

## A Robust Wind Estimation Scheme for Simple Tethersonde

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**Abstract**—This paper presents a robust wind estimation scheme for a simple tethersonde system, which is to use a commercially available radiosonde for recalibration and recovery. A radiosonde system determines wind speed and direction by keeping track of the radiosonde’s position as it rises. However, the method used in the radiosonde system is not suitable for the tethersonde system due to tethering to the ground. Hence, the proposed scheme introduces a drag force caused by the movement of the tethersonde to estimate the wind speed. This paper also evaluates the scheme through simulation in terms of wind speed estimation. Simulation results show that a radiosonde can be utilized as a tethersonde for the low and middle atmospheric observation without modification.

**Keywords**—tethersonde; atmosphere; wind speed; anemometer; radiosonde;

### I. INTRODUCTION

A radiosonde is used in measuring vertical profiles of atmospheric temperature, humidity, pressure, wind speed and wind direction as a balloon ascends through the atmosphere. The balloon typically rises up to an altitude of 35 km from the ground at a rate of a few meters per second. As the balloon ascends, it expands and eventually bursts, and then the radiosonde falls to the ground. Therefore, a radiosonde is not desirable for repeated calibration checks and repeated measurement because the system is discarded after once use [1], [2], [3].

On the other hand, a tethersonde is attached to the ground so that the limitations of a radiosonde can be mitigated by tethering to the ground. A tethersonde, in general, is to measure near the surface atmosphere up to an altitude of 1500 m and provides repeated calibration and measurement by adjusting the length of the tether line. Thus, detailed vertical profiles of meteorological atmosphere in the boundary layer can be obtained [4], [5]. A radiosonde system determines wind speed and direction by keeping track of its position through the use of global positioning system (GPS) receiver [6], [7]. However, unlike other parameters, the wind measurement method used in a radiosonde system is not appropriate for a tethersonde system because the tethersonde cannot move along the wind due to the tethering.

For this reason, this paper presents a simple and robust wind estimation scheme for a tethersonde system. The scheme firstly computes elevation and azimuth angles from the position of the tethersonde. Then, the wind speed is determined based on the drag force and the elevation angle calculated from the

force balance principle. The rest of this paper is organized as follows. In Section II, we describe system overview. Next, the wind speed and direction estimation algorithm is described in Section III. After that we analyze the proposed scheme in terms of wind speed estimation by simulation in Section IV. Finally, we conclude this paper in Section V.

### II. SYSTEM OVERVIEW

A tethersonde system consists of a tethersonde, a balloon and tether line, and a ground receiver system, as shown in Fig. 1. The scheme is to utilize a radiosonde as a tethersonde with or without modification. The tethersonde is equipped with sensors that measure temperature, air pressure, humidity, and GPS receiver to find its location. It periodically measures atmospheric parameters and transmits the parameters to the ground system in the 400 to 406 MHz meteorological band. As the tethersonde ascends, it reports in real time the temperature, humidity, pressure, and its position every second.

The ground system receives the data transmitted from the tethersonde and processes them in a personal computer (PC). Then, the PC estimates wind speed and direction by keeping track of the position of the tethersonde. The balloon and tether line are to suspend the tethersonde and to control its height by winding and unwinding the line. After observation, the tethersonde and balloon are recovered by winding the line.

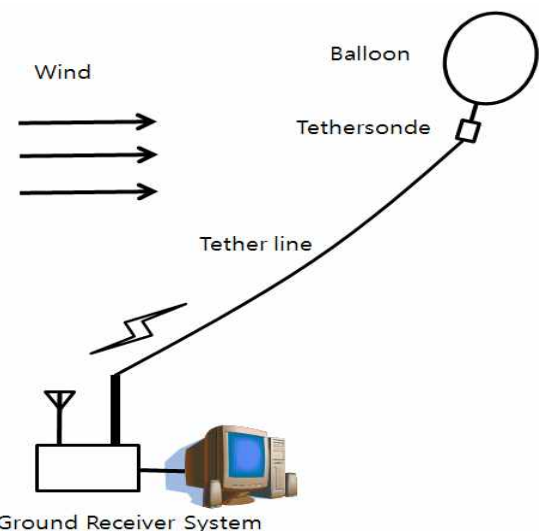


Figure 1. Tethersonde system consisted of a tethersonde, a ground receiver system, and a balloon and tether line

### III. WIND SPEED AND DIRECTION ESTIMATION ALGORITHM

To analyze the movement of a tethersonde caused by wind, a spherical coordinate system is considered. The coordinate system consists of the radius  $r$ , the elevation angle  $\theta$ , and the azimuth angle  $\varphi$ , as shown in Fig. 2. In the figure, the tethersonde is released at the origin point at time 0,  $p(x,y,z)_0$ , and after a time  $t$  the tethersonde is at a position,  $p(x,y,z)_t$ .

Once a tethersonde is launched, it travels horizontally at the same speed of the wind while the tether line is unwinding. When the tether line is released up to its maximum length, the tethersonde travels on the surface of the sphere whose radius is equal to the length of the line. Thus, the movement of a tethersonde can be classified into two stages, releasing stage and tethering stage.

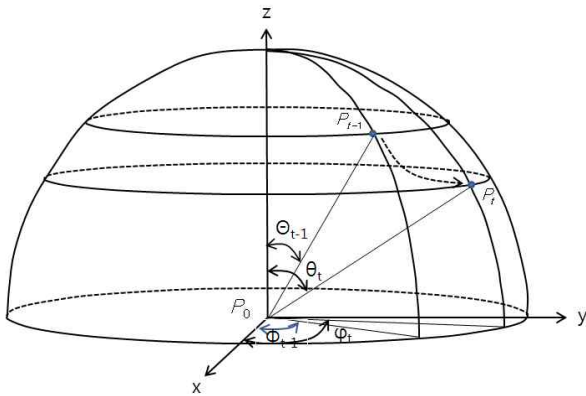


Figure 2. Spherical Coordinate system ( $r, \theta, \varphi$ ), where  $r, \theta$ , and  $\varphi$  represent radial distance, elevation angle, and azimuth angle, respectively.

#### A. Releasing Stage Analysis

Once a tethersonde is released into the atmosphere, the sonde is to rise by a lift force. The lift force consists of buoyant force and drag force,  $F_b$  and  $F_d$ . Consider that  $F_b$  includes the gravity force  $mg$  of the balloon, tethersonde and tether line. Then, the buoyant and gravity forces are calculated from approximately simultaneous tethersonde soundings.

Similarly, the drag force is equal and opposite direction of the buoyant force. Since  $F_d = -F_b$ , the drag force can be determined by evaluating the buoyant force, which is readily calculated from the available data. The average density of the air is obtained from approximately simultaneous radiosonde soundings, and the cross sectional balloon is known. Then, the average lift force and lift speed of the balloon are defined as,

$$F_b = \frac{1}{2} \rho C_d A V_b^2, \quad (1)$$

$$V_b = (2F_b / \rho C_d A)^{1/2}, \quad (2)$$

where  $\rho$  is the density of air,  $V_b$  is the lift speed caused by the buoyant force,  $C_d$  is the drag coefficient, and  $A$  is the cross sectional area of the balloon.

Let  $V_l$  be the average lift speed over the measurement period  $T$ , which denotes the difference between time  $t$  and  $t-1$ . Then,  $V_l$  is given by the equation,

$$V_l = \|\rho(z)_t - \rho(z)_{t-1}\| / T. \quad (3)$$

According to (2) and (3), it is clear that the wind has an ascending air current if  $V_l$  is greater than  $V_b$  and a descending air current if  $V_l$  is less than  $V_b$ .

On the other hand, when the tethersonde is moved from  $p(x,y,z)_{t-1}$  to  $p(x,y,z)_t$ , the horizontal wind speed and direction,  $V_w$  and  $\varphi_w$  can be expressed as,

$$V_w = \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} / T, \quad (4)$$

$$\varphi_w = \arctan[(y_t - y_{t-1}) / (x_t - x_{t-1})]. \quad (5)$$

The values of  $p(x,y,z)_t$  are known since they measured every second. With the information, the horizontal wind speed and direction can be estimated by (4) and (5).

#### B. Tethering Stage Analysis

When the tether line is released up to the maximum length, the tethersonde travels on the surface of the sphere whose radius equal to the maximum length of the line. Fig. 3 represents the relation among buoyant, wind, and tension forces in the tethering stage, where the tethersonde stays at a point or moves on the surface of the sphere. The tethering stage can also be divided into two states, steady state and dynamic state, depending on the position changes of the tethersonde.

Fig. 3 (a) shows the relation of the string tension  $F_T$  to wind force and buoyant force in the steady state, which is represented by  $F_T^2 = F_b^2 + F_w^2$ . In the steady state, the wind speed  $V_w$  can be determined from the buoyant force and the elevation angle. From the relation, the wind force and speed can be calculated by

$$F_w = F_b \tan \theta, \quad (6)$$

$$V_w = (2F_w / \rho C_d A)^{1/2}. \quad (7)$$

The cross sectional areas in (2) and (7) may be different depending on the directions, vertical side and horizontal side. On the other hand, in the dynamic state, the balloon is being moved from  $p(x,y,z)_{t-1}$  to  $p(x,y,z)_t$  during the measurement period, as shown in Fig. 3(b). When the tethersonde moves through the air, a drag force acts opposite direction to the movement of the tethersonde. The relation between acceleration and net force is given by Newton's second law of motion,

$$\sum \vec{F} = \vec{F}_b + \vec{F}_w + \vec{F}_T + \vec{F}_d = m\vec{a}. \quad (8)$$

Let  $\vec{V}_s$  and  $\vec{F}_d$  be the velocity and drag force of the tethersonde on the surface of the sphere, respectively. In this paper, the impact of tether line was ignored for simplicity. Assuming that azimuth angle is constant,  $\vec{V}_s$  and  $\vec{F}_d$  can be written as

$$\vec{V}_s = R\dot{\theta}\vec{a}_\theta, \quad (9)$$

$$\vec{F}_d = \frac{1}{2}\rho C_d A V_s^2. \quad (10)$$

Let  $m$  and  $\vec{a}$  denote the mass and acceleration of the tethersonde, respectively. The acceleration of a tethersonde may be expressed in the spherical coordinate system by taking into account the associated variation in the unit vectors,

$$ma_r = m(\ddot{r} - r\dot{\theta}^2) = F_b \cos \theta + F_w \sin \theta - F_T, \quad (11)$$

$$ma_\theta = m(r\ddot{\theta} + 2\dot{r}\dot{\theta}) = -F_b \sin \theta + F_w \cos \theta - F_d. \quad (12)$$

Where,  $\dot{x}$  and  $\ddot{x}$  denotes the first and second derivative of  $x$ . The wind speed may then be estimated by (8) or (12). Equation (8) can be modified to

$$\vec{F}_w = m\vec{a} - \vec{F}_d - \vec{F}_b - \vec{F}_T, \quad (13)$$

$$V_w = (2F_w / \rho C_d A)^{1/2}, \quad (14)$$

$$\varphi_w = \arctan\left(\frac{y}{x}\right). \quad (15)$$

When a tethersonde stays at a position,  $m\vec{a} = \vec{F}_d = 0$ , equation (14) is equivalent to (7). Therefore, the wind speed and direction can be determined by (14) and (15), respectively.

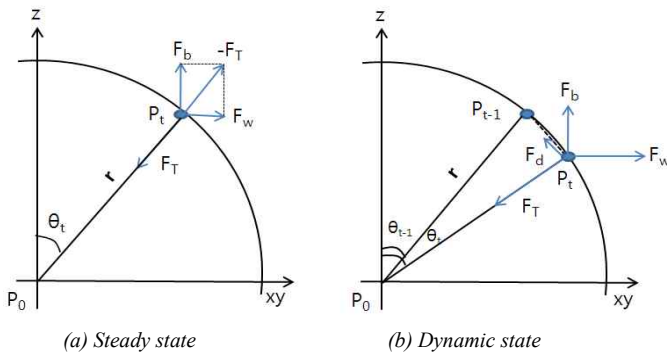


Figure 3. Relationship among lift, wind, and tension force in the tethering stage, where a tethersonde moves on the surface of the sphere.

### C. Wind Estimation Algorithm

From the analysis, the wind speed and direction can be determined in the tethersonde system, as shown in Fig. 4. In the system, the GPS receiver in the tethersonde periodically reports its longitude, latitude, altitude, and wind speed. The ground receiver system then calculates the distance  $R$  between the origin point and current point from the received data. Depending on  $R$ , the algorithm goes into either the releasing stage or tethering stage. When the variation of wind speed is small enough, the algorithm may perform the wind estimation method of the steady state. On the other hand, although the algorithm may cause some error whenever the stages are changed, the error can be recovered in the steady state.

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-- Wind speed and direction estimation algorithm
from position tracking of a tethersonde
--  $V_w$  : horizontal wind speed
--  $\Phi_w$ : wind direction
--  $P(x,y,z)_t$ : tethersonde's position at time t
 $R_t = \sqrt{(x_t - x_0)^2 + (y_t - y_0)^2 + (z_t - z_0)^2}$ 
If ( $R_t = L_{max}$  and  $R_{t-1} = L_{max}$ ) -- tethering stage
 $\theta = \arctan(\sqrt{x^2 + y^2} / z)$ 
 $\vec{V}_s = R\dot{\theta}\vec{a}_\theta$ 
 $F_d = \frac{1}{2}\rho C_d A V_s^2$ 
 $\vec{F}_w = m\vec{a} - \vec{F}_d - \vec{F}_b - \vec{F}_T$ 
 $\varphi_w = \arctan(y / x)$ 
Else -- releasing stage
 $V_w = \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} / T$ 
 $\varphi_w = \arctan[(y_t - y_{t-1}) / (x_t - x_{t-1})]$ 
End;
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Figure 4. Proposed wind estimation algorithm

### IV. SIMULATION RESULTS

To verify the proposed scheme, we considered simulation parameters similar to a radiosonde as described in Table I. From the parameters, we can obtain buoyant force, lift speed caused by buoyant force and the radius of the sphere.

Fig. 5 shows the wind speed versus flight time and the trace of tethersonde in a spherical coordinate system. It was tested with the actual measurement data taken by a radiosonde system in a fine day at a location of longitude 127°(E) and latitude 37°(N). The measurement data include measurement time, latitude, longitude, altitude, and wind speed. The distance from origin to the tethersonde, elevation angle, azimuth angle, and lift speed variation are calculated from the measurement data. In Fig. 5(b), until flight time 270 seconds, the position trace is plotted from the measurement data. After then, the position

trace is plotted from both the distance and altitude that are calculated from the measured wind speed.

TABLE I. SIMULATION PARAMETERS

Parameters	Value	Description
Vol	7000 liters	Volume of balloon
$\rho_{\text{helium}}$	0.178 g/e	Density of helium gas
$\rho_{\text{air}}$	1.293 g/e	Density of air
$m_{\text{sonde}}$	370g	Mass of the balloon and radiosonde
$A_{\text{balloon}}$	$\pi(\frac{3}{4\pi}Vol)^{2/3}$	Sectional Area
$L_{\text{max}}$	1.5 km	Maximum length of tether line

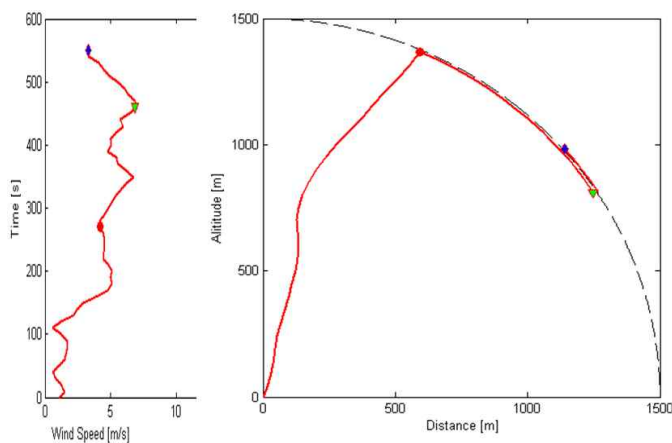
Fig. 5 (a) and (b) have three markers, red circle, green triangle, and blue diamond. The same markers in each plot correspond to each other. Table II represents the detailed values of the three points. For example, the red circle indicates 270 seconds of flight time, 611 m of horizontal distance, 1370 m of altitude, and 4.2 m/s of wind speed. After 270 seconds, the tethersonde moves on the surface of the sphere according to the wind speed and direction. For example, the green triangle shows that the wind speed is increased up to 7.0 m/s at time 469 seconds.

The figure shows that the tethersonde moves up and down along the surface of the sphere with the wind force.

TABLE II. SIMULATION RESULTS AT THREE POINTS

Marker	Time [s]	Distance [m]	Altitude [m]	Elevation angle[deg]	Wind speed [m/s]
circle	270	611	1370	24	4.2
triangle	469	1284	775	58	7.0
diamond	550	1134	982	49	3.3

Accordingly, the radius of the sphere is adjustable by changing the length of the tether line. In a similar manner, the scheme provides more detailed vertical profiles in the low and middle atmosphere by repeatedly winding and unwinding the tether line.



(a) Wind speed vs. flight time (b) Position trace

Figure 5. Wind speed vs flight time and position trace of tethersonde on the sphere.

V. CONCLUSIONS

In this paper, a robust wind estimation scheme for a simple tethersonde system has been presented, which utilizes a commercial radiosonde as a tethersonde for the low and middle atmospheric observation. A radiosonde is not desirable for recalibration and recovery due to discarding after use. To mitigate the limitations, the proposed scheme is to use the radiosonde by tethering to the ground for ascending and descending. However, although the atmospheric measurement techniques in the radiosonde are useful, the method for wind speed and direction measurement is not suitable for the tethersonde system.

The proposed scheme determines wind speed and direction by adopting a drag force in the dynamic state when the tethersonde moves on the surface of the sphere. Simulation results show that the scheme can be used in a simple tethersonde system for wind speed and direction measurement without additional wind sensor. The scheme also provides more detailed vertical meteorological profiles of the low and middle atmosphere by winding and unwinding the tether line. In addition, the observation altitude is extendable more than 1500 m just by increasing of the length of the tether line.

Further studies are needed to analyze the impact of tether line on wind speed estimation and verify the scheme under various environment conditions.

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