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14B.5 OPTIMIZED SCAN STRATEGY FOR PHASED ARRAY WEATHER RADAR

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ABSTRACT –An optimized scan strategy for weather surveillance is presented that is specifically designed to meet Multi-function Phased Array Radar goals in extended range and altitude coverage. The volume coverage pattern (VCP) is divided into multiple sectors in elevation to maximize the volume update rate. The Pulse Repetition Time (PRT) is optimized for the required range. Parsing of the volume on sectors with similar PRTs, allow for block-modular data processing. Each sector is broken down into subsectors in azimuth to provide flexibility in interleaving and beam multiplexing. The sector encompassing the lowest elevations is observed using waveforms designed for range-velocity ambiguity mitigation with enhanced clutter filtering. Superiority of the new scan is in providing rapid update rate for the lower sector (30 seconds) while performing the surveillance for the remaining VCP in 1 minute.

1. PROBLEM

The National Weather Radar Testbed (NWRT) in Norman, OK has a Phased Array Radar (PAR) antenna for meteorological research. PAR provides invaluable information for improved meteorological observations as evidenced by the results of the 2009 PAR Innovative Sensing Experiment (Heinselman 2009). Scientific, academic and engineering communities are investigating the concept and design diversity for the future Multifunction PAR (MPAR). It is neither known which MPAR system design candidate will be chosen nor if MPAR becomes the replacement of the aging fleet for weather surveillance (WS). In this paper it is assumed that MPAR is a 4-faced PAR designed with modern technology (technology of 2010). This is a significant step up from the existing PAR at NWRT (technology of 1970). The MPAR system is tasked to provide primary weather surveillance. The goal is to investigate how MPAR could perform this task, to create a VCP for rapid updates and improved volumetric coverage, and to benchmark it as MPAR Weather Surveillance VCP, (MPAR-WS-VCP-01) for reference and improvement.

2. OVERVIEW

A major component of the existing U.S. weather surveillance radar network is Weather Surveillance Radar -1988 Doppler (WSR-88D), also known as NEXRAD. Surveillance of the atmospheric volume surrounding a NEXRAD site is provided through one of several available volume coverage patterns (VCPs). Commonly used VCPs are designed to observe clear air, precipitation and severe weather patterns.

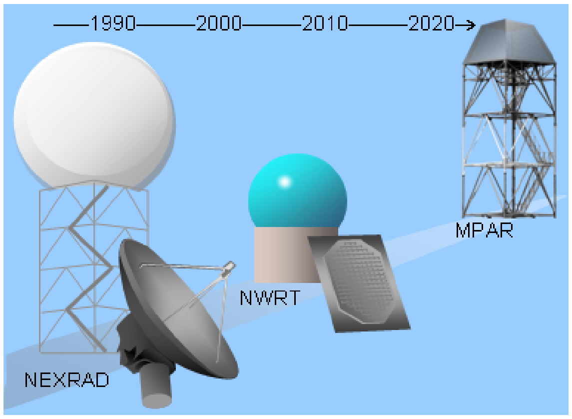

Fig. 1: Weather radars are negatively affected by wind farms. To visually assess the degree of impact, compare images depicting reflectivity from precipitation over a wind farm (a) before suppression and (b) after suppression.

The clear air patterns cover the lowest layers of the atmosphere in 10 minutes. The precipitation and severe weather patterns cover the full depth of storm activity in 5 to 6 minutes. (BASC 2002, ROC 2007).

3. CURRENT NEXRAD COVERAGE

Currently, there are no requirements for future radar coverage, however there are implications of the need to observe 460 km in range and 70 kft in altitude. To construct an optimal surveillance scan for future radar, this information is scrutinized together with the current NEXRAD requirements, radar beam propagation and geometric locations of weather extents (Fig. 2).

Storms beyond 460 km are usually below the horizon. The requirement for NEXRAD coverage is defined in range to be 460 km for reflectivity and 230 km for velocity. At a range of 460 km, the beam center line is pointing at an altitude of 12.5 km, thus only the tops of strong convective storms can be detected. In the region 230 km and 460 km, storm cells can be identified, however, NEXRAD does not require quantitative measurements of precipitation due to large errors and the beam is too high. Even at the range of about 230 km, the lowest altitude that the radar can observe under normal propagation conditions is about 3 km (Fig. 2). At this height the measurement of rain fall on the ground is subject to large errors, especially if the beam is above the melting layer. It is worth to mention that NEXRAD specifications on accuracies are defined only for ranges less than 300 km (ROC/NOAA 2007). In this paper, the proposed scanning strategy will satisfy 460 km coverage for both velocity and reflectivity, regardless of the discrepancy in requirement and substantial understanding.

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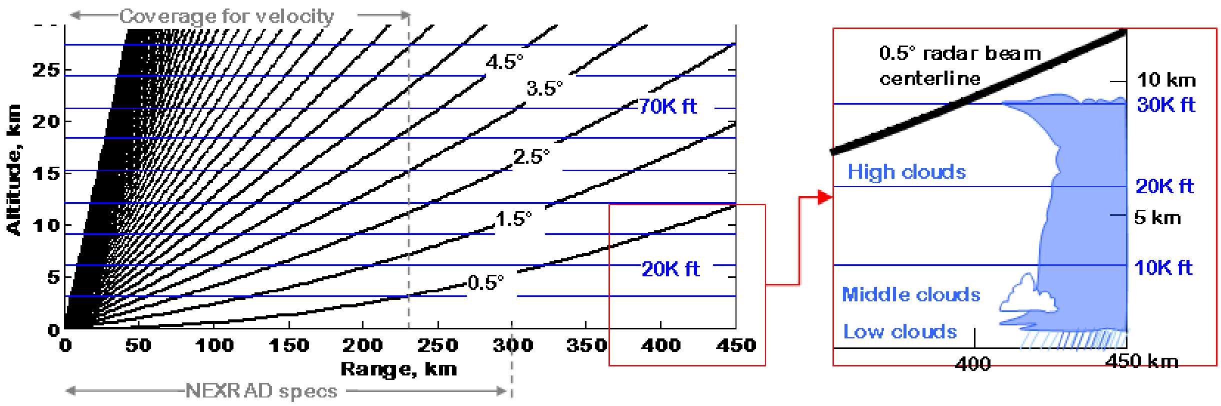

Fig. 2: Radar beam centreline for different elevations and relative weather geometry to scrutinize the potential requirement of 460 km radar coverage in range.

Clouds may exist anywhere in radar volume, with an altitude extent up to 9 km as shown in Fig. 2. Once again, we invite meteorologists to determine if 70,000 feet in altitude is needed to observe clouds that appear to reside below 30,000 feet.

4. OVERVIEW OF VCPS

VCP-11 (OFCM 2006 table 5-1) scan strategy provides volume scan in 5 minutes, and consists of 14 unique elevation scan levels from zero to 20° in elevation with the 6 elevations having no gaps between the one way pattern 3 dB points of adjacent elevation scans. This provides the greatest amount of meteorological base data and is designed for use in severe convection activity conditions.

The VCP-21 (OFCM 2006 table 5-3) scan strategy provides a volume scan in 6 minutes and consists of 9 unique elevation scan levels from zero to 20° in elevation with the lowest 4 elevations having no gaps between the one way pattern 3 dB points of adjacent elevation scans. This VCP sacrifices volume coverage, but the longer dwells afforded by the lower scan rates provide better clutter cancellations and more accurate base data extensions, and slightly better sensitivity.

VCP-31 and VCP-32 (OFCM 2006 tables 5-5, 5-6) scan strategies provide volume coverage of 5 unique elevations in 10 minutes. There are no gaps between one-way pattern 3 dB points of adjacent elevations scans. The primary use is in clear air conditions, although sometimes it is useful for tropical storms or stratiform conditions where extensive precipitation makes acquiring velocity and spectral width data difficult. VCP-31 uses a long pulse width (4.5 μsec) and uniform contiguous waveform types. Consequently, it has the best clutter suppression and the best sensitivity of the available VCPs. VCP-32 uses short pulses.

Note that there has been ongoing research to improve these and other existing NEXRAD VCPs. For example the National Severe Storms Laboratory (NSSL) has been looking for a solution to mitigate range-velocity ambiguity. Recall, that PRT determines the maximum unambiguous range R_a (R_a = PRT×c/2, where c is the speed of light) and maximum unambiguous velocity v_a ($v_a = \lambda/(4\times PRT)$, where λ is the radar wavelength). For example, for long R_a, only small v_a can be detected resulting in velocity aliasing; and for large v_a, only short R_a can be observed causing range folding. Among NSSL's solutions for mitigation of range-velocity ambiguity, Staggered PRT is an effective approach allowing large v_a and extended R_a at the same time. In application to NEXRAD, Staggered PRT can replace two scans, Cut Surveillance (CS) and Cut Doppler (CD), with one and provide improved data quality at a reduced time. In 2007 NSSL presented a potential optimum VCP-14 (OFCM 2006), where they replaced low elevation scans with SPRT scans [Torres 2008]. It is assumed that future NEXRAD optimum VCPs will include Staggered PRTs.

Currently NEXRAD has a variety of VCPs that must be manually chosen to observe certain weather phenomena. Most of these VCPs have embedded surveillance scans that only provide reflectivity data. This data is used to reconstruct velocity aliased and range folded echoes of Doppler scans. It can be concluded that PRTs currently used in Doppler scans do not provide the needed range coverage and often require procedures for unfolding echoes. This could be avoided if the PRTs were chosen to provide the range/altitude coverage for the first trip echoes.

A future scan proposed by MIT Lincoln Laboratory [JAG/PAR 2006] was set up to meet the 1 minute update rate, however it is noted that this scan must be modified to allow more samples at lowest elevation tilts to enable clutter suppression.

It is our interpretation that new surveillance must provide:

– volumetric coverage, that accommodates
  – 460 km in range and 70,000 feet in altitude,
  – range velocity ambiguity mitigation,
  – a sufficient number of pulses for clutter filtering,
– periodic in time with uniform spacing,
– with better than 1 minute update rate, and
– accurate enough to trigger focused scans that must be performed within the 1 minute of the surveillance scan.

If the meteorological coverage needs can be refined, then these adjustments allow for further optimization of timing and coverage for the new VCP.

	El.	# Dwells	# pulses	PRT		PW/PRT	# of beams		time	Range (km)		Elev & Range for 70Kft →		
							Az	El		is	needed			
SPRT	0.5	85	17	2.00E-03	3.00E-03	5.00	1	1	7.225	450.00	450	1	450	450.51
SPRT	1.50	85	17	2.00E-03	3.00E-03	5.00	1	1	7.225	450.00	417	2	416	416.55
SPRT	2.50	85	17	1.50E-03	2.25E-03	6.67	1	1	5.419	337.50	333	3	333	333.68
SPRT	3.50	85	17	1.50E-03	2.25E-03	6.67	1	1	5.419	337.50	274	4	273	273.83
SPRT	4.50	85	11	1.10E-03	1.65E-03	9.09	1	1	2.571	247.50	230	5	229	229.99
SPRT	5.50	85	11	1.10E-03	1.65E-03	9.09	1	1	2.571	247.50	199	6	197	198.15
SPRT	0.5	85	17	2.00E-03	3.00E-03	5.00	1	1	7.225	450.00	450	1	450	450.51
SPRT	1.50	85	17	2.00E-03	3.00E-03	5.00	1	1	7.225	450.00	417	2	416	416.55
SPRT	2.50	85	17	1.50E-03	2.25E-03	6.67	1	1	5.419	337.50	333	3	333	333.68
SPRT	3.50	85	17	1.50E-03	2.25E-03	6.67	1	1	5.419	337.50	274	4	273	273.83
CDX	6.50	85	2	1.20E-03		8.33	1	1	0.510	180.00	172	7	171	172.33
CDX	7.50	85	2	1.20E-03		8.33	1	1	0.510	180.00	154	8	152	153.49
CDX	8.50	85	2	1.00E-03		10.00	1	1	0.425	150.00	137	9	136	137.66
CDX	9.50	85	2	1.00E-03		10.00	1	1	0.425	150.00	125	10	123	124.84
CDX	10.50	85	2	9.00E-04		11.11	1	1	0.383	135.00	114	11	112	114.01
CDX	11.50	85	2	9.00E-04		11.11	1	1	0.383	135.00	105	12	103	105.19
CDX	12.50	85	2	8.00E-04		12.50	1	1	0.136	120.00	98	13	96	98.34
CDX	13.50	85	2	8.00E-04		12.50	1	1	0.136	120.00	91	14	89	91.52
CDX	14.50	85	2	7.00E-04		14.29	1	1	0.119	105.00	87	15	84	86.67
CDX	15.50	85	2	7.00E-04		14.29	1	1	0.119	105.00	82	16	79	81.83
CDX	16.50	85	2	6.00E-04		16.67	1	1	0.102	90.00	77	17	74	77.01
CDX	17.50	85	2	6.00E-04		16.67	1	1	0.102	90.00	73	18	70	73.18
CDX	18.50	83	2	5.00E-04		20.00	5	1	0.017	75.00	70	19	67	70.32
CDX	19.50	83	2	5.00E-04		20.00	5	1	0.017	75.00	68	20	64	67.46
CDX	20.50	83	2	5.00E-04		20.00	5	1	0.017	75.00	65	21	61	64.62
CDX	21.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	62	22	58	61.80
CDX	22.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	60	23	56	59.93
CDX	23.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	58	24	54	58.06
CDX	24.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	56	25	52	56.21
CDX	25.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	54	26	50	54.36
CDX	26.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	52	27	48	52.53
CDX	27.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	51	28	47	51.62
CDX	28.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	50	29	45	49.80
CDX	29.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	49	30	44	48.90
CDX	30.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	48	31	43	48.00
CDX	31.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	47	32	41	46.22
CDX	32.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	46	33	40	45.33
CDX	33.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	45	34	39	44.45
CDX	34.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	44	35	38	43.58
CDX	35.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	43	36	37	42.71
CDX	36.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	43	37	37	42.71
CDX	37.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	42	38	36	41.85
CDX	38.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	41	39	35	40.99
CDX	39.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	40	40	34	40.14
CDX	40.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	40	41	34	40.14
CDX	42.50	79	2	5.00E-04		20.00	5	1	0.016	75.00	40	42	33	39.30
									Total = 59.448					

GOOD
Watch
Problem
Wasting resorses

Staggered PRTs for 6 elevations

Contiguous Doppler scan for all remaining elevations

Range coverage exceeds need due to duty factor

Total dwell: 59.448 seconds

First 4 elevations are scanned twice in a dwell

6

Fig. 3: Example of tabulating radar scan parameters to adjust coverage and minimize time.

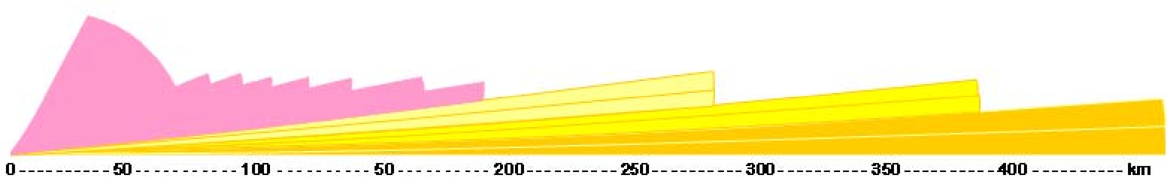

Fig. 4a: The first-trip-range profile of the MPAR-WS-VCP-01. Note that the sharp cut-off for each radar beam is an imaginative depiction of maximum unambiguous range (determined by the PRT), the echoes beyond the cut-off are second-trip and higher-trip returns.

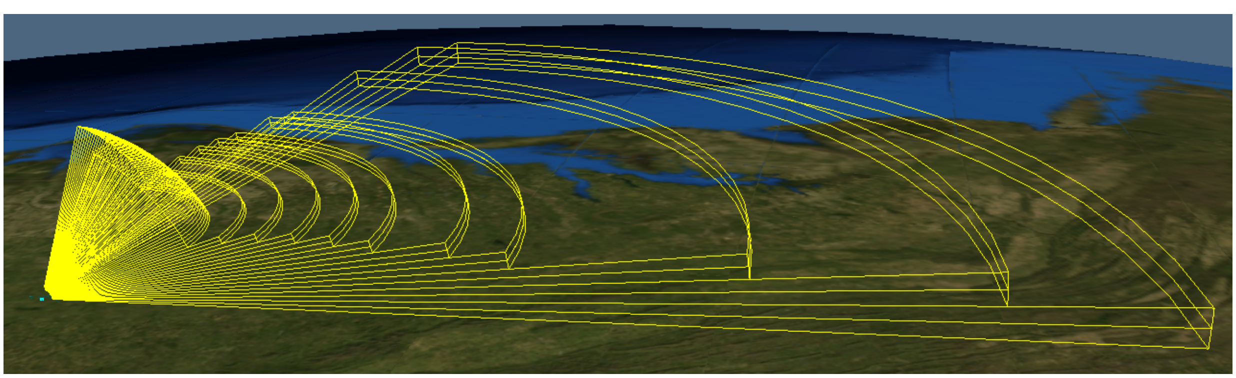

Fig. 4b: Three dimensional profile of MPAR-WS-VCP-01 for one face of 4-faced MPAR. 42 elevation tilts consisting of 6 elevations with staggered PRTs and 36 elevations with uniform PRTs. Four lowest elevations are scanned every 30 seconds, while the remaining volume is scanned within 59.5 seconds.

5. OPTIMAL SCAN DESIGN

For the conditions as stated in Section 4, the design steps and construction of an optimal VCP is presented below.

1. Determine extents of coverage required in altitude (i.e., 22 km) and in range (i.e., 460km).

2. Estimate PRT (T) for required range: T=2 R_a /c.

3. Correct PRT to satisfy radar duty factor (DF). Radar Duty factor is the % of transmitted power with respect to PRT and must be below 20%. Assume pulse width PW=100 μs: DF=(PW/T)*100% = <20%.

4. Select waveform with high time-bandwidth product which enables reduction in number of pulses required to obtain reliable velocity estimates at high elevations.

5. Chose scanning strategy (i.e., uniform for high elevation and short range, staggered for low elevation and long range, etc.).

6. Estimate number of samples from the approximate dwell time (if staggered PRT, choose 17 pairs to support clutter filtering [Torres et al. 2007]. The number of pair is driven by clutter filtering. Because MPAR is electronically scanning radar unlike the mechanically rotating NEXRAD, there is no effect of clutter smearing in MPAR Doppler spectrum. Therefore, the number of pulses/pairs can be significantly reduced. 17 pairs are used here as a starting point that provides a room for optimization.

7. Split scan on clusters (to support focused scan partitioning, beam multiplexing, and parallel data processing applications).

8. Modify chosen PRTs in such a way that each elevation tilt cluster has the same PRT.

9. Adjust scan time by reducing/increasing number of samples.

The scan resulting from these steps can be used for surveillance. The results of surveillance will initiate focused scans that are not described here.

6. EXAMPLE SURVEILANCE SCAN

The designed scan MPAR-WS-VCP-01 is shown in Figs. 3-5. Fig. 3 depicts a work-book spreadsheet for the VCP with 42 elevation tilts scanned in 59.5 seconds. The lowest 4 elevations are scanned twice within this period.

Fig. 4a depicts the profile of the scan with ranges cut off to expose the maximum unambiguous range, or range with first-trip echoes. The lowest 6 elevations are scanned using Staggered PRT (SPRT) with a large number of pulses to support clutter suppression and mitigate range-velocity ambiguity. The number of pulses can be reduced, as was mentioned in item 6 Section 5. In addition, the number of pulses can be further reduced for higher elevations; however, 17 pairs of pulses are kept here to support clustering.

Fig. 5 depicts the front view of the scan (on face). This exposes the size of clusters for different elevations and PRTs. This representation is a bit misleading uncovering a larger pink area than that in Fig.4a. The pink area is scanned using uniform PRT, also referred as Contiguous Doppler (CDX). Note that at elevation angles exceeding 18°, the duty factor limits the choice of faster PRTs and coverage exceeds the requirement. Only one pulse per dwell is needed for beam multiplexing, however, a pulse pair is needed for velocity estimation. Therefore 2 pulses are used for higher elevations. Note that this surveillance scan is designed to provide rapid (22 seconds) update and exceptional coverage for the 6 lowest elevations shown with yellow shades in Fig.4a. The remaining portion of the scan shown in the pink shade in Fig.4a, will trigger a focused scan that may have similar PRT and range coverage characteristics but a higher number of samples per dwell. A three dimensional profile of this scan is shown in Fig.4b.

Note that the presented VCP uniformly covers all 42 elevations in altitude (Fig. 5). NEXRAD VCPs at higher elevations do not provide uniform coverage. Fig. 6 depicts two profiles of the NEXRAD VCP-11 and VCP-21. Pink shaded area indicates elevation tilts that consist of two scans (surveillance and Doppler) needed for de-aliasing. All scans use uniform PRTs. If NEXRAD's approach is sufficient; the timing of the proposed MPAR-WS-VCP-01 can be further reduced.

Fig. 7 (top) depicts a profile of a potential improved scanning strategy for NEXRAD [Torres 2008]. The yellow line indicates tilts using Staggered PRT. The black line indicates tilts that contain two scans, Surveillance and Doppler. The gray shading indicates area where Doppler velocity is not computed. Because Staggered PRT strategy is used to extend maximum unambiguous range while detecting large Doppler velocities, there is no need to use this strategy for short ranges. For shorter ranges, uniform PRT Doppler scan provides excellent performance. Clutter filtering of Staggered PRT is more efficient compared to NEXRAD because on electronically scanning system there is no clutter spectral spread due to antenna rotation. Therefore, split cuts and de-aliasing algorithms at low elevations can be replaced with Staggered PRT scan. Fig.7 (bottom) depicts the MPAR-WS-VCP-01, where fuchsia line indicates CDX (uniform PRT) scans.

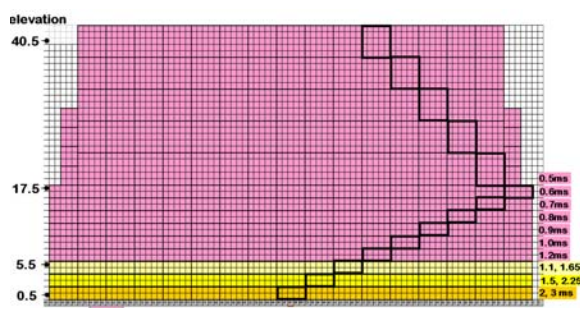

Fig. 5: The front view of the surveillance scan (on face) for MPAR-WS-VCP-01.

7. CONCLUSION

An optimized scan strategy is presented for weather surveillance that is specifically designed to meet the MPAR goals in extended range and altitude coverage. The VCP is divided into multiple sectors in elevation to maximize volume update rate. The PRT is optimized for the required range. Parsing the volume on sectors with similar PRTs allows for block-modular data processing. Each sector is broken down into subsectors in azimuth to provide flexibility in interleaving and multiplexing. The sector encompassing the lowest elevations is observed using waveforms designed for range-velocity ambiguity mitigation with enhanced clutter filtering. Superiority of the new scan is in providing a rapid update rate for the lower sector (30 seconds) while performing the surveillance for the remaining VCP in 1 min.

The interpretation of needs for new surveillance presented here is itemized and consists of: volumetric coverage (460 km range coverage at lowest elevation, 70,000 feet altitude coverage throughout), periodic in time with uniform spacing with better than one minute update rate, accurate enough to trigger focused scans that must be performed within the one minute of the surveillance scan; range velocity ambiguity mitigation, and a sufficient number of pulses for clutter filtering.

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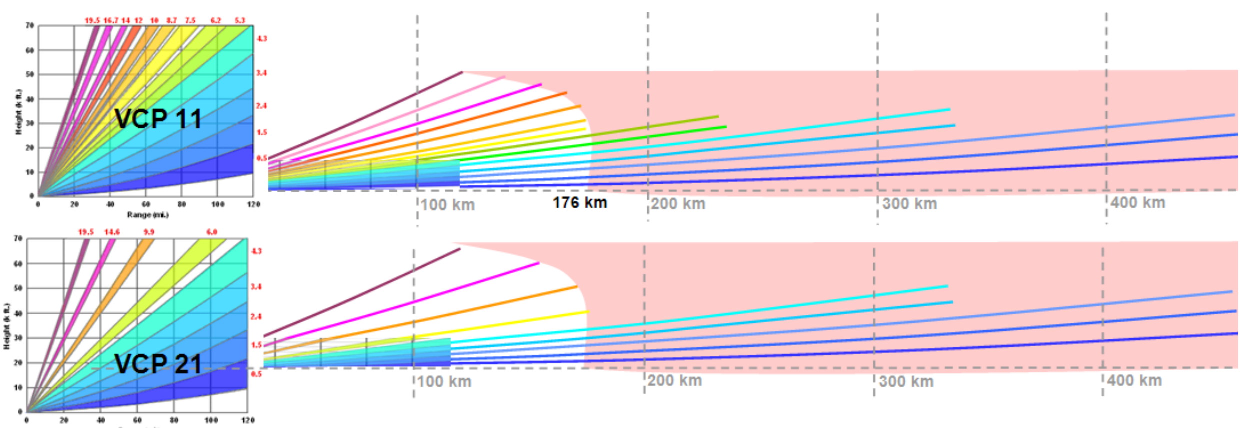

Fig. 6: Depiction of current NEXRAD scan profiles VCP-11 (top) and VCP-21 (bottom). Pink shaded area indicates elevation tilts that consist of two scans (surveillance and Doppler) needed for de-aliasing. All scans use uniform PRTs.

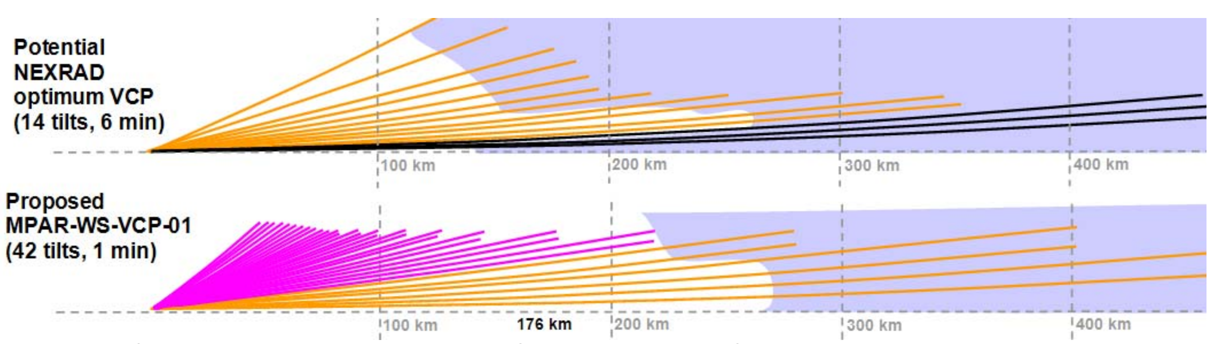

Fig. 7: Depiction of potential improved scanning strategies for NEXRAD (top) and for MPAR (bottom).
The line colour indicates the waveform type: yellow = Staggered PRT, fuchsia = Contiguous Doppler (uniform PRT), black = split cur that contains Surveillance and Doppler scans for each elevation tilts. The gray shading indicates area where Doppler velocity is not computed.