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A MULTISTATIC MPAR CONCEPT

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1. INTRODUCTION

NOAA and FAA are performing concept development and risk reduction for a next-generation Multifunction Phased Array Radar (MPAR). By exploiting highly digital, active electronically scanned array technology, MPAR could subsume a number of current national operational radar functions including surveillance for civil aviation, airport wind shear detection, severe weather observation and warning, quantitative precipitation monitoring and air-domain security. MPAR could provide significant measurement capability enhancements relative to current operational radars, for example, more rapid volumetric scanning of severe weather and height estimation for non-cooperative aircraft targets. Equally important, it may reduce overall life cycle operation and maintenance costs for US national operational radars. The number of radars would be reduced from 629 to 411 (Cho, 2015) and second level engineering, logistics and training - currently managed separately for each of the 7 major operational radar types - would be consolidated.

In spite of very substantial demonstrated cost reductions in active array technology, it is likely that the MPAR antenna will remain a significant factor in acquisition cost. Herd and Duffy (2011) and Conway (2015) estimate that, in production quantities, the panel technology developed for MPAR demonstration activities would cost \$50,000-60,000 per square meter of aperture. With current assumptions on the size of the antennae required for MPAR and the number of radars to be procured, this translates to approximately \$3.5B for the full MPAR network. Recurring costs for exciters, digital receivers, array integration and calibration will also scale with the total quantity of active array aperture to be procured for the MPAR network. Concepts of operation and design innovations that can reduce the size of the aperture required for MPAR are therefore of high interest in creating a favorable business case for the system.

This paper describes a hybrid multi-static MPAR configuration that could significantly reduce the size of antennae required at many of the planned MPAR sites. Instead of a single-outward looking aperture (multiple planar faces on the sides of a frustum, or a cylindrical array), a network of separated, inward-facing antennae would be deployed around a perimeter with linear dimensions approximately equal to the transmitted pulse length. Inside this network, returns would be processed multi-statically with transmit-receive pairs selected as a function of the location of each resolution volume to achieve favorable geometry. Returns from outside the network would be processed monostatically. This approach enables the use of high energy, frequency modulated waveforms and compressive receiving at all ranges of operational interest, thus maximizing system sensitivity for a given aperture size and transmitted power level. The multistatic approach will be particularly advantageous for MPARs that would be sited on or very near to airports as a replacement for current Airport Surveillance Radars (ASR) and Terminal Doppler Weather Radars (TDWR).

2. TERMINAL MPAR

Cho (2015) describes a notional MPAR network configuration based on the premise that airspace coverage and spatial/temporal resolution must at least equal that provided by today's aircraft and weather surveillance radar networks. His analysis indicates that 411 MPARs will be required. Approximately half of these would be full scale or "high resolution" MPARs, sized so as to provide aircraft and weather detection capability equivalent respectively to current long range surveillance radars (CARSR and ARSR- 4) and national Doppler weather radars (WSR-88D). The other half of the network would be smaller "Terminal"

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MPARs sited on or near airports to provide aircraft surveillance and "six-level" precipitation mapping to a range of 60 nmi. In addition, TMPAR would detect low altitude wind shear to a range of approximately 6 nmi from the airport center.

Functional requirements for MPAR are under development with a near term goal of supporting the FAA's "NextGen Surveillance and Weather Radar Capability (NSWRC)". These draft requirements do not specify compromises to antenna beamwidth and system sensitivity that will be appropriate for the smaller TMPAR system. Notionally however, TMPAR has been described using parameters similar to those in Figure 1 (e.g. Weber et al., 2007). These provide azimuth beamwidth and near-airport system sensitivity approximately equal to that of ASRs. The much narrower elevation beam would significantly improve capability for detection of low-altitude wind shear, relative to an ASR, and would improve the ability to suppress ground-clutter interference for low-altitude targets and weather.

TR-elements per face	**4000**
Antenna diameter	**4 m**
Transmitted power	**40,000 W**
Pulse length	**80 µs (with 1 µs "fill pulse")**
Beamwidth (at broadside)	**1.6 degree (az and el)**
Antenna gain	**41 dB**
Wavelength	**10 cm**
Bandwidth	**1 MHz**
Minimum reflectivity	**0 dBZ ***
(Resolution volume) $^{1/3}$	**307 m ***

***Worst case within 6 nmi of radar**

Figure 1. Notional parameters of Terminal MPAR. The radar would consist of 4 planar faces and would typically be located on airport property.

MPAR's low peak-power transmitter will require the use of long pulses and receiver pulse compression to achieve necessary energy-on-target for full-range surveillance. As noted in Figure 1, much shorter, low-energy "fill-pulses" are needed for surveillance in the vicinity of the airport. These must either be transmitted on a separate frequency (increasing spectrum utilization and receiver complexity) or as separated pulse-transmissions (thus increasing time utilization). Receive path dynamic range (and therefore cost) may need to be increased for situations where separation of fill-pulse signals from much stronger returns from the long pulse is required.

The low energy associated with these fill pulses may require a relatively large aperture to meet requirements for detection of low reflectivity weather phenomena such as "dry" microbursts and gust-fronts that have propagated away from the generating storm. For the notional TMPAR parameters above, Figure 2 plots minimum detectable weather reflectivity as a function of range. The critical region for detection of low-reflectivity, near-airport wind shear phenomena (inside 6 nmi) is precisely the region subject to the fill-pulse's 19 dB sensitivity loss. This sensitivity-loss could be mitigated using higher power transmit amplifiers and/or multiple fill-pulses of progressively increasing length. Both approaches, however would add to system cost and complexity, and would be unlikely to recover the full loss of sensitivity.

Another challenge for an on-airport TMPAR is automated detection of wind-shear radial-velocity signatures at very short range. For example, the convergent radial velocity signature associated with a gust front vanishes as it approaches the radar and becomes radially aligned. A microburst occurring on top of a radar produces positive (outbound) radial velocities at all azimuths, which is very different from the signature of a microburst displaced even a few kilometers from the radar.

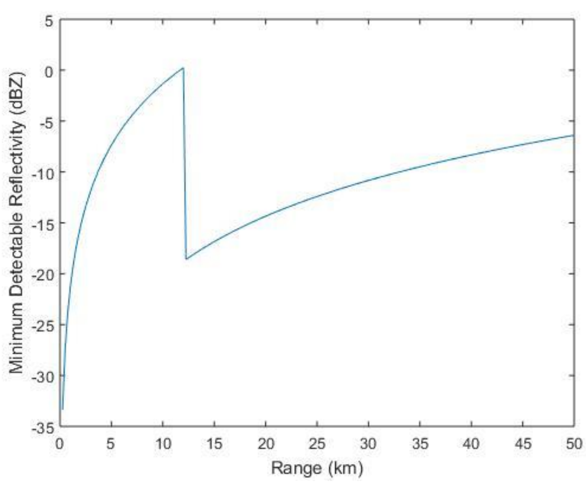

Figure 2. Minimum detectable weather reflectivity (0 dB single-pulse SNR) as a function of range for the notional TMPAR configuration depicted in Figure 1. The calculation is at broadside, where antenna gain is maximum.

Finally, intense ground clutter returns at very short range, for example from airport buildings, may impact detection of much weaker weather returns in operationally significant areas. The multistatic configuration described in this paper mitigates each of these challenges.

3. MULTISTATIC MPAR

Figure 3 illustrates a quasi-multistatic TMPAR concept that eliminates the need for a fill-pulse by separating the transmitting and receiving apertures for signals scattered at short ranges. The four TMPAR faces would be deployed at separated sites around the perimeter of the airport, facing inwards as shown. Each face would sequentially transmit long-pulses only, which would be received and processed by at least two of the other faces in the network as shown. Note that the receiving apertures would need to be simultaneously listening to returns from multiple active range gates along the transmitted radial. Implicit therefore is the assumption that the arrays will be highly digital in order to support the large number of receiving beams necessary.

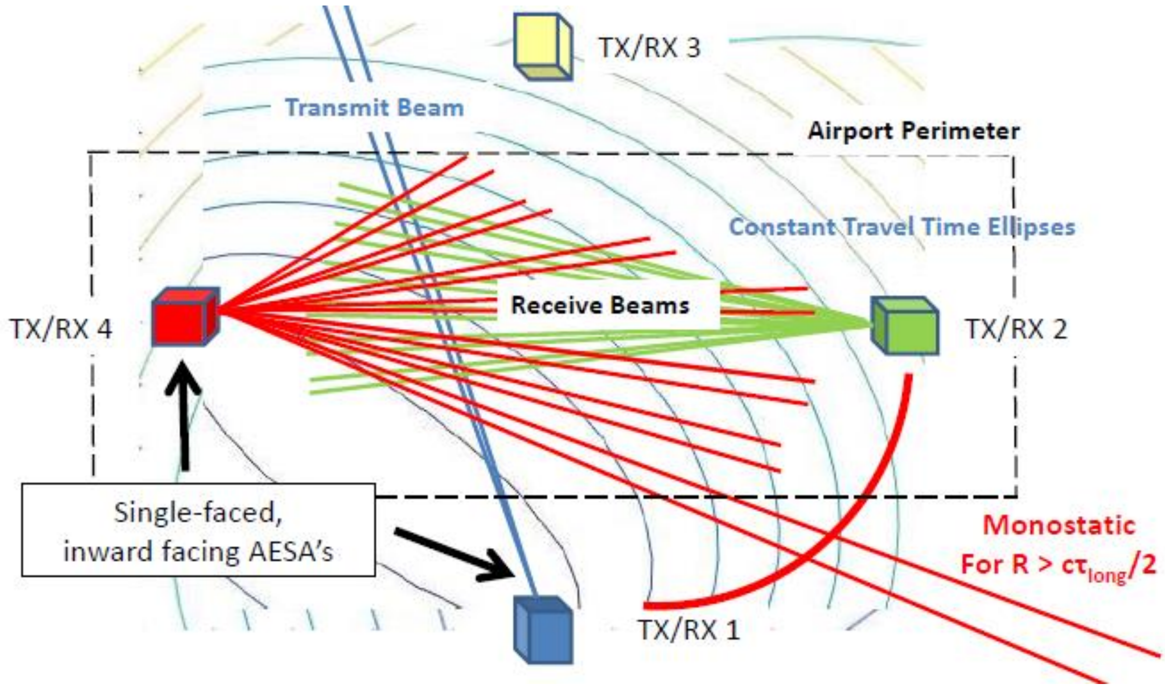

Figure 3: Multistatic MPAR concept as described in the text.

Outside the network, where range is greater than the long-pulse "blind zone", the radar reverts to monostatic operation with each face responsible for surveillance in its 90^o sector. In the figure, for example, TX/RX 4 could be monostatically receiving a pulse it previously transmitted, while simultaneously receiving returns from a just-transmitted pulse from TX/RX 1. Note that the duration of the long pulse sets the approximate minimum separation of the antenna, since to receive multistatically well outside the network would require excessive array scan angles.

As with a monostatic MPAR, the transmitting aperture's beam could be broadened or "spoiled" in azimuth and/or elevation to reduce volume-scan time. Separation of returns from simultaneously active pulse volumes within the spoiled transmit beam would be accomplished using digitally formed receive beams and/or signal arrival time difference. In the former case, isolation is determined by one-way receive beam sidelobe levels and in the latter by the range-time sidelobes of the transmitted waveform.

Pulse transmission times for the different faces would need to be coordinated. After transmission from one antenna, the other antennae would need to receive until the pulse cleared the network, an interval of about 150 µsec for an 80 µsec pulse and antenna separation as described below. This would constrain maximum PRF's to about 1700 sec^{-1}.

At low elevation angles, simultaneous measurement of bistatic Doppler velocity at two or more receivers allows for straightforward estimation of the orthogonal components of the horizontal wind vector in each resolution volume. This capability has the practical benefit of mitigating the need to detect anomalous wind shear signatures directly on top of the radar. The detection algorithms could operate on the vector wind field estimates directly, or remap pseudo-radial velocities to a reference point and use existing single-Doppler wind shear detection algorithms.

Calculations in the remainder of this paper will consider a configuration where the four, inward-looking TMPAR antennae are displaced south, east, north and west of the airport center, each by a distance of 5 km. This is for illustration purposes only and could be modified as required to achieve system performance goals, or to facilitate siting of the antennae.

Figure 4 illustrates geometric considerations using antenna pair 1-2 (the south and east antennae). Although the highest sensitivity is achieved near these antennae, this southeast quadrant is unfavorable in that the forward scattering angle is small. As a result transmit and receive beams intercept ellipsoids of constant range at an obtuse angle, resulting in extension of the scattering volume. In addition, time separation between the direct and scattered signal at the receiver is small in this quadrant, compounding the challenge of suppressing the direct path signal. The most favorable area for bistatic reception is, in fact, near-to or within the quadrant opposite the transmit/receive pair.

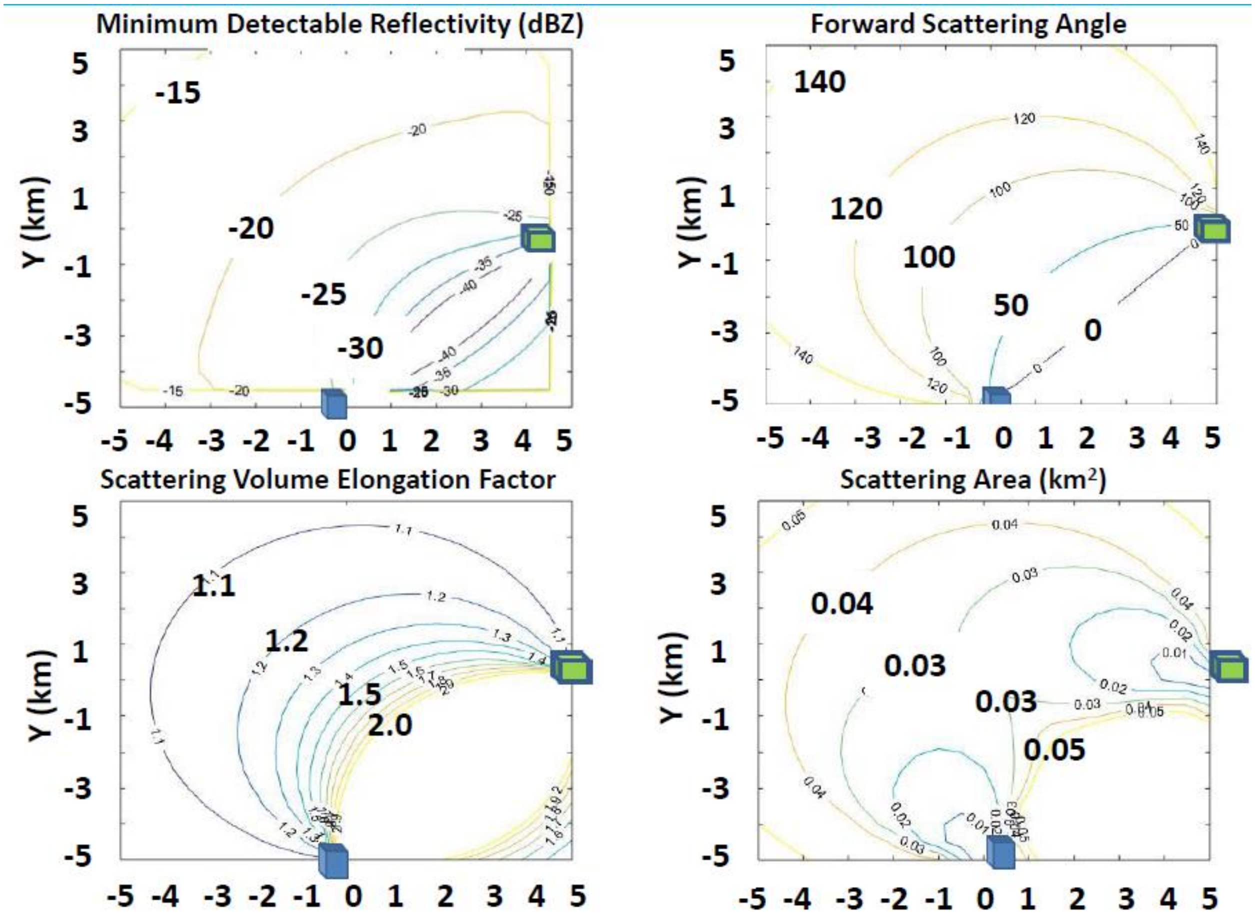

Figure 4: Geometric considerations for bistatic signal reception.

Figure 5 suggests a mapping from location within the network to primary and secondary transmit/receive pairs. The primary pair would be more heavily weighted for reflectivity measurement (and aircraft detection), with the secondary pair enabling multiple Doppler estimation of the wind vector. This mapping is used in subsequent calculations of measurement capability versus position within the network.

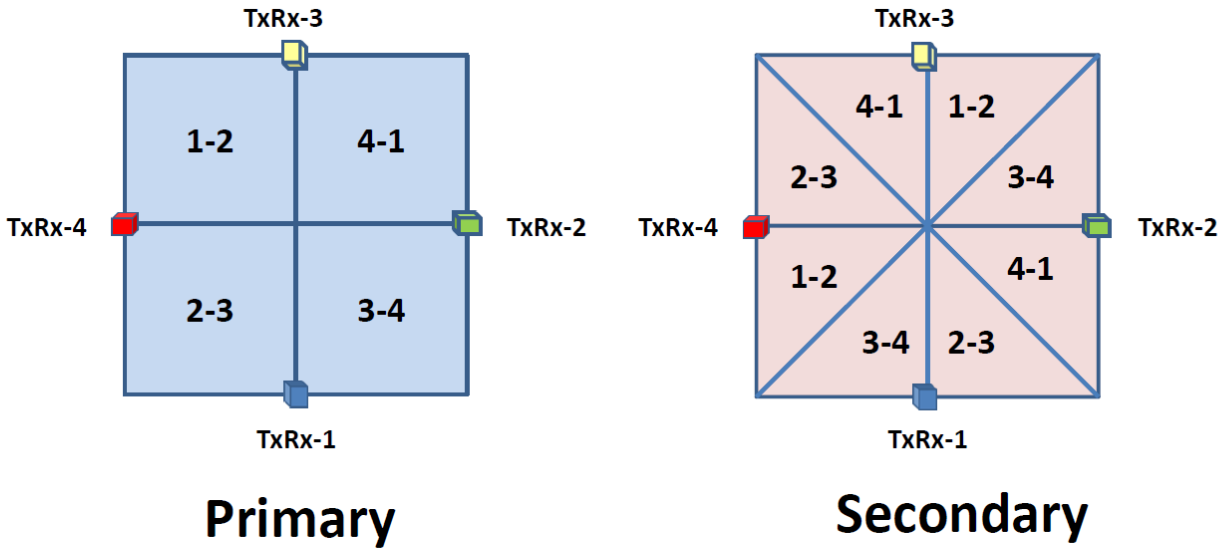

Figure 5: Transmit-receive multistatic processing pairs versus position.

4. CAPABILITY ANALYSIS

Figure 6 shows minimum detectable reflectivity factor at low elevation angle for a monostatic TMPAR located at the center of an airport, and for the multistatic configuration described above. Array parameters for both configurations are taken to be those in Figure 1, and the calculation assumes a single-pulse SNR requirement of 0 dB. Except for ranges within a kilometer of the monostatic radar, the multistatic system's ability to process the high-energy long pulse more than offsets its $1/R^2$ disadvantage. Averaged over the area shown, the sensitivity improvement for the multistatic TMPAR configuration is 10 dB.

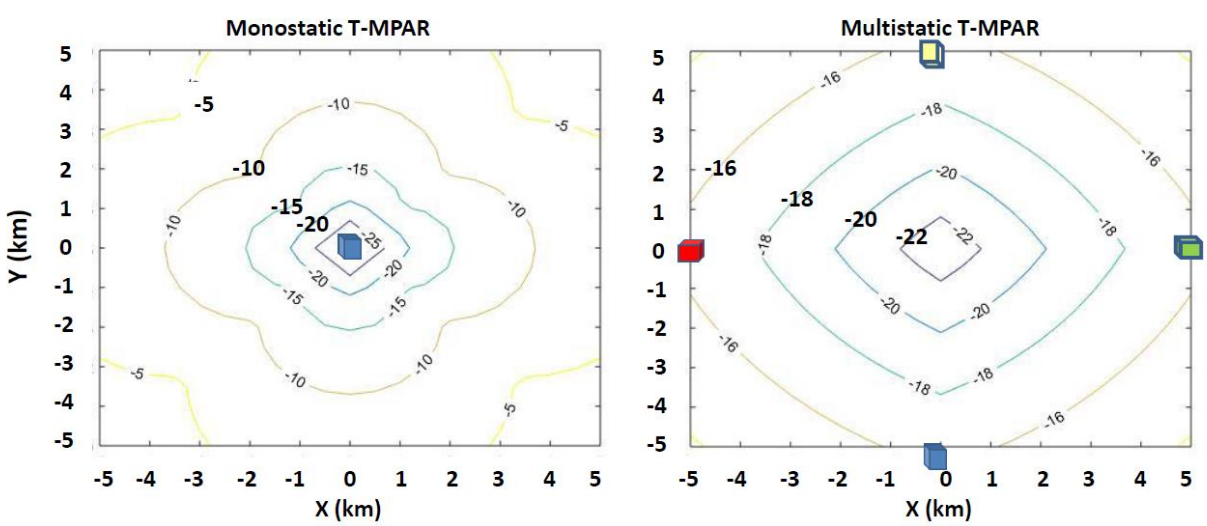

Figure 6: Minimum detectable reflectivity factor for monostatic and multistatic TMPAR configurations.

This enhanced sensitivity could be leveraged in two ways to potentially reduce cost for an MPAR acquisition. Current MPAR deployment concepts (Cho, 2015) invoke the larger "high resolution" MPAR for airports currently equipped with TDWR. This system would be much more expensive than TMPAR as it would employ approximately 4 times as many transmit-receive elements to achieve sensitivity equivalent to TDWR and a beamwidth of approximately 1^{o}. A multistatic configuration would achieve comparable sensitivity using the much smaller TMPAR aperture. Because the antennae would be closer to the airport than current off-airport TDWRs, spatial resolution would likely also be acceptable. Note that at approximately 25 current TDWR airports, a "high resolution" MPAR might subsume both TDWR and WSR-88D services. In this scenario, the "high resolution" MPAR would be necessary owing to the NWS need for long-range weather surveillance.

For non-TDWR airports, the sensitivity shown for the multistatic configuration in Figure 6 is greater than would normally be needed. With the exception of a small number of airports in arid regions of the western US, minimum detectable reflectivity of 0 dBZ would likely be sufficient to detect all convective-related wind shear. The "excess" sensitivity could be traded off for an even smaller TMPAR aperture as discussed in a later section of this paper.

Figure 7 contours the standard deviation of the horizontal wind vector magnitude estimate at low elevation angle, normalized by the individual-receivers' Doppler velocity standard deviations. This normalization removes the effects of PRI, CPI-length, weather spectrum width, SNR and other factors from the calculated standard deviation. The normalized multistatic velocity standard deviation varies from less than 1.5 to 2.5 over the near airport area of interest. Given that TMPAR parameters and waveforms will be chosen to realize Doppler measurement standard deviations of approximately 1 m/s or less, this should not degrade the ability to distinguish wind-shear velocity gradients from noise and clutter residue.

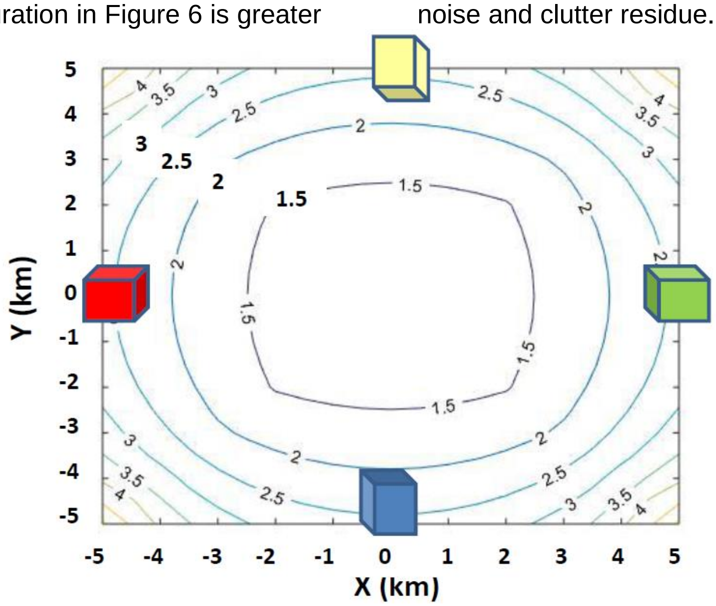

Figure 7: Normalized, standard deviation of the multistatic horizontal wind vector magnitude estimate.

Target localization approaches that determine the effective multistatic pulse-volume are illustrated in Figure 8. The bistatic (i.e. single transmit-receive pair) common scattering volume is the three-way intersection of the transmit beam pattern, the receive beam pattern and the constant-range ellipsoidal shell determined by the antennae locations and signal bandwidth. These "angle-range" weather or aircraft parameter estimates could be averaged from the primary and secondary receivers for each transmitted pulse to reduce parameter estimate variance. For discrete aircraft targets at least, the alternate "range-range" approach illustrated on the right side of the figure would reduce the size of the effective resolution volume in situations where bandwidth is high and/or antennae aperture size is small (i.e. beamwidth is large). It is not clear, however, that the range-range localization concept is appropriate for distributed weather targets.

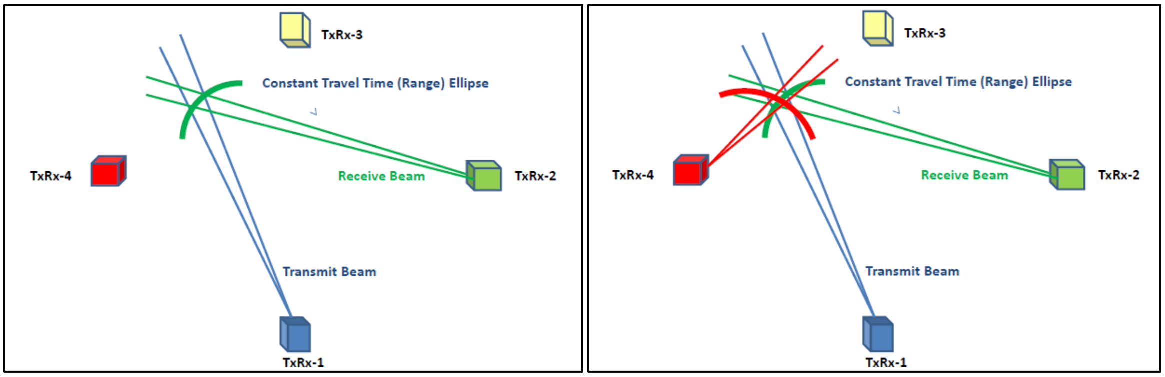

Figure 8: Bistatic angle-range (left) and multistatic range-range (right) localization.

Figure 9 plots the horizontal area of the notional TMPAR's pulse volume for the monostatic configuration, and for the multistatic configuration using angle-range and range-range localization. Within the domain shown, the range from the pulse scattering volume to the multistatic transmit-receive pairs is significantly larger than the corresponding range for the monostatic antennae. This accounts for the larger multistatic pulse volumes. At ranges well outside the network where either configuration would be operating monostatically, this fractional range difference would be small and resolution volumes would be essentially identical. Multistatic range-range processing results in a resolution area that is somewhat smaller in horizontal extent than angle-range processing. However, the range-range common volume does not vary with antenna size so there might be a greater advantage if a smaller TMPAR antenna were used. Note that the intersecting constant-range ellipsoids do not separate rapidly in the vertical direction. Thus the height dimension of the pulse volume is determined by antenna beamwidth for both approaches.

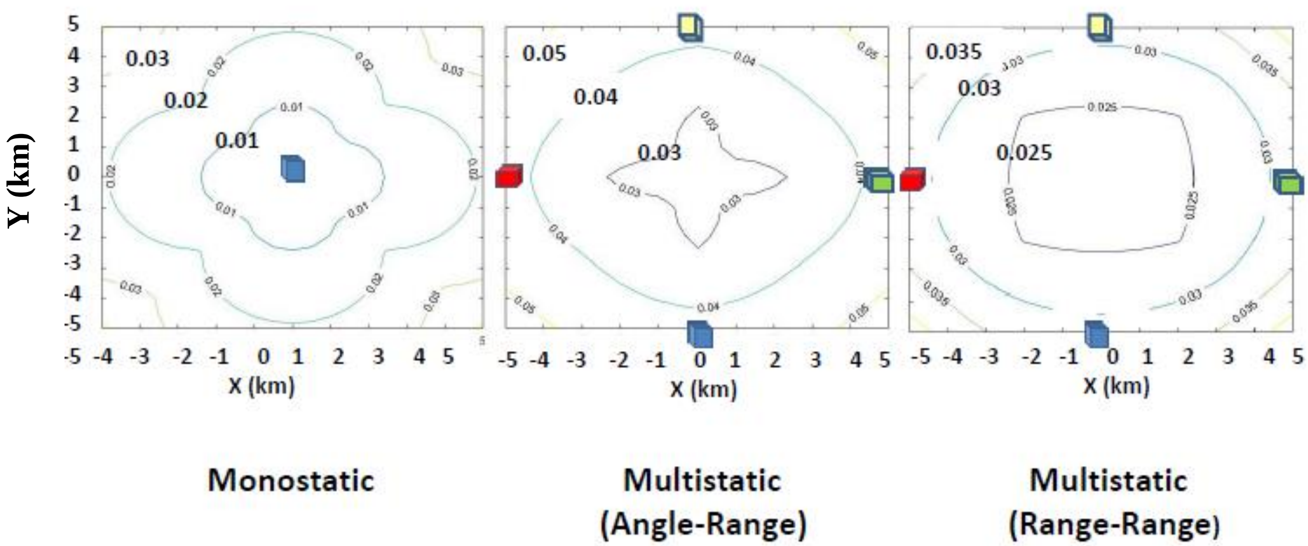

Figure 9: Horizontal area (km^2) of TMPAR pulse volume for monostatic (left), multistatic angle-range (center) and multistatic range-range (right) localization.

5. GROUND CLUTTER, INTERFERENCE AND DYNAMIC-RANGE

For given weather and ground clutter cross-section densities, the weather-to-clutter power ratio increases proportionally to range. Thus the offset between the antennae and processed pulse volumes is advantageous to the multistatic configuration in detecting weather phenomena at the airport. The author's experience in developing the on-airport ASR-9 Weather Systems Processor substantiates that ground clutter is a significant challenge for wind shear detection at short range (Weber, 1987).

If a monostatic TMPAR's short pulse were to be transmitted at the end of the long-pulse, then weather or clutter returns from the high-energy long pulse would be received at the same time as potentially much weaker returns from weather in the fill-pulse range interval. The receivers would require adequate dynamic range on the high-end to operate linearly for the long-pulse returns, while detecting fill-pulse returns above the system noise level. As a specific example, consider a 60 dBZ thunderstorm extending from 12 km to 24 km in range, competing with fill pulse weather returns inside 12 km. For a monostatic TMPAR configuration, dynamic range as large as 82 dB would be required to maintain the weather sensitivity shown in Figure 6. For multistatic TMPAR, this scenario requires a maximum dynamic range of only 60 dB because the short range returns do not suffer a pulse-energy disadvantage relative to the long range returns, and the range from the relevant antennae to the interfering thunderstorm is larger than in the monostatic case.

A more significant factor determining the dynamic range needed for multistatic TMPAR is interference from the direct pulse from the transmitting to the receiving antenna. For the configuration considered in this paper, direct path power would be +38 dBm at the output of the receive beamformer if the transmit and receive beams were directed at each other. This is approximately 142 dB above the receiver noise level. In practice, of course, the transmitting antenna would minimize radiation directed at the receiving antenna through pattern shaping. Conservatively this would provide at least a 40 dB reduction in the direct path power density at the receiving antenna. Dynamic range requirements would depend on the receiving array's analog beamforming, downconversion and digitization architecture. As an example, if digitization is performed at the TR-element level and assuming an element (e.g. patch antenna) gain of 5 dB in the direction of the transmitter, then dynamic range of 66 dB would be required to maintain linearity for the direct path signal. This is well within the capabilities of current digital-at-the-element active array architectures (Caleb Fulton, University of Oklahoma, personal communication).

Suppression of the direct path signal would be accomplished using transmit and receive antenna pattern shaping, offset in reception-time between the direct path and scattered signals and the typically non-zero Doppler velocity of meteorological targets. Conservatively, these four mitigations should provide approximately 160 dB of suppression, which would allow for detection of meteorological returns down to the receiver's noise floor.

6. IMPLEMENTATION CONSIDERATIONS

As noted earlier, the high sensitivity of the multistatic TMPAR configuration discussed is unnecessary at many airports, and could be traded-off for a smaller, less expensive aperture. Figure 10 depicts a down-scaled TMPAR aperture consisting of one-half the number of elements assumed up until now. Sensitivity for detection of aircraft and low-altitude wind shear in the near-airport area would still be adequate, as would be lateral and vertical dimensions of the pulse-resolution volume.

Dimensions (height, width)	3.0 m, 2.4 m
Wavelength	10 cm
Number of TR elements	2000
Element Spacing	0.6 λ
Beamwidth (az, el)	2.1^{o}, 1.7^{o}
Antenna Gain	38 dB
Bandwidth	1 MHz
Transmitted Peak Power	20,000 W
Pulse Length	80 µsec
Minimum Reflectivity	- 4 dBZ *
Resolution Volume $^{1/3}$	370 m *

*Worst case within 6 nmi of airport center

Figure 10. Conceptual multistatic TMPAR antenna.

Even with this smaller aperture, surveillance of terminal approach and departure airspace out to a range of 60 nmi would be --depending on the parameter considered -- equivalent to or better than legacy terminal radars. For example, monopulse-like angle estimation for aircraft targets – enabled by the highly digital array - could improve cross-range position estimates by a factor of 10-20 relative to the physical beamwidth (i.e. to 0.1- 0.2^{o}). Current ASRs estimate target-azimuth by amplitude pattern matching, with a specified accuracy of 0.16^{o}. For six-level precipitation reflectivity mapping in terminal airspace, current ASRs average across three-adjacent 1.4^{o} azimuth beams. Thus effective azimuthal resolution for these precipitation maps is twice the beamwidth indicated in Figure 10. Signal-to-noise for aircraft targets would be 10 dB greater than for legacy ASRs if full-gain on the transmit beam were maintained. For beam-filling weather, sensitivity would be 6 dB greater than for legacy ASRs. Because the broad elevation beams of current ASRs often overshoot the areas of highest reflectivity in storms, the much smaller elevation beamwidth of this multistatic TMPAR antenna would provide more sensitivity for shallow, low-reflectivity precipitation such as snow, and would more accurately represent the peak reflectivity in a storm.

A drawback for the multistatic configuration is of course the need to site four antennae around an airport. It is likely, however, that the smaller, single-faced antenna would reduce significantly the structural requirements for the towers relative to a monostatic radar. Aperture area (and weight) would be reduced more than five-fold, perhaps enabling the use of cell phone like towers as depicted in the photograph.

Environmental approvals, construction and maintenance of these sites would be significantly easier if they could be located on airport property. Table 1 lists acreage at sample United States airports (source: http://www.gcr1.com/5010WEB/). We approximate the linear dimension of each airport as the square root of this area and from that, calculate an approximate upper limit on transmitted pulse length. (As noted previously, the pulse length for the multistatic configuration should not significantly exceed antenna spacing). For the airports considered the associated loss of pulse energy (i.e. sensitivity), relative to the 80 µsec pulse length considered throughout this paper, would range from 2.1 to 4.7 dB. The performance margin of the notional multistatic configuration in Figure 10 is sufficient to allow for this.

Airport	Acreage	Effective Linear Dimension (km)	Maximum Multistatic Pulse Length (μsec)
Chicago O'Hare (ORD)	7,627	5.5	37
Orlando (MCO)	13,302	7.4	49
Fort Myers (FMY)	13,555	7.4	49
Oklahoma City (OKC)	8,081	5.7	38
Colorado Springs (COS)	7,200	5.4	36
Austin (AUS)	4,242	4.1	27

Table 1: Airport acreages, "effective linear dimension" and associated maximum pulse length for a multistatic TMPAR configuration with antennae separated by this dimension.

7. SUMMARY

A multistatic MPAR configuration has been described that significantly enhances sensitivity to weather and aircraft returns at short range. Additional benefits include the capability to estimate the orthogonal components of the wind vector inside the network -- thereby facilitating wind shear detection and strength characterization -- and reduction in radar spectrum and/or timeline usage. The configuration would appear to be most beneficial for so-called Terminal MPAR which FAA may deploy at US airports in place of current ASRs and TDWRs. As noted in this paper, the sensitivity enhancement realized with the multistatic configuration could allow for the use of smaller, less expensive antennae.

The principal drawback to this concept is the need for four separated antenna and processing sites. This drawback could be mitigated by constraining the size of the multistatic network so as to fit within the airport perimeter. The preceding section demonstrates that this would be feasible at most US airports.

The multistatic configuration should be considered as an additional MPAR variant (akin to previously discussed "High Resolution" and "Terminal" configurations), all exploiting a common scalable radar architecture. Thus it could be used only at airports where operational requirements and implementation considerations make it an appropriate solution. In that spirit, we recommend that serious consideration be given to a multistatic option in ongoing refinement of the MPAR concept.

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