8.2 ANALYSIS OF PROPOSED 2007-2008 REVISIONS TO THE LIGHTNING LAUNCH COMMIT CRITERIA FOR UNITED STATES SPACE LAUNCHES

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1. INTRODUCTION

Ascending space vehicles are vulnerable to both natural and triggered lightning. Launches under the jurisdiction of the United States are generally subject to a set of rules called the Lightning Launch Commit Criteria (LLCC) (Krider *et al.*, 1999; Krider *et al.*, 2006). The LLCC protect both the vehicle and the public by assuring that the launch does not take place in conditions posing a significant risk of a lightning strike to the ascending vehicle. Such a strike could destroy the vehicle and its payload, thus causing failure of the mission while releasing both toxic materials and debris.

To assure safety, the LLCC are conservative and sometimes they may seriously limit the ability of the launch operator to fly as scheduled even when conditions are benign. In order to safely reduce the number of launch scrubs and delays attributable to the LLCC, the Airborne Field Mill (ABFM II) program was undertaken in 2000 - 2001. The effort was directed to collecting detailed high-quality data on the electrical, microphysical, radar and meteorological properties of thunderstorm-associated clouds. Details may be found in Dye *et al.*, 2007. The expectation was that this additional knowledge would provide a better physical basis for the LLCC and allow them to be revised to be less restrictive while remaining at least as safe. That expectation was fulfilled, leading to significant revisions to the LLCC in 2003 and 2005.

The 2005 revisions included the application of a new radar-derived quantity called the Volume Averaged Height Integrated Radar Reflectivity (VAHIRR) in the rules governing flight through anvil clouds. VAHIRR is the product of the volume averaged radar reflectivity times the radar-determined cloud thickness. The reflectivity average extends horizontally 5 km west, east, south and north of a point along the flight track

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and vertically from the 0 ^{o}C isotherm to the top of the radar cloud. This region is defined as the "Specified Volume". See Dye et al., 2006 and Merceret et al., 2006 for a more thorough description of VAHIRR. The units are dBZ km (not dBZ km^{-1}) and the threshold is 10 dBZ km. It is safe to fly through an anvil cloud for which VAHIRR is below this threshold everywhere along the flight track as long as (1) the entire cloud within 5 nmi. (9.26 km) of the flight track is colder than 0 C, (2) the points at which VAHIRR must be evaluated are at least 20 km from any active convective cores and recent lightning, and (3) the radar return is not being attenuated within the Specified Volume around those points.
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Analysis of the ABFM data has continued, and two additional revisions to the LLCC were proposed in late 2006. One proposal was to apply the VAHIRR concept to debris clouds, and the other was to reduce the distance outside of anvil and debris clouds within which a vehicle is not permitted to fly. This is referred to as the "stand-off distance" in the rules. This paper discusses these proposed changes in the LLCC and the scientific rationale for adopting or rejecting them based on ABFM II data. Formal adoption or rejection of these proposed LLCC changes is expected in the spring of 2008.

2. REDUCING STAND-OFF DISTANCES FROM ANVIL AND DEBRIS CLOUD

The LLCC not only forbid flight through potentially dangerous clouds, but also limit flight in their immediate vicinity unless certain restrictions are met. The goal is to avoid flight through fields greater in magnitude than 3 kV m^{-1}. The distance within which a launch operator may not fly without meeting these restrictions is referred to in this paper as the "stand-off distance". In many of the LLCC, the stand-off distance is five nautical miles (9.26 km). Based on the ABFM II measurements reported in Merceret *et al.*, 2008, it has been proposed to reduce this to 3 nautical miles (5.52 km) as summarized below.

The fields in anvil clouds penetrated by the ABFM II aircraft became smaller than 3 kV m^{-1} inside the perimeter of the cloud even though fields deeper in the anvil sometimes exceeded tens of kV m^{-1}. External to the cloud perimeter, fields were typically smaller than 1 kV m^{-1}. Figure 1 (Figure 4 from Merceret *et al.*, 2008) shows electric field magnitude as a function of distance from the edge of anvil clouds that had a maximum field magnitude of at least 3 kV m^{-1}. The maximum and average values are shown separately for passes entering cloud and exiting cloud. The hazard threshold of 3 kV m^{-1} is shown by a horizontal dashed line. The cloud boundary is at distance = 0 with cloud on the left and clear air on the right. The behavior of debris clouds is essentially identical (not shown).

These data encompassed penetrations of 18 anvil clouds and 11 debris clouds. With a sample size this small, a careful statistical analysis is required in order to estimate the probability that fields greater than the 3 kV m^{-1} limit will be encountered beyond any proposed reduced stand-off distance. This probability must be small (typically 10^{-4} or less) in order to justify a rule change.

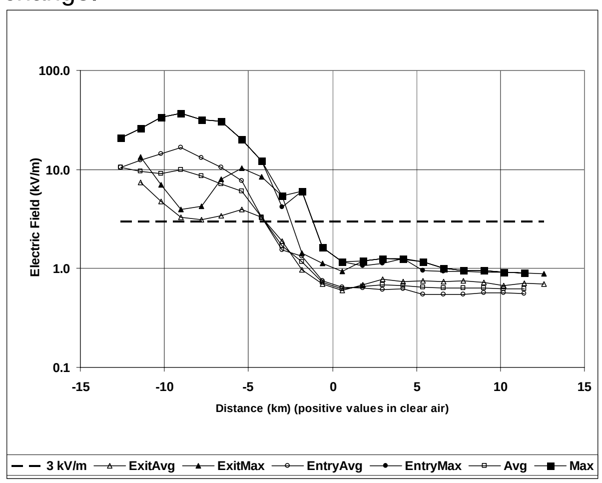

Figure 1. Figure 4 from Merceret *et el.*, 2008. See text for description.

The sample size was too small for a standard extreme value analysis, so three alternative approaches were used. All indicated that a reduction of the standoff-distance to 3 n. mi. (5.52 km) is sufficiently safe.

The easiest but least rigorous method was an *a fortiori* argument as follows, but the argument only applies to anvils:

If the VAHIRR quantity is below the 10 dBZ km threshold provided in the anvil rules, it is safe to fly through the anvil. Outside the anvil there is no radar echo at all, so the VAHIRR quantity, if computed beyond 3 nmi. (5.52 km) outside the cloud, would be zero, which is certainly less than the threshold of 10 dBZ km. That would be safe even within the cloud, so, *a fortiori*, it is certainly safe outside the cloud.

The *a fortiori* argument may be logically sound, but it is not quantitative and it does not apply (yet, at least) to debris clouds since VAHIRR has not yet been incorporated into the debris cloud rules. This led to two statistical approaches.

The first approach was an application of Gaussian statistics. The current stand-off distance from which any change would be made is 5 n. mi (9.26 km) and the proposed relaxation is to 3 n. mi. (5.52 km). The analysis was designed to examine the risk involved in flight through the region between the existing and the proposed limit. The available data in this region covered the range from 6 to 12 km. Data from anvil and debris clouds were combined to maximize the sample size since their behavior was essentially identical.

An exploratory analysis was conducted to determine possible probability distributions that would yield conservative quantitative results. All data in the range from 6 to 12 km were combined for the analysis. Table 1 presents the results.

Quantity	Value	Standard Error
Samples	74	N/A
Minimum field	0.212	N/A
Maximum field	1.004	N/A
Median field	0.589	N/A
Mean field	0.613	0.025
Field std. dev.	0.213	0.018
Skewness	-0.09	0.28
Kurtosis	2.22	0.57
Coef. of variation	0.35	N/A

Table 1. Statistics of combined anvil and debris cloud in the range 6 - 12 km from cloud edge. Fields are in kV m^{-1}. Kurtosis is defined such that the kurtosis of a Gaussian distribution is 3.0.

The table shows that the skewness is nearly zero and the kurtosis is smaller than for a Gaussian distribution. This suggested that a Gaussian distribution would be a conservative fit to the data since it would have broader tails (hence more extreme values) than the measured distribution. Figure 2 shows the measured data overlaid on a Gaussian distribution with the same mean and standard deviation.

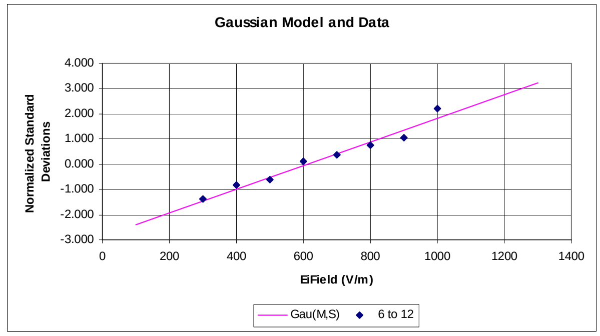

Figure 2. The cumulative probability distribution in normalized standard deviations for the 6 - 12 km electric field magnitude data (V/m) and the Gaussian model having the same mean and standard deviation.

To provide conservatism and margin in the risk analysis, the probability computations were based on the assumption of a Gaussian distribution with a mean given by the measured mean plus three times the error of estimate of the mean. Additional conservatism and margin were provided by using a standard deviation given by the measured standard deviation plus three times the error of estimate of the standard deviation. Thus the parameters of the distribution used for the risk analysis are both "three sigma worst case" parameter values, Mw = 687 and Sw = 266. The results are presented in Table 2. The 0.00E+00 entry represents a probability too small for Excel to handle.

E-field (kV m^{-1})	Model Probability
0.1	9.86E-01
0.2	9.67E-01
0.5	7.60E-01
1.0	1.20E-01
1.5	1.12E-03
2.0	3.95E-07
2.5	4.60E-12
3.0	0.00E+00

Table 2. Probability of exceeding the specified electric field magnitude for a Gaussian model with a mean of 0.687 kV m^{-1} and a standard deviation of 0.266 kV m^{-1}.

Although this analysis was consistent with the qualitative assessment from the *a fortiori* argument and suggested that there was ample safety margin for reducing the stand-off distance as suggested, use of a Gaussian assumption is not standard for quantitative analysis of extreme values, so an additional analysis was performed looking at the distribution of the upper tail of the distribution only.

Exploratory analysis showed that a two-parameter Weibull distribution fit very well. The analysis treated data at each distance outside the cloud separately and computed the probability of exceeding 3 kV m^{-1} at each distance. Table 3 presents the results.

Distance (km)	All Clouds	Clouds > 3 kV m^{-1}
0.6	8.0 E-9	1.9 E-9
1.8	2.5 E-9	2.3 E-11
3.0	1.6 E-10	5.9 E-11
4.2	4.5 E-10	2.4 E-10
5.4	2.9 E-12	< 1.0 E-16
6.6	1.2 E-12	< 1.0 E-16
7.8	1.6 E-12	< 1.0 E-16
9.0	9.3 E-11	< 1.0 E-16
10.2	9.3 E-11	< 1.0 E-16
11.4	6.5 E-10	< 1.0 E-16
12.6	1.1 E-16	< 1.0 E-16

Table 3. Probability of exceeding 3 kV m^{-1} as a function of distance outside the could boundary. The column labeled "all clouds" used data from all clouds in the sample. The column labeled "Clouds > 3 kV m^{-1}" only considered samples from clouds where the magnitude of the electric field reached at least 3 kV m^{-1}. The format "8.0 E-9" means 8.0 x 10^{-9}. Source: O'Brien and Walterscheid, 2007.

All three analyses support the safety of the proposed reduction of the stand-off distances, and it is expected that this will be implemented in the next revision to the LLCC.

3. APPLICATION OF VAHIRR TO DEBRIS CLOUD

The debris cloud rules are similar in purpose and effect to the anvil cloud rules. In both cases, the concern is that the parent thunderstorm that produced the cloud had deposited enough electric charge in the cloud to pose a threat of triggered lightning if a launch vehicle penetrates the cloud. The rules require the launch operator to wait a sufficient amount of time for that charge to dissipate before flight through the cloud is permitted.

The ABFM data suggest that the electric fields in anvil and debris clouds are similarly bounded when the VAHIRR quantity is below the 10 dBZ km threshold used in the VAHIRR-based anvil cloud rules. VAHIRR was not previously incorporated into the debris cloud rules because the required statistical analysis had not been performed to quantitatively confirm the strong qualitative impression. An unpublished extreme value analysis of the ABFM anvil cloud data had shown that the probability of exceeding 3 kV m^{-1} was less than 10^{-4} when VAHIRR was less than 10 dBZ km (Dr. Harry Koons, private communication). If this relationship also holds in debris cloud, then a VAHIRR-based debris cloud rule may be justified.

The analysis used for anvil clouds was not used for debris clouds because the sample size was too small. Instead, the data sequences were decimated to reduce the effects of serial correlation and then combined into a single collection that contained all electric field measurements from the decimated set where VAHIRR was within +/- 5 dBZ km of the 10 dBZ km threshold used for anvils. The data in this 5 - 15 dBZ km "bin" were examined for candidate probability distributions. Again, the Weibull distribution was an appropriate fit. For comparison, anvil clouds were subjected to this same analysis. Data from both the WSR74C and NEXRAD radars were used to derive VAHIRR, and they did not always give exactly the same result, so they were analyzed separately and then combined. Details are presented in O'Brien and Walterscheid, 2008. Table 4 presents the results.

Radar	Debris	Debris95	Anvil	Anvil95
WSR74C	1.1 E-22	4.0 E-5	5.7 E-3	3.0 E-2
NEXRAD	2.7 E-126	7.0 E-8	4.0 E-3	4.0 E-2
Combined	1.5 E-25	5.0 E-6	2.0 E-3	2.0 E-2

Table 4. Probability of exceeding 3 kV m^{-1} for debris and anvil clouds from the Weibull analysis of decimated data for VAHIRR between 5 and 15 dBZ km. The columns with the "95" suffix are the 95% confidence bound of the estimate.

This analysis gives higher risk probabilities for anvils than the one by Dr. Koons cited above, but his methodology was more rigorous. Although the smaller sample size for debris clouds prevented using the more rigorous methodology, the comparison strongly supports the proposition that use of VAHIRR in debris clouds will be at least as safe (10^{-4}) as its use in anvil clouds with the same threshold.

4. DISCUSSION

The proposed changes to the LLCC discussed above should provide additional relief from launch scrubs and delays due to violation of the LLCC while maintaining a high level of safety as provided by the current version of the rules. This translates directly into reduction of cost and delay of spaceflight operations.

This paper has focused only on two major proposed changes to the LLCC that have the direct potential to significantly and safely reduce the number of unnecessary launch scrubs and delays. There are additional changes under consideration that were not discussed above, primarily because they do not change the substance of the LLCC. Instead, they either clarify existing definitions or remove ambiguities within the LLCC or associated definitions and notes. Some additional potential applications of VAHIRR to portions of the anvil or debris cloud rules are also under discussion, but have not yet reached the degree of maturity appropriate to formal presentation in a conference paper.

Among the revisions to definitions are several revisions to the definition of VAHIRR. VAHIRR is not to be computed when any part of its "Specified Volume" lies within the "Cone of Silence" of the radar. A specific definition of "Cone of Silence" will be provided in the next revision. In addition, in order to assure that the volume average used to compute VAHIRR is statistically stable, the definition of VAHIRR will be amended to require that a certain minimum possible fraction of the Specified Volume be occupied by radar echoes for a valid VAHIRR computation. That fraction is still under discussion but will most likely be no less than 5% and no more than 10%.

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