A system and method of determining locations of lightning strikes has been described. The system includes multiple receivers located around an area of interest, such as a space center or airport. Each receiver monitors both sound and electric fields. The detection of an electric field pulse and a sound wave are used to calculate an area around each receiver in which the lighting is detected. A processor is coupled to the receivers to accurately determine the location of the lighting strike. The processor can manipulate the receiver data to compensate for environmental variables such as wind, temperature, and humidity. Further, each receiver processor can discriminate between distant and local lightning strikes.

20 Claims, 1 Drawing Sheet
SYSTEM AND METHOD OF LOCATING LIGHTNING STRIKES

This patent application is related to U.S. Provisional Patent Application Ser. No. 60/182,404, entitled "Method and Apparatus for Accurate Location of Lightning Strikes", filed on Feb. 14, 2000.

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, as amended, Public Law 85-568 (72 Stat. 435; 42 U.S.C. §2457).

BACKGROUND OF THE INVENTION

The present invention relates generally to identifying locations of lightning strikes.

Electronic equipment is susceptible to damage caused by nearby lightning strikes. The accurate knowledge of a lightning striking point is important to determine which equipment or system needs to be tested following a lightning strike. Existing lightning location systems can provide coverage of a wide area. For example, a lightning location system can provide coverage of an area having a 30 km radius. This system, however, has a 50% confidence region of about 500 meters. That is, the system has a 50% confidence that a lightning strike is within 500 meters of an identified location. As such, present lightning location systems cannot be used to determine whether a lightning strike occurred inside or outside of a parameter of an area of concern. One such application of a lightning location system is a space shuttle launch pad for the National Aeronautics and Space Administration (NASA). By accurately determining lightning strike locations, electronic equipment located within the launch pad area can be tested and/or reset to avoid erroneous operation.

One method of determining the location of lightning strikes uses a set of video cameras that are pointed in different directions within the area of concern. If a lightning strike occurs within the field of view of three or more cameras, the location of the strike can be determined. However, if the cameras are not pointed in the correct direction, or either an object or a heavy rain downpour obscures their field of view, it is difficult or impossible to accurately determine a striking point of the lightning. Further, this method has a relatively large uncertainty and does not facilitate an accurate location of the exact point of contact to the ground.

For the reasons stated above, and for other reasons stated below which will become apparent to those skilled in the art upon reading and understanding the present specification, there is a need in the art for a system and method to accurately locate locations of lightning strikes.

SUMMARY OF THE INVENTION

The above-mentioned problems with lightning strike location and other problems are addressed by the present invention and will be understood by reading and studying the following specification.

In one embodiment, a system to determine a location of lightning strikes comprises a processor, and a plurality of receivers coupled to the processor. Each of the receivers comprises an electric field sensor, an acoustic sensor, and a processor to provide a receiver output indicating a calculated time differential between an electric field pulse and a sound wave (thunder). The processor determines the location of lightning strikes in response to the output from the plurality of receivers.

A method is provided for determining a location of lightning strikes. The method comprises locating a network of at least three electric field sensors and at least three sonic sensors in an area of interest, and collecting lightning strike information, including a difference of the time of arrival of an electric field pulse and an associated sound wave from a lightning strike. The method processes lightning strike information recorded by at least three electric field sensors and at least three sonic sensors, including measuring a time difference between the arrival of the electric field pulse and the sound wave at each electric field and sonic sensor. The processor uses the time differentials to produce estimates of the range between the receiver and the lightning strike. The processed information is used to determine the location of the lightning strike.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of one embodiment of a receiver of the present invention;

FIG. 2 illustrates circles defined by a time difference between the arrival of an electric field signal and a sonic signal; and

FIG. 3 is a block diagram of a system of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description of the preferred embodiments, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific preferred embodiments in which the inventions may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that logical, mechanical and electrical changes may be made without departing from the spirit and scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the claims.

The present invention provides a system and method that can accurately locate a lightning strike within an area of interest. In one embodiment, the present invention can accurately locate a lightning strike within a few meters. Further, receivers used to detect lightning strikes can be located at distances of approximately one kilometer and greater apart. As explained below, the present invention uses a combination of electric field and sonic sensors.

The fast varying electric current associated with lightning discharges generates large electric field variations. The electric field waveform propagates at the speed of light in a radial direction from the striking point of lightning. The sudden heating of the air caused by the large currents associated with the lightning discharge produces a sudden expansion of the air near the lightning channel. This results in a sound wave (thunder) that initially, for the first few meters, propagates at a supersonic speed and later propagates at a sonic speed.

For an observer located remotely from a lightning strike location, the electric field waveform arrives earlier than the sonic sounds. This is because the electric field waveform...
travels and a speed of approximately 300,000,000 m/s, while the sound wave travels and approximately 350 m/s. The observer can estimate the distance to striking point by measuring the time difference between the arrival of the electric field waveform and the arrival of the sound wave. This measurement defines a circle, with the observer at the center, on which the lightning strike might have occurred. The second observer and a different location using the same type of measurement also has a circle defined around them in which the lightning might have occurred. These two circles intersect at two points. With the addition of a third observer, a single striking point can be determined. The present invention provides receivers that can be located remotely from each other to accurately determine lightning strike locations.

Referring to FIG. 1, a block diagram of one embodiment of a receiver 100 of the present invention is illustrated. The receiver includes an electric field antenna 110, a microcontroller 130, and a network of at least three receivers at different locations within a perimeter of interest to be monitored for lightning strikes. The microcontroller of each receiving station is used to measure the time difference between the arrival of the electric field pulse and the arrival of the sound wave. The timing information from each receiver 210, 220 and 230 is transmitted back to a central processing location 250, where the timing information is processed to obtain the location of the lightning strike, see FIG. 3. The accuracy of the system can be enhanced in one embodiment by using more than three receivers, such as receiver 240. A network of four or more receivers, for example, can be used to resolve uncertainties introduced by wind speed. Echoes and reflections from objects within the monitored area can be removed using common digital signal processing techniques.

The present invention allows for the accurate location of a lightning strike within a few meters using a combination of electric field and sonic sensors. One advantage of the present system includes the fact that high-speed digitizers are not required. The electric field pulse is used to start a time counter, and the sound wave is used to stop the time counter. A one-millisecond error in determination of the timing can result in an error of about 30 cm. Existing wideband, large baseline lightning location systems require timing accuracies better than a fraction of a nanosecond to achieve this kind of accuracy. The present invention provides an inexpensive and easy to install system, with minimal maintenance and calibration requirements.

The present invention allows for the determination of the distance to a lightning strike without requiring fast recording or digitizing equipment. Further, an algorithm to combine the information from a network of receivers allows for fine-tuning the system. Also, for example, an algorithm can be implemented to determine the location of a lightning strike when the wind is nonzero. This is important since nonzero wind will result in noncircular distance patterns around each receiver.

In another embodiment, the present system discriminates between nearby and distant thunder. Because sound waves are attenuated as they propagate through air, with high frequencies decaying faster than low frequencies, the frequency spectrum of nearby thunder contains higher frequency components than thunder from a distant lightning strike. The characteristic "rumble" from thunder consists mainly of frequencies below 100 Hz, while the "clap" occurred following a close lightning strike contains components above several kHz.

The following receiver algorithm illustrates discrimination between local and distant lightning strikes to avoid erroneous detection outside an area of interest:

```
x = rf("data")
y = abs(y)  
```

Read data file.

Perform time-domain convolution between data file and filter impulse response. This is equivalent to multiplying the spectrum of the thunder data by the frequency response of the filter. The result of the convolution is stored in variable y. Center variable y around zero (remove DC components).

```
ya = avg(y)
y = abs(y)
```

Get the absolute value of y and storage in variable z. This is equivalent to performing a rectification of the filtered thunder signal.

```
l = rf("hpf")  
z = dust  
```

Read highpass filter, cutoff of 200 Hz, finite impulse response (FIR). 31st order. Perform a time-domain convolution between the rectified thunder signal and the low pass filter impulse response. This results in the envelope of the thunder signal.
The primary sources of location error in the described invention are due to variations in the speed of sound and due to the effect of wind. The sound speed in air is a function of the temperature (changing as the square root of the absolute temperature) and the molecular weight. The latter changes due to variations in humidity, which can typically be ignored. By augmenting the present invention with externally measured temperature at the central processor; which allows for the computation of acoustic speed. In another embodiment, data measurement at the central processor is used to compute sound speed. This procedure minimizes the variance of all four variables jointly. This accuracy of this process improves as the number of receivers is increased.

The process is now described in detail. The equation for the range in terms of Xp and Yp the coordinates of the source point and Xi and Yi the coordinates of receiver "i" is given by (ignoring for the moment the wind):

\[ \Delta T_i = \sqrt{\left(\frac{X_i - X_p}{c}\right)^2 + \left(\frac{Y_i - Y_p}{c}\right)^2} \]

where there is one such equation for each detector. If this equation is expanded in terms of the coordinates of the event the following is obtained:

\[ \Delta T_{i} = \Delta T_{p} + \frac{\partial R}{\partial X_p} \Delta X_p + \frac{\partial R}{\partial Y_p} \Delta Y_p \]

Take \( \Delta T_{i} \) to be the measured time difference while \( \Delta T_{p} \) is the time difference that would be measured from an assumed position \( p \) and evaluate the derivatives at the assumed position \( p \), and interpret that the \( \Delta X_p \) and \( \Delta Y_p \) are components of a first order correction to the assumed position in a direction to reduce the difference between the measured \( \Delta T_{i} \) and the computed \( \Delta T_{p} \). By listing these linear equations in rows a matrix equation can be constructed and solve for the \( \Delta X_p \) and \( \Delta Y_p \) values. The derivative terms are:

\[ \frac{\partial R}{\partial X_p} = \frac{X_i}{R} \]

and

\[ \frac{\partial R}{\partial Y_p} = \frac{Y_i}{R} \]

which are easily calculated using the value for an assumed point \( X_p \) and \( Y_p \). The total equation in matrix form looks like:

\[ \begin{bmatrix} \Delta T_{i1} - \Delta T_{p1} \\ \Delta T_{i2} - \Delta T_{p2} \\ \Delta T_{i3} - \Delta T_{p3} \end{bmatrix} = \begin{bmatrix} X_i & Y_i \\ X_i & Y_i \\ X_i & Y_i \end{bmatrix} \begin{bmatrix} \Delta X_p \\ \Delta Y_p \end{bmatrix} \]

In matrix notation this same equations reads:

\[ \Delta \mathbf{R} = \mathbf{H} \Delta \mathbf{X} \]

To solve for the \( \Delta \mathbf{X} \) matrix the generalized inverse of the matrix \( \mathbf{H} \) is taken. The solution is given by:

\[ \Delta \mathbf{X} = \mathbf{H}^T (\mathbf{H} \mathbf{H}^T)^{-1} \Delta \mathbf{R} \]

Once the correction vector \( \Delta \mathbf{X} \) is solved, it can be added to the presumed values of \( X_p \) and \( Y_p \) to create a new estimate.
Thus the estimate at time step \( n \) is transformed into a new estimate a step \( n+1 \). After each step, the size of the residuals, the elements of the \( \delta T \) vector, are evaluated. When they become sufficiently small the process can be considered complete. The final values of the \( X_p \) and \( Y_p \) can be derived transformation from the \( \delta T \) equation to coordinate and the off diagonal terms are their covariants where again,

\[
\begin{align*}
\text{COV}(AT_x) = \text{COV}(\delta T_x) = \sum_{\delta x} = (\sigma_1^2 \sigma_1^2 \sigma_1^2 \sigma_1^2) \\
\text{COV}(AT_y) = \text{COV}(\delta T_y) = \sum_{\delta y} = (\sigma_1^2 \sigma_1^2 \sigma_1^2 \sigma_1^2)
\end{align*}
\]

where the diagonal terms represent the variances of each measurement and the off-diagonal terms represent the covariances between measurements. In the case of random errors only (such as digitizing timing jitter and random variations in the sound waveform) these terms are zero. In the case of systematic errors including the effects of wind, they will not be zero. If the error sources are unknown, such as the wind speed and direction, it can be assumed that the covariances are zero. The matrix can be constructed by inserting identical values for the diagonal elements representing \( \delta X \) measurement and the off-diagonal terms represent the covariance of the errors in the four \( \delta X \) measurements given as follows:

\[
\text{COV} (X_T) = E[\varepsilon X_T^2] = \sum_{\varepsilon T} = (\sigma_1^2 \sigma_1^2 \sigma_1^2 \sigma_1^2)
\]

where the \( \sigma_i \) values to get an ellipse encircling a 95% confidence level. The GDOP is given by:

\[
GDOP = \sqrt{\text{TRACE}(H^TH)^{-1}}
\]

This represents the magnification factor of the error based on the geometry of the lightning detectors and the computed lightning location. The GDOP is relevant to the present invention only in that should it be possible to select the best subset of available measurements (more than 4 receivers) the processor will select those that gave the best GDOP.

A preliminary solution has been provided without modeling any wind effects. Next, estimates of the wind speed and direction from at least four lightning \( \delta T \) measurements can be derived. By returning to the basic equation of \( \delta T \) as a function of wind speed and direction:

\[
\Delta T = \frac{R}{(c - Y_w \cos(\theta - \sigma))}
\]

Again, if a lightning location is assumed and a set of values for the wind speed and direction, this function can be expanded in a first order Taylor series as follows:

\[
\Delta T = \Delta T_0 + \left( \frac{\partial F}{\partial X_p} \right) dX + \left( \frac{\partial F}{\partial Y_p} \right) dY + \left( \frac{\partial F}{\partial V_w} \right) dV_w + \left( \frac{\partial F}{\partial \sigma} \right) d\sigma
\]

where each derivative is evaluated at the assumed values of position and wind characteristics. If four such measurement equations are written in matrix form the following results:

\[
\begin{align*}
\Delta T &= \Delta T_0 + \frac{\partial F}{\partial X_p} dX_p + \frac{\partial F}{\partial Y_p} dY_p + \frac{\partial F}{\partial V_w} dV_w + \frac{\partial F}{\partial \sigma} d\sigma
\end{align*}
\]

The GDOP is given by:

\[
GDOP = \sqrt{\text{TRACE}(H^TH)^{-1}}
\]

This ellipse has semimajor and semiminor axes given by:

\[
\begin{align*}
\sigma_x^2 &= \frac{1}{2} (\sigma_1^2 + \sigma_2^2) + \sqrt{\frac{1}{4} (\sigma_1^2 - \sigma_2^2)^2 + (\sigma_1^2 - \sigma_2^2)^2}
\sigma_y^2 &= \frac{1}{2} (\sigma_1^2 + \sigma_2^2) - \sqrt{\frac{1}{4} (\sigma_1^2 - \sigma_2^2)^2 + (\sigma_1^2 - \sigma_2^2)^2}
\end{align*}
\]

So unless the covariances are zero, the ellipse is inclined with respect to the x axis so that the angle between the semimajor axis and the x axis is given by:

\[
\tan 2\gamma = \frac{2\sigma_{xy}}{\sigma_x^2 - \sigma_y^2}
\]

Note that the value of confidence applied was 68.3%, the probability that the actual value falls within the ellipse is significantly reduced to only 39.4%. Thus many practitioners derive an ellipse based on 2.447 times the one sigma values to get an ellipse encircling a 95% confidence level.

Likewise, there is a covariance matrix of the estimated position values \( X_p \) and \( Y_p \) given as follows:

\[
\text{COV}(X_T) = E[\varepsilon X_T^2] = \sum_{\varepsilon T} = (\sigma_1^2 \sigma_1^2 \sigma_1^2 \sigma_1^2)
\]

where again, the interacting terms are the variances of each coordinate and the off diagonal terms are their covariances already derived transformation from the delta \( T \) equation to the delta \( X \) values to get an ellipse centered on the final estimates of \( X_p \) and \( Y_p \):

\[
f^{\Delta X} = m^T \Sigma_x
\]

Since the covariance matrix is symmetrical and positive definite it represents a quadratic form. If expressed in the following form it gives rise to an ellipse centered on the final estimates of \( X_p \) and \( Y_p \):

\[
f^{\Delta X} = a_1 x + a_2 y + a_3 x y + a_4 x^2 + a_5 y^2 + a_6 x y^2 + a_7 x^2 y + a_8 y^2 x + a_9 x^2 + a_{10} y^2
\]

where the \( A \) matrix elements are the values of the derivatives evaluated at the assumed values of the position, wind speed and direction. The equations for the derivatives are:
To compute the variances proceed:

\[
\alpha = \frac{R}{[1 - \frac{V_w}{c} \cos(\theta - \delta)]} = \frac{v[(X - X_r)]}{c[1 - \frac{V_w}{c} \cos(\theta - \delta)]}
\]

\[
\beta = \frac{(Y - Y_r)}{c[1 - \frac{V_w}{c} \cos(\theta - \delta)]}
\]

\[
\gamma = \frac{R \cos(\theta - \delta)}{c^2[1 - \frac{V_w}{c} \cos(\theta - \delta)]}
\]

\[
\eta = \frac{R \sin(\theta - \delta)}{c^2[1 - \frac{V_w}{c} \cos(\theta - \delta)]}
\]

When the values of the coefficients are evaluated, a simple matrix inversion is computed to find the values of the elements of the AX vector. These four values are then added to the original set of assumed values for the four sought parameters to derive a new set. The residuals (elements of the sigma x matrix) are evaluated between each iteration. When the residuals become sufficiently small, the process is complete. To compute the variances proceed as before with:

\[\Sigma = \Sigma_0,\]

and the error ellipse and GDOP are computed as before with the exception of only using the upper left block of four elements of the sigma x matrix.

This process results in optimal least square estimates of the position of the lightning strike and the errors in those estimates.

Conclusion

A system and method of determining locations of lightning strikes has been described. The system includes multiple receivers located around an area of interest, such as a space center or airport. Each receiver monitors both sound and electric fields. The detection of an electric field pulse and a sound wave are used to calculate a range circle around each receiver in which the lightning is detected. A processor is coupled to the receivers to accurately determine the location of the lightning strike. The processor can manipulate the receiver data to compensate for environmental variables such as wind, temperature, and humidity. Further, the system can discriminate between distant and local lightning strikes.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement, which is calculated to achieve the same purpose, may be substituted for the specific embodiment shown. This application is intended to cover any adaptations or variations of the present invention. Therefore, it is manifestly intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. A system to determine a location of lightning strikes comprising:
   - a processor; and
   - a plurality of receivers coupled to the processor, wherein each of the plurality of receivers comprises an electric field sensor, an acoustic sensor, and a controller to provide a receiver output indicating a calculated time differential between an electric field pulse and a sound wave, the processor determines the location of lightning strikes in response to the output from the plurality of receivers.

2. The system of claim 1 wherein each of the plurality of receivers are located up to at least one kilometer apart.

3. The system of claim 1 wherein the processor compensates for wind speed and wind direction while determining the location of lightning strikes.

4. The system of claim 3 wherein the processor compensates for wind speed and wind direction in the absence of wind speed and wind direction measurements.

5. The system of claim 1 wherein the processor compensates for temperature while determining the location of lightning strikes.

6. The system of claim 1 wherein the processor compensates for humidity while determining the location of lightning strikes.

7. The system of claim 1 wherein the plurality of receivers comprise three receivers.

8. A system to determine a location of lightning strikes comprising:
   - at least three receivers wherein each receiver comprises an electric field sensor, an acoustic sensor, and a controller to provide a receiver output indicating a calculated time differential between an electric field pulse and a sound wave; and
   - a processor coupled to the receivers to determine the location of lightning strikes in response to the output from the receivers.

9. The system of claim 8 wherein the processor compensates for environmental conditions including wind speed and wind direction, temperature and humidity while determining the location of lightning strikes.

10. The system of claim 9, wherein wind speed is corrected for by using angles between the receivers and the lightning location to compute estimated ranges R, using the following formula:

   \[R = \text{TOA} \times \text{V}_w \times \cos(\theta - \delta)\]

where TOA = measured time interval between the electromagnetic and sonic signals

V = effective sonic velocity

\(\text{V}_w\) = actual sonic velocity based on temperature

θ = azimuth direction measured from receiver to source

11. The system of claim 8 wherein each of the receivers are located up to one kilometer apart.

12. A method for determining a location of lightning strikes comprising:
   - locating a network of at least three electric field sensors and at least three sonic sensors in an area of interest;
   - collecting lightning strike information, including a time of arrival of an electric field pulse and an associated sound wave from a lightning strike;
   - processing the lightning strike information recorded by the at least three electric field sensors and the at least three sonic sensors, including measuring a time difference between the arrival of the electric field pulse and the sound wave at each electric field and sonic sensor; and
   - determining the location of the lightning strike.

13. The method of claim 12 wherein determining the location of the lightning strike comprises compensating for environmental conditions including wind speed and wind direction, temperature and humidity.

14. The method of claim 12 wherein the at least three electric field sensors are located up to one kilometer apart.
and the least three sonic sensors are located up to one kilometer apart.

15. The method of claim 12 wherein determining the location of the lightning strike comprises comparing the arrival of the electric field pulse and the sound wave for each pair of receivers.

16. The method of claim 12 wherein the network comprises at least four electric field sensors and at least four associated sonic sensors.

17. The method of claim 16, wherein wind speed is corrected for by using angles between the receivers and the lighting location to compute estimated ranges \( R \), using the following formula:

\[
R = \frac{\text{TOA} \cdot V}{\text{TOA} \cdot V_e - V \cdot \cos (\theta - \Theta)}
\]

where \( \text{TOA} \) = measured time interval between the electromagnetic and sonic signals.

18. The method of claim 12 wherein the processor compensates for wind speed and wind direction while determining the location of lightning strikes.

19. The method of claim 12, wherein the processor compensates for wind speed and wind direction in the absence of wind speed and wind direction measurements.

20. The method of claim 12 wherein processing the lightning strike information comprises discriminating between lightning strikes based upon distance to filter out lightning strikes outside the area of interest.