

Wake Vortex Tracking Using a 35 GHz Pulsed Doppler Radar

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ABSTRACT

A 35 GHz, pulsed-Doppler radar system has been designed and assembled for wake vortex detection and tracking in low visibility conditions. Aircraft wake vortices continue to be an important factor in determining safe following distances or spacings for aircraft in the terminal area. Currently, under instrument meteorological conditions (IMC), aircraft adhere to conservative, fixed following-distance guidelines based primarily on aircraft weight classifications. When ambient conditions are such that vortices will either drift or dissipate, leaving the flight corridor clear, the prescribed spacings are unnecessarily long and result in decreased airport throughput. There is a potential for significant airport efficiency improvement, if a system can be employed to aid regulators and pilots in setting safe and efficient following distances based on airport conditions. The National Aeronautics and Space Administration (NASA), the Federal Aviation Agency, and Volpe National Transportation Systems Center have promoted and worked to develop systems that would increase airport capacity and provide for safe reductions in aircraft separation [1-3]. The NASA Aircraft Vortex Spacing System (AVOSS) [4-7], a wake vortex spacing system that can provide dynamic adjustment of spacings based on real-time airport weather conditions, has demonstrated that Lidar systems can be successfully used to detect and track vortices in clear air conditions. To fill the need for detection capability in low-visibility conditions, a 35 GHz, pulsed-Doppler radar system is being investigated for use as a complimentary, low-visibility sensor for wake vortices. The radar sensor provides spatial and temporal information similar to that provided by Lidar, but under weather conditions that a Lidar cannot penetrate. Currently, we are analyzing the radar design based upon the data and experience gained during the wake vortex Lidar deployment with AVOSS at Dallas/Fort Worth International Airport. As part of this study, two numerical models were utilized in system simulations. The results of this study improve our understanding of the method of detection, resolution requirements for range and azimuth, pulse compression, and performance prediction. Simulations applying pulse compression techniques show that detection is good in heavy fog to greater than 2000 m. Both compressed and uncompressed short pulses show the vortex structure. To explore operational challenges, siting and scanning strategies were also analyzed. Simulation results indicate that excellent wake vortex detection, tracking and classification is possible in drizzle (+15 dBZ) and heavy fog (-13 dBZ) using short pulse techniques (<99ns) at ranges on the order of 900 m, with a modest power of 500 W output. At 1600 m, detection can be expected at reflectivities as low as -13 dBZ (heavy fog). The radar system, as designed and built, has the potential to support field studies of a wake vortex spacing system in low-visibility conditions ranging from heavy fog to rain, when sited within 2000m of the flight path.

1. INTRODUCTION

For some time, industry and government have been working to mitigate the capacity crisis in the National Airspace System. Aircraft spacings are one factor in airport capacity, and the separation criteria in use today are designed to prevent encounters with wake vortices. The National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have been leading efforts to study wake vortices to

predict behavior and to develop systems for wake avoidance with the ultimate goal of reducing the required aircraft separations [6, 7]. Current spacing requirements, given in Table 1 below, are based primarily on aircraft weight classification and are considered overly conservative under most conditions. The requirements are designed to provide a safe separation between aircraft regardless of atmospheric circumstances that affect vortex decay and motion. Efforts to make system changes and replace these spacing requirements have three components: gaining a better understanding of the actual behavior of vortices and the effects on operations; modeling and prediction of vortex behavior, especially decay and advection; and vortex detection, tracking and measurement by the use of sensors. NASA has developed and tested a proof-of-concept system for actively adjusting aircraft spacings based on predicted and monitored vortex behavior. The Aircraft Vortex Spacing System (AVOSS) [8], demonstrated at the Dallas Ft. Worth International Airport (DFW) in July of 2000, incorporated atmospheric sensors, a vortex model for prediction, and vortex sensors for verification to demonstrate the potential for significant improvement in throughput.

Table 1. FAA Wake Avoidance Separation Criteria given in nautical miles.

Following Aircraft	Leading Aircraft			
	Small	Large	B757	Heavy
Small	2.5	4	5	6
Large	2.5	2.5	4	5
Heavy	2.5	2.5	4	4

Small \leq 41,000 lb Maximum Gross Takeoff Weight (MGW)

41,000 lb < Large \leq 255,000 lb MGW

Heavy > 255,000 lb MGW

2.5 nm separation increased to 3 nm when runway occupancy time is > 50 sec

Lidar demonstrated active vortex detection and tracking while serving as a key sensor in the AVOSS field demonstration [4, 5]. In clear visibility conditions, Lidar successfully gathered useful data that improved understanding of the spatial-temporal behavior of vortices, supporting the development and verification of a predictive wake vortex model, the Terminal Area Simulation System (TASS) [9, 10]. Under low visibility conditions, infrared- and visible-wavelength Lidars are limited in detecting and tracking vortices. 35 GHz radar is complimentary to Lidar and the two sensors operating simultaneously can provide invaluable data in ground-based test demonstrations, similar to AVOSS, or ultimately as on-line wind sensors at airports.

2. THE 35 GHZ WAKE VORTEX RADAR (WVR)

The Wake Vortex Radar is a 35 GHz pulsed Doppler system capable of pulse compression and designed for vortex detection in low visibility conditions at short range. The key system characteristics for the WVR follow:

- 35 GHz (Ka band);
- 500 W peak power transmitter for developmental testing;
- Parabolic antenna, Cassegrain feed, 58 dBi gain;
- Antenna scan rate of 1 to 10 degrees/sec;
- Beam width of 0.185° in azimuth (10m cross range @ 3 km)
- 25 KHz and 12.5 KHz pulse repetition frequencies (PRF);
- Unambiguous ranges of 6 km and 12 km;
- 128 range cells and 512 Doppler frequencies;
- Optional, programmable pulse compression up to a 128-bit sequence;

- Pulse length from 5m to 640m.

Based upon the simulations we have completed, the radar we have assembled is capable of detecting and tracking vortices from generation to dissipation under low visibility conditions. It employs advanced real-time signal processing to support field studies, and has programmable pulse modulation to support field experimentation.

At 35 GHz, the radar is sensitive to smaller particles or hydrometeors than X-band weather radar and is still able to penetrate weather. A primary design consideration is resolution cell size. The diameter of a wake vortex normally ranges from a few meters to tens of meters. To resolve the tangential winds using peak detection, a resolution cell has to contain a small enough volume that the tangential velocity of the vortex will dominate the velocity spectrum of the scatterers. The WVR utilizes a large, agile parabolic dish antenna to obtain a narrow beam and can use either short pulses or pulse compression for a short range cell. Range resolution can be as short as 5 m, compressed or uncompressed.

3. RADAR SIMULATION STUDIES

The purpose of this study was to update our radar simulation models, incorporate the results of work done with the Lidar sensor (used in the AVOSS program), and apply them to the as-built radar. We focused upon three topics: detection processing, pulse compression, and potential siting issues. During the design and development of the WVR, two radar simulation models were used in trade and design studies. The first model, the Airborne Doppler Weather Radar System (ADWRS) model [11], was developed to analyze pulsed Doppler weather radar systems. The second model [12, 13] was specifically developed for the design and development of this radar and will be referred to as the vortex radar model or VR model for brevity.

The ADWRS radar simulation, which was used in previous NASA programs to develop radar capability for wind shear and turbulence detection, is a sophisticated tool developed by RTI for NASA and has both radar developmental and complete end-to-end capabilities for simulation of radar performance in the presence of a broad range of real-world effects. The simulation provides a detailed and realistic calculation of the signal characteristics and expected outputs of a coherent pulsed-Doppler radar system. It contains algorithms for direct calculation of radar signal returns for each simulated radar pulse using input weather data files that provide wind velocity components and the radar reflectivity of moisture at any point in space, combined with data permitting calculation of the radar scattering from ground clutter and discrete targets. This well-tested model was used as a reference in the detection studies and applied to the siting investigation.

The VR model was used in the investigation of the efficacy of pulse compression for vortex detection and tracking. This radar model accepts a 2-D grid of data from the Terminal Area Simulation System (TASS) atmospheric model, which provides liquid water content and x and y wind velocities from a simulated wake. The modeled wake is contaminated with clutter and white Gaussian noise prior to processing with the VR model. The user specifies radar parameters such as pulse compression scheme, antenna pattern, and clutter reflectivity/spectrum, and the model computes an estimate of the power spectrum response for the wake vortex target, taking into account radar system losses, propagation effect, antenna pattern effects, and the appropriate range weighting function.

3.1. Detection Studies

Average power is a key factor in detection range and sensitivity in low reflectivity situations (conditions of marginal visibility where Lidar begins to fail and where the radar begins to take over). As the pulse is shortened to sharpen range resolution, the average power decreases. Pulse compression can mitigate this but comes with other drawbacks. Therefore, there is interest in both the need for high resolution in range and in the efficacy of using pulse compression to achieve it. During the AVOSS program, the Lidar did not rely on peak detection (i.e. locating the peak in the velocity power spectrum). The Lidar has a 3m beam width, for excellent crossrange resolution, but the range cell is quite long relative to the vortex, 65 m. In a range cell

this long, the peak in the velocity spectrum will correspond to the ambient wind even when a vortex is present, and the tangential vortex wind will only change the shape of the spectrum. The Lidar detection method looked for changes in the velocity spectrum to find the vortex wind. Processing based on these methods was added to the models in this study and comparisons were made to discover if the Lidar-like processing worked well for the radar and would facilitate the use of longer pulses.

Table 2. Compressed- and uncompressed- pulse cases run using the VR model.

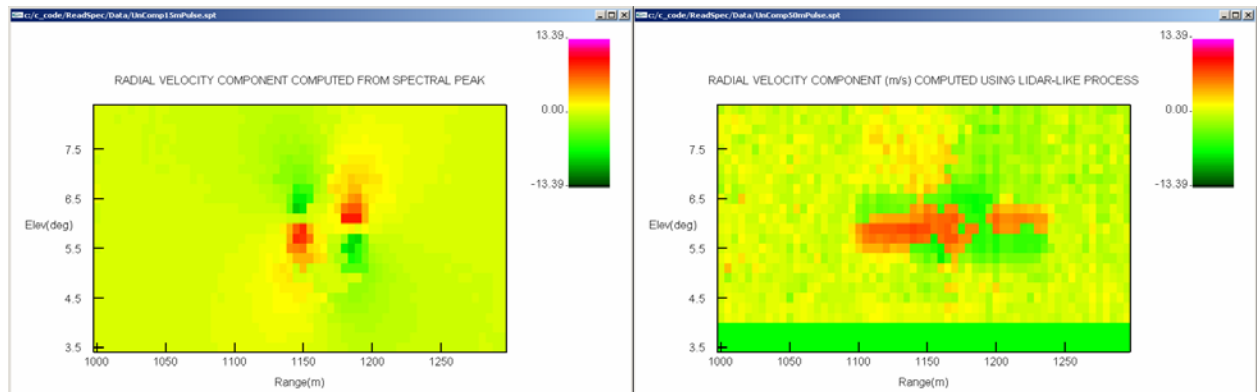
Range Resolution (m)	Compression Code	Compressed		Uncompressed/Actual	
		Length (m)	Time (μ s)	Length (m)	Time (μ s)
4.9	4-Bit Barker	4.9	0.0325	19.5	0.130
5.0	7-Bit Barker	5.0	0.0330	34.7	0.231
5.0	13-Bit Barker	5.0	0.0330	64.5	0.430
5.0	69-Bit Barker ¹	5.0	0.0330	345	2.30
4.9	88-Bit Barker ¹	4.9	0.0330	435	2.90
15	None	-	-	15.0	0.100
19.5	None	-	-	19.5	0.130
34.7	None	-	-	34.7	0.231
50	None	-	-	49.0	0.330
435	None	-	-	435	2.90

¹Sequence of Barker codes

Pulse compression is a method by which the effective range resolution can be shortened without shortening the pulse length and reducing average power. This is done by segmenting a long pulse into pieces, or chips, and using phase modulation to code the pieces. The returned signal is processed to sort and reassemble the information so that an effective pulse length corresponding to the length of a single chip is obtained. For example, based on information in Table 2, an 88-bit phase code with a 5m compressed range resolution has an actual or uncompressed pulse length of 435m and 88 times the average power of a 5m short pulse. Processing is not perfect and the information is not sorted completely into short cells. There is leakage of information from other range cells, and in this application, where reflectivity is minimal and the target is not distinguished by its reflectivity, this signal leakage can be critical. In this study, short-pulse and compressed-pulse cases are compared to get a solid understanding of the tradeoffs between pulse compression and short pulses.

Table 2 lists cases run using the VR model for comparison of performance with compressed and uncompressed pulses. Special processing was added to both of the models, based on the methods used for detection with the Lidar system, and applied for uncompressed, long-pulse cases to see if long pulses could be used without compression. The results with both the ADWRS and VR models showed that peak detection, using compressed, long pulses or uncompressed, short pulses, is superior to the experimental, lidar-like processing. All of the compressed cases have chip sizes that result in 5m, compressed resolution. Uncompressed cases were run using the same overall pulse lengths and for two additional pulse lengths, 15m and 5m. This provides information about uncompressed pulse length versus detection and location, and it allows the comparison of short pulses and compressed pulses. From the results, we are able to see some limitations on the effectiveness of pulse compression.

Figure 1. On the left, the velocity field, versus range and elevation, using peak detection with a 15m uncompressed pulse. A vortex pair, cores located between the twin velocity peaks, is



easily recognized. The color scale is m/s of wind velocity toward the radar. On the right, the velocity field using Lidar-like detection and a 50m uncompressed pulse, oversampled at 5m resolution, for the same vortex pair.

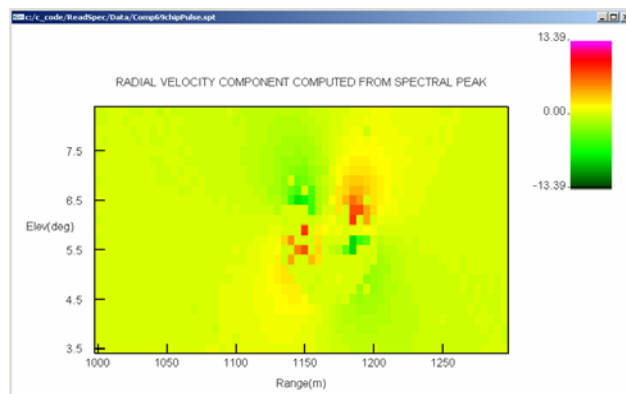


Figure 2. Velocity field for peak detection with the 50m compressed pulse. The cores can be located more accurately with pulse compression, but the resulting 5m compressed, range resolution is not an improvement over the 15m uncompressed case in Figure 1.

Figures 1 and 2 are elevation versus range plots of peak detected wind velocity produced with the VR model. A vortex pair appears between 1140 and 1200m in an atmosphere with reflectivity in the range of -17 to -15 dBZ, corresponding to medium to heavy fog. The vortex pair is clearly defined in the left-hand plot of Figure 1, where a 15m uncompressed pulse was processed by peak detection. This uncompressed pulse clearly located the cores with this detection method. Lidar-like processing was applied to a longer pulse (50m) to produce the right-hand plot. Peak detection with a 50m uncompressed pulse does not work well, because the velocity spectrum is dominated by the ambient wind. Lidar-like processing did not significantly improve detection, and the cores are poorly defined and located. In general this method did not show promise for the radar system, leading to the conclusion that the system should rely on peak detection techniques and that short range cells are required. The point is reinforced further by Figure 2, which presents the results for the same 50m pulse length, but utilizes a 69-bit code for pulse compression. While the wind field is not as well defined as in the 15m, uncompressed case, the cores are more easily located in the compressed pulse case than for the uncompressed, long pulse with Lidar-like processing.

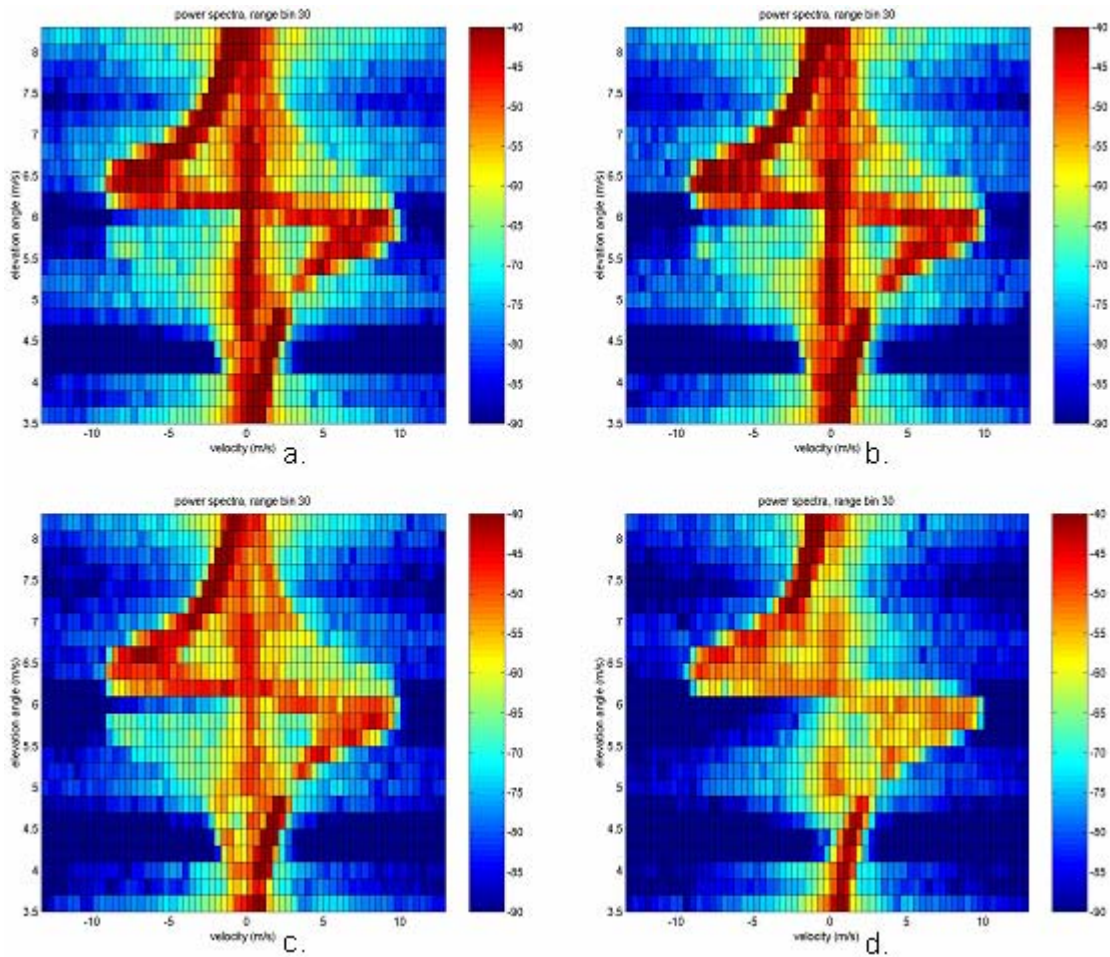


Figure 3. Velocity power spectra for 4 different pulses: a. 13-bit Barker code, b. 69-bit Barker code sequence, c. 88-bit Barker code sequence, and d. 15-meter uncompressed. The horizontal scale is velocity in m/s, from -13 to $+13$ m/s, and the vertical scale is elevation angle in degrees, from 3.5° to just over 8° .

The use of pulse compression is attractive when a short pulse would produce weak returning signals. While pulse compression increases the average power incident on the target, the target wake has approximately the same reflectivity as the surrounding volume. Therefore signal leakage from outside the region containing the vortex can overcome the desired signal, and the ambient wind velocity may dominate the velocity power spectrum. Figure 3 compares velocity power spectra for four pulses. Each plot is set of spectra for a single range cell inside or including a vortex. The ambient wind is at zero velocity and can be clearly seen above and below the vortex. As the beam is scanned in elevation, moving along the y-axis, the vortex winds appear as positive and negative deviations in the wind with a crossover at the core. The radar is sensing tangential winds, so the core diameter is traversed in less than a degree of elevation (at this range, less than 20m). In each plot, the ambient wind can still be seen through the vortex, at nearly every elevation. The spectrum with the smallest component of ambient wind is the uncompressed, short pulse case (plot d.). This pulse, 15m, is on the order of the core dimension. Without pulse compression, pulse lengths approaching 30m begin to fail as the ambient wind line begins to dominate. The 13-bit Barker code, compressed pulse (plot a) has a clear line for the ambient wind, but the tangential winds are still dominant and detection is very good. The longer codes, 69- and 88-bits, are dominated by the ambient wind and provide poor detection. The

conclusion is that pulse compression may be used to advantage, provided the overall pulse length is not long enough to allow leakage of the ambient wind signal to dominate over the tangential vortex winds.

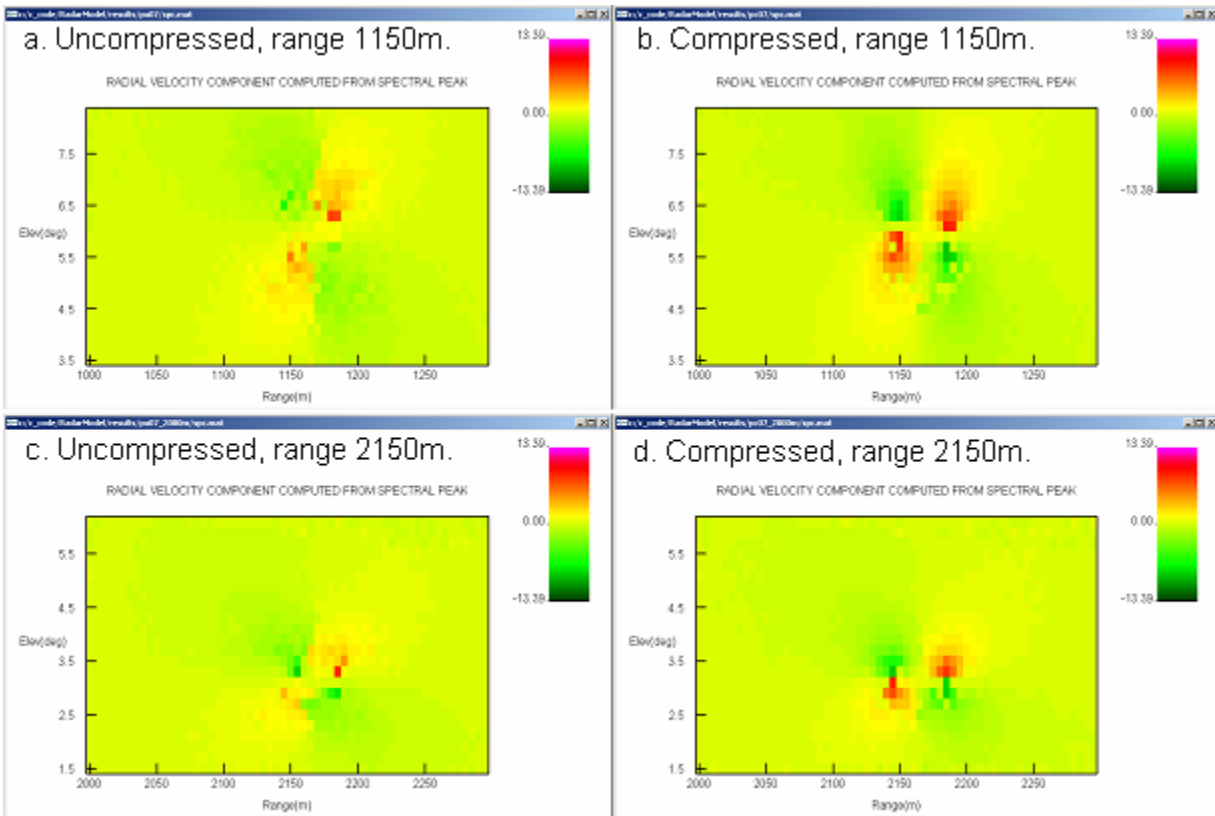


Figure 4. Peak velocity versus range and elevation for $0.231\mu\text{s}$ pulses (34.7m).

The Wake Vortex Radar can be programmed for a range of pulse lengths, compressed and uncompressed, so the most advantageous pulse modulation can be used; however, the most effective modulation will likely prove to be a function of conditions. For the atmosphere and wake used in this study, it is clear that the long codes do not work well, and detection with short, uncompressed pulses degrades as range increases. The short codes used (13-, 7-, and 4-bit) extend the operational range of the radar significantly. Figure 4 shows the effects of doubling the range on a compressed and uncompressed version of a $0.231\mu\text{s}$ pulse. At 1150m range, the uncompressed pulse does a good job of detection, but at twice the range it is clearly failing, while the compressed version continues to detect and locate the vortices well. An exhaustive comparison of pulse options would be time consuming, and results for a single environment (atmosphere, wake, clutter environment, etc.) would not be universally applicable. Eventually, field tests will be required to determine if there is a preferred pulse type, or if pulse modulation must be adjusted to conditions.

3.2. Siting Factors and Radar Performance

The WVR radar must work in a real airport environment, and since airports weren't designed with our sensors in mind, some problems can be expected. For this study, a particular airport, San Francisco International (SFO), was used as an example (Figure 5). SFO is interesting due to factors like limited open space for siting, due to its proximity to water and urban location, and the use of parallel runways. Based on an examination of the location and other information, an example site was chosen, and the ADWRS radar model was then used to evaluate the expected performance of the radar.



Figure 5. A map of the area surrounding San Francisco International Airport [13].

There are limited choices for siting the radar at SFO. The airport is nearly surrounded by water, and the adjacent land area is developed and heavily populated. Suitable sites will most likely not be on airport property, and visits would be required to investigate potential sites. Runways 28L and 28R receive substantial arriving traffic and an area along the water near Highway 101 (circled in Figure 5) is a potential site for the WVR to observe the approach corridor. The radar can be sited perpendicular to the approach paths somewhere on the land south of the runways just north of the Bayshore Freeway. There are some large hotels on this strip, and a parking lot would make a reasonable site for a field deployment. At the location described, the range to the runway is estimated to be 1600m, mostly over water. This is not a desirable offset distance, since the angular scan range is small, the beam will graze the ground or water at low elevation angles, and the cross range spatial resolution degrades compared to closer distances. For the purposes of the radar simulations, a range of 1600m was used as the distance to the approach corridor, and 900m was used as a standard for comparison. The 900m range is useful for comparison, because it removes many of the disadvantages of the 1600m range.

The ADWRS model was used to simulate the as-built radar system using a pulse repetition rate of 12,500Hz, an elevation scan from 1 to 10 degrees, and 128 pulses per measurement. Data was processed to evaluate detection, tracking and circulation estimation for several pulse lengths and two reflectivities as given in Table 2. A data set containing a wake, generated using the AIAA vortex model [14], was used to represent the target atmosphere. Vortex altitude was 80m, core radius was 2m, and vortex separation was 50m. Vortex circulation was set at 400 m²/s. The reflectivity in the volume was scaled to represent light rain or drizzle (15 dBZ) and heavy fog (-13 dBZ), and an ambient wind of 5 m/s toward the radar was included.

Table 2. ADWRS model cases run to evaluate performance. All cases use uncompressed pulses.

Range (m)	Pulse Width (ns)	Range Resolution (m)	Reflectivity (dBZ)
900	33	5	15
900	66	10	15
900	99	15	15
1600	66	10	15
1600	99	15	15
900	66	10	-13
1600	66	10	-13

All of the pulse widths performed well at 900m range in a 15 dBZ atmosphere, providing good to excellent detection. This corresponds to conditions of light rain or drizzle. For the longer pulse, 99ns or 15m, the location and circulation estimates were degraded somewhat due to the lower resolution. Figure 6 shows some sample data for the 66ns (10m) pulse.

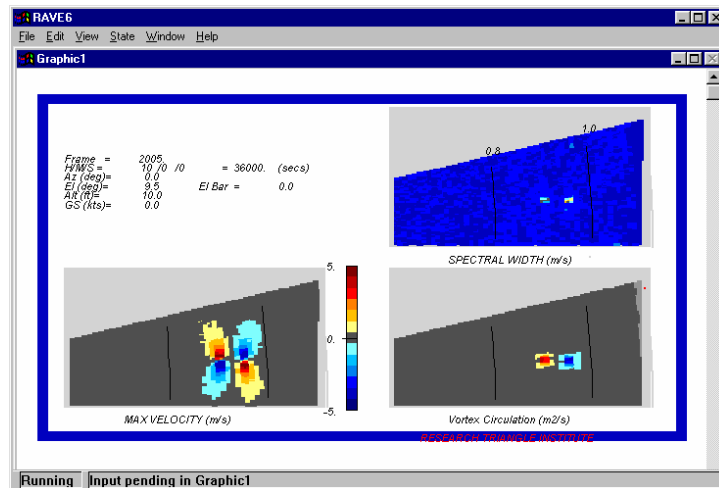


Figure 6. Radar products for a 66ns pulse and 900m range with volume reflectivity of 15 dBZ. All products are plotted versus elevation angle on the vertical axis and range on the horizontal axis. The color scale, applicable to the plot on the lower left, corresponds to velocity in m/s derived by peak detection.

At 1600m, the estimated range to the runways, detection is good with 15 dBZ reflectivity, but the elevation angle is very low and the clutter environment at the airport could be a factor in the field. Figure 7 shows the peak wind velocity for these cases. In Figure 8, the reflectivity has been reduced to -13 dBZ, corresponding to heavy fog. At 1600m range (left hand plot), detection capability has clearly deteriorated but is still good and the cores can be located. The quality of the circulation estimates will deteriorate more quickly. In order to see the effects of increasing range, the wake in the plot on the right is at 900m range.

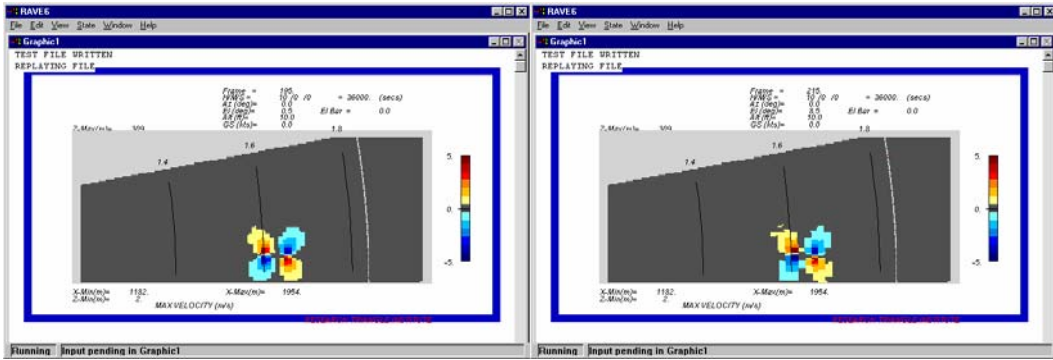


Figure 7. Peak velocity versus elevation and range. The vortices are at 1600m range and the reflectivity is 15 dBZ. The plot on the left is for a 66ns (10m) pulse, and the plot on the right is for a 99ns (15m) pulse.

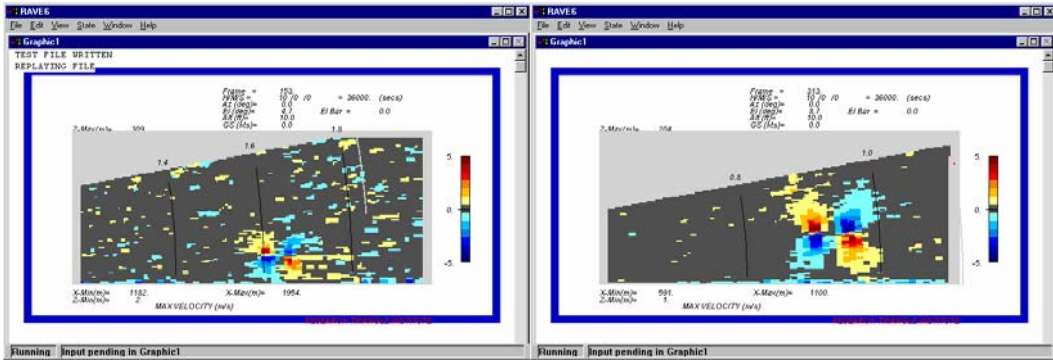


Figure 8. Peak velocity versus elevation and range. The pulse width is 66ns (10m), and the reflectivity is -13dBZ, corresponding to heavy fog. The plot on the left is at 1600m range, and the plot on the right is at 900m range.

4. CONCLUSIONS

Aircraft wake vortices are an important factor in determining safe following distances for aircraft in the terminal area. Currently, fixed spacings are used without regard to actual vortex behavior, which changes with ambient conditions. There is a potential for significant airport efficiency improvement if spacings can be adjusted dynamically based upon predicting and detecting vortex behavior. A 35 GHz, pulsed-Doppler radar system, has the potential to function as a low-visibility sensor for wake vortices and for remote wind measurement. The Wake Vortex Radar can be used in field studies to learn about wake vortex behavior and to further develop a foul weather sensor to support development of a system that regulates following distances based on airport conditions.

Two numerical radar system models have been used to investigate the method of detection, the resolution requirements for range and azimuth, pulse compression, and performance prediction. Long pulse methods derived from Lidar vortex detection techniques do not work well for the radar, providing poor estimations of location and circulation. Simulations applying pulse compression techniques predict good detection in medium to heavy fog (-15 to -17 dBZ) to greater than 2000 m. Both compressed and uncompressed short pulses show the vortex structure. While pulse compression can be used to lengthen the pulse used for wakes, the technique is limited by leakage of the ambient wind signal from neighboring range cells.

To explore operational challenges, siting at San Francisco International airport was considered. Simulation results indicate that excellent wake vortex detection, tracking and classification is possible in drizzle (+15 dBZ) and heavy fog (-13 dBZ) using short pulse techniques at ranges on the order of 900 m. At 1600 m, the approximate range required for the site chosen at San Francisco International, detection can be expected at reflectivities as low as -13 dBZ (heavy fog). The radar system, as designed, will support field studies of a wake vortex spacing system in low-visibility conditions ranging from heavy fog to rain, when sited within 2000m of the flight path.

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