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**APPARATUS AND METHOD FOR DETERMINING WIND
PROFILES AND FOR PREDICTING CLEAR AIR TURBULENCE**

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Cross Reference to Related Application

This application claims the benefit of U.S. Provisional Application No. 60/013,312 filed on March 8, 1996.

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Field of the Invention

The present invention relates generally to an aircraft flight management system, and, an aircraft flight safety system. An apparatus incorporating a passive detector is used for mapping temperature, for detecting the difference in the speed and direction of winds at various altitudes and for predicting clear air turbulence conditions ahead of the aircraft.

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Background of the Invention

Knowledge of wind speed and direction at various altitudes is valuable to aircraft pilots for numerous reasons. Two reasons include fuel consumption and safety. At cruising altitude an aircraft's fuel consumption could be reduced if the pilot was aware of and took advantage of more favorable wind patterns, such as a lower head wind or a higher tail wind. On long haul flights, the selection of favorable winds would result in significant cost savings to the airline.

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However, currently there are no effective methods or apparatus for passive profiling atmospheric winds ahead of an aircraft during flight. Active systems using Doppler LIDAR are expensive and have limited range. One method for determining fuel-efficient aircraft altitudes is described in Gary, U. S. Patent No 4,474,062. This concept is based on determining the air density at altitudes in the

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vicinity of the aircraft's present altitude by use of a microwave radiometer to detect the thermal emission from oxygen to indicate the air temperature at a particular altitude. The temperature is then used to determine the air density at that altitude. Since the weight of the aircraft is known during the flight as the fuel is consumed, it is possible to calculate the aircraft weight-to-air density ratio, W/d . This ratio has an optimum value (depending on the type of aircraft) for which the fuel consumption is minimum. The pilot then has the option to change altitude to achieve a more favorable W/d ratio. This method for determining fuel efficient aircraft altitudes is inadequate since it is based only on the determination of the aircraft weight to air density ratio and doesn't take into account the wind speed and direction at the altitude that has the optimum value of W/d . As a result, it may be determined, for example, that the optimum W/d ratio is at an altitude 4000 ft above the present aircraft altitude. If the pilot increases his altitude by 4000 ft and then finds a significant increase in the head winds, this situation could completely negate any fuel efficiency savings due to having a more optimum W/d ratio.

In Gary, U.S. Patent No. 4,346,595, it is asserted that by knowing the altitude of the local tropopause, it is possible to find efficient flight altitudes by flying about 2000 ft above the tropopause when traveling in a westerly direction and about 2000 ft below the tropopause when going in an easterly direction. The tropopause is generally a broad transitional zone between the troposphere and the stratosphere. From an operational standpoint, it is not practical to use the tropopause as a reference from which to make altitude changes. In addition, the system described in Gary does not take into account local variation in winds that may be present at the new altitudes.

Clear air turbulence (CAT) is a major safety concern for large commercial aircraft. CAT is a weather phenomenon that is due to vertical wind shear in the atmosphere. It usually occurs in temperature inversion layers typically found in the tropopause. CAT results in a rapidly changing airflow over the lift surfaces of the aircraft. Should the forward velocity of the air over the lift surfaces suddenly

decrease, the lift will decrease. In this situation, the aircraft may experience a forced descent due to the down flowing air mass and also by an apparent loss in forward air speed. It is thus desirable that an onboard weather system be capable of providing an advanced warning of such wind conditions.

5 Since the conditions that result in clear air turbulence are not visually apparent nor are they generally detectable by active sensors such as radar, there have been a number of attempts to detect wind shear and clear air turbulence conditions by passive detectors. In particular, attempts have been made to sense air temperature gradients, which are associated with air turbulence, by detecting
10 the radiation emanating from the atmosphere ahead of the aircraft in the infrared and microwave spectral regions. The intensity of the detected radiation varies with the atmospheric temperatures along the line of sight of the detector. Typically these passive systems use a radiometer to measure the thermal radiation from one of the atmospheric gases such as carbon dioxide (CO₂), oxygen (O₂) or water
15 vapor (H₂O) to determine changes in the spatial temperature profile in front of the aircraft. Examples of such approaches based on the infrared emission of CO₂ are provided in U.S. Patent Nos. 3,475,963, 3,735,136, 3,780,293, 3,935,460, 4,266,130, 4,427,306, 4,937,447, 4,965,572, 4,965,573, 5,105,191, 5,276,326 and 5,285,070. Other approaches determine atmospheric temperature by measuring the
20 microwave emission from O₂ as described in U.S. Patent Nos. 3,359,557, 3,380,055, 4,346,595, and 5,117,689. Systems for measuring atmospheric temperature based on infrared emission from H₂O are described in U.S. Patent No 4,266.130 and in the paper by Kuhn *et al.*, "Clear Air Turbulence: Detection by Infrared Observations of Water Vapor" in *Science*, Vol. 196, p.1099, (1977). In
25 addition, there have been several papers written describing these types of passive infrared systems including: S. M. Norman and N. H. Macoy, "Remote Detection of Clear Air Turbulence by Means of an Airborne Infrared System" AJAA Paper No 65-459 presented at the AIAA Second Annual Meeting, San Francisco, CA, July 26-29, 1965; and R. W. Astheimer, "The Remote Detection of Clear Air

Turbulence by Infrared Radiation" in *Applied Optics* Vol. 9, No. 8, p.1789 (1970). In U.S. Patent No. 4,346,595, Gary describes a microwave radiometer for determining air temperatures in the atmosphere at ranges of about 3 km from the aircraft for the purpose of detecting the height of the tropopause and the presence of temperature inversions. He teaches that by flying the aircraft above or below the tropopause or temperature inversion layer, it is possible to avoid CAT. Since the effective range of the microwave radiometer is relatively short, the system doesn't provide sufficient warning time for the aircraft to avoid the CAT condition. The present invention has detection ranges on the order of 100 km which will allow time for the aircraft to change altitude to avoid CAT.

A number of the above systems were not successful or were only partially successful because they were based solely on the measurement of atmospheric temperature in order to predict the presence of turbulence. A more reliable indication of atmospheric turbulence can be realized by determining the Richardson number, Ri . The use of the Richardson number to determine the stability of the atmosphere is well known in meteorology (see, for example, D. Djuric, *Weather Analysis*, Prentice Hall, Englewood Cliffs, NJ, 1994, p. 64). In the present invention, the Richardson number is used to indicate the probability of CAT. In U.S. Patent No. 5,117,689, Gary discussed the correlation of the reciprocal of the Richardson number with the occurrence of CAT conditions. The Richardson number, Ri , contains two components: (1) the vertical lapse rate of potential temperature and (2) the wind shear which is related to the horizontal temperature gradient. A number of the prior art discussions measure the vertical temperature lapse rate. Gary used the inertial navigation system (INS) to measure the East-West and North-South components of the wind (the wind shear) along with a microwave radiometer to measure the air temperature vertical lapse rate. This information is then used to calculate the Richardson number or its reciprocal. The deficiency of the system described in this patent (U.S. Patent No. 5,117,689) is that it determines the Richardson number at relatively close ranges (less than 3 km) and

therefore does not provide advance warning of the CAT condition and that it measures the wind shear only at the aircraft.

Previous approaches for the determination of the range and probability of CAT can be summarized as follows:

5 U. S. Patent No. 5,276,326 to Philpott determines turbulence as a function of temperature vs. range through the analysis of infrared radiometer signals at two or more discrete wavelengths. The temperature associated with a given range as a function of wavelength is then derived through a matrix inversion process. This transition is difficult and requires noise and error free input data to yield valid
10 results. The present invention overcomes this difficulty by using only one wavelength. Gary overcomes the multiple wavelength difficulty in Patent No. 4,346,595 by measuring effective temperature and range at a single wavelength, however no attempt is made to determine the probability of clear air turbulence using the Richardson number (Ri). In U. S. Patent No. 5,117,689, Gary teaches
15 the significance of the Richardson number in CAT prediction but does not suggest a method to derive Ri directly from radiometric measurements of horizontal and vertical temperature lapse rates obtained by combining azimuth and elevation scanning with the aircraft motion to produce a temperature map.

20 Summary of the Invention

It is therefore an object of the invention to provide a method and apparatus for determining both fuel efficient aircraft altitudes and for predicting clear air turbulence. The invention provides a system for passive measurement of atmospheric temperature using a detector for detecting the energy of a narrow
25 wavelength band emanating from a volume of atmospheric gas. The resulting signal can be associated with an effective temperature. The effective temperature can be associated with an effective range.

It is an additional object of the invention to provide a system utilizing a radiometer to detect the radiation of a predetermined wavelength band of CO_2

associated with an effective range that corresponds to the wavelength band in order to measure the temperature of the atmosphere in a predetermined direction and associated with the effective range from the radiometer. A range of suitable wavelengths is 12.2 to 13 μm where the effective range is 90 to 120 km at an
5 altitude of 35,000 ft.

Another object of the invention is to provide a system for generating a temperature map using a passive directional detector which can determine, at predetermined time intervals, atmospheric temperatures in an azimuth plane associated with a predefined range from the detector. The temperature map can
10 then be used to calculate temperature gradients that in turn can be used to compute the vertical wind vector difference and to determine the presence of clear air turbulence.

A further object of the invention is to provide an advisory system using a passive detector on board an aircraft to determine whether the winds at flight levels
15 up to 6,000 ft. above or below the aircraft would be more favorable, either through a lower head wind or a higher tail wind, such that changing altitude would result in reduced fuel consumption. The detector can include an infrared radiometer to determine the temperature field from which the thermal wind at the upper and lower flight levels is calculated.

Yet another object of the invention is to provide an aircraft clear air
20 turbulence warning system that uses a passive detector on board the aircraft to generate signals representing horizontal temperature gradients and vertical temperature profiles that can be used to compute the Richardson number which in turn can be used to generate a warning when the wind shear exceeds a
25 predetermined value.

Brief Description of the Drawings

Fig. 1 is a functional block diagram of the preferred embodiment of the invention;

Fig. 2 is pictorial representation of a scanning array illustrating the operation of a radiometer in the invention of Fig. 1 at three time intervals;

Fig. 3 is a pictorial representation of a section of the atmosphere illustrating the operation of the radiometer of Fig. 1;

5 Fig. 4 is a pictorial representation of an aircraft operating the radiometer of Fig. 1 in a horizontal scan mode;

Fig. 5 is a pictorial representation of an aircraft acquiring a horizontal temperature map according to the invention of Fig. 1;

10 Fig. 6 is a pictorial representation of an aircraft operating the radiometer of Fig. 1 in a vertical scan mode; and

Fig. 7 is a pictorial representation of the determination of the direction and velocity of wind at a level above the flight level of the aircraft according to the invention.

15 Detailed Description of the Invention

Fig. 1 provides an overview, in the form of a functional block diagram, of the operation of the preferred embodiment of the invention which in this case is an apparatus 10 for installation in an aircraft to detect wind vector difference and clear air turbulence. Although the preferred embodiment of the invention is described in terms of its application to aircraft, the invention can have other applications some of which are described below. Installed in a forward, and partially sideways, looking location of the aircraft, such as the nose or a leading portion of a wing is a passive detector 12, preferably a radiometer, for receiving infrared radiation from the atmosphere as indicated by a dashed line 14. Also, as indicated by a block 16, 20 the radiometer 12 is connected to a directional scanning mechanism which permits the radiometer 12 to receive the radiation 14 from different directions in both the azimuth and vertical directions or in only the azimuth direction.

Shown at block 18, the apparatus 10 will convert the sterance or energy L at a particular wave length λ of the radiation 14 as detected by the radiometer 12

into a value T_{eff} which represents the temperature of the atmosphere at an effective range R_{eff} from the aircraft. The concept of converting the radiation 14 into temperature T_{eff} and the effective range R_{eff} will be described below.

Then, as indicated at a block 20, the T_{eff} values obtained will be used to
5 create a horizontal or vertical temperature map of atmospheric temperature ahead of the aircraft as illustrated in Figs. 2-7. As the aircraft progresses along its line of flight, the system data is collected as shown in Fig. 2. The apparatus then generates a temperature map as indicated at 20.

The temperature mapping 20 is used to compute horizontal temperature
10 gradients ∇T , indicated at a block 22, between the temperatures T , contained in the map 20 in a horizontal plane.

As represented by a block 24 and discussed below, the horizontal temperature gradients ∇T can be used to compute vertical wind vector difference for flight levels ahead as well as above and below the aircraft.

15 Effective use of the wind vector difference information generated at 24 can be made, as shown at a block 26, by displaying the wind vector difference at flight levels above or below the aircraft in order to provide the air crew with information as to winds that might be more favorable. This information 24 can also be used as an input to a flight management system, indicated by a block 28, so that it can be
20 combined with other flight parameters to provide guidance as to the most efficient flight regime. In addition, this information 24 can be used to compute the probability of clear air turbulence, as indicated by a block 30 that in turn can be used as an input to a clear air turbulence display or warning system as shown by a block 32.

25 The following is a more detailed description of the various elements and concepts of the invention as shown in the block diagram of Fig. 1.

For example, Fig 2 provides an illustration of the operation of the radiometer 12 in conjunction with the directional scan mechanism 16. In this case the scan mechanism 16 directs the radiometer 12 so as to receive radiation 14 from

what in effect are 3 x 3 arrays 34a, 34b and 34c of points in the atmosphere ahead of the aircraft collecting sterance associated with an effective range R_{eff} at time intervals t_0 , t_1 and t_2 . In the preferred embodiment of the invention, a middle row 36 of the arrays 34a-c is located at the aircraft's flight level while an upper row 38 is located at a level intermediate between the flight level and an upper flight level and a lower row 40 is located at a level intermediate between the flight level and a lower flight level. An illustration of the flight levels is provided in Fig. 7. The radiometer 12 can be any suitable commercially available radiometer or a radiometer of the type described in the above referenced patents such as U.S. Patent No. 4,937,447 to Barrett which is hereby incorporated by reference. In another preferred embodiment, only one horizontal temperature map at one level is used for determining wind difference.

Referring also to Fig. 1 and Fig. 3, the temperature conversion 18 of each point in the arrays 34a-c is accomplished by translating the radiance $L(\lambda)$ received by the radiometer 12, where the wavelength is λ , into a signal that is associated with a temperature T_{eff} of the volume of air seen by the radiometer. The temperature, T_{eff} , is associated with the effective range, R_{eff} , which is the weighted average distance of the signal reaching the radiometer 12. This use of R_{eff} is only useful in conditions for which R_{eff} does not vary significantly during aircraft flight across reasonable distances at a fixed altitude. It has been found that R_{eff} does not vary significantly for normal flight conditions, i.e., R_{eff} is determined by only the wavelength λ , the altitude and latitude of the aircraft and the particular time of year. This has been verified through the use of the FASCODE program. The FASCODE program is a computer model of atmospheric transmission and radiance in the infrared. This program is described and identified in the aforementioned Barrett, U.S. Patent No. 4,937,447. The following Table 1 is a table illustrating the FASCODE (using the mid-latitude, winter atmosphere program) computed effective range R_{eff} vs. λ in the case that λ falls within the preferred band of

wavelengths of CO₂ emission for a zenith angle of 90 degrees and an altitude of 35,000 ft.

Table 1

	<u>Wavelength (μm)</u>	<u>Effective Range (km)</u>
5	12.2	121
	12.3	106
	12.4	98.2
	12.5	84.4
10	12.6	76.6
	12.7	91.8
	12.8	105
	12.9	106
	13.0	89.3

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It has been found that the wavelength 12.2 μm of CO₂ is particularly effective at measuring T_{eff} associated with a range R_{eff} of approximately 120 km for one altitude and latitude. It should be noted that one of the advantages of the invention is that it makes use of previously computed values of R_{eff} so that it is possible to provide accurate maps of atmospheric temperature. Also it is possible to store tables of R_{eff} vs. Altitude and λ vs. R_{eff} such as shown in the Table 1 above in order to adjust the sensitivity of the system and the effective range for various conditions. Alternatively, it is possible to use more than one wavelength λ to measure more than one T_{eff} at corresponding ranges R_{eff} from the aircraft.

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The radiance $L(\lambda)$ detected by the radiometer 12 is a function of the temperature of the naturally occurring CO₂ in the atmosphere. It is possible to associate the temperature of the air in ΔV_{tot} shown in Fig. 3 with a given signal. The total signal, $L(\lambda)$, is the sum of the contributions, $L(\lambda)_i$ of signal from each volume element i along the line of sight of the radiometer 12. Thus

$$L(\lambda) = \sum_i L(\lambda)_i = \sum_i S_i \tau_i \quad (1)$$

where S_i is the radiance intercepted by the detector from a volume element i and τ_i is the transmission of the radiance between the volume element i and the detector.

The temperature T_{eff} is associated with $L(\lambda)$, where T_{eff} is the temperature of a blackbody source which produces the same radiometer signal as $L(\lambda)$. The effective distance R_{eff} is defined according to the equation

$$R_{eff} = \frac{\sum_i R_i L(\lambda)_i}{\sum_i L(\lambda)_i} \quad (2)$$

As indicated at 18 of Fig. 1, the temperature T_{eff} is associated with R_{eff} and a map is generated at 20 with the temperature T_{eff} at a distance R_{eff} in the appropriate direction from the aircraft. For normal flight conditions, R_{eff} does not vary significantly and is determined only by altitude and latitude for a given time of year. With respect to Fig. 3, the altitude of ΔV_{vol} for a R_{eff} of 120 km will be about 1000 ft. above the flight level of the aircraft due to the earth's curvature assuming the radiometer 12 is directed toward the horizon.

Figs. 4-6, illustrate how the temperature mapping 20 can be accomplished. In Fig. 4, an aircraft 42 having the radiometer 12 mounted in its nose causes the radiometer 12 to perform an azimuth scan of 180° . At each of the five positions shown in Fig. 4, the radiometer 12 will detect the radiance 14. In this manner a horizontal temperature map is generated. The radiometer can detect signals sufficiently fast that the motion of the aircraft can be ignored. Fig. 5 shows a series of locations indicated by a set of rectangular boxes 44_{a-d} that correspond to a set of time intervals t_{a-d} as the aircraft 42 proceeds along its flight path, where the temperatures T_{eff} detected for each location 44_{a-d} can be stored in memory. Similarly, as illustrated in Fig. 6, the radiometer 12 in the aircraft 42 can perform a vertical scan so that temperatures of locations above and below the flight path can

be mapped. As a result, it is possible to generate temperature maps for horizontal planes above and below the aircraft 42.

By mapping the temperature fields 20 as described above, it is possible to compute horizontal temperature gradients ∇T as indicated at 22 of Fig. 1. It is also possible, by using the vertical temperature mapping to calculate the temperature lapse rate $\partial T / \partial z$ for use in calculation of the Richardson Number for computing the probability of clear air turbulence.

As illustrated by the representation of Fig. 7, one of the salient features of the invention is the capability of utilizing the temperature gradients computed at 22 to generate values representing vertical wind vector difference or horizontal winds at various flight levels. In this case, only a horizontal mapping at one level is needed. For example, a method according to the invention whereby the thermal wind concepts can be used to compute vertical wind vector difference, ΔV , as indicated at 24 of Fig. 1, makes use of the following relation:

$$\Delta V = - \left[\frac{g \Delta z}{f T} \right] \nabla T \otimes k \quad (3)$$

where g is the acceleration due to gravity, Δz is the distance between Z_1 and Z_2 , f is the Coriolis parameter resulting from the earth's rotation, T is the temperature at said flight altitude Z_1 , ∇T is the vector representing the temperature gradient at the intermediate level Z_3 between Z_1 and Z_2 , k is the unit vector parallel to the aircraft's local vertical and the symbol $\otimes$ represents the vector cross-product operator. In Fig. 7, Z_1 denotes the current flight level of the aircraft, Z_2 denotes the flight level above the aircraft and Z_3 denotes the intermediate level. Equation 3 may be found in any standard meteorological text such as Dynamical and Physical Meteorology by G. J. Haltiner and F. L. Martin, (McGraw-Hill, New York, 1957) p. 204.

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As a result, once the temperature gradients are computed 22 from the temperature field 20 the value of ΔV can be computed at 24 for the upper flight level 48 per equation (3). For an aircraft direction vector, V_{ac} , the vector dot product, $\Delta V \cdot V_{ac}$, is the increase in headwind or tailwind the aircraft would experience at the different altitude. In addition, the vector value ΔV can then be added to the vector value V_1 of the wind at the current flight level 46 to obtain a vector value V_2 which represents the direction and speed of the wind at the upper flight level 48. This value then can also be displayed on the display 26 in order to provide the air crew with information as to the wind at the upper flight level 48.

Alternatively, the display 26 can be used to display just the difference in wind speed along the direction of the aircraft's flight at the upper flight level 48, for example by displaying a simple plus or minus sign along with a value representing the difference in velocity. In addition, the value of V_2 can be used as an input to the flight management system 28 so that factor can be used by the system 28 in determining the most efficient flight regime. Note that the temperatures are only needed in one horizontal plane to determine ∇T , and the wind difference, ΔV .

It will be understood that the above discussed method of determining wind direction and velocity V_2 at the upper flight level 48 would also apply to the determination of wind at a lower flight level below the current flight level 46. In this manner, it is possible to provide on the display 26 or to the flight management system 28 an indication of the winds both above and below the aircraft so that the crew can take advantage of this information in selecting the most fuel efficient altitude.

Another feature of the invention relates to the use of the temperature mapping function 20 along with the computation of vertical temperature gradients 22 to compute the probability of clear air turbulence 30. In particular, the vertical temperature mapping 20 can be used to calculate the lapse rate $\partial T / \partial z$ for determination of the Richardson number Ri which is correlated with turbulent conditions. In this case Ri is computed using the following relations:

$$Ri = \left(\frac{g}{\theta} \right) \frac{\left(\frac{\partial \theta}{\partial z} \right)}{\left| \frac{\partial V}{\partial z} \right|^2} \quad (4)$$

where

$$\theta = T \left\{ \frac{1000}{p} \right\}^{\frac{R}{C_p}} \quad (5)$$

and where θ is the potential temperature, $\partial \theta / \partial z$ is the vertical gradient of the potential temperature, $\partial V / \partial z$ is the vertical wind shear, g is acceleration due to gravity, V is the horizontal wind vector, z is height, T is temperature in Kelvin, p is atmospheric pressure in millibars, R is the universal gas constant and C_p is the specific heat of air at constant pressure. The Richardson number, Ri , is a measure of the probability of CAT. For Ri below 0.21, atmospheric turbulence occurs and CAT is likely. Severity of CAT increases with decreasing Ri . Referring again to Fig. 1, the probability of clear air turbulence is determined at 30 with the result displayed on the CAT display 32.

The embodiment of the invention in Fig. 1 has been described in terms of its use in connection with an aircraft traversing temperature fields in its flight path. However, this type of apparatus can also adapted for use in mapping temperature fields from a fixed geographical position. By using the radiometer 12 at a fixed site to scan temperature at the effective range R_{eff} as described above over a period of time as the weather moves over the radiometer, it is possible to generate a map of the temperature fields for a wide area. The temperature map can then be used for warnings of wind conditions such as clear air turbulence and dry microburst conditions. Another use at a fixed position is to scan the temperature field in 360° azimuth and in elevation to determine wind differences, or CAT at one time.



CLAIMS

We claim:

1. An apparatus for determining the wind vector difference, ΔV , between a first altitude Z_1 and a second altitude Z_2 comprising:

temperature measurement means for measuring a plurality of temperatures at an altitude Z_3 and means for calculating the vector temperature gradient, ∇T , over said altitude Z_3 ; and

wind vector difference computation means, responsive to said vector temperature gradient ∇T , for generating a signal, $\Delta V/\Delta z$ where ΔV represents the wind vector difference between said altitudes Z_1 and Z_2 and Δz is the vertical distance between the altitude Z_1 and said altitude Z_2 .

2. The apparatus of Claim 1 wherein said altitude Z_3 is equal to said altitude Z_1 .

3. The apparatus of Claim 1 wherein said ∇T represents a vector isobaric temperature gradient and said wind vector difference computation means generates said ΔV signal according to the relation

$$\Delta V = - \left[\frac{g \Delta z}{f T} \right] \nabla T \otimes k$$

where g is the acceleration due to gravity, Δz is the distance between Z_1 and Z_2 , f is the Coriolis parameter resulting from the earth's rotation, T is the temperature at said flight altitude Z_1 , ∇T is the vector representing the temperature gradient at the intermediate level between Z_1 and Z_2 , k is the unit vector parallel to the local vertical and the symbol $\otimes$ represents the vector cross-product operator.

4. An apparatus for determining clear air turbulence conditions based on the prediction of the Richardson number comprising:

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gradient means, including a directional passive radiation detector, for determining the vertical lapse rate of the potential temperature, $\partial\theta / \partial z$ where θ is the potential temperature and z is the vertical direction;

wind shear means for determining the vertical wind shear, $\partial V / \partial z$ where V is the horizontal wind vector; and

calculation means responsive to said gradient means and said wind shear means for calculating the Richardson number.

5. An apparatus on board an aircraft for determining clear air turbulence conditions based on the prediction of the Richardson number comprising:

a vertically scanning radiometer for obtaining atmospheric temperature measurements θ over a vertical distance z ahead of the aircraft;

computational means for determining the vertical gradient of the potential temperature, $\partial\theta/\partial z$ and for determining the horizontal wind vector, V ;

calculating means for determining the vertical wind shear gradient, $\partial V/\partial z$ and the Richardson number.

6. The apparatus of Claim 5 further comprising additional computational means for calculating the probability of clear air turbulence from said Richardson number and display means for displaying said probability of clear air turbulence.

7. An apparatus for determining clear air turbulence conditions based on the prediction of the Richardson number comprising:

A passive detector for detecting atmospheric temperature θ at an effective range R_{eff} over a vertical distance z from the aircraft; and

means for:

(i) determining the vertical lapse rate of the potential temperature, $\partial\theta/\partial z$;

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(ii) determining the vertical wind shear, $\partial V/\partial z$ where V is the horizontal wind vector;

(iii) calculating the Richardson number, Ri , from the equation

$$Ri = \left(\frac{g}{\theta} \right) \frac{\left(\frac{\partial \theta}{\partial z} \right)}{\left| \frac{\partial V}{\partial z} \right|^2}$$

and

(iv) calculating the probability of clear air turbulence from said Richardson number.

8. A system for measuring atmospheric temperature comprising:

detector means for detecting radiation $L(\lambda)$ having a wavelength λ from a predetermined direction; and

computational means, responsive to said detector means, for computing a value T_{eff} representing the temperature of the atmosphere at an effective range R_{eff} from said detector means.

9. A method for determining the wind vector difference, ΔV , between a first altitude Z_1 and a second altitude Z_2 comprising:

measuring a plurality of temperatures at an altitude Z_3 and means for calculating the vector temperature gradient, ∇T , over said altitude Z_3 ; and

calculating, responsive to said vector temperature gradient ∇T , a signal, $\Delta V/\Delta z$ where ΔV represents the wind vector difference between said altitudes Z_1 and Z_2 and Δz is the vertical distance between the altitude Z_1 and said altitude Z_2 .

10. A method for determining clear air turbulence conditions based on the prediction of the Richardson number comprising:

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calculating the vertical lapse rate of the potential temperature, $\partial\theta / \partial z$
where θ is the potential temperature and z is the vertical direction;
determining the vertical wind shear, $\partial V / \partial z$ where V is the horizontal wind
vector; and
calculating the Richardson number.

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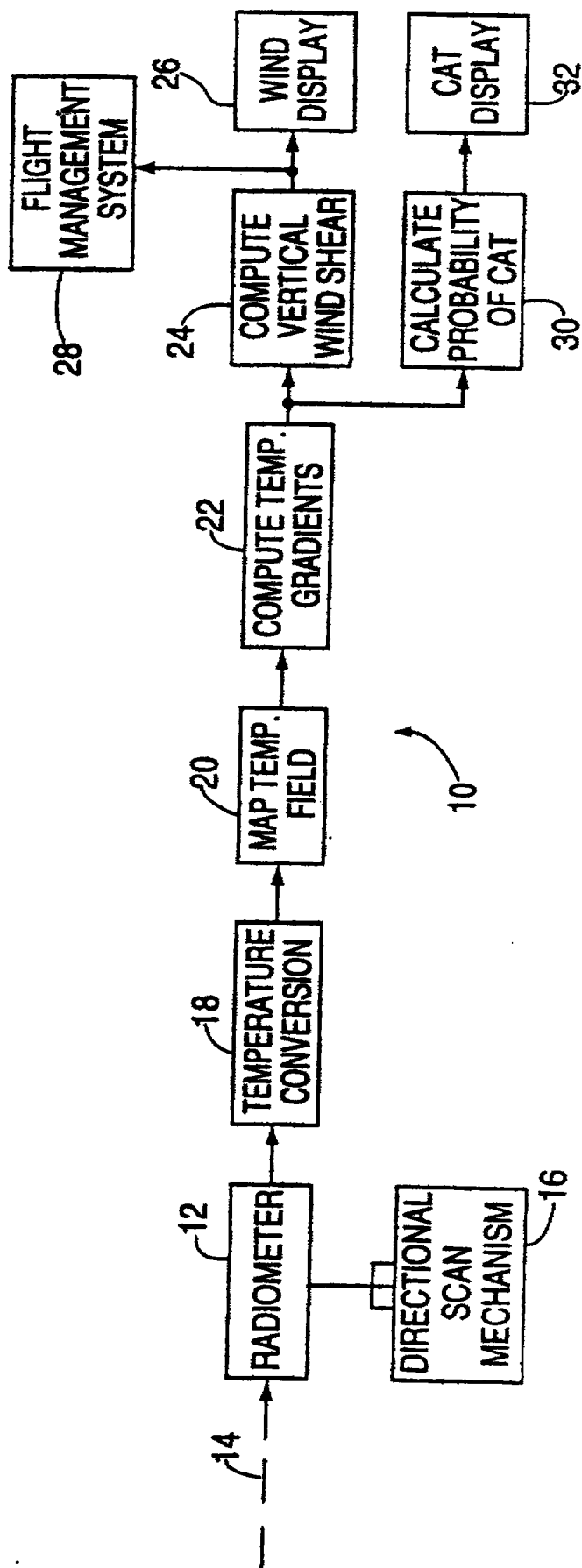


FIG. 1

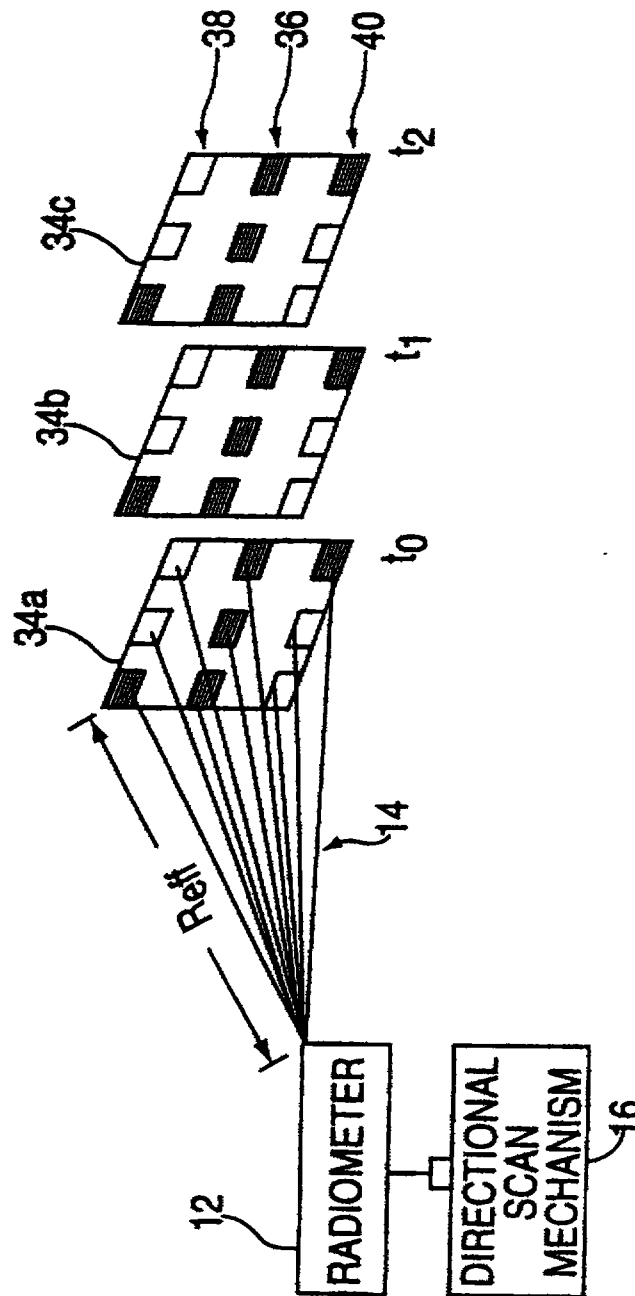


FIG. 2

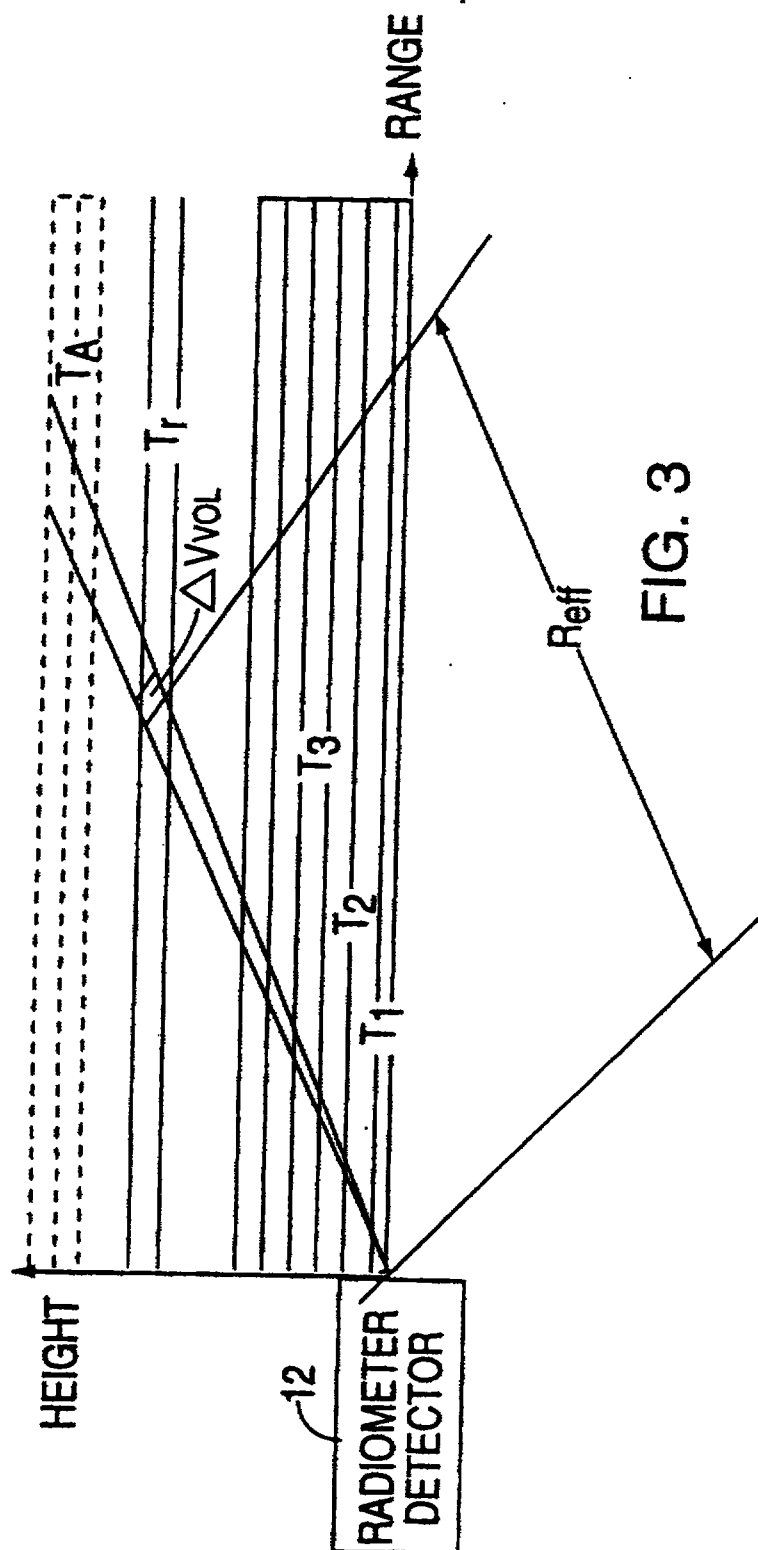


FIG. 3

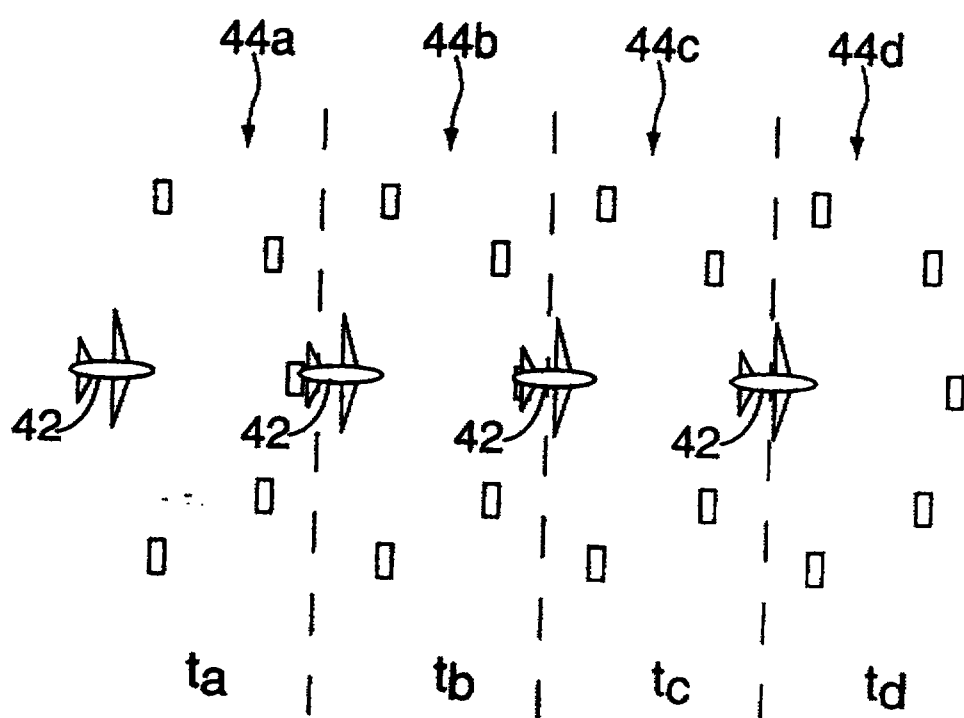


FIG. 5

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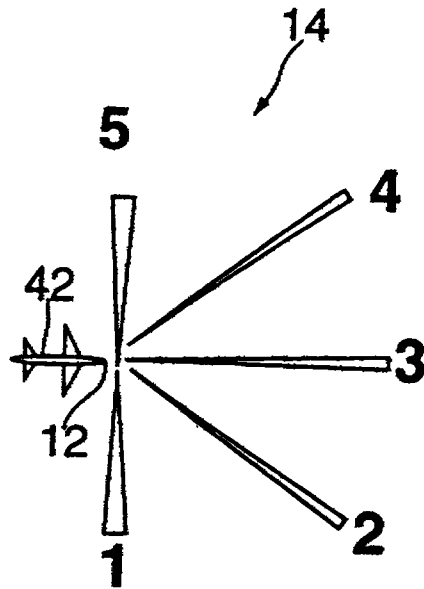


FIG. 4

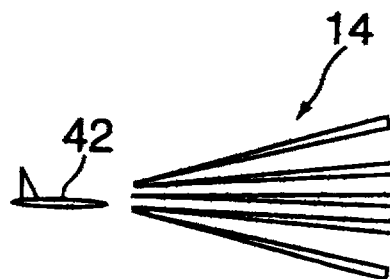


FIG. 6

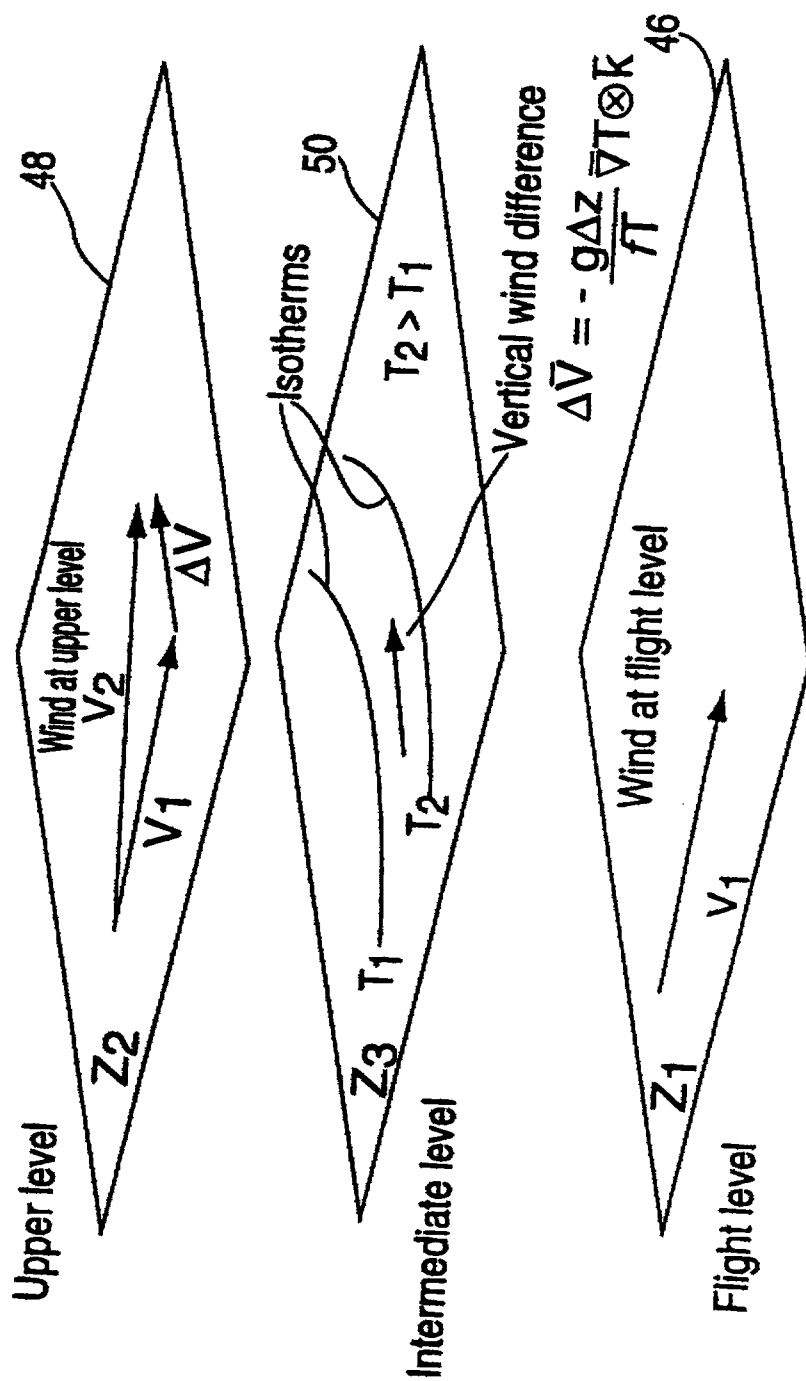


FIG. 7

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be mapped. As a result, it is possible to generate temperature maps for horizontal planes above and below the aircraft 42.

By mapping the temperature fields 20 as described above, it is possible to compute horizontal temperature gradients ∇T as indicated at 22 of Fig. 1. It is also possible, by using the vertical temperature mapping to calculate the temperature lapse rate $\partial T / \partial z$ for use in calculation of the Richardson Number for computing the probability of clear air turbulence.

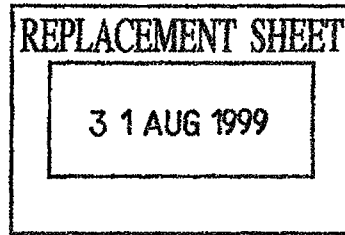
As illustrated by the representation of Fig. 7, one of the salient features of the invention is the capability of utilizing the temperature gradients computed at 22 to generate values representing vertical wind vector difference or horizontal winds at various flight levels. In this case, only a horizontal mapping at one level is needed. For example, a method according to the invention whereby the thermal wind concepts can be used to compute vertical wind vector difference, ΔV , as indicated at 24 of Fig. 1, makes use of the following relation:

$$\Delta V = - \left[\frac{g \Delta z}{f T} \right] \nabla T \otimes k \quad (3)$$

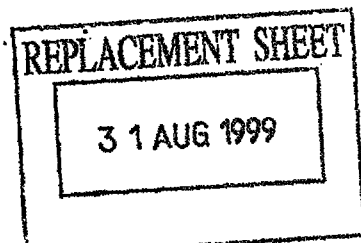
where g is the acceleration due to gravity, Δz is the distance between Z_1 and Z_2 , f is the Coriolis parameter resulting from the earth's rotation, T is the temperature at the intermediate level Z_3 , ∇T is the vector representing the temperature gradient at the intermediate level Z_3 between Z_1 and Z_2 , k is the unit vector parallel to the aircraft's local vertical and the symbol $\otimes$ represents the vector cross-product operator. In Fig. 7, Z_1 denotes the current flight level of the aircraft, Z_2 denotes the flight level above the aircraft and Z_3 denotes the intermediate level. Equation 3 may be found in any standard meteorological text such as Dynamical and Physical Meteorology by G. J. Haltiner and F. L. Martin, (McGraw-Hill, New York, 1957) p. 204.



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Claims:

1. An apparatus for determining the wind vector difference ΔV , between a first altitude Z_1 ; and a second altitude Z_2 , comprising:
 - a. temperature measurement means for measuring a plurality of temperatures T at an altitude Z_3 ;
 - b. means, responsive to the temperature measurement means, for calculating the ∇T , the vector temperature gradient, over the altitude Z_3 ; and
 - c. wind vector difference computational means, responsive to the means for calculating the vector temperature gradient, for determining $\Delta V/\Delta z$, the wind vector difference, where Δz is the vertical distance between altitudes Z_1 and Z_2 .
2. The apparatus of claim 1 where the altitude Z_3 is within about 6000 feet of the altitudes Z_1 and Z_2 .
3. The apparatus of claim 1 where the altitude Z_3 is equal to said altitude Z_1 .
4. The apparatus of claim 1 where the altitude Z_3 is preferably between the altitudes Z_1 and Z_2 .
5. The apparatus of claim 1 further comprising:
 - means, responsive to the temperature measurement means, for generating a map of the plurality of temperatures at the altitude Z_3 ;
 - means for deriving lines of constant temperature from the map; and
 - means, responsive to the lines of constant temperature, for calculating the vector temperature gradient ∇T .



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6. The apparatus of claim 1 where the means for calculating the vector temperature gradient ∇T comprises means for calculating a vector isobaric temperature gradient and the wind vector difference computational means comprises means for determining ΔV according to the equation

$$\Delta V = - \left[\frac{g \Delta z}{f T} \right] \nabla T \otimes k$$

where f is the Coriolis parameter resulting from the Earth's rotation, T is the temperature at altitude Z_3 , and k is the unit vector parallel to the local vertical.

7. The apparatus of claim 1 further comprising means for displaying a representation of ΔV .

8. An apparatus for determining the wind vector difference, ΔV , between a first altitude Z_1 and a second altitude Z_2 , comprising:

temperature measurement means, secured to a platform, for measuring a plurality of temperatures at a constant altitude Z_3 between the first altitude Z_1 and the second altitude Z_2 ;

means, responsive to the means for measuring temperature, for calculating ∇T , the vector temperature gradient, at altitude Z_3 ; and

wind vector difference computation means, responsive to the vector temperature gradient, ∇T , for generating a signal, $\Delta V / \Delta z$ where Δz is the vertical distance between altitude Z_1 and altitude Z_2 .

9. An apparatus for determining wind profile data for use in an aircraft flight management system based on the prediction of the wind vector difference, ΔV , between an aircraft flight altitude Z_1 and a second altitude Z_2 comprising:

horizontal and vertical temperature measurement means, located on the aircraft, for generating a map of temperatures T at constant altitude Z_3 between the first and second altitudes Z_1 and Z_2 ;



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calculation means for calculating ∇T , the vector temperature gradient, at the altitude Z_3 ; and

wind vector difference computation means, responsive to the vector temperature gradient; ∇T , for generating a signal, $\Delta V/\Delta z$ where Δz is the vertical distance between the flight altitude Z_1 and the altitude Z_2 .

10. The apparatus of claim 9 further comprising means for determining clear air turbulence conditions ahead of an aircraft based on the prediction of the Richardson number, the means for determining clear air turbulence comprising:

means for determining $\partial\theta/\partial z$, the vertical gradient of the potential temperature, where θ is atmospheric temperature and z represents a vertical distance ahead of the aircraft;

means for determining $\partial V/\partial z$, the vertical wind shear, where V is the horizontal wind vector; and

means for calculating the Richardson number, Ri , from the equation

$$Ri = \left(\frac{g}{\theta} \right) \frac{\left(\frac{\partial \theta}{\partial z} \right)}{\left| \frac{\partial V}{\partial z} \right|^2}$$

11. The apparatus of claim 10 where the means for determining clear air turbulence further comprises means for determining the probability of clear air turbulence.

12. The apparatus of claim 1 where the temperature measurement means comprises:

detector means for detecting radiation $L(\lambda)$ having a wavelength λ from a predetermined direction; and

computational means, responsive to said detector means, for computing a value T_{eff} representing the temperature of the atmosphere at an effective range R_{eff} from the detector means.

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13. The apparatus of claim 12 where the detector means comprises a passive infrared detector for detecting said radiation $L(\lambda)$.
14. The apparatus of claim 13 where the radiation $L(\lambda)$ corresponds to the energy resulting from the emission of atmospheric CO_2 at the wavelength λ from the portion of the atmosphere at the effective range R_{eff} .
15. The apparatus of claim 14 where the wavelength λ is between $12.2 \mu\text{m}$ and $13.0 \mu\text{m}$.
16. The apparatus of claim 15 where the wavelength λ is $12.3 \mu\text{m}$.
17. The apparatus of claim 12 where the effective range R_{eff} is approximately 120 km .
18. The apparatus of claim 12 where
 - the wavelength λ is between $12.2 \mu\text{m}$ and $13 \mu\text{m}$;
 - the detector means comprises an infrared radiometer and scanning means for scanning said radiometer in the vertical and horizontal directions; and
 - the mapping means comprises means for generating horizontal and vertical temperature maps.
19. A method for determining the wind vector difference, ΔV , between a first altitude Z_1 and a second altitude Z_2 comprising the steps of:
 - a. measuring a plurality of temperatures T at an altitude Z_3 ;
 - b. in response to the step of measuring temperature, calculating ∇T , the vector temperature gradient, over the altitude Z_3 ; and

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c. in response to calculating the vector temperature gradient, determining $\Delta V/\Delta z$, the wind vector difference, where Δz is the vertical distance between the altitudes Z_1 and Z_2 .

20. The method of claim 19 where the altitude Z_3 is within about 6000 feet of the altitudes Z_1 and Z_2 .

21. The method of claim 19 where the altitude Z_3 is equal to the altitude Z_1 .

22. The method of claim 19 where the altitude Z_3 is preferably between the altitudes Z_1 and Z_2 .

23. The method of claim 1, further comprising the steps of:
 in response to step of measuring temperature, generating a map of the plurality of temperatures at the altitude Z_3 ;
 deriving lines of constant temperature from the map; and
 in response to the lines of constant temperature, calculating the vector temperature gradient ∇T .

24. The method of claim 19 where the step of calculating the vector temperature gradient ∇T comprises the steps of calculating a vector isobaric temperature gradient and the step of calculating the wind vector difference comprises the step of determining ΔV according to the equation

$$\Delta V = - \left[\frac{g \Delta z}{fT} \right] \nabla T \otimes \mathbf{k}$$

where f is the Coriolis parameter resulting from the Earth's rotation, T is the temperature at altitude Z_3 , and $\mathbf{k}$ is the unit vector parallel to the local vertical.

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25. A method for determining the wind vector difference, ΔV , between a first altitude Z_1 and a second altitude Z_2 , comprising the steps of:

measuring a plurality of temperatures at a constant altitude Z_3 between the first altitude Z_1 and the second altitude Z_2 ;

in response to the step of measuring temperature, calculating ∇T , the vector temperature gradient, at altitude Z_3 ; and

in response to the step of calculating vector temperature gradient, ∇T , generating a signal, $\Delta V/\Delta z$ where Δz is the vertical distance between the altitude Z_1 and altitude Z_2 .

26. The method of claim 25 where the steps are performed on an aircraft.

27. The method of claim 25 where the steps are performed on the ground.

28. The method of claim 25 where the step of measuring the plurality of temperatures comprises the steps of:

generating a plurality of temperature values representing a plurality of temperatures of the atmosphere at the altitude Z_3 at a predetermined range from the detector; and

generating the vector temperature gradient ∇T from the plurality of temperature values.

29. A method for determining wind profile data for use in an aircraft flight management system based on the prediction of the wind vector difference, ΔV , between an aircraft flight altitude Z_1 and a second altitude Z_2 comprising:

measuring temperature in the horizontal and vertical planes;

generating a map of temperatures T at constant altitude Z_3 between the first and second altitudes Z_1 and Z_2 ;

calculating the vector temperature gradient, ∇T , at the altitude Z_3 ; and

in response to the step of calculating the vector temperature gradient; generating a signal, $\Delta V/\Delta z$ where Δz is the vertical distance between the flight altitude Z_1 and the altitude Z_2 .

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30. The method of claim 29 further comprising the step of determining clear air turbulence conditions ahead of an aircraft based on the prediction of the Richardson number, comprising the steps of:

determining $\partial\theta/\partial z$, the vertical gradient of the potential temperature, where θ is atmospheric temperature and z represents a vertical distance ahead of the aircraft;

determining $\partial V/\partial z$, the vertical wind shear, where V is the horizontal wind vector;
and

calculating the Richardson number, Ri , from the equation

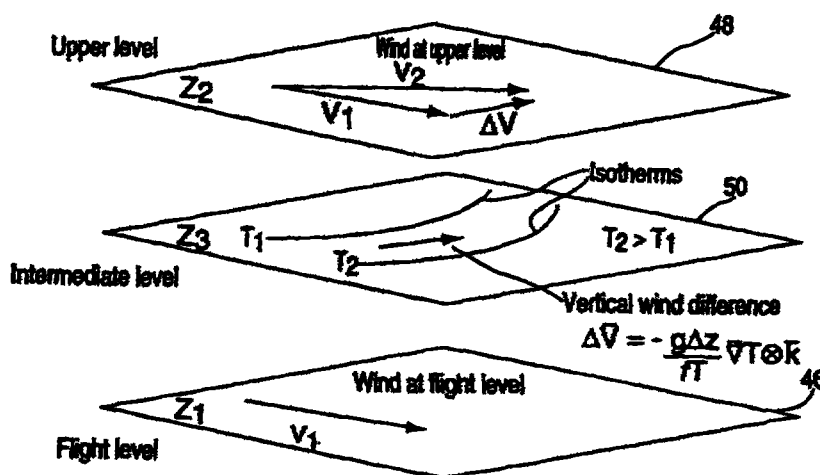
$$Ri = \left(\frac{g}{\theta} \right) \frac{\left(\frac{\partial\theta}{\partial z} \right)}{\left| \frac{\partial V}{\partial z} \right|^2}$$



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(54) Title: **APPARATUS AND METHOD FOR DETERMINING WING PROFILES AND FOR PREDICTING CLEAR AIR TURBULENCE**



(57) Abstract

The invention provides a system for passive measurement of atmospheric temperature using a passive direction detector for detecting the energy of a narrow wavelength band emanating from a volume of atmospheric gas. The resulting signal can be associated with an effective temperature. The effective temperature can be associated with an effective range. The system generates a temperature map which can determine, at predetermined time intervals, atmospheric temperatures in an azimuth plane associated with a predefined range from the detector. The temperature map can then be used to calculate temperature gradients that in turn can be used to compute the vertical wind vector difference and to determine the presence of clear air turbulence.