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Volume Averaged Height Integrated Radar Reflectivity (VAHIRR) Cost-Benefit Analysis

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October 2008

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Executive Summary

Lightning Launch Commit Criteria (LLCC) are designed to prevent space launch vehicles from flight through environments conducive to natural or triggered lightning and are used for all U.S. government and commercial launches at government and civilian ranges. They are maintained by a committee known as the NASA/USAF Lightning Advisory Panel (LAP). The previous LLCC for anvil cloud, meant to avoid triggered lightning, have been shown to be overly restrictive. 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 (Merceret et al. 2006), leading to costly launch delays and scrubs. The LLCC for anvil clouds was upgraded in the summer of 2005 to incorporate results from the Airborne Field Mill (ABFM) experiment at the Eastern Range (ER). 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 Averaged Height Integrated Radar Reflectivity (VAHIRR) was the best metric found (Dye et al. 2006, 2007). Dr. Harry Koons of Aerospace Corporation conducted a risk analysis of the VAHIRR product. The results indicated that the LLCC based on the VAHIRR product would pose a negligible risk of flying through hazardous electric fields. Based on these findings, the Kennedy Space Center Weather Office is considering seeking funding for development of an automated VAHIRR algorithm for the new ER 45th Weather Squadron (45 WS) RadTec 43/250 weather radar and Weather Surveillance Radar–1988 Doppler (WSR-88D) radars.

Before developing an automated algorithm, the Applied Meteorology Unit (AMU) was tasked to determine the frequency with which VAHIRR would have allowed a launch to safely proceed during weather conditions otherwise deemed “red” by the Launch Weather Officer. To do this, the AMU manually calculated VAHIRR values based on candidate cases from past launches with known anvil cloud LLCC violations. An automated algorithm may be developed if the analyses from past launches show VAHIRR would have provided a significant cost benefit by allowing a launch to proceed.

The 45 WS at the ER and 30th Weather Squadron (30 WS) at the Western Range provided the AMU with launch weather summaries from past launches that were impacted by LLCC. The 45 WS provided summaries from 14 launch attempts and the 30 WS from 5. The launch attempts occurred between December 2001 and June 2007. These summaries helped the AMU determine when the LLCC were “red” due to anvil cloud. The AMU collected WSR-88D radar reflectivity, cloud-to-ground lightning strikes, soundings and satellite imagery.

The AMU used step-by-step instructions for calculating VAHIRR manually as provided by the 45 WS. These instructions were used for all of the candidate cases when anvil cloud caused an LLCC violation identified in the launch weather summaries. The AMU evaluated several software programs capable of visualizing radar data so that VAHIRR could be calculated and chose GR2Analyst from Gibson Ridge Software, LLC. Data availability and lack of detail from some launch weather summaries permitted analysis of six launch attempts from the ER and none from the WR.

The AMU did not take into account whether or not other weather LCC violations were occurring at the same time as the anvil cloud LLCC since the goal of this task was to determine how often VAHIRR provided relief to the anvil cloud LLCC at any time during several previous launch attempts. Therefore, in the statistics presented in this report, it is possible that even though VAHIRR provided relief to the anvil cloud LLCC, other weather LCC could have been violated not permitting the launch to proceed.

The results of this cost-benefit analysis indicated VAHIRR provided relief from the anvil cloud LLCC between about 15% and 18% of the time for varying 5-minute time periods based on summaries from six launch attempts and would have allowed launches to proceed that were otherwise “NO GO” due to the anvil cloud LLCC if the T-0 time occurred during the anvil cloud LLCC violations.

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1. Introduction

1.1 Objective

The Kennedy Space Center (KSC) Weather Office is considering funding development of a capability to automatically calculate the Volume Averaged Height Integrated Radar Reflectivity (VAHIRR) using data from the new Eastern Range (ER) 45th Weather Squadron (45 WS) RadTec 43/250 weather radar and Weather Surveillance Radar-1988 Doppler (WSR-88D) radars. Before doing so, the Applied Meteorology Unit (AMU) was tasked to determine the frequency with which VAHIRR would have allowed a launch to safely proceed during weather conditions otherwise deemed “red” by the Launch Weather Officer.

1.2 Background

Lightning Launch Commit Criteria (LLCC) are designed to prevent space launch vehicles from flight through environments conducive to natural or triggered lightning and are used for all U.S. government and commercial launches at government and civilian ranges. They are maintained by a committee known as the NASA/USAF Lightning Advisory Panel (LAP). The LAP was formed to recommend changes to the NASA and USAF LLCC for manned and unmanned launches (Willet et al. 1999). The previous LLCC for anvil cloud, meant to avoid triggered lightning, have been shown to be overly restrictive. 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 (Merceret et al. 2006). They ensure safety, but falsely warn of danger and can lead to costly launch delays and scrubs. The LLCC for anvil clouds was upgraded in the summer of 2005 to incorporate results from the Airborne Field Mill (ABFM) experiment at the ER. 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 VAHIRR was the best metric found (Dye et al. 2006, 2007). Dr. Harry Koons of Aerospace Corporation conducted a risk analysis of the VAHIRR product. The results indicated that the LLCC based on the VAHIRR product would pose a negligible risk of flying through hazardous electric fields.

1.3 Candidate Cases and Data

The AMU manually calculated VAHIRR based on candidate cases from past launches with known anvil cloud LLCC violations. The 45 WS at the ER and 30th Weather Squadron (30 WS) at the Western Range (WR) provided the AMU with launch weather summaries from past launches that were impacted by LLCC. The 45 WS provided summaries from 14 launch countdowns and the 30 WS from 5. The launch attempts occurred between December 2001 and June 2007. These summaries helped the AMU determine when the LLCC were “red” due to anvil cloud. The AMU used WSR-88D radar reflectivity, cloud-to-ground lightning strikes, soundings and satellite imagery to calculate VAHIRR.

Based on the candidate cases provided and data availability, the AMU calculated VAHIRR for six ER launch countdowns and no WR launch countdowns. Although more than six ER countdowns had anvil cloud LLCC violations, radar data were not always available during some periods with anvil cloud observed. Also, some of the 45 WS launch summaries did not have enough detail to identify the time periods of the LLCC violations due to anvil cloud, so VAHIRR could not be calculated. During the WR countdowns, there were no LLCC violations due to anvil cloud. The LLCC violations were due to other issues such as the thick cloud rule or precipitation rule and, therefore, did not qualify for this task.

1.4 Software Resources

Cross sections of radar reflectivity were required to evaluate VAHIRR. The AMU evaluated several software programs capable of displaying cross sections and chose GR2Analyst from Gibson Ridge Software, LLC (<http://www.grlevelx.com/>). In addition to the cross section capability, GR2Analyst could display radar volume scans in 3-D which made it very easy to locate anvil cloud. Also, GR2Analyst could natively read archived WSR-88D Level II files which were freely available for download from the National Climatic Data Center (<http://www.ncdc.noaa.gov/nexradinv/>). It was also important to locate the height of 0° C to calculate VAHIRR. The AMU chose the Universal Rawinsonde Observation (RAOB) software from Environmental Research Services (<http://www.raob.com>) because the software could read-in many different sounding formats and provide a high resolution graphical display with instant mouse-over data readout.

2. Manual VAHIRR Evaluation Process

The 45 WS provided step-by-step instructions for calculating VAHIRR manually. This evaluation process was used for all of the candidate cases when anvil cloud caused an LLCC violation as noted in launch weather summaries.

2.1 Steps for Evaluating VAHIRR

As provided by the 45 WS, the steps to calculate VAHIRR manually are as follows:

- Do conditions violate the Anvil Rule for anvil (attached or detached) within 5 NM or fly through?
 - Yes → continue with VAHIRR calculation.
 - No → VAHIRR is not calculated.
- Is the anvil cloud within 5 NM of the flight path located at altitudes colder than 0° C?
 - Yes → continue with VAHIRR calculation.
 - No → VAHIRR is not calculated.
- Is significant attenuation taking place due to intervening storms or by water on the radome?
 - No → continue with VAHIRR calculation.
 - Yes → VAHIRR is not calculated.
- Are all radar reflectivities at or above 13,123 ft within 10.8 NM of the flight path below 35dBZ?
 - Yes → continue with VAHIRR calculation.
 - No → VAHIRR is not calculated.
- Has lightning occurred within 10.8 NM of the flight path in the last 5 minutes?
 - No → continue with VAHIRR calculation.
 - Yes → VAHIRR is not calculated.
- If all returns within the specified volume are from meteorological targets, determine the average cloud tops using the highest extent of 0 dBZ reflectivities within the specified volume (specified volume = 3 NM left, right, above and below flight path). If non-meteorological returns exist within the specified volume, VAHIRR cannot be calculated.
- If all returns within the specified volume are from meteorological targets, determine the average cloud bases using the lowest extent of 0 dBZ reflectivities within the specified volume or the 0° C level, whichever is highest. If non-meteorological returns exist within the specified volume, VAHIRR cannot be calculated.
- Determine the maximum reflectivity in the specified volume.
- Using the cloud thickness based on the average cloud tops and average cloud bases, determine if the maximum reflectivity is greater than the maximum allowed in Table 1.
 - If the maximum reflectivity is less than that in Table 1, VAHIRR provides relief from the Anvil Rule.
 - If the maximum reflectivity equals or exceeds that in Table 1, VAHIRR does not provide relief from the Anvil Rule.

Table 1. Criteria used to calculate VAHIRR. The first row shows the average cloud thickness and the second row shows the maximum reflectivity permitted for the corresponding cloud thickness in that column.												
Average Cloud Thickness (ft)	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
Maximum Reflectivity Allowed (dBZ)	33.00	16.50	11.00	8.25	6.60	5.50	4.71	4.13	3.67	3.30	3.00	2.75

2.2 Implementation of Manual VAHIRR Evaluation

The AMU calculated VAHIRR adhering to the steps provided by the 45 WS. The conditions that violated the anvil rule were not determined by the AMU but were provided in the launch weather summaries. If the launch weather summary identified a period as “red for anvil cloud” then the first step in the process was satisfied and the rest of the steps were then evaluated. Sections 2.3 through 2.8 describe how the steps for evaluating VAHIRR were addressed.

The stand-off criteria used to calculate VAHIRR requires vehicle clearances in both the horizontal and vertical. In order to determine if anvil cloud, radar reflectivities, lightning or the average cloud bases and tops had occurred within the specified distances, construction of a graphical overlay in the GR2Analyst software was required. The maximum clearance required is 10.8 NM for lightning from any given point along the vehicle’s trajectory, resulting in a spherical stand-off region. The radius of the sphere is 10.8 NM (65,622 ft) from the launch vehicle at all times. Therefore, the stand-off sphere moves with the vehicle as it moves downrange and gains altitude. Figure 1 shows a conceptual diagram of a nominal space shuttle launch trajectory for an International Space Station destination. According to the LAP rules for calculating VAHIRR, the altitude at which VAHIRR can no longer be calculated is approximately 66,000 ft. Therefore, when the shuttle reaches an altitude of approximately 132,000 ft, it is 10.8 NM above this point and it is no longer possible to calculate VAHIRR. At this point the shuttle is about 28 NM downrange from the launch site. Therefore, the total horizontal distance where VAHIRR must be calculated along the launch trajectory is a corridor about 38 NM in length and 10.8 NM to either side of the launch trajectory ground track.

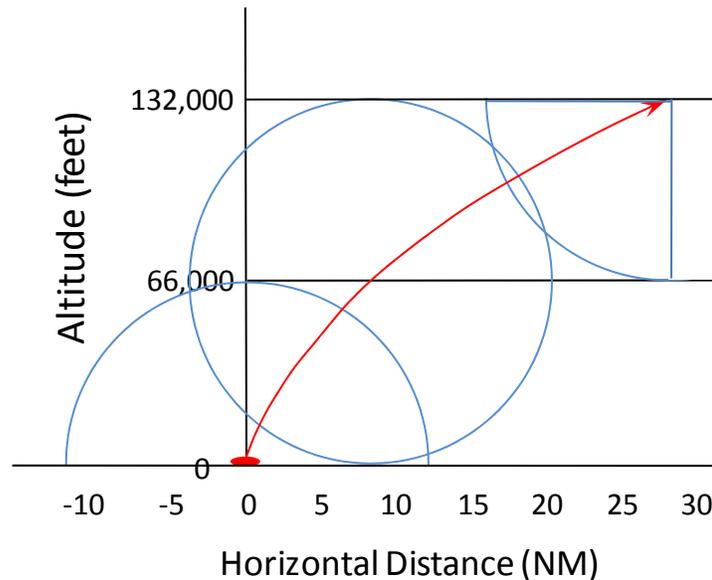


Figure 1. Diagram of a nominal space shuttle launch trajectory for an International Space Station destination. The blue circles each have a radius of 10.8 NM, which represents the clearance required to meet VAHIRR criteria.

Based on the criteria shown in Figure 1, the AMU developed a 2-D representation of the Figure 1 graphic to use as a VAHIRR overlay in the GR2Analyst software with radar and lightning plots. An example of a VAHIRR overlay for a space shuttle International Space Station launch is shown in Figure 2. The distance from the launch site to the end of the flight path is about 28 NM which is the point at which the VAHIRR criteria can no longer be evaluated due to the vehicle’s altitude. The three range rings and associated corridors of 3 NM, 5 NM and 10.8 NM help evaluate the VAHIRR clearance criteria as described in the steps for evaluating VAHIRR in Section 2.1.

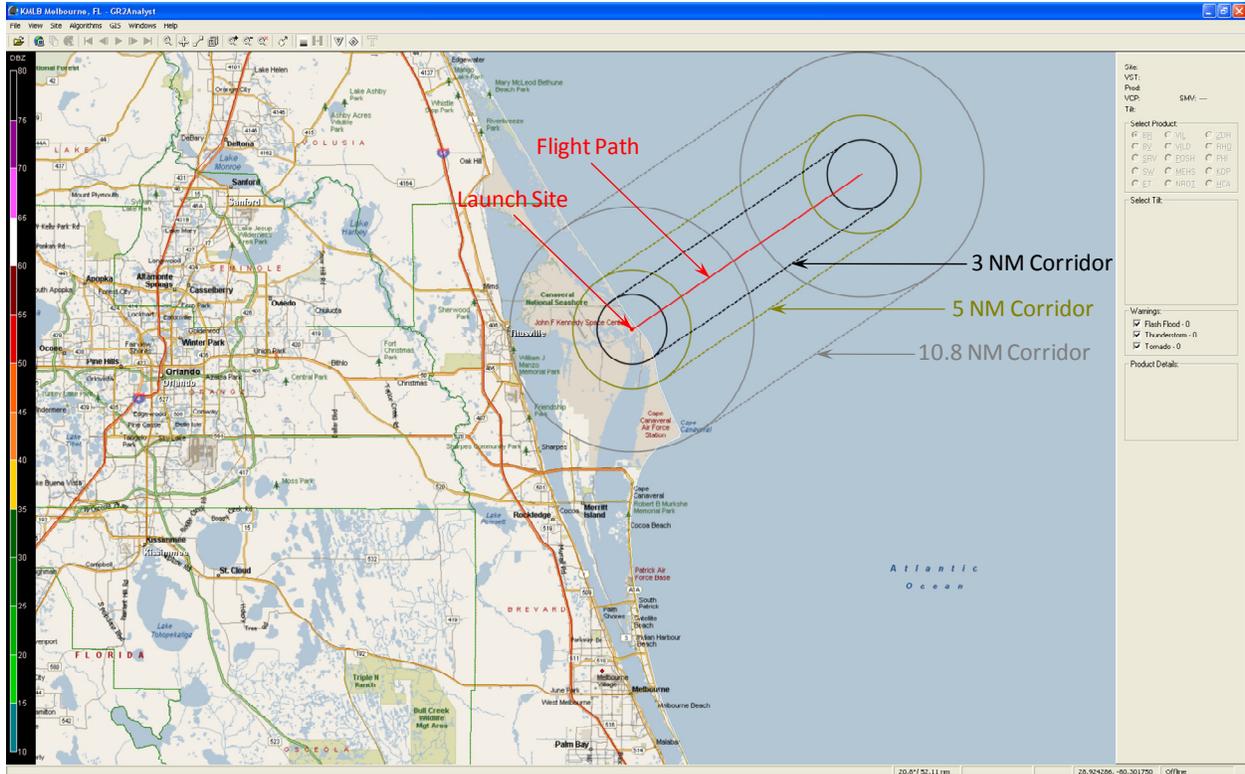


Figure 2. GR2Analyst main window showing the VAHIRR overlay used for a space shuttle launch to the International Space Station at a 51° azimuth. The red dot shows the location of the launch site and the red line represents the flight path from the launch site to 28 NM downrange. The circles represent radii of 3 (black), 5 (olive), and 10.8 NM (gray) from the center of the launch pad and the 28 NM downrange point, and the connecting tangential lines of the same colors represent the corridor.

2.3 Determining Anvil Cloud Location

Using Level II WSR-88D reflectivity data from the Melbourne, FL radar, the AMU displayed the radar reflectivity on the overlay created for GR2Analyst to determine if anvil cloud was within 5 NM of the flight path. This is shown as the area within the olive colored range rings and connecting lines in Figure 2. If the anvil cloud is within 5 NM of the flight path, it must also be located at altitudes colder than 0° C. This was determined by plotting the sounding taken at Cape Canaveral Air Force Station (XMR) in the RAOB software using the rawinsonde released closest to the time of the radar volume scan. An example of how the anvil cloud location was determined for STS-114 during a period the 45 WS launch summary indicated “red for anvil cloud” is described in the following paragraphs.

First, using the GR2Analyst software, the 0.5° tilt of radar reflectivity was displayed as shown in Figure 3. This radar volume scan was valid 4 May 2005 at 1112 UTC. It shows precipitation was west of KSC. Next, using the Volume Mode selection in GR2Analyst allowed a box to be drawn encompassing the outermost range rings in the overlay. This opened the Volume Explorer window as shown in Figure 4. The Volume Explorer provides a 3-D view of the radar reflectivity from all radar tilts in a given volume scan. Figure 4 shows anvil cloud in the vicinity of KSC at altitudes of about 18,000 ft to 31,000 ft. Then, by rotating the image in the Volume Explorer, a plan view of the radar reflectivity is displayed as shown in Figure 5. This provides a view of the location of the anvil cloud relative to the flight path, the 5 NM range rings and associated 5 NM corridor. In this example, anvil cloud was within 5 NM of the flight path. Finally, the anvil cloud within 5 NM of the flight path must be located at altitudes colder than 0° C to compute VAHIRR. To do this, a sounding from XMR taken at a time closest to the volume scan was plotted as a skew-T diagram in the RAOB software as shown in Figure 6. The RAOB software will automatically draw a horizontal line at the freezing level and display the freezing level height in a table on the skew-T diagram. This sounding taken on 4 May 2005 at 1115 UTC indicated all of the anvil cloud was above the 0° C level located at about 12,600 ft.

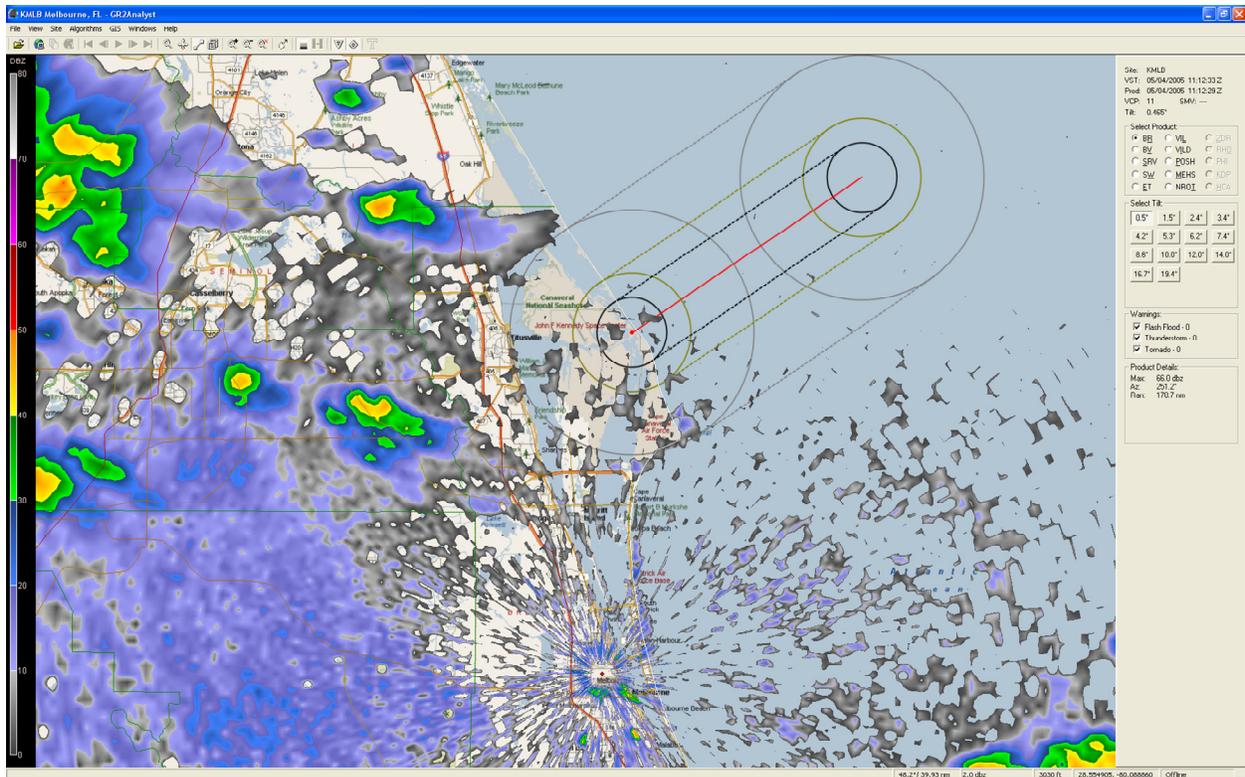


Figure 3. As in Figure 2 showing the 0.5° tilt of radar reflectivity valid 4 May 2005 at 1112 UTC.

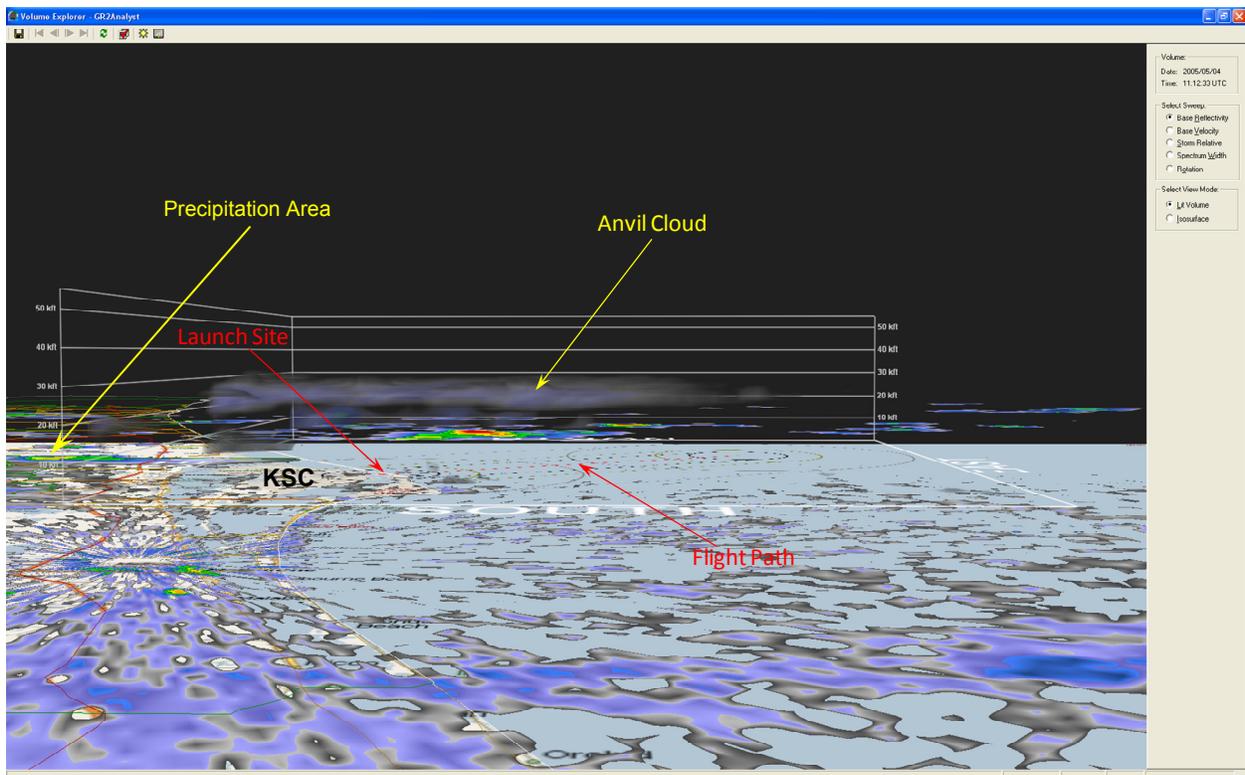


Figure 4. GR2Analyst Volume Explorer window displaying a 3-D view of the radar reflectivity from all radar tilts in a given volume scan valid 4 May 2005 at 1112 UTC. The anvil cloud can be seen at altitudes of about 18,000 ft to 31,000 ft extending eastward from the precipitation area northwest of KSC.

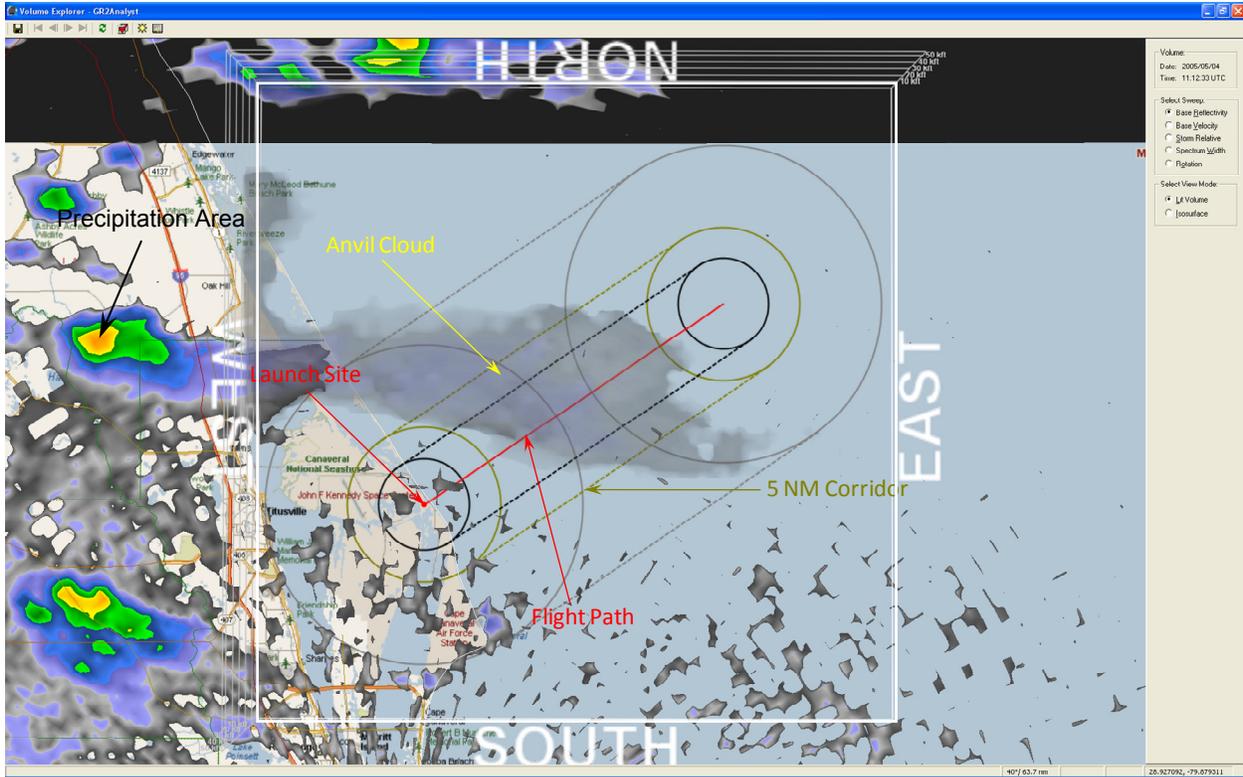


Figure 5. Plan view of the reflectivity displayed in the GR2Analyst Volume Explorer obtained by rotating the image shown in Figure 4. The 3-D volume of reflectivity is bounded by the white square with the labels NORTH, EAST, SOUTH and WEST at its perimeter. Only the 0.5° tilt of reflectivity is displayed outside this square.

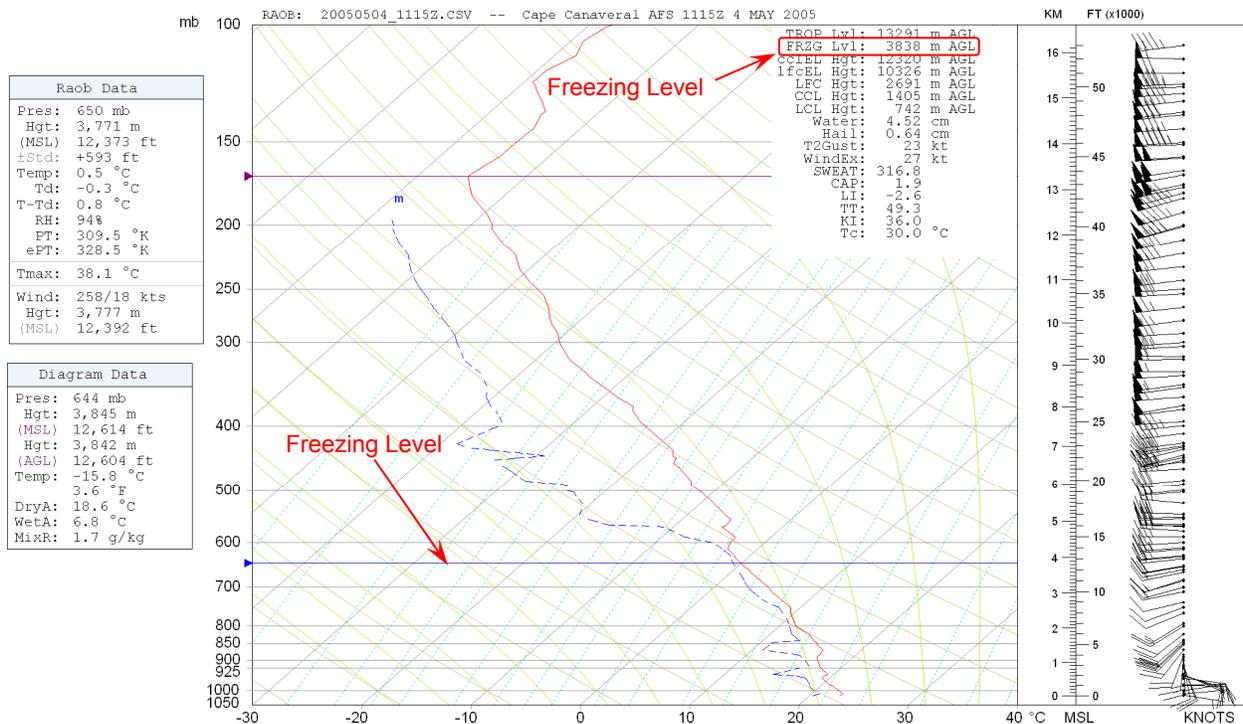


Figure 6. Skew-T diagram of the XMR sounding taken 4 May 2005 at 1115 UTC produced by the RAOB software. The freezing level is indicated in two places: by the horizontal blue line and in the table on the diagram.

2.4 Attenuation

The WSR-88D radar operates in the S-band at a wavelength of about 10 cm and corrects for gaseous attenuation of the microwave radar signal. Therefore, the principal attenuators are a wet radome and intervening precipitation. Both of these attenuators are considered to be small for S-band radars (Story 2006). However, Ryzhkov and Zmric (1995) indicated attenuation may have an effect during extremely heavy rain events.

To test for attenuation, the AMU looked for inconsistency in the radar images while looping the 0.5° tilt reflectivity. Typically, if a wet radome or heavy precipitation were attenuating the radar signal, it would be easily observed in the imagery as inconsistent changes in reflectivity from one volume scan to another. No attenuation occurrences were observed in the data for this task.

2.5 Radar Reflectivities Less Than 35dBZ

All radar reflectivities at or above 13,123 ft within 10.8 NM of the flight path must be less than 35 dBZ in order to calculate VAHIRR. To make this determination, the AMU used the Cross Section tool in GR2Analyst within the 10.8 NM corridor in the VAHIRR overlay (Figure 2). After determining the location of anvil cloud as discussed in Section 2.3, a vertical cross section line was drawn through the anvil cloud as shown in Figure 7.

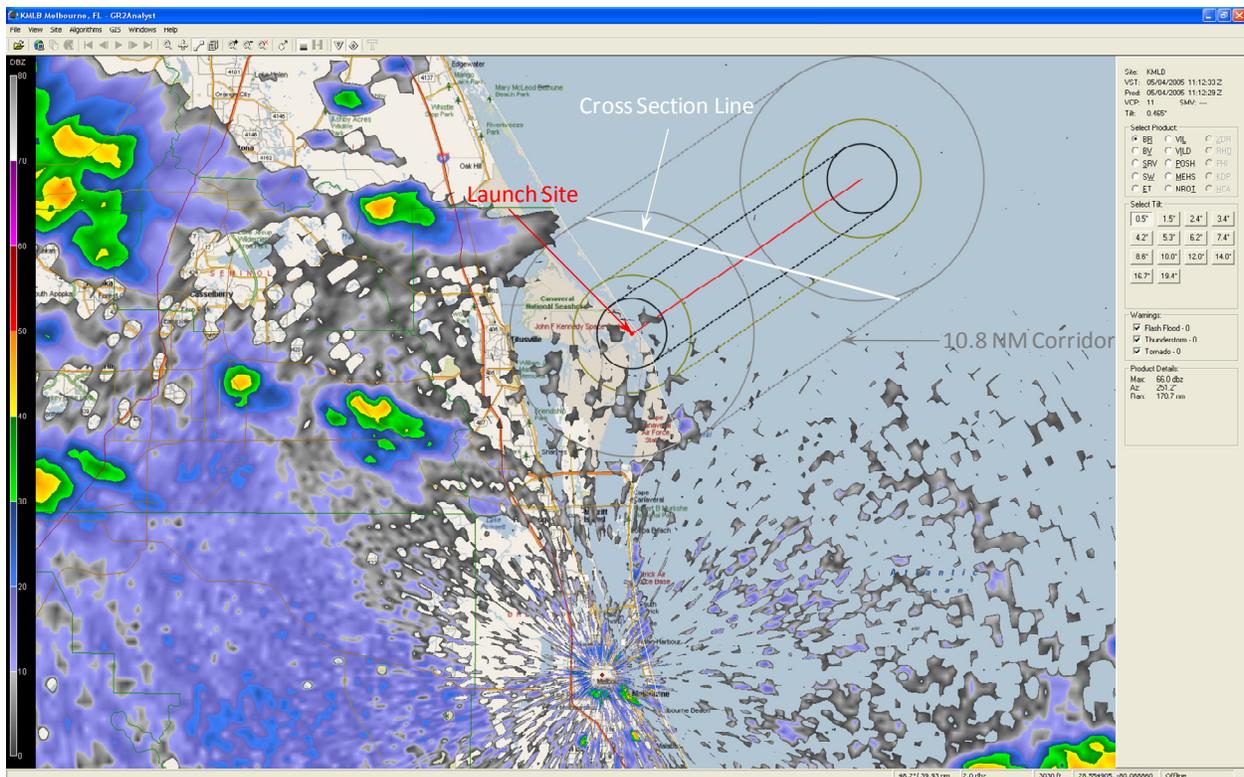


Figure 7. GR2Analyst main window showing the VAHIRR overlay with a cross section drawn (white line) across the 10.8 NM corridor (gray circles and gray lines) in the vicinity of the anvil cloud as shown in Figure 5.

Once the cross section line was drawn, the GR2Analyst Cross Section window automatically opened as shown in Figure 8. The cross section line is visible as the thick solid white line within the 10.8 NM range rings and corresponding corridor from the left side of the image (northwest) to the right side of the image (southeast) approximately parallel to and across the lengthwise center of the anvil cloud. The reflectivity of the anvil cloud was located from just under 20,000 ft to just over 30,000 ft. The reflectivity values in Figure 8 range from a minimum of 0 dBZ (dark gray) to a maximum of 16.5 dBZ (dark purple). The reflectivity values are displayed at the bottom of the window when the mouse is moved over each color in GR2Analyst. Two slider tools called “Position” and “Swing” available in the Cross Section window permitted the cross section line to be moved forward and backward as well as pivot about the point on the left end of the cross section. In this example, this capability allowed the AMU to assess the reflectivity values associated with the anvil cloud vertical cross section to the southwest and northeast

of where the cross section was initially drawn. The slider tools made it easy to quickly assess whether or not any reflectivity values > 35 dBZ were present above 13,123 ft. The AMU determined there were no reflectivity values > 35 dBZ at altitudes above 13,123 ft and, therefore, the steps to calculate VAHIRR could be continued.

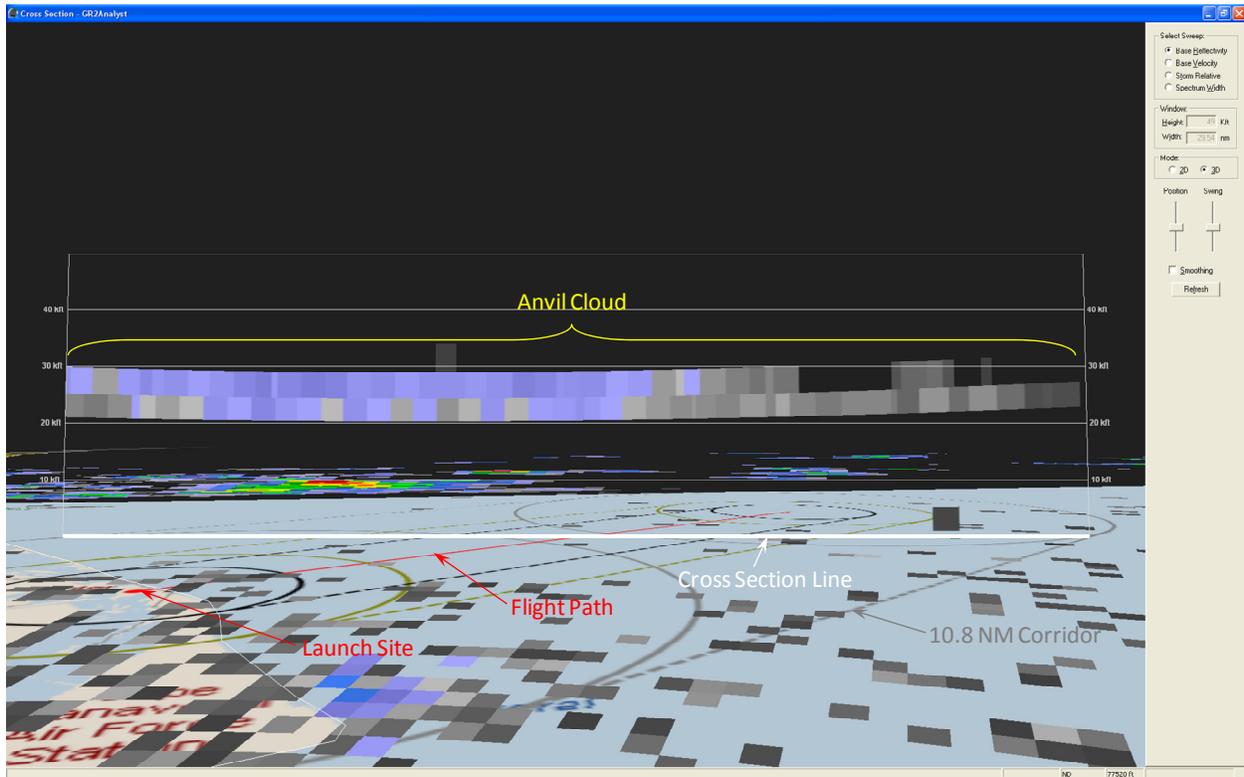


Figure 8. GR2Analyst Cross Section window depicting the anvil cloud in the vertical cross section of reflectivity along the cross section line within the 10.8 NM corridor. The cross section line (thick horizontal solid white line) extends from northwest on the left of the image to the southeast on the right. Increasing altitude is from the bottom to top of the cross section area.

2.6 Lightning

Lightning must not occur within 10.8 NM of the flight path within the last 5 minutes in order to calculate VAHIRR. The AMU used lightning strike data from the ER Cloud-to-Ground Lightning Surveillance System (CGLSS) to make this determination. The CGLSS is a network of six sensors (Figure 9) that collects date/time, latitude/longitude, strength, and polarity information of cloud-to-ground lightning strikes in the KSC area.

The daily CGLSS data were separated into 5-minute intervals ending at the time of each WSR-88D volume scan evaluated. The data were manipulated in Microsoft Excel and saved as dBase 4.0 formatted files. The files were then converted to Placefile format so they could be ingested into the GR2Analyst software and then displayed as an overlay with the radar reflectivity. This allowed the AMU to assess whether or not each lightning strike in a period 5 minutes prior to the radar volume scan occurred within 10.8 NM of the flight path. Figure 10 shows an overlay of CGLSS data on 4 May 2005 at 1152 UTC. Lightning strikes associated with a thunderstorm were located about 35 NM northwest of KSC. Each lightning strike is depicted by a yellow lightning bolt icon within the area highlighted by a red circle.

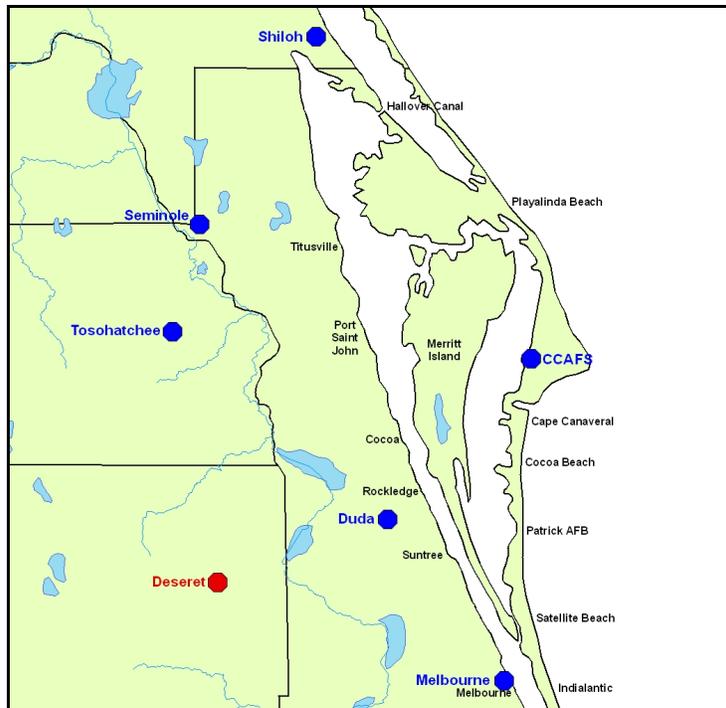


Figure 9. The locations of the six CGLSS sensors are indicated by the blue circles. The location names are next to the circles. The Duda sensor was moved to the Deseret site (red circle) in 2005.

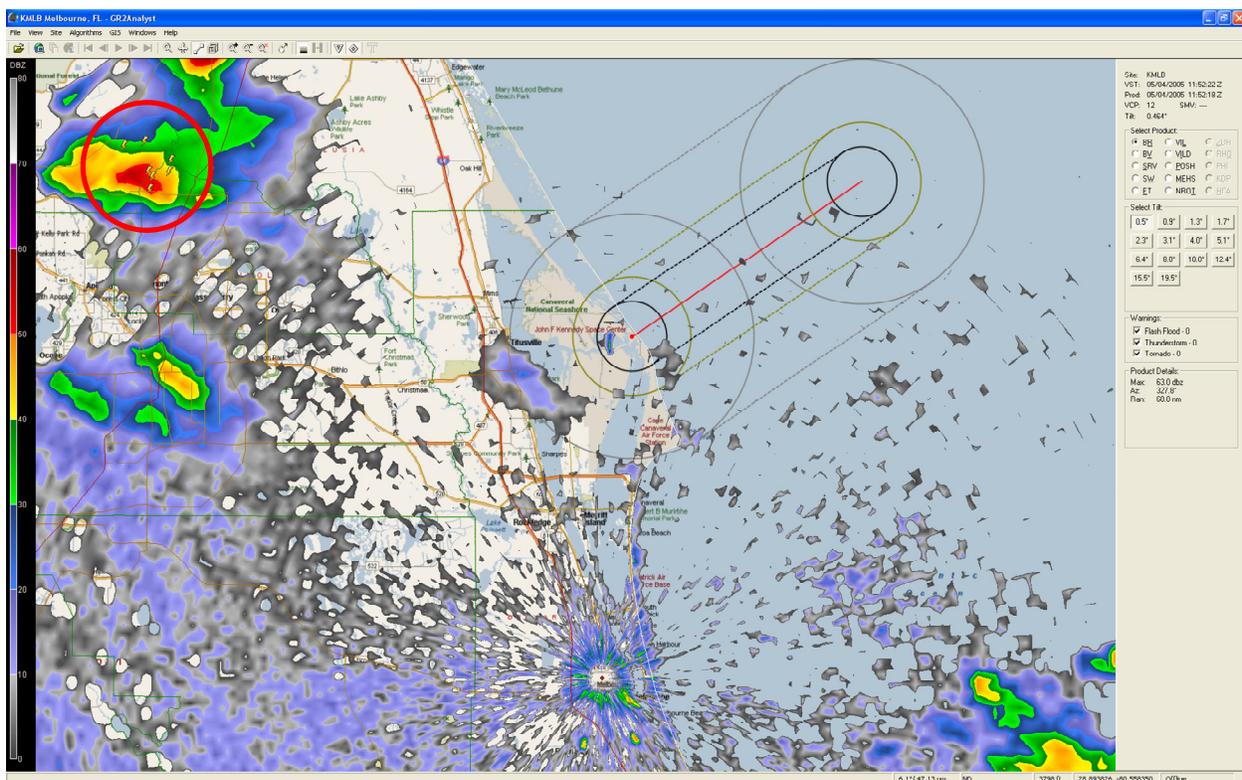


Figure 10. GR2Analyst main window showing the CGLSS data overlaid on the radar reflectivity volume scan valid 4 May 2005 at 1152 UTC. Lightning strikes (yellow lightning bolt icons) occurred between 1147 and 1152 UTC and were located about 35 NM northwest of KSC inside the red circle.

2.7 Anvil Cloud Tops and Bases plus Maximum Reflectivity

The thickness of the anvil cloud must be determined to calculate VAHIRR. To do so, the average height of the cloud tops and average height of the cloud bases must be established. The average cloud tops are determined by using the highest extent of 0 dBZ reflectivities within the specified volume. The average cloud bases are determined by using the lowest extent of 0 dBZ reflectivities within the specified volume or the 0° C level, whichever is highest. The specified volume is defined as 3 NM left, right, above and below flight path.

To determine the average cloud tops and bases, the AMU used the Cross Section tool in GR2Analyst within the 3 NM corridor in the VAHIRR overlay (Figure 2). The cross section line was drawn along the flight path to keep it within the defined specified volume of 3 NM as shown in **Error! Reference source not found.**

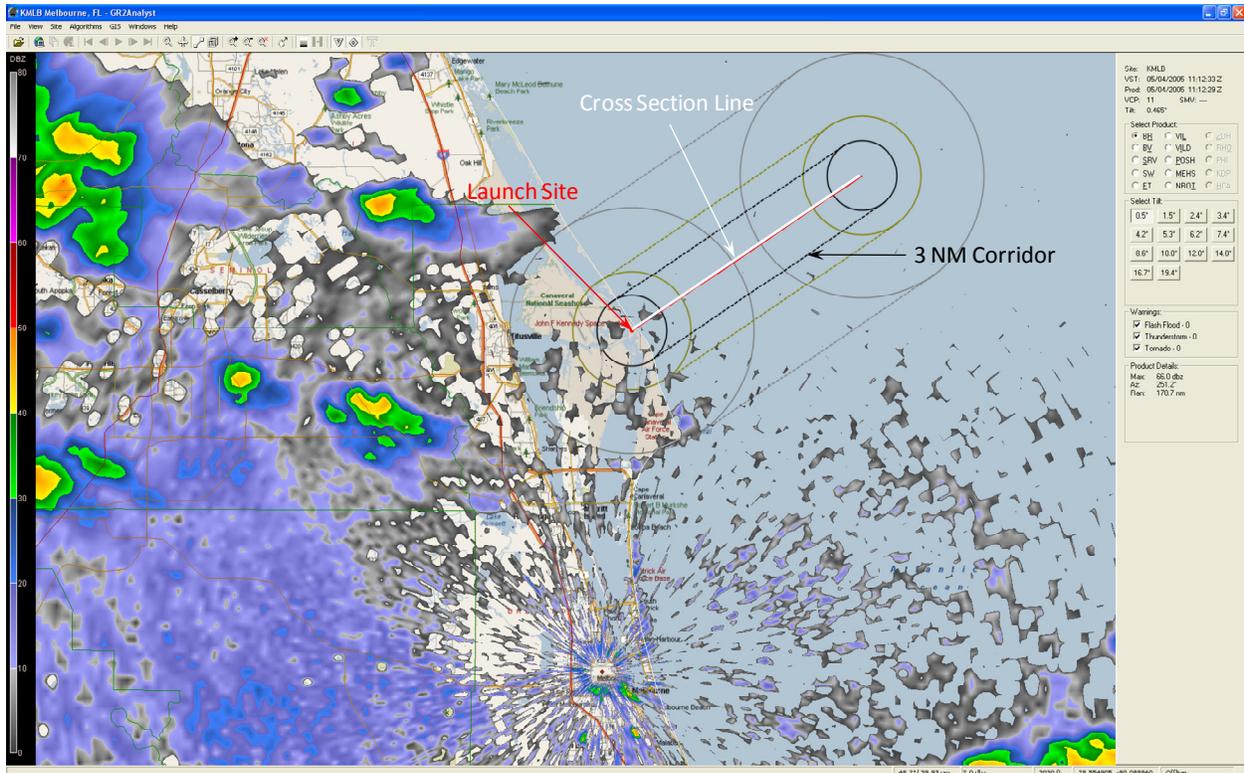


Figure 11. GR2Analyst main window showing the VAHIRR overlay with a cross section drawn (white line) along the flight path and within the 3 NM corridor (black circles and black lines).

Once the cross section line was drawn, the GR2Analyst Cross Section window automatically opened as shown in Figure 12. The cross section line is visible as the thick solid white line drawn along the flight path. The reflectivity indicates the average anvil cloud tops were located at about 29,500 ft. The average anvil cloud bases were located at about 21,000 ft, which was above the freezing level of 12,600 ft. In this example, the AMU determined the anvil cloud thickness was about 8,500 ft.

Once the anvil cloud thickness was known, the maximum reflectivity value of the anvil cloud needed to be determined. The “Position” slider tool was used to move the cross section line forward and backward parallel to the flight path in order to sample the entire anvil cloud within the specified volume of 3 NM. In this example the maximum reflectivity was 16.5 dBZ.

2.8 Determining VAHIRR

The final step to calculate VAHIRR requires using the anvil cloud thickness to determine if the maximum reflectivity is greater than the maximum allowed as shown in Table 1. For this example, with an anvil cloud thickness of 8,500 ft and maximum reflectivity of 16.5 dBZ, VAHIRR would not have given relief to the Anvil Rule. For the maximum reflectivity found, the maximum anvil cloud thickness permitted was 2,000 ft, and for the anvil thickness found, the maximum reflectivity permitted was 3.88 dBZ.

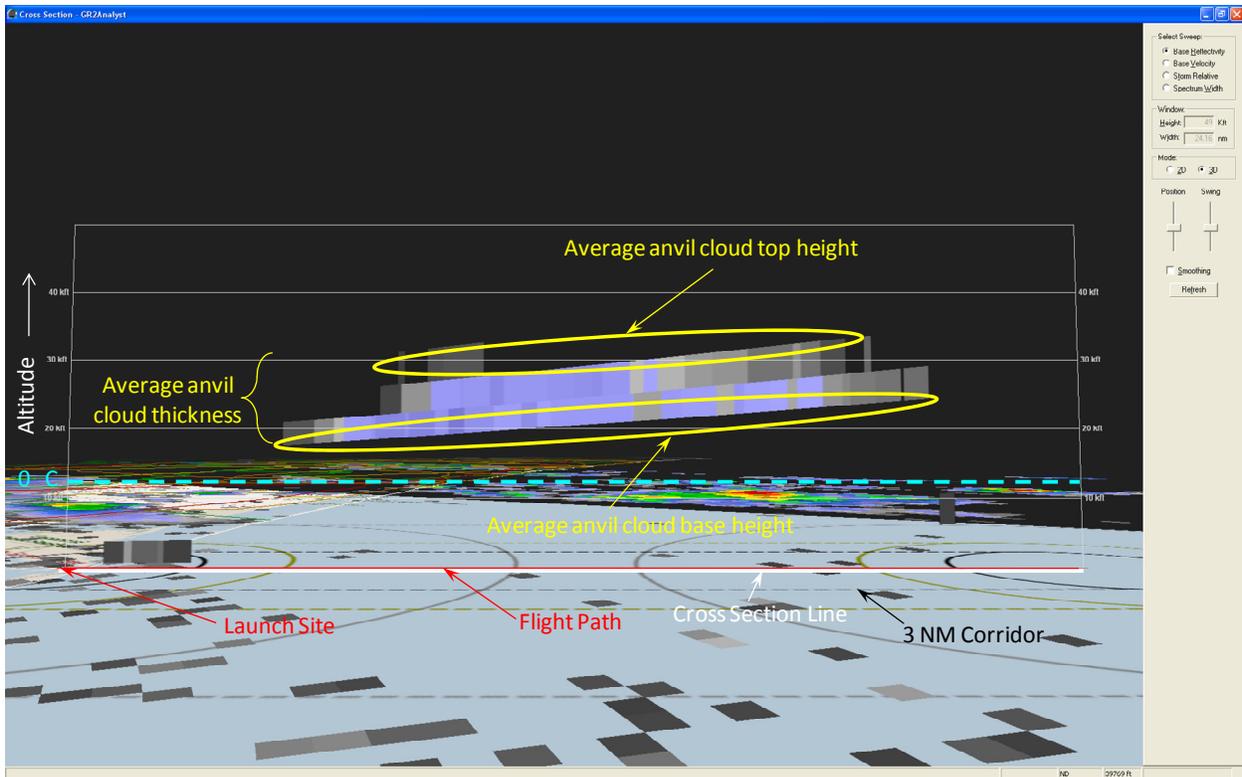


Figure 12. GR2Analyst Cross Section window depicting the anvil cloud in the vertical cross section of reflectivity along the flight path within the 3 NM corridor. The cross section line (thick horizontal solid white line) extends from 3 NM southwest of the launch site on the left of the image to 3 NM northeast of the end of the flight path (horizontal red line) on the right. The freezing level (0°C) is shown by the horizontal dashed white line.

3. Results

Because of the requirement that lightning cannot occur within 10.8 NM of the flight path 5 minutes prior to calculating VAHIRR and each WSR-88D volume scan is about 5 minutes in length, the AMU calculated VAHIRR for every WSR-88D volume scan when the 45 WS launch weather summaries indicated a red condition for anvil cloud and radar data was available.

3.1 Launches Used

The 45 WS provided launch weather summaries for the following 10 operations.

- STS-111 – 30 May 2002
- Delta IV DSCS A3 – 9 March 2003
- Delta II MER-A – 8-9 June 2003
- Delta II MER-B – 28-29 June 2003
- Delta IV DSCS B6 – 28 August 2003
- Delta II GPS – 19-23 June 2004
- Delta II Messenger – 2-3 August 2004
- STS-114 – 4 May 2005 and 13 July 2005
- STS-121 – 1-2 July 2006
- STS-117 – 8 June 2007

These operations were chosen by the 45 WS because they all experienced at least one red condition for LLCC during the countdown. The Delta MER-A operation did not experience any anvil cloud LLCC violations and the Delta IV DSCS A3 launch weather summary did not contain sufficient details for what type or when the LLCC occurred. Therefore, these two operations were not used.

WSR-88D data in Level II format was required to calculate VAHIRR. Archived Level II data from the Melbourne, FL radar was not available for the Delta II GPS operation or for the Delta II Messenger operation, so these two operations could not be used.

Launch weather summaries and data were available for the remaining 6 launch operations. Several of these operations occurred over multiple days due to scrubs. Also, LLCC for anvil cloud was violated for a sufficient amount of time during these 6 operations to conduct a thorough data analysis, the results of which are discussed in Section 3.2.

3.2 Data Analysis

In the 45 WS launch weather summaries from the six launch operations with usable information and data, the anvil cloud LLCC were identified as red for 2,314 minutes. All necessary data required to calculate VAHIRR were available 74% of that time. This included 344 usable 5-minute volume scans of WSR-88D data.

The AMU did not take into account whether or not other weather LCC violations were occurring at the same time as the anvil cloud LLCC since the goal of this task was to determine how often VAHIRR provided relief to the anvil cloud LLCC. Therefore, in the statistics presented here, it is possible that even though VAHIRR provided relief to the anvil cloud LLCC, other weather LCC could have been violated not permitting the launch to proceed.

Of the 344 usable radar volume scans, VAHIRR was not calculated for 95 volume scans due to radar reflectivity values > 35 dBZ above 13,123 ft within 10.8 NM of the flight path and for 32 volume scans due to lightning within 10.8 NM of the flight path and it could not provide relief from the anvil cloud LLCC rule. Therefore, VAHIRR was calculated for 217 of the radar volume scans of which 155 indicated VAHIRR values were too large to provide relief from the anvil cloud LLCC violations. For the remaining 62 volume scans, VAHIRR values were small enough to provide relief from the anvil cloud LLCC violations. However, of these 62 events were combinations of single 5-minute periods and multiple 5-minute periods. This raised the question how much time launch directors and flight directors require to make a decision from “NO-GO” for anvil cloud LLCC violations to

“GO” based on VAHIRR. Therefore, the results are presented as shown in Figure 13 which indicates the number of consecutive 5-minute periods that VAHIRR provided relief for an observed red anvil cloud LLCC condition.

- 18.0% of the time (62 out of 344) VAHIRR provided relief for at least one consecutive 5-minute time period,
- 16.3% of the time (56 out of 344) VAHIRR provided relief for least two consecutive 5-minute time periods,
- 15.7% of the time (54 out of 344) VAHIRR provided relief for least three consecutive 5-minute time periods,
- 15.4% of the time (53 out of 344) VAHIRR provided relief for least four consecutive 5-minute time periods, and
- 15.1% of the time (52 out of 344) VAHIRR provided relief for five or more consecutive 5-minute time periods

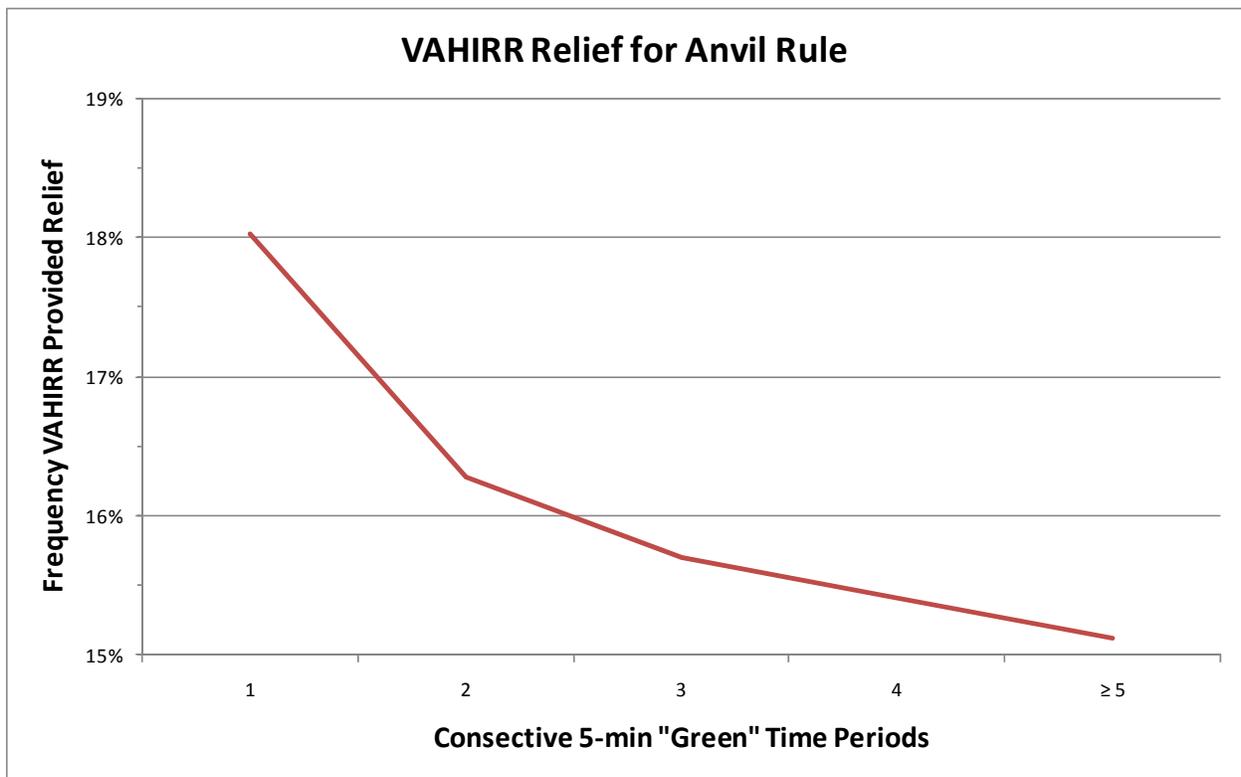


Figure 13. Frequency VAHIRR provided relief to the anvil cloud LLCC rule based on the number of consecutive 5-minute periods when VAHIRR would have allowed a launch to proceed.

4. Summary and Conclusions

The LLCC are designed to prevent space launch vehicles from flight through environments conducive to natural or triggered lightning and are used for all U.S. government and commercial launches at government and civilian ranges. The LLCC for anvil clouds was upgraded in the summer of 2005 to incorporate results from the ABFM experiment at the ER. From numerous combinations of parameters considered, VAHIRR was chosen to have the best correlation of operational weather observations to in-cloud electric fields capable of rocket triggered lightning in anvil clouds. Based on these findings, the KSC Weather Office is considering seeking funding for development of an automated VAHIRR algorithm for the new 45 WS RadTec 43/250 weather radar and WSR-88D radars and tasked the AMU to conduct this cost-benefit analysis.

The 45 WS and 30 WS provided the AMU with launch weather summaries from past launches impacted by LLCC. These summaries helped the AMU determine when the LLCC were “red” due to anvil cloud. The AMU manually calculated VAHIRR using WSR-88D radar reflectivity, cloud-to-ground lightning strikes, soundings and satellite imagery. The results of these calculations indicated VAHIRR provided relief from the anvil cloud LLCC between about 15% and 18% of the time for varying 5-minute time periods based on summaries from six launch attempts and would have allowed launches to proceed that were otherwise “NO GO” due to the anvil cloud LLCC if the T-0 time occurred during the anvil cloud LLCC violations.

Calculating VAHIRR manually is time consuming and not suited for fast-paced operations. It took about 7-8 minutes to calculate VAHIRR manually for each radar volume scan. Given that the WSR-88D volume scans are about 5 minutes in length, would not allow a real time VAHIRR calculation for each volume scan. Additionally, the new 45 WS radar will produce a volume scan every 2-3 minutes making it even more difficult to manually calculate VAHIRR in real time. An automated algorithm would assist Launch Weather Officers in making this critical decision.

References

- Dye, J. E., M. G. Bateman, D. M. Mach, C. A. Grainger, H. J. Christian, H. C. Koons, E. P. Krider, F. J. Merceret, and J. C. Willett, 2006: The Scientific Basis for a Radar-Based Lightning Launch Commit Criterion for Anvil Cloud. Preprints, *12th Conf. on Aviation, Range and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., 4 pp. [Available online at: <http://ams.confex.com/ams/pdfpapers/100563.pdf>]
- Dye, J. E., M. G. Bateman, H. J. Christian, E. Defer, C. A. Grainger, W. D. Hall, E. P. Krider, S. A. Lewis, D. M. Mach, F. J. Merceret, and J. C. Willett, and P. T. Willis, 2007: Electric fields, cloud microphysics and reflectivity in anvils of Florida thunderstorms, *J. Geophys. Res.*, **112**, D11215, doi10.1029/2006JD007550.
- Merceret, F. J., M. McAleenan, T. M. McNamara, J. W. Weems, and W. P. Roeder, 2006: Implementing the VAHRR Launch Commit Criteria Using Existing Radar Products. Preprints, *12th Conf. on Aviation, Range and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., 8 pp. [Available online at: <http://ams.confex.com/ams/pdfpapers/98076.pdf>]
- Ryzhkov, A., and D. Zrnich, 1995: Precipitation and attenuation measurements at a 10-cm wavelength. *J. Appl. Meteor.*, **35**, 2121-2134.
- Story, G. J., 2006: Determining WSR-88D precipitation algorithm performance using the Stage III precipitation processing system, National Weather Association Electronic Journal. [Available online at <http://www.nwas.org/ej/story/>]
- Willett, J. C., H. C. Koons, E. P. Krider, R. L. Walterscheid, and W. D. Rust, 1999: Natural and Triggered Lightning Launch Commit Criteria (LLCC), Aerospace Report A923563, Aerospace Corp., El Segundo, CA, 23 pp.

List of Acronyms

30 WS	30th Weather Squadron	NM	Nautical Miles
45 WS	45th Weather Squadron	NWS	National Weather Service
ABFM	Airborne Field Mill	POR	Period of Record
AMU	Applied Meteorology Unit	RAOB	Universal Rawinsonde Observation software
CCAFS	Cape Canaveral Air Force Station	SMG	Spaceflight Meteorology Group
ER	Eastern Range	WSR-88D	Weather Surveillance Radar-1988 Doppler
KSC	Kennedy Space Center	VAHIRR	Volume Averaged Height Integrated Radar Reflectivity
LAP	Lightning Advisory Panel	WR	Western Range
LLCC	Lightning Launch Commit Criteria	XMR	CCAFS rawinsonde 3-letter identifier
NOAA	National Oceanic and Atmospheric Administration		

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