BALLOON-BORNE HOT WIRE ANEMOMETER FOR STRATOSPHERIC TURBULENCE SOUNDINGS

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ABSTRACT

Balloon-borne sensors for wind and temperature are used since more than 20 years to study turbulence in the stratosphere. Despite that long tradition, turbulence soundings are still technically challenging and the number of soundings is small. We have developed a compact balloon payload for wind turbulence soundings up to 35 km altitude. High resolution wind measurements (vertical resolution: 2.5 mm) are performed with a hot wire anemometer (or constant temperature anemometer, CTA). The measurements are based on the air-flow induced cooling of a wire (about 5 μm diameter). We have integrated a CTA system into a box of 35 cm sidelength. Including telemetry, housekeeping and recovery unit the payload weights less than 5 kg and can be launched at any radiosonde station. The heat transfer from a CTA hot wire is not yet described by a universal expression independent of ambient conditions. We discuss the effect of changing sensor response between calibration and stratospheric flight. The balloon payload has been launched several times since autumn 2007 from our site at Kühlungsborn (54°N, 12°E)and as part of the BEXUS 6 balloon at Kiruna (67°N, 21°E).

Turbulence occurs in the stratosphere on scales between some millimeters and lots of meters. The larger scales are partly known as ”clear air turbulence” (CAT), affecting e.g. air planes leeward of mountain ridges. Even if the knowledge of CAT is still limited it typically occurs on scales of meters, observable e.g. by remote sounders like lidars and radars. Smaller scale turbulence can only indirectly be retrieved from these observations and requires in-situ soundings for detailed analysis. Pioneering work on in-situ soundings has been done in the 1980ies with balloon-borne sensors e.g. by J. Barat and coworkers (e.g. [1, 4]). Their wind measurements resolved scales down to some centimeters which is well within the inertial subrange. Full knowledge e.g. on turbulent energy dissipation rates can only be deduced by even higher resolved soundings covering the turbulent inner scale and parts of the viscous subrange. These measurements have not been available in the 1980ies. Only few soundings have been made in the last decades, so there is still only little knowledge about turbulence in the stratosphere.

1. INTRODUCTION

Due to its small negative or even positive temperature gradient the stratosphere is typically statically stable and well stratified. Nevertheless waves can produce wind shear and may induce some instability leading to wave breaking and turbulence. This turbulence is known to be intermittent and occurs in thin layers only [1]. On average it is small compared e.g. to mesospheric turbulence (cf. e.g. [2]) and it provides only minor input to the energy budget of the stratosphere. On the other hand it modifies the energy transfer by gravity waves from the troposphere into the mesosphere. Even in the statically stable stratosphere the vertical growth rate of gravity waves is smaller than expected for undisturbed propagation (cf. e.g. [3]). Obviously the wave energy already deposited in the stratosphere can not contribute to the mesospheric energy budget.

We describe here an approach using ”constant temperature anemometers” (CTA) for high-resolved in-situ wind soundings. CTA is well known technique in lab-based fluid dynamics but has never been used in the stratospere. We present the instrument design and first soundings with a balloon-borne CTA sensor in the stratosphere. Combined with a standard radiosonde with 10 m vertical resolution the instrument covers the energy subrange (gravity waves), the whole inertial subrange and typically also parts of the viscous subrange. Changing air density and temperature influence the CTA response and is therefore an important issue in the retrieval of turbulent parameters from CTA raw data. We describe a first approach to deal with changing ambient conditions during the ascent. Additionally we specify the technical design of the whole payload including telemetry and recovery concept. First soundings have been performed since autumn 2007 at Kühlungsborn, Germany (54°N, 12°E) and as part of the BEXUS 6 payload at Kiruna, Sweden (67°N, 21°E).

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2. WIND SOUNDINGS BY A CONSTANT TEMPERATURE ANEMOMETER

In this section we describe the basic principle of constant temperature anemometry (hot-wire anemometry). CTA is one of the most practical techniques for flow measurements in gases and liquids. The various aspects of using CTA sensors on a drifting balloon in the free troposphere and stratosphere are discussed below. We use the compact Dantec Dynamics Inc. Mini CTA system together with gold-plated wires of the type 55P03.

2.1. Principle of constant temperature anemometry

Since many years constant temperature anemometry is a well known and widely used technique for flow measurements in gases and liquids. Several extensive studies have described the sensor behaviour and have given theoretical and semi-empirical descriptions of the measured signal [5, 6, 7]. We do not want to repeat this here but shortly emphasize the main aspects with a special focus on our application.

With constant temperature anemometry (hot wire anemometry) a thin tungsten wire is electrically heated $\dot{Q}_E$ to a temperature some 200 K above the ambient temperature. At the same time a negative heat flux occurs due to forced convection, heat flow through the prongs, free convection and radiative cooling:

$$\dot{Q}_E = \dot{Q}_{forcedconv} + \dot{Q}_{freeconv} + \dot{Q}_{rad} + \dot{Q}_{prongs} \quad (1)$$

Free convection and radiative cooling are neglectable due to the small size (mass) of the heated wire (5 μm diameter, 1.25 mm length). The heat flow through the prongs is proportional to the forced convective flow and the above equation simplifies to

$$\dot{Q}_E \approx P \cdot \dot{Q}_{forcedconv} = P \cdot [A + B(\rho U)^n]\Theta \quad (2)$$

with A, B and n sensor dependant constants, U flow velocity, and $\Theta = T_w - T_a$ difference between wire temperature T_w and air temperature T_a. Changes in the convective heat flow (i.e. changes in the wind of the ambient atmosphere) would change the temperature of the wire and by this its resistance. Via a Wheatstone bridge the resistance is balanced and the wire temperature is kept constant. The potential difference across the Wheatstone bridge provides a measurable signal depending on the ambient flow:

$$\dot{Q}_E = \frac{E_{cta}^2}{R_{eff}} \quad (3)$$

$$\Rightarrow E_{cta}^2 \sim \dot{Q}_{forcedconv} = [A + B(\rho U)^n]\Theta \quad (4)$$

with E_{cta} bridge voltage and R_{eff} effective bridge resistance. Obviously the convective heat flux is not only depending on the atmospheric wind, but also on ambient density, temperature and humidity (e.g. [8, 9, 10, 11]. Therefore $\dot{Q}_{forcedconv}$ can hardly be calculated for a specific case. Practically the relation of potential difference across the Wheatstone bridge and wind velocity is deduced from calibration in a known flow. Fig. 1 shows an example for the calibration in a wind tunnel. Two calibration curves are fitted to the measured data points. The King's law gives obviously the best approximation for low wind speeds while the differences vanish for wind speeds larger than 1 m/s. The wind calibration has to be performed for any expected combination of density, temperature and humidity. In fact this is an enormous task for soundings between the ground and the middle stratosphere. In the next section we describe our actual efforts in detail. It can be seen from the calibration that the sensitivity is depending on absolute wind speeds. Typically we achieve a sensitivity of 2 mm/s using a 16-bit ADC. The temporal resolution can be as high as 0.01 ms (at normal pressure).

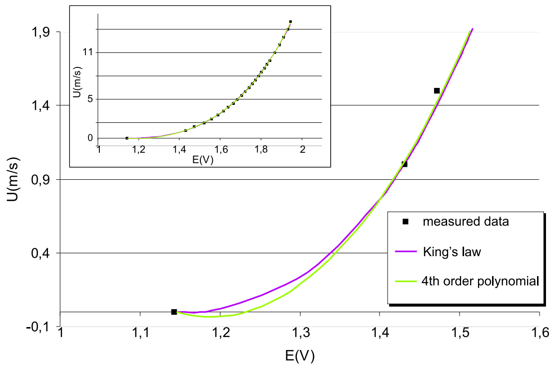

Figure 1. Calibration data for CTA sensor with fitted curves (King's law and 4th order polynomial). At low wind speeds the polynomial underestimates the true wind and gives partly even negative values.

2.2. Adaption to the stratospheric ambient conditions

As described before it is recommended to calibrate the CTA sensor under conditions similar to the ambient conditions during the measurements. For our case, (relative) flow velocities are up to 2 m/s, atmospheric density down to $2 \cdot 10^{23}$, temperature decreases down to $\sim$200 K, and atmospheric humidity may vary between 10 and less than 0.1 g/kg. The exact calibration of any individual sensor for any possible combination of the these parameters is an enormous task and requires sophisticated hardware. In the literature several correction schemes are discussed, to adapt a particular calibration to a different situation. Fig. 2 gives an overview on the available data. Obviously non of these approaches covers the range of parameters necessary for our soundings [5, 7, 8, 9, 10, 11, 12, 13].

The observed voltages can be corrected for changing temperatures. Unfortunately the correction is suggested for differences of only $\pm$5 K, i.e. much less than the temperature changes during our balloon soundings. Also the effects of density changes have been examined for small variations only [11]. We have started a calibration

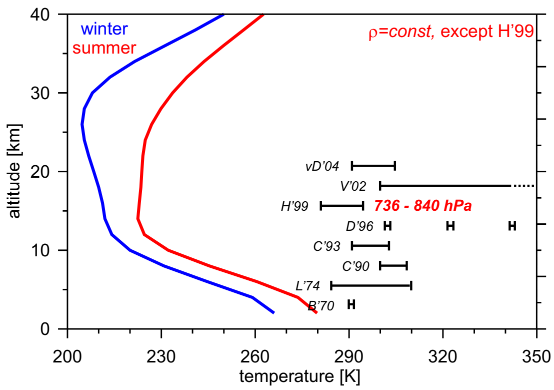

Figure 2. Typical temperature profiles for the mid-latitude troposphere and stratosphere (from [14]) compared to the temperature ranges for CTA calibration reported so far. Up to now there is now knowledge on CTA calibration at low temperatures. Additional uncertainties exist with respect to density effects. References for CTA data are given in the text.

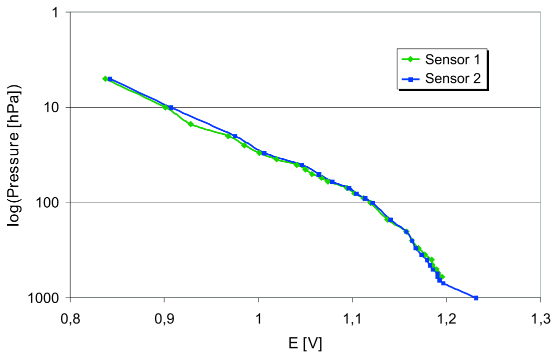

Figure 3. Sensor response at zero wind speed within a vacuum chamber at different pressures. The two different sensors show similar behavior with a changing slope around ∼200 hPa. The tests have been conducted with a 55P13 sensor (similar to 55P03 without gold-plated ends).

study appropriate for our application, covering the pressure (or density) scale of the troposphere and lower/mid stratosphere. Fig. 3 shows the sensor response in a vacuum chamber depending on pressure. As the chamber is too small to insert a wind tunnel, the data are for zero wind speed.

The voltage decreases exponentially with decreasing pressure. Around 200 hPa some change in the convective flow occurs, resulting in an even larger decrease of the voltage. We have measured the density dependance of the wire response with two different sensors. The results are essentially identical. Our study also shows that the sensor sensitivity decreases with decreasing pressure (density). Nevertheless our soundings do not show any limitations for turbulence measurements in the stratosphere due to the decreasing sensor response. These studies at zero wind speed provide no direct method to correct the observed voltages for stratospheric conditions. Therefore

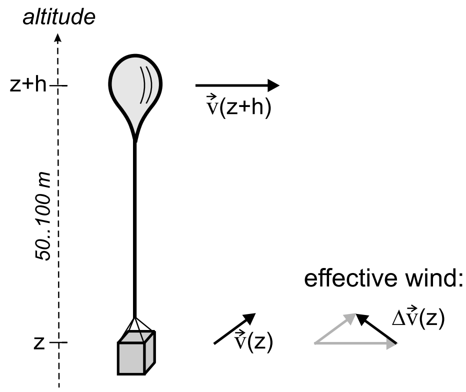

Figure 4. Schematic drawing of the principle of balloon borne wind turbulence soundings.

the absolute wind speeds can not be calculated yet. As a future task we will use a wind tunnel in a vacuum chamber to make a sophisticated calibration at stratospheric density conditions.

Nevertheless for turbulence measurements it is not necessary to derive absolute wind speeds from the CTA signal, i.e. the absolute sensitivity is not important. Instead we make spectral analyses of the voltage signal to retrieve the spectral slope of the observed variation, i.e. the wind variation. If the ambient conditions are sufficiently constant for a particular spectrum, its slope is equal to the slope of the wind spectrum itself. Typically we analyse 4–10 s of data for a single spectrum, representing a profile of 20–200 m vertical extension. Within this period/range the density and temperature are sufficiently constant. Any remaining effect is eliminated during the detrending necessary for the spectral analysis. Additionally it should be noted here that the CTA is not measuring the absolute wind speed at the particular payload altitude. Due to its large diameter (depending on altitude more than ∼3 m) the balloon is following the ambient wind field during its ascend and is assumed as ideal Langrangian tracer. The payload is connected to the balloon by a 50-100 m long rope (see Fig. 4). If we neglect pendulum motions the payload is following the wind field in the height of the balloon. Therefore, for a altitude-constant wind the observed wind in the reference frame of the payload would be zero. Any altitude variation of the wind is observed by the CTA as the difference between the wind vectors in balloon height and in payload height. As a result we get an altitude profile of wind differences with very high vertical resolution. As we are interested in scales much smaller than the balloon diameter the observed fluctuations are the true fluctuations in the payload altitude. Calculations of the true absolute wind profile are not necessary for the turbulence retrieval.

3. THE BALLOON PAYLOAD CONCEPT

We have developed a payload for stratospheric CTA soundings suitable to be launched from any radiosonde station. The payload can be used as one-way instrument if the telemetry conditions are sufficient (no obstruction by trees, houses or terrain). On the other hand the payload can be used with on-board data storage, if a save recovery of the instrument is assured. In the following subsections we describe the payload with its different components and our approach for a lightweight telemetry system with high bandwidth.

3.1. The general payload concept

The balloon-borne sounding system for wind turbulence measurements consists of various instruments for observation and recovery (Fig. 5):

- a He-filled rubber balloon of 2000 g or 3000 g for sufficient buoyancy to reach about 35 km altitude
- a parachute to reduce the descend speed
- a radio beacon (150 MHz, 500 mW radio power) with a cross-dipole antenna for radio bearing of the payload after landing
- an unwinder with 50-100 m rope to achieve a sufficient relative wind and to prevent the payload from traveling in the wake of the balloon
- the scientific payload itself including the CTA and electronics, telemetry, tracking hardware and housekeeping
- a radiosonde (Vaisala RS92) placed a few meters below the payload to measure the atmospheric temperature, humidity and wind with lower resolution.

The payload for the stratospheric CTA sensor consists of a styrofoam box of ∼35 cm width and 30 cm height. The styrofoam is used for insulation against the low ambient temperatures and for shock protection of the electronics at landing. The CTA wire is fitted to a sensor holder that allows elevating the wire ∼20 cm above the top of the styrofoam box. By this the wire is outside the shear layer around the box and possible influences of the box on the measurements are minimized. The wire axis is vertical to have largest sensitivity for horizontal flow and less sensitivity for vertical flow due to the ascend. As the payload is not actively stabilized it may be affected by pendulum and rotational motions. While the pendulum motions have comparatively long periods of a few seconds, the rotations may occur on different scales. In order to minimize them we have attached a wind vane of about 40 cm diameter on a 50 cm boom to the payload box. Remaining motions are monitored by the housekeeping system (see below).

The tungsten wire of the CTA sensor Dantec 55P03 has gold-plated ends connecting it with the wire prongs. The gold-plated ends minimize the (artificial) heat flow from the tungsten wire to the prongs and therefore reduce the

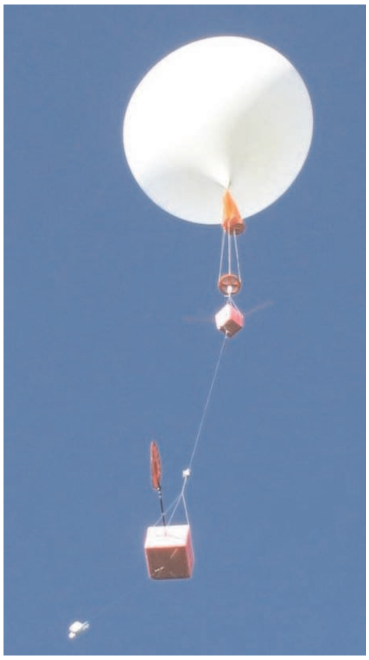

Figure 5. Balloon and payload shortly after start. The rope is only slightly unwinded, yet. The lower red box contains the scientific payload.

noise of the CTA signal. The CTA sensor is connected to a Wheatstone brigde inside the Dantec MiniCTA electronics. The output of the MiniCTA is A/D converted using a 16 bit ADC with 2000 samples per second, i.e. 0.5 ms temporal resolution. The 2000 Hz rate is chosen to resolve scales down to 2.5 mm at 5 m/s ascent speed. It should be noted here that the CTA system is specified up to 100 kHz, i.e. an increase of the wire's response time due to decreasing air density should not affect our temporal resolution. In fact we have observed no degradation of the CTA spectral response with altitude. The velocity resolution due to the 16 bit sampling is approx. 2 mm/s, depending on the particular wind velocity (c.f. Fig. 1). The ADC is connected with a commercial radio modem and data recording system. We describe the telemetry and data recording in the next section.

In the housekeeping electronics the temperature and pressure inside the box are monitored for future analyses. A 6-axis sensor (ADIS16350AMLZ) measures rotation and acceleration at a rate of 50 Hz to allow identification and correction of any spurious maxima in the CTA spectra. Additionally the battery voltage and signal of the CTA are controlled and malfunctions are indicated. All data are stored on-board on an SD-card and can optionally be transmitted via the RS422 protocol. The housekeeping electronics has been developed by our institute.

The payload is tracked during the flight by the GPS windfinding of the Vaisala RS92 radiosonde. During descent we typically loose the radiosonde telemetry signal ∼5 – 10 km above the ground due to obstruction by the terrain. To allow finding and recovery of the payload we have

Figure 6. Receiving antenna for 869 MHz telemetry signal. The four tubes protect one helical antenna, each. The antenna mount is motorized to follow automatically the direction of the payload by evaluating the RS92's GPS data.

added an additional system providing the position of the system for the whole flight including landing. The tracking system is manufactured by NAL Research and combines GPS positioning with an Iridium satellite data link. The temporal resolution for the tracking is about 1 min.

3.2. The balloon telemetry and data recording

The stratospheric turbulence sounder is designed to send the measured CTA signal by telemetry to the ground station. As the data rate from the 16 bit, 2 kS/s ADC is much higher than the bandwidth of the radiosonde (4800 bps) we have developed a separate CTA telemetry and data recording system. This system combines the radio transmission of the data with real-time storage on-board (SD-card) for backup purposes. The telemetry sender consists of an ARF35 radio modem for the 869 MHz band and a crossed-dipole antenna with nearly spherical characteristic. The radio power of 500 mW is intended for a 6 km transmission range. In order to extend this range we are using a system of four Helix antennas which are actively directed to follow the balloon (see Fig. 6). The nominal range for the telemetry is 150 km. The telemetry system has been developed by Reimesch Kommunikationssysteme.

The ARF35 modem has a bandwidth of 38.4 kbps. To transmit the CTA signal with full temporal resolution including some protocol bits we have developed a data compression scheme. This scheme includes a time stamp and a failure detection to recognize transmission errors and re-synchronize the data stream. The compression algorithm makes use of the comparatively small wind changes within a few milliseconds. The algorithm checks for the dynamic range required within a certain period (frame) and saves the average value together with the particular deviations from the mean. For every frame a time stamp and a checksum is added to the transmitted data stream.

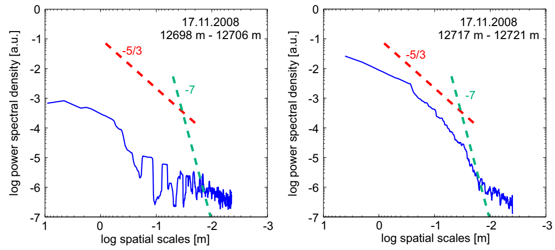

Figure 7. Frequency spectrum after FFT of a 8 m (4 m) data series. In the left figure the spectrum exhibits much less turbulence. The noise level is not totally flat due to some remaining spurious motions of the payload during this flight.

4. FIRST RESULTS

The first successful flight has been performed at 12 December 2007. Since then another two turbulence sensors have been launched at Kühlungsborn (17 November 2008 and 27 January 2009). The flight hardware is continuously improved concerning the position of the radiosonde or the exact sensor type. E.g. for the first flight we have used a simpler CTA sensor without the gold-plated wire (type 55P13). Another CTA sounding took place on 8 October 2008 as part of the BEXUS 6 campaign at Kiruna, Sweden (67°N, 21°E).

Fig. 7 shows the CTA spectrum of the second flight for two thin layers near 12.7 km. The power spectral density is given in arbitrary units due to missing calibration (see above). Slopes of -5/3 and -7 indicate the inertial and the viscous subrange, respectively. Around 12720 m altitude we observed moderate turbulence and the inner scale of turbulence (l_0) can be retrieved in the transition between inertial and viscous subrange at spacial scales of $\sim$5 cm. A few meters below (left figure) turbulence was found much weaker. The spectrum exhibits the noise level of the instrument (scales smaller than 10 cm). The noise spectrum is not totally flat due to some remaining spurious motions of the payload. This may be induced by bumping motions of the rubber balloon, by oscillations of the payload, or by remaining rotations of the payload. The latter is reduced in this flight due to the use of a wind vane (see Figure 5). In the accompanying paper by Theuerkauf et al. we will present less contaminated data from the BEXUS-6 flight. We would like to note here that the spectral resolution of our sensor is more than a factor of 100 finer than instruments available in the 1980ies (c.f. [1]).

5. DISCUSSION, SUMMARY AND OUTLOOK

We have presented the design and first data of a stratospheric wind sensor with very high resolution suitable for turbulence measurements. The first flight took place on 12 December 2007 and the instrument has been improved further since. With a constant temperature anemometer (CTA) we are able to achieve a vertical resolution of 2.5 mm at 5 m/s ascent speed. The CTA is the main part of a balloon payload of less than 5 kg weight. The payload can be launched with a 2000 g rubber balloon from any radiosonde station and includes a high-speed telemetry, housekeeping and tracking system.

During the first balloon soundings several layers of reduced static stability have been observed. The power spectral densities of one of these layers has been presented, showing the transition between inertial and viscous subrange. The resolution is strongly improved compared to previous wind soundings in the 1980ies. A minor drawback of the CTA technique is the required calibration for ambient conditions of density, temperature and humidity. Because there is very known from the literature about CTA measurements at low densities we have started our own lab studies within a vacuum chamber. These studies are by far not completed but show some similarities to effects observed during the atmospheric soundings. We will continue our studies on these topics in future. Nevertheless we can deduce turbulent energy dissipation rates etc. even from the unscaled data as these numbers depend on relative fluctuations and the particular length scales only.

In future we will also be able to identify and correct for any artificial wind fluctuations due to the freely moving payload. For this a rotation and acceleration sensor has been included into the housekeeping electronics. Additionally we will examine whether plastic balloons will reduce the artificial motions of the payload relative to the balloon. Further balloon soundings shall be performed near our institute at Kühlungsborn, Germany (54°N, 12°E) and near Kiruna, Sweden (67°N, 21°E).

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