Dissertations and Theses

11-2012

A Gap Analysis of Meteorological Requirements for Commercial Space Operators

Nicholas Stapleton
Embry-Riddle Aeronautical University - Daytona Beach

Scholarly Commons Citation

Stapleton, Nicholas, "A Gap Analysis of Meteorological Requirements for Commercial Space Operators" (2012). *Dissertations and Theses*. 135.
https://commons.erau.edu/edt/135

A GAP ANALYSIS OF METEOROLOGICAL REQUIREMENTS FOR COMMERCIAL SPACE OPERATORS

by

Nicholas James Stapleton

A Thesis Submitted to the College of Aviation Department of Applied Aviation Sciences
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aeronautics

Embry-Riddle Aeronautical University
Daytona Beach, Florida
December 2012

A GAP ANALYSIS OF METEOROLOGICAL REQUIREMENTS FOR COMMERCIAL SPACE OPERATORS

by

Nicholas James Stapleton

This Thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. John M. Lanicci, Professor, Daytona Beach Campus, and Thesis Committee Members, Dr. Guy Smith, Associate Professor, Daytona Beach Campus, Dr. Lance K. Erickson, Professor, Daytona Beach Campus, and Ms. Katherine A. Winters, Shuttle Launch Weather Officer, 45th Weather Squadron, Cape Canaveral Air Force Station, and has been approved by the Thesis Committee. It was submitted to the Department of Applied Aviation Sciences in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics

Thesis Committee:

John M. Lanicci, Ph.D.
Committee Chair

Guy M. Smith, Ed.D.
Committee Member

Lance K. Erickson, Ph.D.
Committee Member

Katherine A. Winters
Technical Advisor

John M. Lanicci, Ph.D.
Graduate Program Chair
Applied Aviation Sciences

Guy M. Smith, Ed.D.
Department Chair
Applied Aviation Sciences

Tim Brady, Ph.D.
Dean, College of Aviation

Robert Oxley, Ph.D.
Associate Vice President of Academics

2/26/2013
Date

Abstract

Researcher: Nicholas Stapleton

Title: A Gap Analysis of Meteorological Requirements for Commercial Space Operators

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science in Aeronautics

Year: 2012

Commercial space companies will soon be the primary method of launching people and supplies into orbit. Among the critical aspects of space launches are the meteorological concerns. Laws and regulations pertaining to meteorological considerations have been created to ensure the safety of the space industry and those living around spaceports; but, are they adequate? Perhaps the commercial space industry can turn to the commercial aviation industry to help answer that question. Throughout its history, the aviation industry has dealt with lessons learned from mishaps due to failures in understanding the significance of weather impacts on operations. Using lessons from the aviation industry, the commercial space industry can preempt such accidents and maintain viability as an industry. Using *Lanicci's Strategic Planning Model,* this study identified the weather needs of the commercial space industry by conducting three gap analyses. First, a comparative analysis was done between laws and regulations in commercial aviation and those in the commercial space industry pertaining to meteorological support, finding a "legislative gap" between the two industries, as no legal guarantee is in place to ensure weather products remain available to the commercial space industry. A second analysis was conducted between the meteorological services provided for the commercial aviation industry and commercial space industry, finding a gap at facilities not located at an established launch facility or airport. At such facilities, many weather observational technologies would not be present, and would need to be purchased by the company operating the spaceport facility. A third analysis was conducted between the meteorological products and regulations that are currently in existence, and those needed for safe operations within the commercial space industry, finding gaps in predicting lightning, electric field charge, and space weather. Recommendations to address these deficiencies have been generated for the Federal Aviation Administration, U.S. Congress, commercial space launch companies, and areas are identified for further research.

Table of Contents

Appendices

List of Tables

Table

List of Figures

Figure

Chapter I

Introduction

For the first 50 years of space launches in the US, the Federal Government dominated the industry. With the conclusion of the Space Transportation System (Space Shuttle) and the cancelation of the Constellation program, the commercial spaceflight industry will soon become the prominent contributor to low-Earth orbit (LEO) space operations within the US (Office of Science and Technology Policy & National Aeronautics and Space Administration [NASA], 2010). While scientists and engineers who have worked for the federal government may transition into the private sector, there is expected to be a learning curve as new untested rockets are developed, as seen with early launches by the commercial company, Space Exploration Technologies (SpaceX) (SpaceX, 2012). During this transition, many issues must to be scrutinized to ensure the safe operation of both manned and unmanned flight activities.

Among the issues facing new space launch companies, weather safety will be one of the most important. Weather safety has significantly impacted operations of past space launches, both in the US and abroad (Presidential Commission on the Space Shuttle Challenger Accident, 1986; Uman & Rakov, 2003). The commercial aviation industry had a similar experience in its early days, with weather causing the majority of accidents (Allaz, 1998). This study examined the commercial aviation industry for weather-safety lessons learned that can be adopted by the commercial space industry to assist in the prevention of costly accidents that could set the commercial space industry back during a crucial period in its development.

Significance of the Study

This study was used to help determine the implications of proper meteorological support for the operations of the commercial space industry. For the commercial space industry to expand, high investor confidence must exist. Without large amounts of investment capital and public support, the entire industry could falter prior to becoming self-sufficient, as the airline industry almost experienced prior to becoming nearly self-sufficient. Public and investor confidence is built through a successful record of launches, minimal ground or airborne accidents, and no loss of life. The recommendations of this study seek to clarify safety concerns regarding proper meteorological support to help provide stability for the commercial space industry.

Ultimately, this study could make recommendations to the Federal Aviation Administration (FAA) for revising the Code of Federal Regulations (CFR) to cover the meteorological considerations of the commercial space industry. It also could provide a recommended amendment to U.S. Code, entitled National and Commercial Space Programs (2010), to expand the mandate of the National Weather Service (NWS) to include commercial space operations in its aviation obligations. Recommendations, based upon the results of this study, could also be made to individual launch operators and weather support personnel to adapt their “launch commit criteria” to ensure that comprehensive operational meteorological procedures exist for all weather considerations of orbital missions.

Statement of the Problem

As the airline industry expanded, regulation was slow to follow, often spurred by accidents that cost lives and caught the public’s attention (Bailey, 2002). Accidents, caused in large part due to the lack of regulation prior to the Air Commerce Act of 1926 and the introduction of the Civil Aeronautics Authority in 1938, caused public reluctance to fly due to the industry's unreliable safety record (Bilstein, 2001). It was at this time in aviation that meteorological regulations were created to provide necessary limits on the aviation industry that could not be bypassed except in emergencies. These regulations included specific takeoff and landing minima, rules for flying in and around clouds, rules for flying around thunderstorms, and many others.

The development of the commercial space industry is now underway, mirroring many of the challenges and hurdles encountered by the development and expansion of commercial aviation in the first half of the 20th century. Without appropriate preemptive regulation, the commercial space industry could undergo significant setbacks, in both financial and investor confidence, which could devastate the development of the industry as a whole.

It is hypothesized that there is a disparity in overarching regulations that exist between the commercial space industry and commercial airline industry concerning meteorological support. The meteorological regulations in place for the commercial space industry are not as comprehensive as those for the aviation industry (Aviation Programs, 2012; National and Commercial Space Programs, 2010). It is also hypothesized that the current meteorological regulations do not meet the requirements needed for the safe expansion of the commercial space industry. Due to the significantly higher costs of spaceflight ventures, comprehensive meteorological safety regulations should be in place prior to the significant expansion of spaceflight activities. Regulatory inequities between meteorological services provided to the aviation industry and those provided to the commercial space industry must be bridged. If investments are made for preventive regulation and safe operations, the development of the commercial space industry will be enhanced significantly. With the appropriate regulations in place, the industry can forego repeating the mistakes of the early aviation industry.

Purpose Statement

The purpose of this study was to identify the gaps between the aviation and the commercial space industries regarding meteorological regulations, services, and products in order to estimate the meteorological data and analyze requirements of the commercial space industry. This evaluation was accomplished by analyzing the services offered by the NWS Aviation Weather Center (AWC), applicable to the commercial space industry, as well as support provided by the 45th Weather Squadron of the U.S. Air Force for space launches at Cape Canaveral Air Force Station (CCAFS) and NASA Kennedy Space Center (KSC).

Research Questions

Q1: Does a gap exist in meteorological regulations between the commercial aviation industry and the commercial space industry?

Q2: Does a gap exist between meteorological services provided for commercial aviation companies and airports and meteorological services provided for commercial space companies and spaceports?

Q3: Does the meteorological products and regulations for the commercial space industry meet the estimated needs of commercial space operators?

Delimitations

The data on current meteorological considerations of the commercial space industry were based upon research performed on past space launch ventures, both public and commercial. The review examples may not accurately represent the needs and requirements of every company, since there are too many companies developing launch and flight vehicles to adequately cover each type of vehicle. Designs were selected based upon the current trend of commercial launch programs in the US. For the purposes of this study, needs of commercial space operators were restricted to the near future (i.e., next 10 years) . This is to better compare operations to early aviation. Additionally, operations discussed in this study were limited to launch operations.

Limitations and Assumptions

Due to the sensitive and competitive nature of commercial space companies, companies were not willing to provide their meteorological data requirements. Therefore, approximations were made to best fit the requirements, based upon historical requirements. These approximations were made based upon current research and account for weather sensitivities experienced by companies in the past, or requirements derived from spacecraft design. Many methods exist to measure the weather phenomena described in this study. An analysis of each would have overshadowed other important factors of this study. Therefore, only commonly used methods of observing these weather phenomena were discussed.

Definitions of Terms

Cloud Ceiling: The lowest layer of clouds reported as broken or overcast, or over 50% sky cover (FAA, 2010)

Meteorology Regulations: Federal regulations pertaining to meteorological phenomena, technology, operations, and safety in the chapter entitled Commercial Space Transportation (2012), the sections entitled General Operating and Flight Rules (2012) and Operating Requirements: Domestic, Flag, and Supplemental Operations (2012) in the CFR, and U.S. Code under National and Commercial Space Programs (2010).

Launch Operator: The holder of a Launch Operator license, as defined by federal regulation in Types of Launch Licenses (2011). A holder is authorized to conduct launches from one launch site using a single family of vehicles with a specified type of payload, per license.

Launch Overpressure: Loads placed on a rocket by the initial engine exhaust interacting with the launch pad and launch pad ductwork (Troclet, Alestra, Terrasse, Jeanjean, & Srithammavanh, 2005).

Launch Site Operator: The holder of a license to operate a launch site under federal regulations in License to Operate a Launch Site (2011).

Mean Sea Level: The average level of the surface of the sea between high and low water (Sea level, 2011).

Triboelectrification: The generation of an electrical charge caused by friction, used in this study, between the launch vehicle and ice particles (Natural and Triggered Lightning Flight Commit Criteria, 2011).

List of Acronyms

ACA	Accuracy to Cost Analysis

AIM	Aeronautical Information Manual
ASOS	Automated Surface Observing System
AST	FAA Office of Commercial Space Transportation
ATIS	Automatic Terminal Information Service
AWC	Aviation Weather Center
AWOS	Automated Weather Observing System
CAA	Civil Aviation Authority
CFR	Code of Federal Regulations
CCAFS	Cape Canaveral Air Force Station
CIP	Current Icing Product
CME	Coronal Mass Ejection
CST	Commercial Space Transportation
DOT	Department of Transportation
FAA	Federal Aviation Administration
FSS	Flight Service Station
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
JAXA	Japanese Aerospace Exploration Agency
KSC	Kennedy Space Center
LEO	Low-Earth Orbit
LLWAS	Low Level Windshear Alert System
LSO	Launch Site Operator
METAR	Meteorological Aerodrome Report

MSL	Mean Sea Level
NLDN	National Lightning Detection Network
NWS	National Weather Service
OV	Orbital Vehicle
PIREP	Pilot Weather Report
SEP	Solar Energetic Particles
SpaceX	Space Exploration Technologies Corporation
SRB	Solid Rocket Booster
STS	Space Transportation System
TAF	Aerodrome Forecast
TIBS	Telephone Information Briefing Service
TOA	Time of Arrival
TWA	Trans Western Airlines
USPLN	United States Precision Lightning Network
VFR	Visual Flight Rules

Chapter II

Review of the Relevant Literature

History of Meteorology in the Aviation Industry

Anyone who has ever been stuck in an airport because a flight was delayed or canceled due to weather can respect the importance of weather to the aviation industry. Weather played an important role in many early aviation accidents. Early commercial aviation exploits in the United States were largely backed by air mail contracts from the U.S. Post Office (Allaz, 1998). Prior to 1930, airlines received contracts to deliver the mail based on the weight of mail bags. This led to smaller aircraft being developed, rather than the larger passenger aircraft. The Waters Act of 1930 altered contract rates to an amount governed by the available capacity of the aircraft, not the weight of the mail being provided (Allaz, 1998). This sparked the development and use of larger aircraft and led to airlines seeking passengers as a means of expanding revenue for flights. To attract passengers, however, the safety record and comfort level of the population needed to be improved (Allaz, 1998).

Between 1920 and 1927, airmail pilots were forced to land 6,469 times, or an average of once for every 2,380 miles flown (Allaz, 1998). Over that time, the cause of forced landings shifted from 46% mechanical and 54% weather-related to 14% mechanical and 86% weather-related, as forced landings increased from just over 300 a year to just over 1,000 a year (Allaz, 1998). This increase was consistent with an increase in traffic, though often the public was only cognizant of the number of accident, rather than the percentage of accidents (Meisinger, 1920). A significant spike in accidents was noted in 1921 due to the introduction of night flights prior to the advent of lighted airways (Allaz, 1998).

Many early airline operators had false impressions about weather on air routes. Airline operators would fly a route less than a dozen times and use the interpretation of the weather conditions, such as winds, turbulence, cloud cover, and fog, as an indication of whether the weather conditions would be appropriate to fly a route. In a time when meteorologists did not truly understand many aspects of the atmosphere, airline operators were making weather generalizations that inevitably would lead to the deaths of pilots and the loss of cargo (Meisinger, 1920). Meisinger further identified the damage that weather-related accidents did to the public image of aviation, citing it as a hazard to the overall growth of the aviation industry.

Werrell (2010) also highlighted the negative impact weather had on aviation, particularly on the U.S. Army Air Corps' handling of the air mail in 1934. He cited a particularly poor winter weather season and the lack of appropriate meteorological training and instrumentation as a leading cause in the skyrocketing death-rate of airmail pilots, from an average of 12.4 in 1933 to 10 deaths within the first month of 1934. Weather-ignorant pilots would make mistakes, flying into weather conditions well beyond their skills, such as heavy snowstorms in the winter and thunderstorms in the summer. Newspapers of the day covered every crash closely, casting a shadow of doubt on aviation as a successful mode of transportation, intentionally or otherwise (Associated Press, 1928; United Press, 1934). One particular accident hit close to home for legislators in Washington D.C., forcing the issue of the need for regulation (Bailey, 2002). A Trans Western Airline (TWA) Douglas DC-2 ran out of fuel and crashed while trying to find a path through fog on May 6, 1935. Among the casualties was United States Senator Bronson Cutting of New Mexico, a very well-liked Senator (Associated Press, 1935). The result was the formation of the Civil Aeronautics Authority (CAA) in 1938, which finally created a body responsible for enforcing safety in aviation (Bailey, 2002).

The CAA had the authority to create regulations pertaining to any aspects affecting the safety of aviation, including the first regulations covering weather. While the CAA tailored meteorological regulations to commercial aviation, the Civil Aeronautics Act of 1938 also changed the mandate on the Weather Bureau, the predecessor of the NWS, to include specific requirements pertaining to aviation. Included were instructions to create offices and weather stations needed to support aviation and to provide current reports, forecasts, and warnings to air carriers and other civil operations, including private operations (Civil Aeronautics Act, 1938). Though the technology and procedures have been updated, the language of this code has been maintained and the basic responsibilities are still in place. The Federal Aviation Act of 1958 expanded the required operations to include the necessary standards to meet international aviation meteorology requirements and to transfer oversight responsibility for the Weather Bureau from the Department of Agriculture to the Department of Commerce (Federal Aviation Act, 1958).

Despite the implementation of the Civil Aeronautics Act, aircraft accidents due to adverse weather conditions persisted. At times, the FAA, the descendent of the CAA, has been unable to foresee the necessary technology or procedures to prevent the loss of life through weather-related accidents. One notable example is the development of the Low-Level Windshear Alert System (LLWAS) following the crash of Eastern Airlines Flight

66 in 1975 (Meyer, Isaminger, & Proseus, 1999). The Boeing 727 was attempting to make an approach into New York’s John F. Kennedy International Airport too close to a thunderstorm. Flight 66 was caught in windshear and struck the approach lighting system just short of the runway (National Transportation Safety Board, 1976). The original LLWAS system consisted of six wind sensors, one at the center of the airfield and five spread around the outskirts of the field. When another fatal accident caused by windshear occurred, Delta Air Lines Flight 191 into Dallas/Fort Worth International Airport in 1985, an update to the system was made to reduce the false-alarm rate and the development of windshear alerting systems onboard aircraft to identify rapid changes in wind speed or direction (Meyer et al., 1999).

Aviation-related meteorology CFRs. Due to accidents such as those described above, a variety of all-encompassing regulations has been established to prevent weather-related accidents from occurring. These requirements can be drawn from three primary locations: 14 CFR Part 91: Air Traffic General Operating and Flight Rules (2012), 14 CFR Part 121: Operating Requirements: Domestic, Flag, and Supplemental Operations (2012), and the *Aeronautical Information Manual* (AIM) (FAA, 2012).

14 CFR Part 91: Air Traffic General Operating Rules. The Air Traffic General Operating Rules (2012) contain the primary source for meteorological regulation for all of aviation. These rules cover all private and commercial of flight, from general aviation aircraft, to wide-bodied commercial transport aircraft. Meteorological requirements are divided into two categories: Visual flight rules (VFR) and Instrument flight rules (IFR) (FAA, 2012).

VFR flight describes flight for any aircraft not flying within clouds, obscurations to visibility, or precipitation (FAA, 2012). The CFR has very specific requirements for aircraft flying around clouds and in situations where visibility is restricted. Table 1 lists the visibility and cloud clearance minimums for VFR traffic in different airspaces. Class A airspace, located at or above 18,000 feet above mean sea level (MSL), is not included since VFR flight is not permitted in Class A airspace (Basic VFR Weather Minimums, 2004). Though complicated, this system provides specific restrictions to flight traffic in areas of different types of air traffic. Specifically, Class D through B airspaces surround airports with increasing levels of traffic from Class D to Class B (FAA, 2012).

For flight within clouds or any other obscuration, aircraft are controlled under IFR. Aircraft must be certified with additional equipment, and pilots must undergo additional training to fly in instrument conditions. In addition, to perform an instrument approach into an airport, approach equipment must be provided at the airport and approach procedures must be in place (Takeoff and Landing Under IFR, 2009). Because of these requirements, the general operating rules for flying in IFR conditions are much more stringent but less complicated than VFR rules. The primary consideration in IFR is the ability to safely takeoff and land an aircraft. To take off, the visibility must be above a half statute mile for aircraft operating with two engines and one mile for aircraft operating with one engine, unless the airport has minimum takeoff conditions listed. In that case, takeoff conditions must be above the minimum takeoff conditions listed in the instrument procedures for the airport (Takeoff and Landing Under IFR, 2009).

Table 1

Basic VFR Weather Minimums for Aviation.

Airspace	Flight Visibility	Distance from clouds
Class B	3 Statute Miles	Clear of Clouds
Class C	3 Statute Miles	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class D	3 Statute Miles	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class E: Less than 10,000 ft. MSL	3 Statute Miles	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class E: At or above 10,000 ft. MSL	5 Statute Miles	1,000 ft. below and above, 1 Statute Mile horizontally
Class G: 1,200 ft. or less above the surface (Daytime)	1 Statute Mile	Clear of Clouds
Class G: 1,200 ft. or less above the surface (Nighttime)	3 Statute Miles	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class G: More than 1,200 ft. above the surface but less than 10,000 ft. MSL (Daytime)	1 Statute Mile	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class G: More than 1,200 ft. above the surface but less than 10,000 ft. MSL (Nighttime)	3 Statute Miles	500ft below, 1,000 ft. above, and 2000ft. horizontally
Class G: More than 1,200 ft. above the surface	5 Statute Miles	1,000 ft. below and above, 1 Statute Mile horizontally
Flight below controlled airspace and less than 10,000 ft. with special clearance (Special VFR)	1 Statute Mile	Clear of Clouds

Note. From Basic VFR Weather Minimums (2004).

14 CFR Part 121: Operating Requirements: Domestic, Flag, and Supplemental Operations. The Operating Requirements for Domestic, Flag and Supplemental Operations (2012) provide additional requirements on meteorological considerations for operators for compensation or hire that must be followed in addition to the General Operating and Flight Rules. There are five primary sections within this part of the CFR that directly concern weather. For comparison purposes, only regulations concerning takeoff and enroute flight will be examined.

The Operating Requirements: Domestic, Flag and Supplemental Operations states that an aircraft cannot be dispatched for flight unless the person dispatching the aircraft is “thoroughly familiar” with the reported and forecasted conditions for the route of the flight. While the definition of “thoroughly familiar” is not clearly stated or defined, this requirement is used to ensure that no aircraft can take off without an approved staff member of the airline reviewing the relevant meteorological data pertaining to the specific flight (Familiarity with Weather Conditions, 1996). These regulations also require an operator to prove it has a method for “obtaining, maintaining and distributing” weather data, specifically prevailing wind conditions when visibility is restricted. This ensures that in times of adverse weather, pilots have access to the general direction of the wind to ensure the safety of the flight and the use of a proper takeoff or landing heading (Airports: Required Data, 2007).

The Operating Requirements (2012) also cover additional takeoff minima for operations in VFR. In addition to the requirements imposed by the general operating rules discussed above, domestic and international flights for compensation or hire must meet stricter requirements for taking-off. An aircraft in Class G airspace may be able to take off with clouds making up greater than 50% of the sky, commonly referred to as a ceiling, with clouds in the hundreds of feet above the surface, as long as the aircraft remains clear of the clouds. A commercial aircraft in that same airspace must ensure at least a 1,000 foot ceiling prior to taking off, as well as one statute mile visibility during the day, and 2 statute miles of visibility at night. The visibility requirement can be reduced to a half mile if the obstruction is located at the surface and all of the flight beyond one mile of the airport boundary can be made outside of the obscuration (Takeoff and Landing Minimums: VFR: Domestic Operations, 1991). Additionally, this part of the federal regulations covers takeoff minimums for IFR operations specific to commercial carriers. This section provides some leniency in the IFR takeoff minimums established in the general rules. As the aircraft operated by commercial carriers have more advanced and more precise equipment, the holder of a commercial certificate may get specific approval in their operations specifications to takeoff in conditions lower than those in the general rules (Takeoff and Landing Minimums: IFR: All Certificate Holders, 2007).

Finally, a low-altitude windshear system with approved flight guidance, or a similar system capable of detecting and providing avoidance messages, must be equipped on all aircraft built after 1991 (Low-altitude Windshear System Equipment Requirements, 1990). Systems like these significantly improve the safety of the public on commercial flights.

Aeronautical Information Manual. The AIM (FAA, 2012) provides the fundamental elements required to fly within the United States airspace. The information ranges from navigational aids and airport markings, to air traffic control and meteorology. While this document contains information covered in other sections, such as weather minima for VFR flight covered in the Air Traffic General Operating Rules (2012) of the CFR, this section will focus on information that does not appear in either Air Traffic General Operating Rules or Operating Requirements: Domestic, Flag and Supplemental Operations.

Presently, the dissemination of weather information is the joint responsibility of the FAA and the NWS. Many of the products used by aviation come from the NWS, and the NWS is responsible for approximately one quarter of the surface weather observing equipment at civilian airports across the country (FAA, 2012). The NWS and the FAA are both responsible for creating the products required by the International Civil Aviation Organization (ICAO), such as Meteorological Aerodrome Reports (METAR) (FAA, 2012).

By law, the NWS is responsible for creating products to ensure the safety of aviation, including Inflight Advisories, Significant Meteorological Information (SIGMETs), Convective SIGMETS, Airman's Meteorological Information (AIRMETs) and Area Forecasts (FAA, 2012). These products provide information on areas of weather conditions that could be a potential hazard to aviation. Hazards advised in these products include thunderstorms, icing, turbulence, dust or sandstorms, volcanic ash, tornadoes, IFR conditions and hail. The NWS also provides information on the winds aloft from the Service's network of upper air measurements through the use of weather balloons carrying instrument packages known as radiosondes, launched twice daily. The NWS network of weather radars across the country provides for preflight weather planning, among its many other uses. The radar sites can provide locations of light to heavy precipitation, as well as wind conditions inside a storm. The FAA operates smaller radar sites to cover specific airports with higher resolution, typically in areas with heavy air traffic. Weather products to be used for flight planning purposes are specified explicitly by the FAA. Primary products are approved for use in flight planning, while supplementary products, which may be experimental or less accurate, may be used in conjunction with primary products in flight planning (FAA, 2012).

Combined with data from the FAA, private contractors, and supplemental observers, the NWS provides hourly surface observation data from equipment owned by the FAA or the NWS (FAA, 2012). Currently, these two agencies primarily use either the Automated Weather Observing Systems (AWOS) or Automated Surface Observing Systems (ASOS) for surface reports. These systems observe visibility between ¼ mile and 10 statute miles; sensible weather, including precipitation and/or surface obscuration; cloud ceiling and sky cover; air temperature and dew point; altimeter setting in inches of mercury, representing surface pressure; and any additional information that may be useful for aviation operations or forecasting future conditions. METARs are derived from these systems hourly, often automatically. If conditions are rapidly changing, or the boundary between IFR and VFR is being crossed during that hour, special METARs will be issued. In addition to METARs, the ICAO requires Aerodrome Forecasts (TAF) to be produced, which provides forecasted conditions within a 5-statue mile radius of the aerodrome for between 24 and 30 hours in the future. TAFs are products produced every 6 hours by the NWS, to provide forecasted weather conditions for many of the same measurement parameters recorded in METARs, including winds, visibility, cloud cover and ceiling, and sensible weather (FAA, 2012).

The FAA also provides weather support for aviation. Presently, the FAA contracts to maintain a nationwide network of Flight Service Stations (FSS) (FAA, 2012). These stations, which can be either staffed or automated, provide different briefings based upon the flight needs of a pilot. These briefings can be accessed by radio or telephone through the use of the Telephone Information Briefing Service (TIBS). Air traffic controllers can also issue weather avoidance assistance when radio communication traffic is not too high. Though less accurate than NWS radar reports, these are available for pilots in-flight, and relative position between an aircraft and radar reflectivity echoes can be established relatively easily. Controllers are also required to request reports from pilots in certain conditions. These pilot weather reports (PIREPs) are voluntary, but provide confirmation of weather conditions when SIGMETs and AIRMETs are indicated (FAA, 2012).

Flying around thunderstorms can be particularly hazardous. Thunderstorms can produce turbulence, hail, rain, snow, lightning, updrafts, downdrafts, and icing conditions, and can affect an area 20 miles around the clouds producing the storm. Flight within, underneath, or within a 20-mile radius of a thunderstorm is considered to be hazardous, and is highly discouraged to ensure the safety of a flight (FAA, 2012).

History of Weather Impacts on the Space Industry

Lack of proper understanding of meteorological requirements has led to costly accidents in the space launch industry, both in fiscal terms and human life. While many space launch accidents have occurred, for the purposes of this study, three notable historical examples in which weather played a major role will be discussed: the Space Shuttle Challenger accident (Presidential Commission on the Space Shuttle Challenger

Accident, 1986), the loss of the NOZOMI probe (Yoshikawa et al., 2005), and the Atlas/Centaur 67 rocket accident (Christian et al., 1989).

Space Shuttle Challenger. Challenger, designated as Operational Vehicle (OV)-099, was the second operational Space Shuttle Orbiter created for the Space Transportation System (STS) program, first flying in 1983 (Presidential Commission on the Space Shuttle Challenger Accident, 1986). Challenger made its last launch on January 28, 1986, on the scheduled mission STS-51-L. The cause of the accident was the failure of two O-rings at one joint on the Space Shuttle’s Solid Rocket Boosters (SRB) during launch. The failure of these O-rings to maintain a seal allowed hot gas to escape the SRB joint, burning a hole in the External Tank, and igniting the fuel inside. The mount holding the SRB to the External Tank failed, causing the upper portion of the SRB to breach the upper portion of the External Tank. The rupturing tank and forces caused by the failing SRB caused Challenger to break apart over the Atlantic Ocean, 73 seconds after ignition, killing all seven astronauts on board including a civilian teacher (Presidential Commission on the Space Shuttle Challenger Accident, 1986). The launch configuration of a Space Shuttle is shown in Figure 1.

The O-rings that failed were located in the joint of the SRB. As seen in Figure 2, two O-rings are located at each joint of the SRB, a primary O-ring and a secondary O-ring. The primary O-ring was designed to contain all of the heat and pressure of combustion as the zinc chromate putty is burned away. However, the secondary O-ring was designed to contain the heat and pressure fully, should the primary O-ring fail (Presidential Commission on the Space Shuttle Challenger Accident, 1986). On a prior Shuttle launch, STS-51-C the year prior, the primary O-ring had failed, but the mission

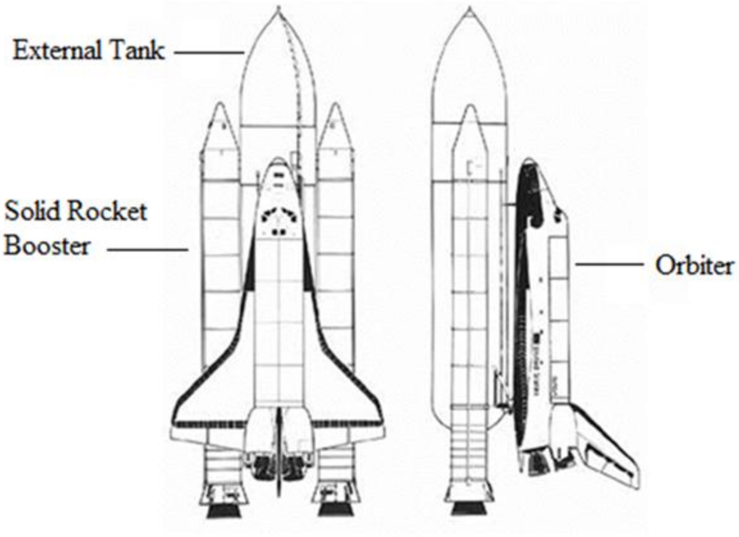

Figure 1. Space Shuttle Configuration, showing the Orbiter and the two SRBs attached to the External Tank in the center. *Note.* Adapted from Presidential Commission on the Space Shuttle Challenger Accident (1986).

was saved due to the proper operation of the secondary O-ring. This was evident on the return of the booster after inspection, as soot was found between the primary and secondary O-rings. The temperature at launch time for STS-51-C was 53 degrees Fahrenheit, the coldest launch temperature at the time. For STS-51-L, the temperature at launch was approximately 31 degrees Fahrenheit, and had been even colder the day prior. Contractors from Thiokol, the company that designed and built the SRBs, admitted in a meeting the day prior that they had concerns over the temperatures, but were pressured into giving launch approval due to the heightened demand to launch after a series of unrelated delays in days prior (Lighthall, 1991). The cold had decreased the integrity and flexibility of these O-rings and, combined with the strongest variation of winds aloft of any prior launch, the O-rings failed (Presidential Commission on the Space Shuttle Challenger Accident, 1986). One aspect that made this disaster even more damaging to

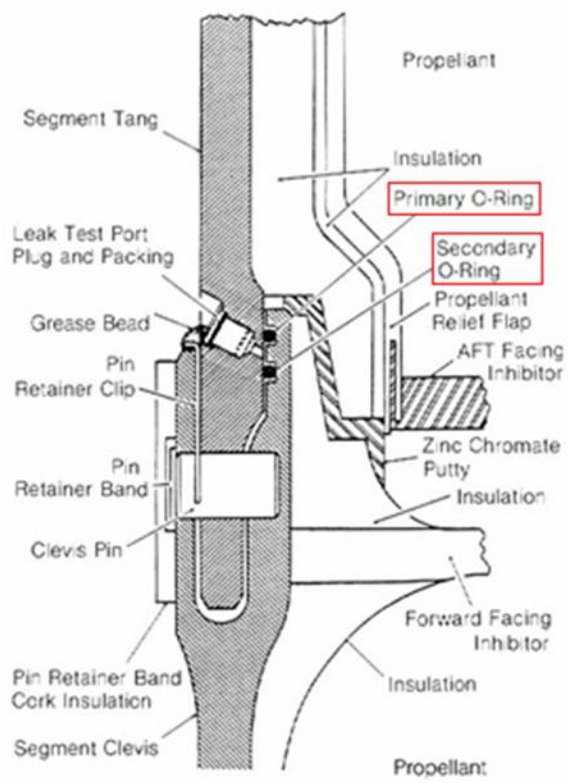

Figure 2. An artist's representation of one of the four joints in each of the Space Shuttle's SRBs. *Note.* The two O-rings are boxed in red; Adapted from Presidential Commission on the Space Shuttle Challenger Disaster (1986).

the image of manned spaceflight was the presence of Christa McAuliffe, the first member of Teachers in Space to be scheduled for launch. This caused extensive media coverage, and news of the accident spread rapidly (Presidential Commission on the Space Shuttle Accident, 1986).

NOZOMI space probe. The Mars Explorer “NOZOMI” was a space probe developed by the Japanese Aerospace Exploration Agency (JAXA) as their first spacecraft to be sent to Mars (Yoshikawa et al., 2005). The probe was designed to study the upper atmosphere of Mars, including the interactions of the solar winds with the planet. Shortly after launch, the craft attempted to perform a maneuver to build up speed by passing close to Earth to use its gravitational pull to accelerate, a maneuver known as a gravity assist. During this gravity assist, a failure occurred in the system providing the fuel to the engine, and the acceleration was much less than planned. In order to continue the mission, a series of gravity assists were used, which significantly increased the time the probe would be in orbit around the Sun. During this time, NOZOMI was damaged by the after-effects of a solar flare, disabling its power supply due to a short circuit in one of the subsystems. This caused significant problems, including a failure of telemetry communications and a failure to keep the fuel at a temperature above freezing. Ultimately, the research team at JAXA was unable to revive NOZOMI fully, and the probe was unable to enter Martian orbit. It is currently drifting in space in orbit around the Sun (Yoshikawa et al., 2005).

Atlas Centaur 67. In 1987, the Atlas family of rockets had been used in the US space program for 30 years, and to this day remains the oldest family of American rockets currently flying (Walker & Powell, 2005). Weather conditions for the March 26 launch date included cloud cover over Cape Canaveral, with a very slow moving cold front and squall line over the Florida panhandle extending into the Gulf of Mexico (Christian et al., 1989). This system was creating cloud-to-ground lightning in the area, but not within five nautical miles of the launch site within 42 minutes of the launch time, nor had there been a single strike within 10 miles over the same time period. However, the Atlas/Centaur rocket was struck by lightning 49 seconds following the launch, causing a memory upset in the guidance-control electronics of the rocket, resulting in an unplanned rotation. This rotation caused the rocket to overstress and it broke apart over the Atlantic Ocean (Uman & Rakov, 2003). The subsequent investigation of the accident determined that a strong negative charge had built up over Cape Canaveral, detected by the ground-based network of electrically sensitive instruments, known as field mills, installed around KSC and CCAFS. This data, combined with other meteorological data collected throughout the day, indicated that while there was no strong convection occurring at the launch site, there was a sufficient electrical field gradient for a strike to occur when the rocket was launched. The highly conductive exhaust plume from the rocket created a low-resistance path, causing a lightning strike through the rocket (Christian et al, 1989; Uman & Rakov, 2003).

Summary

Each new industry must overcome challenges in order to thrive; however, costly setbacks could inhibit an industry from taking root. The commercial space industry must overcome the challenges of operating safely, from launch to landing, and be cognizant of adverse weather conditions that could significantly impact their success and the public's perception of the industry as a whole. Understanding the meteorological concerns for a typical company can ensure that proper regulation is created to guide these space companies to operate safely with respect to weather phenomena. The impact of remaining ignorant of adverse weather conditions has been clearly demonstrated by accidents and loss of people and equipment by government space agencies such as NASA, the U.S. Air Force, and JAXA.

The commercial aviation industry and federal government have gone through an evolution of lessons learned, and as a result, a number of laws and regulations related to meteorology have been created that help to ensure the safe operation of aircraft in adverse weather conditions. Many of these same types of laws and regulations can be applied to the commercial space industry. If these lessons can be learned without the loss of a launch vehicle or human life, the commercial space industry has a much higher chance of long-term success.

Chapter III

Methodology

Research Approach

An adapted version of a strategic planning model, proposed by Lanicci (2003), was used to organize the data used in this study. This model provided information on the important phenomenological, technological, and resource considerations necessary to analyze the meteorological requirements for safe launch and flight operations by a commercial operator. Three gap analyses pertaining to meteorological requirements for supporting commercial space operations were conducted using the strategic planning model, which are described below.

The first gap analysis was conducted between meteorological regulations pertinent to the commercial aviation industry and the meteorological regulations pertinent to the commercial space industry. The analysis identified if any of the areas of the code and regulations relating to meteorological concerns of the commercial space industry fall below the same standard to which the aviation industry is held. A difference indicated a lack of regulatory coverage regarding meteorological concerns for the commercial space industry.

The second gap analysis evaluated the meteorological services provided to aviation companies and the meteorological services provided to the commercial space launch operators. The analysis was conducted to determine if a difference existed between meteorological products and services used to support airlines and other commercial aviation operators, and the products and services used to support commercial space launch and flight operators. Included in this analysis were the services provided by the U.S. Air Force 45th Weather Squadron for launches from CCAFS. A difference indicated a lack of meteorological products and/or services for the commercial space industry.

The final gap analysis was conducted between the products and regulations pertaining to the commercial space industry and the products and regulations necessary to meet the needs prescribed by the *Functional Analysis and Planning* section of Lanicci's (2003) *Strategic Planning Model*. This analysis identified whether sufficient meteorological products and regulations existed that could impact the safety of commercial space launches.

Apparatus and materials. The analysis was conducted using an adapted version of the *Strategic Planning Model* created by Lanicci (2003) (henceforth referred to as *Lanicci's Strategic Planning Model*). It was designed for use by the U.S. Air Force Weather Agency following a 10-year period of reconfiguration of the Department of Defense. *Lanicci's Strategic Planning Model* is divided into three sections: *Input, Functional Analysis and Planning, and Execution*. A pictorial view of this model can be seen in Figure 3.

The first section, *Input*, describes the needs of the organization. For the U.S. Air Force, it was concepts, strategies and doctrine. Lanicci (2003) examined the impact that weather and climate had on planning and executing the concepts, strategies, and doctrine of the U.S. Air Force and determining which aspects of strategy would be realistic or unrealistic due to what is known about impacts of weather and climate on that strategy.

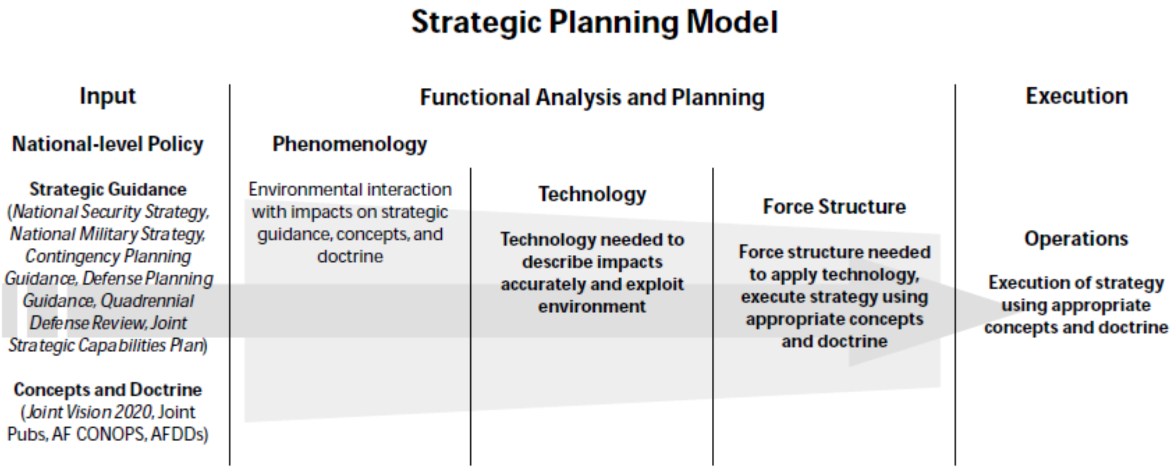

Figure 3. Lanicci's Strategic Planning Model. *Note*. From Lanicci, 2003.

Functional Analysis and Planning is the second section of *Lanicci's Strategic Planning Model*. This section is the core of this model, performing a step-by-step analysis of the weather aspects that an organization is sensitive to, identifying the resulting deficiencies, defining the technology that is needed to resolve the deficiencies, and identifying the resources needed to apply that technology. To facilitate this analysis, this section is further divided into three subsections: *Phenomenology, Technology, and Force Structure*. In the *Phenomenology* subsection, potential meteorological impacts are identified and narrowed. Specific issues can be addressed once the aspects that will not impact an industry are eliminated and the focus is set to an appropriate level. The second subsection, *Technology,* identifies and describes what is needed to measure and predict the phenomena important to the industry. This section is also where phenomena are identified to be beyond the reasonable expense or technological capacity for measurement. Lanicci (2003) also focused on the ability to observe and predict the *effects* of these phenomena, not just the phenomena themselves. Finally, the *Force Structure* subsection identifies the resources available for acquiring, implementing, or using the technology to observe and predict the phenomena and its potential effects. These resources include financial, human, legislative, and organizational resources. An analysis of this section can identify areas that are currently well-covered as well as areas with insufficient resources.

The analysis includes the relative cost of products over 25 years. These costs are bulk estimates based on approximations of technology purchase and installation costs for the purposes of evaluating the relative cost-to-benefit of the technology. Based upon these estimations, the costs fell into natural categories. The researcher divided the costs into the following categories: negligible, low, moderate, high, and very high. Negligible costs indicate the minimal expenses needed to acquire data from free online sources, such as products from the NWS. Low costs represent estimated expenses of less than $100,000 a year, moderate costs represent estimated expenses between $100,000 and $1,000,000 a year, high costs represent estimated expenses between $1,000,000 and $5,000,000 a year, and very high costs represent estimated expenses over $5,000,000 a year. The ACA was conducted by comparing the relative accuracy with the relative cost. The comparisons were then ranked and sorted to provide the categories used.

The final section of *Lanicci's Strategic Planning Model* is the *Execution* section. In this section, actual operations following implementation of the new capabilities are examined and reviewed. The review in this section provides continuous feedback for the system to ensure that the lessons learned and shortcomings observed during implementation are used to ensure success of future and intermediate iterations.

For this study, *Lanicci's Strategic Planning Model* provided a strong framework to identify the needs of the commercial space industry. It also provided significant data that was used to analyze gaps in meteorological regulations, services, and products to meet the needs of the commercial space industry.

Design and procedures. For this analysis, *Lanicci's Strategic Planning Model* was adapted to the commercial space industry. Subsections were also adapted for the needs of the commercial space industry. Specifically, *Input* focused on the estimated meteorological considerations of the commercial space industry. It identified which environmental conditions a company is sensitive to, and what environmental data is required to be collected by the current regulations. Additionally, the third section in *Functional Analysis and Planning* was changed from *Force Structure* in the original model to *Resource Structure* in this study in order to apply the model beyond the military aspects, and better identify how commercial organizations can implement technologies necessary to ensure safe launches with respect to meteorological conditions. For the purposes of this study, the *Resource Structure* was further divided into technology cost, a cost-benefit analysis described as Accuracy-to-Cost Analysis (ACA), non-technical company resource requirements, national coverage of the technology, and likelihood of national implementation of the technology. The third section, *Execution*, was not discussed, as it would require the actual implementation of the capabilities identified in the previous two sections to evaluate adequately; that is beyond the scope of this study.

Three gap analyses were conducted following the analysis of the adapted version of *Lanicci's Strategic Planning Model*. The gap analyses used to answer Research Questions 1 and 2 were performed by analyzing information acquired through the literature review, while the gap analysis used to answer Research Question 3 compared the output from the *Resource Structure* of the *Function Analysis and Planning* section of the model to the current meteorological products and regulations pertaining to the commercial space industry.

Sources of the Data and Data Collection

The majority of the information acquired for this study came from a review of the relevant federal codes and regulations, and literature pertaining to the needs of the commercial space industry. Meteorological services provided by the U.S. Air Force 45th Weather Squadron and launch commit criteria at CCAFS were acquired through documentation and statements from launch weather officers.

Chapter IV

Results

The adapted version of *Lanicci's Strategic Planning Model* was applied to the commercial space industry. A gap analysis was conducted between regulations for the commercial aviation industry and the commercial space industry answering research Question 1. Two gap analyses were conducted from the data gathered in the model, answering research Questions 2 and 3, covering meteorological services and identifying gaps in product and regulatory coverage for the commercial space industry. The results are as follows.

Applying the Model: Input Stage

Compared to the meteorological regulations of the aviation industry, similar regulations for the commercial space launch industry are in their infancy. Currently, weather launch requirements come from two primary sources: the Launch Safety (2012) section of the CFR, and the procedural documents of the United States Air Force, such as those of the 45th Weather Squadron.

Current meteorological regulations for the space launch industry. Many of the meteorological requirements for commercial space launch have come about in the last 2 to 6 years. Eight subsections of the Launch Safety (2012) section of the CFR covered the primary meteorological regulations pertaining to the private space industry at the time of this study.

The most substantial and detailed section of the meteorological regulations pertaining to the commercial space industry is Appendix G to Launch Safety (2012). This appendix, Natural and Triggered Flight Commit Criteria (2011), deals with very specific methods for mitigating lightning strikes, such as those that caused critical damage to Atlas/Centaur 67. This section provides highly detailed descriptions of weather and launch conditions that could cause a natural or triggered lightning strike to occur on a launch vehicle. It also describes the conditions in which an operator is allowed to launch a vehicle near any part of a thunderstorm, or around environments where triggered lightning can occur, including very specific requirements for appropriate flight paths and appropriate launch delay times (Natural and Triggered Lightning Flight Commit Criteria, 2011).

Each operator must adhere to written safety rules that include, among other things, identifying applicable weather conditions in which the launch vehicle can carry out its mission without having any negative impacts on public safety. These rules must be approved by the FAA’s Office of Commercial Space Transportation (AST) prior to commencing initial launch operations for a company’s first launch. The AST is the FAA’s office that deals with all space-related regulations for the US. Included in the rules submitted to the AST must be all the conditions stipulated under the Natural and Triggered Lightning Flight Commit Criteria (2011).

In addition to having these rules in effect, launch operators must have a launch readiness review submitted to the AST. This review must contain the written decision to continue, based upon all factors that could impact the launch, listed out in the Reviews (2006) section of this part of the CFR, including the status of the launch weather forecasts. Prior to launch, the AST must be consulted to ensure that the launch is within the operator’s written safety rules already approved by the FAA/AST (Reviews, 2006). The Launch Safety Officer, a staff member of a Launch Operator in charge of ensuring the safety of the flight, must prove to the AST that the time delay for any hardware relaying meteorological data is within the accepted limitations described by the AST (Time Delay, 2006).

The majority of the remaining meteorological regulations pertaining to the commercial space industry deal with specific parameters to ensure the safety of the population on the ground rather than the safety of the flight. These include wind weighing to ensure an unguided launch vehicle stays on course (Flight Safety Analysis Methodologies, 2006), ensuring a launch can be terminated if the rocket guidance fails or is unable to correct for another error (Support Systems, 2006), and ensuring overpressure blast effects do not impact the general population, which can occur when a launch vehicle is ignited and damage persons and buildings (Far Field Blast Overpressure Effects Analysis, 2006; Far Field Overpressure Blast Effects Analysis, 2006; Troclet et al., 2005).

NASA weather requirements for launch. The Department of Defense has even stricter requirements on launch safety when it pertains to weather conditions. For launches at KSC and CCAFS, launch weather is covered by the 45th Weather Squadron (McNamara, Roeder, & Merceret, 2009). According to the U.S. Air Force *Range Planning and Operations* instruction, hourly weather observations must be taken for temperature, visibility, altimeter setting (atmospheric pressure), cloud ceiling, and surface and aloft winds in order to ensure that no significant change will occur prior to launch (U.S. Air Force, 2011). It also requires all personnel be trained to have adequate knowledge of local weather hazards, and the officer-in-charge of the test range must have specific training on the weather limitations for each launch and how to obtain and analyze meteorological data to ensure the meteorological limitations of a launch are not exceeded (U.S. Air Force, 2011).

Applying the model: Function Analysis and Planning

Using literature on the topic, phenomena important to the commercial space industry were analyzed using the *Functional Analysis and Planning* section of *Lanicci's Strategic Planning Model*. From the *Phenomenology* section, the technology that is commonly used to assess these phenomena was applied, and a review was created to analyze the usefulness and cost effectiveness of the technology. After establishing relevant technology, the resources needed by a company to use this technology beyond the expense of the equipment, including human and support requirements, were discussed. Finally, the availability of this equipment from national sources was evaluated, and the likelihood of the NWS beginning operations with that technology was reviewed.

Phenomenology. Many meteorological conditions can negatively impact the safety of a space launch. Kingwell, Shimizu, Narita, Kawabata, & Shimizu (1991) assembled a fairly comprehensive list of weather conditions that could affect a successful launch. The categories used in their article were: (a) lightning, (b) wind velocity and turbulence profile, (c) temperature, (d) high altitude ice or ash clouds, (e) precipitation, (f) visibility, (g) cloud ceiling, and (h) supercooled water.

As seen in the Atlas/Centaur 67 mission, lightning can be devastating to the success of a launch (Uman & Rackov, 2003). Lightning can damage electrical systems (including the flight termination system), or the structural equipment of a launch vehicle, endanger personnel and facilities on the ground, or even cause the destruction of the launch vehicle itself (Kingwell et al., 1991). Due to this threat, lightning is also the most critical condition in the current commercial space launch regulations. Two different types of lightning are of concern to launches: natural lightning and triggered lightning. Natural lightning typically occurs during a thunderstorm to equalize the unbalanced electric charge that developed inside the thunderstorm. Triggered lightning can occur when no natural lightning has occurred. The cause of triggered lightning is similar to natural lightning, an imbalance of electrical charge. The difference comes from the need for a conduit for the triggered lightning to flow through, that is, an area where the electrical resistance is lower than the atmosphere around it. When a rocket is launched, the vehicle and the exhaust plume trailing behind it can provide a path of low-resistance for the electrical charge to travel through, thus triggering a lightning strike (Qui et al., 2007).

Wind and turbulence information is important to launch for a variety of reasons. Wind can affect the launch path, dynamic pressures on the launch vehicle during ascent, dispersion of debris and the exhaust plume, the safety of crews working on a launch pad, and the stability of a rocket while secured on a launch pad. In particular for unguided vehicles, proper wind analysis, forecasting, and weighing the accuracy and applicability of the observations ensures the launch vehicle remains on its planned flight path. Due to the concerns associated with wind conditions, a large portion of the commercial space launch regulation is devoted to wind analysis. Other impacts of wind and turbulence on launch vehicles include aerodynamic stresses during launch, exterior booster separation and recovery, and impacts on the hazardous range of noise and blast damage (Kingwell et al., 1991).

Temperature can pose a large risk for launches, as seen with STS-51-L (Presidential Commission on the Space Shuttle Challenger Accident, 1986). Components of a craft may be sensitive to cold or hot temperatures while on the pad and during launch. Additionally, super-cold liquid fuel tanks may have a limit on the temperature differential that can easily induce ice accumulation. Temperature extremes can also significantly impact engine performance, an impact that could cause the payload to fail to reach orbit despite the successful operation of the launch vehicle. Additionally, temperature could have an impact on corrosion if equipment is sitting on a launch pad for an extended period (Kingwell et al., 1991).

High altitude ice or ash clouds can also damage a rocket during launch. As a rocket must accelerate to a high velocity to enter orbit around Earth, even relatively small particles in the atmosphere can cause serious damage to a spacecraft. The small ice and ash particles can damage thermal tiles and exterior panels of spacecraft during launch and can seriously impact the operation of equipment such as antennas that are vital to the success of many space launches (Kingwell et al., 1991).

Precipitation, cloud ceilings, and surface visibility can significantly impact the success of a rocket launch. Precipitation and cloud ceilings can both reduce visibility prior to and during launch, and any visibility obscurations can inhibit the ability for ground personnel to visually track the rocket (Kingwell et al., 1991). This could make it difficult for ground personnel to terminate a launch if a failure is occurring, in violation of launch safety regulations (Support Systems, 2006). Visibility can also impact recovery operations of external boosters separated during launch. Precipitation, in particular, can indicate the presence of other conditions which could be dangerous to the safety of a launch, including lightning and high winds (Kingwell et al., 1991). Precipitation also includes hail, which can seriously damage a launch vehicle, as it did with the external tank and SRBs of STS-117, which was forced to return to NASA's Vehicle Assembly Building due to damage caused by golf-ball-sized hail (Jones, 2007).

Supercooled water in the launch path of a rocket can dramatically impact a launch. When supercooled water comes in contact with a surface, it freezes in a layer of ice. As this layer of ice builds up, it can significantly alter the aerodynamics of a launch vehicle. Ice accumulation can cause additional fuel to be spent overcoming the increased drag, control surfaces to no longer be able to keep a rocket on its correct path, or even cause the pressure build-up in front of a rocket to exceed structural limitations (Kingwell et al., 1991).

One factor not considered by Kingwell et al. (1991) is space weather, an issue that is understated by many studies evaluating launch commit criteria. Tretkoff (2010) discussed the crucial need for predicting space weather events due to expected increases in commercial space travelers. He expressed concerns over varying levels of radiation and solar energetic particles, such as those produced by coronal mass ejections (CME). A CME is one type of space weather phenomenon that is produced by the Sun during a reconfiguration of its corona. A CME represents the expulsion of super-hot coronal plasma at high speeds, which streams high-energy particles in the direction of the ejection (Lewis & Simnett, 1999). Another space-weather phenmenon produced by the Sun are the solar winds. The solar winds are also particles ejected from the Sun. These streams of hot particles, usually contained within the Sun's corona due to the strong magnetic field produced by the Sun, escape at two speeds: either fast or slow. Fast solar winds are typically believed to escape from the polar regions of the Sun, where the lines of magnetic flux are less organized. Slow solar winds bubble out from regions of the Sun that are typically constrained by the magnetic flux fields such as at the Sun's equator (Glanz, 1997). Both solar flares and CMEs disperse solar energetic particles (SEP), capable of disrupting or even damaging electronics in space (Space Studies Board, 2008). All three of these solar conditions could jeopardize the safety of a commercial space launch; better observation and forecasting techniques must be developed (Trekoff, 2010).

Technology. Many technologies exist to measure the phenomena that can negatively impact the commercial space launch industry. A detailed analysis has been assembled in Appendix A analyzing many of the technologies used in gathering data in the aviation and space launch industries. This analysis includes relative accuracy, which accounts for both the ability to observe the phenomena and detail in which the equipment can measure the phenomena. For example, when examining precipitation-measuring technologies, a standard sensor on an ASOS unit can measure the amount of rain or snow falling at a single point relatively well. However, the ASOS measurement is the precipitation at a single point (FAA, 2008), whereas a Doppler radar unit, such as those used by the NWS, may not be able to measure precipitation to the tenth of an inch, but it can measure precipitation falling over a large area (124 to 248 nautical miles, depending on the observation mode the radar is in) and consecutive images can convey the movement and development/dissipation of the precipitation (FAA, 2010). Aircraft observation can provide accurate precipitation indications for its flight path, but does have some drawbacks, including the inability to provide the large-scale observations, including storm movement as a radar unit can. This comparison can be seen in Table 2.

Table 2

Technology Analysis for Observing Precipitation

Equipment	Relative Accuracy	Relative Cost (Over 25 years)	ACA
ASOS	Moderate	Low	Moderate
Doppler Weather Radar	High	Negligible	Very Strong
Aircraft Observations	Moderately High	High	Weak

Note. From Appendix A

Many methods exist to measure wind speed and direction, each sensitive to within a single knot of wind speed. Table 3 contains an excerpt from the model data from Appendix A, specifically the section on wind instrumentation.

Table 3

Technology Analysis for Observing Wind and Turbulence Condition

Equipment	Relative Accuracy	Relative Cost (Over 25 years)	ACA
Instrument Towers	High	Low	Strong
Sodar/Wind Profiler	High	Low	Strong
ASOS Anemometer	High	Low	Strong
Doppler Weather Radar	Moderate	Negligible	Strong
Upper Air Soundings	Moderate	Low	Moderate
Aircraft Observations	Moderate	High	Moderate

Note. From Appendix A

Instrument towers in the network at CCAFS, which have a series of measurements over their length, can measure winds at different altitudes throughout the range. ASOS units, often using the same instruments as the towers, have similar accuracy, and can track the surface winds (Kingwell et al., 1991). Doppler radar can also track winds, but only through calculations based on radar reflectivity, and only when precipitation is occurring (Warning Decision Training Branch, 2012). Upper air soundings, typically free-flying balloons carrying a package of instruments called a radiosonde, are often used to track winds at higher altitudes, and more advanced technology has made these measurements more sensitive than ever. A drawback to this method is that the balloons are fully free-flying and can drift considerably with altitude as the balloon's course is altered by the wind. When a balloon reaches its maximum altitude, it may be over 100 kilometers from the point it was released, whereas a rocket launched from the same site may only be 4 or 5 kilometers from the launch site (Kingwell et al., 1991). To address this known deficiency of balloon-borne radiosondes, another wind measurement is acquired at CCAFS, collected by wind profilers. These profilers are able to collect wind and turbulence data directly over the site, up to an altitude of approximately 16 kilometers (52,493 ft.), compared to balloon-based upper air measurements that can reach upwards of 20 kilometers (65,000 ft.) (Martner et al., 1993). Martner et al. found that profilers were able to collect over 85% of the data with a vertical resolution, or data spacing, of approximately 200 meters (650 ft.).

The ability to forecast these phenomena are important to making launch decisions as well. For many of the phenomena, such as temperature, precipitation, cloud ceilings, and visibility, forecast accuracy is high. A forecast verification performed on the 2003-

2004 winter season for a difficult area of terrain by the National Oceanic and Atmospheric Administration (NOAA) found temperature forecast accuracy to be within 3 degrees Celsius for forecast periods of 48 hours or less (Myrick & Horel, 2006). Myrick and Horel found wind speed and temperature to be similarly accurate. Forecasts for other weather phenomena are less reliable. Two phenomena currently difficult to forecast, but essential to the commercial space industry, are lightning and space weather.

No current products exist that are approved to predict lightning for aviation. Walterscheid (2010) presented evidence that correlates lightning prediction to an icing prediction product, the Current Icing Product (CIP), an experimental product designed to forecast icing probability and intensity. However, as lightning data is used in the CIP to predict icing associated with convective activity, it may be found that this correlation is not causation. Statistical models have been created in an attempt to forecast probability of cloud-to-ground lightning (Shafer & Fuelberg, 2008). The model created by Shafer and Fuelberg was shown to be reliable for a number of summer seasons in Florida, though this model and others like it are unable to predict cloud-to-cloud lightning or a charged atmosphere in which triggered lightning could be produced.

Forecasting space weather events is in its infancy; although recent research has been conducted that may increase our capability to predict solar events (Strong, Saba, & Kucera, 2012). Coordinated interagency attention on improving the forecasting of space weather events began in 1994 in the US due to the increasing impact of these events on aviation and other industries (Fisher, 2003). Our current ability to forecast is primarily limited to the solar cycle and data observed from the Sun (Strong et al., 2012). Magnetic activity in the Sun follows a cycle that is approximately 22 years in length, with 11 years between each solar maximum (Strong et al., 2012). Figure 4 shows solar activity, identified by the number of sunspots visible, for the last 2.5 full solar cycles (Strong et al., 2012). Knowledge of this cycle provides forecasters with a general idea of the likelihood of a space weather event impacting Earth. Observing solar events from satellite and solar observatories allows very short-term forecasting, or more correctly, the data from these systems can calculate the arrival time of solar events from their time of occurrence to the time of impact on Earth (Strong et al., 2012).

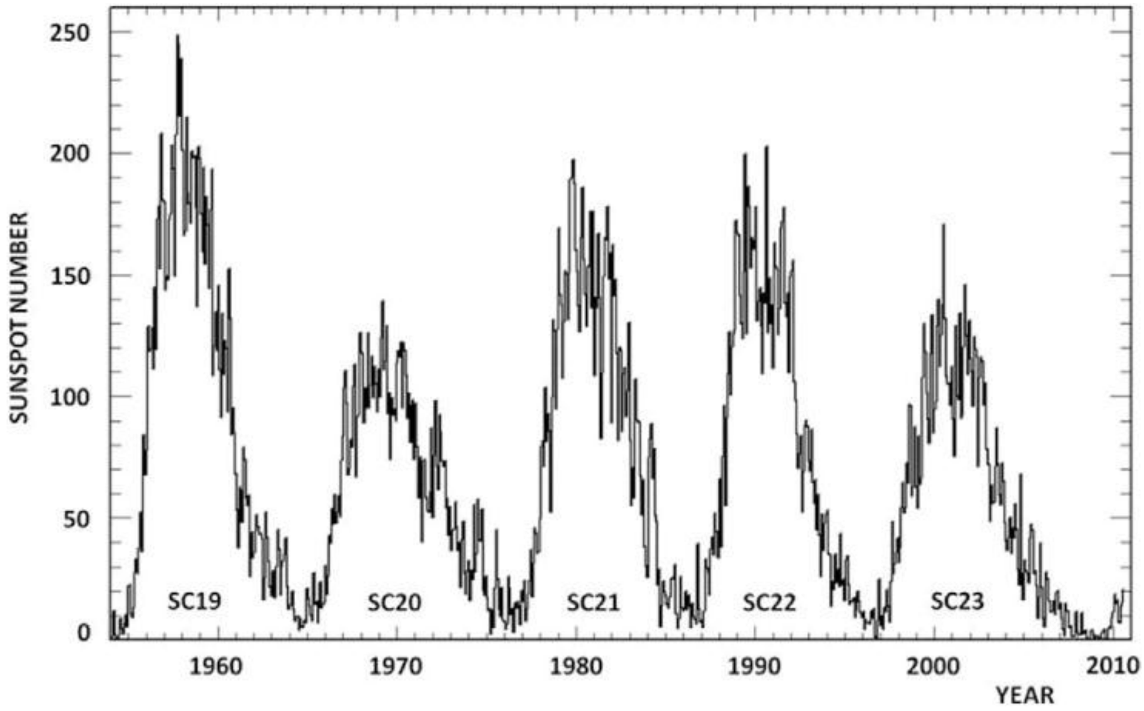

Figure 1. Solar activity, 1954-2011. *Note*. From Strong et al., 2012.

Resource structure. The *Resource Structure* of *Lanicci's Strategic Planning Model* is used to analyze the relative cost for the technology, the ACA, the resources a company would need to use this technology, national coverage of the technology, and the likelihood of national coverage existing in the near future.

The second set of data from the model is located in Appendix B. This appendix contains information regarding the resources a company must have access to, in order to utilize the different technologies discussed in this study. It also contains information regarding whether or not a company building a new spaceport would likely have coverage from the current products nationally, and the likelihood of this coverage extending to cover a spaceport if coverage does not already exist.

A company's resource needs are a subjective measure, based upon the amount of processing needed on the data gathered by a particular technology. Other needs include maintenance for new equipment, aircraft cost, operations and maintenance, and satellite operations. These specific costs are not estimated due to the high variability in each of those services. While these needs are important considerations, a small company might not have the capacity to conduct larger operations, such as aircraft observations or solar observatory operations.

National coverage and national likelihood are based upon the availability of data for a random location in the US to have coverage. For example, ASOS coverage is possible at launch site locations, as many of the current launch sites are associated with airports. The likelihood of an ASOS being set up at a new spaceport is low, and only likely to occur if traffic at the spaceport becomes high. Doppler radar coverage is common at most places in the continental US, but if a company were to set up its operations where coverage was unavailable, it is unlikely a new radar site would be created to accommodate the facility due to the expense of purchasing, installing, and maintaining a new radar facility. For upper air soundings, a national launch network exists, but if a company is in need of accurate wind speeds, the data may be too far away to accommodate their launches, and it would be unlikely that the NWS would set up a new balloon launch site to improve coverage.

For lightning data in particular, changes to national coverage are not likely to occur. Presently, lightning data is available nationally from commercial vendors who contract with the NWS to provide the data (Krider & Koshak, 2003), but real-time data from these contractors costs money. The development of this network stemmed from the federal government not funding a NWS project to create a network as they have with other data sources such as upper air soundings and radar (Orville & Huffines, 2001). One issue with public lightning networks is related to the nature of the lightning they sense. Networks like Vaisala's National Lightning Data Network (NLDN) and WSI's United States Precision Lightning Network (USPLN) rely on time-of-arrival (TOA) sensors and magnetic direction finding (MDF), which record the radio signals produced by lightning strikes, and triangulates their location with other sensors on the network (Vaisala, 2011; WSI, n.d.). Due to the need for triangulation when using TOA and MDF sensors, some cloud-to-cloud lightning events are not recorded, since the TOA and MDF sensors receive conflicting data indicating the source of the strike in multiple locations horizontally (Krider & Koshak, 2003). This means that some data potentially vital to the commercial space industry could be left out of reports. Lightning analysis and forecasting is extremely important. Current lightning launch commit criteria are less stringent than they were 10 years ago, but the lack of accurate lightning forecasting means that many launches must be canceled, to err on the side of safety (McNamara et al., 2009).

Presently, lightning is one of the most common meteorological reasons for the scrub of a launch, with only upper level winds possibly canceling more flights (Roeder & Madura, 2004).

Gap Analyses

Research Question 1. A gap analysis was conducted to identify if a gap existed in meteorological regulations between the commercial aviation industry and the commercial space industry. Multiple gaps were found between the regulations. The largest gap relates to the responsibility for meteorological data. For aviation, the Secretary of Commerce is responsible “to the highest possible degree… observe, measure, investigate and study atmospheric phenomena” and make forecasts, and to maintain facilities to do so. Their responsibility includes making reports and distributing it to people involved in air commerce (Meteorological Services, 2012). The Secretary of Commerce uses the NWS and AWC to fulfill these responsibilities. No similar law exists to provide these same services to the commercial space industry. Additionally, specific meteorological regulations do not exist similar to the Basic VFR Weather Minimums (2004), Takeoff and Landing Under IFR (2009), and the weather responsibilities discussed in the AIM (FAA, 2012).

Research Question 2. A second gap analysis was conducted to identify if a gap existed between the meteorological services provided for commercial aviation companies and airports and the meteorological services provided for commercial space companies and spaceports. It was found that all of the services available to aviation were provided to commercial space companies at the present time for launch operations conducted at or around *current* airports. For launch operations that are occurring or will occur at facilities that are *not* located on a current airfield, nor at KSC, CCAFS, or the Western Range at Vandenberg Air Force Base, California, meteorological services would not be equivalent to those provided for aviation. Primarily, surface measurements, such as those provided by ASOS instruments would not be available. Doppler radar services may not be available either, depending on the location of the airport. Kodiak Launch Complex in Alaska is an example of a spaceport that needed to purchase its own launch weather equipment, as it falls outside of many of the national weather data networks. This launch facility is not located within the range of any of the current NWS weather radar sites. It was also built as a new facility and did not have access to the equipment typically located at commercial airports (FAA, 2011). Other facilities could be set up in areas with insufficient data coverage and face a similar need to purchase equipment and plan their own meteorological support.

Additionally, many products and forecasts are created for aviation that can be used without changes by the commercial space industry, provided they remain free to access as they are presently for aviation. Examples of applicable products include: (a) surface analyses to cover the current weather condition from a regional and national basis and prognosis charts to provide information on surface conditions over the next 24 hours, (b) winds aloft charts, which would provide weighted wind data from across the continental US, (c) SIGMETs, which provide forecast information for convective activity, turbulence, icing, (d) AIRMETs, which provide forecast information for turbulence, icing and weather conditions that may restrict flight tracking and (e) METARs/TAFs, for launch facilities co-located at an airport, which provide observed and forecast surface data for launch facilities. Additionally, commercial space companies would have access to the same weather radar data and satellite imagery as the aviation industry, allowing them to properly gauge precipitation and cloud cover over a company’s facilities.

Research Question 3. A third gap analysis was conducted to identify if a the meteorological products and regulations that are currently in existence are sufficient to meet the estimated needs of commercial space operators for safe operations.

Currently, a majority of the services provided to aviation are available to the commercial space launch industry, and those services would serve the commercial space launch industry well for measuring the weather phenomena the commercial space industry would likely require. Lightning detection is one area where a gap likely exists. Presently, a commercial aviation company can access for free all of the meteorological information they need to safely conduct a flight, a measure that companies could possibly avoid to cut expenses. Commercial launch companies will be forced to purchase some required data, specifically lightning data. Additionally, space weather data cannot currently be predicted to the level that is necessary to ensure the safety of flight from a meteorological standpoint.

By law, the meteorological products and basic services provided to aviation are guaranteed to be provided (Meteorological Services, 2012). A similar guarantee does not exist for the commercial space industry, therefore a gap exists. Finally, as wording for most meteorological regulations is on par with that of the aviation industry, a gap was not found between current and necessary regulations.

Chapter V

Discussion, Conclusions, and Recommendations

The purpose of this study was to identify the gaps between the aviation and the commercial space industries regarding meteorological regulations, services, and products in order to estimate the meteorological needs of the commercial space industry. The results support the hypothesis that gaps do exist between the aviation and commercial space industries.

Discussion

A noteworthy gap was identified between the aviation and commercial space industries relating to the legislative requirements for providing meteorological services and products. Aviation has relied on these products and services provided free of charge by the NWS to observe and predict the weather phenomena crucial to maintaining safe operations. Though companies have the option of hiring external meteorological support, the option of free data from the NWS is available to them. Commercial space launch companies have access to these products and services through the same sources, which cover many of the phenomena the commercial space industry required for safe operations as well. The federal government is not required to continue providing these products free of charge to anyone beyond those engaged in air commerce or air navigation under the current laws (Aviation Programs, 2012; National and Commercial Space Programs, 2010). A budget could be passed that requires the NWS to charge users outside aviation for these services, and thus the commercial space industry would no longer be able receive this data essential to launch safety. It is possible that, without a legislative change, these same products and services would no longer be available to the commercial space industry.

A gap was also found between regulations for the commercial space industry and the aviation industry. This gap related to the Basic VFR Weather Minimums (2004), Takeoff and Landing Under IFR (2009), and the weather responsibilities discussed in the AIM (FAA, 2012). This gap is not considered to be particularly important. The aviation industry, both commercial and private, is sensitive to many of the same weather phenomena. The commercial space industry has many different launch vehicles which have significantly different vulnerabilities. Specific limitations on launch conditions may hinder the commercial space industry more than help it. Commercial space launch companies are required to create and submit to the FAA for approval a set of weather criteria for the company's launches as part of the company's written rule document. This process is nearly identical to the process an airline must undergo for approval of the weather minimums in their standard operating procedures. It was therefore deemed that no changes need to be made based upon this gap.

An additional gap was found to be possible concerning available surface meteorological data available if a newly established launch facility was not co-located at an airport or on a federal launch range. This gap specifically deals with the availability of meteorological equipment and data coverage. Specifically, radar coverage does not cover every possible launch location within the US. This is illustrated at Kodiak Launch Complex in Alaska, where coverage from the NWS Doppler radar site in Anchorage does not extend to cover the facility. Kodiak Launch Complex was the first newly established launch facility within the US, and had to set up many of the technologies necessary to adequately observe weather at their location, including field mills to detect lightning and charge build up, surface analysis for phenomena such as wind, temperature and cloud ceiling, and a commercial weather radar unit (Sardonia & Madura, 2002). While some companies may have enough money to buy this costly equipment; if the federal government does not require or provide this equipment at approved spaceports, companies may purchase only the most essential equipment to reduce costs.

Many weather products are produced for aviation, providing a multi-tiered approach to analyze and forecast weather phenomena. The second gap analysis found many products produced for aviation were sufficient to cover the needs of the commercial space industry. The products discussed above, as well as many other products created by the NWS, report and predict phenomena in sufficient detail to be used for the commercial space industry, and are currently available to commercial space companies. This means that, should the NWS be given the same responsibility to the commercial space industry as the aviation industry, NWS would need to make few modifications to serve the commercial space industry. Instead of another agency making duplicate products for the commercial space industry, the funding could go to the NWS to research methods of forecasting the phenomena the commercial space industry needs, where no products exist.

Additional products that are needed for the commercial space industry include products forecasting lightning potential, electrical charge, and a longer-range forecast of space weather events. These products do not exist primarily because there is not sufficient data to model these phenomena. Research should be conducted to provide more advanced warning for these phenomena.

Conclusions

The FAA is responsible for the safety of both the aviation industry and the commercial space industry. Having evolved from the CAA, and presiding over the regulatory changes related to aviation meteorology, the FAA has institutional memory of the challenges that weather provided the early aviation industry. The adaptation of aviation meteorological regulations to the commercial space industry was apparent in the review of many current meteorological regulations for the commercial space industry, and thus, gaps were still identified.

Additionally, due to the high cost of space launch operations, the federal government has been the primary launch operator for the first 60 years of space launch. Their operational dominance has provided them sufficient time to identify weather conditions that need special consideration for the space launch industry, similar to accidents in aviation in the 1980's highlighting the need for windshear measurements in aviation, to cite one example. Though tragic, the accidents suffered by NASA, the U.S. Air Force, and JAXA resulted in the creation of a framework for identifying the weather conditions that are particularly important during the launch of a spacecraft.

Overall, the commercial space industry benefits from the federal meteorological regulations. More research and support is needed for observing and forecasting both lightning and space weather events, though products currently produced for the aviation industry cover the remainder of the critical weather phenomena for the commercial space industry. Legislative changes should be made to ensure the NWS will continue to provide these products to the commercial space industry, in much the same way as they do for commercial aviation.

Recommendations

Based upon the results, recommendations are appropriate for the FAA, the U.S. Congress and commercial space launch companies. Additionally, meteorological topics that could benefit from future study are discussed.

Recommendations to the FAA. The primary recommendations to the FAA relate to areas that need continuing research. The current ability to forecast lightning may be adequate for aviation, but to ensure launch safety for the commercial space industry, more research needs to be conducted on methods of predicting lightning potential. Additional research should also be conducted on the ability to forecast the conditions necessary for triggered lightning to occur, perhaps through the use of products derived from high-resolution numerical weather prediction models. Such research is needed because so little investigation has been conducted on this subject. Further work on the cessation of favorable lightning conditions is also needed.

Another aspect of meteorology that needs continued research is space weather forecasting. To make rational launch decisions, companies require more than a three day notice on the general likelihood of solar activity. Research should be conducted in an attempt to extend the forecast window beyond three days and to make forecast as specific as possible.

Instrument packages should also be deployed to approved commercial spaceports as is done at major airports. In addition to a typical ASOS unit, which would be necessary for gathering surface data, a small network of field mills could gather the necessary data for commercial space launch operators to make evaluate the likelihood of lightning, natural or triggered, during a launch. Having this equipment available would allow commercial space launch companies to make better decisions using more accurate information on relevant atmospheric phenomenon.

Legislative recommendations. To ensure comprehensive weather support is available to the commercial space industry, it is recommended that the U.S. Congress pursue a legislative change to either: (a) amend the section of U.S. code under Aviation Programs (2012) entitled Meteorological Services (2012) to replace “air commerce” with “air and space commerce” each time “air commerce” is mentioned and replace “air navigation” with “air navigation and space launch” each time “air navigation” is mention, or change “air commerce” and “air navigation” to “operations under this title”, or (b) amend U.S. Code entitled National and Commercial Space Programs (2010) to include a weather commitment similar to the U.S. code Aviation Programs (2012) section entitled Meteorological Services (2012).

Recommendations to commercial space launch companies. To enhance the safety of the commercial launch programs, this study makes two recommendations. The first recommendation is for companies that are not co-located at an existing launch range to deploy weather instruments around launch facilities, regardless of support from the FAA and NWS. Field mills are particularly important at sites supporting vertical launches, to ensure no launches are conducted into an environment that could produce triggered lightning. The second recommendation is to make use of the meteorological products currently employed for the aviation industry. Utilizing these well-tested products limits expenses associated with analyzing and forecasting weather with products that provide duplicate data, which would allow more resources for analyzing phenomena that are not adequately covered nationally, such as lightning.

Further research. With the appropriate data and support from a commercial space launch company, it is believed that *Lanicci's Strategic Planning Model* can be applied to an individual company to ensure its meteorology department or service has the necessary capabilities to observe and predict the phenomena necessary to make appropriate launch decisions. Such an analysis was beyond the scope of this study.

This study concentrated on launch operations of the commercial space industry. *Lanicci's Strategic Planning Model* additionally could be used to analyze ground operations as well.

This study limited its review of the regulation of the commercial space industry to those regulations pertaining to meteorology. A review of the remaining regulations of the commercial space industry may also prove beneficial.

References

Airports: Required Data, 14 C.F.R. pt. 121.97 (2007).

Allaz, C. (1998). *The history of air cargo and airmail from the 18th century*. Paris, France: Christopher Foyle Publishing.

Associated Press. (1928, June 23). Caught in storm, airmail pilot dashed to death. *The Times Recorder*, p. 1.

Associated Press. (1935, May 7). Death toll to 5 in plane crash: Wife of Hollywood movie producer dies; Two others critical. *Jefferson City Post Tribune,* p. 1.

Aviation Programs. 49 USC Subtitle VII (2012).

Bailey, E. E. (2002). Aviation policy: Past and present. *Southern Economic Journal, 69(1),* 12-20.

Basic VFR Weather Minimums, 14 C.F.R. § 91.155 (2004).

Bilstein, R. E. (2001). *Flight in America: From the Wrights to the astronauts.* Baltimore, MD: John Hopkins University Press.

Civil Aeronautics Act of 1938, Pub. L. No. 706, § 304-803, 52 Stat. 973 (1938).

Christian, H. J., Mazur, V., Fisher, B. D., Ruhnke, L. H., Crouch, K., & Perala, R. P. (1989). The Atlas/Centaur lightning strike incident. *Journal of Geophysical Research, 94(D11)* 13, 168-13,177.

Commercial Space Transportation, Federal Aviation Administration, Department of Transportation, 14 C.F.R. ch. III, §400-461 (2012).

Familiarity with Weather Conditions, 14 C.F.R § 121.599 (1996).

Far Field Blast Overpressure Effects Analysis, 14 C.F.R. § A417.29 (2006).

Far Field Overpressure Blast Effects Analysis, 14 C.F.R. § 417.299 (2006).

Federal Aviation Act of 1958, Pub L. No. 85-726, 72 Stat. 731 (1958).

Federal Aviation Administration. (2008). *Pilot's handbook of aeronautical knowledge* (FAA-H-8083-25A). Oklahoma City, OK: US Department of Transportation, Federal Aviation Administration, Airman Testing Standards Branch.

Federal Aviation Administration. (2010). *Aviation weather services* (AC 00-45G). Washington, DC: Author.

Federal Aviation Administration. (2011). *2011 U.S. commercial space transportation development and concepts: Vehicles, technologies, and spaceports.* Washington, DC: Author.

Federal Aviation Administration. (2012). *Aeronautical information manual: Official guide to basic flight information and ATC procedures.* Washington, DC: Author.

Fisher, G. M. (2003). Integrating space weather and meteorological products for aviation. *Bulletin of the American Meteorological Society, 84, 11,* 1519-1523.

Flight Safety Analysis Methodologies and Products for an Unguided Suborbital Launch Vehicle Flown With a Wind Weighing Safety System, 14 C.F.R. § 417 Appendix C (2006).

General Operating and Flight Rules, 14 C.F.R. § 91 (2012).

Glanz, J. (1997). Two spacecraft track the solar wind to its source. *Science, 278, 5337,* 387-388.

Hong, G., Yang, P., Minnis, P., Hu, Y. X., & North, G. (2008). Do contrails significantly reduce daily temperature range? *Geophysical Research Letters, 35,* 1-4.

Jones, T. D. (2007). Hail Atlantis. *Aerospace America, June 2007,* 14

Kingwell, J., Shimizu, J., Narita, K., Kawabata, H., & Shimizu, I. (1991). Weather factors affecting rocket operations: A review and case history. *Bulletin of the American Meteorological Society,72*(6), 778-793.

Krider, E. P., & Koshak, W. J. (2003). *LIS validation studies using lightning at the KSC-ER.* Washington, DC: National Aeronautics and Space Administration.

Launch Safety, 14 C.F.R. § 417 (2012).

Launch Safety Rules, 14 C.F.R. § 417.113 (2006).

Lanicci, J. M. (2003). *Weather operations in the transformation era.* Maxwell Air Force Base, AL: Air University Press.

Lewis, D. J., & Simnet, G. M. (1999). The occurrences of coronal mass ejection at solar minimum and their association with surface activity. *Solar Physics, 191*(1), 185-200.

License to Operate a Launch Site, 14 C.F.R. § 420 (2011).

Lighthall, F. F. (1991) Launching the space shuttle Challenger: Disciplinary deficiencies in the analysis of engineering data. *IEEE Transactions on Engineering Management* 38 (1): 63-74.

Low-altitude Windshear System Equipment Requirements, 14 C.F.R. §121.358 (1990).

Martner, B. E., Wuertz, D. B., Stankov, B. B., Strauch, R. G., Westwater, E. R., Gage, K. S., Ecklund, W. L., Martin, C. L., & Dabberdt, W. F. (1993). An evaluation of wind profiler, RAAS, and microwave radiometer performance. *Bulletin of the American Meteorological Society, 74, 4,* 599-613.

McNamara, T. M., Roeder, W. P., & Merceret, F. J. (2009). The 2009 update to the lightning launch commit criteria. *Proceedings of the 14th Conference on Aviation,* *Range, and Aerospace Meteorology: Atlanta, GA*: American Meteorology Society.

Meisinger, C. L. R. (1920). Climatological factors governing the selection of air routes and flying fields. *Monthly Weather Review*, *48*(9), 525-528.

Meteorological Services. 49 USC § 44720 (2012).

Meyer, D. R., Isaminger, M. A., & Proseus, E. A. (1999). Study of network expansion LLWAS (LLWAS-NE) fault identification and system warning optimization through joint use of LLWAS-NE and TDWR data. *Proceedings of the American Meteorology Society 79th Annual Conference.*

Myrick, D. T., & Horel, J. D. (2006). Verification of surface temperature forecasts from the National Digital Forecast Database over the western United States. *Weather and Forecasting, 21, 5,* 869-892.

National and Commercial Space Programs, 51 USC (2010).

National Transportation Safety Board. (1976). *Aircraft accident report: Eastern Air Lines Inc.: Boeing 727-225, N8845E: John F. Kennedy International Airport: Jamaica, NY: June 24, 1975* (NTSB-AAR-76-8). Washington, DC: Government Printing Office.

Natural and Triggered Lightning Flight Commit Criteria, 14 C.F.R. §417 Appendix G (2011).

Office of Science and Technology Policy & National Aeronautics and Space Administration. (2010). *A Bold New Approach for Space Exploration and Discovery*. Washington, DC: Authors.

Operating Requirements: Domestic, Flag, and Supplemental Operations, 14 C.F.R. § 121 (2012).

Orville, R. E., & Huffines, G. R. (2001). Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989-98. *Monthly Weather Review, 129,* 1179-1193.

Presidential Commission on the Space Shuttle Challenger Accident. (1986). *Report of the Presidential Commission on the Space Shuttle Challenger accident.* Washington, DC: Government Printing Office.

Qui, X., Zhang, Q., Zhou, Y., Feng, G., Zhang, T., Yang, J., Kong, X., Xiao, Q., & Wu, S. (2007). Artificially triggered lightning and its characteristic discharge parameters in two severe thunderstorms. *Science in China Series D: Earth Sciences, 50(8),* 1241-1250.

Reviews, 14 C.F.R. § 417.117 (2006).

Roeder, W. P., & Madura, J. T. (2004). Designing weather support for future ranges – Results from the Advanced Range Technology Working Group Weather Subgroup. *Proceedings of the 11th Conference on Aviation, Range, and Aerospace Meteorology: Hyannis, MA*: American Meteorology Society.

Safety Critical Preflight Operations, 14 C.F.R. §417.121 (2006).

Sardonia, J. E., & Madura, J. T. (2002). Kodiak Star: An overview of operational weather support at the Kodiak Launch Complex for Alaska’s first orbital launch. *Proceedings of the 14th Conference on Aviation, Range, and Aerospace Meteorology: Portland, OR*: American Meteorology Society.

Sea level. (2011). In *The Merriam-Webster Dictionary.* Merriam-Webster Mass Market.

Shafer, P. E., & Fuelberg, H. E. (2008). A perfect prognosis scheme for forecasting warm-season lightning over Florida. *Monthly Weather Review, 136, 6,* 1817-1846.

Space Studies Board. (2008). *Severe space weather events: Understanding the societal and economic impacts: A workshop report.* Washington DC: The National Academies Press.

SpaceX. (2012). *Launch manifest*. Retrieved from http://www.spacex.com/launch_manifest.php.

Strong, K., Saba, J., & Kucera, T. (2012). Understanding space weather: The sun as a variable star. *Bulletin of the American Meteorological Society, 93, 9,* 1327-1335.

Support Systems, 14 C.F.R. § 417.307 (2006).

Takeoff and Landing Minimums: IFR: All Certificate Holders, 14 C.F.R. §121.651 (2007).

Takeoff and Landing Minimums: VFR: Domestic Operations, 14 C.F.R. §121.649 (1991).

Takeoff and Landing Under IFR, 14 C.F.R. § 91.175 (2009).

Time Delay, 14 C.F.R. § A417.21 (2006).

Troclet, B., Alestra, S., Terrasee, I., Jeanjean, S., & Srithammavanh, V. (2005). Identification of overpressure sources at launch vehicle lift-off using an inverse method. *European Conference for Aerospace Sciences (EUCASS), 1.2,* 1-7.

Tretkoff, E. (2010). Space weather in focus: A decade in review. *Space Weather, 8.*

Types of Launch License, 14 C.F.R. § 415.3 (2011).

Uman, M. A., & Rakov, V. A. (2003). The interaction of lightning with airborne vehicles. *Progress in Aerospace Science, 39,* 61-81.

U.S. Air Force. (2011). *Range planning and operations* (Air Force Instruction 13-212). 8 June, 2011.

United Press. (1934, March 9). Army airmail crashes kill 2. *The Pittsburgh Press*, p. 1.

Vaisala. (2011). *Vaisala's NLDN® U.S. National Lightning Detection Network.*

Walker, C., & Powell, J. (2005). *Atlas: The ultimate weapon by those who built it.* Apogee Books: Burlington, Ontario, Canada.

Warning Decision Training Branch. (2012). *Topic 5: Base and derived products.* Norman, OK: National Oceanic and Atmospheric Administration: National Weather Service.

Walterscheid, R. L. (2010). Triggered lightning risk assessment for reusable launch vehicles at four regional spaceports. *Presented to COMSTAC RLV Working Group Meeting.*

Werrell, K. P. (2010). "Fiasco" revisited: The Air Corps & the 1934 air mail episode. *Air Power History, March 2010,*

WSI. (n.d.). *WSI Lightning Data Products and Services.* Retrieved from: http://www.uspln.com/documentation/WSI%20Lightning%20Networks%20Jan11.pdf

Yoshikawa, M., Kawaguchi, J., Yamakawa, H., Kato, T., Ichikawa, T., Ohnishi, T., & Ishibashi, S. (2005). Summary of the orbit determination of NOZOMI spacecraft for all the mission period. *Acta Astronaut.*, *57*(2-8), 510-519.

Appendix A

Functional Analysis and Planning: Technology Analysis

Phenomenology	Technology			
	Equipment	Relative Accuracy	Relative Cost (Over 25 years)	ACA
Lightning	Electric Field Mill	High	Low	Strong
	TOA/Radio Inferometry	Moderate	Moderate	Moderate
	Cloud Analysis	Low	Low	Weak
	Satellite Observations	Moderate	Negligible (High)	Strong(Very Weak)
	Aircraft Observations	Moderate	High	Very Weak
Surface Visibility	ASOS (and RVR)	Moderate	Negligible	Strong
	Surface Estimate	Moderate	Low	Moderate
Wind Profile/ Turbulence	Instrument Towers	High	Low	Strong
	Sodar Profiler (UHF/VHF)	High	Low	Strong
	ASOS	High	Low	Strong
	Doppler Radar	Moderate	Negligible (Moderate)	Strong(Weak)
	Upper Air Soundings	Moderate	Low	Moderate
	Aircraft Observations	High	High	Moderate
Temperature	ASOS	High	Low	Strong
	Upper Air Sounding	Moderately High	Low	Strong
High Altitude Ice/Ash Clouds	Visual Ground Observations	Low	Negligible	Moderate
	Aircraft Radar/LIDAR	High	High	Moderate
	Satellite Observations	Moderate	Negligible (High)	Strong(Very Weak)
Precipitation	ASOS	Moderate[a]	Low	Moderate
	Doppler Radar	High	Negligible (High)	Very Strong (Moderate)
	Aircraft Observations	Moderately High	High	Weak
Cloud Ceilings	Human Estimation	Moderate[b]	Low	Moderate[b]
	Ceilometer (ASOS)	Moderate	Low	Moderate
	Aircraft Observations	Moderately High	Low	Moderate
Super-cooled Water	Aircraft Observations	Moderate	Very High	Very Weak
	Aircraft PIREPS	Low	Negligible	Moderate
Sun/Space	Satellite Observations	Moderately High	Negligible (High)	Strong (Weak)
	Solar Observatory Data	Moderately High	Negligible (Moderate)	Strong (Moderate)

Notes: Table include options for companies to install facilities that provide information publicly and nationally in parentheses. [a]ASOS precipitation is measured at a single point, so accuracy is not comparable to Doppler radar measurements. [b]Human observation accuracy varies greatly with level of experience and skill.

Appendix B

Functional Analysis and Planning: Resource Structure Analysis

Technology		Resource Structure		
Equipment	ACA	Company Resources[a]	National Coverage	National Likelihood
Electric Field Mill	Strong	Small Met. Department, Maintenance	No	Low
Time of Arrival/Radio Inferometry	Moderate	Met. Department, Maintenance	Private[1]	Not Likely
Cloud Analysis	Weak	Small Met. Department	No	Low
Satellite Observations	Strong(Very Weak)	Small Met. Dept., (Satellite Operations)	Private	Not Likely
Aircraft Observations	Very Weak	Met Dept., A/C Ops and Maintenance	No	Not Likely
ASOS (and RVR)	Strong	Small Met. Department, Maintenance	Possible Coverage	Low[b]
Surface Estimate	Moderate	Small Met. Department	No	Not Likely
Instrument Towers	Strong	Small Met. Department, Maintenance	No	Low
Sodar/Wind Profiler (UHF/VHF)	Strong	Met. Department, Maintenance	Most Likely Not	Very Low
ASOS	Strong	Small Met. Department, Maintenance	Possible Coverage	Low[b]
Doppler Radar	Strong(Weak)	Small Met. Dept. (Met and Maint.)	Likely Covered	Not Likely
Upper Air Soundings	Moderate	Met. Department, Maintenance	“Coverage” exists	Low
Aircraft Observations	Moderate	Met Dept., A/C Ops and Maintenance	No	Not Likely
ASOS	Strong	Small Met. Department, Maintenance	Possible Coverage	Low
Radiosonde	Strong	Met. Department, Maintenance	“Coverage” exists	Low
Visual Ground Observations	Moderate	Small Met. Department	No	Not Likely
Aircraft Radar/LIDAR	Moderate	Met Dept., A/C Ops and Maintenance	No	Not Likely
Satellite Observations	Strong(Very Weak)	Small Met. Dept., (Satellite Operations)	Yes	N/A
ASOS	Moderate	Small Met. Department, Maintenance	Possible Coverage	Low[b]
Doppler Radar	Very Strong (Moderate)	Small Met. Dept. (Large and Maint.)	Likely Covered	Not Likely
Aircraft Observations	Weak	Met Dept., A/C Ops and Maintenance	No	Low
Human Estimation	Moderate	Small Met. Department	No	Not Likely
Ceilometer (ASOS)	Moderate	Small Met. Department, Maintenance	Possible Coverage	Low[b]
Aircraft Observations	Moderate	Met Dept., A/C Ops and Maintenance	No	Not Likely
Aircraft Observations	Very Weak	Met Dept., A/C Ops and Maintenance	No	Not Likely
Aircraft PIREPS	Moderate	Small Met. Department	Yes	N/A
Satellite Observations	Strong (Weak)	Small Met. Dept., (Satellite Operations)	Yes	N/A
Solar Observatory Data	Strong (Moderate)	Small Met. Dept., (Large and Maint.)	Yes	N/A

Notes: [a]Met. in this category, is short for meteorology. A/C stands for Aircraft. Satellite Operations would also need larger meteorology departments to process the data, as would solar observatories and Doppler radar sites. Estimates are based upon the amount of data that would need human involvement in processing. [b]If a spaceport is established at a location that is not already an airport, the likelihood of the FAA, NWS, or DoD setting up an automated weather station is unlikely.