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Uncertainties in the measurement of the atmospheric velocity due to balloon-gondola pendulum-like motions

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Abstract

Balloons lead to the highest vertical resolution of air velocity data actually attainable from atmospheric soundings. However, the pendulum-like motion of the balloon-gondola system may significantly affect these measurements if the distance between balloon and gondola is large. This may prevent the study of the highest vertical resolution range obtained. Also, if not appropriately discriminated, these fluctuations could be confused with small scale or turbulent oscillations of the atmosphere. It is shown from simple energy considerations that horizontal and vertical wind velocity perturbations introduced in the observations by the pendulum motion may usually be comparable to typical measurements. Vertical velocity data that were obtained with an instrumented gondola in a zero pressure balloon, which typically reach the lower stratosphere, are analyzed and found to be in agreement with the above statements. The pendulum-like behavior in this sounding seems to be stimulated by the buoyant oscillation of the atmosphere.

Keywords: Balloons; Measurement; Error

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1. Introduction

Zero pressure balloons have one or several openings at the base of the envelope and are therefore said to be open to the external atmosphere. The film is either filled with hot air or a gas lighter than air. These balloons usually fly science and technology missions up to the stratosphere, lasting a few hours to a few days. They vary in volume from several thousand to over one million m^3 and can carry payloads weighing tens of kilograms to a few tons. Their altitude can be controlled by a valve at the top of the balloon and by ballasting. The gondola is typically hung 200 m below the balloon in order to minimize any of its possible influences. This large distance may lead to pendulum-like velocities that are comparable to atmospheric values.

Vertical velocity is notoriously difficult to measure in the atmosphere because it is small under normal conditions (e.g. no deep convection). The corresponding values are typically one or two orders of magnitude smaller than those observed in the horizontal velocity. In particular, if vertical velocity is measured from a balloon gondola, even assuming that the ascent or descent are being tracked with negligible error, some problems attributable to the characteristics of the platform remain. One of the important difficulties is associated to the pendulum-like motion that may affect the anemometer velocity measurements in the gondola (the pendulum "bob"). A similar problem emerges for horizontal wind observations, as the sensors do not measure the horizontal velocity, but rather the smaller difference between balloon and gondola heights (Barat, 1982a,b; Barat and Genie, 1982). Below we perform some calculations and estimations which show that the oscillations may render the measurements unusable for analysis of some spectral vertical wavenumber ranges of velocity data, as the use of a digital filter might remove not only the modeled parasitic pendulum oscillations but also true atmospheric modes. This fact is important, as it affects

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the highest vertical resolution range actually attainable (see e.g. de La Torre et al., 1994), not reached with other platforms and high performance instruments, roughly between 1 m and 100 m. The possible effect of oscillations that might be induced in a gondola under a stratospheric balloon on magnetic field measurements has been studied by Ducarteron and Treilhou (1993).

2. Estimation of velocity measurement uncertainties

We first describe a real balloon flight in order to outline the characteristics of these scenarios. Four zero pressure balloons were launched in Mendoza (32S, 68W) near the Andes Mountains by the end of November and the beginning of December of 1990 by the Ports sounding campaign, which was supported by the French Balloon Program of the Centre National dEtudes Spatiales. Data from the second flight, which started 10.15 UT on December 2 and exhibited the highest quality among the four in vertical velocity, have been here processed. The instrumented gondola was about 200 m under the balloon. The horizontal anemometers failed in measuring zonal and meridional wind components. It was found that the fluctuations of the air vertical velocity were due to density variations and not by the vertical wind velocity (de La Torre et al., 1996), contrary to what has been generally established for the much smaller superpressure balloons. Vertical wind velocity components relative to the gondola were obtained with a sonic anemometer at intervals of 0.5 s with an accuracy of 1 cm s^{-1} (Ovarlez et al., 1978) during the flight. As vertical wind velocity is generally expected to be much smaller than the balloon vertical velocity during ascent or descent, the measured data approximately reflect the opposite of the latter during both stages, whereas at floatation the measurements will rather roughly show the opposite of the balloon response to density fluctuations.

In Fig. 1 we show the balloon vertical velocity during the flight (the opposite of the measured data). A low-pass filter that removed periods shorter than 2 min was applied. The filter was nonrecursive and to avoid Gibbs effects a Kaiser window was used (see e.g. Hamming, 1998). It may be seen that the ascent to the lower stratosphere at about 23 km lasted more than 1 h, less time was spent to float in this zone, whereas the descent took about 3 h.

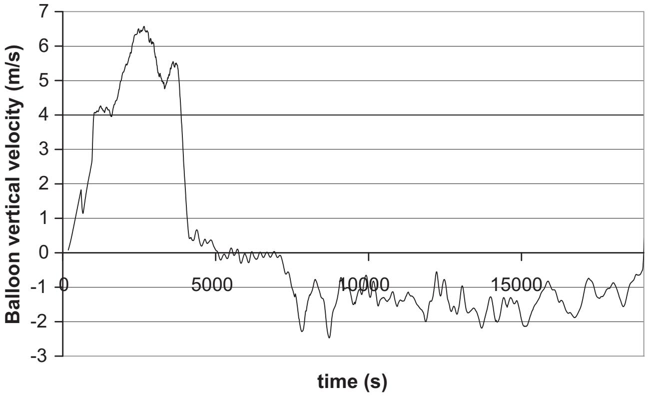

Fig. 1. Balloon vertical velocity during the flight after the application of a low-pass filter that removed periods shorter than 2 min.

The gondola's distance from the balloon $l = 200$ m implies that oscillations with a period of roughly half a minute will contaminate the horizontal velocity observations (period $= 2\pi(l/g)^{0.5}$, where g is gravity). Typical ascent or descent speeds are 0.5–5.0 m s^{-1}, which lead to spurious wavelengths between 14 and 140 m (period times typical ascent speeds). From preliminary test flights with heliosondes a maximum tilt angle $\theta = 5°$ with respect to the vertical direction has been observed (Barat and Genie, 1982). From the transformation of potential energy per mass at the maximum height of a pendulum 200 m long and with a maximum departure of 5° ($gl(1 - \cos 5°) = 7.6\ \mathrm{m}^2\ \mathrm{s}^{-2}$) into kinetic energy per mass at the bottom ($1/2v_x^2$, where v_x is horizontal velocity of the gondola), one finds that the gondola excursion may modify the horizontal velocity up to 3.9 m s^{-1}. This value could be comparable to or even greater than the quantity to be measured. The vertical velocity component will be affected by about half the above period and spurious wavelengths, as it reaches the maximum and minimum velocities twice during a full gondola oscillation cycle. Now we look for an answer for the vertical velocity perturbation amplitude, which will be surely smaller than the horizontal component, but not negligible.

In Fig. 2 we consider a two-dimensional scenario. This simplification may still allow to detect some basic aspects through analytical results. The balloon is supposed to be a fixed point due to its large moment of inertia. If one neglects friction, it follows from the basic energy considerations for a pendulum that at an angle θ

$$\frac{1}{2}v_x^2 + \frac{1}{2}v_y^2 + gl(1 - \cos\theta) = gl(1 - \cos\theta_m) \tag{1}$$

where v_y is the vertical velocity of the oscillating gondola and $\theta = \theta_m$ is the maximum deviation from the vertical direction. Then

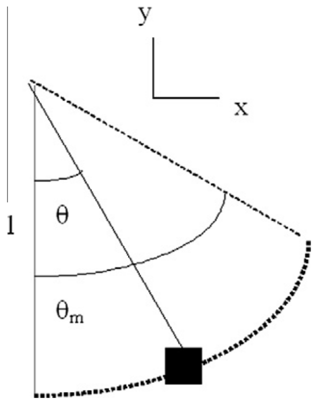

Fig. 2. The gondola oscillation like a pendulum bob. Angles have larger values than in typical situations only for illustration purposes.

$$v^2 = 2gl(\cos\theta - \cos\theta_m) \tag{2}$$

and as $v_y = v\sin\theta$ we obtain

$$v_y^2 = 2gl(\cos\theta - \cos\theta_m)\sin^2\theta \tag{3}$$

To find the angle where the gondola vertical velocity perturbation maximizes, from standard calculus we need to set

$$\frac{d}{d\theta}((\cos\theta - \cos\theta_m)\sin^2\theta) = 0 \tag{4}$$

which yields

$$\cos\theta = \frac{\cos\theta_m}{3} \pm \sqrt{\left(\frac{\cos\theta_m}{3}\right)^2 + \frac{1}{3}} \tag{5}$$

and $\sin\theta = 0$ just for completeness. However, acceptable physical solutions for θ must be restricted to the range $\pm\theta_m$. The value with physical meaning for $\theta_m = 5°$ turns out to be $\theta = \pm 3.53°$, which gives a maximum $v_y = 0.17\ \mathrm{m\,s^{-1}}$. This is close to typical wave vertical velocities.

In order to generalize the above results we show in Fig. 3a the angle θ at which the gondola vertical velocity maximizes in terms of the maximum oscillation angle $0 \leqslant \theta_m \leqslant 10°$. The relation holds nearly linear for the angle range considered (notice that Eq. (5) is not linear). Angles larger than 5° may rather have an academic interest than a practical application. In Fig. 3b we show the corresponding vertical velocity peak value for $l = 200$ m in terms of θ_m, where it can be seen that the perturbation introduced by the pendulum motion becomes increasingly important for rising angles. In Fig. 3c it can be observed that the maximum horizontal velocity perturbation (at $\theta = 0$) only increases in a linear way with θ_m.

We now analyze the above real balloon flight. Fig. 4 focuses on filtered profiles of balloon vertical velocity for the time between 5000 and 5800 s, which belongs to the floatation stage. In the curve that represents vertical velocity after removal of periods shorter than 2 min, there is a clear interval of about 4 min, suggesting that it may be a response to the buoyant period of the atmosphere in the lower stratosphere. The second curve in Fig. 4 represents the vertical velocity band-pass filtered between 6 and 30 s. An oscillation of about 15 s may be clearly seen, in accordance with the above calculations for a gondola about 200 m under the balloon. Moreover, these fluctuations seem to receive some kind of feedback of the buoyant oscillations (note that the largest pendulum peaks occur about 90 s later than the buoyant maxima). Treilhou et al. (2000) already noticed for open stratospheric balloons used for magnetic field measurements this possible coupling mechanism, where the buoyant oscillations could provide the external driving force by periodically moving the vertical position of the suspension point. Without the pendulum calculation the 15 s fluctuations could have been confused with small scale or turbulent oscillations of the atmosphere. Their amplitudes are upto $10\ \mathrm{cm\,s^{-1}}$. This is comparable to typical air vertical velocities at these heights.

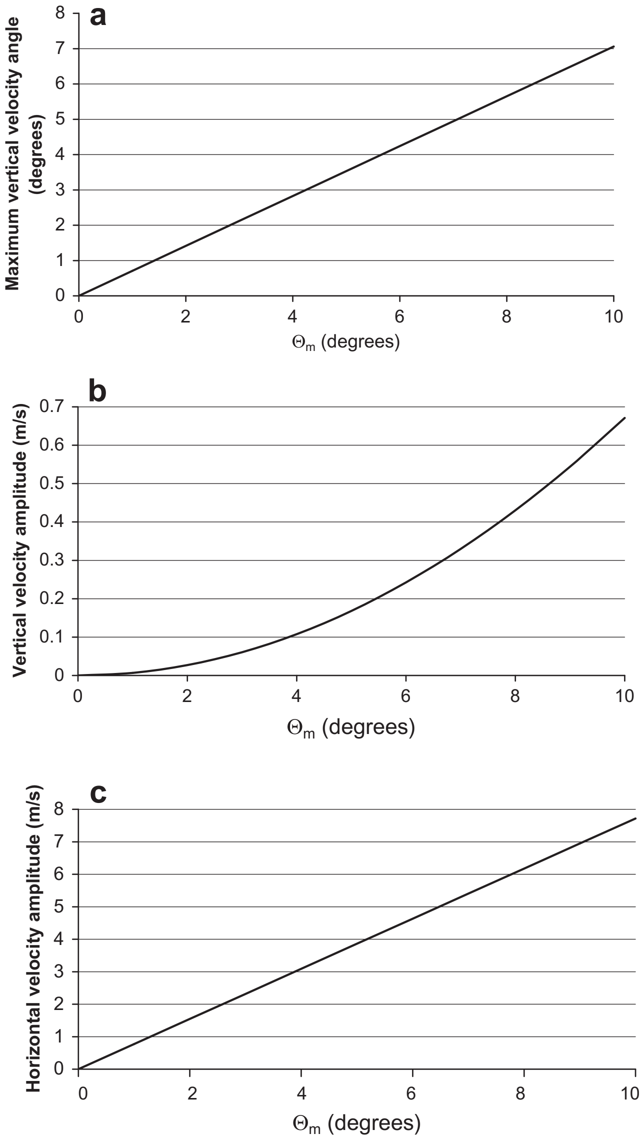

Fig. 3. (a) Angle θ at which the gondola vertical velocity maximizes in terms of the maximum oscillation angle θ_m, (b) the corresponding vertical velocity peak values for $l = 200$ m, and (c) the maximum horizontal velocity (at $\theta = 0$) in terms of θ_m for $l = 200$ m.

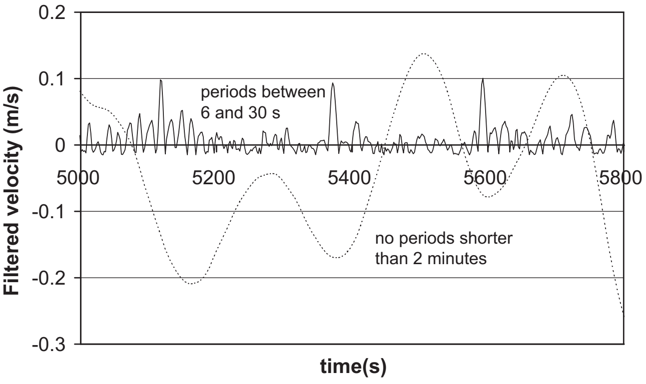

Fig. 4. Filtered balloon vertical velocity profiles during a part of the floatation stage.

For example, from NCEP (National Center for Environmental Prediction) reanalysis data for the closest times, latitudes, longitudes and heights to the balloon floatation, air vertical velocities are typically found to be within ±20 cm s^{-1}.

From the above considerations we conclude that the highest vertical wavelength or frequency range for horizontal and vertical velocities obtained from high performance instruments on board balloon gondolas must be cautiously used, as spurious wavelengths or periods due to gondola pendulum-like oscillations may contaminate the velocity observations. It was shown in an example that these oscillations may be of the order of magnitude of typical air velocity. In addition the present analysis is useful if horizontal or vertical velocity data are missing as in the above example, because then it is not possible to check if (as in a pendulum) a particular vertical velocity oscillation frequency doubles any horizontal one. The observed pendulum fluctuations were here quite regular but not constant, which may render their removal difficult in general situations.

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