7A.6 HYBRID SCAN AND JOINT SIGNAL PROCESSING FOR A HIGH EFFICIENCY MPAR

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1. INTRODUCTION[*]

It has been realized that it is difficult to meet all the MPAR mission requirements with just a single beam from each sector of the MPAR. Increasing the number of simultaneous beams would complicate the MPAR system and its operation, as well as increase the development cost. It is therefore important to find and then decide on an efficient scan strategy and corresponding signal processing for the MPAR design. This is feasible because weather measurements have different requirements for angular resolution and sensitivity at different elevations (Zrnic et al. 2015), and the MPAR will have flexibilities in choosing beamwidth, steering beam direction, and generating waveforms. These flexibilities are useful and should be (and can be) optimized by using a hybrid scan strategy and developing advanced signal processing algorithms.

2. ARRAY CONFIGURATION

For the MPAR to have a 360-degree azimuth coverage, possible array configurations include three faces, four faces, five faces, etc., up to a cylindrical configuration. An optimal configuration would be the one that meets the requirements and has the least number of elements – it is desirable to have the highest performance with minimal cost.

There are two competing factors that determine the optimal number of elements/columns: i) number of faces, and ii) distance between elements/column. The separation distance depends on the angular coverage (maximal scan angle) of each face and needs to be small so that grating lobes are kept outside of real space. Hence, the number of columns can be expressed by

$$N_t = N_f \frac{D}{d} = \frac{N_f[1+\sin(\pi / N_f)}{\phi_0 \cos(\pi / N_f)} \qquad (1)$$

where N_f is the number of faces, D is the length of each face, d is the separation between elements, and ϕ_0 is the beamwidth. By plotting the total number of columns as a function of the number of faces, it is easy to see that the four-face configuration is optimal for one beam per face, with the least number of columns/elements to achieve the same beamwidth. If more faces are combined to form a beam, a cylindrical configuration is optimal, as documented in Zhang et al. (2011).

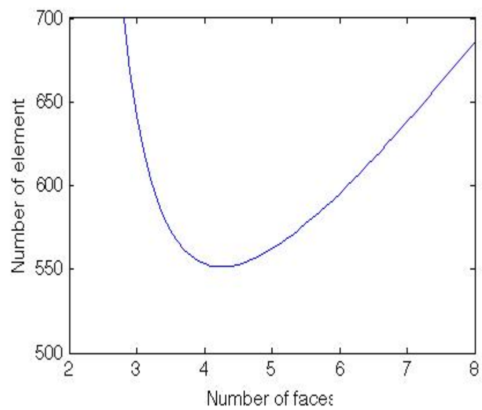

Figure 1: Number of columns/elements as a function of the number of faces. The four-face configuration minimizes the number of elements and is optimal for one beam per face.

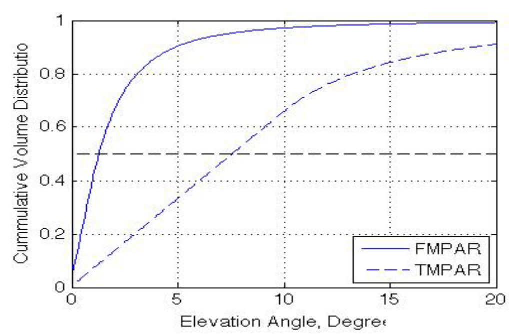

Figure 2: Cumulative volume coverage distribution as a function of elevation.

There are different opinions on the face tilt. For the purpose of having the largest elevation coverage, the antenna face may be tilted to the half of the highest elevation angle. However, this would point the broadside beam to the middle elevation, which is not desirable because the most informative observations of weather are at low elevations. Hence, we use volume coverage as a criterion to determine the angle for the face tilt. Assuming that the region of interest is located between 0 and 16 km above the ground, the

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cumulative volume coverage (up to the elevation) distribution is plotted as a function of elevation angle in Fig. 2. At the median volume coverage of 0.5, the full-size MPAR (FMPAR) requires very little tilt at 1.3 degrees, while the terminal MPAR (TMAPR) needs to tilt at about 7.5 degree.

3. HYBRID SCAN STRATEGY

To efficiently utilize the MPAR resources, we propose a hybrid scan strategy. The hybrid scan strategy includes: i) using a narrow beam with uniform PRTs at low elevations (< 1 degree) to achieve high resolution, sensitivity, and clutter cancellation; ii) using staggered PRT Beam-Multiplexing (SBMX) for middle elevations (1 ~ 8 degrees) to save sampling time (Curtis 2009); iii) using a broad transmitting beam at high elevations (> 10 degrees).

As shown in Table 1 and Figure 3, three kinds of beam scans are used. At low elevations (below 2 degrees), narrow beam and uniform PRTs are used to achieve the sensitivity and clutter mitigation requirements. At each of the 0.5- and 0.9-degree elevations, both long and short PRT sequences of pulses are transmitted and received. The 3.1 ms long PRT allows for an unambiguous range larger than 460 km so that there is no overlaid echoes in reflectivity surveillance. Doppler measurements are made with the short PRT of 0.8 ms to have an unambiguous velocity of ± 31 m/s. The four (red lines in Fig. 3) scans take a total of 185.6 ms.

At median elevations between 1 and 8 degrees, short PRT pulses are transmitted and received, with beam-multiplexing (BMX) among three beams. That is, a pair of pulses are transmitted at the 1st azimuth angle (e.g., 1 degree azimuth), the next pair of pulses at 2nd azimuth (e.g., 11 degree), and then a third pair of pulses at the 3rd azimuth (e.g., 21 degree); then the beam goes back to the 1st azimuth and repeats the process nine times. After the process finishes, there are ten pairs of short PRT pulses, and nine pairs of long PRT pulses at each beam position. Therefore, only one-third of the duration is needed for each beam. This is called Staggered BMX (SBMX) scan strategy. The total time used for the median eight (black lines in Fig.3) scans is 115.2 ms.

At high elevations (larger than 10 degree) where sensitivity is not an issue, a broad beam (BRDB) is transmitted and the broad beam is for reception, or four simultaneous receiving beams are formed.. Combining with the SBMX, the high elevation (blue lines in Fig. 3) scans use 43.2 ms of time.

Adding up the times used for low, medium and high elevations, the total average time for each azimuth is 344 ms, given a data update time of 31.0 s for the volumetric scan (90 degree sector with one beam). This scan strategy facilitates a volumetric scan in about 31 seconds with a single beam from each sector and it would save the MPAR R&D cost by using fewer simultaneous transmitting beams, but it does not consider the super-resolution operation. To address this issue, we conduct fundamental research in signal processing to meet the requirements for weather surveillance, which we discuss in the next section.

Table 1: A Hybrid Scan Strategy for MPAR

	WSR-88D VCP-12			Proposed MPAR scan strategy			
Elevation Slices	WF Type	# of Pulses	Time /per scan(s)	WF Type long PRT: 3.2ms short PRT: 0.8ms	# of Pulses	Time /per azimuth (ms)	Time/per scan(s)
0.5°	CS	15	17.02	long	16	49.6	4.46
0.5°	CD-5	40	14.40	short	54	43.2	3.89
0.9°	CS	15	17.02	long	16	49.6	4.46
0.9°	CD-5	40	14.40	short	54	43.2	3.89
1.3°	CS	15	17.02				
1.3°	CD-5	40	14.40	SBMX	54	43.2/3	1.30
1.8°	B-5	29	14.61	SBMX	54	43.2/3	1.30
2.4°	B-5	30	13.64	SBMX	54	43.2/3	1.30
3.1°	B-5	30	13.64	SBMX	54	43.2/3	1.30
4.0°	B-5	30	12.86	SBMX	54	43.2/3	1.30
5.1°	B-5	30	12.86	SBMX	54	43.2/3	1.30
6.4°	B-5	30	12.86	SBMX	54	43.2/3	1.30
8.0°	CD-6	38	12.68	SBMX	54	43.2/3	1.30
10.0°	CD-7	40	12.46	SBMX+BRDB	54	43.2/3/4	0.324
12.5°	CD-8	44	12.53	SBMX+BRDB	54	43.2/3/4	0.324
15.6°	CD-8	44	12.53	SBMX+BRDB	54	43.2/3/4	0.324
19.5°	CD-8	44	12.53	SBMX+BRDB	54	43.2/3/4	0.324
24.0°				SBMX+BRDB	54	43.2/3/4	0.324
30.0°				SBMX+BRDB	54	43.2/3/4	0.324
35.0°				SBMX+BRDB	54	43.2/3/4	0.324
40.0°				SBMX+BRDB	54	43.2/3/4	0.324
45.0°				SBMX+BRDB	54	43.2/3/4	0.324
50.0°				SBMX+BRDB	54	43.2/3/4	0.324
55.0°				SBMX+BRDB	54	43.2/3/4	0.324
60.0°				SBMX+BRDB	54	43.2/3/4	0.324
Total time			251.1(s)			344 (ms)	31.0 (s)

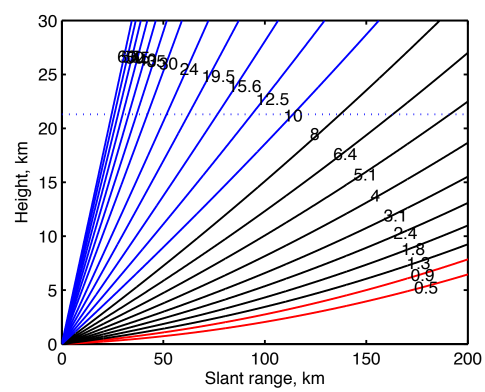

Figure 3: Proposed scan strategy for MPAR: i) long and short uniform PRTs at low elevations (< 1 degree), ii) staggered PRT Beam-Multiplexing (SBMX) for middle elevations (1 ~ 8 degrees); iii) a broad beam at high elevations (> 10 degrees).

4. SUPER-RESOLUTION WITH PAR STEP SCAN

Super-resolution has been proposed and implemented on WSR-88D radars to reveal fine radar signatures of severe weather (Torres and Curtis 2007). There is no doubt that the super-resolution can be done on MPAR by following the same scan strategy (as with a dish antenna) and collecting a long time-series data and then chopping it into different segments for processing to obtain moment data. However, because space (angle) and time are related, the continuous scan has problems of spectrum broadening and beam smearing, as illustrated in Fig. 4a. To collect 2L samples within a beamwidth, the beam center has moved over a beamwidth, with the beam smeared to larger width than the intrinsic beamwidth (as indicated by the solid arc in Fig. 4a). In case of super-resolution, only L samples are used, or 2L samples with aggressive tapering for moment estimation. The continuous scan is not optimal for MPAR because MPAR has agile beam pointing capability.

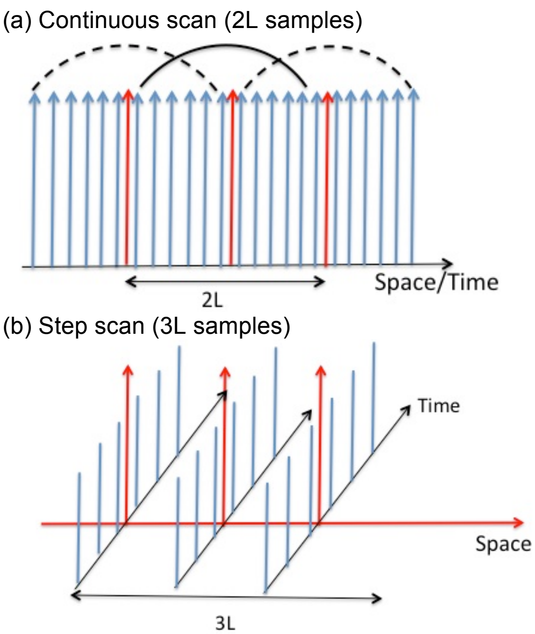

Figure 4: Conceptual sketch of sampling principle for continuous scan (a) with 2L samples for a beamwidth versus that for a step scan (b) which allows 3L samples.

As shown in Fig. 4b, a step scan is used for MPAR operation by pointing the beam in directions separated by half a beamwidth and collecting L samples at each point direction. In this case, space and time are independent, and time-series data are collected at each beam direction. There is no beam smearing and spectrum broadening. The three beam positions with 3L samples correspond to the one segment data with 2L samples in the continuous scan, and all of the 3L samples can be combined and jointly processed for moment estimation, as long as the effective beamwidth is preserved.

Figure 5 shows a comparison of beam patterns between legacy super-resolution beam and the PAR JSP beam. For example, in case of sharpest and least error legacy super-resolution, 20 samples (40 samples for regular resolution) collected with a dish antenna mechanically scanning over a half beamwidth (0.5 degree) are processed to obtain moment data. The effective beam width is 1.11 degrees for the intrinsic beam of 1.0 degree, as shown in Fig. 5a. In the case of PAR JSP operation, 20 samples are collected at each beam direction, separated by a half beamwidth (0.5 degree), and a total of 60 (20:20:20) samples from three adjacent beams are jointly processed to obtain moment estimates. The three beam patterns

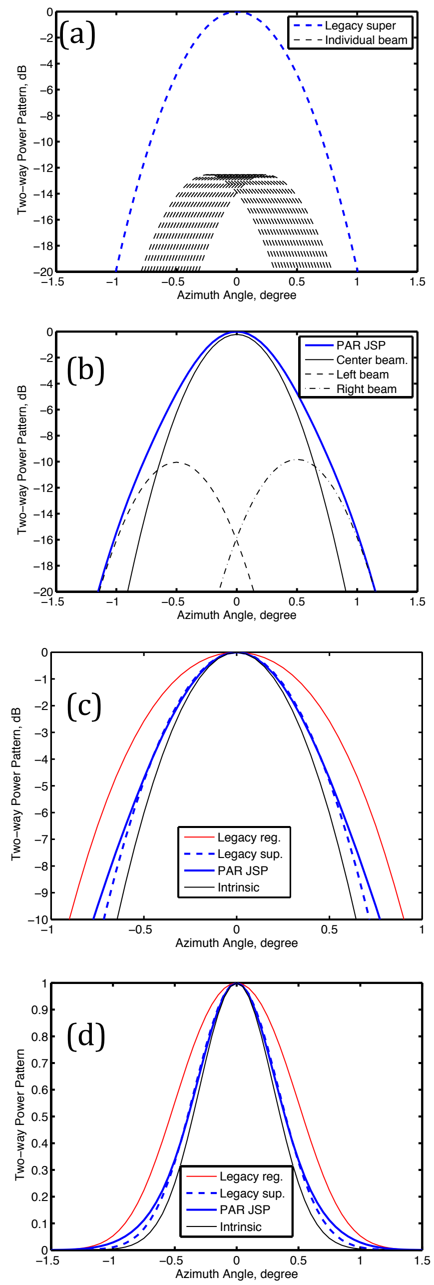

Figure 5: Comparison of antenna patterns between legacy super-resolution beam and the PAR JSP beam: a) legacy super-resolution continuous scan beam patterns, b) PAR JSP step scan beam patterns, and c) & d) comparison of effective beam patterns in decibel and linear unit, respectively.

(in black) and their effective pattern (in blue) are shown in Fig. 5b. The resulting super-resolution and the PAR JSP effective patterns (in blue) are compared in Fig. 5c&d, along with the intrinsic beam pattern (black) and the legacy regular effective pattern (in red). Because a -70 dB Taylor window is applied, the PAR JSP beam with 60 samples has the same power efficiency of 0.5 as that of the legacy super-resolution of 20 samples (compared with 40 samples over 1.0 degree). Since the PAR JSP beam has a similar effective pattern as the legacy super-resolution beam, it is suggested that the super-resolution data can be obtained with the PAR JSP.

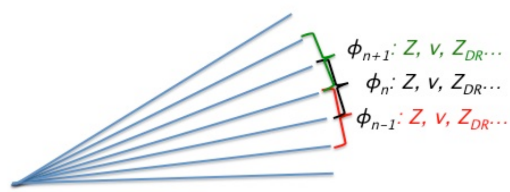

Figure 6: Conceptual sketch of joint processing of MPAR signals for super-resolution and fast data update.

5. JOINT PROCESSING OF PAR SIGNALS

The PAR JSP is called JPARS (Joint Processing of PAR Signals). To obtain super-resolution weather measurements, we propose to collect samples with an azimuth separation of a half-beamwidth and with half the number of pulses of a regular scan, without having to increasing the total data update time. To improve the measurement accuracy, the samples from adjacent beams are jointly processed to obtain moment data, as sketched in Fig. 6. As shown in Fig. 6, let $\mathbf{s}_{n-1}$: $[s(1), s(2),\ldots, s(L)]_{n-1}$, $\mathbf{s}_n$: $[s(1), s(2),\ldots, s(L)]_n$, and $\mathbf{s}_{n+1}$: $[s(1), s(2),\ldots, s(L)]_{n+1}$ be the time-series data at the directions of ϕ_{n-1}, ϕ_n, and ϕ_{n+1}, respectively. Two approaches of JPARS are proposed to obtain high quality data: i) joint average of moment estimates (JAME) for improved weather data quality, and ii) joint processing of synchronized signals (JASS) for clutter filtering.

In the JAME approach, second moments are estimated at each direction from the collected signal $\mathbf{s}^n$. Then, the three adjacent sets of the moments are averaged with the center sets weighted higher than the side sets to obtain final moment estimates for the center beam. For example, a power estimate can be expressed by

$$\tilde{p}_n = a\hat{p}_{n-1} + b\hat{p}_n + a\hat{p}_{n+1} \qquad (2)$$

where a and b are power weighting coefficients that are determined from a selected tapering function as shown in Fig. 7. The step power coefficients (*a* and *b* in (2)) are obtained by calculating the ratio of the power at one beam versus that of the total power and are listed in Table 2.

Table 2: Step power weighting coefficients

Taylor -30dB	0.192	0.616	0.192
Taylor -50dB	0.133	0.734	0.133
Taylor -70dB	0.103	0.794	0.103
Taylor -100	0.081	0.838	0.081

In the JASS approach, the three signals are combined to form **S**: $c_1x[s(1), s(2),\ldots, s(L)]_{n-1}$, $[s(1), s(2),\ldots, s(L)]_n$, $c_2x[s(1), s(2),\ldots, s(L)]_{n+1}$ having 3M samples to estimate radar moments and to mitigate clutter. In the JASS, smooth tapering (shown in Fig. 7a) is used so that frequency sidelobes (window leakage) are low, allowing strong (>50dB) clutter cancellation.

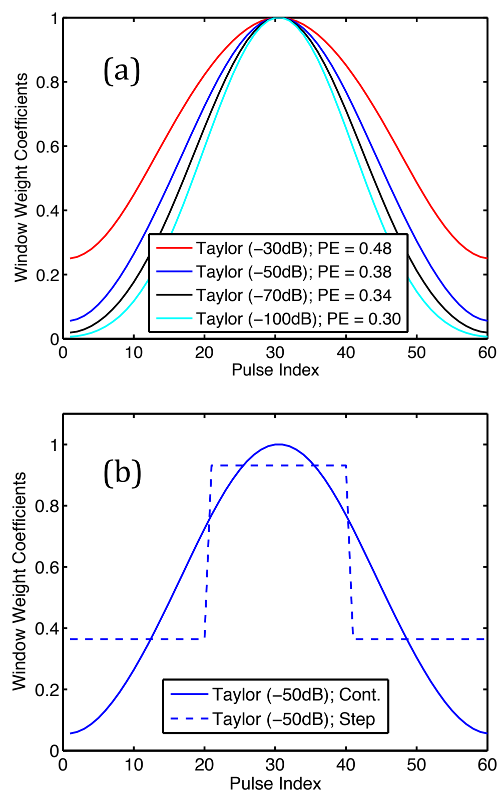

Figure 7: Smooth and step Taylor weighting functions

6. SUMMARY AND CONCLUSIONS

In this paper, a hybrid scan strategy and a joint analysis of synthetic signals are presented for maximizing efficiency in MPAR development and operation so that the PAR resources are optimally utilized. It is shown that super-resolution can be achieved with the JASS of the three adjacent beam signals for MPAR without having to increase scanning time. The JPARS can be implemented on either second moment data as JAME or time series data as JASS. The JPARS for PAR has the following advantages: i) no-spectrum broadening and no-beam smearing, ii) improved weather estimates, and iii) potential in clutter detection and filtering. Please see 7A.2 in the conference programs for the demonstration of this method with the NWRT data.

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