P8R.13 UNIQUE USES OF WEATHER RADAR FOR SPACE LAUNCH

William P. Roeder *, Todd M. McNamara, Billie F. Boyd, Johnny W. Weems, and Stephen B. Cocks
45th Weather Squadron, Patrick Air Force Base FL

1. INTRODUCTION

The Air Force's 45th Weather Squadron (45 WS) provides comprehensive weather service to the Eastern Range (ER) and the Kennedy Space Center (KSC) in support of America's space program. These services include weather support for personnel safety, resource protection, pre-launch ground processing, day-of-launch, post-launch, and special operations. These services are provided for more than 30 space launch countdowns per year by the Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and commercial launch customers.

Weather presents significant challenges to spacelift. Some of the more important weather impacts include natural and rocket triggered lightning, upper-level winds, boundary layer winds (especially downbursts), temperature, precipitation, cloud ceilings, visibility, and severe weather (Harms et al., 2003). Over the last 17 years, approximately one-third of the scheduled launches have launched on time, one-third with delays, and one-third have scrubbed. Approximately one third of those delayed and half of those scrubbed (105 of 216, or 49%) were due to weather (Table 1). The effective use of weather radar yields annual cost savings of millions of dollars through timely weather warnings, watches, advisories and precision customized weather service to various operations. Even more important than the cost savings are the improvements to personnel and launch safety.

This paper presents an overview of the unique weather radar applications used by the 45 WS including their special tools and techniques, the modifications to the local weather radar, and plans to use dual polarization and dual Doppler capabilities.

Table 1
Eastern Range Launch Countdowns
(POR: 1 Jan 88-1 Jun 05, note % refers to total countdowns)

Count-down	**Launch** (on time)	**Launch with Delay**	**Scrubbed Launch**
532(100%)	180 (34%)	136 (26%)	216 (41%)
Cause of Delay		**Cause of Scrub**	
Non-weather 88 (17%)		Non-weather 111 (21%)	
Weather 48 (9%)		Weather 105 (20%)	

*Corresponding Author: William P. Roeder, 45 WS/SYR, 1201 Edward H. White II St, MS 7302, Patrick AFB, FL 32925-3238; e-mail: william.roeder@patrick.af.mil

2. WEATHER AT CCAFS/KSC

Two items contribute to the difficulty of weather support by the 45 WS: (1) the location of the Cape Canaveral Air Force Station (CCAFS)/KSC complex and (2) the extreme weather sensitivity of the mission combined with high cost of error (Harms et al., 1999).

The area of maximum thunderstorm occurrence in the United States is near CCAFS/KSC (Figure 1). These facilities are located in east-central Florida at the east end of a corridor known as 'Lightning Alley', seen in Figure 2 as the red area oriented southwest to northeast across the center of the Florida peninsula. Consequently, thunderstorms and associated lightning and damaging winds represent the single greatest threat to operations on CCAFS/KSC. Therefore, the 45 WS has a strong requirement for the best possible weather surveillance radar.

The number of cloud-to-ground strikes per year is widely variable across CCAFS/KSC. A 1995 study using the local Cloud to Ground Lightning Surveillance System (CGLSS) determined the five-year annual average number of cloud-to-ground strikes ranged from 5 to 13 flashes per km^2 across the complex (Boyd et al., 1995). A more recent climatology using the National Lightning Detection Network (NLDN) has revised that range of flash densities from 3 to 12 flashes per km^2 per year as shown in Figure 3.

Table 2 shows monthly and diurnal frequency of thunderstorms for the Shuttle Landing Facility (SLF) in 3-hourly increments, based on 30 years (1973-2003) of hourly observations at the SLF (Air Force Combat Climatology Center, 2004). These climatological data clearly show a thunderstorm maximum in the summer afternoons, reaching 21 percent of hourly observations for 1500 to 1700 Local Standard Time (LST) in July.

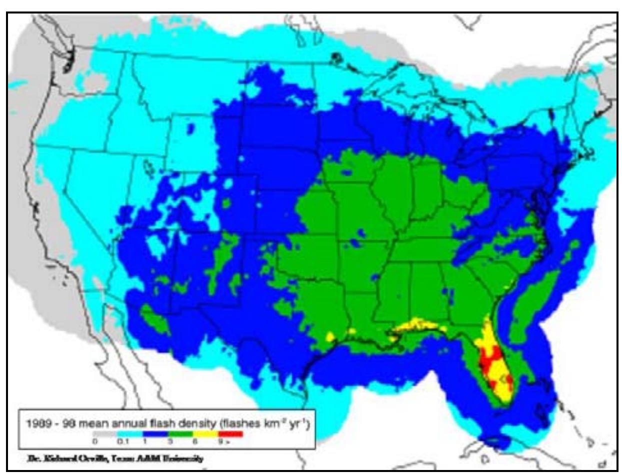

Figure 1. Mean annual cloud-to-ground lightning flash density for the U. S., 1989–1998, from NLDN data (courtesy of Dr. Orville Texas A&M University)

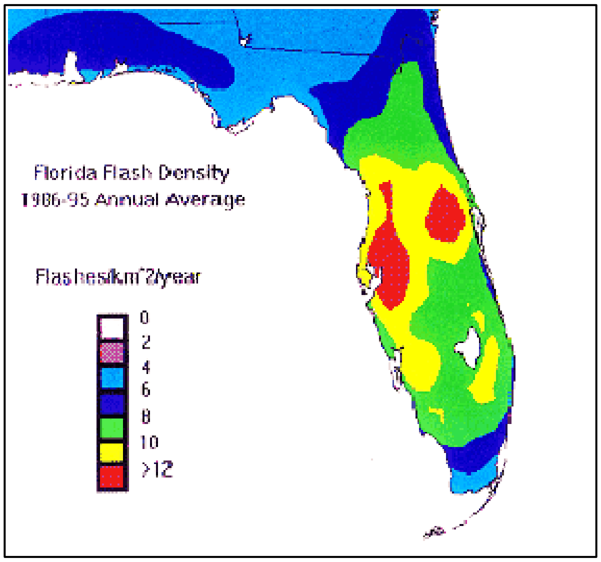

Figure 2. Mean annual cloud-to-ground lightning flash density across Florida, 1986 – 1995, based on NLDN data (courtesy of National Weather Service Melbourne Forecast Office)

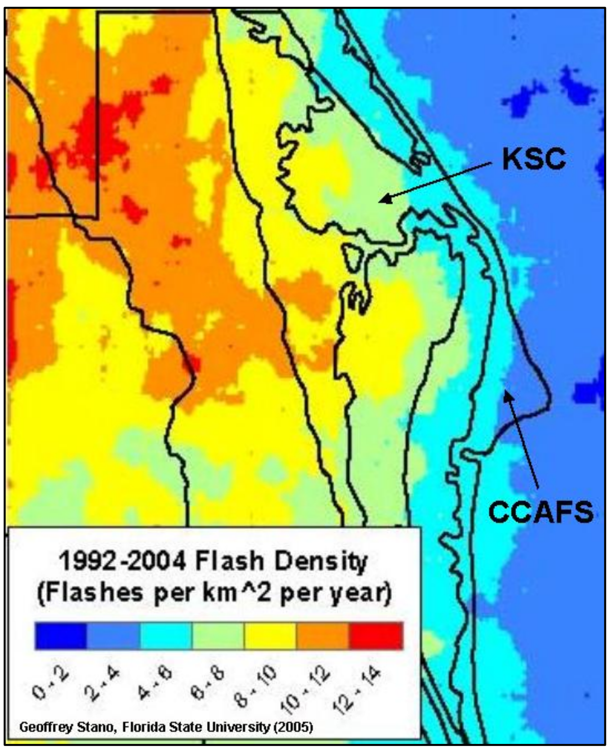

Figure 3. Mean annual cloud-to-ground lightning flash density in the CCAFS/KSC area, 1992-2004, based on NLDN data (courtesy of Mr. Stano, Florida State University)

Table 2

Percent of Hourly Observations with Thunderstorms at the KSC Shuttle Landing Facility (1973-2003) (0%< x < 0.5%) (Operational Climatic Data Summary for KTTS) Air Force Combat Climatology Center (2004)

LST	APR	MAY	JUN	JUL	AUG	SEP
00-02	1	1	1	1	2	2
03-05	1	1	1	1	1	2
06-08	x	1	1	1	1	2
09-11	1	1	3	2	3	3
12-14	3	4	13	14	14	8
15-17	3	6	17	21	19	10
18-20	3	5	10	11	10	7
21-23	1	2	4	3	4	4

3. RADAR APPLICATIONS FOR SPACE LAUNCH

The space program at CCAFS/KSC has several atypical applications of weather radar. These include high precision lightning forecasting, evaluating lightning Launch Commit Criteria (LCC), stringent convective wind prediction, and warning of local hurricane threat. The 45 WS also uses weather radar for applications that are more commonly used, such as severe weather warnings, but only the more atypical applications for space launch will be discussed here.

3.1 Lightning Advisories

The 45 WS uses a two-tiered lightning advisory system to protect outside workers and facilities at thirteen sites with large amounts of outdoor work as shown in Figure 4. A Phase-I lightning advisory is issued with a desired lead-time of 30 minutes when lightning is expected within 5 nautical miles (NM) of predetermined locations such as the launch complexes. Outdoor activities are either cancelled or allowed to continue depending on the amount of lightning protection in-place at the specific worksite. A Phase-II lightning advisory is issued when lightning is imminent or occurring within 5 NM of the predetermined locations. During the time the Phase-II lightning advisory is in effect, all outdoor activities cease. The 45 WS issues an average of over 1,500 lightning advisories per year.

Many of the 5 NM lightning advisory circles for the thirteen sites overlap, requiring high precision forecasting of lightning. The 45 WS uses a suite of four different lightning detection systems to help issue the lightning advisories (Harms et al., 1997). However, radar is the primary tool to predict the onset of lightning. The 45 WS developed 12 empirical lightning forecasting rules-of-thumb to support the lightning advisory requirements discussed above. These rules-of-thumb are known locally as "The Pinder Principles" and are briefly summarized in Table 3 (Roeder and Pinder, 1998). These forecast techniques are organized into two forecast intervals: nowcasting, and longer-than-nowcasting. Nowcasting supports the 45 WS lightning advisories and so applies to short-term forecasts with lead-times of about 30 minutes. Longer-than-nowcasting supports other operational and planning forecasts, such as the Daily 24-Hour and Weekly Planning Forecasts. The nowcasting lightning forecast rules, as updated since Roeder and Pinder (1998), are presented in Table 3. These lightning nowcasting rules use data from the two weather radars used by the 45 WS: 1) a modified WSR-74C operated by the USAF at Patrick AFB and, 2) a WSR-88D operated by the National Weather Service (NWS) at Melbourne, FL (Figure 5). The longer-than-nowcasting rules do not use radar data and so are not discussed in this paper. Local documented experience and independent research have shown electrification of convective cells is closely correlated with the altitude of the -10ºC isotherm (Buechler and Goodman, 1990) (Takahashi, 1984). Some of these rules (Table 3) are based on this correlation, as observed on vertical cross-sections of the two weather radars used by the 45 WS. Since these rules are tied to temperature levels, and associated electric charge production physics, they should be more applicable to other regions, than rules based on height.

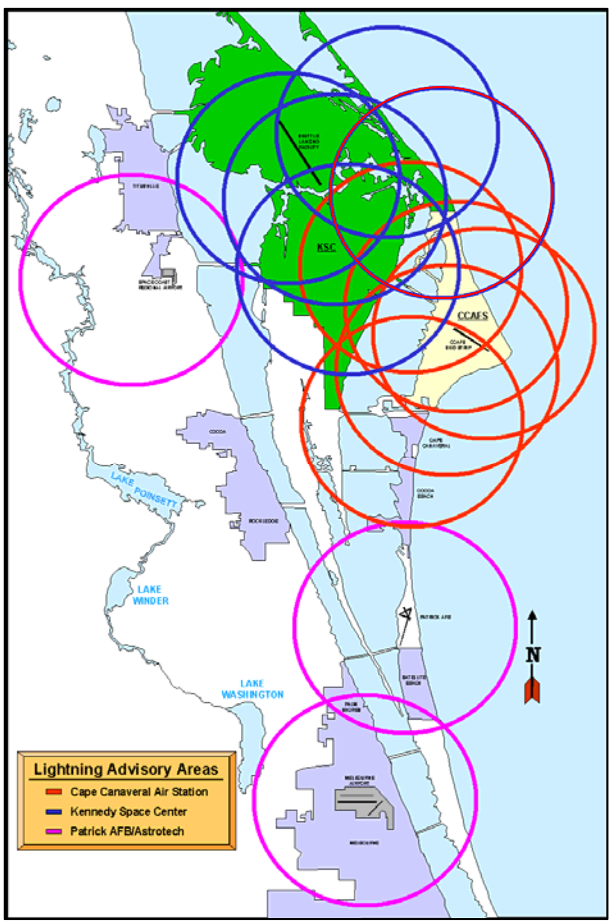

Figure 4. Lightning Advisory Areas (each circle has a 5 nm radius)

Table 3
Radar Lightning Nowcasting Rules

TO FORECAST THIS PHENOMENA	USE THIS RULE
Cellular Thunderstorm Initial In-Cloud (IC) Lightning	Reflectivity: ≥ 37-44 dBZ Temperature: ≤ -10°C Depth: ≥ 3,000 Ft above -10°C Width: 1 NM Duration: ≥ 10-20 min Other: None
Cellular Thunderstorm Initial Cloud-To-Ground (CG) Lightning	Reflectivity: ≥ 45-48 dBZ Temperature: ≤ -10°C Depth: ≥ 3,000 Ft above -10°C Width: ≥ 1 NM Duration: ≥ 10-15 Other: None
Anvil Cloud IC Lightning	Reflectivity: ≥ 23 dBZ Temperature: N/A Depth: ≥ 4,000 Ft Width: ≥N/A Duration: N/A Other: Attached to parent Cb
Anvil Cloud CG Lightning	Reflectivity: ≥ 34 dBZ Temperature: N/A Depth: ≥ 4,000 Ft Width: N/A Duration: N/A Other: attached to parent Cb
Debris Cloud IC Lightning	Reflectivity: ≥ 23-44 dBZ Temperature: ≤ -10°C Depth: ≥ 3,000 to ≥ 10,000 Ft above -10°C Width: N/A Duration: N/A Other: Tops ≥ 30,000 Ft; Smaller reflectivity needs more depth above -10°C; e.g. 23 dBz ≥ 10,000 Ft
Debris Cloud CG Lightning	Reflectivity: ≥ 45-48 dBZ Temperature: N/A Depth: N/A Width: N/A Duration: N/A Other: Tops ≥ 30,000 Ft; Pockets of ≥ 45-48 dBz exist
Lightning Cessation	If above criteria are no longer satisfied, the lightning cessation process as begun, but the time until the actual last lightning is highly variable

The importance of anvil and debris clouds cannot be over emphasized. Anvil cloud can carry electric charge long distances and can be a lightning threat far away from the thunderstorm. Debris cloud can carry electric charge a long time and can be a lightning threat long after the parent thunderstorm has decayed. A debris cloud is a remnant from a decayed thunderstorm, either part of the thunderstorm that became detached, or the remnant of the entire thunderstorm after convection ended. Debris cloud can occur at altitudes significantly lower than anvil cloud and may contain electric charge below 0ºC leading to possible "warm cloud" lightning.

Since electrification occurs in the parent thunderstorm, the -10ºC altitude is less important for anvil and debris clouds, than for cellular thunderstorms. Cellular thunderstorms, anvil clouds, and debris clouds can occur together, greatly complicating the task for the operational forecaster.

The initial rules for using radar to forecast lightning combined reflectivity and depth thresholds. This suggested that a layered Vertically Integrated Liquid (VIL) rule may be useful, where the layer extends from -5°C to -20°C. A layered VIL rule of thumb was developed and a radar product based on that rule of thumb was implemented as forecast guidance (Figure 6). The optimum Layered VIL threshold for any type of lightning was subjectively tuned to be 4 mm (4 Kg/m^2). The -5°C height is used instead of 0°C since some super-cooling usually occurs in strong updrafts and so the freezing process, and thus electrification, doesn't begin until -5°C. The average -5°C height in summer was taken from the CCFAS Range Reference Atmosphere (Range Commanders' Council, 2004). The top of the layered VIL product should be no higher than -20°C, since this is where electrification usually stops. However, the radar lightning advisory product actually goes to cloud top, even if it's higher than -20°C. This was done for ease of implementation and is a reasonable approximation since there is rarely much VIL above -20°C. Two more recent radar techniques are being considered for use at 45 WS. A double simultaneous layered VIL rule provides 25% better skill than the single layered VIL rule. The thresholds and layers are 0.5 mm from -10 to -15°C and 0.25 mm from -15°C to -20°C (D'Arcangelo, 2000). Another new proposed technique is 30 dBZ at -15° (Gremillion and Orville, 1999). The performance of the radar lightning forecast techniques is summarized in Table 4.

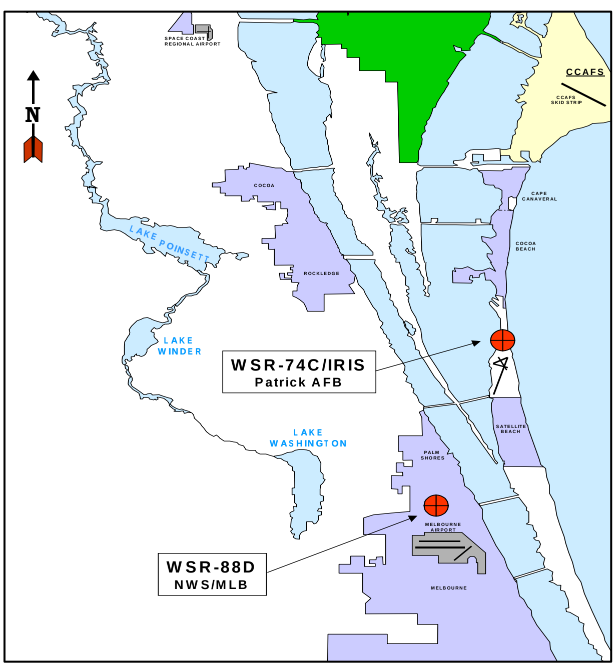

Figure 5. Locations of radars used by 45 WS.

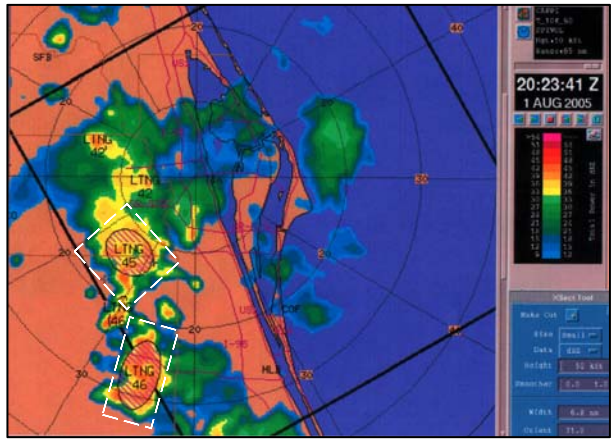

Figure 6. Layered VIL lightning advisory product. Areas with radar layered VIL above -5°C that are ≥ 4 mm (4 Kg/m^2) are marked as a likely lightning area. (potential lightning areas are marked with a text message; the two largest areas are highlighted here with a white dotted box).

Table 4
Performance of Various Radar IC-Lightning Prediction Techniques (D'Arcangelo, 2000)

TOOL	POD *	FAR *	KSS *	OPS UTILITY SCORE **
Pinder Principle	0.72	0.18	0.44	0.48
1 Layered VIL	0.92	0.29	0.26	0.50
2 Layered VIL ***	0.96	0.21	0.51	0.62
Gremillion	1.00	0.29	0.31	0.56

* POD = Probability Of Detection, FAR = False Alarm Rate, KSS = Kuiper Skill Score (0 = random forecasting, 1 = perfect)

** The Ops Utility Score is a locally invented metric that gives a weight of 3 to POD, 2 to KSS, and –1 to FAR and normalizes by the sum of the weights to match importance of these metrics to operations.

*** The mean lead-time for the 2 Layered VIL tool is 9.6 min; mean lead-time has not been measured for the other tools.

3.2 Lightning Launch Commit Criteria Evaluation

Weather presents a significant hazard to all phases of spacelift operations (Boyd et al., 1995). During the generation phase, rockets and payloads are prepared for launch. These activities often occur outdoors and can involve propellants, ordnance, and sensitive electronic systems, all at risk from lightning, wind, severe weather, and rain. During the launch phase, the booster and payload are more at risk from rocket triggered lightning and adverse changes in upper level winds that exceed the booster's structural capability.

To assess the triggered lightning threat, the U. S. Air Force and NASA jointly developed a complex set of Lightning Launch Commit Criteria (LCC) (Boyd et al., 1993). Most of the LCC as listed in Table 5 are for triggered lightning (Roeder et al., 1999). Triggered lightning is an electrical discharge caused by the rocket and electrically conductive exhaust plume passing through a sufficiently strong pre-existing electric field. The triggered lightning process can be viewed as a compression of the ambient electric field until the breakdown potential voltage of air is reached, resulting in a triggered lightning strike (Figure 7). While the exhaust plume is conductive primarily due to its high temperature, composition also plays a role (Krider et al., 1974). Due to this compression, the electric field required for triggered lightning can be two orders of magnitude less than that required for natural lightning. Electric fields sufficient for rocket-trigged lightning can be generated by several sources, as indicated in Table 5. Some phenomena can generate higher electric fields that occur over a shallow depth and are not a triggered lightning threat, examples include: fog, surf, raindrop fracturing, 'Sunrise Effect' (Marshall et al., 1998), and power lines.

The Lightning LCC protect primarily against electric charge generated in the mixed solid-liquid phase of water (normally in the 0 to –20^{o} C layer), either directly at the charge generation site or advected elsewhere after charge generation, e.g. via anvil or debris clouds. However, two LCC are for charge generation from sources other than mixed phase of water: smoke plume and triboelectrification.

The distinction between triggered and natural lightning is important. Ten of the eleven Lightning LCC are for triggered lightning. Even the one natural lightning rule is mostly for triggered lightning, due to charge deposition from the natural lightning, rather than the natural lightning hitting the rocket. The importance of triggered versus natural lightning is also shown by comparing launch scrub rates between ER/KSC and the Western Range (WR). The ER/KSC space launch complex is located near the area of the nation's maximum thunderstorm activity. The WR launch complex is near the nation's minimum thunderstorm activity. The ER/KSC has much more natural lightning than the WR, yet the ER/KSC Lightning LCC scrub rate is slightly less than the WR, 4.7% (Maier, 1999) versus 5.4% (Desordi, 1999), respectively.

The WSR-74C radar is critical in the evaluation of Lightning LCC. This was never more evident than during the Titan IV B-39 launch on 14 Feb 04. The planned launch time for the mission was set for 1821 Universal Coordinate Time (UTC). A low pressure system was located in the Gulf of Mexico moving towards Florida. Mid and upper level clouds ahead of the system extended across northern and central Florida and was clearly evident on radar. The Thick Cloud Lightning LCC forbids launch through a nontransparent cloud layer that is greater than 4,500 ft thick and has parts between the 0°C and –20°C levels. A launch attempt with these conditions could induce a triggered lightning strike resulting in a possible catastrophic loss of the launch vehicle and payload.

Table 5
Lightning Launch Commit Criteria
(details are available at Roeder et al. (1999))

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

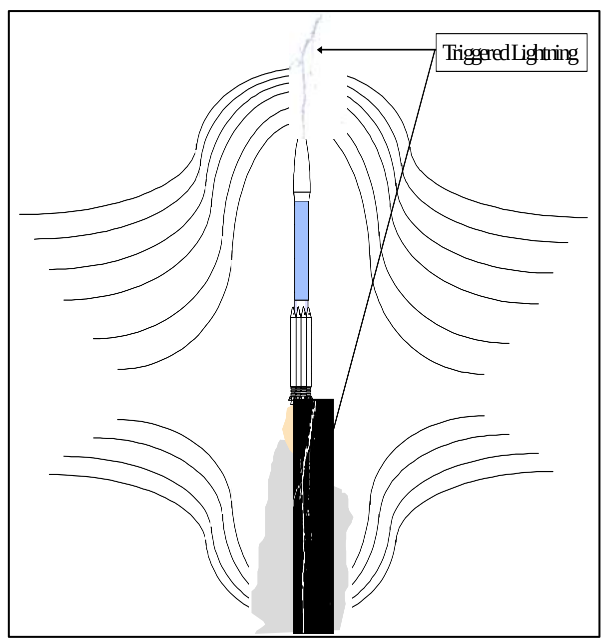

Figure 7. Breakdown voltage of air met or exceeded, resulting in triggered lightning

At 1730 UTC, careful analysis of the 10K and 15K products indicated the thick cloud rule was violated (Figures 8 and 9). Weather reconnaissance aircraft verified this condition and the range was "No Go" for the launch with only 51 minutes left in the countdown. Using the radar, the launch weather officer further interrogated clouds to the southwest and determined that the thickness of the approaching clouds was less than the rule's requirement to produce a triggered lightning event. Again, aircraft confirmed this and a new launch time of 1850 UTC was set based on a window of opportunity indicated by radar data. At 1835 UTC (14 min after the original scheduled launch time), the radar and aircraft indicated the clouds were less than 4,500 ft thick and the Range was now "Go" for launch. At 1850 UTC, the Titan IV safely lifted off and the payload was successfully delivered into orbit. Only 16 min after liftoff, thick clouds violating the rule moved into the area again, as forecasted using the WSR-74C.

The effective use of the WSR-74C data, augmented with aircraft reports and satellite imagery, along with the exceptional forecasting ability of the launch weather officer resulted in the identification and exploitation of a small break in weather conditions. These actions averted a 24-hour launch delay that would have cost in excess of $250,000.

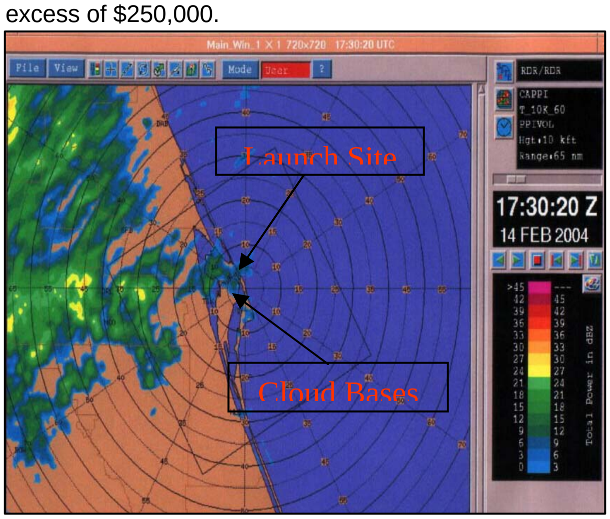

Figure 8. 10,000 ft CAPPI Display

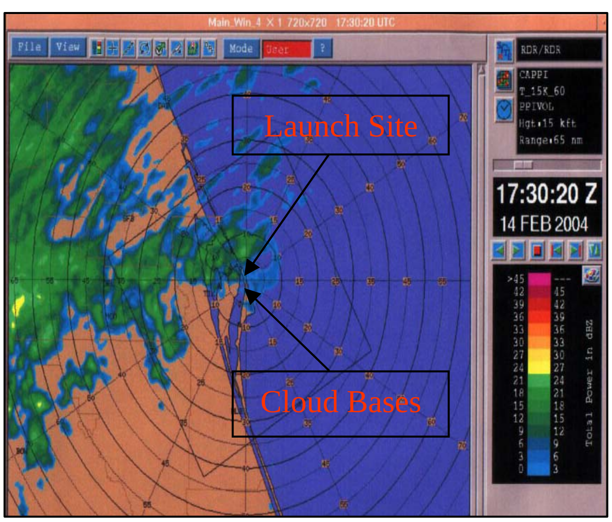

Figure 9. 15,000 ft CAPPI Display

3.3 Convective Winds

The second most frequent warning issued by 45 WS is for convective winds. The convective wind warning and advisory requirements for CCAFS, KSC, and Patrick AFB are listed in Table 6 (Roeder et al., 2003). Weather radar is one of the main tools for nowcasting the occurrence (Wheeler, 1998) and strength of convective winds (Wheeler and Roeder, 1996).

TABLE 6
45 WS Convective Wind Warnings And Related Advisories.

LOCATION	CRITERIA	DESIRED LEAD-TIME
KSC (surface-300 Ft)	≥ 35 Kt	30 min
	≥ 50 Kt	60 min
	≥ 60 Kt	60 min
CCAFS (surface-200 Ft)	≥ 35 Kt	30 min
	≥ 50 Kt	60 min
Patrick AFB (surface)	> 25 Kt	30 min
	≥ 35 Kt	30 min
	≥ 50 Kt	60 min
	Gust Spread ≥ 20 Kt	Observed
	LLWS < 2,000 Ft	Observed
MELBOURNE (surface)	≥ 50 Kt	60 min

The 45 WS has developed several microburst nowcasting techniques, primarily based on weather radar, though there are also some other techniques, as detailed by Wheeler and Roeder (1996). The Echo Top/VIL Wind Gust Potential Chart provides the maximum wind gust expected given the Echo Top and VIL, as observed by radar (Air Weather Service/XOT, 1996). Other research has shown that using the same chart, but using Storm Top rather than Echo Top, provides 16% better accuracy and 29% better discrimination between 45 WS warning criteria (Sullivan, 1999). The Applied Meteorology Unit (Bauman et al., 2004) developed a technique using WSR-88D Cell Trends to predict the onset of downbursts (Wheeler, 1998). The 45 WS has several other radar nowcast tools for downbursts. If the precipitation core reaches the height of the minimum theta-e aloft, a downburst is more likely. Another signature is high reflectivity aloft, being undercut by lower reflectivity. This implies a strong updraft holding lots of water aloft. If the updraft collapses quickly, the water aloft can induce a downburst. Also, a Weak Echo Trench or a Low Reflectivity Notch, which are vertical and horizontal protrusions of low reflectivity into the storm, respectively,

indicates that a downburst is more likely (Figure 10 and Figure 11) (Mackey, 1998).

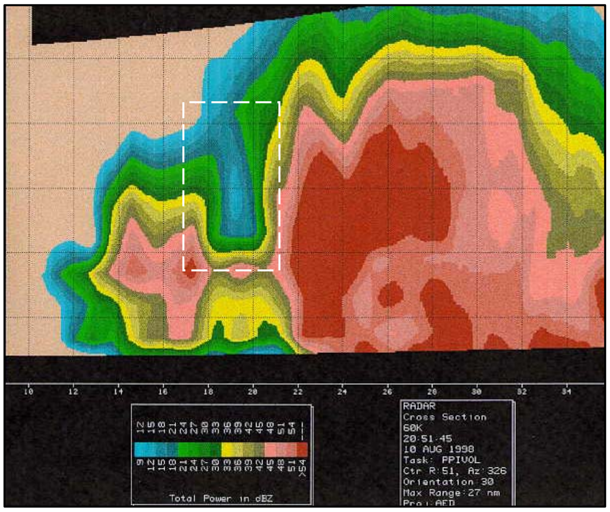

Figure 10. Weak Echo Trench, highlighted by box.

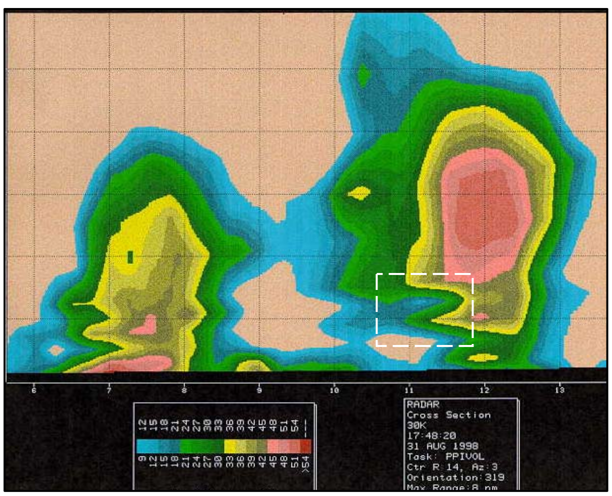

Figure 11. Low Reflectivity Notch, highlighted by box.

3.4 Hurricane Support

Tropical cyclones frequently pose a threat to KSC/CCAFS. Over the recent past there have been several near misses by major hurricanes, as well as several storms passing over the area. These prompted evacuation five times in the past eight years. Radar has been invaluable in tracking the storms. Even if the 45 SW and KSC don't evacuate, radar is essential for issuing tornado warnings, which occur with increased frequency with land falling tropical cyclones, especially in the rain-bands, which can extend over 200 NM from the center of the storm. The National Weather Service Melbourne has developed some local tools that 45 WS also uses to diagnose these tornadoes that include radar morphology and gate-to-gate shear thresholds. Radar is also essential for issuing heavy rain warnings, to allow facilities to prepare for local flooding.

4. EASTERN RANGE WEATHER RADAR

The 45 WS uses many weather systems to provide resource protection and weather support to launch operations as described by Harms et al. (1999). These include four lightning detection and warning systems, a network of 44 meteorological towers, a network of five 915 MHz boundary Doppler Radar Wind Profilers (DRWPs), a 50 MHz tropospheric DRWP, an upper air balloon system, a WSR-74C radar, and a WSR-88D Principal User Processor (PUP).

4.1 Two Weather Radars Used By 45 WS

The 45 WS uses two weather radars to help satisfy the many complex weather support requirements for space launch at the ER and KSC. The WSR-74C at Patrick AFB is at a nearly ideal distance from CCAFS/KSC to provide good resolution and detection of low-level boundaries at CCAFS/KSC. This radar is about 20 miles south of most of the launch pads at CCAFS/KSC. This puts Patrick AFB in the center of the 'cone of silence' of the WSR-74C, which obviously interferes with severe weather and other support at Patrick AFB. However, the WSR-88D has less resolution and low level coverage at its distance from CCAFS/KSC, about 30 miles south-southwest of most of the launch pads, but nearly fills in the WSR-74C cone of silence over Patrick AFB. The 5-cm wavelength of the WSR-74C detects some light precipitation, as required by Lightning LCC evaluation, but suffers moderate attenuation from heavy precipitation. The 10-cm WSR-88D does not detect light precipitation well, but suffers little attenuation. The WSR-74C provides rapid updates of reflectivity only products, while the WSR-88D also provides Doppler velocity and spectrum width products but with slower updates. The radome of the WSR-74C does not have a hydrophobic coating, which leads to attenuation problems with heavy rain over Patrick AFB. The WSR-88D radome does have a hydrophobic coating. The WSR-74C is owned and operated by the USAF, which allows customization of support specifically for the ER/KSC missions, such as an optimized scan strategy and control over operation and scheduling of maintenance to minimize interference with operations. While the 45 WS enjoys excellent cooperation with National Weather Service Melbourne, sometimes their higher-priority public-support missions of the National Weather Service take precedence over 45 WS requirements for the WSR-88D. A comparison of these and other advantages, disadvantages, and synergistic interactions of the modified WSR-74C/IRIS and the WSR-88D as used by the 45 WS are listed in Table 7.

Table 7
Advantages and Disadvantages of the two weather radars used by 45 WS.

	MODIFIED WSR-74C		**WSR-88D**	
	ADVANTAGES	DISADVANTAGES	ADVANTAGES	DISADVANTAGES
WAVELENGTH	5 cm (detects light rain well and some cloud capability)	5 cm (attenuates under heavy rain)	10 cm (doesn't attenuate as much under heavy rain)	10 cm (little cloud and light rain capability)
SCAN RATE	2.5 min (customized scan rate)	N/A	N/A	5 - 10 min (two to five times slower than Modified 74C)
SCAN STRATEGY	One Volume Coverage Pattern (VCP) (Customized to lightning forecasting and Lightning LCC evaluation; easier interpretation)	One VCP (No fine-tuned VCP for other applications; loses capability beyond ≥ 60 NM)	Several VCP (selection for fine-tuned applications)	Several VCP (no VCP for lightning forecasting and Lightning LCC evaluation; complicates interpretation)
POST-PROCESSOR	Sigmet IRIS (customized displays and products; user-friendly windows-based GUI)	Sigmet IRIS (some products on 88D not yet implemented on IRIS)	Multi-Agency Design (some products on 88D not yet implemented on IRIS)	Multi-Agency Design (no customization; tablet old fashioned, not as user-friendly)
LOCATION	PAFB (excellent resolution and low altitude coverage over CCAFS/KSC)	PAFB ('cone of silence' directly over PAFB)	NWS/MLB (nearly fills 'cone of silence' over PAFB)	NWS/MLB (looses some resolution and low altitude coverage over CCAFS/KSC)
OWNER	US Air Force (operation and maintenance done to fit 45 WS needs)	Extra Cost	N/A	NWS/MLB (operation and maintenance done cooperatively, but conflict inevitable)
AGE	N/A	Old (increasing maintenance cost; increased risk of long-term outage)	Newer (less maintenance cost; more reliable)	N/A
RADOME	N/A	No Hydrophobic Coating (attenuation with heavy rain overhead)	Hydrophobic Coating (reduces already small attenuation)	N/A
DOPPLER	N/A	No Doppler (reduced tornado detection capability, no wind profiling)	Doppler (improved tornado detection capability, wind profiling)	N/A
UPGRADES	Potentially Faster Upgrades	Extra Cost	No Extra Cost	Slow Upgrades
STANDARD	Non-Standard (customized to 45 WS special needs)	Non-Standard (increased training)	Standard (military forecasters continue training on radar used at future assignments)	Standard (not customized to 45 WS special needs)
ADDITIONAL SYNERGIES	1) Dual wavelength capability provides objective chaff identification (Roeder, 1995) 2) One radar serves as a "hot" back-up in case the other one fails			

4.2 Eastern Range Weather Radar History

AF weather personnel supporting ballistic missile tests on the Eastern Test Range used a 3-cm wavelength CPS-9 radar during the 1950s and 1960s. The CPS-9 detected light rain and some clouds, but suffered serious attenuation from moderate to heavy precipitation. The size and susceptibility to corrosion of the antenna also created maintenance problems.

A 5-cm AN/FPS-77 radar atop of the Range Control Center on CCAFS replaced the CPS-9 and was used in the 1970's for weather operations. The resident phosphorous memory CRT, Plan Position Indicator (PPI) only, was replaced by a standard radar retention CRT to more clearly and accurately monitor potential severe weather. The location of the antenna, although advantageous for maintenance access and control, presented serious radio frequency interference with sensitive spacelift and spacecraft operations. An attempt to install a trigger mechanism to preclude radiation of critical azimuths had limited success. The radar was required to be totally shut down on numerous occasions to eliminate the possibility of interfering with sensitive spacecraft operations and/or movements. It also presented a "cone of silence" in an area of primary thunderstorm development and launch operations.

Loss or restriction of the radar during the most weather critical portion of these operations was unacceptable. This problem was a significant factor in the subsequent choice to locate the WSR 74C antenna on top of Building 423, at Patrick AFB in 1984. To supplement the AN/FPS-77 radar, dial-up capability to receive a digitized display of the Daytona Beach radar (WSR-57) was added prior to STS-4 in 1982. This dial-up capability was further expanded to include WSR-57 information from Tampa and Miami through the Integrated Storm Information System (ISIS) during the late 1980s (Boyd et al., 2003).

In 1983, the ER purchased and installed a WSR-74C (5-cm wavelength) weather radar to replace the FPS-77. There were several considerations in selection of the WSR-74C: (1) necessity to detect light precipitation, thus the 5-cm wavelength choice, (2) minimization of ground clutter effects; a factor in the remote relocation of the antenna, (3) adaptation of volume scanning capability, (4) dependability; proven history of performance, and (5) ease of operation. Relocation of the antenna solved the RF problem, but created new concerns. Communications, data processing, and relay to the remote site at Cape Canaveral all became problems. Hardware characteristics of the WSR-74C are shown in Table 8.

A project was immediately started to incorporate a volume scan processor developed by McGill University to produce data sets from 24 elevation angles between 0.6 and 35.9 degrees sampled over five minute intervals. This upgrade included a local redesign of the radar pedestal to double the normal rotation rate of the radar. In 1987, the volume scan project was completed, with the WSR-74C radar control and display consoles (one for the Applied Meteorology Unit (AMU) and one for Range Weather Operations (RWO)) located at CCAFS and the transmitter/receiver antenna located at Patrick Air Force Base (AFB) (Austin et al., 1988).

Table 8
WSR-74C Characteristics

PARAMETER	SPECIFICATION
Antennas Assembly	
Type	Elevation over azimuth
Azimuth travel	360^{o} continuous
Elevation travel	-1^{o} to +85^{o}
Parabolic Antenna	
Type	Horn-fed parabolic
Diameter	3.65 m
Polarization	Linear, horizontal
Gain	43 dB, minimum
Beamwidth	1.05^{o} (3 dB)
Transmitter	
Frequency	5625 MHz (5.3 cm)
Peak power output	241 kW
Magnetron type	5083 coaxial
Pulsewidth	4 µs nominal (1.0 µs selectable)
PRF	160 s^{-1} nominal (640 s^{-1} selectable)
Receiver	
Type	Logarithmic
Dynamic range	76 dB, minimum
Bandwidth	0.375 MHz (4 µs pulse)
IF	30 MHz
Gain control	Fixed
Attenuation	User selectable from 0 to 93 dB in 3 dB steps
Sensitivity	Capable of detecting rain rates of 0.25 mm/hr at 370 km

The console, together with other weather equipment was moved to the new Range Operations Control Center (ROCC) when that facility first opened in April 1991. One significant shortfall of the volume scan processing system was the McGill equipment did not control the radar transmitter and receiver functions. This required the continued use of the original control consoles and remote control long-line equipment, which occupied much needed space in the ROCC. It was also the source of significant reliability problems. These shortfalls were resolved by installation in 1997 of the Integrated Radar Information System (IRIS), a commercial off the shelf product by Sigmet, Inc. Data digitization allowed forecasters to construct and display Constant Altitude Plan Position Indicators (CAPPIs), vertical cross-sections, and echo tops, animate displays, and extract point information such as maximum tops and radial location. The CAPPI function is especially useful during launch countdowns to allow interrogation at any desired level. Figure 12 shows an example of a CAPPI during the launch scrub of Space Shuttle STS-108 on 4 Dec 01 due to light rain showers in the area.

In addition to the new capabilities, digital image files of CAPPIs, vertical cross-sections, and echo tops were created by the Central Processing System. The digital image files were sent to Spaceflight Meteorology Group

(SMG) at Johnson Space Center via the Meteorological Interactive Data Display System (MIDDS). SMG integrates the WSR-74C radar data with satellite imagery and lightning detection displays in support of Space Shuttle operations.

The third of the first five nationally procured “NEXRAD” (WSR-88D) was installed at NWS Melbourne in 1989. The ER gained access to that NWS WSR-88D via three Principal User Processors (PUPs); one each located at the RWO and AMU at CCAFS, and one at the Patrick AFB weather station. Addition of the WSR-88D radar significantly enhanced operational capability because of the longer 10cm wavelength and accessibility of velocity vector information. However the volume scanning WSR-74C remained the radar of choice for operations because of its faster volume scan, ease of operation, enhanced customized displays, and total control by local operators. The WSR-88D’s chief contributions would be the identification and processing of severe predictors and as a hot backup.

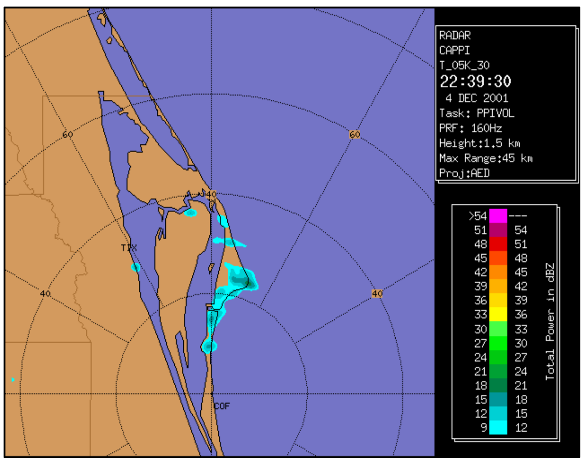

Figure 12. 5,000 ft CAPPI Display

In 2005, the Patrick weather station replaced the PUP workstation with the Open Systems Principal User Processor (OPUP). The new system was a cooperative effort between the Air Force Weather Agency, National Severe Storms Laboratory and the NEXRAD Radar Operations Center with the goal of fulfilling new radar data display requirements that were a result of the re-engineered AFW support philosophy (Chrisman, 2005). Major benefits with the OPUP include the ability to display up to 12 products on a screen and the inclusion of graphic user interfaces (GUIs) to make product manipulation much easier.

The volume scan strategy of the WSR-74C was refined in June 2000 by the Applied Meteorology Unit (Bauman et al., 2004) to better support operations (Short et al., 2000). The new scan strategy (Figure 13) uses twelve elevation angles and maintains the 2.5-minute volume scan.

This scan strategy selection improved vertical resolution of radar coverage by 37% in the climatological 0°C to -20°C layer, where cloud electrification occurs, at the distance from the radar to the launch complexes at CCAFS and KSC. This improved Lightning LCC evaluation and lightning advisories. This scan strategy also eliminated wasted beam overlap. The new scan strategy was also designed to produce constant vertical gaps with range at a fixed altitude between half-beam-widths. This simplifies interpreting the radar products.

The vertical lines in Figure 13 indicate the locations of the closest and most distant launch complexes relative to the radar. The line is thickened between 10,400 feet and 27,600 feet to emphasize the electrically important layer between the average 0°C height minus two standard deviations and the average -20°C height plus two standard deviations. The elevation angles are executed in the following order: 0.4°, 3.2°, 6.6°, 10.9°, 16.1°, 22.4°, 26.0°, 19.2°, 13.4°, 8.6°, 4.8°, and 1.8°. The scan angles are interleaved to complete a full volume scan with minimum vertical motions of the radar antenna to reduce wear on the aging WSR-74C.

The IRIS software was upgraded in 2003 to take advantage of recent improvements to this COTS system. The upgrade improved memory capability and replaced aging control and display hardware.

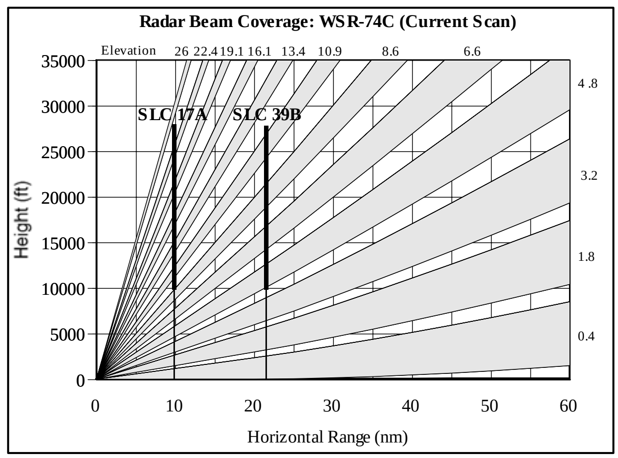

Figure 13. Scan strategy optimized for Lightning LCC evaluation and lightning forecasting.

4.3 Planned Radar Improvements

A major radar improvement is in the planning stages. The plan calls for replacement of the current WSR-74C radar system. The new radar should be a state-of-the-art, dual polarimetric, C-band (4-8 cm) Doppler radar system. The radar will be optimally sited and its data integrated into the display system delivered as part of the Range Standardization and Automation (RSA) Program. Standard volumetric radar products will continue to be updated and provided to forecasters every 2.5 minutes (Harms et al., 2003).

The C-band was chosen for the replacement radar as a reasonable compromise between detection of light precipitation, as required for Lightning LCC evaluation, and attenuation under heavy rain, which degrades severe weather warnings. This is especially true since the less attenuating S-band WSR-88D data is also available to the 45 WS.

The system should provide two operationally significant capabilities that the current WSR-74C does not have. The first of these capabilities would be detection of Doppler velocity. This will significantly aid tornado warnings by detecting the rotation of tornadic thunderstorms. Doppler capability should also help convective wind warnings by detecting thunderstorm outflows that are approaching the area and the divergent pattern of local downbursts. Doppler ability may also improve the forecast of downburst by detecting mid-level convergence of ambient air with low equivalent temperature into thunderstorms, which initiates many downbursts. Doppler ability may also allow detection of upper storm convergence as the downburst begins, but before it reaches the surface. Another possibility of Doppler capability will be combining the radial velocities from the WSR-74C replacement and from the WSR-88D radar at NWS Melbourne. This Dual Doppler capability will allow retrieval of three-dimensional vector wind fields. The wind components will then be available for initialization of the local mesoscale model delivered as part of the RSA Program. The Dual Doppler capability may also be done with bistatic receivers, which are radar receivers located away from the traditional transmitting/receiving radar. These off-site receivers detect the radar beam scattered in directions other than back towards the transmitting radar and then feed that signal to the central processor where the Doppler radial velocities from two or more directions are combined to create the true 3-D velocity field. Since Dual Doppler is done best where radar beams intersect perpendicularly, bistatic receivers can enhance and extend Dual Doppler capability without the cost of extra radar transmitters.

The second capability the radar system should provide is dual-polarization measurements. By transmitting electromagnetic beams polarized in both the vertical and horizontal directions, changes in backscattered signal properties can be used to estimate the size, shape, orientation, type, and number density of hydrometeors. Two of the polarimetric measurements of particular interest are the Linear Depolarization Ratio and Differential Phase Shift. Both of these products have been shown to be useful in identifying regions where high electrical charge is located within cloud areas (Illingworth and Hogan, 2002). The ability to identify electrified cloud regions should significantly improve the 45 WS capability to forecast the onset and ending of lightning, the potential for triggered lightning, and improved convective wind warnings. Dual polarization radar also has considerable promise for improved downburst prediction. Combining dual polarization parameters can infer the type, size, extent, and number density of hydrometeor species. Some hydrometeors are more likely to evaporate and melt rapidly and so help initiate downbursts. Other hydrometeors are more likely to evaporate and melt slowly and so help sustain downbursts so they reach the surface. Thus, dual polarization should help identify the simultaneous conditions that are conducive for downbursts forming and reaching the surface and the intensity of those downbursts at the surface. This is especially true when combined with the radar's Doppler capability to detect convergence of low equivalent potential temperature at a certain level, as measured by radiosondes, being entrained into the thunderstorm. Research conducted using other polarimetric measurements have shown promise in providing more accurate rainfall estimations, unique hail detection capabilities, and estimating horizontal water vapor content within the boundary layer (Keeler et al., 2000).

The radome of the WSR-74C replacement will have a hydrophobic coating. This will significantly reduce the attenuation problems currently experienced with rain over Patrick AFB.

The 45 WS has several ideas for better use of the new radar beyond those listed above (Roeder et al., 2002). Instead of one general purpose scan strategy, several scan strategies might be designed that are optimized for various weather scenarios. Four examples of these specialized scan strategies are now briefly discussed.

The first possible specialized scan strategy would be for better detection of low level boundary lines via longer dwell emphasizing low angles during pre-convective regimes on summer mornings. A hybrid scan might also be used, where the antenna rotation rate is slower for the lower angles, to provide improved detection of low altitude atmospheric boundary lines. This should improve the forecasting of the first thunderstorms of the day and improve initialization of the local numerical model.

The second possible specialized scan strategy would be for better lightning forecasting and better Lightning LCC evaluation. This scan strategy would automatically adapt to completely fill the user-specified 0°C to -20°C levels, based on local real-time radiosonde observations. A different hybrid scan might be used with slower antenna rotation at these angles to more accurately sense this key layer for atmospheric electrification. Any scan angles that could be added after filling the 0°C to -20°C layer, and still maintain the 2.5 min volume scan, would be used to uniformly fill-in angles from 0.4° to 0°C and from -20°C to 26.0°, where the 0.4° and 26.0° angles are the lower and upper limits of the current general purpose scan strategy.

The third possible specialized scan strategy would be for severe weather. This scan strategy would trade range for improved Doppler velocity detection in the local area for tornado detection, downburst detection, and convergence around storms for downburst prediction.

The fourth specialized scan strategy would be for general surveillance, like the current general purpose scan strategy.

Other specialized scan strategies may also be developed. While these specialized scan strategies have obvious advantages for those applications, they also have a draw back of sacrificing overall coverage, which might allow unexpected weather to catch the forecaster unawares. The forecaster would always have to be very aware of which scan strategy was in use. This problem of sacrificed overall coverage could be avoided by using the WSR-88D at NWS Melbourne for general surveillance. Integrating the data from the two radars into a single display would help the forecasters visualize the weather and its threats more effectively.

Another option would be to always alternate the specialized scan strategy of the 45 WS radar with the general purpose strategy on the same radar. But that has the disadvantage of the quality of the volume scan continually changing. The 45 WS might decide that the advantages of a single general purpose scan strategy is more important operationally and no specialized scan strategies would ever used.

The 45 WS might implement specialized products on the WSR-74C replacement. For example, some research has indicated that two simultaneous Layered VILs between -10°C to -15°C and -15°C to -20°C layers provide better prediction of the first lightning from a developing thunderstorm than the current single Layered VIL above -5°C. The AMU developed two WSR-88D Cell Trends tools to predict downbursts and hail, which would be good to implement on the WSR-74C replacement. A Storm-Top/VIL tool has also been shown to outperform the more traditional Echo Top/VIL tool for expected maximum gust if a downburst occurs. If one knew how downburst speeds decay with distance, an integrated downburst tool could be produced – the Cell Trends tool would tell you that a downburst is beginning, the Storm Top/VIL tool would tell you the expected maximum gust, and given the distance to the thunderstorm or rain shower, the speed decay with distance would tell you if that downburst would exceed your warning criteria at your location.

Mimicking the entire suite of WSR-88D Cell Trends products would also be useful. As mentioned elsewhere, dual polarization products will likely be useful for lightning forecasting, lightning LCC evaluation, downburst prediction, and heavy rain warnings. Numerous other specialized operationally focused products are also possible.

Other advanced applications for the WSR-74C replacement are possible. The 45 WS might acquire a weather Warning Decision Support System-Integrated Information (WDSS-II) (Roeder et al., 2003). The WDSS-II would allow automatic integration of the data from the WSR-74C replacement at Patrick AFB, the WSR-88D at Melbourne, and perhaps the TDWR radar at Orlando airport, into a single radar product. Advanced weather warning decision aids are also available on WDSS-II. The WDSS-II also facilitates designing and implementing new weather warning decision aids for local use.

Another application might be the use of ground clutter to correct reflectivity for attenuation. Another application for the far future might be using observations and local models to do 3-D ray tracing of the radar beams depending on the temperature and moisture structure of the real atmosphere. The actual altitude of the radar beams would then be available, even under anomalous propagation. In the best of all worlds, the scan strategy would automatically adapt to keep the radar beams at the desired altitudes.

5. SUMMARY

Space launch has complex weather requirements. With the help of many dedicated individuals in diverse organizations, the Air Force and NASA have established the world's premier instrumentation site for operational meteorology to support America's space program at the Eastern Range. Weather radar is one of the most important of these sensors. The 45 WS uses two weather radars, primarily a modified WSR-74C. A significant upgrade to a Doppler Dual Polarization radar with optimized scan strategies is currently being planned. The goal is to continue with the best weather surveillance radar available to meet space launch requirements.

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