P1.6 THE NEW WEATHER RADAR FOR AMERICA'S SPACE PROGRAM IN FLORIDA: A TEMPERATURE PROFILE ADAPTIVE SCAN STRATEGY

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1. INTRODUCTION

The 45th Weather Squadron (45 WS) is the U.S. Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS), NASA's Kennedy Space Center (KSC), and Patrick AFB (PAFB) in east central Florida. The weather support requirements of the space program are very stringent (Harms et al., 1999). Since central Florida experiences the largest annual cloud-to-ground lightning flash density in the U.S. (Huffines and Orville, 1999), thunderstorms and their related hazards are important to operations at CCAFS/KSC. These hazards include lightning, convective winds, hail, and tornadoes. The 45 WS uses a dense network of weather sensors to meet the operational requirements in this environment (Roeder et al. 2003).

One of the most important weather sensors to the 45 WS mission is the WSR 74C radar at PAFB (Roeder et al., 2005). This radar is near the end of its lifecycle and is being replaced by a new Radtec TDR 43-250 radar. This new radar provides significant benefits over the existing WSR-74C, including Doppler and dual-polarization capabilities (Roeder et al., 2009, this conference).

A new fixed scan strategy was designed to best support the Florida space program (Roeder and Short, 2009, this conference). The fixed scan strategy represents a complex compromise between many competing factors and relies on climatological heights of various temperatures that are important for improved lightning forecasting (Roeder and Pinder, 2008) and evaluation of Lightning Launch Commit Criteria (LCC)(Roeder and McNamara, 2006). The Lightning LCC are the weather rules to avoid natural and triggered lightning strikes to in-flight rockets.

The temperature layer from 0°C to -20°C is vital since most generation of electric charge occurs within it and so it is critical in evaluating the Lightning LCC and in forecasting lightning. The Lightning LCC also considers the ±5°C level to allow for rapidly developing convection. These are two of the most important missions of 45 WS. While one fixed scan strategy that covers most of the climatological variation (±2σ) of the 0°C to -20°C levels with high resolution ensures that these critical temperatures are well covered at all times, it also means that on any particular day the radar could be spending precious time scanning at angles covering less important heights over and around the launch pads at CCAFS/KSC.

The paper describes an ongoing project to develop a user-friendly, Interactive Data Language (IDL) computer program that will automatically generate situation-dependent, mission-optimized radar scan strategies with user adaptive input of the temperature profile and other important parameters. By using only the required scan angles output by the temperature profile adaptive scan strategy program, faster update times for volume scans and/or collection of more samples per gate for better data quality is possible while maintaining high resolution at the mission critical temperature levels. The adaptive scan strategy will select beam angles based in part on vertical resolution mission requirements as defined by the half-power beam widths between vertically adjacent beams (Fig. 1).

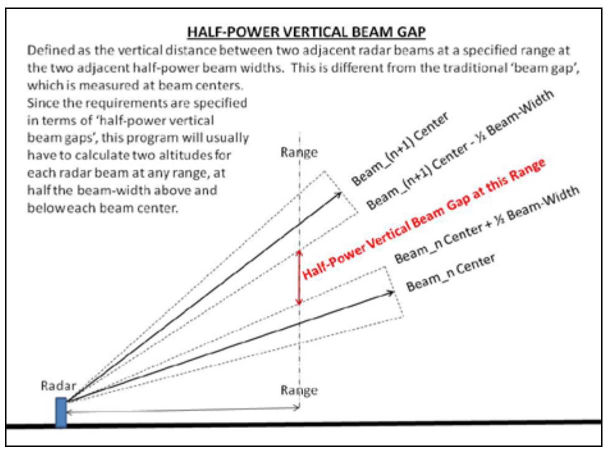

Figure 1. Depiction of the half-power beam gap. The half-power vertical beam gap is defined as the vertical distance between two adjacent radar beams from the bottom of the upper half-power beam width to the top of the lower half-power beam width, as shown above. The half-power beam width of the new radar is 0.95°.

2. OPERATIONAL REQUIREMENTS

The overall operational goal is the generation of variable scan strategies optimized, from user input, for use by the 45 WS using its incoming new weather radar's capabilities and location with respect to CCAFS/KSC. The site of the new radar relative to CCAFS/KSC is shown in Fig. 2. The scan strategy should provide the best compromise between meeting 45 WS operational needs and a fast volume scan.

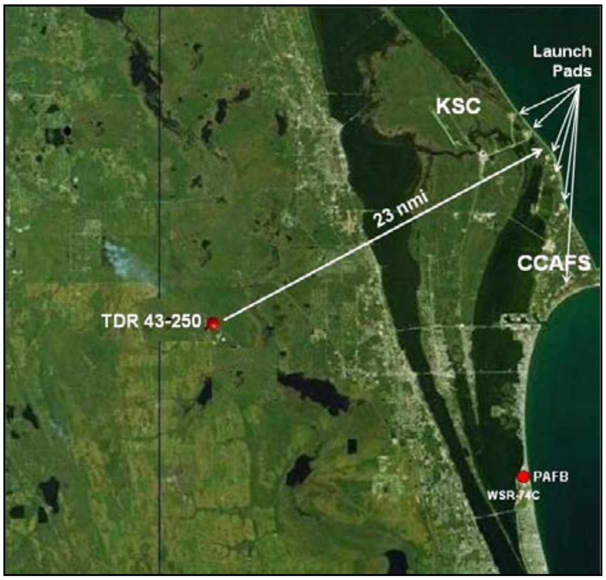

Figure 2. Location of the new Radtec TDR 43-250 radar relative to CCAFS/KSC. The radar is located approximately 23 nmi from the average location of the launch pads.

2.1 Convective and Non-convective Requirements

The temperature adaptive scan strategy can be separated into convective and non-convective components. If convection is expected to occur over the radar domain, then the key operational requirements are: 1) complete radar coverage of the planetary boundary layer (PBL) from the surface to 3,000 ft within 10 nmi of CCAFS/KSC (Fig. 2) with adjacent half-power beams, 2) radar coverage from top of the boundary layer to a user-specified 5°C level with half-power beam gaps ≤ 4,500 ft over the launch pads (note: see Fig. 1 for a definition of half-power beam gap), 3) radar coverage from a user-specified 5°C to -20°C level with half-power beam width gaps ≤ 1,500 ft within ±5 nmi of the launch pads, 4) radar coverage up to 3,000 ft above the user-specified convective cloud top or anvil clouds with decreasing vertical resolution above -20°C within 10 nmi of CCAFS/KSC property, and 5) reduction of the cone of silence by having the highest beam angle exceed the user-specified convective cloud top by 3,000 ft at 10 nmi from the radar. If no convection is expected to occur over the operational domain, then complete coverage of the PBL and excellent coverage from the top of the PBL up to 10,000 ft within 10 nmi of the launch pads is required.

2.2 Key Distance Requirements

The CCAFS/KSC areas have numerous launch pads. Fortunately, most of these are roughly aligned on a circular arc and are about the same distance from the radar (Fig. 2). Thus, for simplicity, a single typical distance from the radar to the launch pads (23 nmi) will be used in the program. However, the distance from the radar to the launch pads will be easily configurable without recoding or recompiling in case a new launch pad at a different distance is constructed. The thick cloud Lightning LCC also has a required distance from the launch pads of ±5 nmi. Often the range of interest for specific radar scanning requirements is located at the distance from the radar to the launch pads plus or minus the thick cloud Lightning LCC distance. See Section 3 and Table 1 for further details. Again, both distances will be easily modified by the user in the configuration file in the event that requirements change.

2.3 Input and Output Requirements

The task for this project is to create an Interactive Data Language (IDL) computer program that will automatically output radar scan strategies that are based on user input of temperature profile data and expected convective or anvil cloud top that meet the core operational requirements above. Since the program could be used in an operational forecasting environment at 45 WS, the resulting IDL program must be fast, accurate, easy to use, robust, well commented and modular.

Input to the program will be via a graphical user interface (GUI) for user-friendly data entry of specified heights at +5°C, -20°C, and expected convective or anvil cloud top. The program will request these parameters at each run and check that the user input value is within expected limits. If the input is out of the expected range, the program will inform the user of the error and ask for the value to be confirmed or if the user wants to enter a new value. The user will also have the ability to modify easily other radar scan parameters, environmental variables, ranges,

Table 1. Convective scan requirements and preliminary design solutions.

OPERATIONAL REQUIREMENT	PRELIMINARY DESIGN SOLUTION
The program shall provide complete scanning of the Planetary Boundary Layer (PBL) in and around CCAFS/KSC, especially around the Indian River and Banana River, to find low-level boundaries that are critical in the formation of new thunderstorms during the summer. Complete means the half-power beam widths of adjacent beams just barely touch.	The initial values for the first three angles will be 0.2°, 1.2°, and 2.2° such that the half power beam widths (0.95°) are adjacent for complete coverage of the PBL. Set these variables in an easily changeable external configuration file, in case these angles need to be adjusted once ground clutter pattern is better understood.
The program shall include one beam at the 5°C height over the launch pads at beam center, unlike most of the other requirements that are at half-power beam edge.	Calculate the center beam required to match that height at distance to launch pad. Again, this is beam center, not half-power beam edge.
The program shall provide adequate scanning in the vertical gap between the 3rd beam (configured to 2.7°) and 5°C above the launch pad, as set in the previous step. Adequate means no half-power beam gap is > 4500 ft in this layer. This 4,500 ft is set in the easily edited configuration file.	If the gap between beam-3 and the 5° beam directly over the launch pads is > 4,500 ft, add another beam such that it is equally spaced in height between the two beams directly over the launch pads between the two beams. Iterate until all the vertical gaps between beam-3 and the 5° beam directly over the launch pads are < 4,500 ft and equally spaced in height. Calculate using the half power beam widths above and below the beams, respectively.
The program shall provide outstanding scanning from 5°C to -20°C within the LCC thick cloud distance (±5 nmi) of the launch pads. Outstanding means no half-power beam gap is > 1,500 ft in this volume. For Lightning LCC evaluation and lightning forecasting, ensure ≤ 1,500 ft gaps at launch pad distance + 5 nmi in this layer. In the program, make all distance in terms of the configuration file variables, rather than hard coding to the current distances.	From the 5°C beam at distance to the launch pads + 5 nmi, iterate up in 0.1° increments, calculating the distance between the bottom of the new beam and the top of the 5°C beam until it exceeds the 1,500 ft limit at distance to the launch pads plus 5 nmi. The previous beam is the desired beam that just barely avoids exceeding the threshold. Repeat starting with the new beam. Continue until new beam is above the -20°C height at distance to the launch pads + 5 nmi. This ensures the resolution requirements are met throughout the ±5 nmi range. The highest beam for this requirement must also meet or exceed the -20°C height at the -5 nmi distance from the launch pads.
The program shall provide excellent scanning of anvil clouds within ±10 nmi of the launch pads. Excellent means the vertical coverage will overshoot the convective cloud top by 3,000 ft with decreasing resolution as defined in the 'possible solution' to the right. The requirement is for ± 10 nmi, but the closer -10 nmi distance is more stringent than the +10 nmi distance, so only the -10 nmi threshold needs be met. Overshoot the convective cloud top (anvil cloud) height by at least 3,000 ft within ±10 nmi of the launch pads to ensure the anvil is fully interrogated for the 'Anvil' LCC and to ensure any measurements required for vertically profiling ice amount in the anvil will be valid. The program will likely need exception handling for when the expected cloud top is ≤ -20°C height. In that case, there is no need for anvil cloud angles, since the 5°C to -20°C requirement already satisfies them.	From the last highest beam in the previous step, find the vertical gap to the second highest beam in the previous step at distance to the launch pads -10 nmi. Find a new beam with a vertical gap 2 times the previous vertical gap at distance to the launch pads -10 nmi. Keep adding beams, increasing the vertical gap by 2 times of the successive new gap at distance to the launch pads -10 nmi until the height at that distance meets or exceeds the convective cloud top height plus 3,000 ft. Successively higher beams get increasingly farther apart. The multiplicative factor of 2 and the 3,000 ft overshoot should be easily set in an external data file. The 2x multiplicative factor is an estimate and should be tuned for the actual initial default of the program.
The program shall provide very good reduction in the size of the cone of silence. Very good means beams shall be added to bridge the gap between the top angle for the anvil requirement above, with decreasing vertical resolution as specified in the 'possible solution' to the right, until the highest beam overshoots the expected convective cloud top by 3,000 ft within ±10 nmi of the radar (not the launch pads). The 10 nmi and 3,000 Ft distance parameters are user configurable. The need for this cone of silence angle will be made into a user configurable yes/no toggle since WSR-88D data may be available in the future to fill in the cone of silence of the Radtec radar. May need exception handling if the need for anvil clouds is turned off in the exception handling in the above step.	Continue adding additional angles above the last angle in the previous step with 2 times the previous vertical gap at 10 nmi from the radar (not the launch pads) until the height of the half power bottom of the beam at 10 nmi from the radar exceeds the convective cloud top height plus 3,000 ft at 10 nmi from the radar. Successively higher beams get increasingly farther apart. The vertical gap grows by 2 times with each iteration. The 2x should be the same multiplicative growth factor used in the previous step, i.e. if the user reconfigures this number, that new factor is used here too. Climatologically, only one additional angle is expected for cone of silence during the summer.

heights and elevation angles of specific interest in a configuration file without recoding or recompiling the IDL program. The expected limits for the user-input heights will also be set in this externally configurable file.

Output from the program will be a file containing the temperature profile optimized radar scan elevation angles. The elevation angles will be interleaved to reduce long-term wear on the radar and to provide slightly faster scan strategies. The elevation angles proposed by the program will be added to the radar manually. The program will also display a graph of the half power beam width elevation angles and their height coverage versus horizontal range. This visual check of the output elevation angles will be important both to ensure proper functioning of the program and to build user confidence.

3. PRELIMINARY DESIGN

3.1 Convective

A detailed discussion of preliminary design solutions that satisfy the convective requirements of the temperature-profile adaptive scan strategy are provided in Table 1 above along with the associated operational requirements.

3.2 Non-convective

As in the convective design, the first three angles shall be chosen to provide complete coverage of the PBL and will be read from the configuration file. The default values, which will depend on a further evaluation of the ground clutter pattern, will be initially set to 0.2°, 1.2°, and 2.2°. Next, calculate the beam angle needed for the beam center to be at the clear-air maximum height at the launch pad distance from radar minus the clear air distance. The three distance variables will be read from the configurable file and initially set to 10,000 ft, 23 nmi and 10 nmi, respectively. The resulting angle will be around 7.4°, but will need to be calculated each time, in case any of the variables are changed. This angle becomes beam-7 in the scan strategy. Add three beams to fill in the gap between the top PBL angle (beam-3) and the highest angle (beam-7). The gaps shall be increasingly large for each successive gap. One potential solution to this requirement is based on increasing proportions of the difference in distance between beam-3 and beam-7 and the number of gaps to be filled. Since there are four gaps to be filled, assign weights of 1/10, 2/10, 3/10, and 4/10 to beam-4, beam-5, Beam-6, and Beam-7, respectively.

3.3 Elevation Angle and Height Calculations

The IDL program will account for Earth's curvature and refraction of the radar beam. In this context, horizontal range is equivalent to arc distance along the curved Earth's surface. To account for curvature and refraction, we iteratively solve Equations 2.28a,b in Doviak and Zrnic (1993, p. 21) for beam height (or elevation angle) when given elevation angle and horizontal range (or beam height and horizontal range). Standard refraction is assumed by default but the value of dn/dh (i.e., the vertical derivative of the refractive index with height) can be modified in the configuration file to account for non-standard refraction.

The error in estimating elevation angle and height associated with ignoring curvature and standard refraction effects at typical ranges for this application (< 28 nmi) are fairly small (< 0.3° and 1000 ft). Even so, these errors could affect the accuracy of the scan design and the utility of the resulting radar data under certain circumstances. Since the approach above as implemented in IDL is fast, robust and accurate, we chose to include these well known radar propagation and Earth curvature effects. Including these effects makes the radar scan tool more flexible in case of non-standard refraction or if the launch locations change relative to the radar and the distances (and hence errors associated with ignoring curvature and refraction) increase. It also makes the temperature profile adaptive scan strategy program a more general tool that can be used for other applications at any distance required.

4. PRELIMINARY RESULTS

At this stage in the ongoing project, we have implemented all of the preliminary design solutions for the convective and non-convective scan strategy requirements (Table 1) in IDL and have begun testing for accuracy of the software and performance of the proposed solutions. The configuration file has been implemented robustly in IDL to maximize ease of editing by the user but still ensure accuracy and completeness. The IDL program also handles user height inputs that are out of expected climatological ranges. The program currently outputs the elevation angle list in interleaved order, as required, in text format.

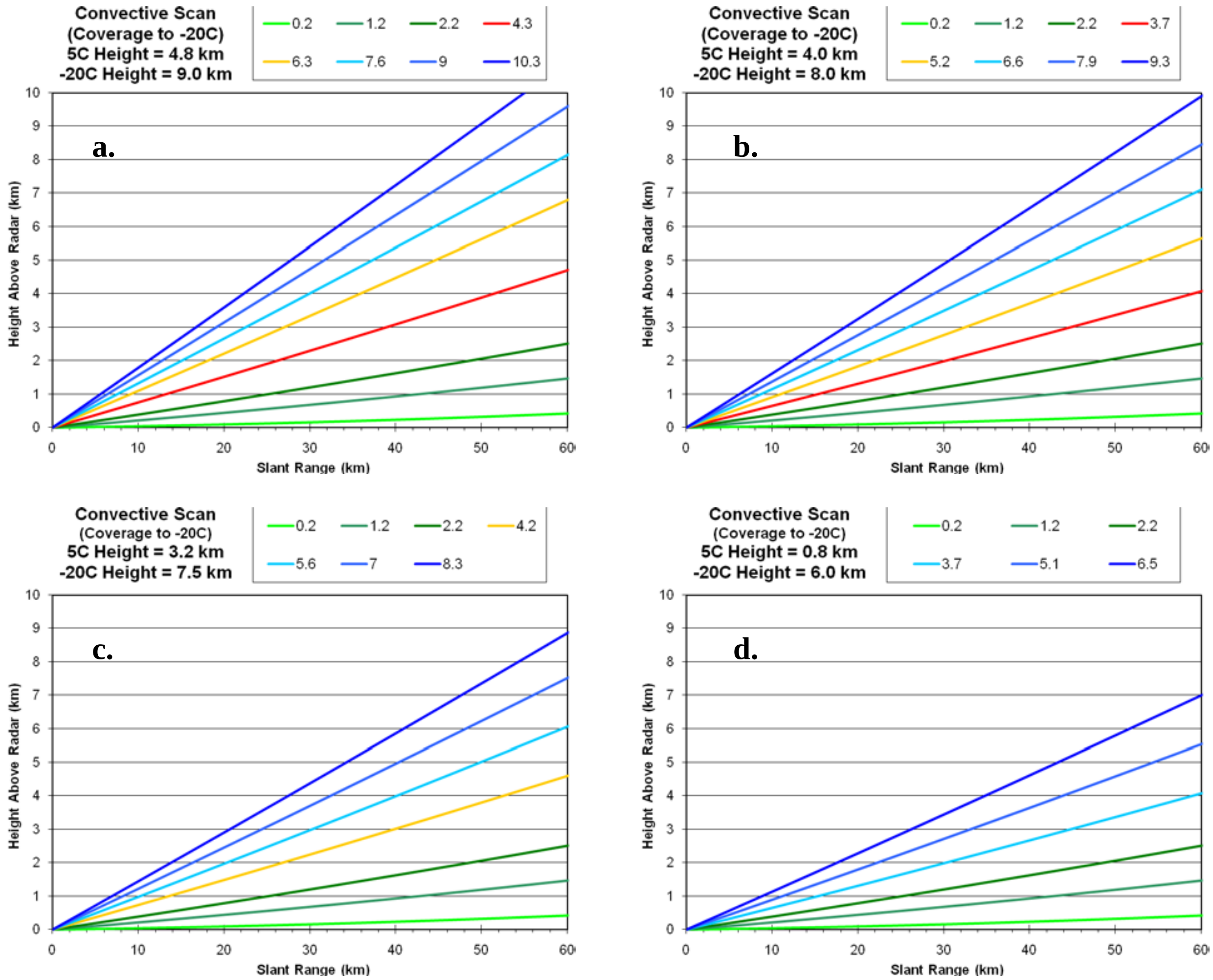

Figure 3. Demonstration of the PBL beam requirements (green lines), PBL to 5°C gap beam requirements (red lines), 5°C beam requirement (yellow), and mixed-phase lightning (5°C to -20°C) beam requirements (blue lines) for differing user-input temperature profile conditions. a) 5°C = 4.0 km and -20°C = 8.0 km, b) 5°C = 3.2 km and -20°C = 7.5 km, c) 5°C = 0.8 km and -20°C = 6.0 km, and d) 5°C = 0.8 km and -20°C = 6.0 km. The specific elevation angles (°) are shown in the legend at the upper right of each panel. Note that the environment gets progressively colder from a) to d). The launch pads are located at approximately 43 km in slant range from the radar. Note that the mixed-phase lightning requirements (blue lines) are designed to cover just above the -20C height at approximately 52 km in range (launch pad + LCC thick cloud distance = 23 nmi + 5 nmi = 28 nmi ≈ 52 km). The elevation angles to cover the launch pad distance - LCC thick cloud distance are not shown (23 nmi – 5 nmi = 18 nmi ≈ 33 km). In addition, the elevation angles to cover convective cloud tops or anvil clouds and cone of silence reduction are not shown.

A demonstration of the program's ability to satisfy the first three of five convective scan requirements (see Section 2.1), with varying user-input temperature profiles, is shown in Fig 3. The range of temperatures and heights chosen for Fig. 3 reflect the approximate range of climatological conditions observed over the CCAFS/KSC region from summer to winter. As the user-input temperature profile gets progressively colder, the heights of the mixed-phase zone (5°C to -20°C) lower and so the mixed-phase lightning beam angles (blue lines) progressively shift to lower heights over the launch pads plus the LCC distance (approximately 52 km in slant range). The elevation angles to cover the launch pads minus the LCC distance are not shown (approximately 33 km in slant range). Likewise the elevation angles for convective cloud tops and anvil clouds, and reduction of the cone of silence are not shown. The temperature adaptive nature of the scan strategy design insures that the radar is targeting the mixed phase lightning zone at high vertical resolution, regardless of the environmental conditions.

The methodology also eliminates unnecessary beam angles. For example, the program automatically determines whether a PBL to 5°C gap beam is required (red elevation angles in Fig. 3). If not, then the radar beam is eliminated (cf Figs. 3b,c). The program also automatically determines whether the 5°C height is effectively in the PBL at the launch pads (yellow line in Fig. 3). If so, this requirement and radar beam is eliminated (Fig. 3d). Although not shown, if the mixed phase lightning layer depth were to decrease significantly, then the program would automatically only output the necessary number of radar beams required to maintain the required high vertical resolution specified in Table 1 and another radar beam(s) could be eliminated from the scan strategy. When unnecessary radar beams are eliminated, the scan volume can finish faster, providing better temporal resolution or more samples can be taken at each range gate, providing higher quality data.

5. ONGOING WORK AND FUTURE IMPROVEMENTS

We are currently testing the accuracy and performance of the convective and non-convective design solutions as implemented in the IDL programming language. Once testing and any necessary adjustments to the scan strategy are complete, we will focus on providing easy-to-use GUI input and output interfaces to the IDL program. GUI interfaces will allow quick and easy use by 45 WS forecasters in an operational setting.

We plan to add scan timing, including the ability to select associated radar scan parameters such as wavelength, scan rate and acceleration limit, number of pulses (samples), pulse width, PRF/PRT, and hence the maximum unambiguous range and Doppler velocity. This future capability will allow us to estimate and hence optimize scan timing and/or polarimetric and Doppler radar data quality (i.e., number of pulses), depending on the mission and operational needs of 45 WS. Addition of these scan parameters will also allow full optimization of the scan strategy for 45 WS to customize their radar support for a variety of launch missions and facility-related activities at CCAFS, KSC, and Patrick AFB. For example, this capability will allow for the creation of special scan operations such as severe weather and long range modes, which will be added as user-selected options similar to the non-convection option already available. The severe weather scan strategy would trade a shorter maximum range of approximately 60 nmi for a higher maximum unambiguous maximum Doppler velocity of approximately 35 kt. The severe weather in east central Florida has three main causes: multiple low-level boundary interaction during the normal thunderstorm season (late May-late September), rain bands from land-falling tropical cyclones, and strong cold fronts typically February-April. As a result, adaptive scan strategies for each of two or all three of these scenarios may be needed. The long-range scan strategy would be reflectivity-only to gain a large maximum range of approximately 300 nmi at the cost of Doppler velocity capability. This long-range scan would support an infrequent 45 WS mission.

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