11B.7 USE OF WEATHER RADAR TO SUPPORT AMERICA'S SPACE PROGRAM -- PAST, PRESENT, AND FUTURE

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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 and resource protection, pre-launch ground processing, day-of-launch, post-launch, and special operations 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. Over the last 15 years, approximately one-third of the scheduled launches have launched on time, one-third with delays, and one-third have scrubbed. Of those scrubbed, 50 percent were due to weather conditions (92 of 183). The effective use of weather radar information produces annual cost savings of millions of dollars through timely management decisions along with the paramount contribution to launch and personnel safety.

2. WEATHER SUPPORT REQUIREMENTS

Weather presents a significant hazard to all phases of spacelift operations. During the processing phase, launch vehicles and their payloads are prepared for flight. These activities, which often occur outdoors, can involve propellants, ordnance, and sensitive electronic systems, all at risk from lightning strikes, winds, severe weather, and precipitation. Two items contribute to the difficulty of weather support by the 45th Weather Squadron: (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.

2.1 Weather Lightning Advisories

The area of maximum thunderstorm occurrence in the United States is near the CCAFS/KSC complex. Days with thunderstorms exceed 50% in July and August at the KSC Shuttle Landing Facility.

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Consequently, thunderstorms and associated lightning and damaging winds represent the single greatest threat to operations on CCAFS/KSC. Lightning flash density is highly variable within the CCAFS/KSC area, varying between an average of 5 to 13 flashes/km^2/year. Therefore, the 45 WS has a strong requirement for the best possible weather surveillance radar.

Using a modified WSR-74C as the primary tool, the 45 WS provides meteorological watch service to protect people and facilities against dangers from lightning within a 5nm radius in 13 specific locations (Figure 1). Many of these lightning advisory areas closely overlap creating perhaps the most complex and challenging lightning advisory requirements in operational meteorology. The goal is to meet or exceed the desired lead time of 30 min as often as possible to give customers as much time as possible to take protective measures and provide timely termination of the advisories to allow safe return to work. To help meet this challenge, the 45 WS has developed many radar-based lightning forecast tools.

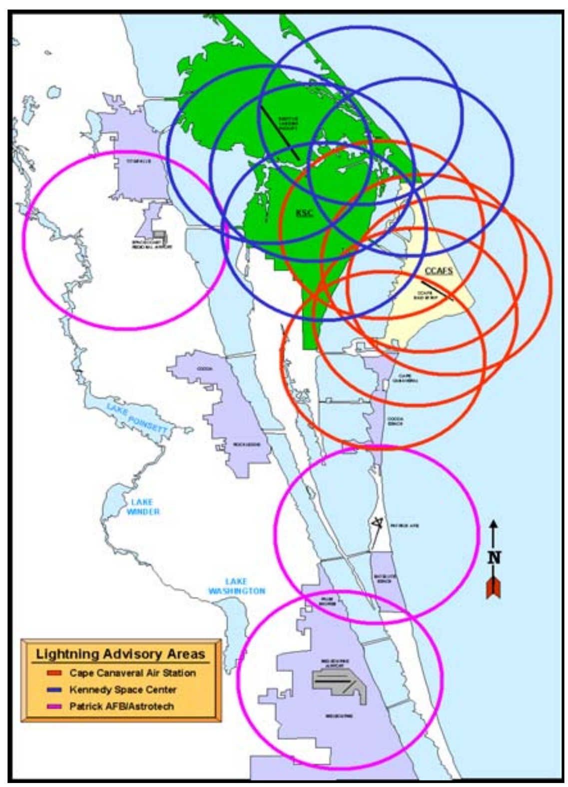

Figure 1. The 13 lightning advisory points supported by 45 WS and the 5 NM safety buffer around each.

2.2 Triggered Lightning Evaluation

During the launch phase, the booster and its payload are more at risk due to the possibility of the vehicle triggering a lightning strike, or adverse changes in upper level winds that exceed the booster's structural capability. To assess the triggered lightning threat, the United States Air Force and NASA jointly developed a complex set of Lightning Launch Commit Criteria (LCC).

Most of the LCC 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 or exceeded, resulting in a triggered lightning strike. 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 is two orders of magnitude less than those required for natural lightning. Electric fields sufficient for rocket trigged lightning can be generated by several sources, as covered by the LCC. 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' (Marshal et al, 1999), and power lines.

The 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. The distinction between triggered and natural lightning is important. Ten of the eleven 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 bolt intercepting the rocket.

2.3 Convective Winds

The second most frequent warning issued by 45 WS is for convective winds. KSC warning requirements are $\geq$ 35 Kt, $\geq$ 50 Kt, and $\geq$ 60 Kt below 300 Ft with desired lead-times of 30 min, 60 min, and 60 min, respectively. CCAFS requires $\geq$ 35 Kt, $\geq$ 50 Kt below 200 Ft with desired lead-times of 30 min and 60 min, respectively. Weather radar is one of the main tools for nowcasting the occurrence and strength of convective winds (Wheeler and Roeder, 1996).

2.4 Hurricane Support

Tropical cyclones pose a threat to KSC/CCAFS. Over the recent past there have been several narrow misses by major hurricanes, as well as several minor storms passing over the area. Those narrow misses prompted evacuation three times in the past seven years. Radar has been invaluable in issuing tornado warnings, which can occur in rain bands over 250 NM from the land falling eye, and in issuing heavy rain warnings.

3. WEATHER SYSTEMS

In addition to the WSR-74C, the 45 WS uses many weather systems to provide resource protection and weather support to launch operations as described by Harms et al. (2003). These include lightning detection and warning systems, a network of meteorological towers, a network of five 915 MHz boundary Doppler Radar Wind Profilers (DRWPs), a 50 MHz tropospheric DRWP, an upper air balloon system, and WSR-88D Principal User Processors.

3.1 Weather Radar History

AF weather personnel supporting ballistic missile tests on the ER used a 3cm wavelength CPS-9 radar during the 1950s and 1960s. The CPS-9, although extremely capable of detecting lighter precipitation and some clouds, suffered serious attenuation from moderate to heavy precipitation.

A 5cm AN/FPS-77 radar, placed on top of the Range Control Center (RCC) located on Cape Canaveral, replaced the CPS-9 and was used in the 1970s to support 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 on top of the RCC, although advantageous for maintenance access and control, presented serious RF interference with sensitive spacelift and spacecraft operations. An attempt to install a trigger mechanism to preclude radiation at critical azimuths was initiated with 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.

Loss or restriction of the radar during weather critical portions of these operations was unacceptable, as was the cone of silence problem. 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.

In 1983, the ER installed a WSR-74C (5cm wavelength) weather radar to replace the FPS-77. There were several considerations in selection of the WSR-74C: (1) requirement to detect light precipitation, thus the 5cm 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 became problems. 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 (Austin, et al., 1988). 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. Two WSR-74C radar control and display consoles were installed, one for Range Weather Operations (RWO)) located at CCAFS and one for the Applied Meteorology Unit (AMU) (Ernst et al., 1995). The transmitter/receiver antenna was located at Patrick Air Force Base (PAFB).

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 this 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 need space in the ROCC. It was also the source of significant reliability problems. (These shortfalls were resolved by installation of the IRIS/Open software in 1997, discussed in following sections). 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.

In addition to the new capabilities, digital image files of CAPPIs, vertical cross-sections, and echo tops were created by the Central Processing System and sent to the Meteorological Interactive Data Display System (MIDDS) where they could be transmitted and integrated with satellite imagery and lightning detection displays and provided to the Spaceflight Meteorology Group.

The third of the first five nationally procured “NEXRAD” (WSR-88D) was installed at the Melbourne National Weather Service (NWS) Office in 1989. The ER has 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 would remain 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.

3.2 Current Modified WSR 74C/IRIS Configuration

In 1997 a project was completed which upgraded the system to the IRIS/Open software (Boyd et. al., 1999). That system increased volume scan update rate from every five minutes to every 2.5-minutes. It is more user-friendly, customized local products, makes cross section development easier and provides the capability to display reflectivity over any user-defined range with user defined color-coding. These new features enable routine detection and display of weak reflectivity features such as nonprecipitating clouds and mesoscale boundaries (e.g. fine lines and sea or river breeze) close to the radar. Following each 2.5-minute volume scan build cycle, the system generates the following products, each available for display: Vertical Cross Sections, Maximum Reflectivity, Maximum Echo Top, Vertically Integrated Liquid (VIL), Track/Forecast Product Display (TRACK), Constant Altitude PPI (CAPPI), and Warn/Centroid Product Display (WARN).

The volume scan strategy was refined in June 2000 by the AMU to better support operations (Short, et al., 2000). The new scan strategy (Figure 2) employed by the 45 WS WSR-74C uses twelve elevation angles and maintains the 2.5-minute volume scan. This new scan strategy selection improved radar coverage 37% in the climatological 0°C to -20°C layer, where cloud electrification is generated. This scan strategy also improved Lightning LCC evaluation and lightning advisories as well as eliminating wasted beam overlap.

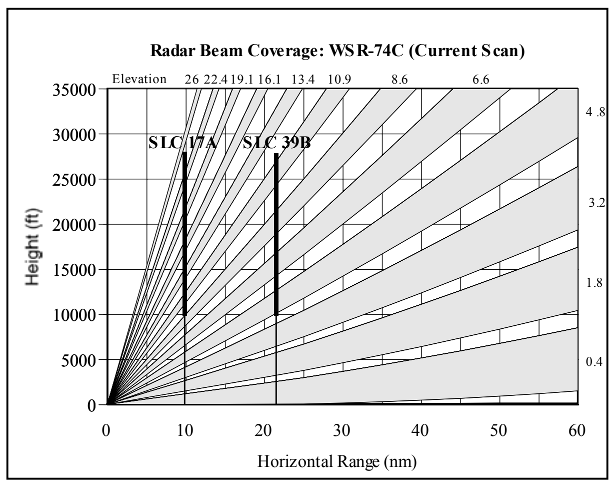

Figure 2. Scan strategy

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 2 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 stand 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°. Furthermore, the interweaving of angles on an up/down cycle reduces bearing wear.

The Commercial-Off-The-Shelf (COTS) IRIS/Open software was upgraded in 2003 to take advantage of improvements to this COTS system.

3.3 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 will 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.

The system should provide two operationally significant capabilities that the current WSR-74C does not have. The first being the ability to retrieve three-dimensional vector wind fields. This will be accomplished by installing a network comprised of the active transmitting weather radar along with one or more bi-static receivers. The receivers for this network will be non-transmitting, non-scanning and remotely located from the active radar. This network of a single transmitting radar and multiple passive receivers will act much like a network of multiple transmitting radars, in that it will receive the radar beam scattered into two or more directions, including the backscatter to the transmitting radar. This will allow retrieval of three-dimensional vector wind fields. The wind components will than be available for initialization of the local mesoscale model delivered as part of the RSA Program. Dual Doppler may also be done with Melbourne's NWS WSR-88D.

The second is dual-polarization measurements. By transmitting electromagnetic beams polarized in both the vertical and horizontal directions, changes in 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 (LDR) and Differential Phase Shift (KDP). 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's capability to forecast the onset and ending of lightning, the potential for triggered lightning, and improved convective wind warnings. Research conducted using other polarimetric measurements have shown promise in providing more accurate rainfall estimations, unique hail detection capabilities, and horizontal water vapor content estimates (Keeler et al., 2000).

4. 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 and Kennedy Space Center. Weather radar is one of the most important of these sensors. The 45 WS uses two weather radars, primarily a modified WSR-74C that has undergone extensive modifications. The goal is to continue with the best weather surveillance radar available to meet space launch requirements.

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