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Robust Low Cost Airport Wake Vortex Sensor

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A conventional Radar Acoustic Sounding System atmospheric profiler has been converted into a wake vortex sensor that can detect, track, and measure aircraft wake vortices under all weather conditions. The resulting wake vortex sensor has been operated automatically with real-time processing at New York's Kennedy International Airport, where wakes from aircraft in all weight classes were detected. Comparisons with other wake vortex sensors are presented and show consistent vortex tracking with a very low false alarm rate. Possible applications of the sensor to wake vortex avoidance systems are discussed.

I. Introduction

AIRCRAFT wake vortices may be dangerous to following aircraft during landing and takeoff. Since the advent of jumbo jets in the 1970s, the Federal Aviation Administration (FAA) imposed three- to six-mile minimum spacings between leader and follower aircraft, depending on aircraft weight category. These spacings are overly conservative most of the time, causing airport delays and reduced capacity, particularly in bad weather. Based on simulations,[1] the FAA has projected airline savings of $5 billion a year if spacings could be safely reduced by 30 s during high airport traffic periods (because vortices often decay quickly or are rapidly moved out of the glide path by crosswinds).

A. Sensor Application

Wake vortex sensors can play various roles in mitigating the wake vortex hazard.

1) Data can be collected on the behavior of wake vortices. Such data can be used to optimize separation standards and procedures for avoiding wake vortex encounters. Another application is to develop algorithms for defining weather conditions when wake vortex separations can be reduced.

2) Real-time wake vortex sensors can be used to demonstrate the safety of new separation standards and procedures and thereby facilitate user acceptance.

3) Dynamic wake vortex separation systems attempt to adjust aircraft spacings according to the current weather conditions and an understanding of how safe spacings vary with weather conditions. Such systems will require a real-time wake vortex sensor to assure that the assigned spacings (assumed to be safe based on prior observations) are, in fact, safe.

B. Sensor Requirements

Many sensor technologies for detecting and measuring vortices have been studied and evaluated over the last 25 years, including microwave and millimeter wave radar, sodar, lidar, and anemometer-based ground wind lines.[2] Each falls short with respect to a subset of the following: vortex detection sensitivity, vortex track capability, all-weather operation, automatic operation, real-time measurement, airport operational constraints, and cost. This paper presents tests at Kennedy International Airport (JFK) that have shown that a Radar Acoustic Sounding System (RASS) wake vortex sensor satisfies all of the preceding criteria. The RASS vortex sensor has detected, tracked, and measured vortex strength of small, large, and heavy arriving aircraft under all weather conditions.

II. RASS Vortex Sensor

A. Principle of Operation

Radar backscatter from clear air is the result of small natural fluctuations of the air's index of refraction. Because the air's refraction index is a function of density, an acoustic signal, which consists of a spatial pattern of condensations and rarefactions, produces in situ refractive index variations. Radar pulses reflect from these acoustically induced variations, enhancing clear air radar return by more than 40 dB. The RASS technique was developed at Stanford University in the 1970s[3–5] and is currently used to obtain vertical temperature profiles of the lower atmosphere.

Figure 1 illustrates a (cylindrical) vortex within a transverse RASS resolution volume. Figure 2 illustrates schematically how vortex rotation affects the acoustic beam. In the presence of a vortex, some segments of the acoustic wave front speed up whereas others slow down, depending on location within the vortex. This results in a radar Doppler spectrum that is a mapping of the vortex's line-of-sight velocity distribution. The sensor calculates vortex circulation (strength) using the Betz vortex model outside the vortex core.[6]

B. Sensor Design

The RASS vortex sensor was developed from a conventional 915-MHz RASS atmospheric profiler.[6,7] Modifications include a new radar receiver, improved radar transmitter, new acoustic radiators, new displays, and significantly expanded software and signal processing. The details of the hardware and software changes are documented elsewhere.[6] This paper will present field test results.

The RASS vortex sensor measures the spectrum of the RASS return every 2.5 s. Processing algorithms convert the spectrum into an estimate of vortex circulation under a number of simplifying assumptions.[6]

RASS coverage is dictated by the overlap of the radar and acoustic beams. Testing to date has utilized a single radar beam with multiple displaced acoustic beams to account for the well-known translation effects of crosswind on the return signal location. Additional radar

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beams can be added to obtain greater coverage and/or better angular resolution on vortex location. Operation at elevation angles less than half the angular beam width can lead to ground clutter problems.

Radar range gates localize the vortex in range. The smallest range gate is 45 m [limited by Federal Communications Commission (FCC) radar bandwidth regulations]. The relatively coarse range resolution means that both vortices may be detected in the same range gate. Although theoretically feasible, present processing algorithms do not distinguish the rotational sense of the vortex and hence determine which vortex is being detected in a particular range gate.

Figure 3 shows a typical RASS test configuration, where the beam was oriented perpendicular to the aircraft approach path near the middle marker (typical aircraft height of 60 m). The radar and acoustic antennas were located 120 m from the extended runway centerline and the elevation angle was 12 deg. Note that, with this single-beam test configuration, vortices are generated above the RASS beam and cannot be detected until they descend into the beam. Slowly descending vortices drifting toward the RASS will eventually be too high to be detected, whereas vortices drifting away from the RASS may drop below the beam coverage. More complete coverage could be achieved by 1) using multiple narrower beams and 2) locating the antennas farther from the extended runway centerline.

C. Operational System Features

The most recent RASS deployment in October 1998 incorporated a number of features required by an operational system.

1) The RASS radar beam detected aircraft arrival in real time. The processing software transmitted an arrival message over the data collection network where it was logged along with the other aircraft detectors: Mode-S receiver, lidar range finder, and an acoustic noise sensor.

2) Measured vortex circulation in each range gate was calculated and displayed in real time.

3) One of the drawbacks to the present RASS is the sound level required to obtain good signal-to-noise ratios. To minimize annoyance from the sensor's acoustic emission, an aircraft passing through the RASS radar beam automatically activated acoustic radiation for 180 s during which time the RASS sensor could detect, measure vortex strength, and track vortices in six range gates. Acoustic annoyance can be further minimized by limiting sensor operation to periods of high airport traffic when aircraft separations are a safety and capacity issue. During high traffic periods, aircraft generated noise would be much louder than RASS acoustic radiation. (In a new RASS, it is possible to reduce radiated acoustic power from 100 to 10 W and increase average radar power increased from 10 to 100 W with no change in performance.)

III. 1994–1995 Test Results

In 1994 the Volpe National Transportation Systems Center (part of U.S. Department of Transportation) was tasked by the FAA to evaluate the capabilities of the RASS vortex sensor. For this purpose Volpe installed a Wake Vortex Ground Wind Line perpendicular to the extended 31R runway centerline at JFK Airport, in close proximity to the RASS vortex sensor, which was located 170 m from the extended runway centerline.[8] The Wind Line monitored lateral vortex motion over a distance of ±107 m from the extended runway centerline with vertical wind and crosswind anemometers mounted on 9-m poles. The locations of the two vortices were taken as the poles showing the highest and lowest crosswind. Note that the Wind Line can detect vortices only when they are no higher than 30–40 m from the ground.

Figure 4 shows a typical plot comparing wind-line vortex position with RASS circulation in each of four range gates.[9] The features of this complex plot will be described in sequence.

1) The x axis is the vortex age in seconds.

2) The main y axis is the lateral distance from the RASS location.

3) The boxes and x are the wind-line locations of the two wake vortices. Note the 15-m resolution, which is the wind-line pole spacing.

4) The lines labeled with Range Gate numbers are the lower limits of each range gate (range gates do not overlap). In other words, Range Gate 1 extends from 90 to 150 m.

5) The calculated circulation for each range gate[6] is plotted on a y axis starting at the lower limit of the range gate. The width of the range gate corresponds to 300 m^2/s. The observed peaks in circulation more or less correspond to the time a vortex is centered in the range gate, as would be expected.

The RASS was operated at three elevation angles: 9, 12, and 15 deg. The 9-deg elevation angle (as in Fig. 4) gave the best correlation between wind-line and RASS vortex tracking. The higher elevation angles missed more vortices, presumably because they were below the RASS beam.

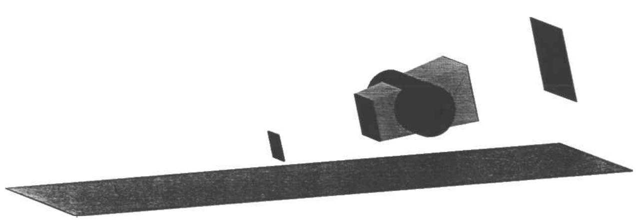

Fig. 1 Vortex within a transverse RASS resolution volume.

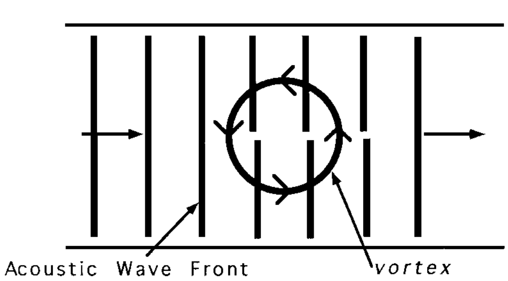

Fig. 2 Vortex effect on the RASS acoustic wave front.

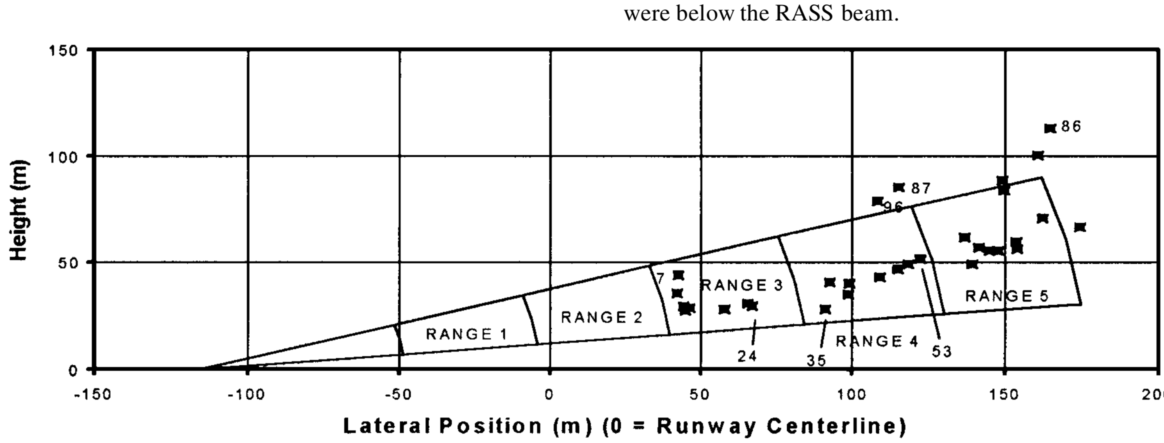

Fig. 3 RASS configuration in November 1996 at JFK. Data points labeled with vortex ages compare lidar vortex trajectory to RASS range bins.

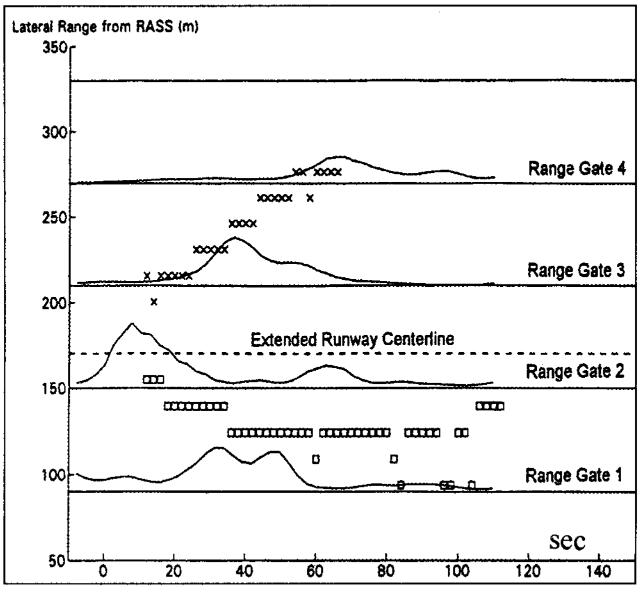

Fig. 4 Sample B-747 run from 1994 test (9-deg elevation angle).

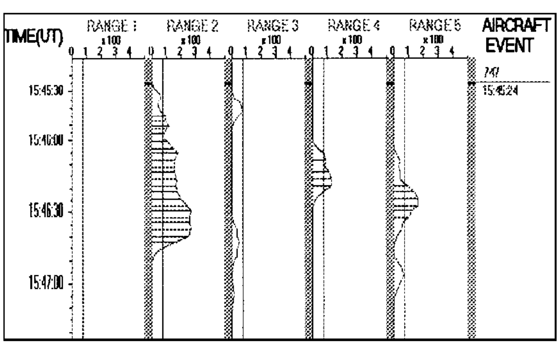

Fig. 5 RASS data for B-747 run 294 on 20 November 1996.

The RASS had a few false vortex detections because of strong wind gusts and turbulence where the Wind Line also gave false detections. In the 1998 tests, false alarms because of wind gusts and turbulence were eliminated.

In 1995 tests, vortex data were collected under rain, fog, and high wind conditions. The data again showed that RASS radar range gates with vortex detections correlated with Ground Wind Line vortex locations for all weather conditions. A unique feature of RASS is that signal-to-noise ratio increases in rain and fog at all ranges because acoustic attenuation decreases rapidly with increased humidity. Because the greatest impact of vortices on air traffic flow is when instrument flight rules are in effect, a sensor whose performance does not degrade in inclement weather is an important operational feature.

IV. 1996 Test Results

The 1996 test included a continuous wave (cw) lidar that could track vortices in both height and lateral position. One B-747 run was selected to verify that the RASS detections occurred when the lidar-detected vortex was located at the correct RASS range and angle. Figure 5 shows the RASS data for the selected run, which was unique in having signals in Ranges 2–5. The lidar vortex locations were also unique for this run, showing vortex heights above 100 m. Figure 3 shows the lidar location data plotted on top of the RASS range bin locations. The vortex age (seconds) is indicated for some of the lidar locations.

The interpretation of the consistency between Figs. 3 and 5 depends on a number of assumptions.

1) The lidar measured only the port vortex. The Wind Line showed that the starboard vortex remained close to the runway centerline until age 80 s. The starboard vortex near the runway centerline gives the signal observed in Range 2 in Fig. 5.

2) The RASS appears to track the port vortex across Range Gates 3–5, making the transition from Range 3 to 4 at about 27 s and from Range 4 to 5 at about 54 s.

The data from the two sources are consistent.

1) The transitions for Ranges 2 and 3 and 4 and 5 occur at the correct ages.

2) The port vortex lingers and weakens in Range 5, finally moving out of the RASS beam.

3) The port vortex signal remains small until it is near the Range 3 and 4 boundary. Perhaps the initial signal is small because the vortex is on the boundary between Ranges 3 and 4.

V. 1998 Test Results

In October 1998 concurrent RASS, Wind Line, and pulsed lidar measurements were made at the JFK test site. Arriving aircraft types were identified using the Mode-S squitter for domestic aircraft and the airport arrival logs for foreign aircraft. Figure 6 shows the ambient crosswind for the two test days presented in this paper.

A. Exit Time

The RASS radar antenna was located 220 m from the extended centerline of JFK runway 31R. The start time of the first RASS range gate was delayed, so that the boundary between Ranges 2 and 3 coincided with the extended runway centerline. Because each gate had a width of 45 m, Ranges 2 and 3 together comprise a safety corridor of ± 45 m with respect to the runway centerline, a definition that is used in the Volpe Center's Vortex Advisory System[10] and NASA's Aircraft Vortex Spacing System.[11] A key parameter of both dynamic spacing systems is the safety corridor exit time.

For the purposes of this paper, corridor exit time was defined as the time at which both vortices departed the safety corridor, i.e., when measured vortex circulations dropped and remained below 37 m^2/s inside the corridor. In the event that neither vortex was detected inside the corridor, exit time was defined as the time at which the first vortex was detected outside the corridor.

Figure 7 shows corridor vortex exit times for large and heavy aircraft landing on each of the two test days. Note that exit times were generally much shorter on 22 October than on 21 October. Note also that on 21 October some vortices bounced back into the RASS beam after first descending below. All nine vortex bounces occurred around 2:00 p.m. when the crosswind began to oscillate between positive and negative velocities (Fig. 6).

Figures 8 and 9 compare the exit times measured by the Wind Line and the RASS for 21 and 22 October, respectively. As in Fig. 7, exit times were much shorter on 22 October. Exit time values were obtained for the Wind Line for only two-thirds of the RASS cases, presumably because the Wind Line can detect vortices only if they are near the ground. The correlation in exit time values for the two

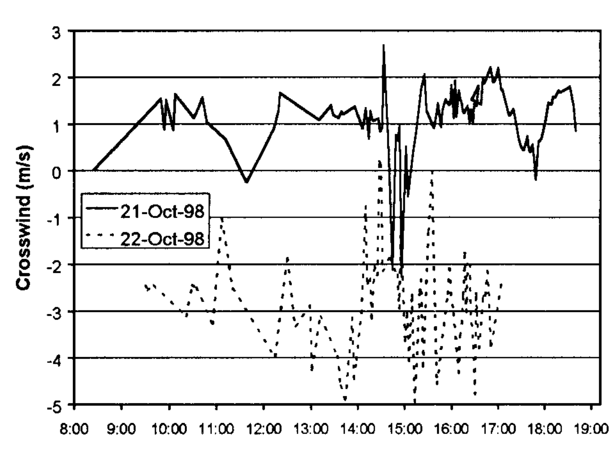

Fig. 6 Crosswind component for two test days.

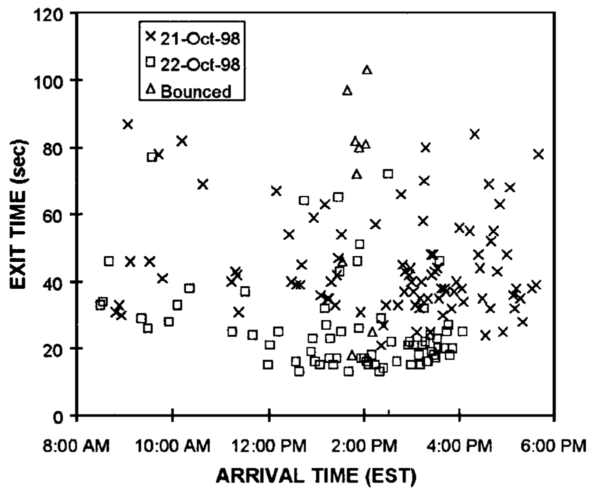

Fig. 7 Exit times for large and heavy aircraft on 21 and 22 October 1998.

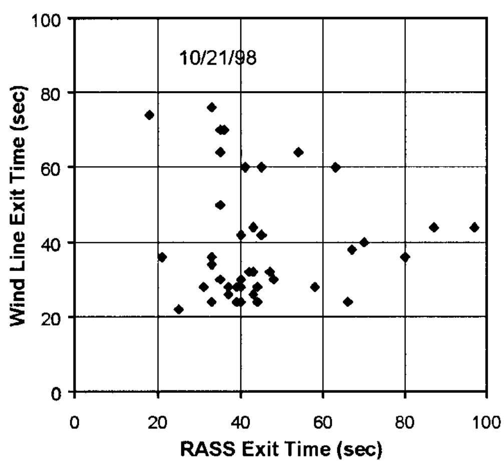

Fig. 8 Comparison of RASS and Wind Line exit times on 21 October 1998 (one RASS point off scale at 139 s).

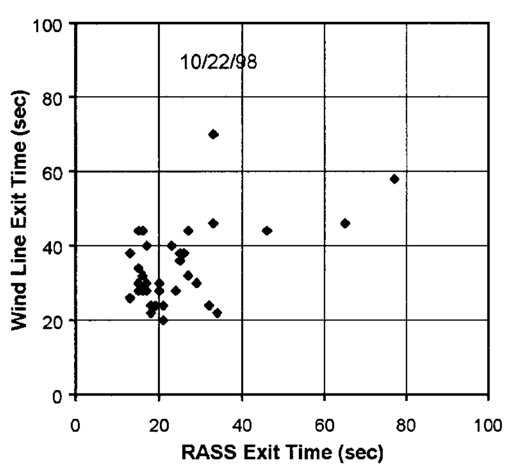

Fig. 9 Comparison of RASS and Wind Line exit times on 22 October 1998.

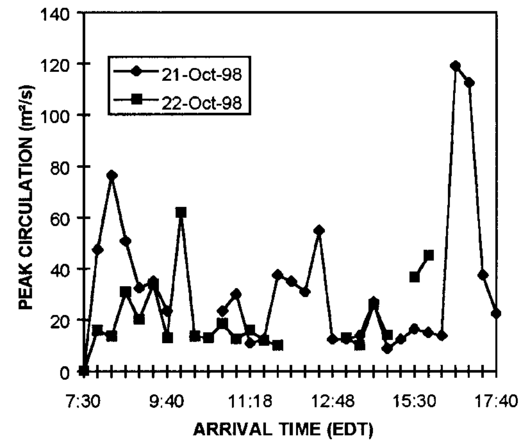

Fig. 10 Peak circulation of Jetstream 4101 aircraft.

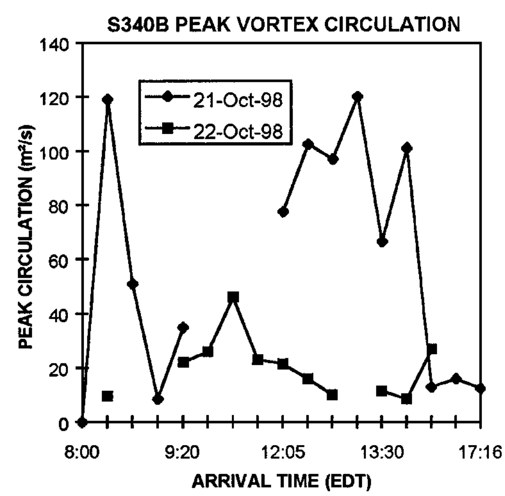

Fig. 11 Peak circulation of Saab 340B aircraft.

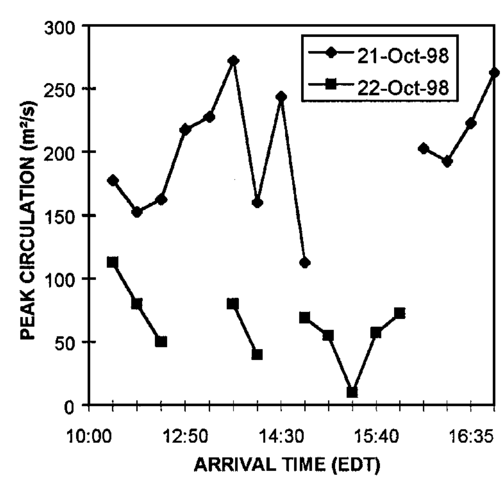

Fig. 12 Peak circulation of B-757 aircraft.

sensors is not impressive, probably because of differences in spatial coverage and sensitivity for the two sensors.

B. Circulation Data

Circulation data for 21 and 22 October 1998 have been plotted in several ways. Figures 10 and 11 show peak wake vortex circulation for Jetstream 4101 and Saab 340B (both small aircraft) and illustrate the sensor's high detection sensitivity. Figures 12 and 13 present similar data for B-757 and B-767 arrivals, respectively. A gain constant in the circulation algorithm was selected after the October 1998 tests to provide a reasonably good fit between calculated circulations and the recorded circulation measurements. More precise circulation values will require RASS sensor calibration by another sensor that can measure circulation, e.g., a lidar.

Figures 10–13 show significantly different circulation values on the two test days (lower and more stable on 22 October). The lower values on 22 October are likely caused by the rapid vortex transport on that day away from the RASS (negative crosswind in Fig. 6); the

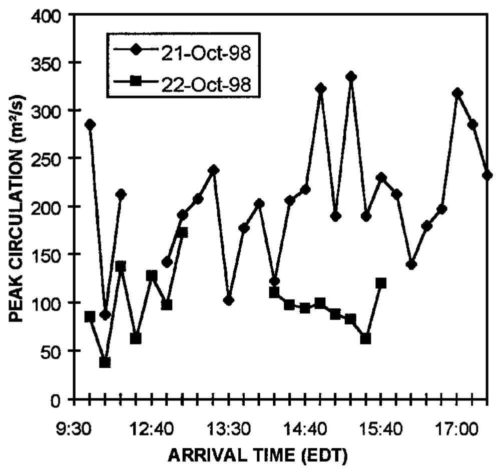

Fig. 13 Peak circulation of B-767 aircraft.

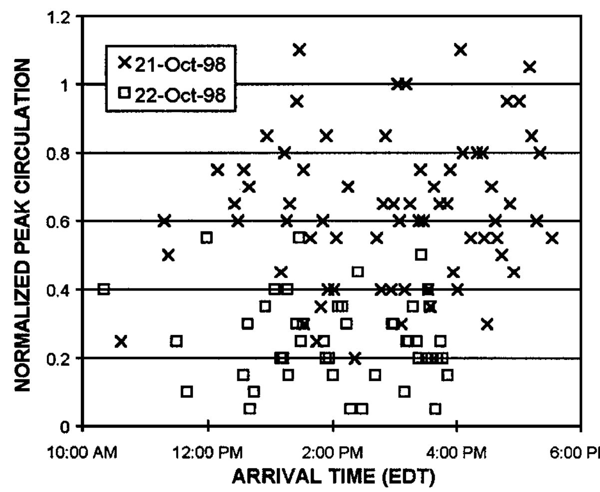

Fig. 15 Normalized peak circulation for large/heavy aircraft.

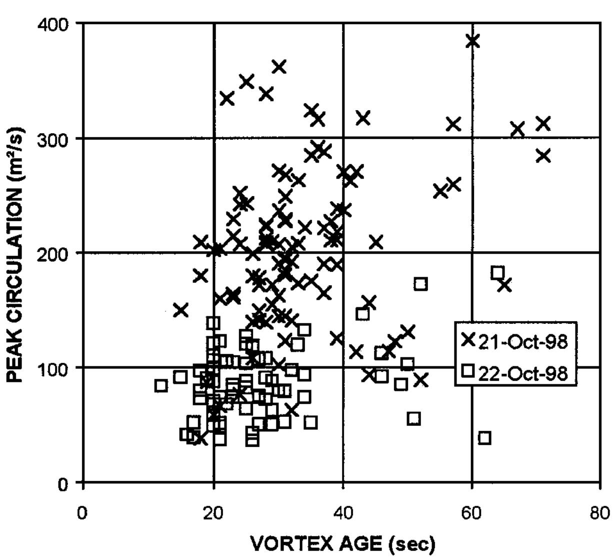

Fig. 14 Peak circulation vs vortex age for large/heavy aircraft.

vortices may not have reached the center of the RASS beam before being transported out of the safety corridor. Figure 14 provides more information concerning this hypothesis by plotting peak vortex circulation against the vortex age when the circulation was measured. The majority of the peak circulation values were at larger ages on 21 October than on 22 October, giving some support to the hypothesis that the lower peak circulation values on 22 October were related to rapid transport away from the runway centerline.

Knowing the aircraft type made it possible to calculate the theoretical vortex circulation for each arrival, derived from its wingspan, maximum landing weight, and an assumed aircraft speed at the middle marker. With this information, each arriving aircraft's normalized circulation was computed by dividing its measured circulation by its theoretical circulation. Normalization removes the effect of aircraft size.

Figure 15 shows normalized peak circulation for all large and heavy aircraft that landed on each test day. Normalized peak circulation hovered around 0.7 on the first test day and around 0.2 on the second. By combining real-time Mode-S data with RASS vortex data, the normalized circulation for each arriving aircraft can be fed back in real time to an automated aircraft spacing system to verify vortex strength predictions.

VI. Other Applications

The RASS sensor sitings used for the tests reported here were not optimal for operational use but were selected to allow for comparisons with other wake vortex sensors. Two additional locations where the sensor's unique characteristics would be useful are:

1) Vortex measurements near the outer marker (500-m altitude) where little data on vortex behavior exist. The RASS could be pointed vertically, using sound shields to minimize the impact of sound on the neighborhood. The range gates would track vortex descent. Three beams across the approach path would give lateral tracking.

2) A wide fan-beam RASS could track vortices generated on takeoff. The variability of aircraft height on takeoff requires that a large volume of space must be monitored for wake vortices.

VII. Conclusions

The tests described in this paper have shown that a RASS vortex sensor has detected, tracked, and measured vortex strength of small, large, and heavy aircraft landing at JFK International Airport in all weather conditions with a low false alarm rate. Sensor capabilities satisfy requirements for planned automated wake vortex avoidance systems. Completely automatic RASS operation has been successfully demonstrated. Annoyance from RASS-radiated acoustic signals has been minimized by limiting acoustic radiation to a 180-s period following aircraft passage through the sensor's radar beam. Further reduction is possible.

Acknowledgments

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References

[1]Baart, D., Rovinsky, R. B., Monk, H., and Schweiker, M., "Effect of Reduced Intrail Separations on Capacity," Rept. DOT-VNTSC-FAA-92-7.1, Volpe National Transportation Systems Center, Cambridge, MA, Oct. 1991.

[2]Hallock, J. N., "Aircraft Wake Vortices: An Assessment of the Current Situation," Rept. DOT-VNTSC-FAA-90-6, Volpe National Transportation Systems Center, Cambridge, MA, Jan. 1991.

[3]Marshall, J. M., "A Radio-Acoustic Sounding System for the Remote Measurement of Atmospheric Parameters," SU-SEL-70-050, Radioscience Lab., Stanford Univ., Stanford, CA, 1970.

[4]Marshall, J. M., Peterson, A. M., and Barnes, A. A., "Combined Radar-Acoustic Sounding System," *Applied Optics*, Vol. 11, 1972, pp. 108–112.

[5]North, E. M., Peterson, A. M., and Pang, H. D., "RASS, a Remote Sensing System for Measuring Low-Level Temperature Profiles," *Bulletin of the American Meteorology Society*, Vol. 54, 1973, pp. 912–919.

[6]Rubin, W. L., "Radar-Acoustic Detection of Aircraft Wake Vortices," *Journal of Atmospheric and Oceanic Technology* (in press).

[7]Rubin, W. L., "Glide Slope Surveillance Sensor," U.S. Patent # 5,208,600, 1993.

[8]Abramson, S., and Burnham, D., "Ground-Based Anemometer Measurements of Wake Vortices from Landing Aircraft at Airports," *AGARD Conference Proceedings 584, The Characterization and Modification of Wakes from Lifting Vehicles in Fluids*, 1996, pp. 13-(1–7).

[9]"Performance of RASS Vortex Detection/Measurement System," Rept. DOT-VNTSC-FAA-99-10, Volpe National Transportation Systems Center, Cambridge, MA, June 1999.

[10]Spitzer, E. A., Hallock, J. N., and Wood, W. D., "Status of the Vortex Advisory System," *Proceedings of the Aircraft Wake Vortices Conference*, Rept. FAA-RD-77-68, Volpe National Transportation Systems Center, Cambridge, MA, 1977, pp. 326–334.

[11]Hinton, D. A., "An Aircraft Vortex Spacing System (AVOSS) for Dynamical Wake Vortex Spacing Criteria," *AGARD Conference Proceedings 584, The Characterization and Modification of Wakes from Lifting Vehicles in Fluids*, 1996, pp. 23-(1–12).