A New Wind Sensor for Rocket Launches

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The purpose of this research was to design and develop a low cost wind measurement device using a tethered pilot balloon, tracked with an observing telescope. A telescope-mounted Celeston SkyScout® sensor provides line of sight elevation and azimuth angles using a GPS receiver, and triaxial accelerometers and magnetometers. Balloon altitude was controlled by measuring deployed tether length and elevation angle. This equipment proved to be inexpensive, practical and suitable for wind compensation of academic sounding rockets.

Nomenclature

B	=	Buoyancy Force = ρ *Vol g (N)*
C_d	=	Drag Coefficients.
D	=	Drag Force *(N)*
d	=	Deployed tether length (*m*)
g	=	Acceleration due to gravity *(m/s²)* → (m/s^2)
h	=	Balloon altitude (*m*)
Re	=	Reynolds Number
S	=	Reference area = Balloon cross section area (m^2)
T	=	Tensile Force *(N)*
V	=	Wind speed *(m/s)*
Vol	=	Volume of balloon (m^3)
W	=	Weight of balloon and He gas and tether *(kg)*
ρ	=	Density (kg/m^3)
θ	=	Elevation Angle (*Deg)*

I. Introduction

Unmodeled errors in the wind profile traversed by a fin-stabilized sounding rocket are by far the largest single cause of trajectory prediction error. Safe operations imply control of rocket impact points by measurement of the winds and compensation via changes in launch rail azimuth and quadrant elevation angles. The objective of this project was to develop a functional wind measurement system (hardware & software) suitable for wind compensation of California State University Long Beach (CSULB) Prospector sounding rockets.

This research explores a new wind measurement concept. Many techniques for wind measurement exist. The classical Robinson cup anemometer with azimuth vane is a good approach at the lower altitudes attainable with a tower or mast. For higher altitudes, Doppler lasers and a network of whistles and audio microphones have both been satisfactorily developed. Finally, most sounding rocket wind measurements have used a sequence of free flying weather balloons observed with stereo theodolites. All these existing techniques are either too expensive (by a factor of ~10) or generate data at altitudes too low to be useful. However University launch vehicle programs need an inexpensive technique to measure winds at or below about 2 km altitude. Above 2 km, aviation weather data obtained from the Federal Aviation Authority (FAA) is normally used.

To solve this problem we chose to measure the deflection of a Tethered Pilot Balloon (TPB). Only one balloon is used per launch and a single telescope with an attached Celeston SkyScout® sensor that measures the pilot balloon's (pibal) azimuth and elevation angles. The balloon altitude is controlled by measurements on tether length.

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Figure 1 is a conceptual sketch of our sensor. A SkyScout® sensor attached to the telescope barrel measures the pilot balloon's (pibal) azimuth and elevation angles. The balloon's altitude is controlled by measurements on tether length. In service, the telescope is pointed at the pibal while the tether length is adjusted to place it at the desired altitude. Only then are the final elevation and azimuth angles read from the SkyScout®.

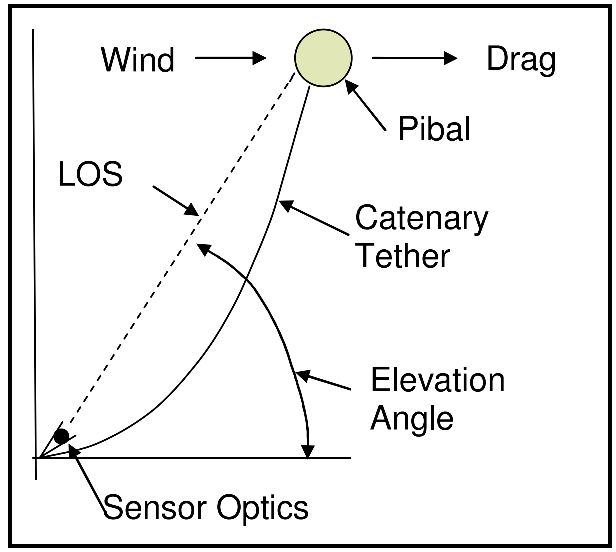

Figure 1. Sensor Concept

II. Development Philosophy:

Because this technique has not previously been used, we adopted a two-phase approach to reduce development risks and increase student confidence. First, we built a very crude, inexpensive prototype to learn as much as possible. Then, after assimilating the lessons learned in testing, an operational sensor was designed and built from commercial off the shelf components. Also, we compared various ways to implement each sensor function; for example, we selected a magnetic compass to measure the balloon azimuth after comparing it with using a landscape feature as a fiducial reference and measuring from that with a protractor.

III. Sensor Design

A. Sensor Design - Balloon Sizing:

The Tethered Pilot Balloon (TPB) concept will work as long as the balloon drag increases monotonically with wind speed. However, the existing sphere drag data in Ref 1 (See Fig 2) can be used to prepare Fig 3. The boundary layer on the sphere near its equator transitions from laminar (smooth, orderly) flow to turbulent (chaotic, disorderly) flow near where the low speed drag is greatest, causing a pronounced nonlinearity.

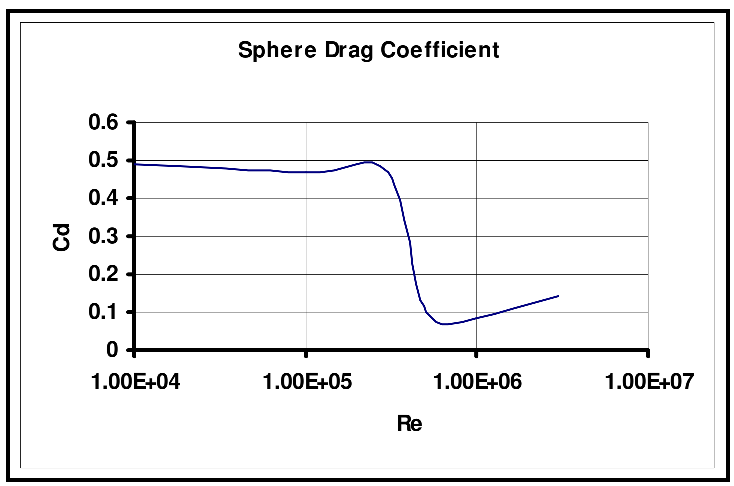

Figure 2. Incompressible Sphere Drag Coefficients.

Turbulence causes the outer, inviscid flow to remain attached to the sphere for a greater extent which increases back-side pressure recovery and reduces drag. The laminar/turbulent transition depends on the Reynolds Number (wind speed * balloon diameter / kinematic viscosity). Since kinematic viscosity, a fluid property, does not change for our design problem, the balloon diameter must be selected to provide a wind speed range appropriate for our application. Knowing that rockets would not normally be launched into wind speeds greater than 20-25 fps, Fig 3 shows that a balloon radius of about 1.5 feet is a good choice. In service, balloon size is controlled by inflating the balloon until it just fits inside a cardboard template with a 36" hole. Further trade studies led us to the select a natural color latex balloon for greater visibility against a variety of backgrounds.

B. Sensor Design - Spectra 2000:

Spectra 2000™ is the trade name of a special polyethylene fiber recently brought to market by Honeywell, and is one of the world's strongest and lightest fibers. It is truly remarkable material, abrasion resistant, much stronger than steel yet light enough to float on water. For our tether, we used commercial Spectra 2000™ fishing line 0.011" diameter with an advertised ultimate strength of 30 lb. We know of only one problem; our test data showed that it is so smooth that most knots are no more than ⅔ as strong as the parent material.

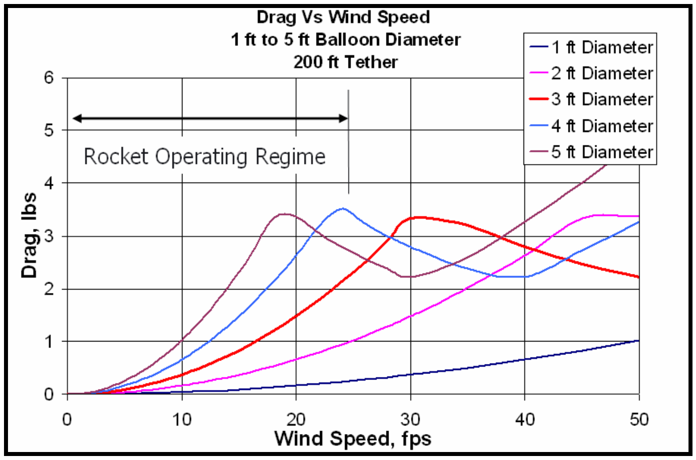

Figure 3. Drag Curve

C. Sensor Design -Telescope and Azimuth/Elevation Measurements:

Our inexpensive (<$100) prototype telescope used a bubble level and protractor to measure elevation angle and a pocket compass to measure azimuth. Prototype testing revealed many operational deficiencies. Since the prototype had no spotting scope, the pibal was difficult to track. The telescope mounting had a dead zone near zenith, and needed a right angle eyepiece. In addition, the magnetic compass was subjected to interference, especially from the threaded steel rod used to adjust the elevation protractor. Finally, the elevation angle protractor itself was difficult to mount and read.

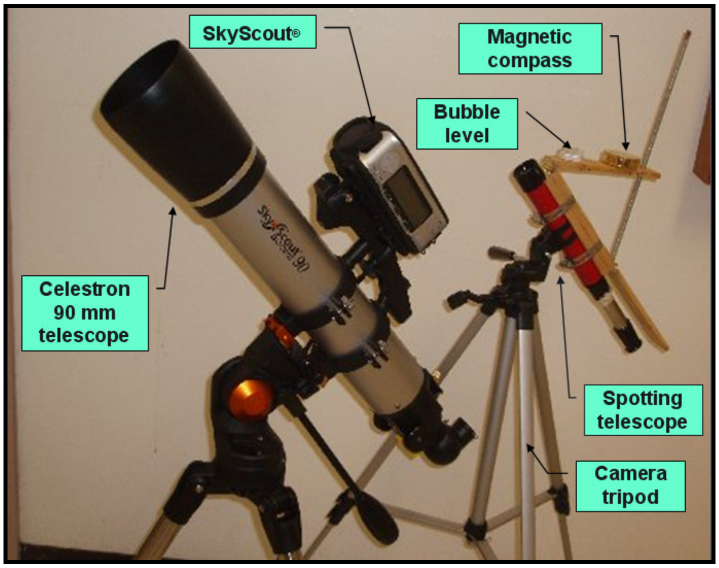

Photo 1. Telescope

Prototype (right) and Operational (left) Equipment

The operational sensor uses a Celeston SkyScout® mounted on a 90 mm Celeston® telescope sold together for about $700. This combination is described in more detail in Ref. 5. SkyScout® is, in effect, a high-tech "hand-held planetarium" first sold in 2006. SkyScout® uses an internal Global Positioning System (GPS) receiver for geolocation. Once the location has been determined, triaxial magnetometers are used to measure the telescope barrel azimuth angle. Elevation angle is found from triaxial accelerometers in the SkyScout®. Both prototype and operational sensors are shown in Photo 1.

D. Sensor Design - Winch and Tether Length Measurement:

The prototype winch was made from a strong plastic milk crate with a hand cranked axle made from scrap aluminum pipe. To estimate the tether length deployed, a stock clerk's tally counter was rigged to measure drum revolutions.

The requirements for the operational sensor reflect experience with the prototype. The awkward hand crank was replaced with a cordless electric drill. A more robust means of measuring deployed tether length is provided by a commercial bicycle odometer described in Ref. 6 and calibrated with a traffic wheel odometer. Both winches are shown in Photo 2.

E. Sensor Design – Software:

There are four forces acting on the pibal, tether tension, balloon weight, buoyancy and drag. Since the balloon is in static equilibrium, Newton's Third Law can be solved for the drag as a function of the elevation angle. Because drag varies as wind speed squared, a measurement on the elevation angle leads to a wind speed estimate as shown in Fig. 4.

A simplified straight line tether model of the sensor helps illustrate how the sensor software works. First, note that the actual software includes refinements not in the simplified model. A centenary tether, variation of density with altitude, and variation of C_d with Reynolds Number are considered in our software.

The static equilibrium equations based on Newton's Third Law are:

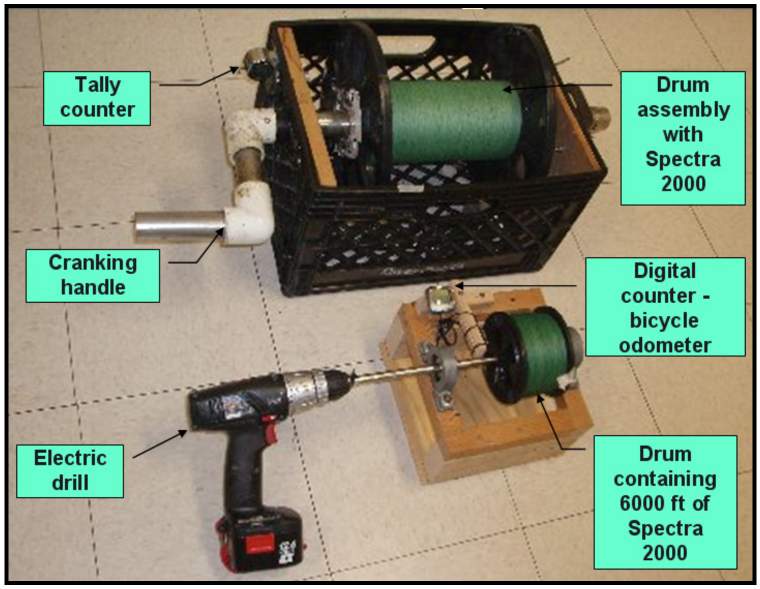

Photo 2. Winch

Prototype (top) and Operational (bottom) Equipment

$$\sum Y \uparrow: \quad B = W + T\cos\theta \qquad (1)$$

$$\sum X \rightarrow: \quad D = \tfrac{1}{2}\rho V^2 S C_d = T\sin\theta \qquad (2)$$

Since all parameters except elevation angle θ are known, the equilibrium equations can be solved for wind speed as a function of the elevation angle:

$$V = \sqrt{\frac{2(B - W)\tan\theta}{\rho S C_d}} \qquad (3)$$

As described elsewhere (Ref. 7), knowledge of the balloon altitude is critical to the principal sensor application which is predicting rocket trajectories in the presence of a wind field. Given both the elevation angle and deployed tether length measurements, the balloon altitude can be estimated from

$$h = d\sin\theta \qquad (4)$$

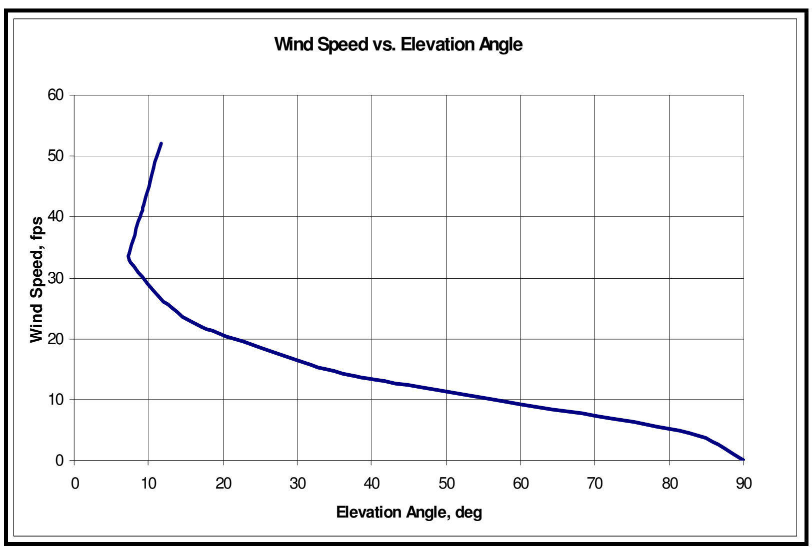

Figure 4. Calibration Curve

For low balloon altitudes and low wind speeds, these approximations provide surprisingly accurate results. While these approximations are not implemented in our software, they provide useful insights. Measurement of θ is sufficient for estimating wind speed since all other parameters can be assessed a priori with good accuracy, and the addition of measured tether length is adequate to estimate balloon altitude.

Measured azimuth angles correspond directly to the wind direction. The TPB software ingests telescope elevation and azimuth angles from the SkyScout®. Software output the estimated wind speed and direction at altitude. The software also generates the required tether length for the pibal altitude required by pre-launch planning. This is used to adjust the deployed tether length prior to taking the final azimuth and elevation readings.

The calibration curve in the software is shown in Fig. 4. As the elevation angle decreases, the wind velocity increases up to approximately 30 fps where the elevation angle is ~10°. The elevation angle minimum (~10°) corresponds to boundary layer transition from laminar to turbulent near the balloon equator. Since the curve becomes double-valued when the elevation angle is less than ~15°, the sensor cannot be used when the wind speed exceeds ~25 ft/sec. However, as noted above, rockets would usually not be launched if winds exceeded 20-25 fps.

The TPB software was developed on Microsoft Excel®, an excellent choice, because engineers have easy access to it. Its interface is use friendly, and multiple graphs can easily be generated for analysis of atmospheric wind conditions.

F. Sensor Design – Testing:

The sensor and its subsystems have been extensively tested as summarized in Table 1.

Table 1. Summary of Testing Conducted on Both Prototype and Operational Sensors

Testing Summary		
Type of Test	**Test Objective**	**Results**
Tether line test - using weights	Determine the maximum tensile load of tether line rated for 30 lbs. Determine best type of knot	The Spectra 2000 tether line breaks at a lower than manufacturer quoted maximum value. The tether broke at 20 lbs. Fisherman's knot worked well.
Tether line test - using Electronic Tensile machine	Determine maximum tensile load of tether line rated for 30 lbs. Best kind of knot and its breaking value	The Spectra 2000 tether line breaks at a lower than manufacturer-quoted maximum value. The Tether gave way at 19 lbs. The line always broke on the body itself and did not come off the knot.
Balloon inflation test	The balloon was inflated with helium to ensure it could safely be inflated to the desired 36" diameter.	The manufacture-recommended diameter was 29 inches, but we found the balloon could be inflated to 36 inches without causing any problems.
System Functional Test with Prototype Sensor in the campus parking lot	Validate functional capability of the complete sensor. Discover any issues needing later correction	Due to wake turbulence from campus buildings we were unable to observe the balloon with 100' of tether. This was overcome by increasing the balloon altitude from 100 to 200 ft. We also found we needed to have a right angle eye piece and table for operational ease.
System functional test with Prototype Sensor in the Mojave FAR Site	Validate functionality capability of the complete sensor in the field. Measure wind profile for P- 8 launch	First balloon deployment failed when tether failed in high winds. Second deployment successful in low winds. Winch hand cranking unsatisfactory when balloon deployed to altitudes of > 300'. Better seat needed for telescope operator. Collection of Aviation WX from FAA was successful. Winds at 500' & 1000' successfully measured for P-8 launch.
Tether length calibration	Calibrate the tether length measurement for the operational winch	Tether was deployed indoors, and its length, as measured with a bicycle odometer on the winch, was compared with measured length from a traffic wheel sensor.
Operational System functional test	Functional test of operational sensor in the Mojave Desert	Useful wind data acquired. Winch and software modifications needed in the future. Procedures need to be more explicit and better documented.

IV. Conclusion

Our wind sensor development project has been successful. To ensure safe flight operations, continuous improvements will be needed for future CSULB launches as they continue to evolve, ultimately paving the way to the research needed for reusable space vehicles.

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References

Books

1. Hoerner, S.F. *"Fluid Dynamic Drag, Hoerner Fluid Dynamics",* Bricktown, N.J. 1965. sections 3-4,
2. Hale, Francis. *"Introduction to Aircraft Performance, Selection and Design",* New York: Wiley 1984.

Web Sites

3. *"Weather Stations and Weather Instruments, Pilot balloons",* Scientific Sales. Inc, March 2007. http://www.scientificsales.com
4. *"The ultimate high-strength, light-weight performer: SPECTRA® 2000",* Honeywell Company, January 2008. http://www.honeywell.com/spectra.
5. *"MySkyScout.com: A Match Made for the Heavens",* Celestron® Company, January 2008 http://www.celestron.com/skyscout/
6. *"Sigma Sport® Online, Bike Computer Heart Rate Monitor… (Bicycle odometer)",* Sigma® Germany, January 2008. http://www.sigmasport.com/us/startseite/

Proceedings

7. Mejia, Oscar. *"Trajectory Simulation for the P-8A Launch Vehicle",* AIAA Region 6 Student Conference Proceedings, Phoenix AZ, 18-19 April 2008.