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Report on the Radar/PIREP Cloud Top Discrepancy Study

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Executive Summary

The objective for this study is to document and understand the differences in echo heights on the WSR-88D and WSR-74C radars and cloud top heights reported by the contract weather aircraft in support of space launch operations at Cape Canaveral Air Station (CCAS), Florida. These inconsistencies are of operational concern since various Launch Commit Criteria (LCC) and Flight Rules (FR) describe, in part, safe and unsafe conditions as a function of cloud thickness.

This study focuses on:

- Cloud top (or echo top) height inconsistencies between the contract weather aircraft reports and those observed on the two weather radars (WSR-88D and WSR-74C).
- Identification of atmospheric conditions that may produce anomalous propagation of radar signals which result in misleading user display products (e.g. echo top heights).

The Range Weather Operations (RWO) forecasters use various products from the two weather radars to evaluate weather-related LCC and FR. Specifically, reflectivity intensity estimates from the weather radar are used to determine the location, distribution, movement, thickness, intensity, and trends of rain showers, cumulus clouds, thunderstorms, anvils, and debris clouds near the launch site or projected flight path of the vehicle. For weather radar applications a standard atmosphere is assumed. Large departures from the standard atmosphere like temperature inversions, produce anomalous index of refraction gradients and significant deviations in actual ray path from those predicted by the Effective Earth Radius Model. These conditions are refereed to as Anomalous Propagation (AP). Operators must watch for atmospheric departures from the standard.

A radar's transmitted energy is reflected by the Earth's surface and refracted by the atmosphere, which affects both the accuracy and the total coverage of a radar. For typical weather radar configurations with standard atmospheric conditions, the Earth's refractivity effect is limited to ground clutter near the radar because of side lobes and interference from nearby structures. However, refraction occurs near or at a distance from the radar due to atmospheric conditions and must be considered as it greatly affects the display of radar data. Unfortunately, it is very difficult to accurately predict the precise path of the radar beam because of the lack of information about the structure of the atmosphere along the beam's path and the dynamic nature of the atmosphere.

The 45 Weather Squadron (45WS) has documented 2 cases where radar-detected echo tops and weather aircraft reports of cloud top heights were as much as 1.2 km (4000 ft) different. The 2 cases were during a Delta launch operations on 30 December 1995 between 1000 and 1348 UTC and another Delta operation on 12 September 1996 between 0500 and 0849 UTC. From the analysis of the rawinsonde, profiles of Index of Refraction (IR), and WSR-88D data from 30 December 1995 it is evident that atmospheric refraction (superrefraction and/or ducting) caused the cloud height discrepancies between the weather radars and the reported conditions from the contract weather aircraft. During the launch operation a strong inversion formed at about 14000 ft. causing the weather radar beams to be bent back more toward the Earth and thus displaying erroneous radar height information and stronger radar returns (Anomalous Propagation (AP)). It also appears that atmospheric refraction (superrefraction and/or ducting) caused the radar beams to be trapped or bent back toward the Earth, which

resulted in the radar echo top errors on 12 September 1996. The atmospheric conditions (very dry air advecting over a moist layer) were similar to the 30 December 1995 event that caused the radar beam to be bent back toward the Earth thus causing higher radar echo tops to be display on the weather radars. From the analysis of the rawinsonde and profiles of IR, it is evident that superrefraction and/or ducting caused the cloud/echo height discrepancies between the weather radars and the contract weather aircraft.
The differences between the echo tops displayed on the radars and the aircraft observed top can be attributed to atmospheric conditions (strengthening inversion or areas of temperature and water vapor discontinuity) that caused the radar beam to be refracted downward or trapped (i.e. superrefraction and/or ducting).
Most significant refraction gradients are in the vertical. Therefore, the problem is generally treated as two-dimensional with profiles of vertical refraction (i.e. index of refraction or refraction index). The two types of refraction that caused the echo height inconsistencies are:

- Superrefraction - Beam curvature is downward, more sharply than normal. Echo top measurements will be too high because of the differences in beam curvature from standard. Estimated echo tops will be HIGHER than standard. When AP occurs, it is more frequently due to superrefraction.
- Ducting (Trapping) - Beam curvature is downward, equal to or greater than the earth's curvature. Echoes close to the radar will be distorted (may appear higher), and the radar will detect echoes at longer ranges. This type of refraction is usually associated with very dry conditions. However, dry conditions above a moist layer can also produce this type of propagation resulting in misleading radar returns.

Both of the echo/cloud top inconsistencies cases illustrate that deviations from standard atmospheric conditions can cause anomalous propagation of radar beams resulting in misleading radar returns. Instead of following the path predicted by the 4/3 earth's radius model the radar beam is bent further downward toward the earth because of changes in the vertical gradient of IR with height. When the radar beam is abnormally bent in this fashion, the radar returns can be misleading and abnormal (i.e. blocky, stretched). Furthermore, the calculated echoes tops will probably be higher than normal due to the abnormal bending of the radar beam (See Figure 5.1).
The two occurrences of reported cloud/echo top discrepancies can be attributed to deviations from standard atmospheric conditions. During both launch operations much drier air in the mid-levels advected into the CCAS area over a lower moist layer in the atmosphere. Atmospheric refraction (superrefraction and/or ducting) was identified as the cause of the discrepancies between reported cloud top heights by the contract weather aircraft and those as identified by both radars. The atmospheric refraction caused the radar beam to be refracted toward the Earth more than normal. This anomalous propagation causes the radar target to be displayed erroneously, with higher cloud top heights and a very blocky or skewed appearance.

1.0 Introduction

1.1 Purpose of the Report

This report documents the results of the Applied Meteorology Unit's (AMU) investigation of inconsistencies between pilot reported cloud top heights and weather radar indicated echo top heights (assumed to be cloud tops) as identified by the 45 Weather Squadron (45WS). The objective for this study is to document and understand the differences in echo top characteristics as displayed on both the WSR-88D and WSR-74C radar and cloud top heights reported by the contract weather aircraft in support of space launch operations at Cape Canaveral Air Station (CCAS), Florida. These inconsistencies are of operational concern since various Launch Commit Criteria (LCC) and Flight rules in part describe safe and unsafe conditions as a function of cloud thickness.

This study focuses on:

- Cloud top (or echo top) height inconsistencies between the contract weather aircraft reports and those observed on the two weather radars (WSR-88D and WSR-74C).
- Identification of atmospheric conditions that may produce anomalous propagation of radar signals which result in misleading user display products (e.g. echo top heights).

The 45 Weather Squadron (45WS) has documented 2 cases where radar-detected echo tops and weather aircraft reports of cloud top heights were as much as 1.2 km (4000 ft) different. The 2 cases were during launch operations on 30 December 1995 between 1000 and 1348 UTC and 12 September 1996 between 0500 and 0849 UTC.

1.2 Organization of the Report

The remainder of the report is organized as follows. Section 2 describes differences between the WSR-88D and McGill radars; Section 3 details radar propagation; Section 4 describes the two case studies listed above; Section 5 presents a list of issues and concerns with radar propagation; and a summary and list of recommendations are included in Section 6.

2.0 Radar Background

2.1 WSR-74C and WSR-88D Radars

The PAFB WSR-74C (5 cm) radar consists of a WSR-74C radar controlled by a Volumetric Scan Processor developed by McGill University (McGill). The WSR-74C radar is a C-band weather radar which is capable of detecting the presence and intensity of precipitation within a 370 km (200 NM) radius of PAFB. The PAFB McGill radar is used primarily for weather support to Eastern Range (ER) operations at PAFB and at CCAS/KSC. It was installed at PAFB in March 1984. In 1987 the radar system was modified to include the McGill Volumetric Scan Processor. The processor subsystem controls the antenna, raising it through 24 different elevation angles in a five minute period and collects, stores and processes the three-dimensional reflectivity data. Subsystem display workstations are located in the Range Weather Operations (RWO) and the AMU in the Range Operations Control Center (ROCC) at CCAS. The workstations can produce and display a number of user selected products including Constant Altitude Plan Position Indicator (CAPPI) reflectivity products from 1.5 to 19.8 km (5000 - 65000 ft), reflectivity vertical cross-sections, and echo-top reflectivity products. Echo top products are displayed as the height of the 18 dBZ Maximum.

The NEXRAD WSR-88D (10 cm) radar is located at the Melbourne NWS Forecast Office. The WSR-88D has greater sensitivity and Doppler capability. The radar is used to support the space launch community and also is used in support of NWS and FAA requirements. It became certified for operations in March 1994. As a fully coherent "Doppler" radar, the WSR-88D provides not only information on the location, distribution, and intensity of precipitation, but also provides measurements of the radial component of motion of the scatterers and the dispersion of radial velocities in the sampling volume.

The WSR-88D includes the following:

- A radar composed of transmitter, receiver, antenna and associated support circuitry,
- Dedicated signal processors which produce estimates of reflectivity intensity, radial velocity, and spectrum width, and
- Data analysis and display subsystems which produce meteorological products and displays.

WSR-88D radar data displays are generated by the Principal User Processor (PUP). Echo tops products display the maximum height of the 18.5 dBZ return. PUPs with dedicated communications lines to the NWS MLB WSR-88D are located in the MLB NWS office, the RWO and AMU at CCAS, the Base Weather Station at PAFB and at SMG at JSC.

The RWO weather forecasters use various products from the two weather radars to evaluate weather-related LCC and flight rules. Specifically, reflectivity intensity estimates from the weather radar are used to determine location, distribution, movement, thickness, intensity, and trend of rain showers, cumulus clouds, thunderstorms, anvils, and debris clouds near the launch site or projected flight path of the vehicle. To further enhance these reports, the RWO uses pilot reports from a contract operated aircraft for LCC and flight rule evaluation.

2.2 Radar Scan Strategies

The specific strengths and weaknesses of each system are important because the radar scan strategy and the current atmospheric conditions may cause radar returns which can be misleading to the operator. The WSR-88D uses several Volume Coverage Patterns (VCPs) while the WSR-74C uses one scan strategy, see Taylor (1994) for a detailed comparison of WSR-88D and WSR-74C scan strategies. The scan strategy of each radar is defined by beam width, the number of elevation scans and angles and the refresh rate (VCP11 = 5 min, VCP21 = 6 min and VCP31/32 = 10 min).

The fraction of a vertical cross-section of the atmosphere illuminated by the radar is determined by estimating the radar beam paths using the Effective Earth Radius Model (EERM) (Doviak and Zrnic, 1993) and the radar elevation angles and beam widths. The EERM (Figure 2.1) model estimates beam height, **h**, as a function of great circle distance, **s**, and the elevation angle of a ray leaving the radar, **q**, as

$$h = a_e * \left[\frac{\cos(\theta)}{\cos\left(\theta + \frac{s}{a_e}\right)} - 1 \right]$$

In this model, $\mathbf{a_e}$ is the effective earth radius and, based upon research results, is

$$a_e = 4a/3$$

where **a** is the earth's radius.

For weather radar applications, this EERM model can be used for all elevation angles if **h** is restricted to the first 10-20 km (32000 - 66000 ft) of the atmosphere and if the index of refraction has a gradient of approximately -1/(4**a**) in the first kilometer of the standard atmosphere. Large departures from the standard atmosphere like temperature inversions, produce anomalous index of refraction gradients and significant deviations in actual ray path from those predicted by the Effective Earth Radius Model. These conditions are refereed to as Anomalous Propagation (AP). Operators must watch for atmospheric departures from the standard.

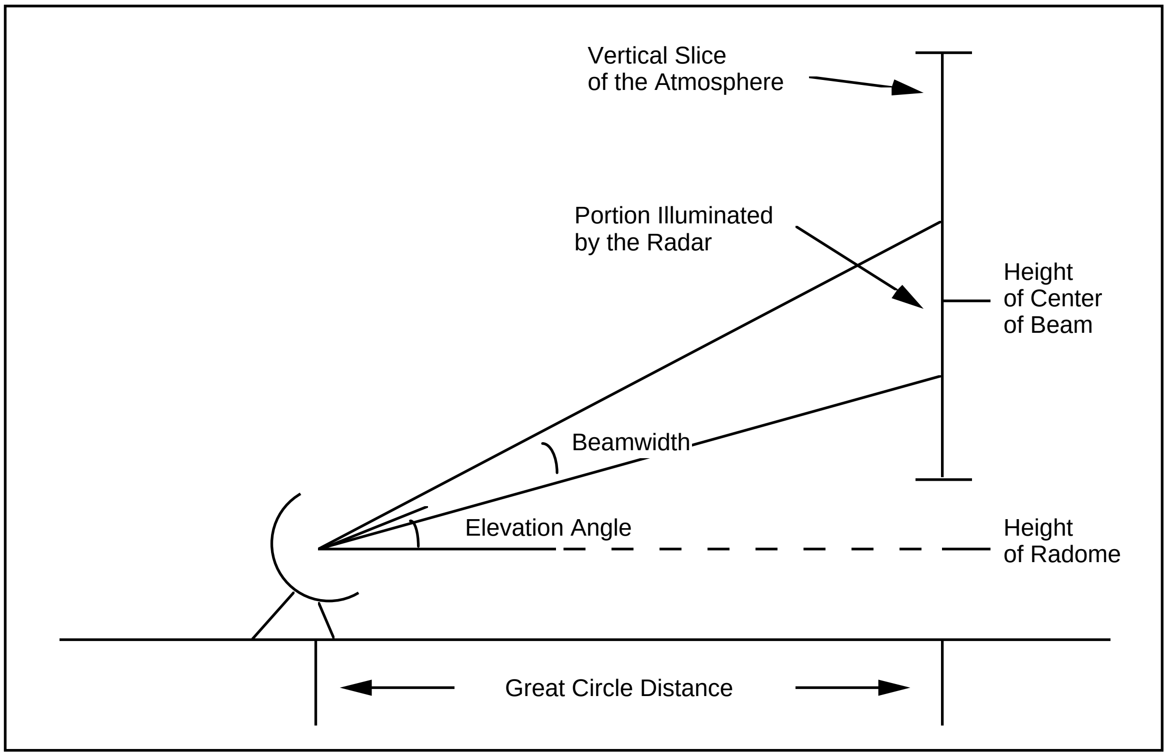

Figure 2.1. Conceptual illustration of the fraction of a vertical section of the atmosphere illuminated by one elevation scan of a radar.

The WSR-74C (5 cm radar) has a five minute update rate, a beam width of 1.1°, and uses 24 different scans from 0.6° to 35.97° elevation. The radar beam coverage of the McGill radar is illustrated in Figure 2.2. Although the lowest elevation scans provide good coverage, they are not efficient since they have considerable overlap. In addition, although the McGill radar uses 24 scans, the higher elevations scans are not contiguous resulting in gaps in radar coverage at higher altitudes near the radar.

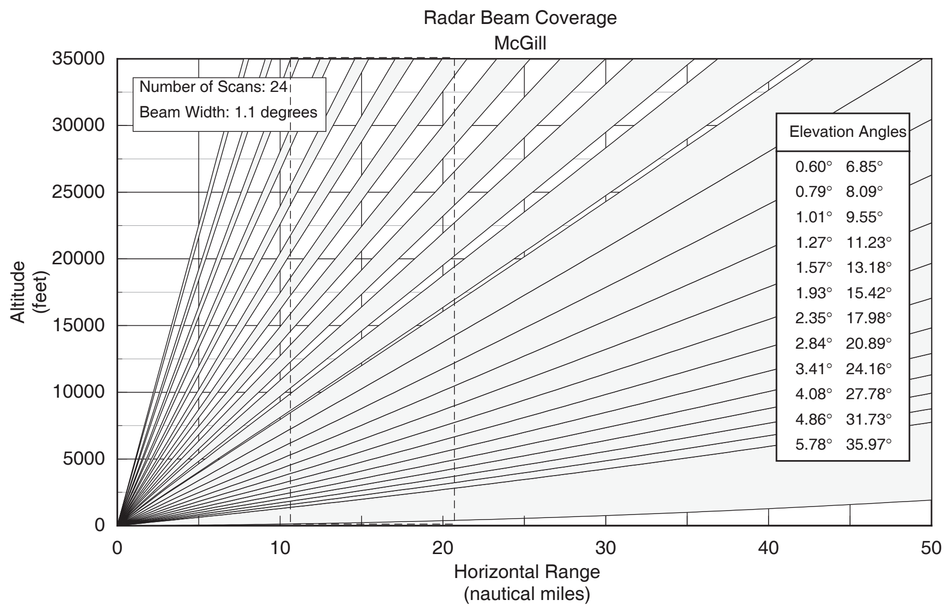

Figure 2.2. Radar beam coverage of the WSR-74C / McGill radar located at Patrick Air Force Base. Vertical dashed lines highlight CCAS location.

The WSR-88D is a 10 cm radar with a 0.95° beam width and uses two standard precipitation VCPs, deep convection scan (VCP 11) and the standard precipitation scan (VCP 21). KMLB Unit Radar Committee has decided that the locally-invoked default VCPs will be VCP 11 for precipitation and VCP 32 for clear air mode operation.

VCP 21 scans from 0.48° to 19.51° elevation (9 slices) and has a six minute update rate (Figure 2.3). The lowest five elevation scans are contiguous; however, there are severe coverage gaps at most altitudes near the radar. VCP 21 is used primarily to reduce process loading on the Radar Products Generator (RPG) when severe weather is not expected. VCP 21 is not adequate for use in the evaluation of weather LCC and flight rules.

The deep convection scan strategy (VCP 11) uses 14 scans from 0.48° to 19.51° elevation and has a five minute update rate. The radar beam coverage of the VCP 11 is illustrated in Figure 2.4. The lowest seven elevation scans are contiguous, provide good radar coverage, and are more efficient (i.e., no overlap) than the corresponding McGill scans. The highest seven elevation scans are not contiguous resulting in gaps in radar coverage at higher altitudes near the radar.

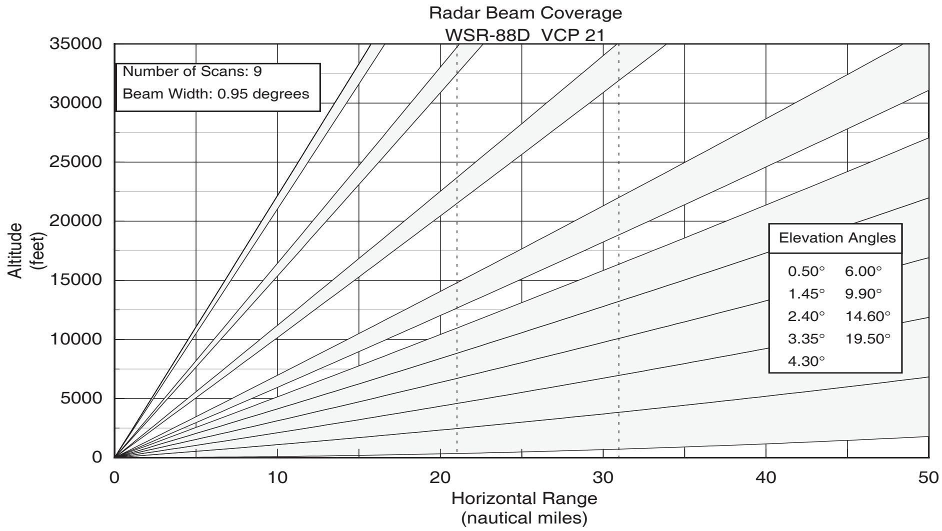

Figure 2.3. Radar beam coverage for VCP 21 of the WSR-88D weather radar. Vertical dashed lines highlight the CCAS area.

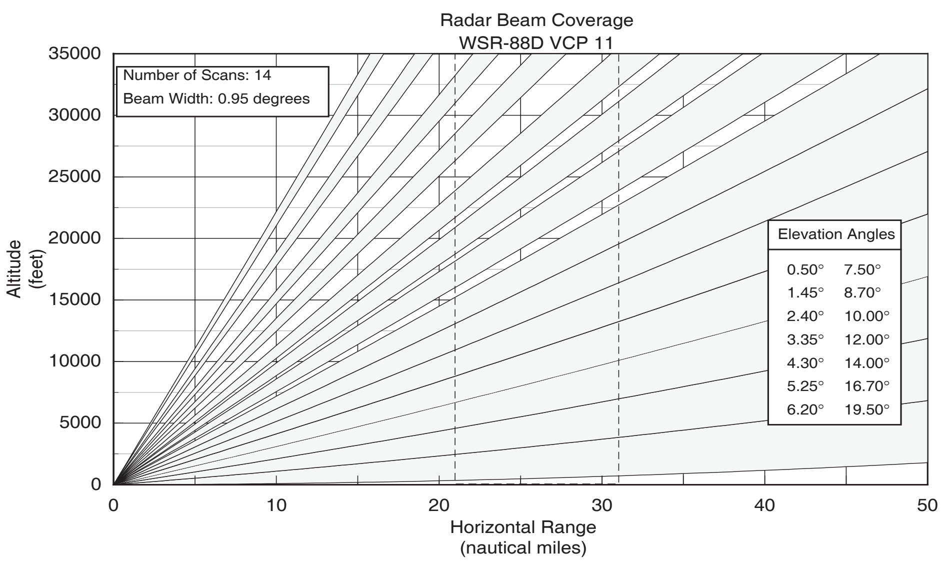

Figure 2.4. Radar beam coverage for VCP 11 of the WSR-88D weather radar. Vertical dashed lines highlight the CCAS area.

3.0 Radar Propagation

A radar's transmitted energy is both reflected by the Earth's surface and refracted by the atmosphere, which affects both the accuracy and the total coverage of a radar. For typical weather radar configurations with nominal atmospheric conditions, the Earth's refractivity effect is limited to ground clutter near the radar because of side lobes and interference from nearby structures. However, refraction occurs near or at a distance from the radar due to atmospheric conditions and must be considered as it greatly affects the display of radar data. The problem with refraction, is that it is virtually impossible to describe how a beam is affected objectively along the beams path because of the real-time changes in the atmosphere (non-standard).

As a radar beam propagates through the atmosphere, it does not follow a straight path, but is refracted or bent, following somewhat the earth's curvature (Figure 3.0). The amount that the beam is bent depends of the atmosphere's three-dimensional reflectivity gradient. Most significant refraction gradients are in the vertical; therefore, the problem is generally treated as two-dimensional, with profiles of vertical refraction (i.e. index of refraction or refraction index).

Atmospheric Refraction types (Figure 3.0):

- Subrefraction - Beam curvature is upward. This results in a shortened range of the radar because the beam overshoots the targets. This is caused by temperature lapse rate being steeper than normal and moisture increase with height. Estimated echo tops will be LOWER than standard.
- Normal - Beam curvature is downward, but not as much as the curvature of the Earth. This is the normal (standard atmosphere) condition. The radar signal processing software assumes this type of radar beam propagation. Refraction decreases with height.
- Superrefraction - Beam curvature is downward, more sharply then normal. Echo top measurements will be too high because of the differences in beam curvature from standard. Estimated echo tops will be HIGHER than standard. When AP occurs, it is more frequently due to superrefraction.
- Ducting (Trapping) - Beam curvature is downward, equal to or greater than the earth's curvature. Echoes close to the radar will be distorted (may appear higher), and the radar will detect echoes at longer ranges. This type of refraction is usually associated with very dry conditions. However, dry conditions above moist layer can also produce this type of propagation resulting in misleading radar returns.

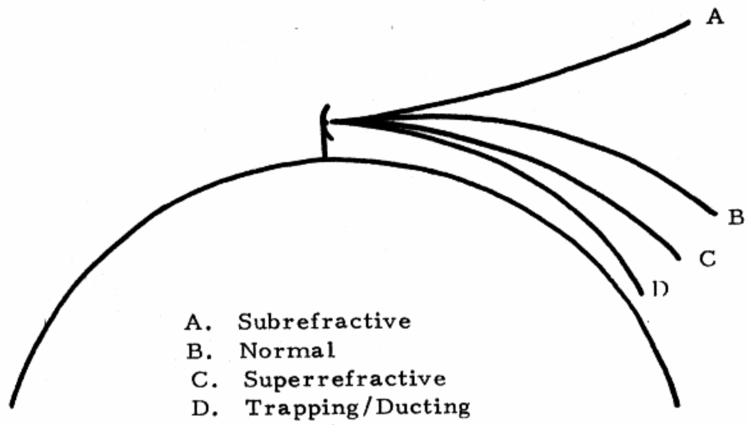

Figure 3.0. Radar beam paths through various atmospheric refractive conditions.
Atmospheric refraction is a function of pressure, temperature and water vapor. Thus, accurate range and height estimates of radar targets require precise calculations of radar beam propagation. However, this is very difficult as it would require knowledge of the atmosphere's pressure, temperature, and moisture content along the path of the radar beam. Consequently, the WSR-88D and McGill radar systems use the standard atmosphere to predict radar beam propagation. Generally, this assumption works well. However, it does mean that if there is any change in the standard pressure, temperature and water vapor distribution, errors can occur in the reported versus true height and range of a detected radar target.

For example, besides inversions aloft, where warmer, drier air is advecting into an area, inversions also exist near thunderstorms, especially in the decaying stage. The outflow from a thunderstorm (cooler air), is much colder than the surface air it is displacing and forcing upward, resulting in a temperature inversion.

4.0 Case Study Analysis

The AMU was tasked to investigate the cloud height discrepancies reported by the weather aircraft and those interpreted on the weather radar for two cases. To accomplish the task the AMU and 45 WS did a literature search to see if any like studies had been accomplished. The results of these searches were negative. Upper air data was requested from Computer Sciences Raytheon (CSR) and the WSR-88D base-level II data was requested from the NWS Melbourne office. No McGill archive data was available. The CCAS rawinsonde data consisted of all rawinsondes starting at 0000 UTC for the day of interest leading up to the launch. The WSR-88D radar data was a complete day's worth of data from 1200 UTC the day before the launch to 1200 UTC the day of the launch. The 45 WS LWO launch folder was also requested.

4.1 Delta II/NASA XTE Operation

A Delta II/NASA XTE rocket was successfully launched at 1348 UTC, 30 December 1995. The operation had been attempted 6 times earlier but was scrubbed each time due to upper level winds being out of tolerance (loads) or a vehicle problem.

In the days previous to 30 Dec, the LWO had briefed that there was a 40% chance of violating safety weather constraints, due to the Thick Cloud and Disturbed Weather LCC and flight rules. Because of the concern for thick clouds, an AF contract weather support aircraft would be used to investigate weather (layered clouds) near the launch pad (Complex 17).

On the evening of the Operation, the main weather feature affecting the local area was a weak inverted upper-level trough moving from west to east across central Florida. An area of rain and rainshowers was associated with this trough and was also generally moving from west to east.

Early in the launch count the RWO was RED for launch due to violation of the Thick Cloud and Disturbed Weather rules (LCC) but the countdown continued. As the count progressed the AF contract weather aircraft reported observed cloud tops as much as 1.2 km (4000 ft) lower than echo tops displayed on either weather radar. Other discrepancies included the weather aircraft reporting light precipitation in the area while at times the radar showed echoes of 25-35 dBZ or possible moderate precipitation within 5 NM of the launch pad. Reports from the contract weather aircraft reported only light precipitation in the area up to an hour before the launch. Toward launch time the aircraft reported thin clouds with bases at 3.9 km (13000 ft) and the clouds only 2-300 hundred feet thick. By 1320 UTC the areas of radar detectable moderate precipitation (25-35 dBZ) moved out of the 5 NM constraint widow and all launch weather rules were observed GREEN for launch.

4.1.1 Analysis of Data

There was very little documentation of the McGill radar data set so the AMU relied on the WSR-88D base level II data from the NWS Melbourne office for radar analysis. In one of the after action reports it was stated that "McGill vertical slices showed solid precipitation to 18000 ft near the pad." Aircraft and observations discounted the radar observation. The surface weather observation from the Shuttle Landing Facility's (SLF) form 10;

- At 1355 UTC the reported weather conditions were, 47 SCT 70 BKN 120 BKN 8RW- 64/63 2SC 6AC 1AC.
- At 1406 UTC the reported weather conditions were, 38 SCT 75 BKN 8.

Figure 4.1 shows the Cape Canaveral rawinsondes at 0548 and 1308 UTC. At 0548 UTC the atmosphere was moist up to 600 mb (14000 ft), with a inversion at about 600 mb. From 0548 to 1348 UTC it can be noted that the inversion at about 600 mb became much stronger. This change is probably associated with the upper-level trough as drier air advected into the Cape area from the west prior to the launch operation. This strong inversion could cause AP to be displayed on the radars screens and a distortion of the displayed echoes because of the atmospheric ducting and superrefraction (trapping or bending of the radar beam). This type of radar beam bending is shown in Figure 3.0, both beam's C and D represent the curvature a beam would take under strong atmospheric inversions.

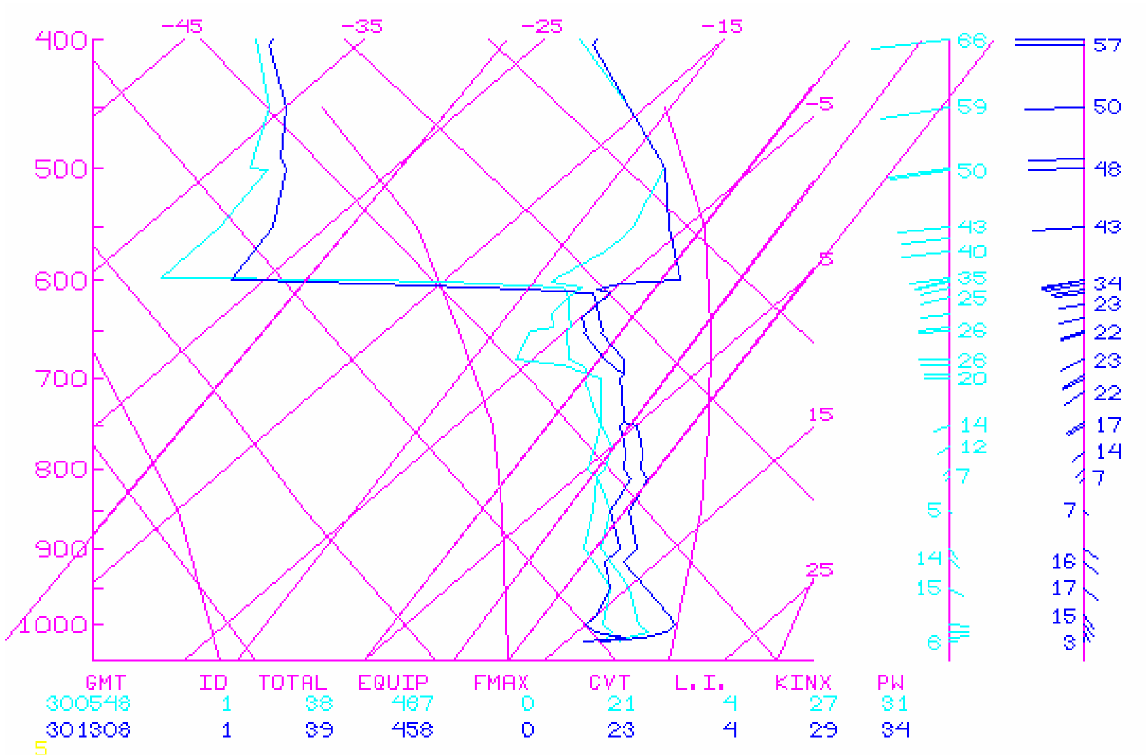

Figure 4.1. Cape Canaveral rawinsondes at 0548 and 1308 UTC. Note the change at 1308 UTC as the inversion strengthened significantly at about 600 mb.

Figure 4.2 is a 1.5° WSR-88D base reflectivity product from the NWS Melbourne level II archive data at 1008 UTC, approximately 3 1/2 hours prior to launch. Most of the precipitation was located to the E-NE of Complex 17 and to the NW-W. This precipitation continued to move northeast throughout the period. Most of the rainshower intensity stayed between 15 and 30 dBZ (over land).

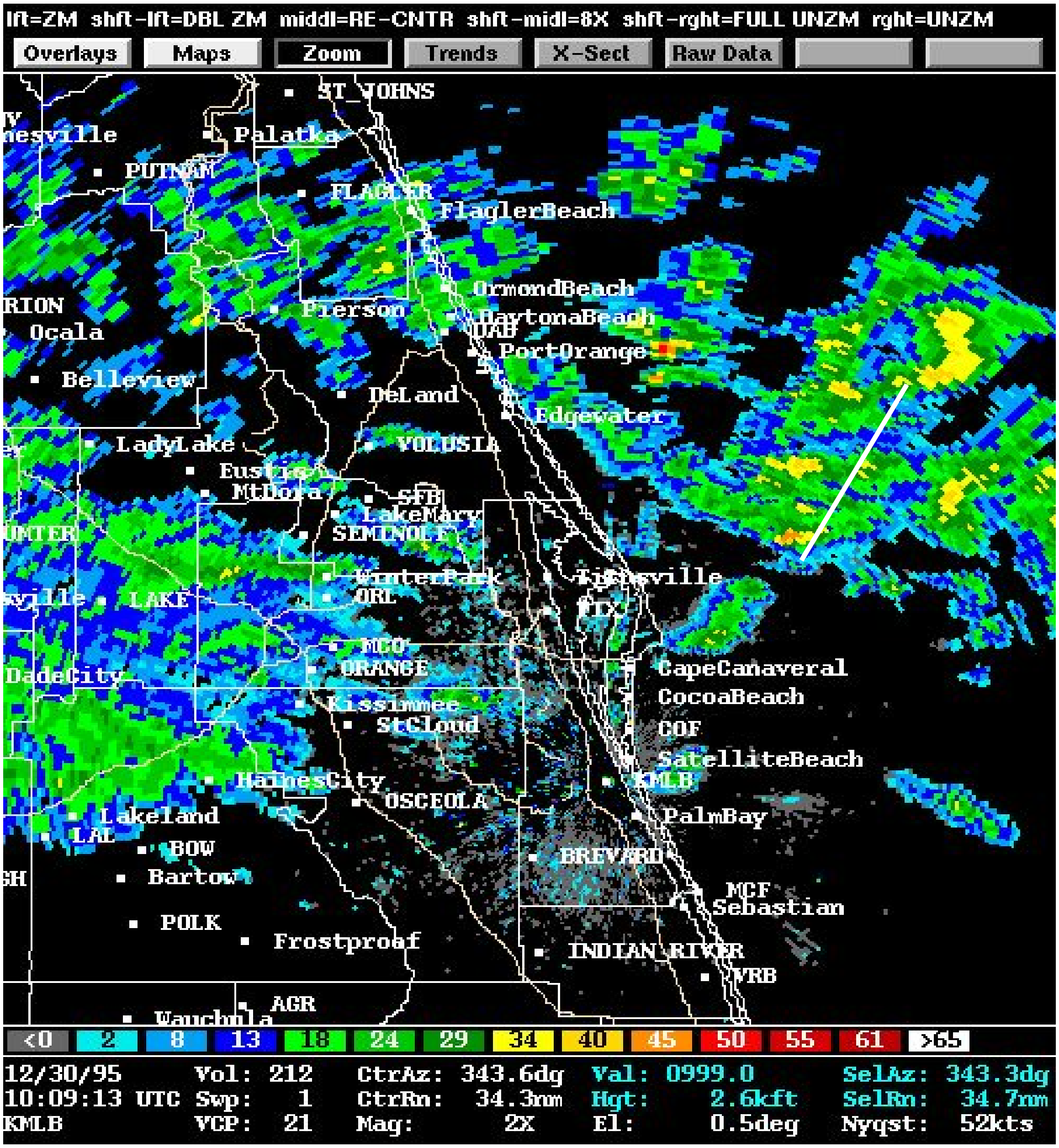

Figure 4.2. WSR-88D base reflectivity image at 1008 UTC. White line marks a cross-section (Figure 4.3).

A radar cross-section was generated across the precipitation pattern to the northeast of complex 17 (A-B dash line) (Figure 4.3). The displayed radar data has a very skewed or stretched appearance and the tops have a truncated appearance. This AP effect was caused by the strong inversion bending the radar beam more toward the Earth instead of following its normal path. The weather aircraft at this time was reporting cloud tops at about 4 km (13000 ft). However, as can be noted on the figure the WSR-88D was identifying echo tops near 6 km (19000 ft). The strong inversion has truncated the echo tops and displacing them (AP) so they appeared higher than the actual observed cloud tops.

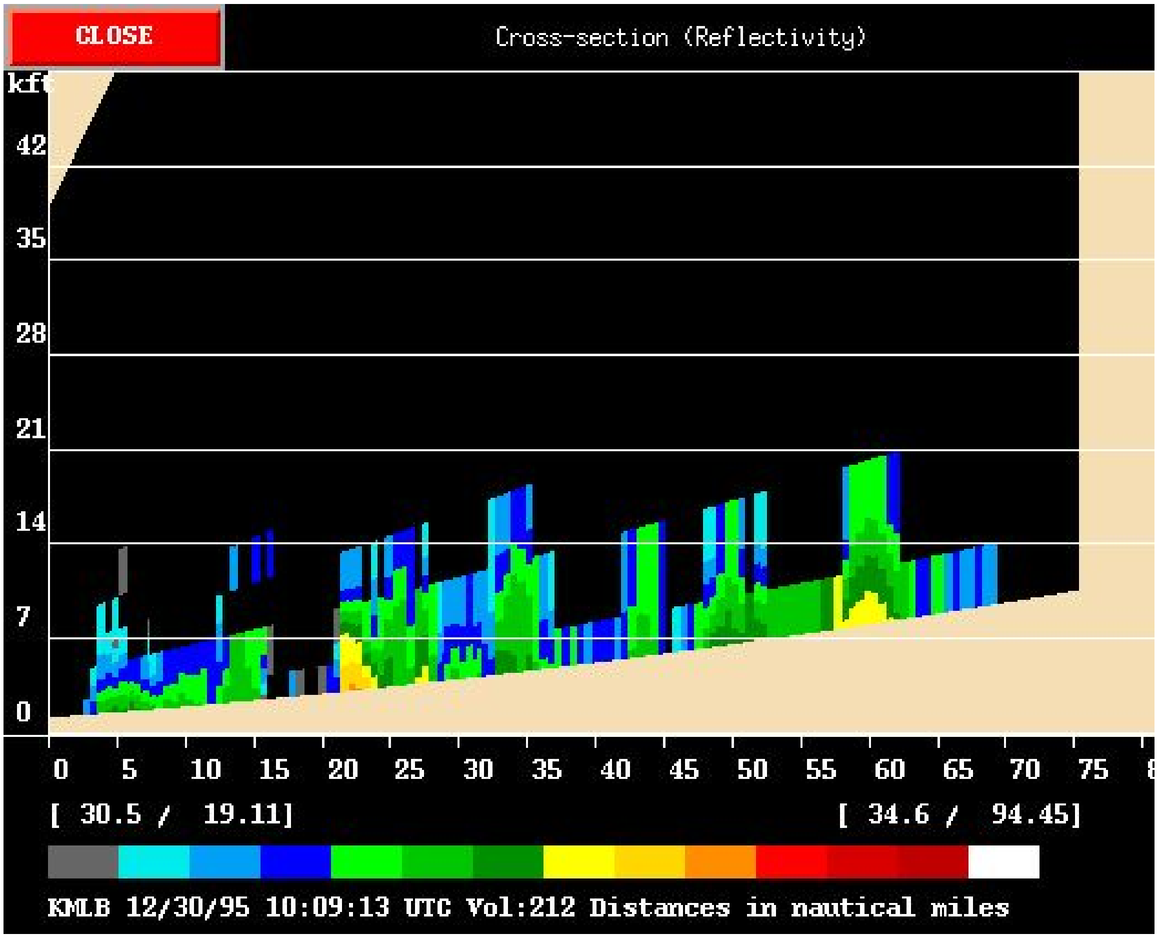

Figure 4.3. Cross-section of radar data showing a vertically stretched appearance of echoes along the SW - NE cross-section. Also notice the blocky or stair step appearance of echoes.

Later in the launch countdown, at t-30 minutes, (Figure 4.4) most of the precipitation has moved to the north of the launch pad (Complex 17) and extends from west to east. The strongest echoes as shown by the radar extend to the N-NE of Complex 17 by about 15-25 miles.

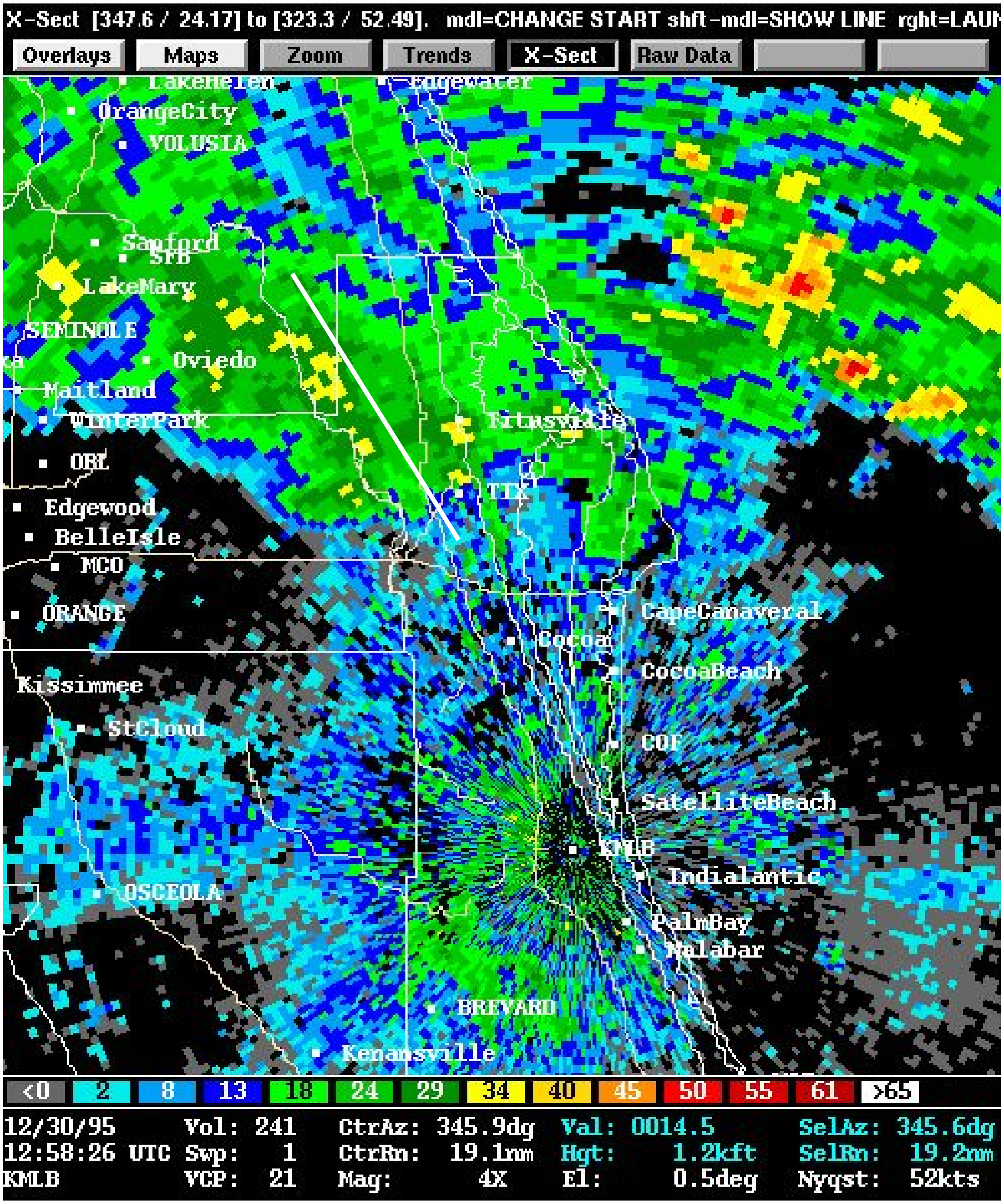

Figure 4.4. WSR-88D base reflectivity image on 30 December 1995 at 1348 UTC. White line is a cross-section through the echoes W-NW of Complex 17.

A cross-section along a SE-NW line to the northwest of Complex 17 was done (Figure 4.5). Again the showers have a very stretched and truncated appearance. This can be attributed to AP, superrefraction and/or ducting, where the radar beam is being trapped and bent back toward the Earth due to the very dry air advection above 10000 ft. Just prior to this time the weather aircraft was reporting cloud tops at about 3 km (10000 ft). By 1348 UTC all showers as depicted by the radar and observed by the weather aircraft are at least 5 NM away from Complex 17 and the Delta rocket was launched successfully.

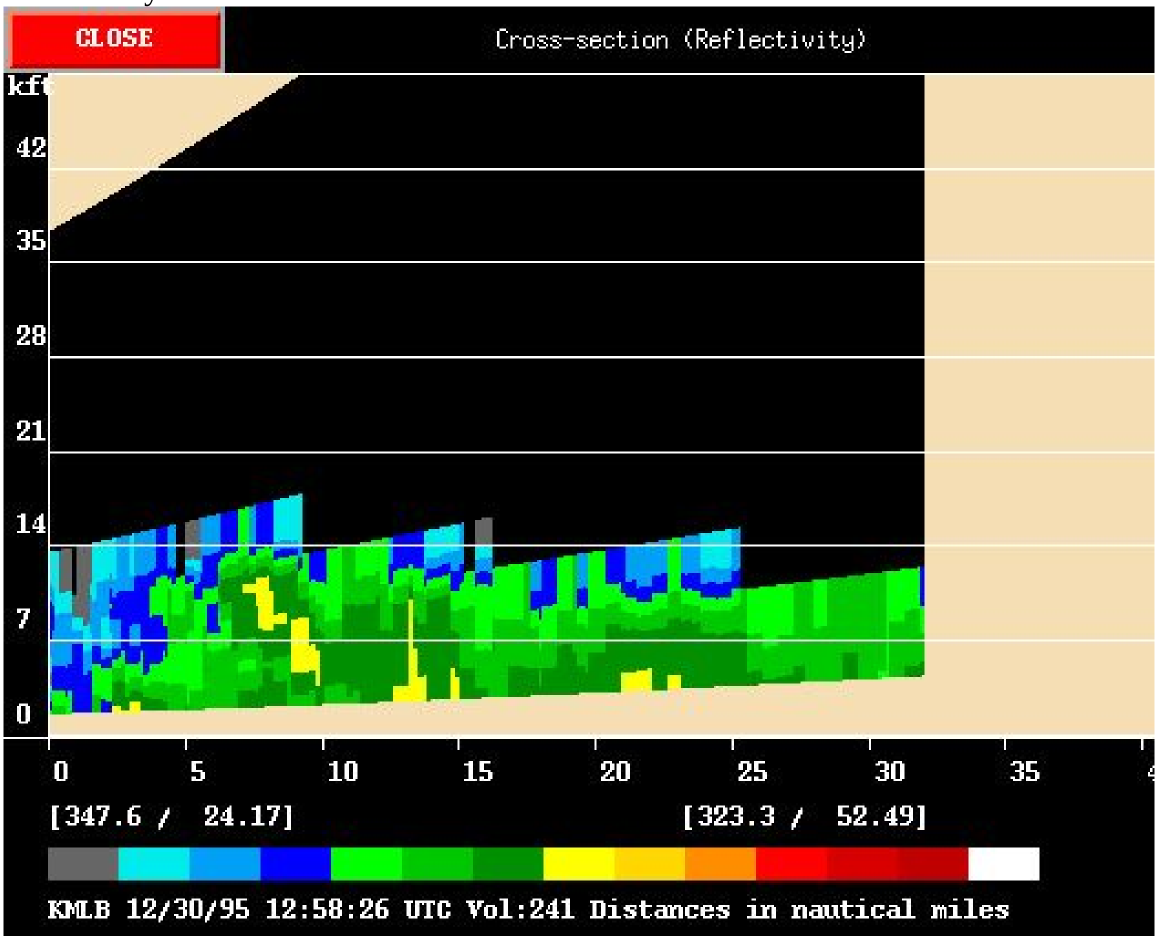

Figure 4.5. Cross-section (See A-B line in figure 4.4) at 1315 UTC from SE to NW along an area of precipitation west - northwest of the Cape.

To define the AP layer or identify atmospheric conditions that cause refraction, Index of Refraction (IR) profiles was plotted for launch. IR is the ratio of the distance a wave would have traveled in a vacuum to the distance it actually travels in the atmosphere, in unit time. It takes into account temperature, partial pressure of water vapor and pressure in the atmosphere. The refractive index is very sensitive to a change in moisture content in the vertical and is fairly sensitive to a change in temperature with height.

The radar images for the 30 December 1995 event were also reviewed by Mr. Tim O'Bannon from the NWS Operation Support Branch (OSF). His conclusions were similar, that the dry air advection over the lower moist air probably caused the radar beam to be bent or trapped (AP).

Figure 4.6 is a profile of the Δ IR (change in IR ((N units) over 1000 ft in height)) plotted for the Delta launch operation on 30 December 1995 at 0548 and 1308 UTC which was just prior to the Delta launch. Notice the jump in the IR delta between 13000 and 15000 ft. This abrupt change in the gradient can be attributed to the very strong inversion and is indicative of AP that developed at this level. The contract weather aircraft reported cloud tops near the 13000 - 15000 ft level. However, both weather radars were showing higher tops (16000 - 18000 ft), above the strong inversion layer. This is because the radar beam being trapped or bent back toward the Earth due to the developing inversion and displacing the actual and displayed echo tops.

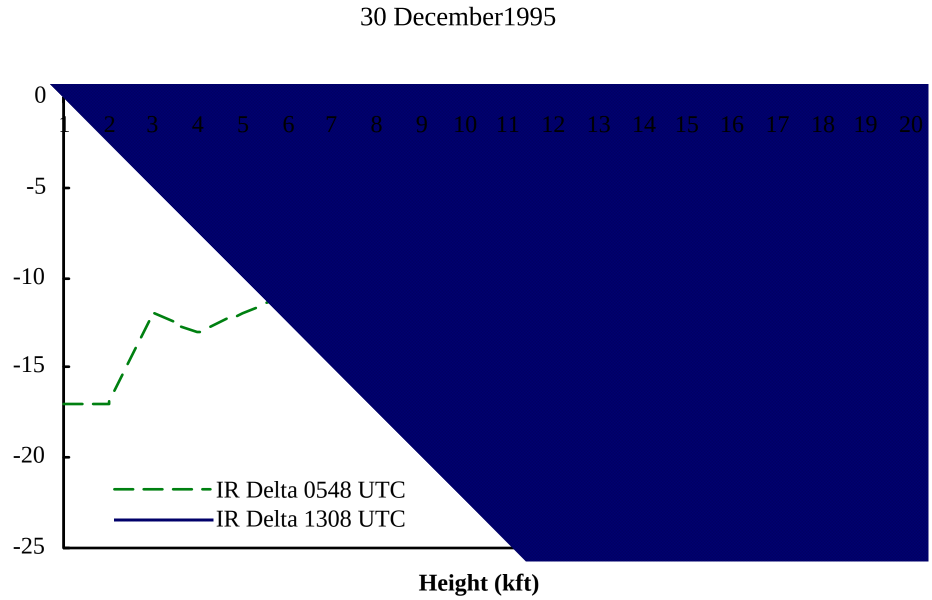

Figure 4.6. Profiles of the change in IR per 1000 ft on 30 December 1995 at 0548 and 1308 UTC. A strong substance inversion caused rapid change in IR values from 13000 to 15000 ft. The abrupt change is indicative of AP.

4.1.2 Case Summary

From the analysis of the rawinsonde, profiles of IR, and WSR-88D data it is evident that atmospheric refraction (superrefraction and/or ducting) caused the cloud height discrepancies between the weather radars and the reported conditions from the contract weather aircraft. The strong inversion that developed because of the advection of dry air above the lower moist layer during the Delta operation caused the weather radar beams to be bent back more toward the Earth and thus displaying erroneous radar height information and stronger radar returns (AP).

4.2 Delta II GPS II-27 Operation

During the Delta II GPS II-27 launch operation on 12 September 1996 between 0500 and 0849 UTC, there was also a discrepancy between cloud top information reported by from the contract weather aircraft and echo top information from the WSR-88D and McGill radar systems. The radar reported tops were reported higher than those observed by the weather aircraft, similar to the first case.

The day before the launch, the LWO had briefed that there was a 30% chance of violating Safety weather constraints, mainly due to Disturbed Weather and Layer Cloud weather LCC and flight rules. The major concern for the LWO was the possible development of rainshowers overhead or offshore near the launch complex. An AF contract weather support aircraft would be used to investigate the weather (layered clouds) near the launch pad (complex 17).

In this case, the differences between the pilot reports of cloud top heights (lower) and the echo tops from the weather radar were as much as 3.5 km (10000) ft, most differences were in the 3000 - 5000 ft range.

For this operation the main weather feature affecting the Cape Canaveral region was a weak subtropical ridge located over Florida. Generally, the synoptic flow was weak out of the south-southeast in the lower levels and west-northwest above 5000 ft. In this type of environment, developing showers with tops below 8000 ft moved from the southeast to northwest and showers with tops above 8000 ft moved from the west.

4.2.1 Analysis of the Data

For this Delta launch there was very little documentation of the McGill radar data and the NWS MLB base level II WSR-88D data was defective and could not be used. The AMU relied on CCAS rawinsonde information to analyze atmospheric conditions for AP. Analysis of the 0349 UTC rawinsonde showed a moist atmosphere up to 500 mb. Between the 0349 UTC rawinsonde and the 0834 UTC rawinsonde dry air in the mid-layers had advected in from the west. The skew-t diagram (Figure 4.7) displays the changes that took place between 0349 UTC and 0834 UTC. Much drier air can be observed above 650 mb. This type of day air over very moist air can cause AP and bent the radar beam as shown in Figure 3.0 (beams C and D).

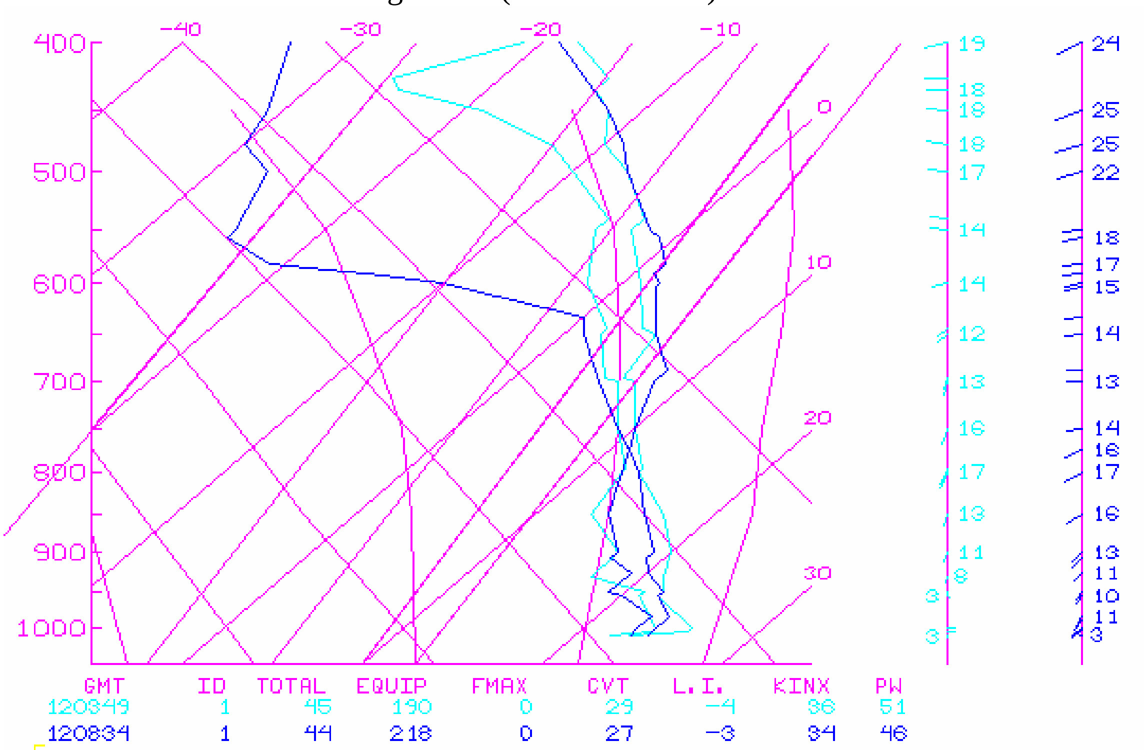

Figure 4.7. Rawinsondes at 0349 and 0834 UTC on 12 September 1996. On the 0834 UTC plot much drier air can be seen above 700 mb. This type of atmospheric discontinuity can cause AP.

The change in Δ IR (N units) with height were plotted for the 2 rawinsondes on 12 September 1996. Figure 4.8 is a profile of the change of IR with height (Δ IR (N units) per 1000 ft)) at 0348 and 0834 UTC. The analysis of the profiles indicates an abrupt change took place leading up to the 0834 UTC rawinsonde between 12000 to 14500 feet. This change is associated with the warmer, drier air advecting in from the west over the lower moist layer (around 14000 ft). This area of rapidly drying air is very close to where the contract weather aircraft was reporting cloud tops. Both weather radars were indicating higher echo tops. This was probably because of the much drier air aloft causing atmospheric superrefraction and/or ducting (AP).

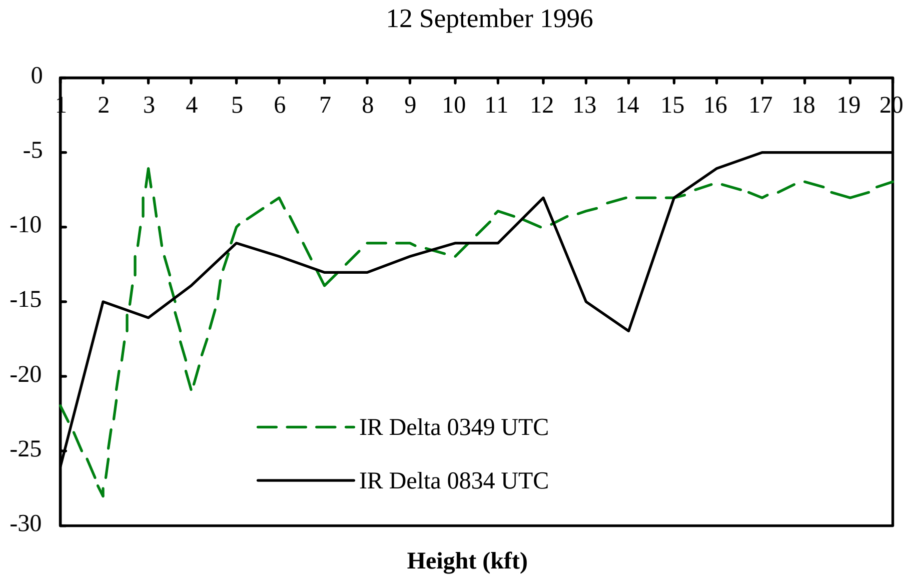

Figure 4.8. Profiles of the change in IR per 1000 ft. Dry air advection by 0834 UTC has cause atmospheric ducting (AP) above 13000 ft.

4.1.2 Case Summary

It appears that atmospheric refraction (superrefraction and/or ducting) caused the radar beams to be trapped or bent back toward the Earth, which resulted in the radar echo top errors on 12 September 1996. The profiles of the Δ IR shows an area of discontinuity around 13000 ft developing between 0349 UTC and 0834 UTC. The atmospheric conditions (very dry air advecting over a moist layer) were similar to the 30 December 1995 event that caused the radar beam to be bent back toward the Earth thus causing higher radar echo tops to be display on the weather radars. From the analysis of the rawinsonde and profiles of IR it is evident that superrefraction and/or ducting caused the cloud/echo height discrepancies between the weather radars and the contract weather aircraft.

5.0 Issues and Concerns

From the analysis of the 2 cases of differences between the radar detected echo top and the observed aircraft cloud top it appears that anomalous propagation (superrefraction and/or ducting) was the cause of the reported inconsistencies. The cloud top difference between an area of precipitation as shown on either radar and its observed altitude as determined by aircraft can be attributed to atmospheric conditions (strengthening inversion or areas of temperature and water vapor discontinuity) that causes the radar beam to be bent downward or trapped (i.e. superrefraction and/or ducting).

Both of these cases illustrate the problems that changes in the "standard" atmospheric conditions can cause anomalous propagation of radar beams resulting in misleading radar returns. Instead of following the projected 4/3 earth's radius the radar beam is bent further downward toward the earth because of change in the vertical gradient of IR with height. When the radar beam is abnormally bent in this fashion the radar data will be displayed abnormally (i.e. blocky, stretched) and the calculated echoes tops will probably be higher than normal due to the abnormal bending of the radar beam (Figure 5-1). The radar assumes that the beam has continued in space along its projected path instead of being bent downward.

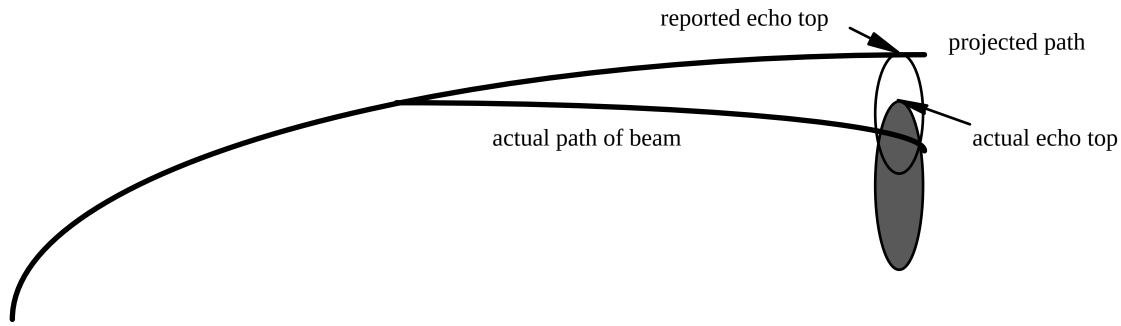

Figure 5-1. Model of project versus actual radar beam and calculated echo top.

In addition to the beam bending (refraction) due to atmospheric conditions, there are other characteristics of the two radars that should be considered when analyzing the radar data. A list of those considerations include:

- Beam filling - (1/2 power points) When the lower part of the radar beam intersects the top of a target, the center of the beam is 1/2 beam width higher than the lower edge of the beam. This will cause the target to be displayed 1/2 beam width higher, this can be up to 1200 ft from the radar to the CCAS area.
- Radars only detect water droplets (precipitation). Precipitation tops will be lower than actual cloud tops.
- Two radars viewing same target. May see differences in tops, intensities and patterns because of different viewing angles (VCPs), time of observation, distances, and radar calibrations (C-band, Doppler).

This report also highlights two major concerns:

- Since cloud top information and accuracy is extremely important in support of space launch operation, LWO's need to be aware of atmospheric conditions at all times that could cause data to be miss representative. Each rawinsonde should be examined for AP signatures.
- Reported versus observed cloud tops or cloud structure can be different due to radar anomalies as detailed in this report.

6.0 Summary and Recommendations

This report examined the two cases of reported cloud/echo top discrepancies and attributed the differences to atmospheric conditions. Much drier air in the mid-levels advected into the CCAS area over a lower moist layer in the atmosphere. Some background radar information was presented. Scan strategies for the McGill and WSR-88D were reviewed along with a description of normal radar beam propagation influenced by the Effective Earth Radius Model. Atmospheric condition prior to and leading up to both launch operations were detailed. Through the analysis of rawinsonde and radar data, atmospheric refraction or bending of the radar beam was identified as the cause of the discrepancies between reported cloud top heights by the contract weather aircraft and those as identified by both radars. The atmospheric refraction caused the radar beam to be further bent toward the Earth than normal. This radar beam bending causes the radar target to be displayed erroneously, with higher cloud top heights and a very blocky or skewed appearance.

It is recommended that a McIDAS command be developed that would analyze each new rawinsonde for conditions that could cause atmospheric refraction. This utility could be graphical, textual or both. It would compute the index of refraction gradient every thousand feet and if the value exceeded a set value it would alert the LWO or forecaster to the potential problem of refraction. This along with the continued use of weather aircraft would allow the LWO to feel more confident that all LCC and flight rules are being met and not being violated. If tasked the AMU could assistance in the development of this utility.

7.0 References

R. J. Doviak and D. S. Zrnic, 1993: Doppler Radar and Weather Observations, Academic Press, Inc., 562 pp.

G. E. Taylor, 1994: Report on the Comparison of the Scan Strategies Employed by the Patrick Air Force Base WSR-74C / McGill Radar and the NWS Melbourne WSR-88D Radar, NASA Contractor Report, 30 pp.