570	0.6573	0.6578	0.5913	0.6665	0.6546	0.5576	0.6395	0.6298	0.5934	0.5638	0.6031
22	0.5763	0.6442	0.635	0.6562	0.6681	0.0000	0.6771	0.6891	0.7203	0.7517	0.6824	0.6906	0.789	0.792	0.6928	0.8387	0.8437	0.8432	0.8731	0.6573	1	0.9034	0.8061	0.7344	0.7375	0.6237	0.7445	0.7186	0.69	0.6837	0.6897
23	0.545	0.6257	0.5991	0.6217	0.6308	0.6309	0.6611	0.6712	0.0840	0.7226	0.6161	0.6788	0.7631	0.7637	0.693	0.7959	0.7802	0.8282	0.8568	0.6578	0.9034	0.0500	0.8539	0.7433	0.7763	0.0009	0.805	0.7709	0.738	0.7547	0.7458
25	0.5001	0.559	0.5568	0.5796	0.5848	0.5608	0.589	0.0078	0.0227	0.6328	0.592	0.6049	0.0793	0.0794	0.6194	0.0970	0.6799	0.7398	0.7538	0.5913	0.8061	0.8539	0.0000	0.0803	0.7405	0.7034	0.8028	0.7684	0.8021	0.6367	0.7791
20	0.5052	0.5963	0.6741	0.5946	0.6057	0.5547	0.7402	0.7674	0.0003	0.0972	0.0003	0.7040	0.7701	0.7000	0.7715	0.7013	0.6964	0.8017	0.8263	0.0005	0.7344	0.7455	0.0003	0.0640	0.0042	0.7652	0.7793	0.0001	0.7214	0.001	0.7495
2/	0.5251	0.5059	0.5966	0.5636	0.5363	0.5461	0.6757	0.6064	0.6501	0.6650	0.602	0.7249	0.6655	0.7200	0.6999	0.6090	0.6552	0.6002	0.6797	0.5576	0.7375	0.7763	0.7405	0.7652	0.8402	0.0492	0.0090	0.9230	0.8452	0.7039	0.8004
20	0.4020	0.5056	0.5392	0.4797	0.5363	0.4003	0.0004	0.6507	0.0001	0.5059	0.5362	0.6762	0.0000	0.0202	0.0000	0.0009	0.6471	0.0902	0.0797	0.0070	0.0237	0.0059	0.0004	0.7002	0.0492	0.0400	0.0402	0.0009	0.0403	0.0542	0.0300
30	0.4081	0.5587	0.5752	0.5494	0.5877	0.5338	0.6348	0.6612	0.6225	0.6400	0.5883	0.6866	0.7271	0.6952	0.7020	0.6884	0.634	0 7747	0.768	0.0000	0.7186	0.7709	0.7684	0.8001	0.00000	0.8859	0.0443	1	0.8602	0.8101	0.9401
32	0 449	0.4997	0.522	0.5137	0.544	0.4879	0.5652	0.502	0.5744	0.578	0.5628	0.6197	0.6598	0.6468	0.6449	0.6303	0.5971	0 708	0 7020	0.5034	0.0100	0 738	0.8021	0.7214	0.8154	0.8453	0.9035	0.8692	1	0.8767	0.9200
33	0.455	0.5172	0.5203	0.5279	0.5506	0.5154	0.5689	0.5878	0.5937	0.5948	0.5228	0.5899	0.639	0.6398	0.619	0.6342	0.598	0.6896	0.6896	0.5638	0.6837	0 7547	0.8387	0.681	0.7639	0 7712	0.8543	0.8191	0.8767	1	0.8587
34	0.4601	0.5184	0.545	0.5204	0.5651	0.5081	0.5005	0.6153	0.5035	0.0	0.567	0.6416	0.6802	0.6641	0.6778	0.6523	0.602	0 7206	0 725	0.6031	0.6807	0 7458	0 7701	0 7405	0.8604	0.8088	0.9401	0.032	0.0200	0.8587	1

greater than 10,000 V m⁻¹ when compared to all other field mill readings within a two-hour window before and after these "spiked" readings occurred. After consulting with the CCAFS/KSC SMEs, we deemed these datapoints erroneous and deleted them.

After completing this process and eliminating these datapoints, we again condensed these raw field mill readings into 15-minute means and 15-minute maxes and correlated them against each other. However, again this process discovered that multiple field mills in various years contained correlations below 0.5. Once more returning to the raw field mill readings this process sought out those years and field mills that contained low correlations. Not unlike the last iteration, this process discovered the same problem aforementioned. However, instead of discovering field mill readings greater than 19,000 V m⁻¹, we discovered field mill readings above 15,000 V m⁻¹ acting as previously mentioned. Not every value above 15,000 V m⁻¹ acted with the same deviations as those greater than 19,000 V m⁻¹, however, when they acted with the same dispersion as earlier mentioned we deleted these values. Both of these data processing steps involving deleting erroneous field mill readings above 19,000 V m⁻¹ and 15,000 V m⁻¹ are displayed in Figures 9 and 10.

After removing these erroneous values, the correlations between each field mill voltage readings for each hour for every year maintained a correlation of greater than 0.5, which is in keeping with what the SMEs of expected. This process eliminated approximately 0.004% of all one-minute field mill readings. After completing this process our analysis noticed one more outlier. Figure 11 displays the max of 1 hour means for Field Mill 14. Upon further investigation this outlier met the criteria of maintaining a difference of greater than 10,000 V m⁻¹ amongst its counterpart field mills and within itself by minute, however, it did not exceed 15,000

26

V m⁻¹. To preserve the accuracy of the dataset this process eliminated that datapoint. After this last process, we discovered no other anomalies.



Figure 9: Visualization of the data detection process for erroneous field mill readings exceeding $19,000 \text{ V m}^{-1}$.



Figure 10: Visualization of the data detection process for erroneous field mill readings exceeding $15,000 \text{ V m}^{-1}$.



Figure 11: Displays a datapoint found that indicated an error in the dataset, this datapoint was eliminated.

3.3 Condensing the Dataset

After checking for and removing erroneous data, we condensed the data into two major categories. At this point, the dataset recorded almost every field mill voltage reading for every minute of every day from January 1998 through August 2015, approximately 312 million rows. However, this exhaustive dataset represented an unrealistic time window for an operational meteorologist to monitor in practice. Therefore, the CCAFS/KSC indicated that they did not require a field mill climatology (scientific study of climate) based upon 1-minute increments, instead preferred 1-hour increments. Therefore, we condensed these 60-minute values into 1-hour mean values and 1-hour max values for every field mill for every year. Afterwards, our data set included 18 years of 1-hour means of every field mill and 18 years of 1-hour maxes for every field mill.

3.3.1 Assessing yearly affect

After building the 1-hour means and maxes datasets, we assessed whether year affected either the mean or max voltage readings of the field mills. Using voltage readings of the field mills as the dependent variable, we conducted an Analysis of Variance (ANOVA) with the independent variables of year, month, and time (hourly diurnal effect) based on SME input. Additionally, we considered a temporal effect of voltage readings by adding a lagged variable. A lagged variable isolates the temporal effect of hour by ascertaining how much field mill readings are affected by the voltage reading in the previous hour. It is important to note that the goal of this step is to not build a predictive regression model of voltage readings but instead determine how significant the effect year has on voltage readings relative to the other variables in the analysis.

Respor	nse Sy	s_M	ean					Respo	nse Sy	s_Mea	n			
Effect	Sumn	nary						Effect	Sumr	nary				
Sourc	e LogW	/orth					PValue	Sourc	е	LogW	orth			
Time	3 793.485				0.00000	00000 Lag 1 Sys_Mean 28569.87								
Month	onth 555.818				0.00000	Month		2/8	737					
Year	38	8.998	1				0.00000	Year		1	.596			
Sumn	nary of	Fit						Summ	narv of	Fit				
RSquare			0	.04456	63			RSquare			0.	617087		
RSquare Adj 0.044225						RSquare Adj 0.616948								
Root Me	an Squar	e Erro	r 6	60.98	78			Root Me	an Squar	e Error	41	8.8025		
Mean of	Respons	e	3	77.79	19			Mean of	Respons	e	37	78.0726		
Observa	tions (or	Sum V	vgts)	1443	51			Observa	itions (or	Sum Wgt	S)	143955		
Analy	sis of l	Varia	ance					Analy	sis of	Varian	се			
		5	Sum of							Sur	n of			
Source	DF	S	quares	Mea	n Square	F Ratio		Source	DF	Squa	ares	Mean Square	F Ratio	1
Model	51	29404	487526	5	7656618	131.9661		Model	52	4.0675e	+10	782217838	4459.736	
Error	144299	6.304	45e+10	4	36904.88	Prob > F		Error C. Total	143902	2.5246	+10	1/5395.55	< 0001*	
C. Total	144350	6.598	35e+10			<.0001*		C. IUlai	145954	0.09106	+10		<.0001	
Effect	Tests							Effect	Tests					
			S	um of								Sum of		
Source	Nparm	DF	Sa	uares	F Ratio	Prob > F	F	Source		Nparm	DF	Squares	F Ratio	Prop > F
Year	17	17	10140	05343	13,6529	<.0001	•	Vear		23	23	244/3/885	1 7732	<.0001
Month	11	11	115347	70277	240.0086	<.0001	•	Month		11	11	57404703.5	29.7534	<.0001*
Timo	22	22	167010	1007	100 5007	+ 0001		Les 1 C		4		0.7700+.10	0151060	< 0001*

Table 4: Displays the linear regression model for the 1-hour means, year reveals least predictive.

As shown in Table 4, whether we incorporate the hour before field mill's voltage reading or not, year has the smallest relative effect on field mill voltage readings. Furthermore, when properly accounting for the temporal effect (as evident by the greatly improved coefficient of determination from 0.04 to 0.62) year at best has a marginal relative effect. Because of this minimal yearly effect, we further condensed the dataset furthermore into one averaged calendar year. Thus, instead of 18 years of 1-hour means and 1-hour maxes for 31 field mills, we condensed field mill voltage readings into an average calendar year. As an aside, the SMEs at Cape Canaveral also noted with other ongoing research that year had negligible effect on frequency of lightning strikes.

3.3.2 Principal Component Analysis

Upon discovering that the linear regression model presented the year as a very unlikely predictor, we sought a specific combination of field mills to represent the dataset. Therefore, the analysis took the correlations and performed Principal Component Analysis (PCA). A PCA seeks to determine what linear combination of variables best explains the variability of the entire dataset. In our case, these variables consist of all the field mills. The analysis and its findings located in Table 5 display that the first principal component of field mills accounts for 79% of the variability. The next phase is to view the eigenvectors. The eigenvectors explain the weight needed for each input to obtain the prescribed 79%. The eigenvectors located in Figure 12 and Table 6 resemble a uniform distribution, which suggests a relative average or global (system-wide) mean. After taking the mean for every field mill of every year for each hour of the year we then consolidated by taking the mean and max of every field mill. More is explained on how we did this in 3.4.2.

Table 5: : Displays the PCA for the means on the left and the maxes on the right, the total supersedes 100, due to rounding.

Princip	al Comp	onents:	on Correlat	tions	Princip	al Comp	onents:	on Correlat	ions
Number	Eigenvalue	Percent	20 40 60 80	Cum Percent	Number	Eigenvalue	Percent	20 40 60 80	Cum Perce
1	26.1860	79.352		79.352	1	26.2158	79.442		79.4
2	2,4431	7,403		86,755	2	2.3547	7.135		86.5
3	1.0138	3.072	ĪIIII	89.827	3	1.3919	4.218		90.7
4	0.8379	2.539		92.366	4	0.7975	2.417		93.2
5	0.7202	2.182		94.549	5	0.6787	2.057		95.2
6	0.3025	0.917		95.465	6	0.2769	0.839		96.1
7	0.2416	0.732		96.197	7	0.2581	0.782		96.8
8	0.1762	0.534		96.731	8	0.1882	0.570		97.4
9	0.1605	0.487		97.218	9	0.1597	0.484		97.9
10	0.1469	0.445		97.663	10	0.1482	0.449		98.3
11	0.1363	0.413		98.076	11	0.1332	0.404		98.7
12	0.1193	0.362		98.437	12	0.1207	0.366		99.1
13	0.1147	0.348		98.785	13	0.1115	0.338		99.5
14	0.1094	0.332		99.117	14	0.1050	0.318		99.8
15	0.0975	0.295		99.412	15	0.0980	0.297		100.1
16	0.0904	0.274		99.686	16	0.0968	0.293		100.4
17	0.0758	0.230		99.916	17	0.0817	0.248		100.6
18	0.0743	0.225		100.141	18	0.0793	0.240		100.8
19	0.0708	0.215		100.355	19	0.0750	0.227		101.1
20	0.0665	0.202		100.557	20	0.0682	0.207		101.3
21	0.0609	0.185		100.742	21	0.0658	0.199		101.5
22	0.0575	0.174		100.916	22	0.0637	0.193		101.7
23	0.0563	0.170		101.086	23	0.0586	0.178		101.9
24	0.0532	0.161		101.248	24	0.0579	0.176		102.0
25	0.0476	0.144		101.392	25	0.0520	0.158		102.2
26	0.0441	0.134		101.526	26	0.0507	0.154		102.3
27	0.0390	0.118		101.644	27	0.0462	0.140		102.5
28	0.0354	0.107		101.751	28	0.0388	0.118		102.6
29	0.0325	0.098		101.849	29	0.0382	0.116		102.7
30	0.0271	0.082		101.932	30	0.0360	0.109		102.8
31	0.0260	0.079		102.010	31	0.0345	0.105		102.9
32	0.0217	0.066		102.076	32	0.0284	0.086		103.0

Table 6: Displays the eigenvectors for the 1-hour means on the left and maxes on the right.

FM #	Eigenvectors		FM #	Eigenvector
1	0.154		1	0.156
2	0.159	1 [2	0.160
4	0.169	1 [4	0.170
5	0.170	1 [5	0.170
6	0.173	1	6	0.174
7	0.163] [7	0.165
8	0.177	[8	0.177
9	0.178	[9	0.177
10	0.174] [10	0.173
11	0.181	1	11	0.181
12	0.180	[12	0.180
13	0.173	1	13	0.175
14	0.184] [14	0.184
15	0.183] [15	0.182
16	0.179	[16	0.180
17	0.183] [17	0.183
18	0.177		18	0.176
19	0.186] [19	0.185
20	0.186		20	0.184
21	0.180	1	21	0.181
22	0.179] [22	0.179
23	0.170		23	0.167
24	0.173] [24	0.170
25	0.170] [25	0.171
26	0.177	[26	0.177
27	0.177		27	0.177
28	0.163		28	0.165
29	0.176	[29	0.176
30	0.176	[30	0.174
31	0.166	[[31	0.167
32	0.166	[32	0.167
33	0.166] [33	0.165
34	0.172		34	0.171



Figure 12: Displays the 1-hour means on the left, maxes on the right eigenvectors for the PCA.

3.4 Building the GAR database

After the accuracy process and data consolidation, the next phase sought to numerically define a violation. In the current LLCC for the field mill rule states that, barring no other violations, when a field mill is less than 1000 V m⁻¹ a launch may occur. However, after 1000 V m⁻¹ more restrictions apply that require the checking of other instrumentation to launch. At 1500 V m⁻¹ the LLCC does not permit launch unless there are no clouds in the sky. In order to classify voltage readings in order to build and test a model, we have the following groupings based on the absolute voltage reading: Green: less than 1000 V m⁻¹; Amber: Greater than or equal to 1000 V m⁻¹, however less than 1500 V m⁻¹; Red: Greater than or equal to 1500 V m⁻¹. Forthcoming, this is called the GAR for Green, Amber and Red.

3.4.1 Three Groups of the dataset

After creating the GAR database, we created multiple ways to assess the validity of the final model. Firstly, we sought to create 1-hour blocks for the mean and max of every field mill, 1-hour blocks of the mean and max of a central cluster of field mills and 1-hour blocks for the mean and max of Field Mill 14. The analysis pinpointed Field Mill 14 when conducting the

correlational analysis. During this analysis Field Mill 14 displayed consistently high correlation with all field mills throughout the years. Furthermore, this field mill consistently displayed the highest of the lowest correlations. To view how Field Mill 14 held up with its counterparts located at the CCAFS/KSC during 1998 – 2015 Figure 13 displays the field mill with the highest, lowest correlation through the years. Figure 14 displays the same results however shows the 2nd highest of the lowest correlations throughout these years.

The central cluster embodies the only five field mills within five nmi of any launch site. The LLCC states that every field mill within 5 nmi of a launch site must remain below 1000 V m⁻¹ in order to launch without violating the field mill rule. Therefore, any of these five field mills theoretically could suffice for any launch. These five field mills are: 13, 14, 15, 16, 19 (Range Generation Next 2019). These central field mills can be seen indicated by the dark circle in Figure 15.



Figure 13: Displays the percent of years Field Mill 14 held the highest of the lowest correlations.



Figure 14: Displays the percent of years Field Mill 14 held the second highest of the lowest correlations.



Figure 15: Displays all the field mill locations and draws particular attention to the central cluster of field mills: 13, 14, 15, 16, 19.

3.4.2 Subgroups of the aforementioned groups

Using the means and maxes of the three groups of the dataset (System Maxes/Means, Central Cluster Maxes/ Means, FM 14 Maxes/Means) we strove to isolate different interpretations of the data. Consequently, for each group of the data set this analysis created two subgroups. These subgroups sought to utilize the means and maxes of both the One-hour means and One-hour maxes datasets. Therefore, the first subgroup took the mean of every max field mill value. The max took the max of every field mill for this block of time. This repeated for the Central Cluster and Field Mill 14. When comparing these datasets, we notice three major indications that differentiates them. First, these different dataset's ranges vary greatly from one another. Secondly, the means do not hold constant across the datasets and thirdly, the number of outliers decreases as we move away from maxes and into means. To understand the flow and process of how we created these databases please see Figure 16. To view the differences in two of these databases and to understand why the analysis chose to sub divide these groups please see Figures 17. The flowchart in Figure 16 details ten light blue and light green rectangles. These ten boxes display the ten different datasets that were left after analysis. These databases feed the final model and serve as the conclusive data component that will run its veracity against the second launch database provided by the CCAFS/KSC.

3.5 Conclusion

In conclusion, we discussed how we obtained the data, processed it and prepared it, why and how we condensed it, and the final pieces that feed into the validation process. In Chapter IV we discuss and present the patterns and findings of the methods documented in Chapter III. Ultimately, Chapter IV specifies which GAR subgroup database, if any, best serves as a proxy to

35

use in lieu of tracking all the LLCC rules. Lastly, we conclude with any validation shortfalls and disconnects.



Figure 16: Displays the flowchart and the 10 different databases this thesis analyzed.



Figure 17: Displays the distributions of the three subsets of the maxes, the above displays the max of the maxes.

IV. Results and Analysis

4.1 Introduction

In this chapter we first present the visual patterns illustrated when investigating the effects of year, season, month, and diurnal (hourly) with respect to the percentages as denoted in the GAR databases. Next we discuss the regression models that reflect which of the GAR databases best predicts the percentage of red, amber and green. This analysis determines which of the previous 10 datasets described in Chapter III will progresses to validation and the ultimate presentation and or adoption by the CCAFS/KSC. Lastly, we discuss the empirical validation results presented through the final model. For all statistical testing we apply an alpha value of .05.

4.2 The Datasets

After categorizing the datasets into the GAR percentage models, we sought to understand these models by graphing their distributions. Starting with the Red max percentages Figure 18 displays that only the *Max of System Maxes, Max of System Means*, and *Max of Cluster means* hold dissimilar distributions from their counter parts. We viewed the Amber percentage box plots displayed in Figure 19 and saw that only *the max of system maxes* contained a dissimilar distribution from its counter parts. Finally, after examining both the Red and Amber plots we needed to confirm our observations with the Green percentage. In Figure 20 we recognize a slight shift from the previous two while simultaneously confirming that the only distribution that remains dissimilar from its counter parts continues to be *the max of system maxes*. However, next we test this hypothesis with a linear regression model to verify that the percentages created by *the max of the system maxes* generates the best climatology to test with the empirical dataset.











Figure 20: Displays the Amber percentage distributions, the left displays the maxes, right the means.

4.3 Field Mill Data

After visually testing these distributions we next sought to test these values in a linear regression model to determine the best climatology. The biggest difference between the reported R^2 and the adjusted R^2 was .0004. Due to this insignificant differential, forthcoming we will only mention R^2 and refrain from mentioning the adjusted R^2 . The variable that predicted the GAR percentages overwhelmingly continues to be the 1-hour lag variable (the previous hour's GAR percentage).

However strong the Lag variable remained, the other variables provided strong predictors for the GAR percentages as well. These variables are Month, Diurnal, Lagging 1-hour, and Lagging 2-hours. We tested these variables for every dataset in every GAR category. As displayed in Table 7 for the Red and Green criterion the max of system maxes obtained the highest R² at .738 and .711 respectively. Comparing the R² values with the box plots aforementioned we see that the only model to be greatly different in the Red category was the max of system maxes. However, differing from the visual inspection, the highest Amber R² originated with *the mean of system means* and is .173.

One of the plausible reasons for the Amber value receiving such a low R² is due to the low sample size of Amber criteria. In the raw dataset we continually witnessed the Amber criteria existing when atmospheric electricity transitions from low atmospheric electricity to a great quantity of electricity. Consequently, in the original 1-hour block max and mean databases the Amber criteria accounts for .8% of total values. Conversely, the Red criteria remains at 3.7% and 1.5% for these databases respectively. Therefore, because of the low R² in the Amber criteria, we did not consider using *the mean of system means* in the empirical validation. As seen in Tables 7 and 8 and supported by the visual models in almost every other category *the max of system maxes* maintained a wider range and a higher R^2 .

Maxes	Red	Amber	Green
Mean of System Maxes	0.655	0.135	0.697
Max of System Maxes	0.738	0.120	0.711
Mean of Cluster Maxes	0.624	0.097	0.657
Max of Cluster Maxes	0.657	0.089	0.657
FM 14 Maxes	0.619	0.079	0.624

Table 7: Displays the R^2 for the Maxes models.

Table 8: Displays the R^2 for the Means models.

Means	Red	Amber	Green
Mean of System Means	0.415	0.173	0.561
Max of System Means	0.619	0.147	0.697
Mean of Cluster Means	0.409	0.118	0.527
Max of Cluster Means	0.474	0.113	0.578
FM 14 Means	0.398	0.109	0.515

4.3.1 Field Mill Patterns

The secondary research question sought to graph the year, season, month, and diurnal patterns of the CCAFS/KSC field mills. Therefore, commencing with the year we noticed no trend from year to year as exhibited in Figures 21 - 23. This endorses the linear regression model, located in Chapter III, which found the yearly effect to have a very low differential coefficient (F Ratio).

After discerning no year affect, we sought to detect a seasonal pattern. Figure 24 displays the max percentage of the five max models each month. This along with Figure 25 demonstrates that the CCAFS/KSC experiences two seasons, a warm and cold season. Figure 26 took the minimum of the Green percentages for these same five models and follows the same

pattern. Discovering these seasons consisted of comparing typical Floridian transition months (May and October) in each year to discern when the weather shifted from cold to warm. However visible the transition from cold to warm, there was no discernable transition *month* that appeared in the field mill voltage readings. Even though we did not locate a transition month in the voltage readings, we intended to utilize the seasonality of the field mill as a predictor in the regression model. However, because the month, season and warm/cold variables essentially report different versions of the same numbers we sought to discern which variable acted as the best predictor. Nonetheless, when applying both the season (Winter, Spring, Summer, Fall) and the warm/cold predictors, both value's R² remained lower than the month's R².



Figure 21: Displays the year pattern for the Red criteria.



Figure 22: Displays the yearly pattern for the Amber criteria.



Figure 23: Displays the yearly pattern for the Green criteria.



Figure 24: Displays the monthly pattern for the Red Criteria.



Figure 25: Displays the monthly pattern for the Amber Criteria.



Figure 26: Displays the monthly pattern for the Green Criteria.

Embedded in each month is a possible daily pattern, but we did not discern any when looking at the year by 365 days. However, moving on to the diurnal pattern it's important to remember that the time for these graphs is in GMT. The diurnal pattern for the Red criteria suggests an even transition from cold to warm throughout the day as seen in Figure 27. This indicates that atmospheric electricity follows temperature patterns. However, when looking at the Amber and Green criteria graphs, we perceive a distinct transition period. In Figure 28 and 29 it displays this transition period beginning at 1100 GMT. More discussions on this pattern follow in Chapter V.



Figure 27: Displays the diurnal pattern for the Red criteria.



Figure 28: Displays the diurnal pattern for the Amber criteria.



Figure 29: Displays the diurnal pattern for the Green criteria.

4.4 Empirical Data Validation

One way of validating the field mill climatology developed in this thesis involves comparing the modeled patterns to similar assessments in other locales. Figures 30-32 originate from Krider et al. (2006) and show the likelihood of experiencing lightning in the three different regions. Since field mills are designed to detect electrical fields, one would expect the climatology described in this thesis to somewhat reflect the likelihood of lightning patterned elsewhere. When comparing Figure 26, which shows the climatology of experiencing a low field mill voltage reading (the Green percentage) to Figures 30-32, the graphs are remarkably similar. In all cases, one can see that the climatology proposed by this thesis reflects a lower Green percentage trend during the summer months and a much higher one in the Winter months. This comparison suggests that the climatology patterns ascertained from the field mills at Cape Canaveral are comparable to even areas quite geographical dissimilar.



Figure 30: First sample distribution in Krider et al. (2006) for comparing to Figure 26 in this thesis. DOY = Day of the Year.



Figure 31: Second sample distribution in Krider et al. (2006) for comparing to Figure 26 in this thesis. DOY = Day of the Year.



Figure 32: Third sample distribution in Krider et al. (2006) for comparing to Figure 26 in this thesis. DOY = Day of the Year.

With respect to assessing how well the developed climatology corresponds to the LLCC rules, we look to comparing the GAR percentages presented by the developed climatology to successful launches at Cape Canaveral. We used various sources easily documented on the internet recording all CCAFS/KSC launches dating from 2005 to 2020. In total, we recorded the moment a successful launch occurred for 159 instances. The reason our research chose this approach is because NASA (2017) states that every LLCC must be met in order to launch. Therefore, by this definition, no launch can take place unless, all the LLCC criteria have been satisfied. Therefore, we know that during these 159 instances we have specific times in which the CCAFS/KSC did not witness the possibility of a lightning strike, triggered or natural.

Using these 159 instances we tested them to observe the corresponding percentage of a violation in the field mill climatology we created. Figure 33 displays how our field mill

climatology contrasts against empirical launch data. The high amount of red percentages in the left side of the figure, detail that out of 159 instances, 140, (88%) occur during hours when the percent of violating any LLCCs remains at or below 15%. Therefore, according to our climatology, a majority of successful launches corresponds with a low chance of violating the LLCC. The mean of the red percentages was calculated at 7%, while the median was, 6%. Since we know that the LLCC was not violated during the time of these launches we know that our model can be used as a basis for building a climatology for all 10 LLCCs. Figure 34 and 35 detail the corresponding Amber and Green percentages.



Figure 33: Details the Red % when comparing to successful launches.



Figure 34: Details the Yellow % when comparing to successful launches.



Figure 35: Details the Green % when comparing to successful launches.

4.5 Conclusion

In summary, we demonstrated the difference between the datasets by comparing the ranges using a set of graphs. Furthermore, we used a linear regression model to select which dataset to test against the empirical dataset. The regression model indicated the *max of the system of maxes* as containing the best R². After using the *max of the system of maxes* to construct the model we tested it against the results found in Krider et al. (2006) as well as to 159 successful space launches. In the next chapter we discuss how these results could be used by the CCAFS/KSC and suggest further areas of research that if combined with this examination could provide a complete LLCC climatology.

V. Conclusions

5.1 Introduction

The purpose of this chapter is to add a resolution to the methods and results applied to the primary research problem and the outcomes of these results. We also discuss how these resolutions relate to past research with the surface electric field mills. Furthermore, we consider expanding and changing the methodology to solve the same problem. We also suggest future work that can be explored regarding this research. Finally, we offer conclusions on how to apply this research operationally.

5.2 Results and Past Research

Due to the occurrence and severity of a lightning strike during a space launch, the need for this research is obvious. Having a field mill climatology that is used to accurately assess the possibility of an LLCC violation will help forecasting and save money on launches. Using the max of system maxes we constructed this climatology and tested against a dataset of launches that occurred in Cape Canaveral. The empirical launch data test proved the effectiveness of this climatology.

To construct this climatology, we first sought to assess whether we could use field mill data to expect LLCC violations. Next we sought to determine whether we should use the entire system, a cluster of field mills or just one field mill. Finally, we strove to learn how to assess the field mills whether by max or mean and how that changes the climatology. When viewing and comparing this climatology with similar studies, we found the work of Krider et al. (2006). However, our research did not exactly parallel all research regarding the field mills. Using the 15 – minute correlation matrices we strove to test the results found in Lucas et al. (2017). When testing the difference between coastal field mills and inland field mills our results did not

indicate any significant difference between these two groups. More research into why this occurred did not fit into the scope of this thesis.

Because of this effectiveness of this climatology and the subsequent validation, the CCAFS/KSC asked for a tool that easily displays the climatology we built. The tool allows any user with access to Microsoft Excel to place any day of the week and a one-hour time slot and Excel will relay the historical climatological GAR percentage. A screen shot of this tool can be seen in Figure 36.

W				
	lien is uie		')	
Month	Day	Start Time (GMT)	End Time (GMT)	
12	25	13:01	14:00	
Fill in G	Grev squa	res only		
		<u>.</u>		
	Date & T	ime Reque	sted (GM]	Г)
December /	25	1.01.00 PM		2.00.00 E
December /	25	1.01.00 P M	-	2.00.00 1
Chance of violation				
Green	Amber	Red		
77%	8%	15%		

Figure 36: Details a screenshot of the tool provided by this thesis to the CCAFS/KSC.

5.3 Alternative Methodology and Future Research

Because we used other research to validate our climatology, we also discovered alternate methods in developing this research. The electric field mill serves as one tool used by the CCAFS/KSC to measure the propensity of a lightning strike, triggered or natural. The CCAFS/KSC holds numerous tools including radar, doppler, weather balloons etc., to understand the weather's inclination for lightning. Although the findings of this thesis remain important, the field mill only serves as one component of the larger lightning avoidance system. For a complete LLCC climatology to be built future research needs to consider integrating a radar climatology. Murray and Krider (2005) discusses the difficulty substituting a field mill for radar.

As discussed in Chapter II radar measures the reflectivity of a cloud (more transparent a cloud, the less potential for lightning). Thus, both components serve as very different tools that can detect the dangerous potential of an electrified cloud.

This thesis seeks not only to build a field mill climatology but to understand how that climatology acts when compared to other LLCC. Specifically, how does the field mill climatology contrast when compared to cloud to ground and intra cloud lightning data? The CCAFS/KSC archives this data and allows open access for anyone to download from the KSC archive mentioned in Chapter III. Adding both radar and lightning data could provide an exceptionally robust climatology.

This past data should also be compared over many years. A major finding for our research discovered that over 18 years of field mill data, the variable that mattered the least when it came to observing the empirical launch dataset, was, the year. If this is the case, further research could prove this phenomenon with radar, and lightning. Doing so could save on the costs of archived weather data and possibly divert research to looking at recent data instead of the past.

5.4 Final Remarks

While this topic requires further research to verify the findings, the outcome of this study was significant. With just a field mill climatology, our climatology demonstrated a mean red percentage of 7% during successful launches, indicating that an overwhelming majority of the time the field mill climatology expected the CCAFS/KSC to launch when a launch actually occurred. This climatology demonstrated the surface field mill data serves to understand the relationship with all 10 LLCCs. If researched further, this process could be replicated to include lightning, radar and other datasets thus making it a true and complete climatology of all the

53

LLCC violations at the CCAFS/KSC. Therefore, we recommend that the CCAFS/KSC use this climatology to support LLCC violation forecasting and training.

Bibliography

- 45th Weather Squadron. 2016 . "LLCC Evaluations 2009 2016." Florida: 45th Weather Squadron.
- Aranguren, D., J. Inampues, H. Torres, J. Lopez, and Ernesto Perez. 2012. "Operational analysis of electric field mills as lightning warning systems in Colombia." 2012 International Conference on Lightning Protection (ICLP). Vienna: IEEE.
- Dwter, Joseph R., and Martin A. Uman. 2013. "The Physics of Lightning." *Physics Reports*, October 9: 147-241.
- Forward, Keith M., Daniel J. Lacks, and R. Mohan Sankaran. 2009. "Methodology for studying particle–particle triboelectrification in granular materials." *Journal of Electrostatics* 179-183.
- Harrison, L. P. 1946. Lightning Discharges To Aircraft and Associated Meteorologiacl Conditions. Washington, D.C.: National Advisory Committee for Aeronautics.
- Japaridze, Mikhail . 2019. *TASS Russian News Agency*. May 27. Accessed October 31, 2019. https://tass.com/science/1060233.
- Kennedy Space Center. 2019. "Field Mill Schedule for Routines." Cape Canaveral, August 12.
- Krider, E. P., Willett, J. C., Peng, G. S., Simmons, F. S., Law, G. W., and Seibold, R. W. (2006).
 Triggered Lightning Risk Assessment for Reusable Launch Vehicles at the Southwest
 Regional and Oklahoma Spaceports (ATR-2006(5195)-1), El Segundo, The Aerospace
 Corporation.
- Lucas, G. M., J. P. Thayer, and W. Deierling. 2017. "Statistical analysis of spatial and temporal variations." *Journal of Geophysical Research: Atmospheres* 1158 1174.
- Mazur, Vladislav. 2016. Principles of Lightning Physics. Bristol: IOP Publishing.
- Merceret, Francis J., John C. Willett, Hugh J. Christian, James E. Dye, Phillip E. Krider, John T. Madura, Paul T. O'Brien, David W. Rust, and Richard L. Walterscheid. 2010. *A History*

of the Lightning Launch Commit Criteria and the Lightning. NASA Special Paper, KSC: NASA.

- Moskowitz, Clara. 2009. 5 Shuttle Launch Scrubs Cost Millions. July 16. https://www.space.com/6991-5-shuttle-launch-scrubs-cost-millions.html.
- Murray, Natalie D., and E. Phillip Krider. 2005. "Surgace Observations of the Electric Field and the Radar Relectivity of Decaying Thunderstorm Anvils and Debris Clouds at NASA Kennedy Space Center." *Meteorological Applications of Lightning Data*. Phoenix: National Center for Atmospheric Research.
- NASA. 2008. "Anvil Cloud." Photograph. John F. Kennedy Space Center, February 4.
- —. 1987. "Atlas Centaur 67 Lightning." Photograph. Cape Canaveral: John F. Kennedy Space Center.
- —. 2006. "Lightning and the Space Program." NASA Facts. Cape Canaveral: John F. Kennedy Space Center.
- —. 2017. NASA Standard for Lightning Launch Commit Criteria for Space Flight. Technical Standard, Kennedy Space Center : NASA.
- Patel, Neel V. 2018. *This is why rocket launches always get delayed: Weather, weather, and sometimes boats.* December 19. https://www.popsci.com/why-scrub-rocket-launch/.
- Pomeroy, Ross. 2013. *Apollo 12 Was Struck by Lightning During Launch*. February 17. https://www.realclearscience.com/blog/2013/02/apollo-12-struck-by-lightning.html.

Range Generation Next. 2019. "Eastern Range Instrumentation Handbook." Dulles, October 15

- Roeder, William E. 2019. "Communication between Bill Roeder and Capt Shane Gardner." WPAFB, November 19.
- Roeder, William E. 2019. "LLCC Climatology by Lake Nona High School & the 45th Weather Squadron." Cape Canaveral, October 29.

- Seroka, Gregory N., Richard E. Orville, and Courtney Schumacher. 2012. "Radar Nowcasting of Total Lightning over the Kennedy Space Center." *Amercian Meteorological Society* 189-204.
- Stano, Geoggrey T., Henry E. Fuelberg, and William P. Roeder. 2010. "Developing empirical lightning cessation forecast guidance." *Journal of Geophysical Research Vol. 115* 1-18.
- Strong, Greg J. 2012. "Cloud Climatologies for Rocket Triggered Lightning from Launches at Cape Canaveral Air Force Station and Kennedy Space Center." *Theis*. Monterey: Naval Postgraduate School, March.
- Suckow, Elizabeth. 2009. "National Advisory Committee for Aeronautics Overview." NASA History Division. April 23. Accessed August 6, 2019. https://history.nasa.gov/naca/overview.html.
- Uman, Martin A. 2008. *The Art and Science of Lightning Protection*. Cambridge: Cambridge University Press.
- Willett, John C., Francis J. Merceret, Philip E. Krider, T. Paul O'Brien, James E. Dye, Richard L.
 Waltershcheid, Maribeth Stolzenburg, Kenneth Cummins, Hugh J. Christian, and John T.
 Madura. 2016. *Rationales for the Lightning Launch Commit Criteria*. Rationale, Kennedy Space Center: NASA.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 074-0188			
The public re data sources, other aspect Information notwithstand valid OMB c PLEASE 1	eporting burden fo gathering and ma of the collection o Operations and Re ling any other prov control number.	r this collection c intaining the data f information, inc ports (0704-0188 vision of law, no p URN YOUR F	of information is estimated to a needed, and completing and cluding suggestions for reducin (3), 1215 Jefferson Davis High- person shall be subject to an p CORM TO THE ABOVE	average 1 hour per re- reviewing the collect ng this burden to Dep way, Suite 1204, Arli enalty for failing to c CADDRESS.	sponse, including ion of information artment of Defens ngton, VA 22202 omply with a colle	the time for reviewing instructions, searching existing . Send comments regarding this burden estimate or any se, Washington Headquarters Services, Directorate for .4302. Respondents should be aware that ection of information if it does not display a currently	
1. REPOR	T DATE (DD-A 22-03-2020	<i>1М-ҮҮҮҮ)</i>)	2. REPORT TYPE Mas	ter's Thesis		3. DATES COVERED (From – To) October 2018 – March 2020	
TITLE AN	ND SUBTITLE	;			5	a. CONTRACT NUMBER	
USING	G A FIELE) MILL C	LIMATOLOGY	TO ASSES	S ALL	GRANT NUMBER	
EIGHTNING EACHERTCONNET CRITERIA			PROGRAM ELEMENT NUMBER				
6. AU	THOR(S)				5	5d. PROJECT NUMBER	
Gardner	r, Shane C.	Capt USA	ΛF		5	5e. TASK NUMBER	
					5	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology		8. PERFORMING ORGANIZATION REPORT NUMBER					
2950 I WPA	AFIT-ENV-MS-20-M-2 WPAER OH 45433 8865				AFIT-ENV-MS-20-M-204		
9. SPON Mr. Wi 1201 Ed	9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S Mr. William Roeder 45 WS/SYS ACRONYM(S) 1201 Edward H. White II St. MS 7302 Patrick AFB. FL 32925-3238 45 ws					10. SPONSOR/MONITOR'S ACRONYM(S) 45 WS	
DSN 467-8410 Email: william.roeder@us.af.mil			11. SPONSOR/MONITOR'S REPORT NUMBER(S)				
12. DIST DISTI	RIBUTION/. RIBUTION S	AVAILABII STATEMEN	LITY STATEMENT IT A. APPROVED FO	R PUBLIC RE	LEASE; DIST	FRIBUTION UNLIMITED.	
13. SUPP This ma United	LEMENTAL aterial is de States.	RY NOTES clared a w	ork of the U.S. Go	overnment ar	nd is not su	bject to copyright protection in the	
14. ABST Station (lightning (LLCC). thesis us modelin readings demonst hands-on Launch will serv	FRACT Due CCAFS) ba g strike. Thi To date, not es the voltag g the entiret into a salier rates not on a within the Alliance cor re to ensure	to the dang lances betw is process is o empirical ge readings y of the LL nt collection ly the valid CCAFS reg ntinue to reas scheduling	ger and cost of light veen the mission of light s mediated through a modeling of these r of the surrounding CC rules statisticall n of 9,000 green, an ity of this modeling gion; the first of its t quest the use of the around probable lig	ning striking a launching and a set of rules c ules has been CCAFS surfac y. Converting aber, and red z process but a ype. As clien Cape Canaver htning violatio	a space vehic cessation the alled the Lig established. ce field mill g approxima cones for me lso produced ts such as S al space por ons, thereby	cle, the Cape Canaveral Air Force bereof to minimize the risk of a ghtning Launch Commit Criteria To alleviate this shortcoming, this s to establish the viability of tely 312,000,000 field mill voltage etcorological operators, this thesis d an easy to understand tool to use paceX, Blue Origin, and United t, the tool provided by this research maximizing operational capability.	
15. SUBJECT TERMS Lightning, LLCC, Cape Canaveral, Field Mills							
16. SECUL OF: N/A	RITY CLASSI	FICATION	17. LIMITATION OF	18. NUMBER	19a. NAM Dr. Edwar	E OF RESPONSIBLE PERSON d White, AFIT/ENC	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	ABSTRACT UU	of pages 70	19b. TELEF (937) 255 DSN)(Ed	PHONE NUMBER (Include area code) 5-3636, ext. 4540 (NOT ward. White@afit.edu)	
		1			U		

Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std. Z39-18