469 The 2009 Update To The Lightning Launch Commit Criteria

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1. INTRODUCTION

The 45th Weather Squadron (45 WS) is the U.S. Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS), NASA Kennedy Space Center (KSC), and Patrick AFB (PAFB). The weather requirements of the space program are very stringent (Harms et al., 1999). In addition, the weather in east central Florida is very complex. This is especially true of summer thunderstorms and associated hazards. Central Florida is 'Lightning Alley', the area of highest lightning activity in the U.S. (Huffines and Orville, 1999). The 45 WS uses a dense network of weather sensors to meet their operational requirements in this environment (Roeder et al., 2003). One of the most important weather support requirements for space launch from CCAFS/KSC is to forecast and evaluate the Lightning Launch Commit Criteria (LLCC).

This paper will summarize the 2009 updates to the LLCC. The first major improvement allows closer approach to anvil clouds under some conditions. The second major improvement allows the use of the Volume Averaged Height Integrated Radar Reflectivity (VAHIRR) criteria in debris clouds. Both of these improvements are based on new analysis of the second Airborne Field Mill experiment (ABFM-II) (Dye et al., 2007) and provide increased launch opportunity while maintaining safety. This upgrade also provides refined wording of the LLCC and definitions for easier use in operations and training.

The 2009 LLCC were approved for operational use on 24 Oct 09. The first launch to use the new LLCC was the NASA ARES-1X on 28 Oct 09. The second use of the new LLCC was an Atlas launch on 23 Nov 09, in which the new rules avoided a 1-day scrub that would have occurred under the old rules and avoided a $1.4 million dollars cost.

This paper assumes the reader is familiar with the LLCC. If not, the LLCC are listed in full in Appendix-1 with associated definitions, explanations, and examples in Appendix-2. In addition, background, history, evaluation practices, and the previous 2005 LLCC are discussed in Roeder and McNamara (2006).

2. Lightning Launch Commit Criteria Overview

The LLCC are the weather rules to avoid natural and rocket triggered lightning strikes to in-flight rockets. The LLCC consist of 11 major rules (Table-1). Each one of these rules has its own subset of requirements, which are detailed in Appendix-1 and Appendix-2.

Table 1. List of Lightning Launch Commit Criteria.

1. Lightning
2. Cumulus Clouds *
3. Attached Anvil Clouds
4. Detached Anvil Clouds
5. Debris Clouds
6. Disturbed Weather
7. Thick Cloud Layers
8. Smoke Plumes
9. Surface Electric Fields
~~10. Electric Fields Aloft~~ *(removed due to lack of electric field profiles)*
10. Triboelectrification
11. "Good Sense" Rule (suspected triggered lightning threat, not explicitly listed in other LLCC)

* A variation of the Cumulus Clouds LLCC for orographic cumulus exists for use only at Kodiak Space Launch Complex in Alaska.

The LLCC are complex and require intensively trained meteorologists to evaluate them under operational conditions. Most of the LLCC are for rocket triggered lightning. Rocket triggered lightning is lightning caused by the rocket itself. There are many atmospheric phenomena that generate increased electric fields that are not large enough to generate natural lightning. However, an in-flight rocket amplifies an ambient electric field, primarily from its long hot ionized exhaust plume. In the case of a large rocket, such as a space launch vehicle, that amplification can be a factor of 100 or more. If the ambient electric field is large enough and the amplification is large enough, the

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breakdown voltage of air is reached and triggered lightning may result. Rocket triggered lightning tends to strike the leading tip of the rocket, travel along and/or into the rocket and then follow the exhaust plume toward the surface. An example of a triggered lightning strike is shown in Figure-1. This lightning strike was triggered by the Atlas/Centaur-67 shortly after launch from CCAFS on 26 Mar 1987 and led to the destruction of the space launch vehicle and payload. This event led to a complete overhaul of the lightning rules and began the "modern" era of LLCC, much of which persists in the 2009 update. Since that time, no space launch using the LLCC has resulted in a triggered lightning. This event also led to the formation of the Lightning Advisory Panel (LAP), which provides independent expert recommendations on LLCC changes. The LAP consists of atmospheric electricity and other experts from university, government, and commercial agencies (Table-2).

One of the primary reasons for the LLCC is to avoid compromising the in-flight termination system of a rocket. The in-flight termination system allows the rocket to be destroyed in case it goes off course and possibly endangers off-base people and resources. The LLCC also avoid lightning that could damage the space launch vehicle and payload. All space launches under USAF, NASA, and FAA governance must follow the same LLCC.

The LLCC as of 2005, their history, and the weather sensors used to evaluate the LLCC were described in Roeder and McNamara (2006). Most of the LLCC upgrades in 2005 were based upon analysis of the data collected from the ABFM-II of 2002-2001 (Dye et al., 2007). The LLCC improvements from the ABFM-II included redefining the radar edge of anvil cloud from 10 dBZ to 0 dBZ for improved safety, and the addition of the Volume Averaged Height Integrated Radar Reflectivity (VAHIRR) criteria to identify new safe anvil cloud conditions to reduce unnecessary launch scrubs.

3. The 2009 Lightning Launch Commit Criteria

The 2009 updates to the LLCC are summarized in Table-3. Three of the LLCC were significantly improved in the 2009 upgrade: 1) Attached Anvil Clouds, 2) Detached Anvil Clouds, and 3) Debris Clouds. In addition, a fourth LLCC was removed, the Electric Field Aloft rule. Table-3 is only a brief summary of the changes to in the 2009 LLCC. Appendix-1 provides the complete LLCC, which requires Appendix-2 for a complete understanding. These changes were based on continued analysis of the data collected under ABFM-II (Dye et al., 2007). A specialized set of definitions, explanations, and examples are mandatory to the operational evaluation and understanding of the LLCC. Some of the definitions are non-standard in meteorology and have a special meaning in the LLCC context. These definitions, explanations, and examples are listed in Appendix-2. This paper and its appendices are **not** for operational use. The LLCC are continuously reviewed for improvements, so the LLCC may have changed since this paper was written in Jan 10.

Figure 1. Triggered lightning strike to the in-flight Atlas/Centaur-67 mission on 26 Mar 87. Shown here is the triggered lightning following the exhaust plume to the ground at the launch pad. The space launch vehicle and payload were destroyed as a result of this triggered lightning.

Table-2. Lightning Advisory Panel members.

Member	Affiliation
Dr. Krider (chair)	University of Arizona
Dr. Christian	University Alabama/Huntsville
Dr. Dye	National Center for Atmospheric Research, NOAA
Dr. O'Brien	Aerospace Corporation
Dr. Rust	National Severe Storms Laboratory, NOAA
Dr. Waltersheid	Aerospace Corporation
Dr. Willet	Private Consulting Meteorologist

Table-3. Quick reference for the 2009 LLCC. Major changes for 2009 are highlighted in blue. Some details of criteria are omitted for brevity's sake. See Appendix-1 and Appendix-2 for full details.

No.	Name	**Avoid** launch if . . .
1	Surface Electric Fields	≥ /1000/ V/m, ≤ 5 nmi, ≤ 15 min unless . . . (see Appendix-1 and Appendix-2)
2	Lightning	Lightning or thunderstorm cloud producing lightning ≤ 10 nmi, ≤ 30 min unless . . . (see Appendix-1 and Appendix-2)
3	Cumulus Clouds *	• Cloud tops ≤ -20°C, ≤ 10 nmi • Cloud tops ≤ -10°C, ≤ 5 nmi • Cloud tops ≤ -5°C, ≤ 0 nmi unless . . . (see Appendix-1 and Appendix-2)
4	Attached Anvil Clouds	• ≤ 10 nmi to > 5 nmi, ≤ 30 min since lightning, unless anvil w/in 10 nmi ≤ 0°C • ≤ 5 nmi to > 3 nmi, ≤ 3 hr since lightning, unless anvil within 5 nmi ≤ 0°C • ≤ 3 nmi, unless anvil within 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria met
5	Detached Anvil Clouds	• ≤ 10 nmi to > 3 nmi, ≤ 30 min since lightning, unless anvil within 10 nmi ≤ 0°C • ≥ 0 nmi to ≤ 3 nmi, ≤ 30 min since lightning, unless anvil within 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria met • ≥ 0 nmi to ≤ 3 nmi, > 30 min to ≤ 3 hr since lightning, unless field mill and radar criteria met or anvil within 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria met • Through, unless ≥ 4 hr since lightning and ≥ 3 hr since detachment or anvil within 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria met
6	Debris Clouds	• ≥ 0 nmi to ≤ 3 nmi, ≤ 3 hr since detach/form, unless a radar criteria and a field mill criteria met or debris within 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria • Through, unless debris ≤ 5 nmi ≤ 0°C and VAHIRR/VAHIRR application criteria met
7	Disturbed Weather	Through (see Appendix-1 and Appendix-2 for details)
8	Thick Cloud Layers	Through, ≥ 4500 ft thick with parts ≤ 0°C to ≥ -20°C, or connected to thick cloud layer within 5 nmi
9	Smoke Plumes	Through cumulus formed from smoke plume or ≤ 60 min detach
N/A	Electric Field Aloft	Removed
10	Triboelectrification	Through any cloud, ≤ -10°C, velocity ≤ 3000 ft/sec, unless treated or tested/analyzed
11	Good Sense	Notify Launch Decision Authority if risk of triggered lightning not otherwise covered is suspected

* A variation of the Cumulus Clouds LLCC for orographic cumulus exists for use only at Kodiak Space Launch Complex in Alaska. This orographic cumulus rule allows closer approach to the cloud under some conditions.

3.1 Changes To Attached Anvil Clouds LLCC

The Attached Anvil Cloud LLCC was modified to allow closer and/or sooner approach to the cloud under some conditions. This was based in part on the analysis of electric fields as a function of distance from anvil cloud (Merceret et al., 2008) and in part on further analysis of the ABFM-II data (Dye at al., 2007). A new stand-off distance of 3 nmi was added, sometimes replacing 5 nmi. In addition, a new safe condition for anvil clouds was added. Launch within various new distances of anvil clouds is now allowed under some conditions if those clouds are colder than 0°C. A comparison of the new rule to the old rule is provided in Table-4.

3.2 Changes To Detached Anvil Clouds LLCC

The modifications to the Detached Anvil Cloud LLCC were very similar to those made to the Attached Anvil LLCC discussed in section-3.1. A comparison of the new rule to the old rule is provided in Table-5.

3.3 Changes To Debris Cloud LLCC

The Debris Cloud LLCC was modified to allow closer and/or sooner approach to the cloud under some conditions. This was based on further analysis of the ABFM-II data (Dye at al., 2007). A new stand-off distance of 3 nmi was added under some field mill and radar conditions. In addition, launch within 5 nmi is now allowed if the debris cloud is colder than 0°C and the VAHIRR and VAHIRR application criteria are met. A comparison of the new rule to the old rule is provided in Table-6.

3.4 Changes To Electric Field Aloft LLCC

The Electric Field Aloft rule was removed from the LLCC. This was done since there is no practical way to evaluate this rule operationally. The electric fields along the entire flight path must be known instantaneously to evaluate this rule. The only known technology to measure electric fields aloft under all weather conditions, including clear air, is airborne electric field mills. Unfortunately, airborne field mills require extensive maintenance and calibration to be useful for LLCC evaluation making use of airborne field mills very expensive. In addition, electric fields aloft can vary rapidly horizontally, vertically, and temporally, especially in and around thunderstorm, anvil, and debris clouds. Thus, a large fleet of airborne field mill equipped aircraft would be required to evaluate the electric fields along the flight path adequately with the required spatio-temporal resolution for LLCC evaluation. This fleet of aircraft would be excessively expensive and logistically untenable. Finally, all support aircraft have to go to a safety point about 10 nmi from the flight path about 12 min before takeoff to avoid endangering the space launch vehicle and aircraft. As a result, the electric fields last measured by the airborne field mills would no longer be representative for the flight path under many weather conditions. This rule has been removed from the LLCC; the previous rule is provided for comparison in Table-7.

3.5 Other Changes To The LLCC

Other changes to the LLCC include listing the Surface Electric Field LLCC first to emphasize the importance of surface electric field mills to both launch safety and increased launch opportunity. In addition, a procedure to evaluate the LLCC when multiple rules might apply to the same weather phenomena was added. Sometimes two or more LLCC might apply. This is especially true for remnants from thunderstorms which can sometimes reasonably be classified as either debris cloud or detached anvil cloud. The common practice at 45 WS is to evaluate all LLCC that might apply and use the safest most conservative of those evaluations, i.e. if any of the possible LLCC is 'red' then the overall evaluation is 'red'. This practice was codified into the new LLCC for the benefit of new launch weather officers at 45 WS and other space launch ranges, especially the commercial space launch ranges being developed under regulatory control of the FAA.

Several changes were made to the LLCC definitions. In particular, the anvil cloud definition was changed to require the upper outflow or blow-off to come from convective clouds reaching -10°C or colder to be classified as anvil. This will prevent anvil-like clouds from warmer, insufficiently electrified clouds from needlessly stopping space launch. The VAHIRR application criteria were moved to the definitions to avoid repetition of the same complex verbiage in many LLCC and to make evaluation of the LLCC easier. The definitions clarified that anvil cloud is not part of the parent thunderstorm for use in calculating the distance from thunderstorm in the LLCC.

Table-4. Comparison of the 2009 Attached Anvil Cloud LLCC to the previous LLCC.
The major changes are highlighted in blue.

ATTACHED ANVIL CLOUDS Do not launch under the following conditions unless 'no constraint' is specified		
Standoff Distance	2009 LLCC	Previous LLCC
> 10 nmi	No constraint	No constraint
≤ 10 nmi	≤ 30 min since last lightning in attached anvil cloud or parent cloud * or No constraint if anvil cloud ≤ 10 nmi of flight path is < 0°C	≤ 30 min since last lightning in attached anvil cloud or parent cloud
≤ 5 nmi	≤ 3 Hr since last lightning in attached anvil cloud or parent cloud * or No constraint if anvil cloud ≤ 5 nmi of flight path is < 0°C	≤ 3 Hr since last lightning in attached anvil cloud or parent cloud or No constraint if VAHIRR and VAHIRR application criteria met along flight path for > 30 min
≤ 3 nmi	Any Time or No constraint if anvil cloud ≤ 5 nmi of flight path is < 0°C and VAHIRR ≤ 1 nmi of flight path is met and VAHIRR application criteria is met	N/A *(3 nmi constraint changed from 5 nmi, see next block above)*
Through	Included in new ≤ 3 nm, see block above	Any Time or No constraint if ≥ 3 Hours since last lightning with VAHIRR Met Along Flight Path

* If no lightning in the cloud or its parent cloud, then the criteria is satisfied
FMs = all surface electric field mills

Table-5. Comparison of the 2009 Detached Anvil Cloud LLCC to the previous LLCC.
The major changes are highlighted in blue.

DETACHED ANVIL CLOUDS Do not launch under the following conditions unless 'no constraint' is specified		
Standoff Distance	2009 LLCC	Previous LLCC
> 10 nmi	No constraint	No constraint
≤ 10 nmi	≤ 30 min since last lightning in anvil cloud or parent cloud before detachment or No constraint if anvil cloud ≤ 10 nmi of flight path is < 0°C	≤ 30 min since last lightning in detached anvil cloud or parent cloud before detachment
≤ 5 nmi	N/A *(5 nmi constraint changed to 3 nmi, see next block below)*	≤ 3 hr since last lightning in detached anvil cloud or parent cloud before detachment or No constraint if VAHIRR and VAHIRR application criteria met along flight path for > 30 min or FMs w/in 5 nmi < |1000| V/m for ≥ 15 min and Max reflectivity of anvil cloud ≤ 5 nmi of flight path < 10 dBZ for ≥ 15 Minutes
≤ 3 nmi	≤ 30 min since last lightning in anvil cloud or parent cloud before detachment * or No constraint if anvil within ≤ 5 nmi is < 0°C and VAHIRR ≤ 1 nmi of flight path is met and VAHIRR application criteria is met	N/A *(3 nmi constraint changed from 5 nmi, see next block above)*
≤ 3 nmi	> 30 min to ≤ 3 hr since last lightning in anvil cloud or parent cloud before detachment or No constraints if FMs < 5 nmi of anvil cloud and FMs ≤ 5 nmi of flight path all < |1000| V/m for ≥ 15 min and Max reflectivity of anvil cloud ≤ 5 nmi of flight path < 10 dBZ for ≥ 15 Minutes or anvil within ≤ 5 nmi is < 0°C and VAHIRR ≤ 1 nmi of flight path is met and VAHIRR application criteria is met	
Through	≤ 4 hr since lightning in anvil cloud after detachment * or ≤ 3 hr after detachment or No constraint if Anvil cloud ≤ 5 nmi of flight path < 0°C and VAHIRR along flight path is met and VAHIRR criteria is met	≤ 4 hr if lightning in anvil cloud after detachment or ≤ 3 hr after detachment or Any time VAHIRR along flight path and VAHIRR criteria are met not met > 30 min

* If no lightning in the cloud or its parent cloud, then the criteria is satisfied
FMs = all surface electric field mills

Table-6. Comparison of the 2009 Debris Cloud LLCC to the previous LLCC.
The major changes are highlighted in blue.

DEBRIS CLOUDS Do not launch under the following conditions unless 'no constraint' is specified		
Standoff Distance	2009 LLCC	Previous LLCC
> 5 nmi	No launch constraints	No launch constraints
≤ 5 nmi	No launch constraints *(5 nmi constraint changed to 3 nmi, see next block below)*	Do not launch if ≤ 3 hr since detachment or ≤ 3 hr since decay of parent cloud to debris cloud top > -10°C unless FMs* w/in 5 nmi < |1000| V/m for ≥ 15 min
≤ 3 nmi	Do not launch if ≤ 3 hr since detachment or ≤ 3 hr since decay of parent cloud to debris cloud top > -10°C or No constraint after detachment or decay of parent cloud to debris cloud top > -10°C if FMs < 5 nmi of debris cloud and FMs ≤ 5 nmi of flight path all < |1000| V/m for ≥ 15 min and Max reflectivity of debris cloud ≤ 5 nmi of flight path < 10 dBZ for ≥ 15 Minutes or No constraint after detachment or decay of parent cloud to debris cloud top > -10°C if Debris cloud ≤ 5nm of flight path < 0°C and VAHIRR ≤ 1 nmi of flight path is met and VAHIRR application criteria are met	N/A *(3 nmi constraint changed from 5 nmi, see next block above)*
Through	Do not launch if ≤ 3 hr since detachment or ≤ 3 hr since decay of parent cloud to debris cloud top > -10°C or No constraint after detachment or decay of parent cloud to debris cloud top > -10°C if Debris cloud ≤ 5nm of flight path < 0°C and VAHIRR ≤ 1 nmi of flight path is met and VAHIRR application criteria are met	Do not launch if ≤ 3 hr since detachment or ≤ 3 hr since decay of parent cloud to debris cloud top > -10°C

FMs = all surface electric field mills

Table-7. Comparison of the 2009 Detached Anvil Cloud LLCC to the previous LLCC. The major changes are highlighted in blue.

ELECTRIC FILED ALOFT Do not launch under the following conditions unless 'no constraint' is specified		
Standoff Distance	2009 LLCC	Previous LLCC
N/A	Removed	If the instantaneous electric field along the flight path ≤ $E_{critcal}$ for ≥ 15 min, where $E_{critical}$ is a specified function of altitude, then the following LLCC need not apply: Attached Anvil Clouds, Detached Anvil Clouds, Debris Clouds, Disturbed Weather, Thick Cloud Layers, Smoke Plumes, and Surface Electric Fields

4. On-going Improvements

The development of a LLCC climatology for CCAFS/KSC and sensitivity analysis is being developed by the Naval Postgraduate School. The climatology will provide the probability of violating each LLCC and the probability of violating any LLCC diurnally and seasonally. This will be useful in mission planning, launch forecasting with a lead-time of a few days or more, and in planning future LLCC research. The sensitivity analysis will identify the LLCC that will provide the largest gains in launch opportunity for the smallest change in rule thresholds. Those LLCC might provide the most cost-effective change in the future.

The LAP is documenting the history and rationale of the LLCC. This will be useful in training and during countdowns, especially to ensure all launch related personnel understand the purpose and importance of the LLCC to mission assurance and launch safety.

5. Future Improvements

Several improvements to the LLCC are desired for the future.

5.1 Improve 'Thick Cloud' LLCC

First, the Thick Cloud rule is known to always warn of triggered lightning potential but has a false alarm rate much higher than 80% (Roeder and McNamara, 2006) (ABFM-I, 1992a) (ABFM-I, 1992b) and is a frequent source of scrubs or delays to space launch. Therefore, a third ABFM experiment, focusing on improving the Thick Cloud rule, would likely yield operationally important improvements. The Thick Cloud rule was one of the two focuses of ABFM-II, along with anvil clouds, but a drought during the experiment precluded collecting data on thick clouds despite being scheduled during a climatologically conducive time.

5.2 Automated VAHIRR Radar Product

The VAHIRR criterion for anvil and debris clouds is currently being evaluated with a manual work-around that overestimates the actual VAHIRR value (Merceret et al., 2006). As a result, the full amount of increased launch opportunity from VAHIRR is not being realized. A radar product to evaluate VAHIRR exactly would provide the full benefits of VAHIRR. However, VAHIRR is a complex calculation that is difficult to estimate manually, especially under time pressures of real-time operations. The launch weather officers would have to trust the VAHIRR radar product absolutely. As a result, any VAHIRR product would have to be tested extremely well (Barrett et al., 2008) to ensure it can be trusted for space launch safety.

5.3 Dual Polarization Radar LLCC

The 45 WS is acquiring a dual polarization weather radar (Roeder et al., 2009). Such radar may be able to infer electric fields aloft (Carey et al., 2009) well enough under some conditions to be used in a new LLCC. Extensive work would be needed to develop such a new LLCC, including a third ABFM experiment.

5.4 Radar/Lightning Studies Of Attached And Detached Anvil Clouds And Thunderstorms

Specialized lightning climatology studies could also help improve the LLCC. These studies would have to use lightning sensors that detect all lightning, especially intra-cloud and other types of lightning aloft, such as the Four Dimensional Lightning Surveillance System that serves CCAFS/KSC (Murphy et al., 2008). The frequency distribution of lightning distance outside of the cloud edge of thunderstorms would be useful for refining the 10 nmi stand-off distance in the Lightning rule. The distribution of flash distances

from the edge of attached and detached anvil clouds would also be useful. These distributions could be done as a function of downrange distance and age or time since detachment. Likewise the distribution of lightning flashes versus time in detached anvil clouds would be useful. The time evolution of VAHIRR in attached anvil, detached anvil, and debris cloud, and reflectivity in detached anvil would be useful, as would the frequency that either attached and/or detached anvil cloud reaches 0°C or warmer. The frequency that the first lightning forms in or travels into anvil cloud and distance distribution and time since first flash when lightning does form in or enters the anvil would also be useful.

5.5 Surface Electric Field Mill Studies

Other useful studies include the frequency of surface electric field above 1,500 V/m in fog and other weather conditions when electrifying clouds within 10 nmi are not observed. In addition, a tool to infer the probability of LLCC violation from computer forecast models could be used in mission forecasts, which begin several days before countdown.

5.6 Refined 'Disturbed Weather' LLCC Definition

A refined definition of 'associated' in the Disturbed Weather LLCC is desired along with further clarifying examples.

5.7 Remote All Weather Electric Field Profiling

Finally, a method to detect the electric field along the flight path under all weather conditions would be very useful. This would allow reinstating the Electric Field Aloft and relaxing several LLCC (Table-6). Unfortunately, to do this under operational conditions would likely require remote sensing of the electric fields and the technology to do this is not available and would likely require basic science research to develop. Although highly desired, there is little hope this will be developed in the foreseeable future.

6. Summary

The 2009 update to the LLCC were presented. This update increased launch opportunity while maintaining safety. The major changes were to the rules for attached anvil clouds, detached anvil clouds, and debris clouds. The addition of anvil cloud being colder than 0°C within various distances of the flight path now allows closer approach to those clouds under some conditions. The debris cloud rule now includes the radar VAHIRR criteria. The phrasing of the LLCC and supporting definitions were refined for easier use under operational conditions and easier training.

7. Acknowledgements

The LLCC could not have achieved their current state of excellence without the many years of selfless dedication of the Lightning Advisory Panel. This paper was reviewed by Mr. John Madura, Chief KSC Weather Office.

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APPENDIX-1

The 2009 Lightning Launch Commit Criteria

The LLCC listed here are **NOT** for operational use. The LLCC are continuously reviewed for improvements and may have changed from the time this paper was written in Jan 10.

These LLCC are written in the format preferred by the FAA. USAF and NASA customers use different words from those used by FAA, e.g. FAA uses the word 'flight path' while USAF and NASA use 'launch path'. However, the technical content, such as standoff distances and wait times are the same.

A word or phrase highlighted in quote marks is defined in Appendix-2. These definitions are essential for proper operational evaluation and understanding of the LLCC. Many of these definitions are nonstandard and are specialized for LLCC use.

A-1.1 General Principles

Each of the LLCC requires clear and convincing evidence to trained weather personnel that its constraints are not violated. A launch operator must not initiate flight unless the constraints of all LLCC are satisfied. Whenever there is ambiguity about which of several LLCC applies to a particular situation, all potentially applicable LLCC must be applied. Under some conditions trained weather personnel can make a clear and convincing determination that the LLCC are not violated based on visual observations alone. However, if the weather personnel have access to additional information such as measurements from weather radar, lightning sensors, electric "field mills," and/or aircraft, this information can be used to increase both safety and launch availability. If the additional information is within the criteria outlined in the LLCC, it would allow a launch to take place where a visual observation alone would not.

The launch operator must employ:

(1) Any weather monitoring and measuring equipment needed to satisfy the lightning flight commit criteria.

(2) Any procedures needed to satisfy the lightning flight commit criteria.

If a launch operator proposes any alternative lightning flight commit criteria, the launch operator must clearly and convincingly demonstrate that the alternative provides an equivalent level of safety.

A-1.2 Surface Electric Fields LLCC

(a) A launch operator must not initiate flight for 15 minutes after the absolute value of any "electric field measurement" less than or equal to 5 nautical miles from the "flight path" has been greater than or equal to 1500 volts/meter.

(b) A launch operator must not initiate flight for 15 minutes after the absolute value of any "electric field measurement" less than or equal to 5 nautical miles from the "flight path" has been greater than or equal to 1000 volts/meter unless either Section 1 or Section 2 is satisfied:

(1) All clouds less than or equal to 10 nautical miles from the "flight path" are "*transparent*;" or

(2) All "clouds" less than or equal to 10 nautical miles from the "flight path" have "cloud

tops" at altitudes where the temperature is warmer than +5 degrees Celsius and have not been part of convective "clouds" with "cloud tops" at altitudes where the temperature is colder than or equal to −10 degrees Celsius during the last 3 hours.

A-1.3 Lightning LLCC

(a) A launch operator must not initiate flight for 30 minutes after any type of lightning occurs in a "thunderstorm" if the "flight path" will carry the launch vehicle less than or equal to 10 nautical miles from that "thunderstorm." An attached "anvil cloud" is not considered part of its parent "thunderstorm," but is covered instead by the Attached "Anvil Clouds" LLCC.

(b) A launch operator must not initiate flight for 30 minutes after any type of lightning occurs less than or equal to 10 nautical miles from the "flight path" unless all three of the following conditions are satisfied:

(1) The "cloud" that produced the lightning is greater than10 nautical miles from the "flight path;"

(2) There is at least one working "field mill" less than 5 nautical miles from each such lightning discharge; and

(3) The absolute values of all "electric field measurements" less than or equal to 5 nautical miles from the "flight path," and at each "field mill" specified in paragraph (b)(2) of this section, have been less than 1000 volts/meter for 15 minutes or longer.

A-1.4 Cumulus "Clouds" LLCC

For the purposes of this LLCC, "cumulus 'clouds'" do not include cirrocumulus, altocumulus, or stratocumulus "clouds." An attached "anvil cloud" is never considered part of its parent cumulus "cloud," but is covered instead by the Attached "Anvil Clouds" LLCC. Detached "Anvil Clouds" applies to any detached "anvil cloud." "Debris Clouds," applies to "debris clouds."

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 10 nautical miles from any cumulus "cloud" that has a "cloud top" at an altitude where the temperature is colder than or equal to -20 degrees Celsius.

(b) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 5 nautical miles from any cumulus "cloud" that has a "cloud top" at an altitude where the temperature is colder than or equal to -10 degrees Celsius.

(c) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through any cumulus "cloud" with its "cloud top" at an altitude where the temperature is colder than or equal to -5 degrees Celsius.

(d) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through any cumulus "cloud" that has a "cloud top" at an altitude where the temperature lies in the range from warmer than -5 degrees Celsius to colder than or equal to +5 degrees Celsius unless all three of the following conditions are satisfied:

(1) The "cloud" is not producing "precipitation;"

(2) The distance from the center of the "cloud top" to at least one working "field mill" is less than 2 nautical miles; and

(3) All "electric field measurements" less than or equal to 5 nautical miles from the "flight path," and at each "field mill" specified in paragraph (d)(2) of this section, have been greater than −100 volts/meter, but less than +500 volts/meter, for 15 minutes or longer.

A-1.5 Attached "Anvil Clouds" LLCC

For the purposes of this LLCC, if there has never been lightning in or from the parent "cloud" or "anvil cloud," sub-sections (a) and (b) shall be considered satisfied, but sub-section (c) shall still apply.

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 10, but greater than 5, nautical miles from any attached "anvil cloud" for the first 30 minutes after the last lightning discharge in or from the parent "cloud" or "anvil cloud" unless the portion of the attached "anvil cloud" less than or equal to 10 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius.

(b) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 5, but greater than 3, nautical miles from any attached "anvil cloud" for the first three hours after the last lightning discharge in or from the parent "cloud" or "anvil cloud" unless the portion of the attached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius.

(c) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 3 nautical miles from any attached "anvil cloud" unless all three of the following conditions are satisfied:

(1) The portion of the attached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where

the temperature is colder than 0 degrees Celsius;

(2) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) at every point less than or equal to 1 nautical mile from the "flight path;" and

(3) All of the "VAHIRR application criteria" are satisfied.

A-1.6 Detached "Anvil Clouds" LLCC

For the purposes of this LLCC, detached "anvil clouds" are never considered "debris clouds."

For the purposes of this LLCC, if there has never been lightning in or from the parent "cloud" or "anvil cloud," sub-sections (a), (b), (c), and (d)(1)(i) shall be considered satisfied, but sub-sections (d)(1)(ii), and (d)(2), shall still apply.

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle less than or equal to 10, but greater than 3, nautical miles from a detached "anvil cloud" for the first 30 minutes after the last lightning discharge in or from the parent "cloud" or "anvil cloud" before detachment or after the last lightning discharge in or from the detached "anvil cloud" after detachment unless the portion of the detached "anvil cloud" less than or equal to 10 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius.

(b) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle between 0 (zero) and 3 nautical miles, inclusive, from a detached "anvil cloud" for the first 30 minutes after the time of the last lightning discharge in or from the parent "cloud" or "anvil cloud" before detachment or after the last lightning discharge in or from the detached "anvil cloud" after detachment unless all three of the following conditions are met:

(1) The portion of the detached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius;

(2) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) at every point less than or equal to 1 nautical mile from the "flight path;" and

(3) All of the "VAHIRR application criteria" are satisfied.

(c) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle between 0 (zero) and 3 nautical miles, inclusive, from a detached "anvil cloud" less than or equal to 3 hours, but greater than 30 minutes, after the time of the last lightning discharge in or from the parent "cloud" or "anvil cloud" before detachment or after the last lightning discharge in or from the detached "anvil cloud" after detachment unless Section (1) or Section (2) is satisfied:

(1) This section is satisfied if all three of the following conditions are met:

(i) There is at least one working "field mill" less than 5 nautical miles from the detached "anvil cloud;"

(ii) The absolute values of all "electric field measurements" less than or equal to 5 nautical miles from the "flight path," and at each "field mill" specified in paragraph (c)(1)(i) of this section, have been less than 1000 V/m for 15 minutes; and

(iii) The maximum radar reflectivity from any part of the detached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" has been less than +10 dBZ for 15 minutes.

(2) This section is satisfied if all three of the following conditions are met:

(i) The portion of the detached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius;

(ii) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) at every point less than or equal to 1 nautical mile from the "flight path;" and

(iii) All of the "VAHIRR application criteria" are satisfied.

(d) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through a detached "anvil cloud" unless Section (1) or Section (2) is satisfied

(1) This section is satisfied if both of the following conditions are met.

(i) At least 4 hours have passed since the last lightning discharge in or from the detached "anvil cloud;" and

(ii) At least 3 hours have passed since the time that the "anvil cloud" is observed to be detached from the parent "cloud."

(2) This section is satisfied if all three of the following conditions are met.

(i) The portion of the detached "anvil cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius;

(ii) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) everywhere along the "flight path;" and

(iii) All of the "VAHIRR application criteria" are satisfied.

A-1.7 "Debris Clouds" LLCC

The 3-hour time period defined in this Section must begin again at the time of any lightning discharge in or from the "debris cloud."

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle between 0 and 3 nautical miles, inclusive, from a "debris cloud" for 3 hours after the "debris cloud" is observed to be detached from the parent "cloud," or after the "debris cloud" is observed to have formed by the collapse of the parent "cloud top" to an altitude where the temperature is warmer than −10 degrees Celsius unless Section (1) or Section (2) is satisfied:

(1) This section is satisfied if all three of the following conditions are met:

(i) There is at least one working "field mill" less than 5 nautical miles from the "debris cloud;"

(ii) The absolute values of all "electric field measurements" less than or equal to 5 nautical miles from the "flight path" and at each "field mill" employed by paragraph (a)(1)(i) of this section has been less than 1000 volts/meter for 15 minutes or longer; and

(iii) The maximum radar reflectivity from any part of the "debris cloud" less than or equal to 5 nautical miles from the "flight path" has been less than +10 dBZ for 15 minutes or longer.

(2) This section is satisfied if all three of the following conditions are met:

(i) The portion of the "debris cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius;

(ii) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) at every point less than or equal to 1 nautical mile from the "flight path;" and

(iii) All of the "VAHIRR application criteria" are satisfied.

(b) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through any "debris cloud" during the 3-hour period defined in paragraph (a) of this section, unless all three of the following conditions are met:

(1) The portion of the "debris cloud" less than or equal to 5 nautical miles from the "flight path" is located entirely at altitudes where the temperature is colder than 0 degrees Celsius;

(2) The "volume-averaged, height-integrated radar reflectivity" is less than +10 dBZ-km (+33 dBZ-kft) everywhere along the "flight path;" and

(3) All of the "VAHIRR application criteria" are satisfied.

A-1.8 "Disturbed Weather" LLCC

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through a "cloud" "associated" with "disturbed weather" that has "clouds" with "cloud tops" at altitudes where the temperature is colder than or equal to 0 degrees Celsius and that contains, less than or equal to 5-nautical miles from the "flight path," either:

(1) "Moderate precipitation" or greater; or

(2) Evidence of melting "precipitation" such as a radar "bright band."

A-1.9 "Thick Cloud Layers" LLCC

For the purposes of this section neither attached nor detached "anvil clouds" are considered "thick cloud layers."

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through a "cloud layer" that is either:

(1) Greater than or equal to 4,500 feet thick and any part of the "cloud layer" along the "flight path" is located at an altitude where the temperature is between 0 degrees Celsius and −20 degrees Celsius, inclusive; or

(2) Connected to a "thick cloud layer" that, less than or equal to 5 nautical miles from the "flight path," is greater than or equal to 4,500 feet thick and has any part located at an altitude where the temperature is between 0 degrees Celsius and −20 degrees Celsius, inclusive.

(b) A launch operator need not apply the lightning commit criteria in paragraphs (a)(1) and (a)(2) of this section if the "thick cloud layer" is a cirriform "cloud layer" that has never been "associated" with convective "clouds," is located entirely at altitudes where the temperature is colder than or equal to −15 degrees Celsius, and shows no evidence of containing liquid water.

A-1.10 Smoke Plumes LLCC

(a) A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through any cumulus "cloud" that has developed from a smoke plume while the "cloud" is attached to the smoke plume, or for the first 60 minutes after the cumulus "cloud" is observed to be detached from the smoke plume.

(b) Section E, Cumulus "Clouds," applies to cumulus "clouds" that have formed above a fire but have been detached from the smoke plume for more than 60 minutes.

A-1.11 "Tribolelectrification" LLCC

A launch operator must not initiate flight if the "flight path" will carry the launch vehicle through any part of a cloud, *specifically including all "transparent" parts*, at any altitude where both Section (a) and Section (b) are satisfied:

(a) The temperature is colder than or equal to −10 degrees Celsius; and

(b) The launch vehicle's velocity is less than or equal to 3000 feet/second;

unless Section (1) or Section (2) is satisfied:

(1) The launch vehicle is "treated" for surface electrification; or

(2) A launch operator has previously demonstrated by test or analysis that electrostatic discharges on the surface of the launch vehicle caused by "triboelectrification" will not be hazardous to the launch vehicle or the spacecraft.

A-1.12 Good Sense LLCC

While not a separate rule, the LLCC require a launch operator to inform the Launch Decision Authority if any atmospheric conditions not covered in the other LLCC might present a lightning risk to the in-flight rocket. This guideline is to allow for previously unrecognized phenomena that might be a lightning hazard.

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APPENDIX-2

Definitions, Explanations, And Examples

The definitions listed here are **NOT** for operational use. The LLCC and their definitions are continuously reviewed for improvements and may have changed from the time this paper was written in Jan 10.

For the purpose of this appendix, distance from an electric "field mill" is measured differently than distance from any other object or measurement point: Distance between a "radar reflectivity" or "Volume Averaged Height Integrated Radar Reflectivity" ("VAHIRR") measurement point and any object or the "flight path" is the *shortest separation* (horizontal, vertical, or slant range) between that point and the *nearest part* of the object or "flight path." Similarly, distance between the "flight path" and any object is the *shortest separation* between any point on the "flight path" the *nearest part* of that object. For example, "every point less than or equal to 1 nautical mile from the 'flight path'" (see Attached "Anvil Clouds" LLCC) means that the "VAHIRR" threshold must be satisfied at every point throughout the entire volume defined by a 1 nautical mile radius from every point on the "flight path." (See also the additional explanation beneath the definition of "cloud.") In contrast, distance between a "field mill" or an "electric field measurement" and any object or the "flight path" is always measured *horizontally* between that mill or measurement point and the nearest part of the *vertical projection* of the object or "flight path" onto the surface of Earth. For example, "from the center of the 'cloud top' to at least one working 'field mill'" (see Cumulus "Clouds") means that the *horizontal* distance between the "field mill" and a point on the surface directly beneath the center of the "cloud top" must be less than 2 nautical miles.

The following terms are defined here and appear in quotes wherever they are used in accordance with these definitions elsewhere in this appendix.

Anvil Cloud: a stratiform or fibrous "cloud" produced by the upper outflow or blow-off from "thunderstorms" or convective "clouds" having tops at altitudes where the temperature is colder than or equal to -10 degrees Celsius.

Associated: two or more "clouds" are causally related to the same "disturbed weather" system or are physically connected. "Clouds" occurring at the same time are not necessarily "associated." A cumulus "cloud" formed locally and a cirrus layer that is physically separated from that cumulus "cloud" and that is generated by a distant source are not "associated," even if they occur over or near the launch point at the same time.

Average Cloud Thickness: the altitude difference (in kilometers, km hereafter) between the average top and the average base of all clouds in the "specified volume." The cloud base to be averaged is the higher of (1) the 0 degree Celsius level and (2) the lowest extent (in altitude) of all "radar reflectivity" measurements of 0 dBZ or greater. Similarly, the cloud top to be averaged is the highest extent (in altitude) of all "radar reflectivity" measurements of 0 dBZ or greater. Given the grid-point representation of a typical radar processor, allowance must be made for the vertical separation of grid points in computing "average cloud thickness". The cloud base at any horizontal position shall be taken as the altitude of the corresponding base grid point minus half of the grid-point vertical separation. Similarly, the cloud top at that horizontal position shall be taken as the altitude of the corresponding top grid point plus half of this vertical separation. Thus, a cloud

represented by only a single grid point having a "radar reflectivity" equal to or greater than 0 dBZ in the "specified volume" would have an "average cloud thickness" equal to the vertical grid-point separation in its vicinity.

Bright Band: an enhancement of "radar reflectivity" caused by frozen hydrometeors falling and beginning to melt at any altitude where the temperature is 0 degrees Celsius or warmer.

Cloud: a visible mass of suspended water droplets or ice crystals. The "cloud" is considered to be the entire volume enclosed by the visible, "nontransparent cloud" boundary as seen by an observer, or, in the absence of a visual observation, by the 0 dBZ "radar reflectivity" boundary. A visual evaluation of transparency is preferred whenever possible.

Distance: the distance from the "cloud" to a point in question refers to the separation between the point and the nearest part of that "cloud." Specifically, the wording, "less than or equal to 10 nautical miles from any cumulus 'cloud'" means that the "flight path" must not penetrate either the *interior* of the "cloud" itself or the volume between 0 and 10 nautical miles, inclusive, *outside* the "cloud" boundary. On the other hand, "between 0 and 3 nautical miles, inclusive, from" refers *only* to the volume at a distance that is greater than or equal to 0, but less than or equal to 3, nautical miles *outside* the "cloud" boundary, specifically omitting the interior of the "cloud" itself, such as in the "Debris Clouds" LLCC.

Cloud Layer: a vertically continuous array of "clouds," not necessarily of the same type, whose bases are approximately at the same level.

Cloud Top: the visible top of the cloud, or, in the absence of a visual observation, the 0 dBZ radar top. A visual evaluation of "cloud top" is preferred whenever possible.

Cone Of Silence: the volume in an inverted circular cone centered on the radar that is generated by all elevation angles greater than the maximum elevation angle used in the radar scan strategy. For the purpose of "VAHIRR" calculation this volume is capped by the observed maximum "cloud top" height, the observed tropopause height, or an altitude of 20 km (66 kft), whichever is lowest.

Cumulonimbus Cloud: any convective "cloud" with any part at an altitude where the temperature is colder than –20 degrees Celsius.

Debris Cloud: any "cloud," except an "anvil cloud," that has become detached from a parent "cumulonimbus cloud" or "thunderstorm," or that results from the decay of a parent "cumulonimbus cloud" or "thunderstorm."

Disturbed Weather: a weather system where dynamical processes destabilize the air on a scale larger than individual "clouds" or cells. Examples of "disturbed weather" include fronts, troughs, and squall lines.

Electric Field Measurement: the 1-minute arithmetic average of the vertical electric field (E_z) at the surface of Earth, measured by a ground-based "field mill." The polarity of the electric field is the same as that of the potential gradient; that is, the polarity of the field at Earth's surface is the same as the dominant charge overhead. Do not use interpolated electric field contours for purposes of this appendix. An ‘electric field measurement' less than or equal to 5 nautical miles from the 'flight path' is not applicable if the altitude of the flight path everywhere above the 5 nautical mile circle around the "field mill" in question is greater than 20 km (66 kft).

Field Mill: a specific class of electric-field sensor that uses a moving, grounded conductor to induce a time-varying electric charge on one or more sensing elements in proportion to the ambient electrostatic field.

Flight Path: the planned nominal flight trajectory, including its vertical and horizontal uncertainties specified by the three-sigma guidance and performance deviations.

Moderate Precipitation: a "precipitation" rate of 0.1 inches/hr or a "radar reflectivity" factor of 30 dBZ.

Nontransparent: "cloud" cover is "nontransparent" if one or more of the following conditions is present:

(a) Objects above, including higher "clouds," blue sky, and stars, are blurred, indistinct, or obscured as viewed from below; or objects below, including terrain, buildings, and lights on the ground, are blurred, indistinct, or obscured as viewed from above; when looking through the "cloud" cover at visible wavelengths (the sun and moon may not be used to evaluate transparency);

(b) Such objects are seen distinctly only through breaks in the "cloud" cover; or

(c) The "cloud" cover has a "radar reflectivity" factor of 0 dBZ or greater.

Precipitation: detectable rain, snow, hail, graupel, or sleet at the ground; virga; or a "radar reflectivity" factor greater than 18 dBZ at any altitude above the ground.

Radar Reflectivity: the radar return from hydrometeors, in dBZ, measured by a meteorological radar operating at a wavelength greater than or equal to 5 cm. A "radar reflectivity" measurement is valid only in the absence of significant attenuation by intervening "precipitation" or by water or ice on the radome.

Specified Volume: the volume bounded in the horizontal by vertical planes with perpendicular sides located 5.5 km (3 nautical miles) north, east, south, and west of the point at which "VAHIRR" is being computed. The volume is bounded on the bottom at the altitude where the temperature is 0 degrees Celsius, and on the top by a fixed altitude of 20 km (66 kft).

Thick Cloud Layer: one or more "cloud layers" whose combined vertical extent from the base of the bottom layer to the "cloud top" of the uppermost layer exceeds a thickness of 4,500 feet. "Cloud layers" are combined with neighboring layers for determining total thickness only when they are physically connected by vertically continuous "clouds," as, for example, when towering "clouds" in one layer contact or merge with "clouds" in a layer (or layers) above.

Thunderstorm: any convective "cloud" that produces lightning.

Transparent: any "cloud" that is not "nontransparent" is "transparent."

Treated: a launch vehicle satisfies both of the following conditions:

(a) All surfaces of the launch vehicle susceptible to ice particle impact are such that the surface resistivity is less than 10^9 "Ohms per square;" and

(b) All conductors on surfaces (including dielectric surfaces that have been coated with conductive materials) are bonded to the launch vehicle by a resistance that is less than 10^5 ohms.

Triboelectrification: the transfer of electrical charge between ice particles and the launch vehicle when the ice particles collide with the vehicle during flight.

Volume-Averaged, Height-Integrated Radar Reflectivity (VAHIRR): the product of the "volume-averaged radar reflectivity" and the "average cloud thickness" in a "specified volume" surrounding any point at which "VAHIRR" is being computed (units of dBZ-km). The "specified volume" must not contain any portion of the "cone of silence" above the radar, nor any portion of any sectors that may have been blocked out for payload-safety reasons. Volume-averaged radar reflectivity is the arithmetic average (in dBZ) of the "radar reflectivity" in the "specified volume." Normally, a radar processor will report reflectivity values interpolated onto a regular, three-dimensional array of grid points. Any such grid point in the "specified volume" is included in the average if and only if it has a "radar reflectivity" equal to or greater than 0 dBZ. If fewer than 10% of the grid points in the "specified volume" have "radar reflectivity" measurements equal to or greater than 0 dBZ, then the "volume-averaged radar reflectivity" is either the maximum "radar reflectivity" (in dBZ) in the "specified volume," or 0 dBZ, whichever is greater.

VAHIRR Application Criteria: the individual grid-point reflectivity measurements used to determine either the "volume-averaged radar reflectivity" or the "average cloud thickness" must be meteorological "radar reflectivity" measurements. For "VAHIRR"-evaluation points along the "flight path" itself (*not* those at a prescribed distance away from the "flight path"), the "volume-averaged, height-integrated radar reflectivity" is not applicable at any point that is less than or equal to 10 nautical miles from any "radar reflectivity" of 35 dBZ or greater at altitudes of 4 km (13 kft) or greater above mean sea level, nor is it applicable at any point that is less than or equal to 10 nautical miles from any type of lightning that has occurred in the previous 5 minutes.