ATOMIC OXYGEN SENSOR SYSTEMS AIMING IN-FLIGHT MEASUREMENTS ON A SOUNDING ROCKET

Stefanos Fasoulas, Stefan Loehle, Andreas Steinbeck and Martin Eberhart

Institute of Space Systems, University of Stuttgart, 70569 Stuttgart
Email: fasoulas@irs.uni-stuttgart.de

ABSTRACT

The energy balance of Earth's middle atmosphere involves numerous mechanisms that are quite well understood qualitatively. However, there is a lack of important data to determine the effects on a quantitative basis. Within a common project, led by the Leibniz-Institute of Atmospheric Physics, and as part of an instrument package, we develop two sensor systems aiming at the direct, time-resolved measurement of the atomic oxygen concentration aboard a sounding rocket. One system is based on solid state electrolytes (FIPEX), the second on the measurement of heat flux differences on two materials with different catalytic efficiency (PHLUX). FIPEX flew successfully on a platform of the International Space Station and PHLUX is currently awaiting its first flight aboard ESA's reentry capsule EXPERT. Thus, both sensor systems have been flight-qualified, but not yet in the density regime of the meso- and lower thermosphere. Moreover, the overall design of the experiments must be adapted with respect to the expected flow regime on a sounding rocket. Within this paper, both, the sensor principles and the chosen designs are introduced. Basic approach, sensor setup and location, and sensor electronics are described. The expected signals are simulated using predicted atomic oxygen concentrations between 75 km and 130 km altitude.

1. INTRODUCTION

Although very tiny from a cosmic point of view, Earth's atmosphere experiences a variety of complex interactions of natural or anthropogenic origin. These complex phenomena lead sometimes also to surprising results, at least at first sight. One surprise has been for example that the coldest point in the atmosphere is found at an altitude of about 90 km above the polar region during the local polar summer, i.e. under continuous sunlight (see Fig. 1, [1, 2]). Obviously, this region (i.e. 50–110 km altitude, mesosphere / lower thermosphere, MLT) is of high interest in order to understand the complex occurring physical and chemical phenomena.

A project led by the Leibniz-Institute of Atmospheric Physics Kühlungsborn, has therefore the goal to further investigate the phenomena associated with the different heat sources in the MLT. For this, it is planned to launch two instrumented sounding rockets under different geophysical conditions, i.e. one during local wintertime and a second during the transition between winter and summer conditions. These campaigns shall be accompanied by additional meteorological rockets to be launched in the same time frame and by a variety of ground based measurement techniques.

The planned instrumentation of the sounding rocket campaigns comprises experiments for the time resolved measurement of total densities and of different species, e.g. CONE (COmbined measurement of Neutrals and Electrons [3, 4]), Langmuir-type electron probe [5], other ion and electron probes [6], NO- and O-photometer [7], Faraday-cup for particle measurement [8], and two experiments supplied by the Institute of Space Systems (IRS) for the direct and time-resolved measurement of atomic oxygen FIPEX and PHLUX. The latter two are described in this paper.

The interest for the time-resolved measurement of atomic oxygen becomes obvious if considering the potential heat sources in the MLT. Here, three main and interacting heat sources have been identified [9]:

- Absorption of solar UV and EUV–radiation.
- Heating by exothermal chemical reactions.
- Dissipation of gravity wave energy by turbulence.

The absorption occurs predominantly by the photodissociation of molecular oxygen (O_2 and O_3) in different wavelength regimes, producing subsequently atomic

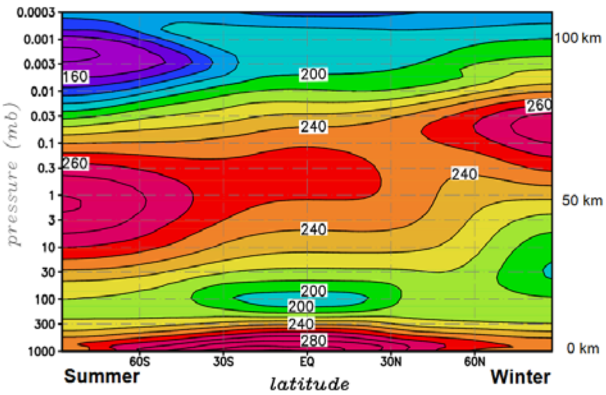

Figure 1: Temperature isolines of Earth's atmosphere (in Kelvin). Note that the coldest region is at about 90 km altitude and above the South Pole, however, during the southern summer under continuous sunlight conditions (!) [1, 2].

Proc. '20th ESA Symposium on European Rocket and Balloon Programmes and Related Research'
Hyère, France, 22–26 May 2011 (ESA SP-700, October 2011)

oxygen (e.g. [10]). Parts of the absorbed energy is then released to heat by collisions, parts are re-emitted to space and parts are temporarily stored as (potential) chemical energy mainly in atomic oxygen and other oxygen containing species (e.g. OH) [11]. Later on, the stored potential chemical energy may be released as heat by three body recombination reactions of atomic oxygen with O, O_2 and O_3 as well as by reactions with hydrogen containing species (H, OH und HO_2) with O, O_2 und O_3. The heat released by these reactions represents indeed the major contribution to the total heating rate for altitudes of about 80–90 km.

Very similar to the heating processes, atomic oxygen is also significantly involved in equivalent cooling processes. For example, one dominating heat sink in the global radiation budget of the MLT is the emission of infrared radiation in the 15 µm band of CO_2. Because of the low density, the respective energy levels are in non-equilibrium (n-LTE), their population depends on the amount of collisions between CO_2 and atomic oxygen, and thus also the amount of the associated infrared radiation. Additionally, it is also interesting to note that commonly used, satellite based methods measure the emissions in the aforementioned 15 µm band in order to produce atmospheric temperature profiles. Thus, without exact values for the atomic oxygen concentrations the results can be misinterpreted with an error of several 10 K [12, 13].

Certainly, also the dissipation of kinetic and potential wave energy and the associated transport phenomena especially if incorporating atomic oxygen are also of general interest. An overview of the occurring effects, their importance and their interaction with the atomic oxygen concentration is given for example in [3, 14].

In the following sections the two approaches by the IRS for the measurement of atomic oxygen during the planned mission are outlined. The measurement principles are described and the preliminary design is reported.

2. SENSOR SYSTEMS

The sounding rocket to be flown will be equipped with two experiment decks: One on the upper side and one on the backside above the thruster. The upper deck is covered with a fairing during launch. The fairing is released in about 50 km altitude, and all sensor systems on the upper deck are then facing the atmospheric gases. On the lower deck, the sensors are integrated in an intermediate ring which connects the payload to the rocket motor. The interface ring is jettisoned together with the thruster and thus, the lower deck is facing ambient air.

The sounding rocket itself is controlled in an upright position during the complete trajectory. The flight trajectory is a suborbital flight path as depicted in Fig. 2 with a duration of roughly 6 min and a planned maximum altitude of about 130 km. Sensor systems are requested to acquire data at least above 50 km and as high as possible, i.e. at least up to 120 km.

Both sensor systems developed by the IRS (FIPEX and PHLUX) are arranged on one interface ring to the rocket structure. They consist mainly of two sensor heads which are mounted closely to each other and with the same distance to the rocket center axis in order to provide similar flow conditions. Fig. 3 illustrates the positioning on the upper deck of the rocket. Fig. 4 shows the expected atomic and molecular oxygen partial pressures for the planned flight trajectory. A maximum in atomic oxygen concentration is expected at about 100 km, i.e. at about 1:40 min after launch.

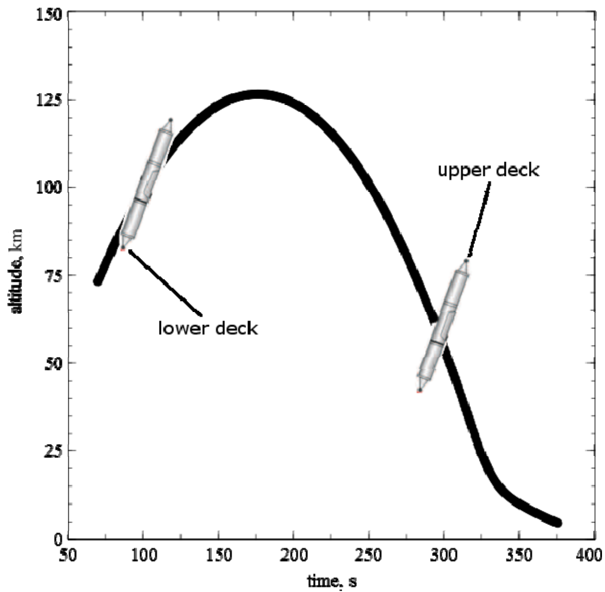

Figure 2: Flight trajectory of the sounding rocket.

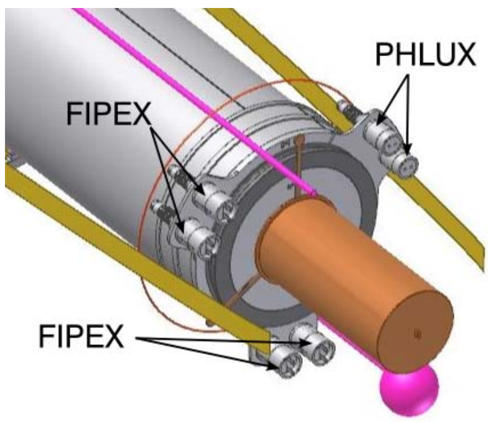

Figure 3: Sensor positions of FIPEX and PHLUX on the upper experiment deck of the sounding rocket.

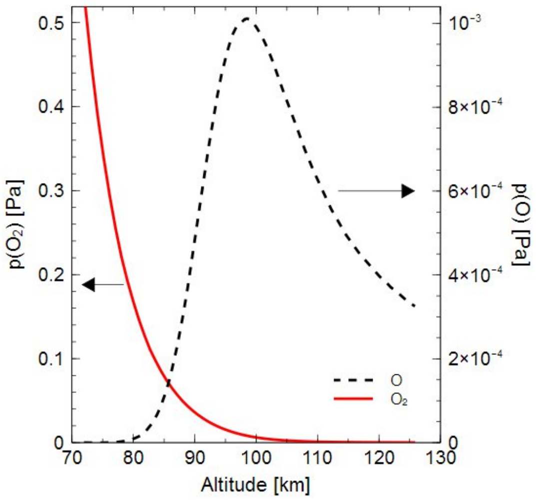

Figure 4: Partial pressure of molecular and atomic oxygen vs. rocket flight altitude.

3. FIPEX Sensor System

FIPEX and the associated sensors have a long development and application heritage, including an application on the external platform EuTEF onboard the International Space Station, measuring the residual atomic oxygen concentration at very high altitudes. An overview about the developments is given e.g. in [15-17].

The core of the FIPEX system, the sensor, is an ion conducting ceramic, a solid electrolyte. Various materials with this property are known; here yttria-stabilized zirconia is used allowing selectively oxygen anions O^{2-} to be conducted at elevated temperatures (above approx. 400°C).

An amperometric principle and flat design is then used, i.e. the oxygen flux through the electrolyte is determined by measuring the current at an applied voltage (Figs. 5, 6). Consequently, if a diffusion barrier limits the oxygen flux from the ambient air to the cathode, the resulting electrical current depends on the ambient oxygen concentration (every oxygen molecule or atom at the cathode is transported through the electrolyte; the oxygen concentration at the cathode becomes zero, the current is limited). Electrodes are needed for the signal measurement but also in order to provide the oxygen ions by adsorbing and reducing oxygen from the vicinity and guiding the newly formed anions to the three-phase-boundary between electrode and electrolyte.

The measurement range and the maximum detectable oxygen partial pressure can be adapted by adjusting the overall porosity of the diffusion layers, the active electrode areas, and the number of adsorption places for the

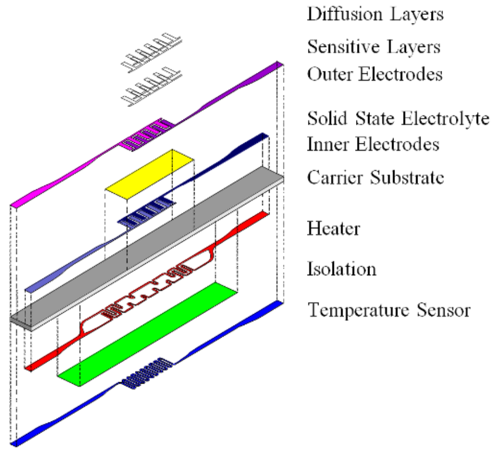

Figure 5: Principle design of multi-layer sensor elements manufactured by screen printing and subsequent sintering.

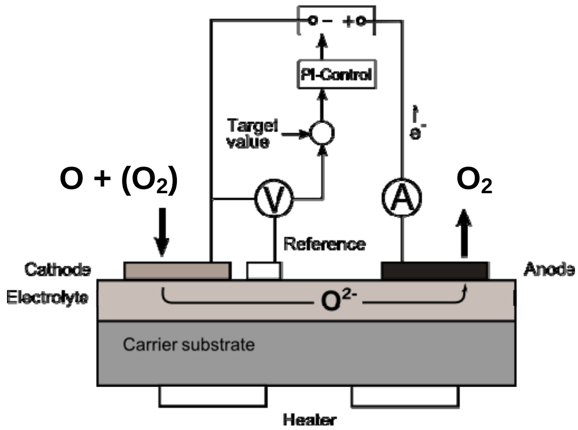

Figure 6: Schematic setup of a 3-electrode sensor.

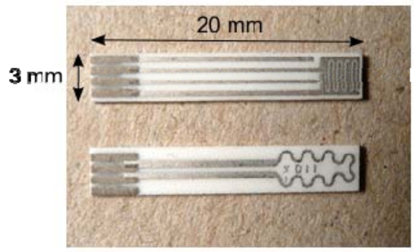

Figure 7: Picture of the screen-printed multi-layer oxygen sensor.

oxygen molecules at the electrodes that allow for an electron transfer reaction.

The applied voltage has also to be controlled such that constant conditions at the cathode can be guaranteed. For this purpose, a third electrode is positioned very close to the cathode. This so-called reference voltage is now controlled to a target value. The setup of such a design is shown schematically in Fig. 6. Note that all electrodes are placed on the same side of the ceramic and that an electrical heater element works on the other.

Finally, the material properties of the electrodes are of importance for the sensor performance. They have to show a high catalytic activity for the adsorption and reduction of neutral oxygen at the surface. Choice of the cathode material determines also the sensitivity to the different oxygen species. We use for example a metal for the additive measurement of both, atomic and molecular oxygen. The latter experiences a dissociative absorption first whereas atomic oxygen may be reduced directly upon arrival. Another cathode material has a very much lower capability for the dissociative adsorption, thus it is more sensitive to atomic oxygen. Subsequently, it is now possible to determine the partial pressures of both species by using two sensors with different cathode materials.

A picture of the sensor for molecular and atomic oxygen is shown in Fig. 7. The typical response time t_{90} as demonstrated for many other applications is lower than 50 ms. The combination of the two sensors forms a FIPEX probe head as shown Fig. 8. Both sensors are mounted in a common housing that is attached to the interface ring of the rocket, see Fig. 3.

The calibration of both sensor types is performed in a vacuum chamber, where a quadrupole mass spectrometer serves as reference for the gas composition. Atomic oxygen is produced by a microwave plasma generator attached to the chamber or by a high vacuum atomic source based on a glowing tungsten wire [17, 18].

Figures 9-10 show finally the expected sensor signals which have been estimated based on the trajectory data, the MSIS-90-atmospheric model and the calibration curves previously obtained for the sensor types flown on the ISS-mission.

Sensor signals will be measured in intervals of 0.01 s (100 Hz), resulting in a vertical spatial resolution of 0-9 m depending on the rocket velocity. The expected signals will range from 1-20000 nA and have to be recorded with a resolution of 0.1 nA.

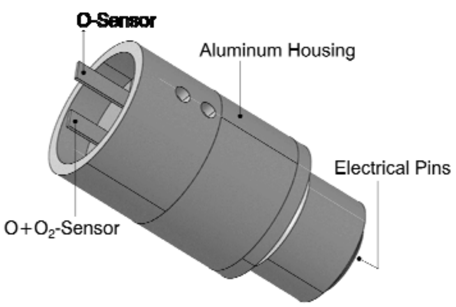

Figure 8: Setup of the sensor head, comprising one sensor for atomic oxygen and one for both atomic and molecular oxygen measurement.

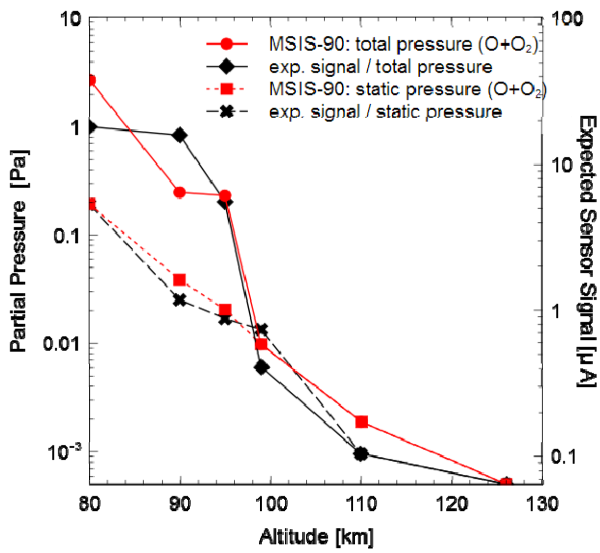

Figure 9: Expected signal for the sensor capable to measure molecular and atomic oxygen.

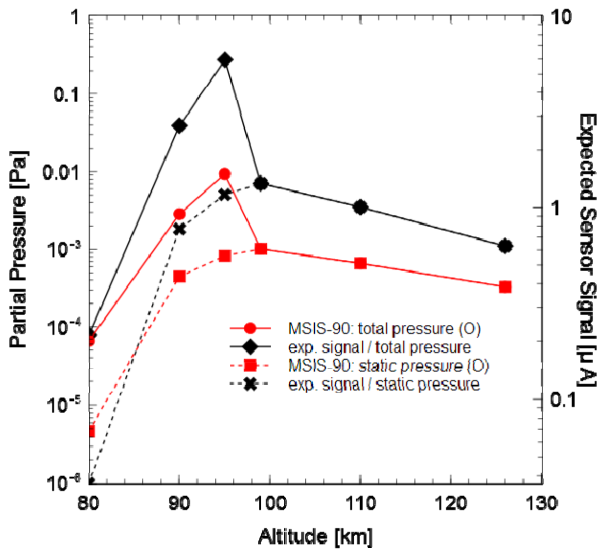

Figure 10: Expected signal for the sensor capable to measure atomic oxygen.

4. PHLUX Sensor System

The catalytic based sensor system PHLUX proposed for the mission is based on the experience gained during the development of a similar sensor system, also called PHLUX, for EXPERT, a re-entry mission lead by ESA [19, 20]. The principle bases on the temperature measurements on two different materials. Different materials in chemical reactive or space environments may experience different heat fluxes leading to different surface temperatures despite an exposure to the same flow conditions. This is due to the amount of re-radiated energy from the surface, which arises from the specific emissivity (a material and surface texture-dependent quantity) but also due to the catalytic properties of the materials. On high catalytic materials, the number of recombination reactions of atomic species to molecules of the surrounding gas is much higher than on non-catalytic materials. The measured heat flux is therefore increased, i.e. in addition to convective and radiative heat flux, a further input of energy occurs resulting from the release of chemical binding energy to the catalyst. A characteristic value for the catalytic activity of a material is the recombination coefficient γ, which is defined by the ratio of number of recombining particles to the total number of particles impinging on the surface. In addition, the energy accommodation factor β is important which describes the ratio of the energy absorbed by the material to the total amount of energy released by chemical reactions. Since both variables always occur at the same time, often the effective recombination coefficient is applied, which is obtained by multiplying the two variables.

By combining high and low catalytic material samples, the convective and chemical part of the total heat flow can be separated from each other based on the measured temperature difference on both samples. This measured temperature difference, or more precisely, the differing heat fluxes derived by a signal difference between two sensors (usually temperature sensors) is therefore a direct measure of the amount of dissociated species, and thus in the case of the upper atmosphere, of the atomic oxygen amount.

Figure 11 depicts the estimation of the expected temperature difference between two different catalytic materials as a function of altitude. The approach is based on the assumption of particle fluxes calculated from the MSIS-90 atmospheric model. Important is here, that there is no need to measure absolute temperature but the temperature or heat flux difference between the different materials, which leads to an essential simplification of the measurement. Crucial for the successful application of the described method is the use of fast-response temperature sensors in order to obtain a high resolution in time and space over the complete trajectory.

Therefore, thin film PT100 resistance thermometers (L220P, Heraeus Sensor Technology) have been chosen due to their low thermal capacity. For the low catalytic surface the bare sensor can be used as the PT100 cover material is made of SiO_2, which has one of the lowest known recombination coefficients and is often used as reference for low or non-catalytic materials. The other sensor is coated with silver or platinum. Both act highly catalytic with respect to the atomic oxygen recombination. As platinum belongs to the noble metals, it is chemically inert. Silver produces a thin but stable layer of silver oxide at atmospheric conditions. Constant properties of the surface conditions are important to avoid additional influences which are difficult to evaluate in post flight analysis.

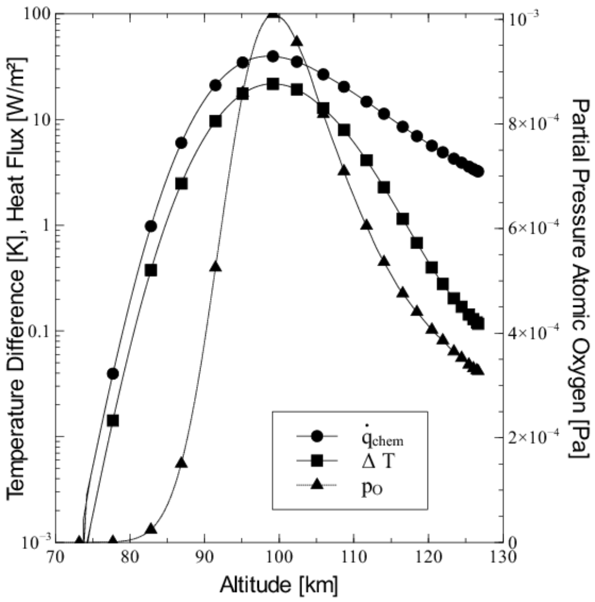

Figure 11: Partial pressure of atomic oxygen for Earth's atmosphere, estimated temperature difference and resulting heat flux on different surface.

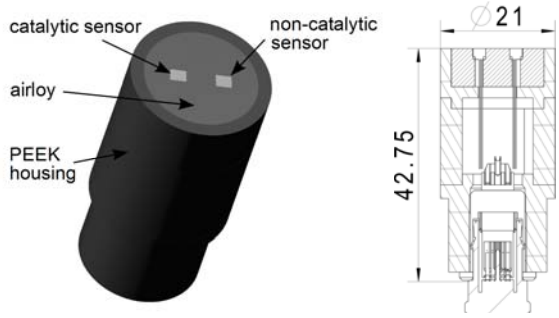

Figure 12: Design of PHLUX sensor head.

The thermal insulation is realized by an aerogel-like material which however has a different composition, called airloy. It is a hydrophobic material with a similar thermal conductivity as aerogel (λ_{Airloy}=0.02 W/mK) but with much higher mechanical strength to resist the mechanical vibrations during launch. The housing of the sensor head is made of PEEK (polyether ether ketone) which has high mechanical strength and chemical resistance properties. The thermal conductivity of PEEK is also very low (λ_{PEEK}=0.25 W/mK). Both, the airloy and the PEEK housing shall insure the proper insulation of the temperature sensors to the structure. An 8-pin push-pull connector at the bottom of the housing is used to easily connect the sensor heads to the sounding rocket. The 8 pins are needed for the four-point probes method which improves the electrical impedance measurement of the PT100 sensors. This measurement technique eliminates the impedance contribution of the contact and wiring resistances, thus becoming independent of wire length. Finally, an additional fine wire thermocouple with a diameter of 10 µm is placed in the connector at the bottom of the housing. This element provides a reference temperature between all sensor heads and additionally the temperature difference between the resistance thermometers on top and the connector temperature. Thus, the heat loss due to the sensor wires can be determined. The sensor head itself has an outside screw thread to mount it safely to the mechanical interface. The size of one sensor head is given with an outer diameter of 22 mm and a total length without the connector of 42 mm. The mass is approximately 30 g (Fig. 12).

The electronics unit allows the simultaneous recording of 2 PHLUX sensor heads which involves in total the measurement of 4 resistance thermometers each with four-point probe method and 2 thermocouples. The data is transformed by a 16 bit A/D converter. The different data values are then composed to a single data word of 17 bytes length and sent to the on-board electronics of the sounding rocket via RS422 interface. The polling frequency for PHLUX is actually 500 Hz. The power consumption is roughly 1.5 W and the overall dimensions of the electronics unit are 80 x 80 x 60 mm.

5. Summary

This paper describes the current development status of two measurement techniques for atmospheric sounding rocket campaigns for the direct, spatially resolved determination of the atomic oxygen concentration in the mesosphere up to the lower thermosphere. Both systems have been developed in the past for the measurement of atomic oxygen in other fields, i.e. in high altitudes onboard the International Space Station or during re-entry. The further development for an application on sounding rockets is straight-forward and the measurement principles seem appropriate for the extension of the application range.

An extensive calibration in the relevant density regimes is currently scheduled for the next months in order to determine more precisely all important characteristics for the test campaigns, the first of which is planned for January 2012. Once qualified, demonstrating the capability to measure atomic oxygen with high time resolution, the results of the new sensor systems could then assist to the further understanding of the complex phenomena and interaction occurring in Earth's atmosphere.

Acknowledgments

Financial support of the complete campaign by the German Space Administration (DLR) under contract number 50 OE 1001 is gratefully acknowledged. The authors thank all colleagues from the Institute of Atmospheric Physics, especially Markus Rapp, and the DLR-MORABA team for the excellent co-operation. The support of Dr. Laure Plasmatechnologie GmbH for the coating of the PHLUX sensors is highly appreciated.

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