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Broadening Traditional Aviation Meteorology Education to Support Spaceflight Operations

Thomas A. Guinn
Embry-Riddle Aeronautical University - Daytona Beach, guinnt@erau.edu

Nicholas J. Stapleton
Leidos, nickanoki@gmail.com

Katherine A. Winters
USAF 45th Weather Squadron, katherine.winters@us.af.mil

Bradley M. Muller
Embry-Riddle Aeronautical University - Daytona Beach, mullerb@erau.edu

Debbie M. Schaum
Embry-Riddle Aeronautical University - Daytona Beach, schaumd@erau.edu

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Introduction

Meteorological support for spaceflight (both space-launch and on-orbit) operations, while similar to that for traditional aviation operations, presents significant additional challenges that standard aviation weather classes do not typically address. Guinn and Rader (2012) examined the topics covered in meteorology courses supporting 22 different accredited professional flight B.S. degree programs and found the primary focus to be largely on general aviation hazards (e.g., icing, turbulence, thunderstorms) and aviation products (e.g., AIRMETS, SIGMETS). None of the schools examined listed weather support to spaceflight operations as a topic area in their course descriptions. However, with the burgeoning commercial space industry projected to produce between $300 million and $1.6 billion in revenue between 2012 and 2022 (Tauri Group, 2012), the need for universities to be able to educate commercial space operators and future meteorologists on the weather and space-weather impacts to spaceflight operations becomes increasingly important. At the Embry-Riddle Aeronautical University Daytona Beach campus (ERAU-DB), the projected growth in the commercial space industry has led to the advent of a new degree program, Spaceflight Operations (SO), and prompted investigation into the requirements necessary to extend traditional aviation meteorology instruction to include space-launch and on-orbit weather requirements. While traditional aviation meteorology instruction does overlap with that for spaceflight weather support, it does not cover the full-spectrum of impacts both SO and meteorology students must understand to provide appropriate safety margins for these operations.

To address this challenge, ERAU-DB worked with the U.S. Air Force's (USAF) 45th Weather Squadron (WS) at Patrick Air Force Base, FL, to identify weather topics necessary for spaceflight support beyond those required for traditional aviation meteorology instruction. These topics include increased spacecraft and system weather sensitivities, triggered lightning, triboelectrification, vertical distribution of winds and turbulence within *and* above the troposphere, and space-weather impacts. The purpose of this paper is to discuss briefly each of these topics with the goal of initiating conversations within and between the spaceflight operations and aviation weather communities towards broadening meteorology education for support to spaceflight operations. While our list of weather impacts on spaceflight operations presented in this paper is not considered exhaustive, it does provide a solid foundation for more detailed discussions.

Background

Perhaps the best way to demonstrate the importance of expanded meteorology education on spaceflight operations is by highlighting two historical and costly space-launch disasters where weather was the primary causal factor. These include the Space Shuttle Challenger accident of 1986 (Presidential Commission on the Space Shuttle Challenger Accident [PCSSCA], 1986) and the Atlas/Centaur 67 rocket accident of 1987 (Uman & Rakov, 2003).

The devastating Challenger accident on January 28, 1986, highlights the increased weather sensitivities of spacecraft and launch vehicles compared to traditional commercial aircraft. During the launch, two O-rings on the Space Shuttle's Solid Rocket Boosters (SRB) failed to maintain proper seal under subfreezing temperatures (PCSSCA, 1986). The failed O-rings initiated a chain of events that caused the fuel tank to rupture and ultimately led to the breakup of the vehicle 73 seconds after ignition (PCSSCA, 1986). The Commission attributed the O-ring failure to temperatures that were colder than the Space Shuttle had previously experienced during launch (31°F outside air temperature compared to the previous coldest launch temperature of 53°F) (PCSSCA, 1986). In addition, the Commission also noted the O-rings could have been resealed by the deposition of aluminum oxide, but the resealing may have been disturbed by thrust vectoring in response to wind shear aloft (PCSSCA, 1986). While this example may be unique to the Shuttle, it does illustrate the enhanced weather sensitivities of spaceflight operations.

Another devastating incident occurred on March 26, 1987 when lightning struck an Atlas/Centaur 67 rocket 49 seconds after launch, damaging the guidance-control electronics leading to overstress and subsequent breakup over the Atlantic Ocean (Uman & Rakov, 2003). Despite there being no significant convection occurring at the launch site, there was a sufficient electrical field gradient for a strike to occur when the rocket was launched (Christian et al., 1989). 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). This incident highlights the importance of induced or “triggered” lighting, a topic that has little impact on traditional aviation operations and is not addressed in traditional aviation weather courses (Guinn & Rader, 2012).

Analysis and Discussion

In an effort to broaden the weather learning outcomes of a traditional aviation meteorology course to encompass the needs of spaceflight operations, we have analyzed some of the distinct differences required for spaceflight operations education that are not currently included in traditional aviation meteorology curricula.

Differences in Meteorological Requirements

While traditional aviation meteorology courses provide knowledge of weather and space-weather impacts on horizontal flight within the troposphere, they do not cover the environmental impacts on orbital or sub-orbital aircraft during vertical flight through the troposphere, stratosphere, and mesosphere. In addition to the flight phase, weather also has a tremendous impact on pre- and post-launch operations, which can differ significantly from traditional aviation support. These operations include the transport of the launch vehicle to the launch pad, the movement of explosives, toxic chemical and fuel procedures, and vehicle recovery actions. Because of the sensitivity of spaceflight operations, educational programs should include these meteorological concerns in any curricula that seeks to be relevant for those meteorology majors desiring to provide spaceflight support as well as those pursuing degrees in SO. Kingwell, Shimizu, Narita, Kawabata, and Shimizu (1991) provided an excellent and comprehensive review of the potential meteorological impacts to rocket operations. In their paper, they discussed four broad categories of weather impacts: lightning, wind, turbulence (vertical wind profiles), temperature and humidity.

Since the goal of this paper is to highlight the broadening of traditional aviation meteorology education, we have chosen an alternative categorization. First, we combine into one category those weather topics that are common to both traditional aviation operations and space-launch operations but that have *increased* sensitivities. This category includes wind, temperature, and precipitation. Next, since traditional lightning impacts both space-launch operations as well was traditional operations, we focus instead on triggered lightning and triboelectrification. In addition, similar to Kingwell et al. (1991) we also include vertical wind profile analysis. Lastly, we include a discussion of space-weather impacts on operations. The resulting five categories are increased weather sensitivities, space-weather impacts, triggered lightning, triboelectrification, and vertical distribution of winds and turbulence within and above the troposphere.

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Increased weather sensitivities. Compared to traditional aviation operations that take place almost entirely in the troposphere or lower stratosphere, orbital and suborbital flights traverse a much greater vertical portion of the atmosphere. They, therefore, experience exposure to a much wider range of environmental conditions. Since the flights are nearly vertical and at much greater speeds, changes in the environmental parameters experienced by the spacecraft are much more rapid than for ordinary aircraft. Even on the ground, the increased complexity of the systems makes them more vulnerable to variations in atmospheric conditions. The sensitivity of the Space Shuttle O-rings to temperature is one such example. Other examples include increased sensitivities to winds, clouds and precipitation.

We contend wind sensitivities are greater for space-launch operations than for ordinary aviation because orbital and reusable sub-orbital aircraft typically land unpowered and are therefore more susceptible to wind direction and speed than conventional powered aircraft. For example, the Space Shuttle required 15 knots or less crosswinds during the day and 12 knots or less during night landings (National Aeronautics and Space Administration Kennedy Space Center [NASA KSC], 2003). These are approximately equal to the crosswind thresholds of small general-aviation aircraft, such as a Cessna 172 (Cessna, 1998). Comparatively, larger commercial aircraft, such as Boeing 757, have demonstrated crosswind-landing thresholds of 36 knots (Cashman, 2014). Likewise, there may be other wind constraints associated with returning reusable space-launch vehicles. In addition to landing, forecasters must also properly forecast near-surface winds to ensure the potentially toxic plumes created during the burning of solid rocket fuel do not violate air quality standards downwind (Kingwell et al., 1991). So, while winds affect both traditional aviation and space-launch operations, the unique sensitivities for space-launch operations requires support meteorologists to be acutely aware of acceptable observed and forecasted wind conditions over a much narrower window of thresholds.

During ground operations, liquid or frozen precipitation has a similar impact on spacecraft as it does on traditional aircraft (e.g., reducing visibilities during movement of spacecraft and during early phases of flight) but the risks are much greater for space-launch operations. Low visibility and ceilings often prevent launches because they could obscure the view of the vehicle from ground controllers (Kingwell et al., 1991). This would make it difficult for launch personnel to terminate the launch in a timely manner in the advent of a failed system (Support Systems, 2006). During the flight phase, the sensitivities increase. Ice particles, for example, can seriously erode space vehicles during the reentry phase due to their high-speed impacts when compared to traditional aircraft (Kingwell et al., 1991). As another example, masses of high-altitude, mesospheric ice particles, known as noctilucent clouds, were considered a threat to the tiles on the Space Shuttle (Couvault, 1988; Kingwell et al., 1991). In contrast, noctilucent clouds pose no threat to traditional aviation operations so traditional aviation weather courses do not include this topic (Guinn & Rader, 2012). These increased sensitivities to weather reveal limitations of a traditional aviation weather course for educating students in supporting spaceflight operations.

Space weather impacts. Space weather typically refers to highly accelerated particle and electromagnetic radiation from the Sun (or other stars), its interaction with Earth's atmosphere and magnetic fields, and the impacts of this interaction on our technological systems and health (National Oceanographic and Atmospheric Administration Space Weather Prediction Center [NOAA SWPC], 2010). Space weather is a direct concern for conventional aviation operations typically only on polar flight routes during active solar periods, where there can be high-frequency (HF) radio blackouts and elevated risks of particle radiation exposure to pilots and crew (NOAA SWPC, 2010). However, space weather can adversely affect manned and unmanned spacecraft leaving the stratosphere in several ways. Collisions with low-energy charged particles (electrons) during solar events can cause spacecraft surface and bulk charging resulting in damage to electronic components, while collisions with high-energy particles (protons) can cause even more significant damage to computer memory (NOAA SWPC, 2010). In addition, geomagnetic storms increase the density of the thermosphere, resulting in unexpected drag, potentially causing a space vehicle to slow or even change orbit (NOAA SWPC, 2010). Understanding thermospheric density changes is even more critical for manned spaceflight to ensure proper collision avoidance with space debris as well as to make accurate re-entry predictions (Qian & Solomon, 2012). In addition, for manned spaceflight, solar radiation storms can create high-radiation hazards to crew and passengers, especially during extra-vehicular activities (NOAA SWPC, 2010). Meteorologists providing services to spaceflight operations must understand the space-weather environment and provide information to customers concerning solar events, such as solar flares and coronal mass ejections that may potentially cause a space-weather constraint violation. As an example, on January 8, 2014, Orbital Sciences Corporation scrubbed their launch of an Antares rocket from NASA's Wallops Flight Facility due to excessive radiation resulting from solar flares and coronal mass ejections the day prior (Fox, 2014). The concern was that excessive high-energy protons could potentially cause the avionics to fail. For these reasons, students need to understand potential space-weather impacts to spaceflight operations and be able to interpret products from NOAA's Space Weather Prediction Center and translate any operational impacts.

Triggered or induced lightning. While natural lightning poses a threat to both terrestrial aviation and space-launch operations, vehicle-triggered lightning is a far greater risk for orbital and suborbital vehicles. Most aviation-weather courses cover natural lightning monitoring and avoidance (Guinn & Rader, 2012); however, meteorology instruction for space-launch operations must also include techniques for monitoring and assessing the risk of triggered lightning. Instructors need to ensure students are closely familiar with natural and triggered lightning flight commit criteria published in the code of federal regulations (National and Triggered Lightning Flight Commit Criteria [NTLFCC], 2011), which provide the environmental conditions necessary to safely initiate a launch without triggering a lightning strike. Using the NTLFCC (2011) criteria as a guide would require students to become more proficient in cloud identification to determine the cloud types, thicknesses, and temperatures that are indicative of increased risk of triggered lightning. In addition, instructors would need to expand traditional aviation-weather radar interpretation techniques to include analysis of advanced radar information such as maximum radar reflectivity data (National Aeronautics and Space Administration, Scientific and Technical Information Program [NASA STI], 2016) and volume-averaged, height-integrated radar reflectivity data (Bauman, 2008) for determination of the potential for triggered lightning. Further, students would require an increased knowledge of basic electrical fields and the ability to evaluate data from atmospheric-electrification sensors, such as field mills, to determine the potential for lightning strikes.

Triboelectrification. In addition to triggered lightning, students must also understand the concept of triboelectrification (or frictional charging) and the impact it has on safe operations. Triboelectrification refers to the charge buildup and subsequent discharge on a launch vehicle during the launch. The charge buildup occurs when the vehicle passes through

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regions of cloud containing ice crystals at spacecraft speeds slow enough to prevent the ice crystals from melting (National Aeronautics and Space Administration [NASA], 1974). If the charge buildup becomes significant enough then discharges may occur, damaging electrical systems, communications equipment, or possibly the vehicle itself (NASA, 1974; Winters, Roberts, & McGrath, 2011). Unless the launch vehicle is specifically treated for surface electrification or the operators have demonstrated through test or analysis that electrostatic discharges on the surface of the launch vehicle due to triboelectrification will not harm either the launch vehicle or spacecraft, then ice-particle clouds (e.g., cirrus clouds) could potentially cause launch cancellation or postponement (NASA KSC, 2003). Such was the case for the Ares I-X launch in October 2009, which operators postponed due to the potential for triboelectrification presented by high, thin cirrus clouds directly over the launch area (Winters et al., 2011). Although triboelectrification also occurs in commercial aviation, static wicks on aircraft readily dissipate these charges (Bergqvist, 2013).

Vertical wind profile analysis and turbulence. Upper-level winds and turbulence, while important to terrestrial aviation support for forecasting wind shear and turbulence, become even more critical for supporting spaceflight operations because of the increased complexity of the aerodynamics as well as the potential for control problems and structural issues resulting from strong wind shear (Kingwell et al., 1991). For NASA Space Shuttle operations, as an example, the computer system used vertical wind information to generate the steering commands on the launch vehicle during take-off and to determine the resulting aerodynamic loads on the vehicle (NASA, 2010). In addition, the winds help determine the direction, speed and development of upstream clouds that may lead to cloud electrification concerns discussed previously (NASA, 2010). Like the Space Shuttle, commercial sub-orbital flights would likely have similar constraints during ascent. Meteorology courses covering spaceflight support would therefore require more training on the analysis of vertical wind profiles and turbulence.

Challenges and Limitations

The broadening of traditional aviation meteorology courses to support spaceflight operations is not without challenges and limiting factors. First, the meteorology regulations governing spaceflight operations are not nearly as mature as are those for traditional aviation operations (Stapleton, 2012). In addition, the National Weather Service (NWS) provides robust suites of data and products for aviation whereas products unique to spaceflight support are more limited (Stapleton, 2012). Lastly, opportunities for students to gain experiential learning by providing weather support to real-world space-launch operations are limited, if not non-existent.

Maturity of Meteorological Regulations

Because the meteorological regulations covering spaceflight operations are not currently as developed as those for commercial aviation, products to support commercial spaceflight operations are not as widely available, making consistent meteorology education more challenging. For traditional aviation operations, the U.S. statutes clearly define responsibility for meteorological support; that is, the Secretary of Commerce is obliged to observe and study atmospheric phenomena as well as forecasting probable weather conditions (Meteorological Services, 2012). To implement these responsibilities, the Secretary of Commerce uses the NWS's Aviation Weather Center. No similar law currently exists to provide these services to the commercial space industry. Additionally, specific meteorological federal regulations do not exist similar to the Basic VFR Weather Minimums (2014), Takeoff and Landing Under IFR (2016), and the weather responsibilities discussed in the Aeronautical Information Manual (Federal Aviation Administration Aeronautical Information Manual [FAA AIM], 2016). The only currently existing criteria address lightning launch commit criteria, mentioned earlier, as published in the NTLFCC (2011).

Limited Data, Products and Product Support

The aviation community, including higher education institutions, have relied on products and services provided free of charge by the NWS to predict and inform about weather conditions critical to maintaining safe operations. Though airlines and other commercial aviation operations (both part 121 and 135 operations) have the option of hiring external meteorological support through approved Enhanced Weather Information Systems (FAA, 2014), free data from the NWS also is available. Commercial spaceflight companies have access to these products and services through the same sources, and these products and services do overlap with many of the phenomena the commercial space industry requires for safe operations as well. However, the federal government is not required to continue providing these products or develop new 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). For this reason, educational institutions would likely not have free access to more specialized products designed to support space-launch operations. Most notably, electric field mill data for predicting triggered lightning potential, such as used by the USAF 45th Weather Squadron, are not available at all space-launch facilities and not disseminated through the NWS. Due to the expense of field mill systems, schools would likely need to simulate this information (and possibly other specialized data) through archived or modeled data.

In contrast to space-launch weather support, for on-orbit support the NWS's Space Weather Prediction Center (SWPC) does provide a host of space-weather products (University Corporation for Atmospheric Research, 2009). Instructors could use these products in a classroom setting to aid students in assessing the potential for critical on-orbit hazards caused by geomagnetic and solar radiation storms.

Limited Opportunity for Support to Real-World Operations

For traditional aviation operations, there are often opportunities to provide experiential, real-world learning, such as ERAU-DB's support of the Women's Air Race Classic. For spaceflight operations, however, there are no similar opportunities to support decision-making directly affecting real-world launches due to the significantly greater risks and costs involved. Students would instead need to gain experiential learning for meteorology support through simulations. While simulations can limit the realism of the support, they do offer the benefit of allowing for a greater frequency of operational support experiences over a greater range of atmospheric conditions. That is, schools can conduct simulations multiple times per year with many different weather scenarios.

Summary

With the growth of commercial space operations both in industry and as an academic subject, the need for broadening traditional aviation weather education to include support to both space-launch and on-orbit operations is becoming increasingly important. This includes educating both future spaceflight operators and meteorologists, alike, on the potential weather and space-weather impacts on these operations. While there is some overlap between the weather support required for traditional aviation operations versus spaceflight operations (e.g., thunderstorms and convection, aircraft/spacecraft icing, ceiling and visibility, excessive winds), there remain distinct differences that make traditional aviation meteorology education inadequate for this support. In this paper, ERAU-DB has worked closely with the USAF 45th WS to identify several key weather topics that should be included in any meteorology education aimed at supporting spaceflight operations, both manned and unmanned. These additional topics include the increased weather sensitivities of spacecraft versus traditional commercial aircraft, induced lightning and triboelectrification concepts, detailed vertical wind profile analyses, and space weather impacts. In addition, we have uncovered several educational challenges requiring creative solutions, such as the limited ability for experiential learning through support to real-world operations and the limited availability of weather resources and products specific to spaceflight operations. The goal of this paper is to begin a conversation for the expansion of aviation meteorology education to include support to spaceflight operations and help produce career-ready graduates, both meteorologists and spaceflight operators, for this rapidly growing field.

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