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A Radionuclide Counting Technique for Measuring Wind Velocity

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INTRODUCTION

There are several types of anemometers currently in use for both applied research and industrial applications. Many types of anemometers are designed to furnish only a single component of wind velocity; cup anemometers are an example (ref. 1). However, some physical situations warrant knowledge of the three components of wind velocity. Appropriate anemometers have been designed to furnish this information. A discussion of the advantages and the limitations of various types of anemometers can be found in the literature (ref. 2). The characteristics of some of them are briefly summarized below.

The hot-wire and hot-film type anemometers, which depend on the cooling power of the wind, are in general of small size and well-suited for use in a wide range of atmospheric pressures (refs. 3 to 5). For transient flow measurements, the hot-wire anemometer has no rival. Its frequency response extends to several hundred kilohertz. However, calibration is found to change with ambient temperature, with contamination of the wire, and with prolonged use. The hot-wire instruments are fragile and not very suitable for large wind-direction fluctuations. The hot-film instruments, on the other hand, are more rugged and also offer the advantage of substantial signal-to-noise ratio gain due to the high resistance of the film, though their frequency response extends only to a few kilohertz. The main use of the hot-film anemometers has been the measurement of turbulent liquids, though they can be used for the measurement of turbulent fluctuations in gases as well.

The three-axis sonic anemometer is based on the fact that the speed of sound increases or decreases depending on whether the sound is traveling in the direction of the wind or against the wind. This anemometer simultaneously measures the three components of velocity and seems to be sensitive only to wind components along the acoustic paths (refs. 6 and 7). Its frequency response is limited only by pathlength, and its calibration remains stable for extended periods. However, path averaging limits use of this type of anemometer to heights of 4 meters and above.

In the case of anemoclinometers, which are small in size, the wind velocity components are determined from pressure differences between the various sets of points on a metal sphere (ref. 8). The frequency response is reasonably good, limited only by the time constant of pressure transducers, but the probe needs to be oriented into the wind.

Remote wind velocity measurements in the atmosphere using laser Doppler methods have also been reported (refs. 9 to 11). These methods are nonintrusive, have advantages of remote sensing in inaccessible locations, and provide good velocity resolution. However, they require powerful lasers and rather delicate signal processing equipment.

Finally, the three-axis propeller anemometers and the propellers-on-bivane anemometers (ref. 12) are simple in design and moderate in cost. However, these anemometers are hampered by the limitations on their response, inherent in their structure.

In the spirit of continuing efforts for developing different kinds of anemometers, we describe a new technique for measuring wind speeds and direction. This technique is based on inverse-square-law variation of the counting rates as the radioactive source-to-counter distance is changed due to wind drag on the source ball. A feasibility study using a weak bismuth-207 radiation source and three Geiger-Muller (GM) radiation counters was conducted, and the results are described in this paper. Martian atmosphere parameters were used to illustrate the various characteristics and limitations of the technique. However, the use of the technique is not restricted to Martian or Mars-like environments.

An anemometer based on the proposed concept would be portable, yet not too fragile. It would be small and economical, would require low power, and could be used for extended periods of time, even in remote inhospitable places which are not easily accessible. The proposed anemometer would be usable in all noncorrosive media and in all locations, except places with no local gravitational force. The instrument would be a totally self-contained unit, capable of high accuracy and good frequency response (<1 kHz). Calibration of the anemometer would be affected only by changes in humidity. Thus, in fair weather, it would have long-term calibration stability, and its performance could be expected to remain unchanged after long-term continuous use. The only requirement is that the radiation detectors should be checked periodically to make sure they are working properly. These anemometers would require low maintenance and can measure the wide range of wind velocities normally encountered on Earth (up to 100 m/sec).

The physical principle of the technique and the experimental results, including a description of the apparatus, typical results, and frequency response characteristics, are described in this report. A discussion of a double-pendulum arrangement, useful for covering wider wind-speed ranges, is presented in the appendix.

SYMBOLS

A	cross-sectional area of the source ball
C_D	drag coefficient for a sphere
C_i	counting rate in the ith counter
D	drag on the source ball
d_i	distance of the ith counter from the source ball
$\frac{d\ell_x}{dV}$	rate of change of ℓ_x with wind velocity
$G_i(\theta,\phi)$	geometrical correction factor for the ith detector for the source ball displacement (θ,ϕ)
g	acceleration due to gravity
k	$= C_D \rho A/2mg$
ℓ_x	source ball displacement from its undisturbed position along x-axis
m	mass of source ball

N radioactive source disintegration rate (i.e., number of radiations per second emitted by the source)

R_{ij} ratio of counting rates in counters i and j

$R_{ij}(\theta,\phi)$ R_{ij} for the source ball displacement angles θ and ϕ

S_i area of the ith counter projected in a plane normal to d_i

V wind velocity

$\alpha_i(\theta,\phi)$ source self-absorption correction factor for the ith detector for the source ball displacement (θ,ϕ)

$\varepsilon_i(\theta,\phi)$ radiation detection efficiency for the ith detector for the source ball displacement (θ,ϕ)

θ angle of source ball displacement from the local vertical

ρ density of the medium in which the source ball moves

ϕ angle of source ball displacement from a reference line in the counter plane

PRINCIPLE OF THE PROPOSED TECHNIQUE

The technique is based on the dependence of counting rate on the solid angle subtended by the radiation counter at the location of the radioactive source. The source can be deposited on the lower side of a light, hollow sphere, such as a plastic table-tennis ball. The ball surface can be punctured with symmetrically distributed holes or otherwise appropriately roughened for aerodynamic stability. If the source is suspended by a flexible wire over the counter window, a certain counting rate determined by the source strength is obtained. If, however, the source position is changed due to wind drag on the source ball, the solid angle subtended by the counter at the source will decrease; consequently, a reduced counting rate will be observed.

A calibration graph of counting rate as a function of source position can help determine the source position (and hence the drag on the source ball) if the counting rate is known. Such a simple graph, however, will not enable one to determine the direction in which the source has moved. The counting rate will not change if the source is moved along the circumference of a circle whose center lies on the center of the projection of the counter window on the source plane. This ambiguity can be easily removed by using three coplanar radiation counters located at equal distances along the circumference of a circle with the source hanging over the center of the counter circle (see fig. 1(a)).

It should be noted that the counter plane is at right angles to the vertical line through the source support point. The relative counting rates in the three detectors will depend on the source position. Suppose that the source ball B is displaced through an angle (θ,ϕ) to position B' under the influence of drag D imposed on it by wind velocity V (see fig. 1(b)). The distances d_i between the displaced position of the source ball and the three counters are given by

$$\left.\begin{aligned} d_1 &= B'F = \{[h + \ell(1 - \cos\theta)]^2 + r^2 + \ell^2 \sin^2\theta - 2r\ell \sin\theta \cos(120 - \phi)\}^{1/2} \\ d_2 &= B'G = \{[h + \ell(1 - \cos\theta)]^2 + r^2 + \ell^2 \sin^2\theta - 2r\ell \sin\theta \cos\phi\}^{1/2} \\ d_3 &= B'H = \{[h + \ell(1 - \cos\theta)]^2 + r^2 + \ell^2 \sin^2\theta - 2r\ell \sin\theta \cos(120 + \phi)\}^{1/2} \end{aligned}\right\} \quad (1)$$

where h is the height of the undisturbed source ball from the counter plane; ℓ is the length of the suspension string; r is the radius of the counter circle; and F, G, and H are the respective locations of detectors 1, 2, and 3. Thus, the counting rates C_i in the three detectors will be

$$\left.\begin{aligned} C_1 &= N\, \alpha_1(\theta,\phi)\, G_1(\theta,\phi)\, \varepsilon_1(\theta,\phi) \\ C_2 &= N\, \alpha_2(\theta,\phi)\, G_2(\theta,\phi)\, \varepsilon_2(\theta,\phi) \\ C_3 &= N\, \alpha_3(\theta,\phi)\, G_3(\theta,\phi)\, \varepsilon_3(\theta,\phi) \end{aligned}\right\} \quad (2)$$

where N represents the number of source radiations (particles) emitted per second, and α_i, G_i, and ε_i represent the source self-absorption correction factor, the solid angle correction factor, and the radiation detection efficiency, respectively, for the ith detector. The source geometrical correction factor $G_i(\theta,\phi)$ is related to d_i by the equation $G_i(\theta,\phi) = S_i(\theta,\phi)/d_i^2$, where S_i represents the detector surface area normal to d_i.

By calculating the relative counting rates R_{ij} in the three pairs of detectors for various combinations of θ and ϕ, it should be possible to develop theoretical calibration curves of $R_{ij}(\theta,\phi)$ versus θ and/or ϕ. Such calibration curves can then be used to determine the displaced source ball position under the test wind field. The direction of the source ball displacement ϕ is the same as the wind direction. The magnitude of the source displacement angle θ is related to the wind speed as follows (see fig. 1(a) for geometrical definition):

$$\tan\theta = \frac{D}{mg} \quad (3)$$

where

$$D = \frac{1}{2}(C_D \rho A)V^2 \quad (4)$$

Substituting for D in equation (3) gives

$$\tan\theta = \left(\frac{C_D \rho A}{2mg}\right)V^2 = kV^2 \quad (5)$$

where

$$k = C_D \rho A / 2mg \tag{6}$$

m source ball mass

C_D steady sphere drag coefficient

ρ density of the atmosphere

V wind velocity

The value of the constant k can be easily determined by using appropriate values for the various parameters in equation (6). Thus, for $C_D = 0.47$ (drag coefficient for a smooth, unperforated, spherical source ball, ref. 13), $\rho = 1.23 \times 10^{-3}$ g-cm^{-3} (Earth), $\rho = 1.23 \times 10^{-5}$ g-cm^{-3} (Mars), $A = 5$ cm^2, $m = 10$ grams, $g = 981$ cm-sec^{-2} (Earth), and $g = 375$ cm-sec^{-2} (Mars), k is calculated to be 1.47×10^{-7} cm^{-2}-sec^2 for Earth and 3.85×10^{-9} cm^{-2}-sec^2 for Mars (ref. 14). Based on a calculation of k and measurement of source ball displacement angle θ, the wind speed is easily calculated using equation (5). As is evident from equation (5), the sensitivity of the instrument would be greatly dependent on the value of the source displacement angle θ. The source ball mass should therefore be so adjusted as to keep $\theta < 45°$.

It should perhaps be pointed out that a value of $C_D = 0.47$ for a spherical source ball is correct only in the case of an unperforated ball. If the source ball has to be perforated or otherwise roughened for reasons of aerodynamic stability, the value of C_D could increase significantly, depending on the size, number, and distribution of the perforations or the surface roughness parameter.

Although the counting rates in individual counters C_i and the relative counting rate in any pairs of counters R_{ij} can be easily calculated from equations (2), it may be more expedient to use experimentally obtained data on counting rate ratio in order to avoid possible complications caused by slow drifts in radiation detector efficiencies as well as changes in electronic system gains. Such calibration curves were developed using experimentally obtained counting rate data in the individual detectors and were used in the present study.

In certain atmospheric environments, the wind speeds vary widely. For example, the geostrophic wind velocity (constant level surface) ranges from about 25 to 142 m/sec for 85° to 10° latitudes (ref. 15), whereas on Mars, the wind velocity ranges from about 5 to 50 m/sec in the Northern Hemisphere and goes up to 90 m/sec in the Southern Hemisphere (refs. 3 and 4). These large ranges of wind speeds will require a special design for source mounting in order to maintain a reasonably uniform sensitivity if a single instrument is to be used throughout the range of wind speeds anticipated. This problem is further discussed in the appendix.

EXPERIMENTAL RESULTS

System Description

Figure 1(a) shows the general layout of the experimental system used in the feasibility study. Three Geiger-Muller tubes were located at equal distances along the circumference of a circle with a 0.3-m diameter. A 1-microcurie bismuth-207 electron source was attached to the bottom of a 0.025-m-diameter, plastic, hollow spherical ball. (1 microcurie equals 3.7×10^4 becquerels.) The ball was suspended from a rod at a height of 0.15 m from the Geiger-Muller counter plane. The source ball was moved along straight lines inclined at different angles with respect to the three counters in order to simulate different wind velocities. These lines, called configurations, are shown in figure 2.

Counting rates in the three detectors were measured for a preselected time for different source-counter configurations. Figure 3 shows individual counting rates in the three detectors as a function of angle of displacement of the source ball from the local vertical for a particular configuration. From the data of the type shown in this figure, relative counting rates were determined for the detector pairs (1,2), (2,3), and (3,1). Figure 4 shows relative counting rates R_{12} and R_{23} for various configurations.

It is clear from figure 4 that the source-counter configuration, and hence the direction of motion of the source ball with respect to a predetermined reference line, can be easily determined from the measured values of the relative counting rates in the three detectors. For example, if the ratio of the counting rates in detectors 1 and 2 (R_{12}) is 4.18 and the corresponding value for detectors 2 and 3 (R_{23}) is 2.00, then the source is displaced through an angle $\theta = 10°$ in configuration 1(-). Similarly, if $R_{12} = 2.00$ and $R_{23} = 1.40$, the source is displaced through an angle $\theta = 2°$ in configuration 2(-). A noteworthy feature of figure 4 is that appropriate combinations of detector channels permit a reasonably uniform sensitivity across the entire angular range ϕ.

Typical Results

In order to test the usefulness of the calibration curves of the type shown in figures 3 and 4, a collimated fan operating at a steady, reduced speed was directed at the source ball. The source ball moved away from its equilibrium rest position by an angle fluctuating between 1° and 2° along a line designated by configuration 2 in figure 3. The relative counts in the three detectors were within 10 percent of those expected for a source angular displacement of 1.5° in configuration 2.

By moving the fan to different positions, the source ball was made to move in different directions (i.e., follow different configurations), and the relative counting rates in the three detectors were measured. In each case, the agreement between the observed and expected counting rates was equally good. However, when the fan was turned on at high speeds, the source ball position fluctuated rather strongly between 4° and 8° from the local vertical, and the source ball had a tendency to move along a circular area. This behavior could be due to vortex shedding by the source ball, reflected wind fronts from the laboratory walls impinging on the source ball, or even the possible presence of unsteady wind components in the fan-generated "high-speed" wind field.

Reed and Lynch (ref. 16) reported some data on aerodynamic drag forces experienced by a ping-pong ball anemometer, aerodynamically similar to the one used in the present study. Their static calibration data obtained in a low-speed wind tunnel indicate that the drag force on the ping-pong ball remains steady (i.e., no vortex shedding) up to wind speeds of at least 20 m/sec - a velocity much higher than the one that caused unsteady displacement and a slight tendency for circular motion of the source ball in the present study. It would thus appear that the reflected wind fronts from the laboratory walls, coupled with the possible presence of a significant fluctuating component in the incident wind field, are the likely causes of the source ball fluctuation/rotation under the high-fan-speed conditions in this study. These high-speed tests also highlighted the need for optimum mechanical design of the source ball suspension assembly for damping high-frequency wind speed fluctuations.

It should be pointed out that experimentally measured counting rates and counting rate ratios - rather than the calculated values based on the source detector distances - have been used in this study. As indicated previously, this procedure minimizes the effects of slow drifts in the radiation detector efficiencies as well as changes in electronic system gains.

Frequency Response of the System

The frequency response of an instrument based on the proposed principle would be a strong function of the response time of the radiation detectors used. In the present study where GM counters were used to detect electrons, wind direction fluctuations at 0.1 kHz can be measured with an accuracy of about 10 percent for 10^4 source counts per second at the detector. However, the frequency response is not inherently limited in the measurement concept. It is determined primarily by the radiation detector response time. For a radiation detection system having a response time of 0.01 μsec, a frequency of 10 kHz is possible with an accuracy of the order of 1 percent with a source count of 10^8 per second at the detectors. These calculations do not include the effects of inherently slower mechanical component response functions which may well be the limiting factors in determining the overall instrument frequency response. It would thus appear that instruments based on the proposed principle would be more appropriate for velocity fluctuations of less than 1 kHz.

CONCLUDING REMARKS

A new technique for measuring wind speeds over a wide range (up to 100 m/sec) has been described. The technique is based on the inverse-square-law variation of the counting rate as the radioactive source-to-counter distance is changed by the movement of the source due to wind velocity. An anemometer based on the proposed principle would be usable in all noncorrosive media and in all locations, except places with no local gravitational force. It would be suitable for measuring wind fluctuation rates of up to 1 kHz, being limited only by the inherently slower mechanical response functions of the suspension system.

Even though the discussions presented here have assumed that the radiation counters are in a plane normal to the local vertical and that the wind direction is parallel to the counter plane, cases when the counter plane is not normal to the local vertical and when the wind is moving at an angle other than 90° to the local vertical can be easily treated by appropriately modifying the calibration constant of the instrument. The presence of a vertical wind component introduces lift in addition to the drag caused by the horizontal component, thus requiring a change in the calibration constant. This type of wind motion, however, is not usually encountered near terrestrial or planetary surfaces.

Geiger-Muller tubes and a weak electron source were used in the experimental system described in this paper. It may, however, be preferable to use semiconductor counters and stronger radioactive sources for higher accuracy as well as higher frequency response. It may also be necessary to use gamma radiation sources in certain terrestrial applications.

No attempt has been made to optimize the source mounting assembly or the source-counter geometry in this study. The sole purpose has been to investigate the feasibility of a radionuclide counting technique for wind speed measurements.

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APPENDIX

DISCUSSION OF AN ANEMOMETER WITH UNIFORM SENSITIVITY OVER A WIDE RANGE OF WIND SPEEDS

As indicated in the main text, certain atmospheric environments experience large changes in wind speed. In order to measure wind speeds with reasonably uniform sensitivity over these wide ranges, it will be necessary to use either a series of instruments with overlapping ranges or a single instrument with an adjustable source ball weight and/or size. Neither of these two alternatives appears to be satisfactory for practical reasons.

A novel approach might involve the use of a double pendulum incorporating a heavier, metallic ball of the same dimensions as the lighter, plastic source ball. Figure 5 shows a schematic diagram of such a system. For lower velocities, the lighter source ball will be displaced a considerable amount, while the heavier, metallic ball will barely move from its normal equilibrium position. For higher velocities, the source ball will be displaced through almost 90°, but the displacement of the heavier ball will be much less, thus offsetting the loss of sensitivity associated with larger angles of source ball deflection. By a proper system design, it may be possible to keep the impact of the wake of the upper heavier ball on the lighter source ball to a minimum, thus ensuring its stability. Such a double-pendulum system is described below. For the sake of simplicity, the problem of source ball displacement is discussed in one dimension only, but the treatment can be easily extended to three dimensions.

Consider two balls of masses m_1 and m_2. The first (heavier, metallic ball) is attached to a fixed support by a light inextensible string of length ℓ_1. The second (lighter, plastic source ball) is attached to the bottom of the first ball by a similar string of length ℓ_2. If the two balls have the same diameter and similar surface roughness characteristics, the drag force on them will be equal, and the equilibrium conditions can be described by the following equations (see fig. 5):

$$\tan \theta_1 = \frac{2D}{(m_1 + m_2)g} \tag{A1}$$

$$\tan \theta_2 = \frac{D}{m_2 g} \tag{A2}$$

where θ_1 is the angle of displacement of the first (heavier) ball, and θ_2 is the angle of displacement of the second (lighter) ball.

These equations can be used to design a system that may be appropriate for a wide range of wind velocities. The sensitivity of such a system will depend strongly on the rate of change of the source ball position with wind speed. For the one-dimensional case, one obtains

$$\frac{d\ell_x}{dV} = 4k_1\ell_1 V \cos^3 \theta_1 + 2k_2\ell_2 V \cos^3 \theta_2 \tag{A3}$$

where ℓ_x is the displacement of the source ball from its normal undisturbed position and

$$k_1 = \frac{C_D \rho A}{2(m_1 + m_2)g} \tag{A4}$$

$$k_2 = \frac{C_D \rho A}{2m_2 g} \tag{A5}$$

In the case of a single-pendulum anemometer, the corresponding equation will be

$$\frac{d\ell_x}{dV} = 2k\ell V \cos^3 \theta \tag{A6}$$

Figure 6 shows a graph of $d\ell_x/dV$ as a function of velocity for single- and double-pendulum arrangements for a specific case. It is apparent that the use of a heavy compensating ball considerably improved the sensitivity of response of the instrument.

It should be emphasized, however, that a part of the suspension string of the lower source ball may be exposed to the wake of the first ball at higher wind speeds, thus making the position of the source ball unstable. If proper mechanical design does not alleviate the problem, one of the following two approaches might provide the solution:

(1) Use alpha counting for lower speeds and electron counting for higher speeds. This can be accomplished by depositing americium-241, an alpha source, on the lower (lighter) ball and bismuth-207, an electron source, on the upper (heavier) ball and using a retractable, thin (<1 mg/cm^2) metal absorber in front of each detector. Both electrons and alpha particles would be counted at lower speeds when the absorber foil would be retracted, whereas only electrons would be counted at higher speeds when the absorber foil would be introduced in front of each detector. Thus, any instability in the position of the lower (lighter), americium-241-bearing ball at higher speeds will not affect the counting rates, which will be affected only by the position of the upper (heavier) ball bearing bismuth-207, an electron emitter.

(2) Use a reversible double-pendulum system wherein each ball will have bismuth-207 sources of equal strength deposited on it. For lower speeds (5 to 20 m/sec), the lighter ball will be suspended below the heavier ball, whereas these positions will be reversed at higher speeds (20 to 100 m/sec). By a suitable adjustment of the source weights and suspension string lengths, the lower ball can almost always be kept out of the wake of the upper ball.

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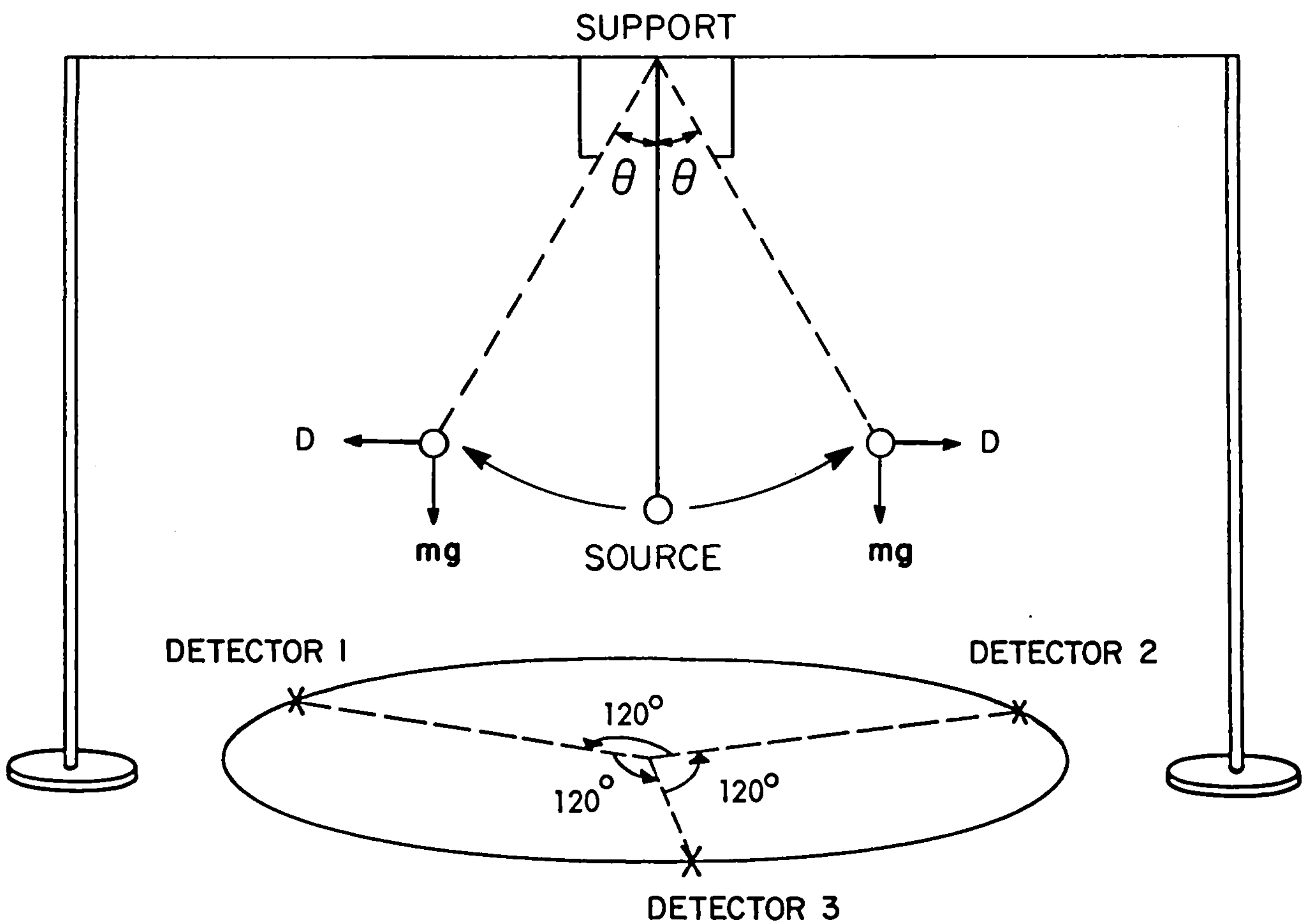
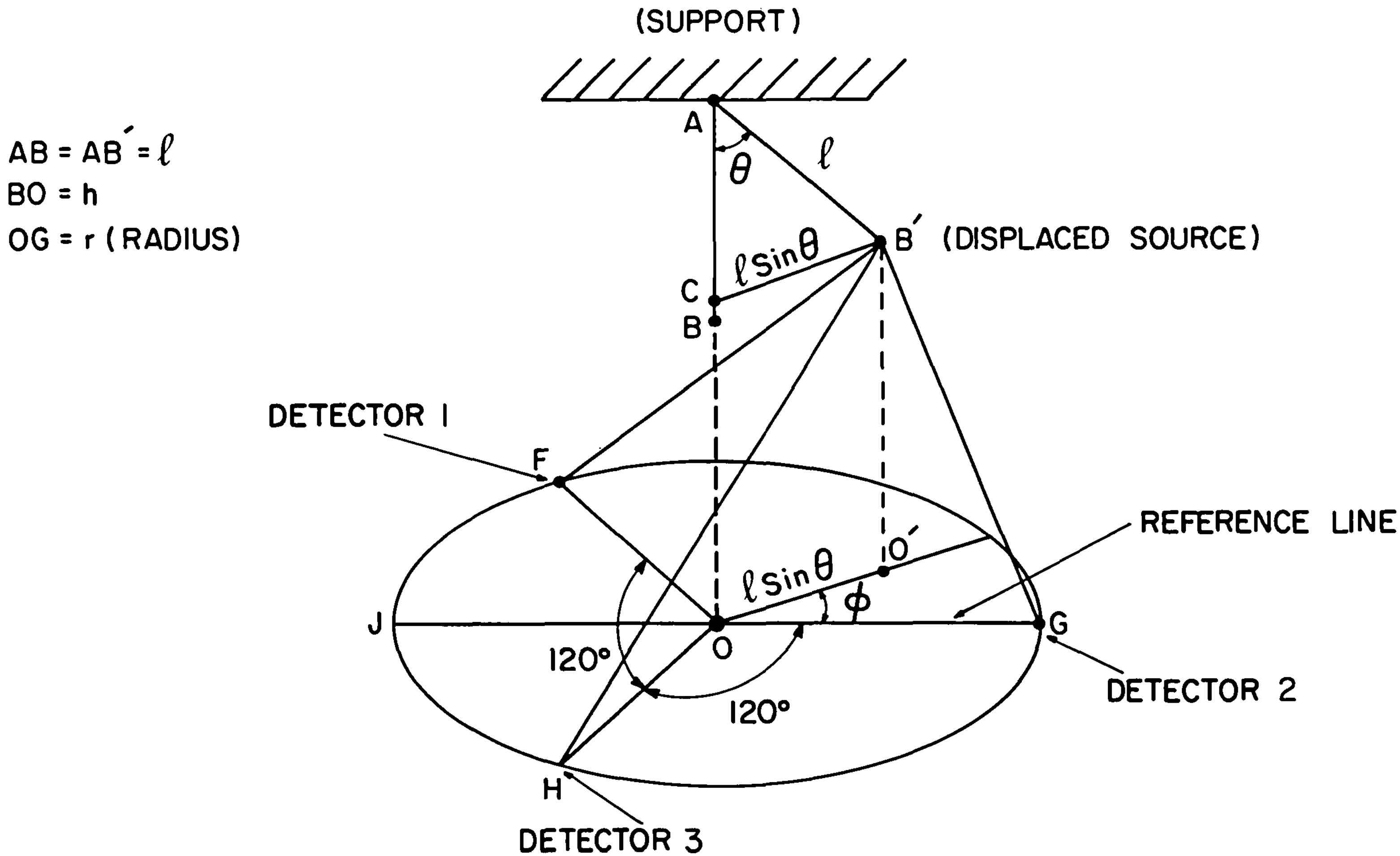


(a) Schematic diagram (not to scale).

Figure 1.- The radioactive counting anemometer.



(b) Schematic illustration of the effect of wind on the source-counter geometry.

Figure 1.- Concluded.

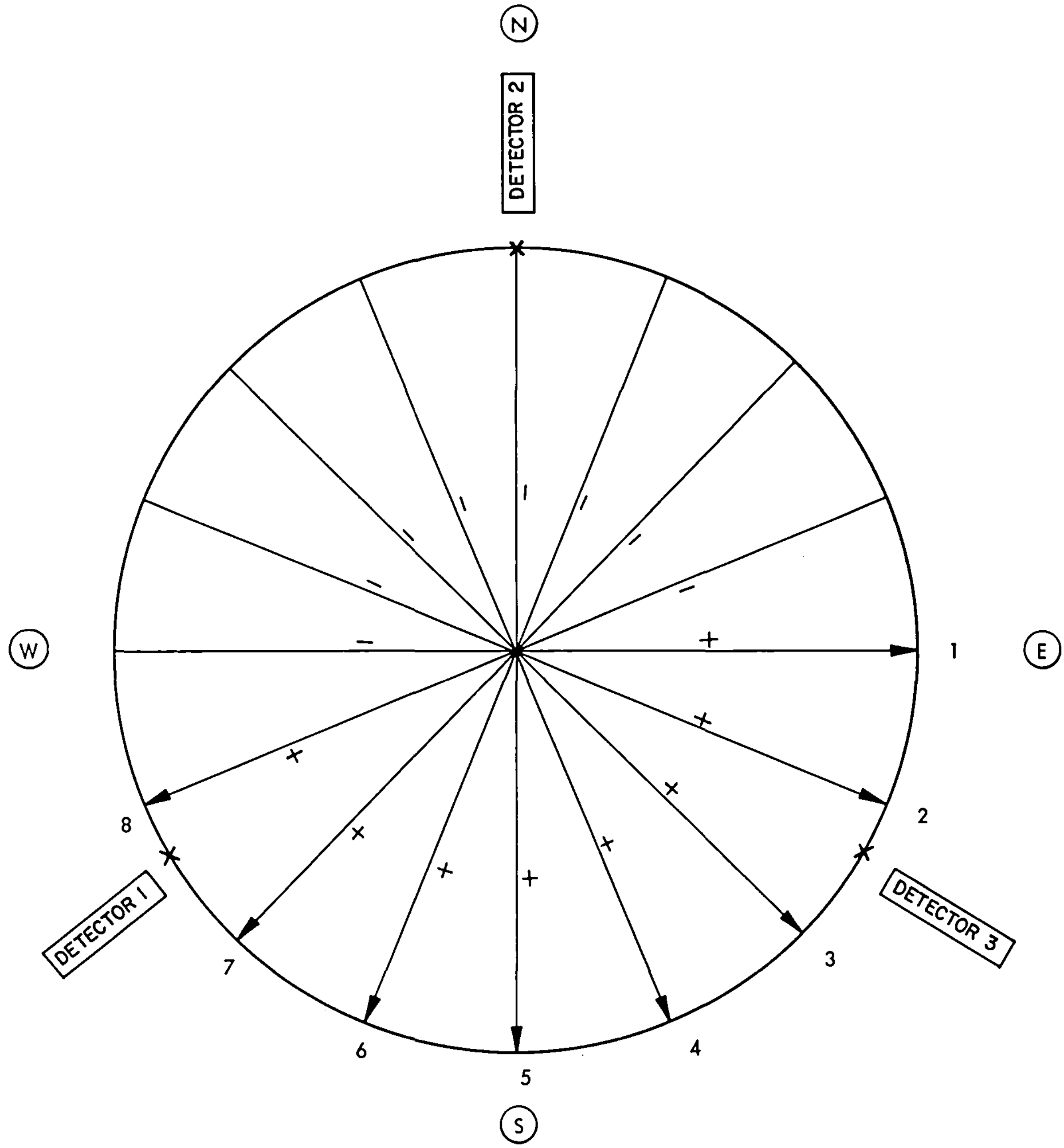
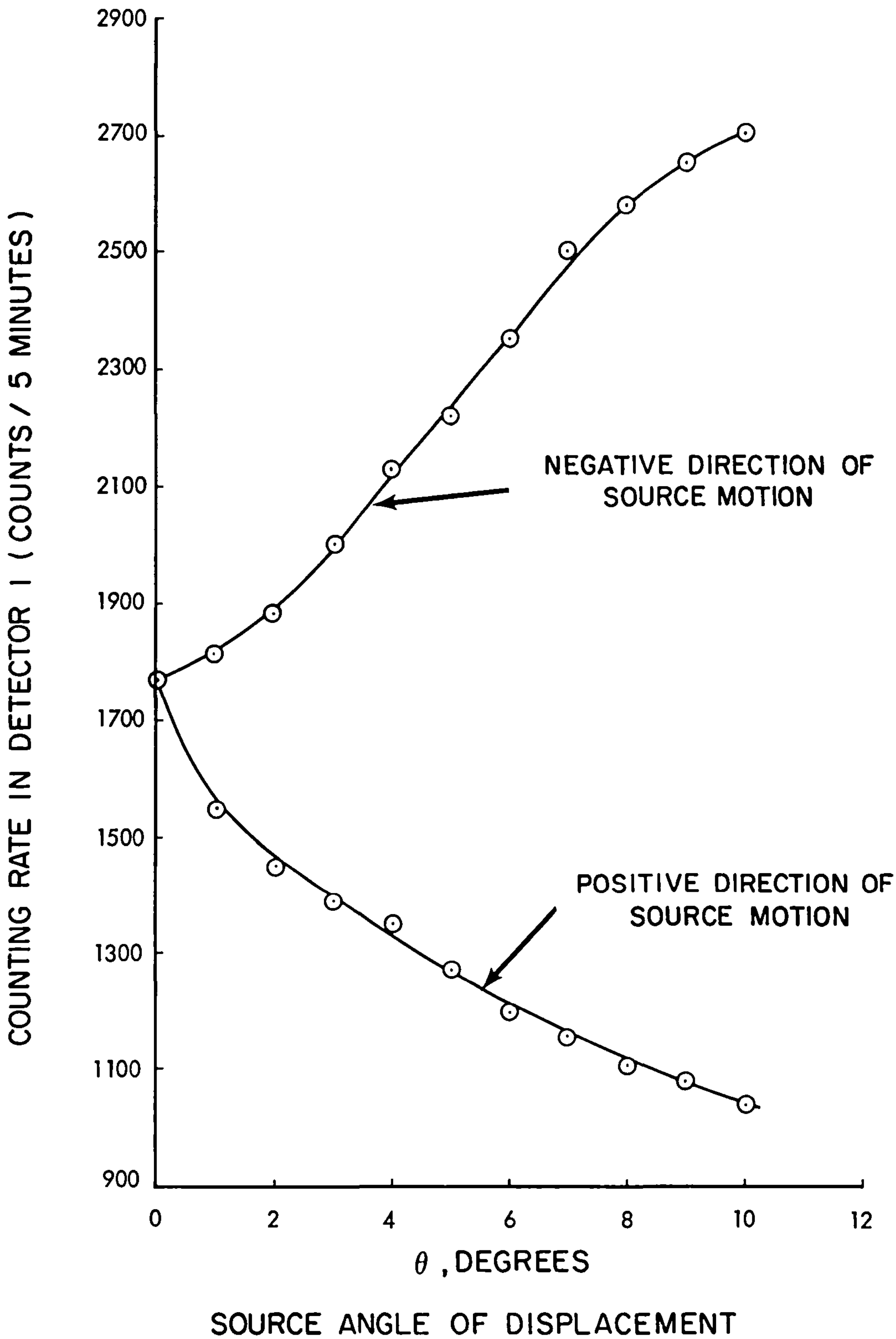
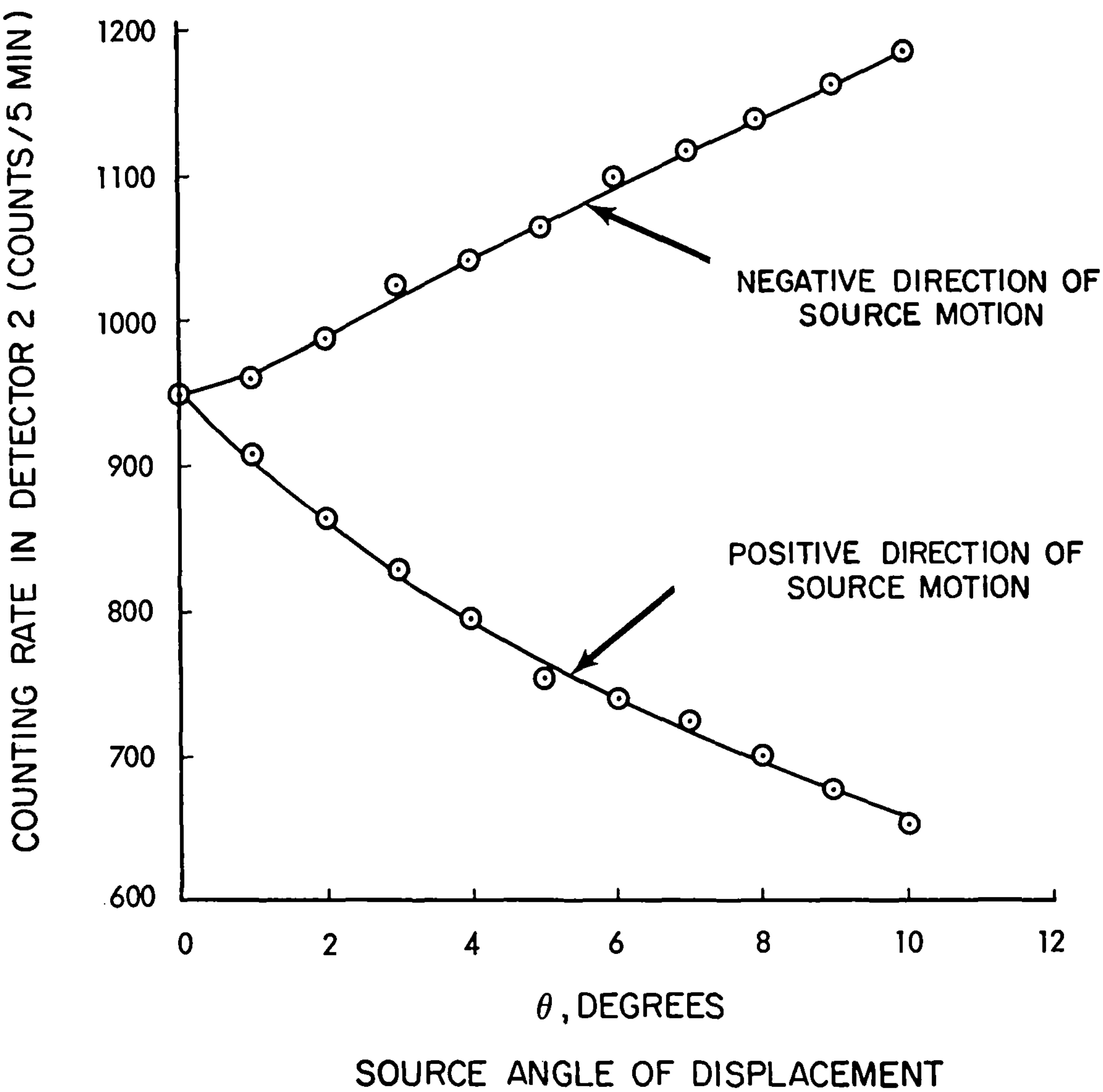


Figure 2.- This figure shows the source motion relative to the three counters. The numbers 1 through 8 along the circumference indicate the various configurations of the source motion. The direction of the source motion in a given configuration is indicated by ± signs. For a given angular displacement θ, the source ball could move in either direction in any configuration depending on the direction of the drag (and hence wind direction) on it. The magnitude of the angular displacement of the source ball θ is dependent on the magnitude of the drag (and hence wind speed) acting on it.



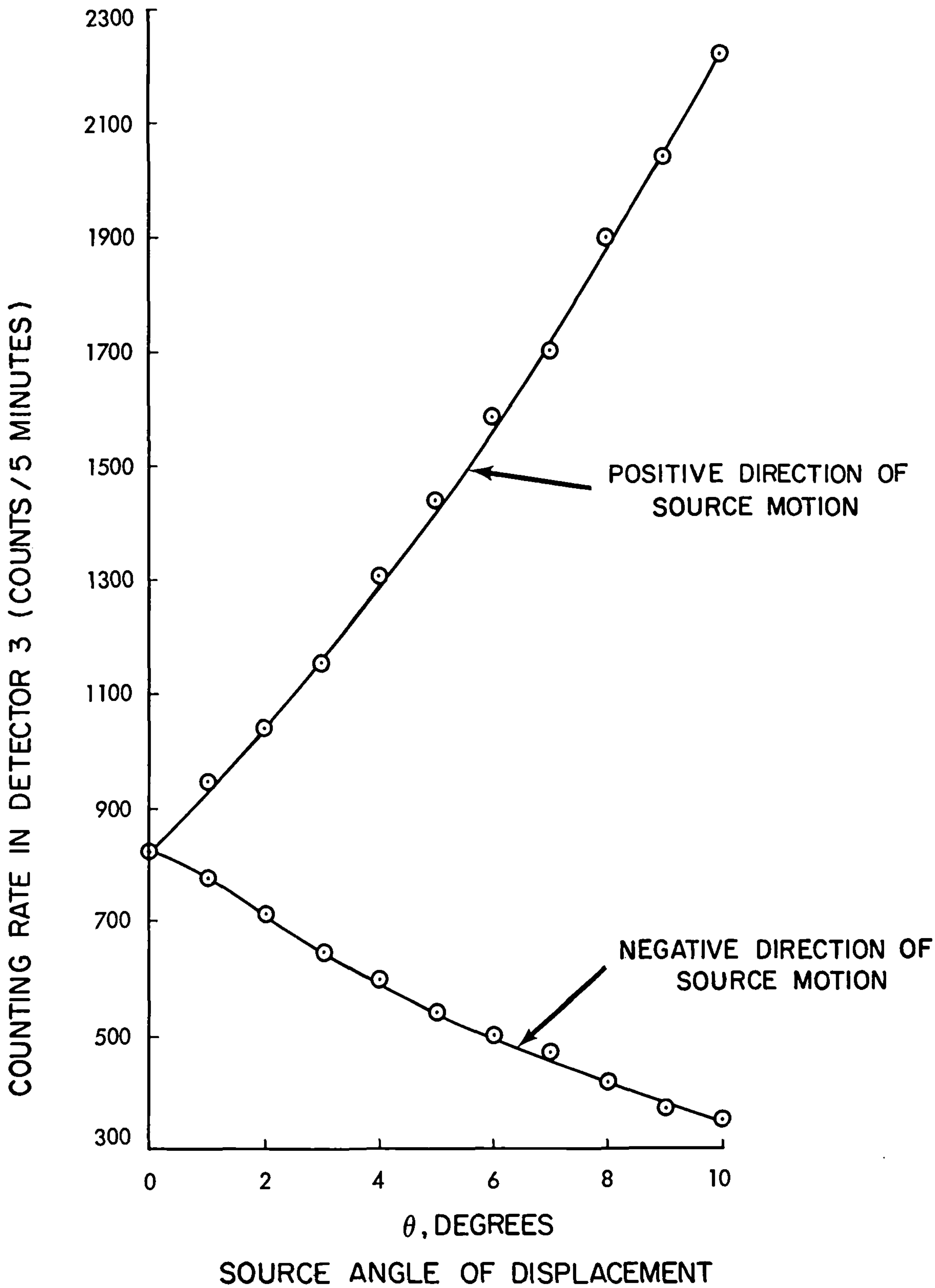
(a) Detector 1.

Figure 3.- Individual counting rates in the three detectors as a function of the angle of displacement of the source in configuration 2.



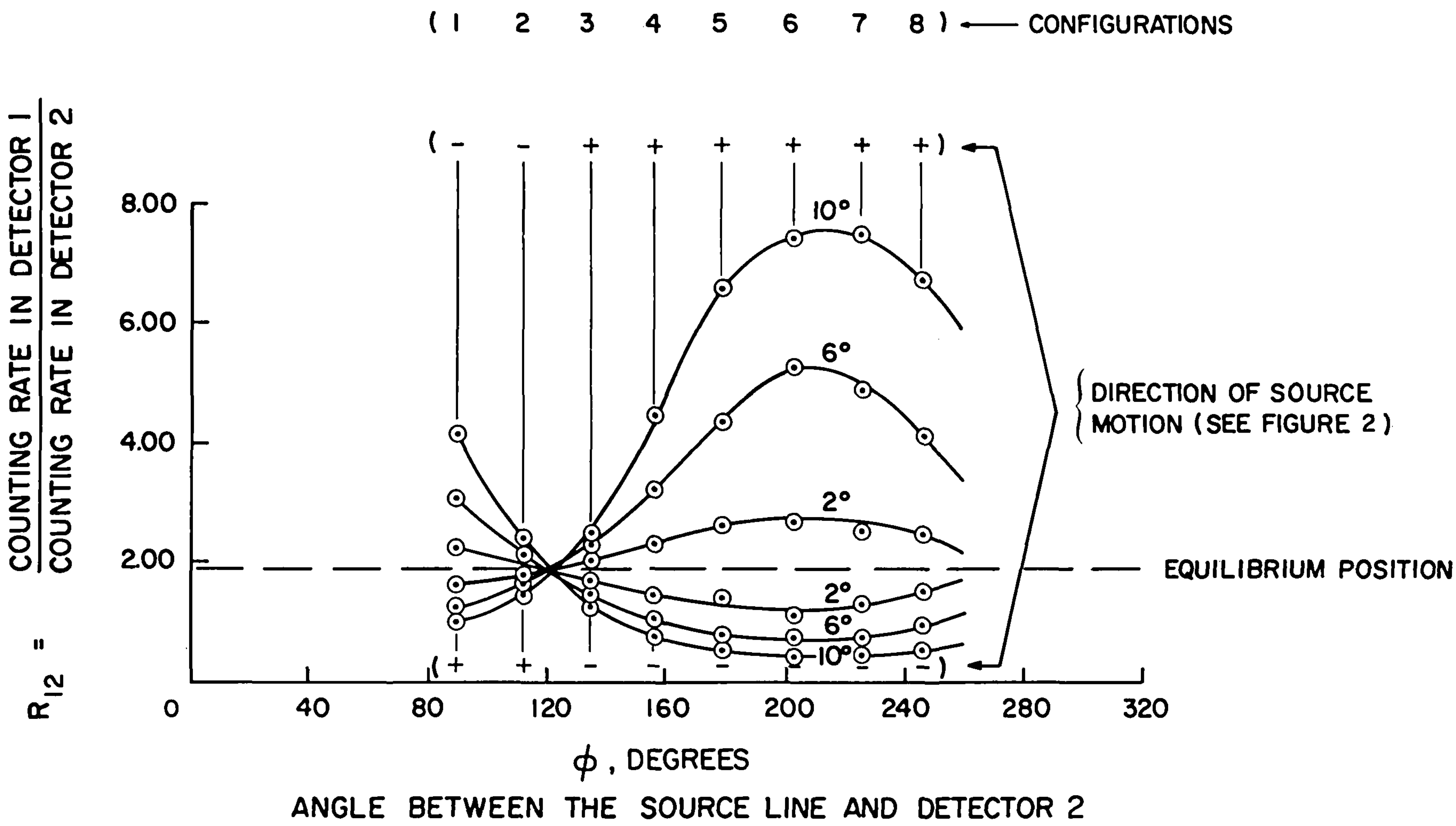
(b) Detector 2.

Figure 3.- Continued.



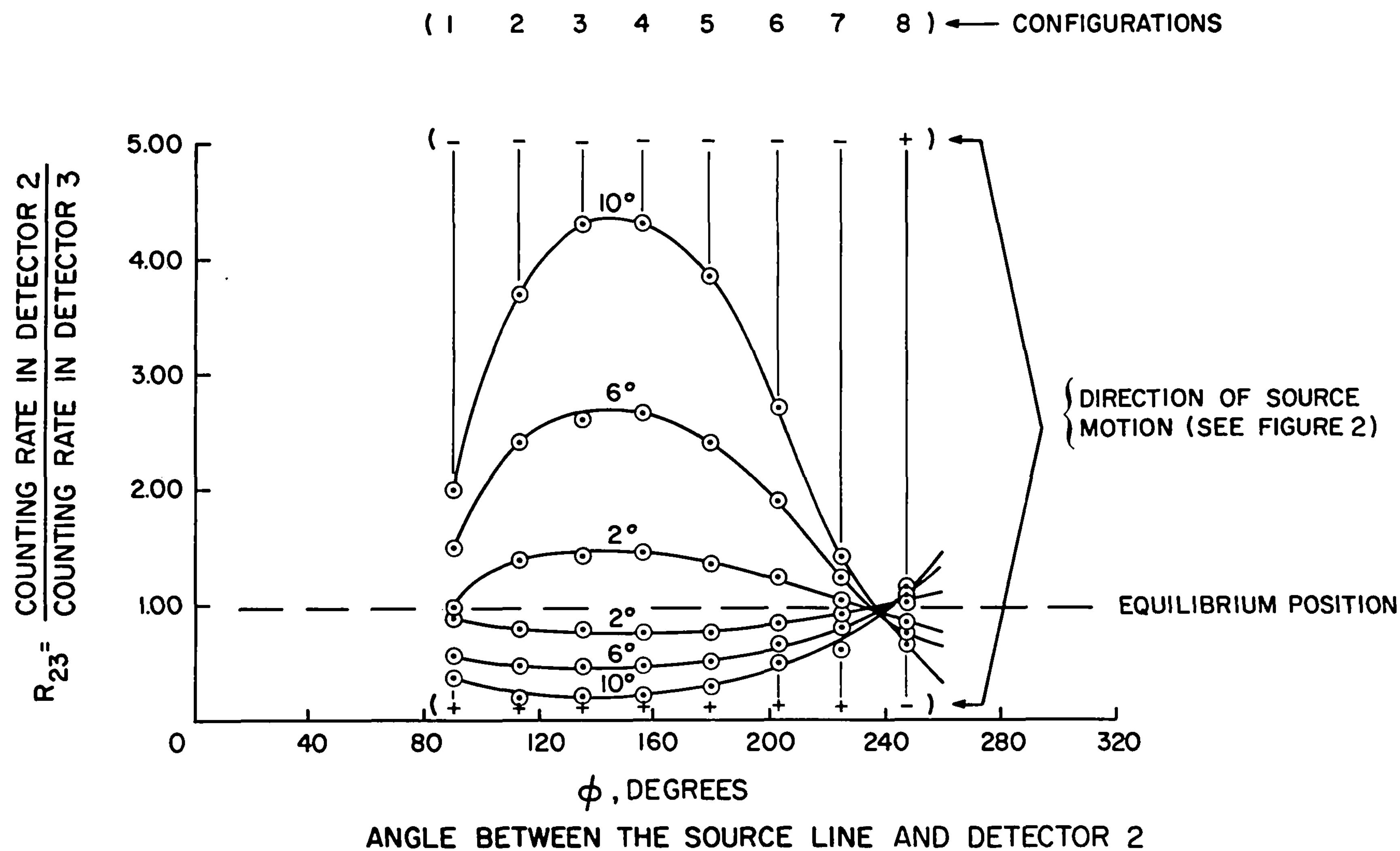
(c) Detector 3.

Figure 3.- Concluded.



(a) Detectors 1 and 2.

Figure 4.- Ratio of the counting rates in two detectors as a function of the angle between the source line and detector 2 for various configurations. The numbers on the curves indicate the angle through which the source ball has moved from its original vertical position.



(b) Detectors 2 and 3.

Figure 4.- Concluded.

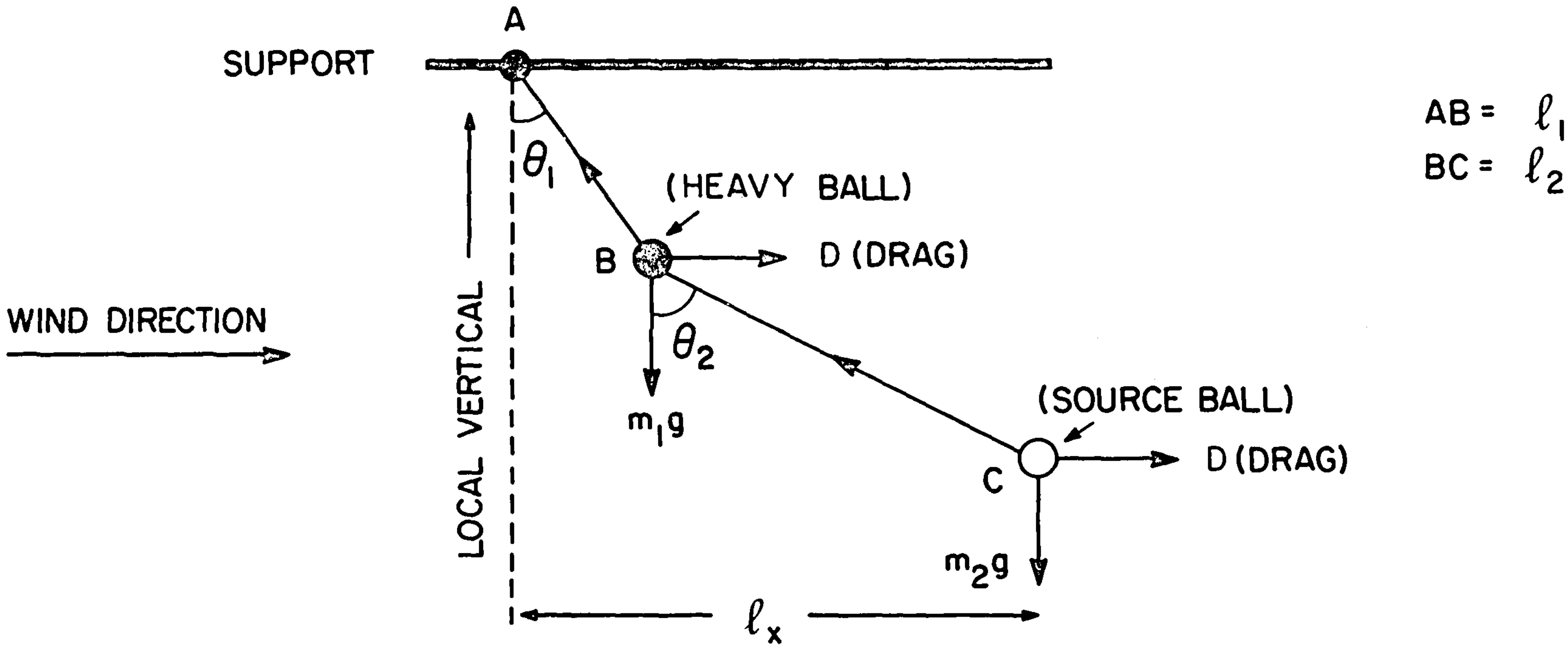


Figure 5.- A typical double-pendulum system orientation in the presence of wind drag.

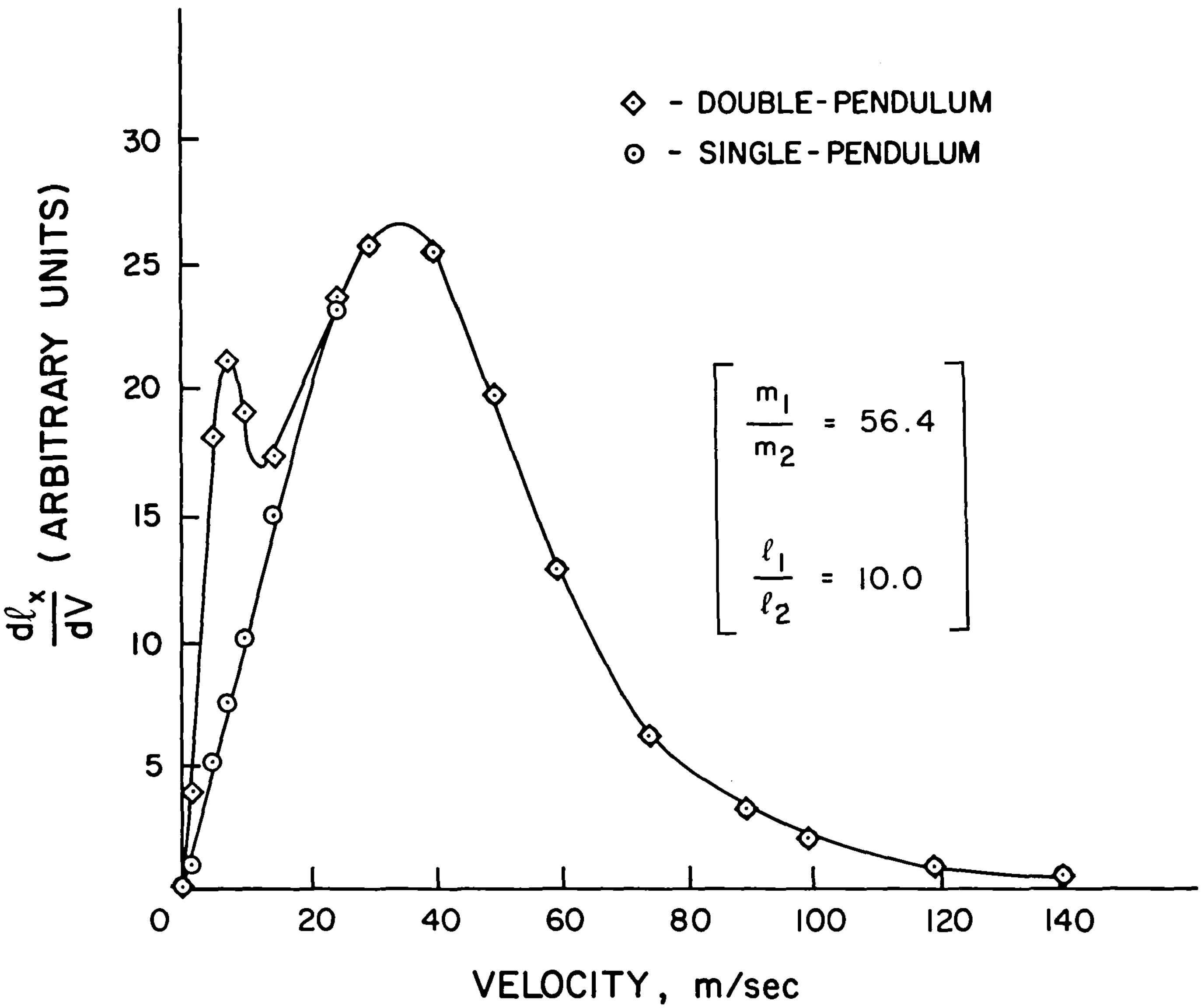


Figure 6.- A comparison of the sensitivity of single-pendulum and double-pendulum arrangements of the anemometer for various values of the wind speed.

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16. Abstract

A new technique for measuring wind velocities of meteorological interest is described. It is based on inverse-square-law variation of the counting rates as the radioactive source-to-counter distance is changed by the movement of the source caused by the wind velocity. The technique is usable anywhere, for all noncorrosive media, except in places with no local gravitational force. Measurements reported herein indicate that the proposed technique may be suitable for measuring wind speeds up to 100 m/sec, which are either steady or whose rates of fluctuation are less than 1 kHz.

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Radionuclide counting technique	Wide velocity range	
Wind speed		
Wind direction		Subject Category 35

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