8.7 IMPLEMENTING THE VAHIRR LAUNCH COMMIT CRITERIA USING EXISTING RADAR PRODUCTS

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1. INTRODUCTION

Lightning Launch Commit Criteria (LLCC) are rules designed to prevent space launch vehicles from flight through environments conducive to natural or triggered lightning. Background material about them may be found in Krider *et al*. (2006) and Roeder and McNamara (2006). Even ranges located in areas where natural lightning is rare may be subject to conditions conducive to rocket triggered lightning (Roeder et al., 1998). To assure avoidance of a triggered lightning event like that which destroyed an Atlas Centaur (AC-67) at the Eastern range in 1987, the LLCC are extremely conservative. Some of these rules have had such high safety margins that they prohibited flight under conditions that are now thought to be safe 90% of the time.

The LLCC for anvil clouds was upgraded in the summer of 2005 to incorporate results from the Airborne Field Mill Experiment (Dye *et al*., 2004). This experiment collected data from a weather research aircraft that carried electric field mills and cloud physics sensors. Data were collected during three periods: summer 2000, winter 2001, and summer 2001. These data, combined with the dense network of weather sensors routinely used at the Eastern Range and Kennedy Space Center (Roeder et al., 2003), especially the WSR-74C/IRIS radar (Roeder et al., 2005), were extensively analyzed from 2001 to 2005. Numerous combinations of parameters were considered to develop the best correlation of operational weather observations to in-cloud electric fields capable of rocket triggered lightning in anvil clouds. The Volume Average Height Integrated Radar Reflectivity (VAHIRR) was the best metric found. The introduction of VAHIRR has permitted improvements to the LLCC that maintains their current level of safety but increases launch availability. The increased launch availability comes from VAHIRR-based LLCC that permit flight under conditions where it was previously forbidden. Unfortunately, VAHIRR is not a product currently generated by any of the operational range radar systems including the WSR-88D used at most American ranges and the WSR-74C used for the Eastern Range and Kennedy Space Center. Before VAHIRR can be used to its fullest advantage, software must be written and certified for these radar systems to generate the product. It will be several years until an operational VAHIRR product is operationally available. There is, however, an immediately available work-around.

This paper defines VAHIRR and compares the VAHIRR-based LLCC with the pre-VAHIRR version. It specifically identifies the conditions under which relief from flight restrictions is provided. It also provides a procedure for interim implementation of the VAHIRR LLCC using currently available standard radar products. This interim procedure is more restrictive than the full implementation with dedicated software will be, but allows a large part of the benefit of the new rules to be realized now. The only required radar products are a Maximum Reflectivity (MAX) product over a user-selected layer and some method of determining cloud thickness. Cross sections or a combination of Constant Altitude Plan Position Indicator (CAPPI) and Height Of Highest Reflectivity (ECHO TOP) products can be used for the thickness determination. The specific methodology used at the Eastern Range is described in detail.

2. VAHIRR DEFINED

The definition of VAHIRR as provided in the revised anvil LLCC is as follows:

2.1 *Definition*

The Volume-Averaged, Height-Integrated Radar Reflectivity (units of dBZ-kilometers) is the product of the Volume-Averaged Radar Reflectivity and the Average Cloud Thickness

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within a Specified Volume relative to a point along the flight track.

where

The Specified Volume is bounded in the horizontal by vertical, plane, perpendicular sides located 5.5 km (3 n. mi.) north, east, south, and west of the point on the flight track, on the bottom by the 0 degree Celsius level, and on the top by the upper extent of all cloud.

and where

The Volume-Averaged Radar Reflectivity is the arithmetic average (in dBZ) of the cloud radar reflectivity within 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 within the Specified Volume is included in the average if and only if it has a radar reflectivity equal to or greater than 0 dBZ.

and where

The Average Cloud Thickness is the altitude difference (in kilometers) between the average top and the average base of all clouds within 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 cloud radar reflectivities 0 dBZ or greater. Similarly, the cloud top to be averaged is the highest extent (in altitude) of all cloud radar reflectivities 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 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 within the Specified Volume would have an Average Cloud Thickness equal to the vertical grid-point separation in its vicinity.

2.2 *Qualification of Radar Reflectivity Definition*

The Volume-Averaged, Height-Integrated Radar Reflectivity measurement must be made in the absence of significant attenuation by intervening storms or by water or ice on the radome itself. The Volume-Averaged, Height-Integrated Radar Reflectivity measurement is invalid at any point on the flight track that is within 20 km of any radar reflectivity of 35 dBZ or greater at altitudes of 4 kilometers above mean sea level or greater, and at any point that is within 20 km of any type of lightning that has occurred in the previous 5 minutes. 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. The individual grid-point reflectivities used to determine either the Volume-Averaged Radar Reflectivity or the Average Cloud Thickness must be meteorological reflectivities.

3. THE VAHIRR-BASED LLCC

The new VAHIRR-based anvil rules are presented below in their operational format. Their adoption was based on extensive research reported elsewhere (Dye *et al.*, 2006). The numbering scheme within the rules below does not match that used elsewhere in this paper because it has been retained from the operational documents.

3.1 *The Attached Anvil Rule*

G417.9 Attached Anvil Clouds

(a) A launch operator must not initiate flight if the flight path will carry the launch vehicle through or within 10 nautical miles of a nontransparent part of any attached anvil cloud for the first 30 minutes after the last lightning discharge in or from the parent cloud or anvil cloud.

(b) A launch operator must not initiate flight if the flight path will carry the launch vehicle through or within 5 nautical miles of a nontransparent part of any attached anvil cloud between 30 minutes and three hours after the last lightning discharge in or from the parent cloud or anvil cloud ***unless both of the following conditions are satisfied:***

(1) The portion of the attached anvil cloud within 5 nautical miles of the flight path is located entirely at altitudes where the temperature is colder than 0 degrees Celsius; and

(2) The volume-averaged, height-integrated radar reflectivity is less than +10 dBZ-km everywhere along the portion of the flight path where any part of the attached anvil cloud is within the specified volume.

(c) A launch operator must not initiate flight if the flight path will carry the launch vehicle through a nontransparent part of any attached anvil cloud more than three hours after the last lightning discharge in or from the parent cloud or anvil cloud ***unless both of the following conditions are satisfied:***

(1) The portion of the attached anvil cloud within 5 nautical miles of the flight path is located entirely at altitudes where the temperature is colder than 0 degrees Celsius; and

(2) The volume-averaged, height-integrated radar reflectivity is less than +10 dBZ-km everywhere along the portion of the flight path where any part of the attached anvil cloud is within the specified volume.

3.2 T*he Detached Anvil Rule*

G417.11 Detached Anvil Clouds

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

(a) A launch operator must not initiate flight if the flight path will carry the launch vehicle through or within 10 nautical miles of a nontransparent part of 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 lighting discharge in or from the detached anvil cloud after detachment.

(b) A launch operator must not initiate flight if the flight path will carry the launch vehicle between 0 and 5 nautical miles from a nontransparent part of a detached anvil cloud between 30 minutes and three hours after the last lightning discharge in or from the parent cloud or anvil cloud before detachment or after the last lighting discharge in or from the detached anvil cloud after detachment ***unless G417.11(b)(1) or G417.11(b)(2) is satisfied:***

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

(i) There is at least one working field mill within 5 nautical miles of the detached anvil cloud;

(ii) The absolute values of all electric field measurements made at the Earth’s surface within 5 nautical miles of the flight path ***and at*** each field mill specified in paragraph (1)(i) of this section have been less than 1000 volts/meter for 15 minutes or longer; and

(iii) The maximum radar return from any part of the detached anvil cloud within 5 nautical miles of the flight path has been less than 10 dBZ for 15 minutes or longer.

(2) ***This section is said to be satisfied if both of the following conditions are met:***

(i) The portion of the detached anvil cloud within 5 nautical miles of 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 everywhere along the portion of the flight path where any part of the detached anvil cloud is within the specified volume.

(c) A launch operator must not initiate flight if the flight path will carry the launch vehicle through a nontransparent part of a detached anvil cloud ***unless either G417.11(c)(1) or G417.11(c)(2) is satisfied:***

(1) ***This section is said to be 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 said to be satisfied if both of the following conditions are met:***

(i) The portion of the detached anvil cloud within 5 nautical miles of the flight path is located entirely at altitudes where the temperature is colder than 0 degrees Celsius; and

(ii) The volume-averaged, height-integrated radar reflectivity is less than +10 dBZ-km everywhere along the portion of the flight path where any part of the detached anvil cloud is within the specified volume.

3.3 *Comparison with Previous LLCC*

Rules G417.9 and G417.11 presented above are designed to supersede corresponding rules 3a and 3b of Willet *et al.*, 1999. The rule numbering format has been changed to accommodate proposed adoption of these rules by the Federal Aviation Administration (FAA) under 14 CFR part 417 for use at all spaceports under their jurisdiction. In the discussion that follows, Rules 3a and 3b will be referred to as the “old” rules and the VAHIRR derived rules as the “new” rules.

Both the old rules and the new rules provide a substantial margin of safety for flight. The goal of both sets of rules is to avoid flight through electric fields exceeding 3 kV m^{-1}. That threshold has been determined to be well below the minimum field required for triggering a lightning strike to an ascending launch vehicle. A quantitative estimate of the protection provided by the old rules is not available. An extreme value analysis (unpublished) by Dr. Harry Koons of the Aerospace Corporation indicated that the new rules provide a probability of less than 10^{-4} of exceeding fields of 3 kV m^{-1}.

The advantage of the new rules is that under some conditions of operational significance, they will permit a launch to proceed where the old rules would not. This additional "launch availability" reduces the cost and delay associated with unnecessary launch scrubs due to weather constraints. The differences for attached anvils are shown in table 1. The differences for detached anvils are shown in table 2. In the tables, distances are shown in nautical miles (NM) rather than SI units (km) because the rules are operationally implemented in English units. One NM = 1.852 km.

	Time Since Last Lightning	
Standoff (NM)	Old Rules	New Rules
Flight through	Never	3 hours if VAHIRR satisfied
$0 < x \leq 5$	3 hours	3 hours if VAHIRR not satisfied OR 30 minutes if VAHIRR is satisfied
$5 < x \leq 10$	30 minutes	30 minutes
$X > 10$	Any time	Any time

Table 1. Differences between the old and new LLCC for attached anvils. The gains over the old rule if VAHIRR is available are highlighted in green.

	Time Since Last Lightning	
Standoff (NM)	Old Rules	New Rules
Flight through	4 Hrs (since any anvil lightning) and 3 Hrs after detachment	4 Hrs (since any anvil lightning) and 3 Hrs after detachment OR 30 minutes if VAHIRR is satisfied
$0 < x \leq 5$	3 hours (anvil lightning or time of detachment) UNLESS surface field mills read below 1K V/m within 5 NM AND radar reflectivity has been < 10 dBZ for at least 15 min.	3 hours (anvil lightning or time of detachment) UNLESS EITHER surface field mills read below 1K V/m within 5 NM AND radar reflectivity has been < 10 dBZ for at least 15 min. OR 30 minutes if VAHIRR is satisfied
$5 < x \leq 10$	30 minutes	30 minutes
$X > 10$	Any time	Any time

Table 2. Differences between the old and new LLCC for detached anvils. The gains over the old rule if VAHIRR is available are highlighted in green.

The tables are interpreted as follows: To fly within the distances of an anvil specified in the Standoff column, the launch operator must wait for the time specified in the old/new rules columns subject to the conditions listed in that column. The clock for the waiting time starts at zero with the last lightning discharge in the parent thunderstorm or the anvil, whichever is later.

Improved launch availability is highlighted in the tables. In these cases, the required waiting period is shortened or a waiting period is created where flight was previously forbidden unconditionally. The use of VAHIRR would allow an average increased safe launch opportunity of an estimated 30% under anvil conditions, with increased opportunity of up to 800% in the case where a four hour wait is reduced to 30 minutes. This could represent an average annual cost savings of about $75,000 by avoiding needless launch scrubs.

4. IMPLEMENTATION WITH CURRENT RADAR PRODUCTS

4.1 *General Concept*

The following description of the methodology for using the VAHIRR-based LLCC with existing radar products is taken verbatim from the directions provided with the new LLCC. It will be necessary to use this work-around until software has been deployed on the operational radar systems to compute the VAHIRR quantity.

Such software is currently under development for the WSR-88D radars in use at the Eastern and Western Ranges (Gillen and Merceret, 2006).

The VAHIRR quantity referred to in Rules G417.9 and G717.11 requires computation of both a volume average reflectivity and an average cloud thickness. These quantities are then multiplied to produce the VAHIRR. Neither of these quantities is currently available as a product on the WSR-88D and WSR-74C radar systems used to support launch operations. This instruction provides a methodology for evaluating VAHIRR criteria with currently available radar products. The methodology provides a result that is more conservative than a direct VAHIRR computation, but it should still permit the launch customer to reap much of the benefit of the new rule.

Part I. Determination of average cloud thickness. The definition of the VAHIRR requires determination of the average cloud top and the average cloud base above the height of the 0C isotherm within a square having sides 5.5 km (3 n. mi.) north, east, south, and west of the ground projection of each point in the flight track. Average cloud thickness is defined as the difference of these two numbers. If the average cloud thickness cannot be determined at each point on the flight track, the maximum thickness within 5.5 km (3 n. mi.) of the flight track may be used.

To determine the average cloud top height, the launch weather team may use any existing radar product that gives the height of the 0 dBZ cloud top, including "maximum height of reflectivity" and cross section products. If the average height cannot be determined, the maximum height of the 0 dBZ reflectivity may be used. If the maximum height cannot be determined, use 18 km (60 kft) for the average cloud top.

The average height of the cloud base should be derived from radar data. It is the *average* of the higher of (a) the bottom of the portion of the cloud producing a radar reflectivity of 0 dBZ or greater or (b) the height of the 0C isotherm where the 0 dBZ reflectivity extends below that level. If the average height of the cloud base cannot be determined, use the higher of (a) the height of the 0 degree C isotherm or (b) the lowest portion of the cloud producing a radar reflectivity of 0 dBZ or greater anywhere within each 5.5 km (3 n. mi.) square defined above.

Part II. Volume Averaged Radar Reflectivity (VARR). There is no operationally feasible way to use existing radar products to compute a volume average reflectivity. A conservative substitute is the *maximum* reflectivity since the volume average will always be smaller than the maximum. The WSR-88D has a "User Selectable Layer Composite Reflectivity (URL)" product and the WSR-74C has a "Max" product with user selectable base and top. The launch weather team should configure these products with the bottom of the layer at the height of the 0 degree C isotherm and the top above the height of the highest radar beam within 7.8 km (4.2 n. mi.) of the ground-projected flight track in the scan strategy being used. The WSR-88D product will have to be configured at the RPG and included in the product scheduler for the PUP used by the launch weather team.

Part III. Evaluating the constraint. The VAHIRR constraint is satisfied for a point on the flight track if the "URL" or "Max" radar product (see Part II above) everywhere within the corresponding square (defined above) is less than 10 dBZ-km divided by the average cloud thickness in km within the same square (see Part I above). (In English units, this threshold would become 33 dBZ-kft divided by the average cloud thickness in kft.) This constraint must be satisfied for every point on the flight track.

4.2 *Implementation at the Eastern Range*

The 45th Weather Squadron (45 WS) implemented the new VAHIRR “work-around” procedures using a five step process. The steps were as follows: 1) review and thoroughly comprehend the rule, 2) develop and conduct training with Launch Weather Officers (LWOs), 3) perform preliminary testing using current weather radar products and the work-around method for evaluating VAHIRR, 4) provide training to launch decision authorities and customers and 5) update launch documentation.

From an operational perspective, the first three steps of this process were crucial. A considerable amount of dialogue transpired between the LWOs and other 45 WS meteorologists, the KSC Weather Office and the Lightning Advisory Panel to ensure the intricacies of VAHIRR and the “work-around” procedures were completely understood. During the training phase, the 45 WS training flight developed a comprehensive training presentation emphasizing the key steps in the VAHIRR evaluation process. The training course included challenging weather scenarios which gave LWOs the opportunity to assess the criteria in a controlled environment rather than evaluating VAHIRR with no or limited experience on launch day. Operational products were developed such as an easy to use nomogram displaying the maximum reflectivity for different cloud thicknesses (Table 3). Preliminary testing revealed limitations of the radar in the evaluation process and gave LWOs valuable experience in assessing VAHIRR before using it operationally. Overall, the plan used to implement the new Anvil Cloud Rule was effective and eased evaluating VAHIRR.

Average Anvil Thickness (Ft)	Maximum Reflectivity Allowed (dBZ)
1,000	33.00
2,000	16.50
3,000	11.00
4,000	8.25
5,000	6.60
6,000	5.50
7,000	4.71
8,000	4.13
9.000	3.67
10,000	3.30
11,000	3.00
12,000	2.75

Table 3. Maximum allowable reflectivity for average anvil cloud thicknesses.

The first opportunity to evaluate the VAHIRR criteria during an actual launch operation was for Space Shuttle Discovery's Return-to-Flight mission on 13 July 2005. Discovery was scheduled to lift-off from launch complex 39B, Kennedy Space Center, Florida at 1945Z on a hot, humid summer afternoon. The Bermuda High pressure ridge stretched across Central Florida allowing the sea breeze to develop along the space coast. By 1400Z, isolated showers and thunderstorms developed due to the convergence associated with the sea breeze front. Showers remained stationary with a slight drift westward as the sea breeze moved inland. At 1513Z, a cumulonimbus cloud developed 15 NM (27.8 km) to the northwest of complex 39B with cloud tops reaching 25 kft (Figure 1). A smaller cell located 6 NM (11 km) northwest was dissipating. The Anvil Cloud LLCC was not violated at this time.

By 1536Z, the maximum reflectivity product indicated that the cell 15 NM (27.8 km) to the northwest continued to develop while the smaller cell to the northwest had dissipated. The cloud top of this cell reached heights of 30 kft and northwesterly upper level winds began carrying anvil cloud towards the launch pad (Figure 2). For the next 30 minutes, the cumulonimbus cloud began to dissipate as reflectivity dropped. The anvil cloud continued to advect slowly towards the launch pad and flight path.

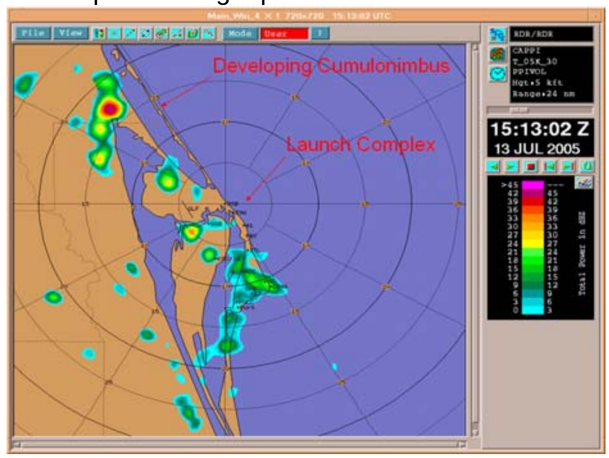

Figure 1. 10K Constant Attitude PPI Product .

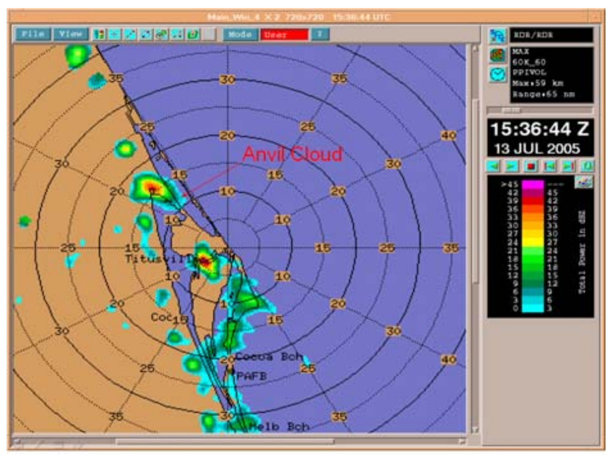

Figure 2. Maximum Reflectivity Product

At 1605Z, it was apparent on the maximum reflectivity product that the attached anvil cloud was within 5NM (9.3 km) of the launch pad (Figure 3). Weather observations indicated that the anvil cloud was nontransparent and the time of the last lightning discharge from the anvil cloud and/or parent cell had been 40 minutes. The combination of these three factors (attached anvil within 5nm, anvil was nontransparent, and last lightning discharge was less than 3 hours ago) violated the anvil LLCC. However, further investigation was required to determine if VAHIRR was less than 10 dBZ-km (33 dBZ-kft operationally) and relief from the Anvil Cloud LLCC was applicable in this situation.

of 15 dBZ-kft. Since VAHIRR is less than 33 dBZ-kft, the Anvil LLCC would not normally have been violated. However, the 35 dBZ within 20 km part of the LLCC precluded the use of the VAHIRR exemption in this case.

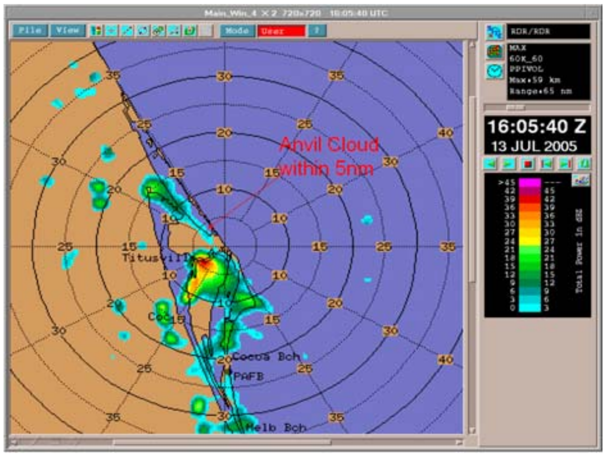

Figure 3. Maximum Reflectivity Product.

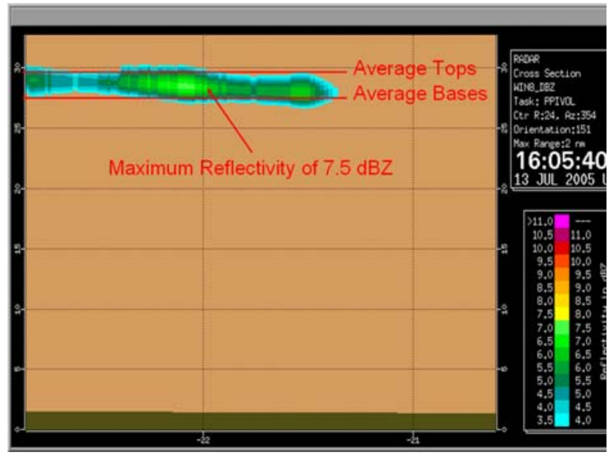

Figure 4. Vertical Cross Section

As mentioned above, the VAHIRR caveat can not be evaluated if any radar reflectivity of 35 dBZ or greater at altitudes of 4 km or greater is within 20 km of the flight path and no lightning has occurred within 20 km of the flight path in the past 5 minutes. In this case, a cell with 35 dBZ was within 20 km and lightning had occurred in the past 5 minutes. However, the evaluation of the VAHIRR was completed in case the intensity of the cell decreased below 35 dBZ or lightning decreased in frequency. At the time of evaluation, there was no significant attenuation from rain on the radome and the cone of silence around the antenna was not a factor.

VAHIRR was computed by first finding the average thickness of the anvil cloud that extends into a 3 NM (5.5 km) square around each point in the flight track. Figure 4 shows a vertical cross section across this specified volume where the anvil cloud exists in the square around the flight path. Average tops are 29 kft and average bases are 27 kft giving an average thickness of the cloud of 2 kft. The 0^o Celsius level was 15.7 kft so the average base of the clouds was used to compute the average cloud thickness. If any of the anvil layer extended below 0°C, that portion would have to be excluded from the average thickness calculation. The reflectivity product (Figure 3) and the vertical cross section indicated a maximum reflectivity of 7.5 dBZ resulting in a VAHIRR value

5. FUTURE LLCC IMPROVEMENT FROM THE AIRBORNE FIELD MILL EXPERIMENT

In addition to the VAHIRR improvements in the Anvil LLCC discussed here, the Airborne Fieldmill Experiment, the radar definition for cloud edges was reduced from 10 dBZ to 0 dBZ in the summer of 2003. This was implemented immediately to improve launch safety since in-cloud electric fields that may have been enough for rocket triggered lightning were observed between 5 dBZ and 10 dBZ. No threatening fields were observed below 5 dBZ, so a radar cloud edge definition of 0 dBZ was adopted for a margin of safety.

The Airborne Field Mill Experiment database continues to be analyzed for further LLCC improvements. For example, some analysis has indicated that the electric fields fall off faster with distance from anvil clouds than had been believed previously (Ward and Merceret, 2004). Further analysis could lead to new anvil LLCC with considerably reduced standoff distances. The reduction could be as much as a factor of three in some cases.

6. DISCUSSION AND CONCLUSION

The development of VAHIRR-based LLCC provide safe relaxation of several of the current lightning constraints to launch. In the absence of a work-around, operational implementation of these new rules would have to wait until the software necessary to compute VAHIRR on the operational radars could be developed, tested and certified. This paper presents such a work-around using existing products available both on the Eastern Range WSR-74C and the WSR-88D NEXRAD used at the Western Range and elsewhere in the US and its possessions.

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