

USPTO PATENT FULL-TEXT AND IMAGE DATABASE

(14 of 23)

United States Patent
Rubin

5,208,600
May 4, 1993

Glide slope surveillance sensor

Abstract

A surveillance sensor for detecting and monitoring aerodynamic conditions in a vicinity of an aircraft landing glide slope utilizes a radar transmitter to illuminate the glide slope. Radar reflections from aircraft induced vortices, clear air turbulence, and glide slope cross winds are received by a monopulse radar system wherein a sum beam doppler spectrum and a difference beam doppler spectrum for the radar returns is determined. The sum and difference beams doppler spectra are processed to determine the aerodynamic conditions in the glide slope vicinity. These aerodynamic conditions are assessed to determine whether aerodynamic hazardous conditions exist in the glide slope region.

Inventors: **Rubin; William L.** (Whitestone, NY)

Appl. No.: **07/844,767**

Filed: **March 2, 1992**

Current U.S. Class:

342/26D

Current International Class:

G01S 13/95 (20060101); G01S 13/00 (20060101); G01S
013/95 ()

Field of Search:

342/26

References Cited [Referenced By]**U.S. Patent Documents**

[Re33152](#)

January 1990

Atlas

[4103300](#)

July 1978

Gendreu et al.

[4351188](#)

September 1982

Fukushima et al.

Primary Examiner: Tubbesing; T. H.

Attorney, Agent or Firm: Levine; Seymour

Claims

I claim:

1. A surveillance sensor for monitoring and detecting aerodynamic conditions in a vicinity of an aircraft landing glide slope comprising:

means for transmitting a radar signal;

monopulse means for receiving backscatter of said radar signal in range bins of predetermined length through a sum beam and a difference beam;

doppler spectrum means coupled to said sum and difference beams for providing a sum beam doppler spectrum and a difference beam doppler spectrum;

processor means coupled to said doppler spectrum means for processing said sum and difference beam doppler spectra and for providing signals representative of aerodynamic conditions; and

means responsive to said signals representative of aerodynamic conditions for assessing said aerodynamic conditions and for providing hazardous condition warning signals when hazardous aerodynamic conditions are detected.

2. A surveillance sensor in accordance with claim 1 wherein said processor means includes:

means for normalizing said difference beam doppler spectrum to said sum beam doppler spectrum to establish a normalized difference beam doppler spectrum; and

means responsive to said normalized difference beam doppler spectrum for providing a signal representative of an aircraft generated vortex elevation angle.

3. A surveillance sensor in accordance with claim 2 wherein said processor means further includes:

velocity means responsive to said normalized difference beam doppler spectrum for providing a signal representative of vortex cross wind velocity; and

location means responsive to said cross wind velocity representative signal and said elevation angle representative signal for providing a signal representative of vortex location.

4. A surveillance sensor in accordance with claim 3 wherein said velocity means includes:

means responsive to said difference beam doppler spectrum for providing a signal representative of acoustic wave azimuth deviation angle from said glide slope in each range bin;

means responsive to signals representative of azimuth deviation angles in azimuthally adjacent range bins for providing a signal representative of said cross wind velocity.

5. A surveillance sensor in accordance with claim 3 wherein said processor means further includes means coupled to said location means for providing a signals representative of vortex lateral movement rate and direction.

6. A surveillance sensor in accordance with claim 1 wherein said processor means includes vortex strength means responsive to said sum beam doppler doppler spectrum for providing a signal representative of vortex strength.

7. A surveillance sensor in accordance with claim 1 wherein said vortex strength means includes:

backscatter means responsive to said sum beam doppler spectrum for providing signals representative of clear air and vortex backscatter; and

strength means responsive to said clear air and said vortex backscatter signals for providing a signal representative of vortex strength.

8. A surveillance sensor in accordance with claim 7 wherein said processor means further includes means coupled to said strength means for time monitoring said signal representative of vortex strength and determining said vortex strength decay rate.

9. A surveillance sensor in accordance with claim 8 further including acoustic noise means for radiating acoustic noise along said glide slope such that vortex acoustic signals are enhanced and time for determining said vortex decay rate is extended.

10. A surveillance sensor in accordance with claim 7 wherein said processor means further includes means responsive to said clear air backscatter representative signal for providing signals representative of strength and location of radial wind shear.

11. A surveillance sensor in accordance with claim 7 wherein said processor means further includes means responsive to said clear air backscatter representative signal for providing signals representative of strength and location of air turbulence.

12. A surveillance sensor in according with claim 11 wherein said tracker means includes:

angle means responsive to said sum beam spectrum for providing signals representative of azimuth and elevation angles of said aircraft in each range bin;

peak means for providing a signal representative of peak amplitude of said sum doppler spectrum in each range bin, said peak amplitude being representative of backscatter from said aircraft; and

position means coupled to said angle and peak means for tracking said aircraft range bin position and azimuth and elevation angles in said range bin position.

13. A surveillance sensor in accordance with claim 12 wherein said position means includes means for providing a trigger when said aircraft is in a predetermined range bin and wherein said monopulse means includes monopulse antenna means for providing said sum and difference beams, said monopulse means including means for providing a beamwidth switchable between first and second beamwidths in response to said trigger coupled from said position means.

14. A surveillance sensor in accordance with claim 12 wherein said position means includes means for providing a trigger when said aircraft is in a predetermined range bin and wherein said transmitting means and said monopulse means include means responsive to said trigger for providing a pulse repetition rate (PRR) switchable between a first PRR and a second PRR.

measure of vortex rotational velocity or strength. The temporal and spatial rates at which vortex "Bragg" frequency declines relative to that for surrounding air is a measure of vortex decay rate.

The measured "Bragg" doppler frequency and doppler spectral width for clear air return in each range bin permits the determination of radial wind shear and turbulence as a function of range.

Azimuth arrival angle rate of change of the clear air "Bragg" signal received by the monopulse antenna is a measure of cross wind velocity. This is the result of a cross range shift of the acoustic wavefront by the cross wind.

Since the azimuth angle of arrival is a function of range for a given cross range shift, it is necessary to know the range bin in which the monopulse measurement is being made. Increased cross wind estimation accuracy can be achieved by adding two receive antennas on either side of the monopulse antenna operating as a two element interferometer to measure the rate of change of clear air backscatter azimuth direction.

The peak doppler frequency in the sum beam doppler spectrum for the range bin containing the aircraft is directly related to the radial velocity of the aircraft. The magnitude of the normalized monopulse difference beam spectrum associated with this doppler frequency is a quantitative measure of aircraft angle deviation from the monopulse antenna boresight (in azimuth or elevation depending on the mode in which the measurement was made).

When aircraft generated acoustic noise is not available to excite the glide slope, an acoustic radiator aimed up the glide slope that is colocated with the radar transmit antenna can provide alternate excitation of the glide slope and thereby permit the measurement of clear air wind shear and turbulence, but not cross wind velocity, in a manner similar to that previously described for an aircraft acoustically excited glide slope.

In addition, the auxiliary acoustic radiator permits measurements of the temperature of vortices generated by the aircraft which has just landed to be extended over a longer time period to provide a more accurate measurement of the temporal decay rate of the newly generated vortices.

It will become apparent from the description of the Preferred Embodiments that the invention:

- (1) enhances the detectability of clear air motion and vortices in arrival and departure glide slopes by amplifying and processing "Bragg" radar reflections in a glide slope that is acoustically excited by acoustic noise emanating from landing and departing aircraft;
- (2) enhances the detectability of clear air and vortex "Bragg" echoes in clutter by virtue of the large doppler difference between "Bragg" backscatter and ground clutter;
- (3) locates vortices and aircraft in azimuth and elevation in each range bin from monopulse measurements on vortex and clear air "Bragg" backscatter as well as conventional aircraft echoes, respectively;
- (4) provides an estimate of vortex rotational velocity in each range bin and its rate of decay by measuring vortex temperature and rate of decline of vortex temperature as a function of time based on vortex "Bragg" frequency measurements;
- (5) provides a spatial estimate of the rate of decay of vortex rotational velocity from the rate at which vortex "Bragg" frequency decreases with increasing range;

function of range. Since vortices form directly behind an aircraft, knowledge of aircraft position in the radar beam provides the initial location of newly formed vortices. From measured cross wind velocity in each range bin, subsequent locations in azimuth can be computed.

Radar reflections are enhanced as a result of the "Bragg" effect and, under favorable circumstances, the quasi-spherical shape of the propagating acoustic wavefronts will focus radar reflections back towards the radar transmitting antenna. The most favorable circumstance occurs when the radar and the acoustic source are co-located. In this case the backscatter is focussed onto a spot on the transmitting antenna, greatly enhancing the received echo. When the acoustic source is an aircraft displaced from the radar, the "Bragg" signal strength received by the radar is reduced. As will explained subsequently, the received signal magnitude may be estimated using geometric optics.

There are three main effects limiting "Bragg" backscatter detection range: (1) acoustic attenuation by the air, (2) crosswind displacement of acoustic wavefronts, and (3) turbulence disrupting the transverse coherence of the acoustic wavefront.

Acoustic attenuation is not important at about 100 Hz, but increases rapidly with frequency. For frequencies around 1 kHz, typical values are about 6-8 db/km and at 2 kHz the attenuation is about 16 db/km. The preferred embodiments, for illustrative purposes, utilize a radar frequency of 915 MHz, which corresponds to a "Bragg" acoustic frequency of 2.02 kHz at 0.degree. C.

Since a cross wind in the glide slope displaces vortices as much as it displaces an acoustic wave, the absence of vortex "Bragg" return in the approach corridor, due to a strong cross wind, is unambiguous. Before the acoustic wave is shifted out of the corridor by the cross wind, the transverse displacement of the acoustic wave may be measured as a function of time, thus permitting cross wind velocity to be determined.

Turbulence disturbs the transverse coherence of the acoustic wave. "Bragg" backscatter geometry, however, doesn't change substantially, even for strong turbulence. This can be explained physically by noting that the acoustic wave front can be decomposed into two parts, an unperturbed spherical wavefront and a random wavefront caused by atmospheric turbulence. The incident radar wave will be scattered by the random part producing a small background scatter level over a large solid angle. The backscatter geometry will be the same for the unperturbed spherical acoustic wave except for reduced amplitude. Local atmospheric velocity fluctuations due to turbulence will increase the doppler spectral width of "Bragg" backscatter, which may be measured to indicate the magnitude of the turbulence present.

An acoustic wave within the radar beam travels away from or towards the radar at the speed of sound, depending upon whether a range bin is in front of or behind the aircraft. Hence, a "Bragg" backscatter will have positive or negative doppler shift with a magnitude which corresponds to the velocity of sound. This large doppler shift associated with the "Bragg" return facilitates the discrimination from ground clutter returns.

Because the velocity of sound in the vortices and the surrounding clear air are initially unknown, acoustic excitation of the glide slope must encompass a band of "Bragg" frequencies in the vicinity of 2 kHz which corresponds to the velocity of sound at 0.degree. C. The spectrum of the aircraft noise easily satisfies this requirement.

The stages in a vortex life span are shown in FIG. 1. A wake vortex originates in the vorticity shed from the generating wing of the aircraft. In the planar sheet phase, wing vorticity is shed in an approximately planar sheet 1 with a width approximately equal to the span of the generating wings. Thereafter, the

sheet commences to form a self-induced scroll-like shape 2 behind the aircraft, during a phase known as vortex roll-up. Before the aircraft has moved 10-20 wing spans the roll-up process is completed, trapping practically all of the aircraft hot engine exhaust in the vortices, concentrating wing vorticity in two approximately circular cores referred to as the viscous vortex pair 3a,3b. Various interactions sometimes occur in these cores after formation, creating instabilities which cause the wake to break up rapidly. If catastrophic instabilities do not occur, the viscous vortex pair phase commences during which the cores expand under the influence of both atmospheric and aircraft-induced turbulence, as indicated by the expanded cores 4a,4b. After the viscous vortex pair phase, the final regular decay process, known as the decaying impulse stage, takes place. During this phase, the cores continue to expand to eventually merge and fill an approximately elliptical region 5 of vorticity.

Most of a vortex life span is spent in the viscous vortex-pair stage. FIG. 2 shows a viscous vortex-pair wake 6a,6b behind an aircraft with progressively increasing vortex diameters reflecting vortex aging. The preferred embodiments, to be described, detect, locate, and track vortices which remain in the glide slope after a vortex generating aircraft has passed.

FIG. 3 shows a standard aircraft landing approach. In accordance with the invention, a monopulse radar antenna is located at the threshold. A landing aircraft enters the glide slope 12 at the outer marker, not shown, and proceeds down the glide path 12 past the middle marker 13 and the threshold 11 for a landing on the runway 14. The aircraft is nominally 50 feet above ground level as it passes over the threshold. The standard landing glide slope angle is 3.degree..

Two backscatter geometries, shown in FIG. 4, are detected by the monopulse radar. The first 4-1, "Bragg" reflection from vortices generated by previous aircraft and surrounding clear air in front of an incoming aircraft 4-3 and the second 4-2, "Bragg" reflection from vortices generated by the incoming aircraft and surrounding clear air behind the incoming aircraft.

As illustrated in FIG. 4, vortices 4-4a and 4-4b intercept a very small portion of the radar beam at all ranges. The "Bragg" reflected signal amplitude from a vortex can be computed by recognizing that a vortex consists of a relatively narrow cylinder of acoustically excited air having a temperature different from surrounding air. Such a cylinder constitutes an end-fire array, as indicated at 4-5 and 4-6 with elements separated by one half the radar wavelength λ_{RF} and a spatial length equal to radar range bin width D. The end-fire array is aimed back towards the source of the incident radar wave with a beamwidth equal to:

When the acoustic wavefront 4-7 and a radar wavefront 4-8, provided by a radar system monitoring the glide slope, are slightly skewed due to a crosswind, vortex return will still be received by the radar monopulse antenna as long as they remain within the end-fire array beamwidth. There may, however, be a slight change in Bragg frequency due to the slightly different directions of the acoustic and electromagnetic wavefronts.

Still referring to FIG. 4, a 2-axis monopulse radar antenna 4-9 may be located at the threshold to illuminate the glide slope and receive "Bragg" reflections. The monopulse antenna may be positioned on the glide slope center line while an optional monopulse auxiliary receive antenna with elements 4-10a and 4-10b positioned on either side of the monopulse antenna may also be utilized. Both the monopulse antenna and the monopulse auxiliary receive antenna point approximately 5.degree. up the glide slope relative to the ground.

Because of their proximity to the glide slope, the monopulse antenna 4-9 and auxiliary receive antenna 4-10a, 4-10b must be constructed of frangible materials or held in place with easily broken couples. Such a requirement may be satisfied by a planar array which may be constructed to provide monopulse

Sound pressure is measured in dynes/cm.². The reference sound pressure level of 0 dB is defined as 0.0002 dynes/cm.² (10.⁻¹⁶ watts/cm.²). Hence any other sound pressure P can be written as:

where S is dB above 0.0002 dynes/cm.². Since 1 millibar is approximately equal to 1000 dynes/cm.², sound pressure in millibars becomes:

The rms refractive index of modulation is

For T=273.degree. K. (0.degree. C.):

With the above, the radar reflection coefficient r is given by :

A radar frequency of 915 MHz, which was previously selected for the preferred embodiments, corresponds to a wavelength in air of 0.3279 meters. For D=150 meters and $\lambda_{RF} = 0.3279$ meters:

From page 26 and 27 of "Measuring The Annoyance of Aircraft Noise" (AFIT/NR 87-71T) the noise generated by a jet during takeoff at a points 1.0 km in front of and behind the aircraft results in a sound pressure level in the band 1200-2400 Hz of 115 dB. It will be shown subsequently that the "Bragg" doppler bandwidth is equal to v/D where v is sound velocity and D is range bin size. For a 150 meter range bin the "Bragg" doppler bandwidth is 2.2 Hz. Assuming conservatively that a landing aircraft generates 10 dB less noise, the sound pressure level in a doppler bandwidth of 2.2 Hz is 77.6 dB. In this case,

For a transmit beamwidth of 8.degree. azimuth and 4.degree. elevation, the fraction of radar signal power intercepted by a pair of vortices, each 1 meter in diameter, at range R_{0} (1000 meters) is given by 1.612×10^{-4} . In this case the energy backscattered E_{REFL} towards the radar antenna for a 1 microsecond pulse (150 meter range bin) and transmitter peak power P_{T} , is given by:

By duality, the fraction of signal energy intercepted by the monopulse antenna sum beam with 8.degree. azimuth and 4.degree. elevation beamwidths is also given by 1.612×10^{-4} . Hence the the energy E intercepted by the monopulse sum beam is;

The S/N out of a matched filter for a single pulse is $(2E/N_{0})$. Therefore, the signal at the output of the matched filter is:

Coherent integration significantly increases the above single pulse S/N. Hence the calculation of peak transmitted power is deferred until this quantity is established.

Refer now to FIGS. 5A and 5B, wherein elements previously discussed bear the originally assigned reference numerals. A radar signal is generated by transmitter 5-5 and radiated by antenna 5-2, which with receiving antennas 5-1 and 5-3 comprise the monopulse antenna 4-9 shown in FIG. 4. This signal may be a pulse of one microsecond in duration at a pulse repetition rate (PRF) of 2048 Hz. Radar echoes are received by antennas 5-1 and 5-3 which are coupled in an azimuth monopulse configuration. In this mode the azimuth beamwidth of each antenna is 8.degree..

Echoes received by antennas 5-1 and 5-3 are coupled to coherent receivers 5-4 and 5-6, respectively, wherein received pulses in each range bin are coherently detected and summed. The number of pulses summed is yet to be discussed. Sequentially received sum samples from receivers 5-4 and 5-6 are

each range bin. The relationship between the difference frequency and vortex strength may vary with the type of aircraft generating the vortices and requires experimental determination.

A signal representative of the vortex strength is coupled from the vortex strength computer 5-19 to a vortex decay tracker 5-23 which detects changes in vortex strength and provides an estimate of the vortex decay rate, in each range bin, as a function of time. Though not shown in FIG. 5A, a complementary estimate of vortex decay rate may be obtained from a determination of vortex temperature decay as a function of range along the glide slope.

The signals representative of vortex strength, vortex decay rate, vortex location, vortex lateral movement rate and direction, and cross wind velocity, yet to be discussed, are coupled to a vortex hazard assessor 5-24 wherein a vortex hazard assessment within the glide slope is performed. Vortex hazard assessor 5-24 computes how long it will take for vortices to decay to a point where they are not hazardous to the following aircraft and how long it will take a crosswind to blow potentially hazardous vortices out of the glide slope. A signal representative of the vortex hazard assessment is coupled to an aircraft spacing processor 5-25 which utilizes the hazard assessment to provide spacing recommendations between landing aircraft to FAA aircraft controllers.

The accuracy with which vortex strength and decay rate can be estimated depends on the resolution with which the radar can measure temperature. To establish the temperature resolution it is first necessary to determine the "natural" doppler spectral width of "Bragg" backscatter.

Let λ_a correspond to the optimum "Bragg" wavelength. If radar range bin width is denoted by D , then $M=D/\lambda_a$ is the number of Bragg wavelengths encompassed by the radar range bin. Increasing the number of acoustic wavelengths by one in the range bin produces a "Bragg" echo null. It is equivalent to distributing 360 degrees of doppler phase shift over the range bin and summing. Let λ_b correspond to the Bragg wavelength which results in a null. Then

From the above it may be readily verified that the difference Δf between the null frequency f_b and the optimum "Bragg" frequency f_a is

Thus the "natural" doppler spectral width of a "Bragg" echo is a function only of sound velocity v and range bin width D and is independent of the "Bragg" frequency and the radar carrier frequency. This width defines the separation between the peak "Bragg" doppler frequency and the first spectral null. It is also approximately equal to the 3db Bragg spectral width.

From the above expression the "Bragg" spectral width for a range bin 150 meters wide is 2.2 Hz. Based on this "Bragg" doppler spectral width, optimum detection and estimation performance will be realized when the coherent observation interval for "Bragg" backscatter is around 0.45 seconds.

With the determination of "Bragg" spectral width, the radar's ability to resolve temperature differences is calculated as follows. It is well known that the velocity of sound in air as a function of absolute temperature is given by

from which it follows that

For two different temperatures T_1 and T_2 Since $(v_1 + v_2)$ is closely equal to 2×331 m/s,

Doppler resolution Δf is related to Δv by the conventional doppler relation with f_{RF} equal to 915 MHz and

amplitude, which is characteristic of reflected clear air sidelobe levels, is still 40 db or more greater than vortex return and therefore easily detected. It follows that for an acoustic attenuation of 16 db/km clear air returns are detectable out to 2.5 km.

This can be summarized as follows. Clear air backscatter can be processed to measure radial wind shear and turbulence (but not cross wind velocity) using an acoustic radiator colocated with the radar monopulse antenna, that radiates approximately 3 watts of acoustic power to acoustically excite the glide slope. The output S/N for clear air returns will exceed (S/N)₀ up to the maximum instrumented range of 2.5 km, for range bins in which the acoustic wave has not been blown completely out of the radar beam.

The FAA vortex warning system 5-25 in FIG. 5A requires a vortex sensor to detect the vortices generated by each landing aircraft and track their transport in the critical approach region. This system was studied by the FAA several years ago, but was never implemented because the required sensor heretofore did exist.

The information coupled to FAA vortex warning system 5-25 by vortex hazard determinator 5-24 is sufficient to enable its operation as originally proposed. Vortex position is displayed to the following aircraft via lights installed at the landing runway threshold. Red and green lights provide the approaching pilot with the approach corridor vortex status information. A green light indicates that the approach corridor is free of the vortices generated by the preceding aircraft. Red light patterns provide the pilot with lead-time information.

A "rippling" red light indicates a vortex is expected to persist in the corridor for more than 60 seconds. The number of lights indicate vortex strength. The information conveyed by the colored light patterns is sufficient to allow the pilot to make a timely decision on whether to proceed with the approach or to initiate a go-around.

Tests were run by the FAA to determine the feasibility of using lights as a means to communicate to the pilot the corridor vortex status. Bright light, adverse weather, and night conditions were simulated using an instrumented runway model to test the detectability of the vortex lights amid the normal approach light pattern.

Under all conditions using standard airport lights, the patterns were detected by the test subjects and the correct meaning identified. Most important, the light pattern was always detected in time before an altitude of 100 meters was reached, the critical height for the initiation of a go-around. The displayed light pattern is also repeated on the controller's console so that when conditions conducive to long vortex persistence in the corridor are observed, the traffic flow may be adjusted to minimize the need for a go-around.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than of limitation and that changes within the purview of the appended claims may be made without departure from the true scope and spirit of the invention in its broader aspects.

* * * * *

[Images](#)

[View Cart](#)

[Add to Cart](#)

[Hit List](#) [Previous](#) [Next](#) [Top](#)
[Home](#) [Quick](#) [Advanced](#) [Pat Num](#) [Help](#)