Acoustic Backscatter Radar System for Tracking Aircraft Trailing Vortices

Martin Balser,* Charles A. McNary,† and Arthur E. Nagy‡
Xonics, Inc., Van Nuys, Calif.

The safety hazard posed by potential encounters with invisible vortices from preceding aircraft imposes stringent limitations on aircraft spacing in the terminal area, hence on traffic-handling capacity. An acoustic backscatter radar system has been developed to detect and track such vortices, and thereby to provide the information for more advanced air traffic procedures that would eliminate the uncertainty and delay caused by vortices. The system is fully engineered and operates in real time. Examples of the real-time display and of vortex tracks from Boeing 747's landing at the Los Angeles International Airport are given in the paper.

I. Introduction

THE trailing vortices behind large aircraft pose a serious threat to lighter following aircraft, particularly around airports where the traffic density is high. The introduction of the jumbo jets, including the Boeing 747, Lockheed C-5 and L-1011, and Douglas DC-10, has made the threat particularly acute. The crash of a DC-9 in July 1972, ascribed to vortex activity,[1] attests dramatically to the fact that the threat is not restricted to small private aircraft. Measures taken to reduce the probability of dangerous vortex encounters for aircraft during the landing and takeoff operations at busy airports can have a serious detrimental effect upon the utilization efficiency and traffic-handling capacity. The measures include wide lateral spacing of parallel runways for independent operations, extended spacing of aircraft at high-density airports, with possible extra limitations on small aircraft operating intermixed with large commercial flights.

The circulation in a vortex represents the energy imparted to the atmosphere by the airplane due to induced drag, and is proportional to lift. The vortex is thus an essential phenomenon associated with aircraft flight. Vortex decay as well as its motion are affected by atmospheric conditions, especially atmospheric wind, and vortex structure and decay also depend strongly on airplane characteristics, e.g., trim, engine location, control surface angles, etc. Accurate prediction of the structure, intensity, and location of aircraft wake turbulence is not possible at present.

The areas of greatest concern are the approach and takeoff lanes in the vicinity of airports. Here the high traffic density and low altitude that limits the ability to recover from a vortex encounter combine to produce the most serious threat to safety. In order to achieve a higher utilization of airport runways and air space while assuring protection against vortex hazards, it is therefore essential to know the position and hazard of vortices along the flight path in the terminal area.

Several techniques have been proposed to detect these vortices, including acoustic,[2,3] laser,[4] and some passive[5] methods. We believe the most promising of these techniques to be that of acoustic radar, in particular radar based on acoustic scattering by inhomogeneities in the vortex flow. This approach yields a signal whose frequency content can be related to the velocities of the scattering medium, which in turn allows estimation of both the strength of the vortex and its location.

The authors have been active in the development of Doppler acoustic radar systems for vortex warning for over three years. During this period, much of the emphasis has been on bistatic configurations (wherein the radar transmitter and receiver are separated, and the scattering angle is therefore less than 180°). Extensive tests during this period have, in addition to demonstrating the capability of such a system to detect, track, and estimate the strength of vortices from a wide variety of aircraft, yielded a large body of information on the characteristics of the vortices themselves.[2]

Certain theoretical considerations prompted our early emphasis on the bistatic, or oblique scattering, approach and inhibited any major attempt at developing a monostatic acoustic radar, i.e., one in which the receiver is colocated with the transmitter, although it is difficult to estimate quantitatively the penalty incurred according to the theory by backscatter relative to oblique scatter. The few experimental attempts that we made in conjunction with earlier tests in 1971 did in fact yield substantial backscatter returns, although lack of accurate calibration prevented a quantitative comparison with forward scatter returns at that time.

Numerous technical advantages accrue to a backscatter system compared with a bistatic system, including a much shorter range to target, with correspondingly higher spatial resolution and signal strength. The logistics are also much simpler, since passage of information, including synchronization signals, between widely separated sites is eliminated. The real-estate problem is greatly eased in that only one site is required, and that along the runway extension rather than off to the side. In addition, some scanning capability along the flight path is facilitated. Finally, and by no means least, the cost of constructing and maintaining a single site is lower than that associated with multiple sites. These potential advantages led to the decision to develop and test a full-scale engineering prototype backscatter system with a real-time display, so that a realistic evaluation of its performance could be obtained.

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*Senior Vice-President.

†Manager, Acoustic Sensing Group.

‡Assistant Manager, Acoustic Sensing Group.

II. Technical Background

An aircraft in flight generates the needed lift by accelerating air downwards. The velocity shear between the outside air (beyond the wing tips) and that with a downward velocity component results in a pair of vortices that is left trailing along the flight path. Another description considers the pressure system around a finite lifting wing. The pressure below the wing exceeds that on the upper surface. Near the wing tip the air tends to flow from the bottom around the tip to equalize the pressure. The resulting circulation contributes to the vortex. A more detailed discussion of this, with graphical aids, can be found in Goldstein.[6]

Several qualitative features of the vortex history might be noted. After a very short transition region, a vortex core is formed somewhat inboard of the wing tip. It has a diameter of the order of 1 m or more for large aircraft. A rotating flow in approximately solid-body motion and, in the absence of engine exhaust entrainment, an associated low pressure and temperature region exist within this core. There is also an axial velocity component. The flow is in some sense turbulent, although radial velocity perturbations are likely to be strongly suppressed by the rapid rotation (since turbulence tends to be dampened by stretching of vortex lines). Outside of the core, the rotational velocity decreases with increasing radius. In the classical model, the region outside the core is in potential flow so that all the circulation is contained in the core; in fact, the circulation may increase slowly with increasing radius, depending on the specific actual radial dependence of velocity.

In addition to the air in the immediate vicinity of the wing tip, some of the turbulent boundary-layer flow over the wing and the hot turbulent exhaust from the jet engines can eventually become part of the vortex system. This also is true of any secondary vortices (as from the flaps or horizontal tail surfaces). Boundary layers from the body surfaces are also within the induced velocity field of the tip vortices, and roll up to add to the complexity of vortex flow. It is clear from an extensive review of the available literature that although these general ideas are understood, a detailed comprehension has not been reached.

The conventional analysis used to estimate the signal strength to be expected from the acoustic scattering by a vortex involves a first-order approximation, the result of which is an expression for the scattering cross section per unit volume $\sigma(\theta)$ in the direction θ ($\theta = 0$ for forward scatter, $\theta = \pi$ for backscatter). This expression may be given in the form[7]

$$\sigma(\theta) = 2\pi k^4 \cos^2\theta \left[\frac{\cos^2\theta/2}{c^2} E(2k \sin\theta/2) + \frac{1}{4T^2}\, \Phi(2k \sin\theta/2) \right] \quad (1)$$

where $E(K)$ = the spectrum of velocity fluctuations with wave number K; $\Phi(K)$ = the spectrum of temperature fluctuations; c = the velocity of sound; T = the temperature; and $k = 2\pi/\lambda$, with λ the wavelength of the acoustic wave. At these acoustic frequencies, velocity and temperature fluctuations are the only anticipated sources of significant, i.e., observable, scattering in the atmosphere. In particular, scattering by particulate matter is negligibly small.

The spectra $E(K)$ and $\Phi(K)$ in Eq. (1) may in general be expected to decrease with increasing K, and thus result in somewhat weaker scattering for backscatter than for lesser scattering angles. The explicit angular factors are however, more dramatic in their effect. For example, the factor $\cos^2\theta$ that multiplies the whole expression indicates that there should be no scattering at all at right angles to the direction of incidence, consistent with the physical intuition that a longitudinal acoustic wave in an isotropic medium should not excite waves with motion perpendicular to its own. More relevant to this discussion is the term $\cos^2\theta/2$ associated with the velocity fluctuations, which indicates that those fluctuations contribute nothing to the backscattered signal. As was noted earlier, however, the current state of understanding of the problem is insufficient to estimate with any accuracy the relative strengths of the temperature and velocity contributions, the second and higher order scattering contributions, or the contributions of rays that are refracted sufficiently so that scattering which occurs at an angle somewhat smaller than 180° may ultimately return in the backscatter direction.

As in numerous comparable situations, an empirical approach is frequently preferable to awaiting an improved fundamental understanding. Let us consider briefly some of the factors affecting performance of a backscatter system. Its chief technical drawback, just discussed, is the weakness by an unknown amount of the backscatter cross section relative to that for an obliquely scattered signal. In addition, the backscatter system will (as is described in Sec. III) employ a pulse modulation that incurs a further penalty of perhaps 5 or 6 db relative to the oblique CW system. On the other side of the ledger, a backscatter system installed along the approach path can reduce the range to the vortex, typically by a factor of 2. Assuming an R^3 range dependence (because of beamfilling in the direction of the vortex axis), this gives a 9 db advantage to the backscatter system. In addition, the attenuation may be reduced, depending on atmospheric conditions, by as much as 10 db compared to a bistatic system. Finally, most or all of the pulse-CW deficit may be recovered by driving the transmitter at higher power during its on time. (Heating characteristics of candidate drivers have been found to permit operation with high-power pulses and a small duty factor at a mean power virtually equal to the rated CW power.) Thus, although backscatter is intrinsically weaker than forward scatter, much (or even all) of that (indeterminate) difference may well be made up by the factors just cited. Indeed, since the signal-reducing factors in backscatter are range independent, whereas the relative gain factors, and particularly attenuation, are strongly range dependent, there is always a range beyond which the backscatter system will yield greater signals.

The preceding discussion covered the factors that determine the strength of the scattered signal. It remains now to cover the process whereby the desired information is extracted from the received signal. That processing is based on the principle of the Doppler shift imposed on the transmitted signal when it is scattered by a moving object. In this case, the scattering "object" is the inhomogeneity introduced into the acoustic beam when it encounters the temperature and velocity fluctuations of a vortex. To review the phenomenon briefly, Fig. 1 shows a scatterer S moving at a velocity $\mathbf{v}$. If the radar transmits a frequency f, the scattered signal from the scattering object is received at a frequency shifted from f by an amount f_d given by

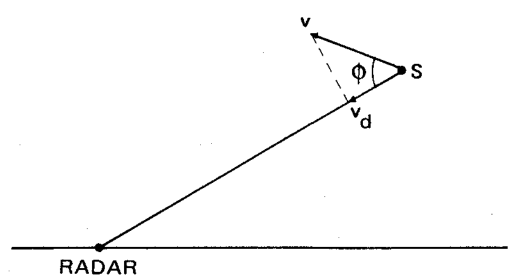

Fig. 1 Doppler velocity for a monostatic radar.

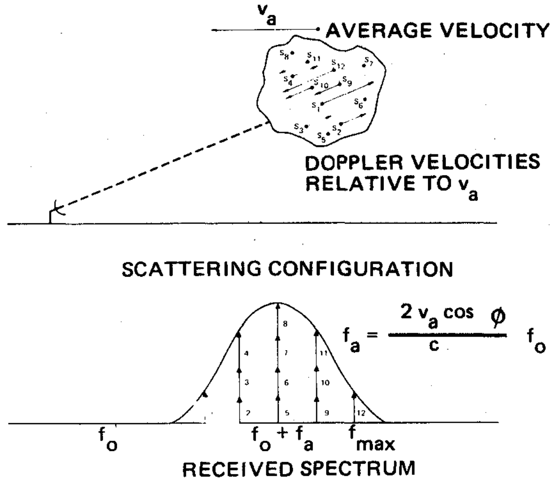

Fig. 2 Doppler spectrum for a distribution of scatterers.

$$f_d = \frac{2v_d}{c}f = \frac{2vf}{c}\cos\phi \qquad (2)$$

where c is the velocity of propagation, in this case of sound. The quantity v_d is the Doppler velocity, or that component of velocity in the direction of the radar, and ϕ is the angle between v and the direction of the radar. It is this component that determines the Doppler shift in frequency. The reader unfamiliar with scattering theory should note carefully that a scatterer moving perpendicularly to the direction from the radar to the scatterer will scatter just as strongly as a scatterer moving in another direction; the scattered return will simply be observed unshifted, at the transmitted frequency f, i.e., $f_d = 0$. Note also that the Doppler frequency f_d carries a sign, i.e., Doppler velocities toward the radar give rise to positive Doppler shifts, those away from the radar to negative Doppler shifts.

For an assemblage of scatterers moving with different velocities, the returned signal will contain components corresponding to all the Doppler velocities, giving in general a spectrum of Doppler frequencies according to the relative strengths of the scatterers with each velocity. This is illustrated in Fig. 2. This description may be taken as a crude model of a vortex, which may be considered to be a collection of small subvolumes, each moving with its local velocity. Thus, for example, in a circulating motion, the portion of the vortex in the scattering volume that is moving toward the radar gives the maximum positive Doppler shift, the portion moving away the maximum negative shift, and the rest give components in between that fill in the spectrum.

This greatly simplified model of the relation between the spectrum of the received signal and the characteristics of the vortex from which it was scattered has been extended to an idealized, but quantitative and moderately realistic, vortex and scattering model.[2] The principal assumptions were that the vortex is composed of a solid-body core, i.e., that the tangential velocity is proportional to radius out to the "core radius," and that the flow beyond that radius is potential, i.e., inversely proportional to radius; that the illuminating radar defines a circular region of arbitrary (selectable) radius; and that the scattering cross section per unit volume is the same at all parts of the vortex. The sensitivity of the results with respect to reasonable variations from these and the other assumptions was examined, and it was found that the predominant features of the calculated spectra were not substantially changed by the modifications in assumptions.

Figure 3 shows a sequence that illustrates both the calculated spectra and the observed spectra to which they were compared. The three curves depict varying cases as

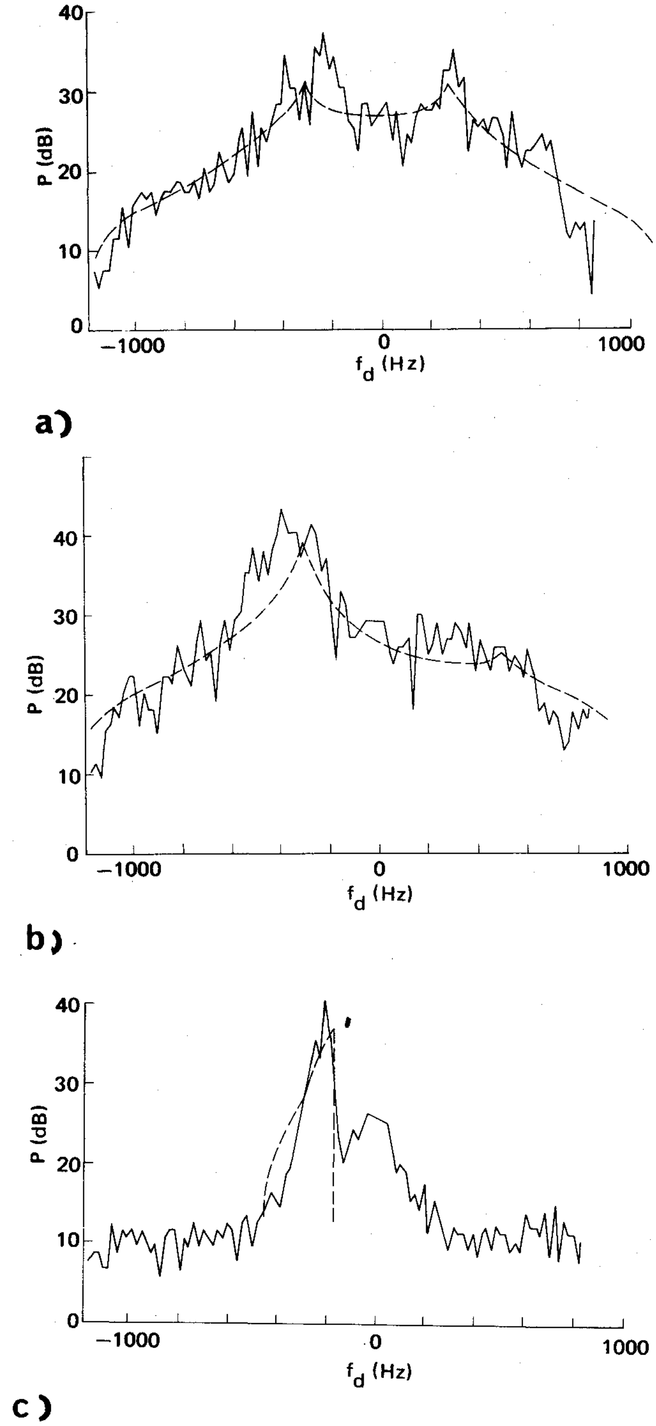

Fig. 3 Observed vortex spectrum after aircraft passage, and corresponding theoretical spectrum (dashed curve). a) t = 28.9 sec. b) t = 29.1 sec. c) t = 30.3 sec.

the vortex moves through the observation volume. In each case, the dashed curve is the spectrum calculated for a vortex core radius one-fourth as large as the radius of the observation volume. In Fig. 3a, the vortex is centered in the observation volume, and the spectrum is symmetric in upward and downward velocity. As the vortex center moves about halfway toward the edge of the observation volume, more downward than upward velocities are seen in the spectrum (Fig. 3b). Finally when the vortex is centered at nearly twice the radius of the observation volume from its center, only a relatively narrow, low-velocity contribution remains, as seen in Fig. 3c, corresponding to the tangential motion well removed from the vortex core. (The truncated feature in Fig. 3b and 3c at zero Doppler is an artifact unrelated to vortex scattering.) Figure 3 may

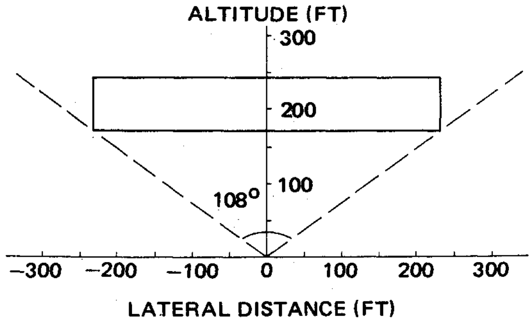

Fig. 4 Backscatter radar coverage at one station of approach zone.

be taken to illustrate both the ability of an acoustic Doppler radar to obtain spectra corresponding to the velocity structure of a vortex and the rather good match that it is possible to obtain to those spectra with an idealized model. The latter in turn allows one to interpret observed spectra in terms of vortex velocity characteristics. Reference 2 contains a far more detailed description of this analysis and data interpretation.

To summarize, Doppler analysis of signals scattered from aircraft vortices has provided spectral information that is consistent with a model of both the flow and the scattering process. The backscatter mechanism promises to provide a signal of sufficient power for use in the practical application of the sensor as an airport system. A radar that combines backscatter and Doppler analysis offers some significant potential system, logistic, and economic advantages over other proposed approaches to vortex detection.

III. Backscatter System Description

Coverage requirements for a backscatter system located at one station along the extension of an airport runway are illustrated in Fig. 4. The approach zone is indicated in the figure to be at an altitude of 200 ft, although the geometry is similar at all altitudes, so that the angular coverage requirements are independent of the altitude. The angle subtended at the radar site by the approach zone is seen to be 108°. It would appear at present that the most efficient system design would utilize two sectors of about 55° each to cover the complete sector; in this manner, the antenna designs can be greatly facilitated. For this initial demonstration, it was decided that a single section of about 55° be covered. It is clear that the complete coverage can then easily be obtained by duplicating the equipment after the performance has been evaluated in the region half the size of the desired coverage.

The test system operates as follows. A transmitting antenna radiates a single fan beam 55° long and 5° wide, which illuminates the plane perpendicular to the direction of flight. This beam is generated by a row of 10 square horns, each equipped with its own driver, all of which are operated in phase. The modulation is a pulse train, with a pulse length typically of 40 to 80 msec (corresponding to a height resolution of 20 to 40 ft) and a pulse repetition interval of about 1 sec (more or less depending on the altitude being covered).

The receiving antenna is a parabolic dish located in the immediate vicinity of the transmitting antenna. An array of microphones is employed along a line in the feed plane that generates a set of pencil beams. These pencil beams together cover the same fan-shaped region illuminated by the transmitter, but each pencil beam is examined separately to obtain the corresponding angular resolution.

A vortex that scatters energy back to the receiver is located as shown in Fig. 5. Two coordinates are required to fix the location in the plane of coverage common to the

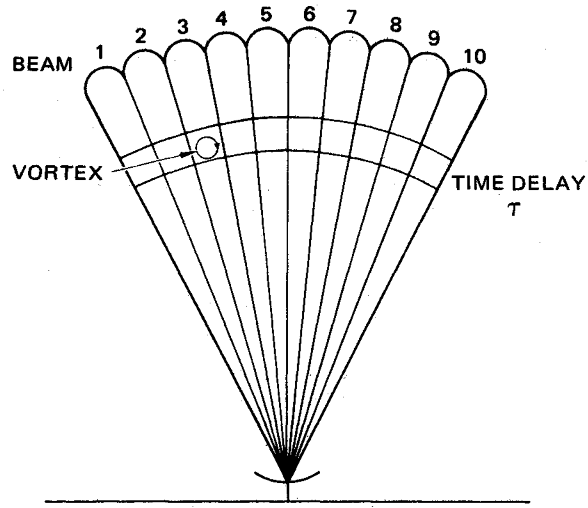

Fig. 5 Vortex location procedure.

two antennas. One of these is provided by the specific receiver beam in which the vortex is detected. The position along that beam is given by the time delay τ after the transmission of the pulse at which the scattered signal is received. In Fig. 5, the vortex is shown to be detected in beam 3 at a range determined by the delay τ. (Note that a large vortex may occupy more than one resolution cell.) It is important to bear in mind that the width of the spectrum, and not just its amplitude, is used in identifying the disturbance as a vortex, in fixing its location accurately and in estimating the hazard.

One of the vital considerations in acoustic radar systems is the design of the antennas to reduce sidelobes as much as possible. For the transmitter antenna, this minimizes the potential annoyance to people and interference at the receiver. For the receiving antenna, it minimizes the level of interference, particularly from the generating aircraft, and the time interval over which that interference is important. In order to develop improved techniques of shielding acoustic antennas to achieve low sidelobe levels, the authors have utilized an antenna pattern-

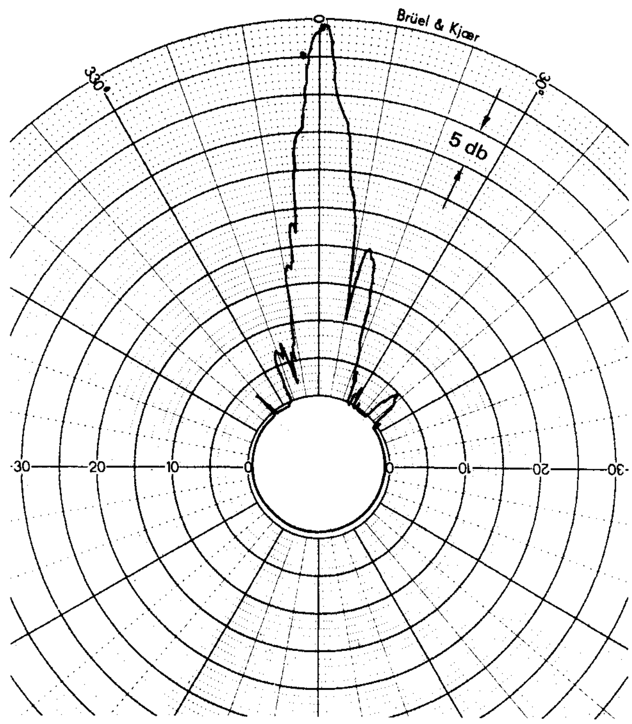

Fig. 6 Measured single-beam acoustic antenna pattern.

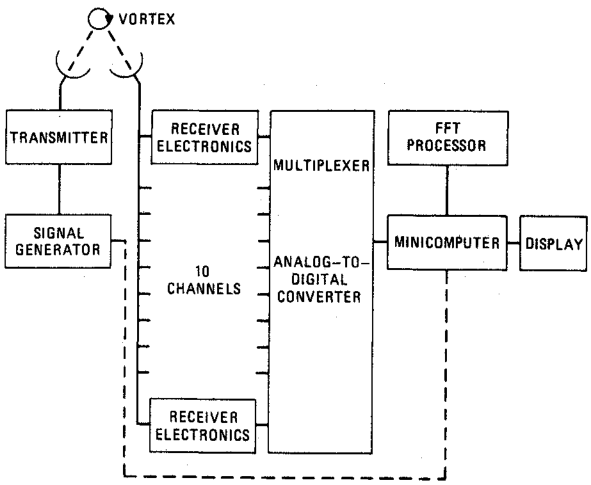

Fig. 7 System block diagram.

measuring range to experiment with new ideas and verify results. An example of a pattern recently obtained for a single-beam acoustic antenna is shown in Fig. 6. Note that virtually all sidelobes are down 50 db or more at angles more than 20° from boresight. While results are not quite so striking for similar multiple-beam antenna patterns, similar techniques assure highly efficient interference-resistant performance.

The block diagram of the system is presented in Fig. 7. The pulse modulation is radiated by the transmitter, and the timing is communicated to the processor. The ten received signals corresponding to the beams are preprocessed in the block labeled "Receiver Electronics," one to each channel. The preprocessing consists basically of amplification and filtering stages to produce at the output a signal of the desired bandwidth and voltage level. Next the channels are rapidly cycled through and a sample taken and digitized with sufficient sampling frequency to define unambiguously the spectrum passed by the filter. These digital samples are stored in memory until a block of data corresponding to the pulse length is accumulated. This step and the remainder of the processing are managed by the mini-computer. Each of the ten segments of data is Fourier-transformed by the special-purpose Fast-Fourier-Transform, or FFT, processor.

The resulting spectra are stored, and all of the spectra for a given transmitted pulse are examined to determine whether a vortex return is present. The algorithms for accomplishing this identification are based on the observed behavior of signals scattered from vortices, as described briefly in Sec. II. If vortex activity is detected, some of these signal properties, such as spectral spread and shifts, are used to establish the location of the vortex. Finally, the computer drives the display device to show the position of the vortex. All of this procedure is carried out in real time, and new position and tracking information is available with each new pulse, approximately once a second.

IV. Test Results

The system described in Sec. III was constructed during the spring of 1973. It was then installed on the approach to runway 24L at the Los Angeles International Airport. This is the runway most frequently used for landing by heavy jet aircraft, and the distance of about 4800 ft from the end of the runway corresponded to an aircraft altitude of about 275 ft.

Figure 8 is a photograph of the antenna system in place at the measurement site. The system is trailer-mounted and is easily moved into position or between sites. The smaller of the two structures is the transmitting antenna. For the tests described in this report, each of the ten drivers was supplied with 40 w of peak power during the pulse period of 60 msec. At the radiated frequency of 4.5 kHz, the driver-horn combination has an efficiency in the range of 10 to 15%, so that a total somewhat in excess of 40 acoustic w was radiated during the pulse transmission. The pulse repetition interval was 1 sec, and the duty factor of 0.06 yields an average radiated power level of about 2.5 w.

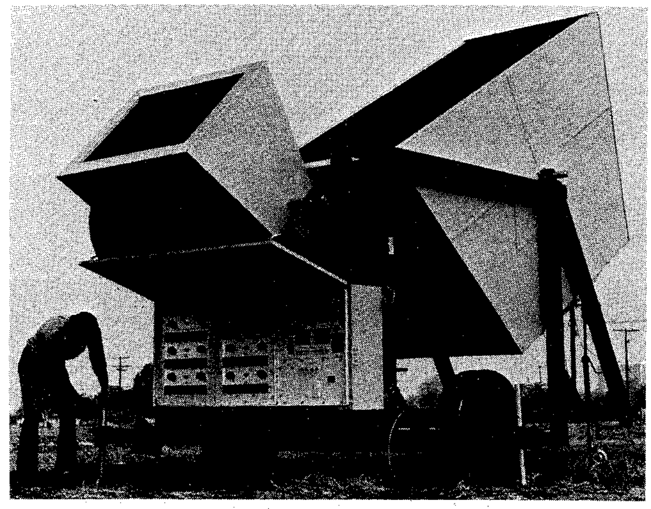

Fig. 8 Acoustic backscatter radar antenna subsystem at LAX site.

The larger of the two structures in Fig. 8 is the receiving antenna. The antenna surface is a paraboloid of 6-ft diam. As is the case with the transmitting antenna, the actual beam-forming components of the antenna are located at the base of the larger structures, most of which consists of the acoustic shield designed to minimize sidelobe interference for both antennas. The receiving antenna and some of the electronics for the transmitting antenna were designed to satisfy other configuration and range requirements in addition to the one being discussed here, and as a consequence, the equipment is not as compact and simplified as it might be if it were designed for this purpose alone. Thus, in particular, for backscatter operation to altitudes of 300 ft, the receiving antenna would be approximately one half the size of the one shown in Fig. 8.

It can also be noted from Fig. 8 that the antennas were not pointed straight up, but rather at an angle of 30° from the vertical. This was done, in view of the limited angular

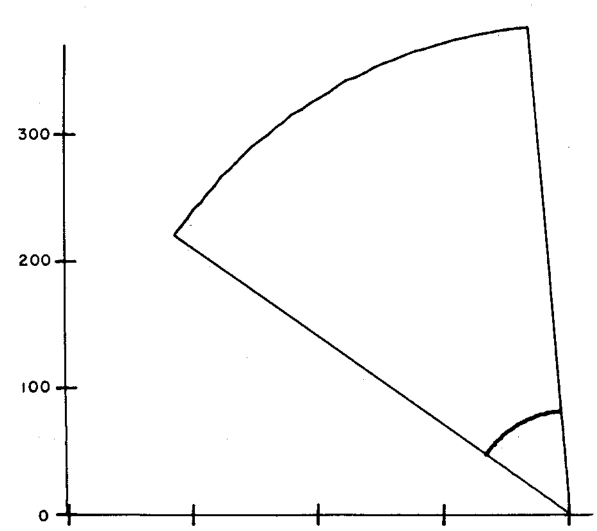

Fig. 9 Spatial radar coverage depicted on the display scope.

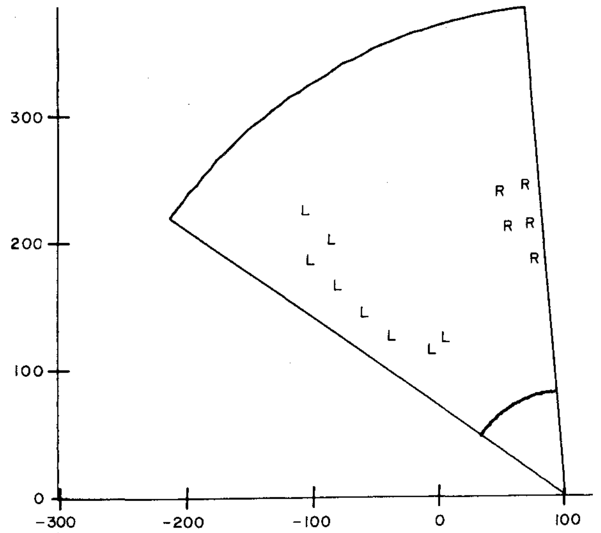

Fig. 10 Photograph of vortex tracks on the real-time display.

field of view, in order to achieve the full coverage of one of the vortices. In order that the other vortex be observed at least on occasion, the radar was displaced 100 ft off the runway extension line. The resulting spatial coverage is shown in Fig. 9, a photograph of the real-time display as it appears when the entire system begins to process the incoming data. Both height and cross-track distances are given in feet. Zero cross-range coincides with the extension of the runway centerline. The center of a landing aircraft is thus nominally above this point and, for this station, at an altitude of about 275 ft. For reference, the wingspan of a Boeing 747 is 196 ft.

This acoustic equipment and the associated real-time processing equipment have now been employed during normal landing operations of aircraft at the Los Angeles International Airport. In addition to the system components shown in Fig. 7, a 14-channel instrumentation tape recorder was used at the time of these operations to record the signals from each of the individual beams before the multiplexer and analog-to-digital conversion. This facility allows the remainder of the system to be demonstrated in pseudo-real-time (i.e., at the real-time rate but later in time) at the convenience of the viewer. More important, it provides the opportunity to the analyst to vary the parameters in the detection and decision logic and compare the results when they are applied to the same test data.

Two illustrations will suffice to demonstrate both the operation of the system and the variability of vortex motion that underlies the need for a detection and tracking system. The two flights were observed and recorded on 19 July 1973 and were both Boeing 747's. The appearance of the display during the middle of one of these vortex tracks is shown in Fig. 10. The symbols L and R stand for the left and right vortices, respectively. Since the display device is a storage tube, all the detections from the beginning of the run until the time shown appear on the screen. Each second the decision logic determines whether one or more vortices is within the field of view and, if so, the sense of that vortex, and displays the appropriate letter at the deduced locations. The flash of each new location displays the motion of the vortex very graphically when viewed in real time; for permanent records and further analysis, all of the display information is stored in the computer and can be read out at the completion of the run.

Figure 11 is a plot of the vortex tracks obtained from the stored information for the same flight illustrated in Fig. 10, which passed over the radar site just before its landing. The resolution cells shown in Fig. 11 are those determined by the receiver beams and the pulse length, and correspond to the positions of the letters displayed in

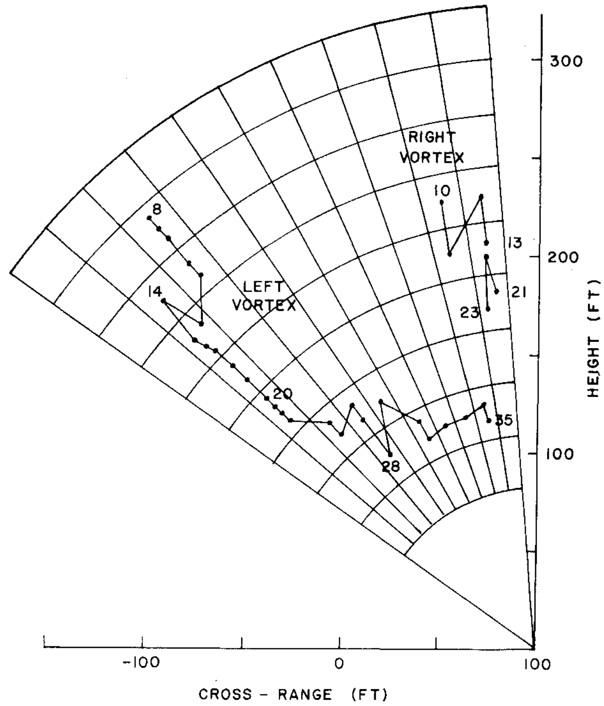

Fig. 11 Vortex tracks from Boeing 747 landing at LAX at 3:24 PM on July 19, 1973.

Fig. 10. The numbers associated with some of the track positions identify the time of vortex detection at those locations in seconds after aircraft passage overhead. It is seen in Fig. 11 that the left vortex was tracked from 8 sec (after aircraft passage) until it left the field of view at 35 sec. During this interval, a detection was made for every transmitted pulse, i.e., once per second, and no false alarms were recorded at any time during the minute of observation. The rate of descent of the left vortex during the first 10–15 sec of observation can be seen from Fig. 11 to be about 8 fps, and a lateral speed toward the right of about 6 fps is also evident.

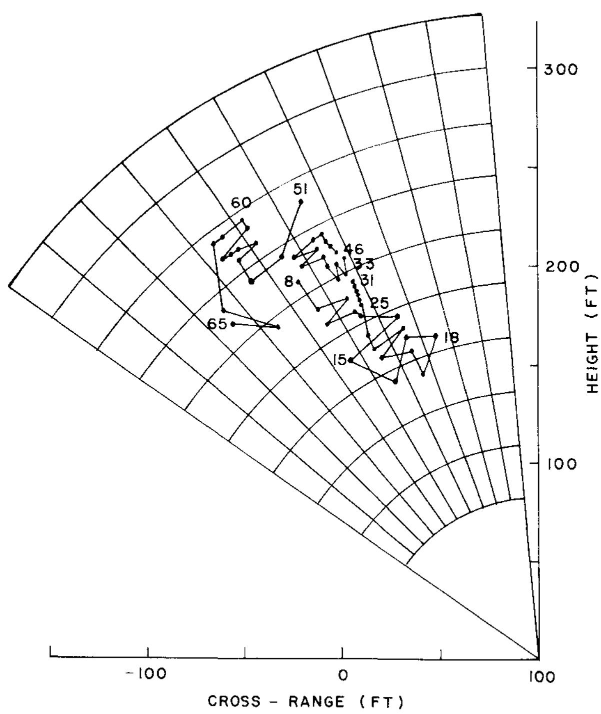

Fig. 12 Vortex track from Boeing 747 landing at LAX at 2:10 PM on July 19, 1973.

Several detections of the right vortex were made during the early part of the track separated by about 150 ft from the left vortex, which is a reasonable distance. The few later detections of the right vortex may perhaps have been made from the portion of the vortex within the field of view even though the core is just outside or from a weaker observation of the core in a sidelobe; such detections at the edge of the field of view may therefore not represent true position.

In contrast, Fig. 12 shows the track of the left vortex from another 747 that landed slightly more than an hour before the one whose tracks are shown in Fig. 11. It can be seen that the initial descent of the vortex from 8–20 sec after aircraft passage is similar to the previous example. The subsequent motion of the vortex is, however, substantially different. After 20 sec, while the vortex is still well within the field of view, it is seen to reverse its downward course and return to an altitude of well over 200 ft. The vortex remains virtually static for nearly 40 sec. (For some reason, no left vortex detections were made from 47–50 sec, and false-alarm right-vortex detections were made at the same time.) The vortex is seen finally to dissipate or drift out of the field of view 65 sec after aircraft passage. It is just this sort of unpredictable behavior that, in the absence of a confident method of determining the location of hazardous vortices, imposes conservative spacing requirements on virtually all air traffic to prevent the possibility of a dangerous encounter.

The data presented here represent part of the results of a limited test program that was conducted in July 1973. Tracks were also obtained on DC-10 and 727 aircraft that utilized the runway during the brief period of operation.

V. Summary

This paper has described the first engineered, real-time system for detecting and tracking aircraft trailing vortices. The system is a backscatter acoustic radar that utilizes the signature characteristics of Doppler shift and spread in the scattered signal to identify and locate the vortex disturbance and distinguish it from wind and other returns and interference. It has been successfully demonstrated on traffic landing at the Los Angeles International Airport, and examples of vortex tracks obtained from Boeing 747's are given in the paper.

Lacking information on vortex location other than that it is erratic and unpredictable, the only reasonable response is that currently adopted, i.e., to space aircraft so widely that the vortex can be expected to have decayed even if it is located in the path of a trailing aircraft. The cost of this approach is high in time, money, and traffic-handling capacity, but the potential cost in lives of ignoring the danger forbids any other approach at the moment. The system described here provides the required real-time information on vortex location, and thereby opens the door to new air traffic procedures that eliminate the unnecessary costs and delays, while preserving and even enhancing the safety of air terminal operations.

References

[1]"Aircraft Accident Report Delta Airlines, Inc., McDonnel Douglas DC-9-14, N3305L Greater Southwest International Airport, Fort Worth, Texas, May 30, 1972," NTSB Rept. NTSB-AAR-73-3, March 1973.

[2]Balser, M., Nagy, A. E., and McNary, C. A., "Acoustic Analysis of Aircraft Vortex Characteristics," FAA-RD-72-81, July 1972, Federal Aviation Administration, Washington, D.C.

[3]Burnham, D., Kodis, R., and Sullivan, T., "Observations of Acoustic Ray Deflection by Aircraft Wake Vortices," *Journal of the Acoustic Society of America*, Vol. 52, No. 1, July 1972, pp. 431–433.

[4]Huffaker, R. M., Jelalian, A. V., and Thomson, J. A. L., "Laser-Doppler System for Detection of Aircraft Trailing Vortices," *Proceedings of the IEEE*, Vol. 58, No. 3, March 1970, pp. 322–326.

[5]Hallock, J. N., "Pressure Measurements of Wake Vortices Near the Ground," *Journal of Aircraft*, Vol. 9, No. 4, April 1972, pp. 311–312.

[6]Goldstein, S., *Modern Developments in Fluid Mechanics*, Oxford Press, New York, 1938; also Dover, New York, 1965, Sec. 12.

[7]Little, C. G., "Acoustic Methods for the Remote Probing of the Lower Atmosphere," *Proceedings of the IEEE*, Vol. 57, No. 4, April 1969, pp. 571–578.