NEW VERSION OF BALLOON HYGROMETER FOR IN SITU WATER VAPOUR MEASUREMENTS IN THE UPPER TROPOSPHERE AND LOWER STRATOPSHERE (FLASH-BM)

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ABSTRACT

The fluorescent technique is well recommended for in situ water vapor measurements in the upper troposphere, stratosphere and mesosphere on board balloons, high-altitude aircrafts and rockets. New version of the balloon optical fluorescent hygrometer (FLASH-BM) is presented. Special attention is devoted to the calibration procedures, stability, accuracy and precision of the flight instrument. New version of the vacuum ultraviolet hydrogen lamp is used for dissociation of the water vapour molecules. Technical specifications of this lamp as well as the procedure of the absolute calibration of its intensity are described. Some results of FLASH-BM test flight are presented and discussed.

1. INTRODUCTION

Water vapor plays a unique role in atmospheric processes as a key chemical and radiative component. Traditionally, the global radiosonde network provides good vertical resolution of the lower troposphere humidity profiles. But due to significant problems arising at low temperatures and humidity, radiosondes give only rough estimates of water vapor concentration in the upper troposphere and tend to have very poor performance in the stratosphere. Satellite-borne and ground-based remote sensing provides valuable data on stratospheric water vapor concentration on a global scale, with the vertical resolution of the obtained profiles being, however, not better than 1-2 km. Improvement of the employed technique and creating new instruments become increasingly more important in meeting ever-growing requirements for the accuracy and resolution of atmospheric observation. The development of the remote techniques for studying the stratosphere also implies validation of the data obtained by *in situ* measurements.

A limited number of techniques are used for *in situ* measurements of the upper troposphere and stratosphere humidity. Among them, the fluorescent technique, offering high accuracy and fast response, has proved reliable. Based on this technique, an optical fluorescent hygrometer FLASH has been developed at Central Aerological Observatory. While FLASH instrument has been designed for use both on board balloons and high-altitude aircrafts, here we focus on the balloon modification of the hygrometer – FLASH-BM.

2. PRINCIPLE OF OPERATION

The fluorescent hygrometers for water vapor *in situ* measurements in the upper atmosphere with balloon, high-altitude aircraft, rocket were created and applied for atmospheric studies.[1-8] The fluorescent method[1] is based on the photodissociation of H_2O molecules at wavelengths below 137 nm and subsequent fluorescent relaxation of the exited OH* radical produced. For Lyman-alpha dissociation of water vapor the process can be expressed as

$$H_2O + h\nu(121.6nm) \rightarrow OH^*(A^2\Sigma^+) + H\,(^2S) \qquad (1)$$

The electronically excited OH* radical either fluoresces at 310 nm

$$OH^*(A^2\Sigma^+) \rightarrow OH(X^2\Pi) + h\nu \quad (305\text{ -}325\text{ nm}) \qquad (2)$$

or is quenching by collisions with air molecules

$$OH^*(A^2\Sigma^+) + N_2, O_2 \rightarrow \text{products} \qquad (3)$$

A photomultiplier with an interference filter measures the intensity of fluorescence which is signature of the parent molecules of H_2O. The intensity of fluorescence is obtained as

$$J = [OH^*] * A = \frac{[H_2O] * F_\lambda \sigma_{H_2O} * \varphi * A}{A + k_q * [air]} * \exp\{-\sigma_{O_2} * [O_2] * L\} \qquad (4)$$

where L- the length of the absorption between the lamp and interaction region;

$[OH^*]$, $[H_2O]$, $[air]$, $[O_2]$- number densities of $OH^*(A^2\Sigma^+)$, H_2O ,air and oxygen respectively;

A - Einstein transition probability ;

F_λ - photon flux of the light source;

σ_{H_2O}, σ_{O_2} - cross sections of water vapor and oxygen for Lyman -α respectively;

φ - the quantum yield of photodissotiation;

k_q - quenching coefficient;

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In determining the photon flux, absorption by oxygen has to be taken into account. At air pressure below 10^{-1} hPa the quenching by air and oxygen absorption are negligible[1] and the fluorescence intensity becomes

$$J = [H_2O] * F_\lambda \sigma_{H_2O} * \varphi \quad (5)$$

This condition applies to the laboratory experiments described in this paper. In the other limiting case $P_{air} > 10$ hPa, i.e. in the atmosphere up to 35km, $K_q * [air] >> A$ and hence

$$J = \frac{[H_2O]}{[air]} * \frac{F_\lambda \sigma_{H_2O} * \varphi * A}{k_q} * \exp\{-\sigma_{O_2} * [O_2]L\} \quad (6)$$

Thus, under condition with negligible oxygen absorption, the fluorescence gives a direct measurements of the atmospheric water vapor mixing ratio in this case. The coefficient $F_\lambda \sigma_{H_2O} * \varphi$ in (6), representing optical properties is different for each hygrometer, thus a laboratory calibration of the instrument is necessary.

3. INSTRUMENT DESIGN

3.1 Overview of the instrument

The FLASH-B instrument was developed at Central Aerological Observatory, Russia for balloon-borne water vapor measurements in the upper troposphere and stratosphere. The instrument is based on the fluorescent method, which uses H_2O molecules photodissociation at a wavelength $\lambda < 137$ nm followed by the measurement of the fluorescence of excited OH radicals. The source of Lyman-alpha radiation (λ =121.6 nm) is a hydrogen discharge lamp while the detector of OH fluorescence at 308 -316 nm is a HAMAMATSU R647-P photomultiplier run in photon counting mode with an narrowband interference filter for selecting the fluorescence spectral region. The intensity of the fluorescent light sensed by the photomultiplier is directly proportional to the water vapor mixing ratio under stratospheric conditions (30 – 150 hPa) with small oxygen absorption (3% at 50 hPa).

The modified version of the optical hygrometer named FLASH-BM (Fluorescent Advanced Stratospheric Hygrometer for Balloon) had significantly reduced dimensions and weight. It was successfully applied for water vapor measurements on board of long and short duration balloons. Based on this experience the recent version of FLASH-B integrated with Vaisala RS-80 radiosonde has been developed for regular balloon soundings.

The instrument uses the open layout where the optics is looking directly into the outside air. This arrangement is suitable only for nighttime measurements with a solar zenith angle larger than 94^0, at which sun light no longer reaches the detector. The co-axial optical layout allows reducing the size of the instrument to 106x156x242 mm with a total weight of 0.980 kg including batteries. The sketch of the hygrometer's design is shown in Fig.1.

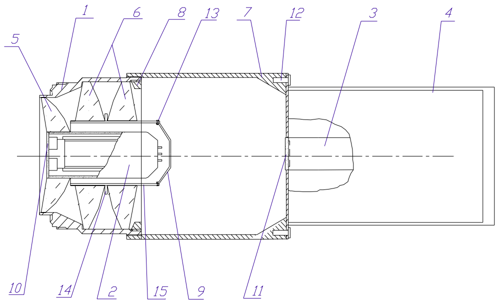

Fig. 1 Hygrometer design. 1 – kovar mounting, 2 – hydrogen lamp, 3 – photomultiplier, 4 – electronic unit, 5 – convex-concave lens, 6 – biconvex lenses, 7 – connecting tube, 8 – thread bushing, 9 – lamp housing, 10 – window-filter of the lamp, 11 – interference filter, 12, 13 – screw, 14 – teflon ring

It is important to mention that in the FLASH-BM version the plastic lenses (instead of quartz) could be used.

3.2 Description of the VUV lamp

The source of vacuum UV (VUV) radiation used in the FLASH-B instrument is a hydrogen glow-discharge lamp filled with a mixture of hydrogen and helium at the total pressure of 3-10 hPa.

Hollow cathode lamps having hydrogen-helium filling were used as sources of vacuum ultraviolet radiation for dissociation of water vapor molecules in reaction (1). The spectrum in the VUV range is dominated by hydrogen Lyman alpha at 121.6 nm (10.2 eV)/ but molecular band emission of hydrogen is also seen in VUV range.

Lamps (CHROMDET CDL-1070) showed at Fig.2 were made by technology, providing high accuracy of positioning of the light beam. Discharge channel of the lamp was performed of corundum ceramics which unlike glass does not emit gases released from the walls as a result of interaction with discharge plasma.

Lamps radiation intensity was measured at the laboratory by means of flow-type ionization chamber developed by CHROMDET. Ionization chamber does not have the window because the flow of ionized substance was under atmospheric presser. This allowed avoiding uncertainty associated with window transmission. Hexane (1000 ppm) in a mixture with

Figure 2. VUV hydrogen glow-discharge lamp

nitrogen was used as a ionized substance because proximity Hexane IP (10, 17 eV) to Lyman alpha photon energy. Photoionization cross-section was taken from literature. Total cross-section of VUV absorption also needed for calculation of absolute Lyman alpha flux was measured ourselves.

Flow-type ionization chamber used also for checking of L-alpha stability

Unlike the more sophisticated hygrometers based on the fluorescence technique, FLASH-BM doesn't use VUV photon flux control. However the hydrogen glow-discharge lamps used in the FLASH-BM instrument have been proved to have very stable intensity of the Lyman-alpha emission over both operation and storage time. Every lamp is subjected to continuous laboratory tests for stability of the emission intensity which is checked before the flight. In addition the instrument uses the narrowband interference filter centered at 310 nm with 8 nm bandwidth and out-of-band extinction of 10^{-5} thus reducing the possible effect of the stray light backscattering.

The background signal caused by the night sky emissions in the absence of fluorescence light is detected using lamp modulation with 1 kHz square wave with 1/16 duty cycle and synchronous demodulation of the signal received. The background signal is detected while the lamp is off and then subtracted from the fluorescence signal.

What makes in-flight lamp intensity control unnecessary?

1. Every lamp is tested for long and short term stability by manufacturer and in the CAO lab.
2. Lamp intensity is known to be proportional to the discharge current, which is accurately stabilized by the lamp driver (< 0.1 %)
3. Lamp intensity temperature dependence is less than 3 % within -70° C .. +40 ° C range.
4. Ascent and descent stratospheric profiles always match below the contamination threshold (70 – 90 mBar)

3.3 Electronic design

The **electronic part**, shown in Fig. 3 and Fig. 4, provides lamp modulation, PMT signal processing and demodulation, PMT heat setting and transmission of the data over telemetry channel. The essential feature of signal detection is lamp modulation with 1 kHz square wave with 1/16 duty cycle (OSC) and synchronous demodulation of the signal received. Such setup allows increasing signal-to-noise ratio several-fold, improving the sensitivity, and widening the dynamic range of the hygrometer. When the lamp is on, the counter is counting the fluorescence photons, and when the lamp is off, the counter is subtracting dark counts. The output signal of PMT is collected into internal counter of microcontroller. Each second the microprocessor reads counter value and transmits to the ground by means of the 403 MHz transmitter that is also part of the radiosonde. The value of duty cycle can be changed fro 1/1 to 1/16 depending on the hygrometer's option.

An important part of the new version of the hygrometer is the use of fast microcontroller (ARM TDMI) to control the setup and operation of the hygrometer. Microcontroller provides 1 kHz lamp modulation signal, which control Lamp Driver for Lamp flashing. Using internal DAC, microcontroller can set up and keep up the Lamp current value very precisely. The second DAC is set up photomultiplier (PMT) voltage value in PMT power supply. Internal ADC measure the PMT voltage for keep up the value in 1 V precision in all operating conditions. During the balloon flight the microcontroller is set up inside temperature and control of heater, for keep the instrument temperature the same value as under calibration.

Hygrometer has the pressure sensor onboard. The PMT is switched on by pressure sensor output at 2 km altitude, for avoidance the PMT go blind by big ground lights during the balloon launching. In descending below 2 km the Lamp and PMT are switched off.

Microcontroller have several interfaces for connecting to different radiosondes. For communicate to Vaisala RS92 radiosonde it has interface converter from UART to SPI port. The hygrometer data going to RS92 radiosonde by digital interface and download to the ground station in composition radiosonde data. Using UART interface, hygrometer can work with other radiosonde system, like Meteolabor SRS-34 (Switzerland), Meisei RS-06G (Japan), Intermet (USA). Power consumption of hygrometer is 0,5 A x 12 V. Four Lithium batteries size C with around 4 A/h capacity, for example SAFT LSH 1, provides hygrometer operation during 4 hours of balloon flight.

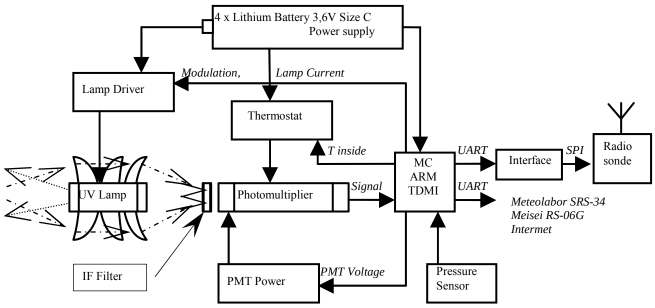

Figure 3. Block-diagram of FLASH-BM

Figure 4. Electronic unit of FLASH-BM

The new FLASH-B firmware allows

- easy and flexible adjustment and control of all systems
- all operations are performed by the one microcontroller
- easy integration with analog and digital interfaces
- currently established interfaces to Vaisala RS-92, RS-80, Meteolabor SRS-C34, Meisei RS06G, Intermet

3.4 Calibration of the hygrometer

The FLASH-B hygrometer is not an absolute instrument for water vapor measurements. Every hygrometer has to be calibrated in the laboratory before the flight. The laboratory studies showed that calibration coefficients remain constant in time. The lamp intensity, being the most influencing factor for calibration, is checked directly before the flight.

The accuracy of the FLASH-B instrument is determined by the calibration error estimated as 4% in the 3 – 100 ppmv range. The measurement precision is 5.5% calculated for 4 seconds integration time at stratospheric conditions. The total uncertainty of the measurement is less than 10% at the stratospheric mixing ratios greater than 3 ppmv increasing to about 20% at mixing ratios less than 3 ppmv.

For calibration a laboratory facility capable of simulating atmospheric conditions is used. In particular, the large range of water vapor mixing ratios (1-1000 ppmv), pressure from 1000 to 3 hPa and temperature down to 190 K can be generated by the calibration setup. The scheme of calibration bench is shown in Fig.5.

The calibration procedure is performed as follows: after purging the system with dry air for 1 – 2 hours, the airflow boosted by the compressor is dried passing a silica gel dehumidifier and then divided into two branches of which one is moistened in a H_2O bubbler. Via the two flow controllers the airflows of both branches are mixed together in a homogenizer producing variable H_2O mixing ratios.

After passing the homogenizer the mixed airflow is divided so that one branch flows through a commercial reference dew point hygrometer MBW 373L to determine the H_2O mixing ratio, while another branch goes to the stainless steel chamber cooled down to 210 K in the low temperature freezer. The fluorescence hygrometer is flanged to the chamber via vacuum caulking. The pressure in the chamber is reduced by the vacuum pump to 50 hPa. The calibration is started with the lowest H_2O mixing ratio, which is then increased stepwise. Every calibration point is measured for about 15 minutes.

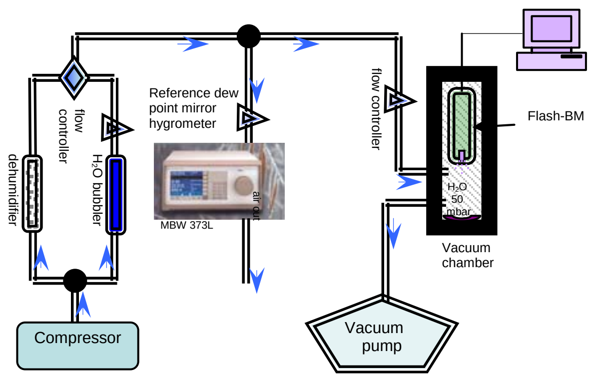

Figure 5. The scheme of calibration bench

The calibration fit function is linear in the pressure range of 30 – 150 hPa and water vapor mixing range of 1 – 300 ppmv. At higher pressures the VUV absorption by oxygen and water vapor is taken into account. The lamp stray light being constant doesn't affect the calibration since the calibration coefficients are determined as the slope of the regression line.

5. Flight tests

The results of tests balloon flight with new version of FLASH-BM is presented in Fig.6. Ascent and descent stratospheric profiles match below the contamination threshold (21 km). It confirm that the intensity of VUV lamp during the flight is stable.

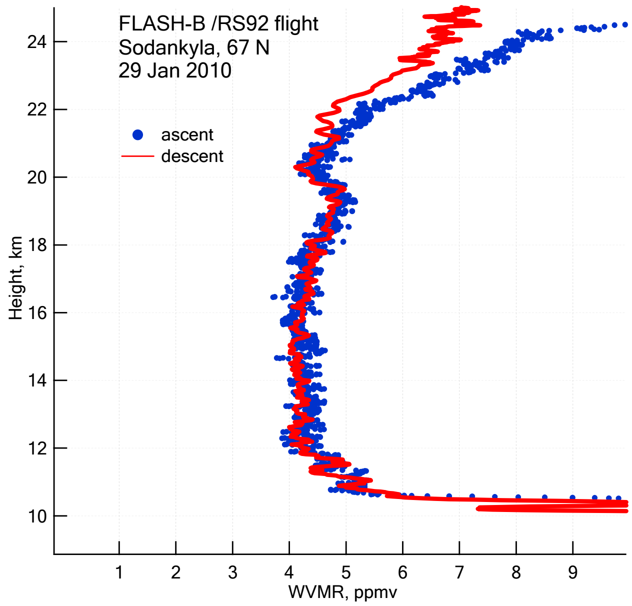

Figure 6. The results of balloon flight with new version of FLASH-BM.

5. CONCLUSIONS

1. A new, upgraded version of FLASH-B instrument has been created (FLASH-BM) with new highly stable hydrogen lamp, new optics and new electronics and firmware. Improved electronics are based on modern components. FLASH-BM is easily assembled, adjusted, calibrated and has flexible interface support. FLASH-BM was successfully tested in the lab and in the soundings

2. Using coaxial optical scheme, electrical modulation of a hydrogen lamp with a frequency of 1 kHz, PMT in photon counting mode, synchrodemodulation of the fluorescent signal is the basis of the new version of the open-type hygrometer without an aspiration system.

3. The hygrometer FLASH-BM can be used together with the Vaisala RS-92, RS-80, Meteolabor SRS-C34, Meisei RS06G, Intermet radiosondes

4. The total accuracy mainly depends on the calibration procedure and does not exceed 10%. 3 sec averaging of the flight raw data provides a possibility to study the fine structure of the observed vertical water vapor profile.