TIME RESOLVED ATOMIC OXYGEN MEASUREMENT IN THE ATMOSPHERE WITH THE PAYLOAD UNIT APOLLON

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Abstract

This paper gives details of the development and verification of an engineering model of an external secondary payload unit for multi-point time resolved measurement of atomic and/or molecular oxygen as a key parameter of the lower thermosphere. The atomic and/or molecular oxygen measurement is based on solid oxide electrolyte micro-sensors which operate at an elevated temperature of 600-700°C, heated by an electrical resistance. The science unit named APOLLON (Atmospheric Portray of Oxygen Level with Low Orbit Network) consisting of the micro-sensor itself, the necessary electronic I/F circuitry, harness and the mechanical platform/housing and can be placed on a satellite platform in free flow. The actual flux required for an accurate measurement will be obtained from the attitude of the satellite with respect to its direction of motion. Details of the technology, the design and the verification tests of the science unit APOLLON will be presented as well as potential applications and an outlook of future work.

1. INTRODUCTION

In-situ measurements of atomic and molecular oxygen in the thermosphere are key measurements that may potentially support several space agencies programs including Earth observation, Space Situational Awareness, and scientific programs. Such measurements have the potential to substantially contribute to atmospheric science but also to modeling efforts of the upper atmosphere that affect satellite drag and contaminate or de-grade spacecraft surfaces. All this drive the need for a high-resolution, atomic oxygen sensor secondary payload unit.

A small sensor system based on solid oxide electrolyte micro-sensors designed by Dresden University of Technology is able to distinguish and measure in-situ the time resolved behavior of atomic and molecular oxygen as a key parameter of the lower thermosphere. Atomic oxygen is the dominant species this region and therefore its measurement is crucial in the correlation and validation of atmosphere models. Moreover, erosion of spacecraft surfaces due to interaction with atomic oxygen is a serious concern. In principle, this sensor system can be attached as an independent small secondary payload on the outside of any satellite in low earth orbits and can therefore be used to establish a global, high resolution atomic oxygen measurement network.

The science unit named APOLLON (Atmospheric Portray of Oxygen Level with Low Orbit Network), developed by Hoch Technologie Systeme (HTS) GmbH, located in Coswig, Germany and Dresden University of Technology, Institute for Aerospace Engineering in Dresden, Germany, consisting of these micro-sensors itself, the necessary electronic I/F circuitry, harness and the mechanical platform/housing. In order to develop a product adaptable to a large range of spacecraft, concepts of three different APOLLON designs were evaluated, designed and tested.

2. ATOMIC OXYGEN SENSOR

2.1. Atomic Oxygen

Space vehicles in low altitudes orbit the Earth with a velocity of about 8 km/s in a rarefied atmosphere. Above the mesopause (starting at about 85 km) the molecular oxygen is dissociated because of the solar radiation in the UV- regime beyond 175 nm wavelength. Subsequently, atomic oxygen dominates above this altitude up to about 1000 km compared to oxygen and nitrogen molecules. Because drag of space vehicles in low Earth orbit is mainly influenced by the density of the flow, it is important to know the conditions on hand relatively exact. [1]

However the atmosphere's composition is influenced by the solar radiation and the Earth's magnetic and gravitational field, the exact constitution at a given point depends upon many different parameters, which include long-term, short-term and spatial variations. Many different semi-empirical models were developed in the past with which it is possible to calculate the data for any spatial position at a given time. Though, the results of these models may differ by more than one order of magnitude. Thus, the prediction of total density and gas partial pressures for satellites and the International Space Station (ISS) flying at these altitudes is insufficient.

2.2. Sensor Design

The oxygen sensor, called FIPEX (ϕ-(Phi=Flux)-Probe-Experiment), in general is able to distinguish and to measure atomic and molecular oxygen at very low ambient pressures. The design of the oxygen sensor element as further developed is straight forward for small size, low power consumption and high sensitivity in high vacuum conditions. The sensor plate geometry is 3.0 x 3.0 x 0.5 mm³, resulting in a reduced heater power of less than 1 Watts at 660°C.

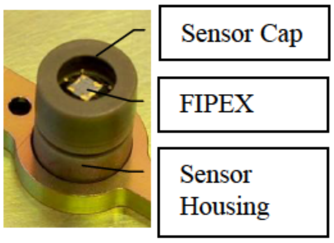

FIGURE 1. Oxygen sensor element with sensor housing

The working principle of the Dresden University of Technology developed oxygen sensors is based on the ion conductivity of ceramic materials. For oxygen conducting solid state electrolytes, e.g. yttria-doped zirconia, the conductivity starts at high temperatures. Therefore, the sensor is heated by a resistance heater to approx. 660°C. Based on noble metal ceramic compounds and sensitive additives and manufactured by screen printing technologies (thick-film) and thin-film technologies, the oxygen sensor basic function is based on the amperometric three-electrode principle where the electrical current is measured along the electrochemical polarization control. According to Faradays' law, this current is proportional to the mass flux by electrolysis. Thus, oxygen is non-dissoziative adsorbed and transformed to oxygen ions under a potentiometric-Nernst- principle polarisation control. These ions are conducted through the solid electrolyte towards the anode, where they recombine to oxygen molecules. Additionally, a diffusion barrier limits the oxygen flux to the cathode. If this flux limitation is high enough, the oxygen partial pressure almost vanishes at the cathode. In this particular case, the measured current is limited directly by the diffusion of the oxygen to the cathode and therefore a linear dependence on the oxygen partial pressure is achieved due to the diffusion law. Under low-pressure conditions the oxygen molecule flux is naturally limited by effusion laws. In order to distinguish the atomic oxygen (AO) from the molecular oxygen (O2) different cathode materials are used.

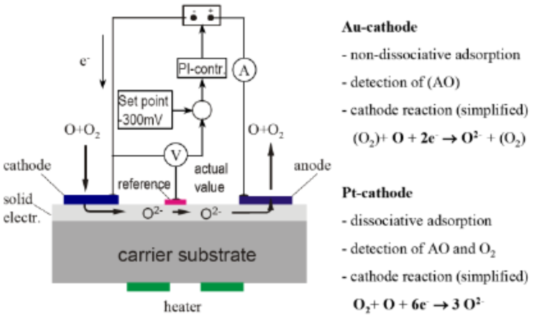

FIGURE 2. Sketch of the amperometric measurement principle

2.3. Potential Applications

During the definition phase of the study, the team contacted 25 companies and research institutes in the European space community, in order to gather a preliminary set of generic and specific technological requirements including user needs and potential applications. Detailed results of the market survey can be found in [2] and [3]. The potential market for an atomic and molecular oxygen sensor unit for space includes the following aspects:

- Knowledge of the atmosphere
- Knowledge of the satellite drag
- Knowledge of the degradation

2.3.1. Knowledge of Atmosphere

The APOLLON science unit has the potential to perform in-situ measurements for a time period in the order of months, instead of minutes to explore the lower thermosphere. All atmospheric models and users of these models can benefit from the measurements obtained by APOLLON in the lower thermosphere as APOLLON provides a sensor system that can measure and distinguish the time resolved behavior of the main residual gas species in Low Earth Orbit that is atomic oxygen and molecular oxygen. The measurements as planned have the potential to give enough experimental data to correlate the main models of the upper thermosphere (e.g. NRLMSISE, DTM, METM).

2.3.2. Knowledge of Satellite Drag

One important aspect to gain the knowledge of atomic oxygen is the deceleration of spacecraft due to atmospheric drag. In principle, one potential application could be the calculation of the current drag by the satellite itself. That is important for missions with limited access to a tracking station and where the precise orbit determination is time critical. Here, the satellite can measure the atomic oxygen by APOLLON science unit, calculate the atmospheric drag using the knowledge of the attitude and the drag coefficient and then compare the predicted with the actual trajectories. The satellite could be able to predict and continuously update its trajectories with reduced or even without receiving tracking data from ground.

2.3.3. Knowledge of Degradation

As atomic oxygen shows several interactions and erosion effects on spacecraft materials, e.g. erosion of exposed structural materials, degradation of thermo-optical properties, degradation of optical measurement devices, the prediction of these erosion effects is very important for the missions. To predict the atomic oxygen and the degradation of material properties, models like NRLMSIS-00; Drag Temperature Model (DTM), Marshall Engineering Thermosphere (MET) and the Russian GOST are used base on orbit, surface orientation, atomic oxygen density and solar activity. Here, the spacecraft can measure the atomic oxygen by APOLLON science unit, calculate the degradation (mass or thickness loss) using the knowledge of the fluence of atomic oxygen and the atomic oxygen induced erosion rates of the material.

3. APOLLON SYSTEM INTEGRATION

3.1. General

APOLLON is the general name of the science unit based on two FIPEX sensors and consisting of the sensor unit, the PCB unit and the mechanical support structure. There are three configurations. System 1 is a self standing unit consisting of sensor unit, electronic circuit and housing with defined mechanical interface and harness for large satellites. System 2 is an independent unit without an own housing. It is mounted on an adapter plate intended for use as outer wall of a satellite, e g. CubeSat. This system will have integrated electronics and harness with connectors. System 3 is a compact unit with a mechanical adapter, carrying the two FIPEX sensors without electronics. The electronic circuitry is to be separately integrated into the satellites electronic and connected to the compact unit by harness.

3.2. Sensor Unit

The sensor unit consists of the mechanical sensor unit and the FIPEX sensor. The FIPEX sensor is the main part of the system and needs to heat up to 660°C to be able to measure the oxygen density. The housing of the sensor is designed to withstand this temperature and thermally isolate the FIPEX sensor from the environmental structure. The sensor housing with the already included FIPEX is attached to the sensor unit by means of the sensor connector. The sensor connector provides the ability for replacement of the sensor housing with the included FIPEX sensors. The FIPEX is protected by means of a red tagged sensor Cap to protect the sensor from the environmental effects during MAIT and on ground storage. As late as possible before launch the Sensor needs to be replaced by a new one. The mechanical sensor unit is used to connect the FIPEX sensors with the PCB unit. Furthermore, this mechanical sensor unit is needed to fix the sensors in their position.

3.3. System Configuration 1

This system is shown in Fig. 3 and Fig 4. It is designed to be easily manageable and adaptable onto a large range of spacecraft. Basically the interface is designed to ensure an easy accommodation process. That is why the science unit is mechanical adapted by means of four screws onto the attachment points of the spacecraft. The most suitable data and power connection has been evaluated and placed on the back side of the science unit. The system configuration 1 consist of two main assemblies, the system configuration 2 and an additional housing. Both assemblies are fixed by means of screws and pins. System configuration 2 can be used without changing its setup what leads to a large manufacturing and accommodation effort. The assembly and integration of the APOLLON engineering model (EM) was performed inside the HTS and TUD laboratories. All steps were noted in the as-run assembly and integration procedures starting with the sensor integration. The resulting configuration status of the APOLLON EM hardware was documented in the as built configuration list.

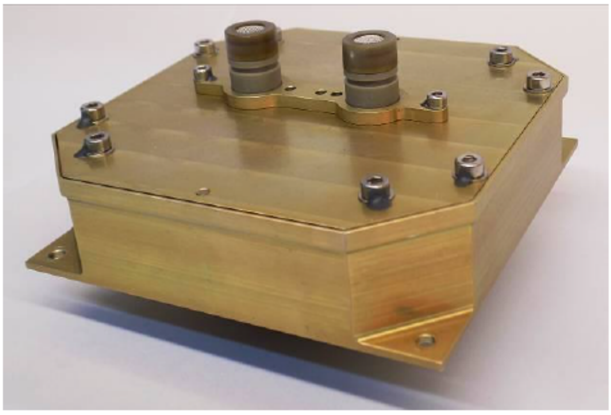

FIGURE 3. System configuration 1 after final assembly

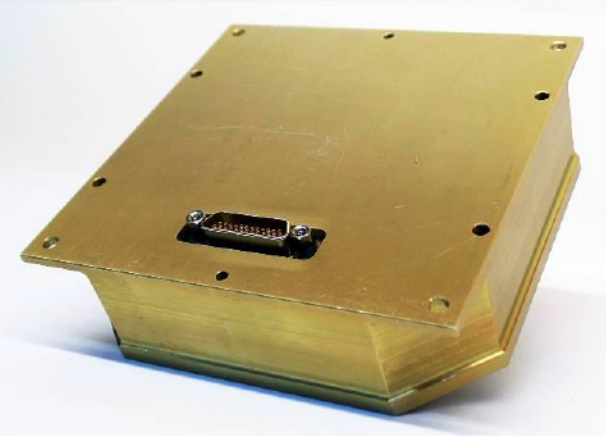

FIGURE 4. Connector position of system configuration 1

3.4. System Configuration 2

The APOLLON system configuration 2 shown in Fig. 5 consists of a fixed arrangement of FIPEX Sensor, Sensor Unit and PCB Unit by means of a Common Plate (Adapter Plate). This system is designed to be a part of the APOLLON system configuration 1 without changes. In this configuration the system can be implemented onto the outer wall of the spacecraft by means of the common plate. The PCB unit is allocated inside the spacecraft, connected by means of a wire with a D-Sub connector to the communication and power system and four screws to install the system onto the spacecraft.

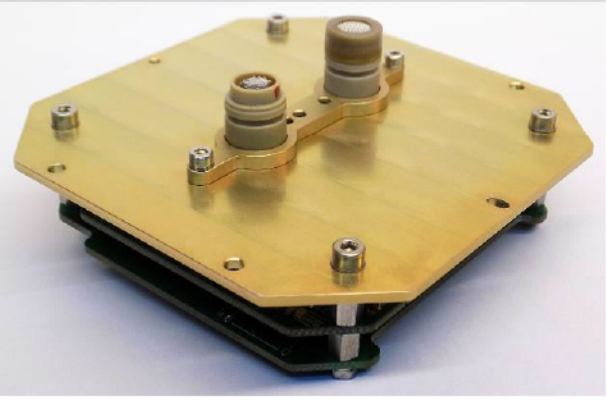

FIGURE 5. System configuration 2 after final assembly, front sensor shown without sensor cover

3.5. System Configuration 3

The APOLLON system configuration 3 is shown in Fig. 6 and Fig 7. It is designed to ensure a wide range of accommodation configurations. The PCB unit can be positioned inside the spacecraft in several positions. The sensor unit with the FIPEX sensors and a small housing is connected on the outer wall of the spacecraft. The wire can be leaded through a cut out in the outer wall of the spacecraft to the system. After this step the system can be fixed by means of two screws.

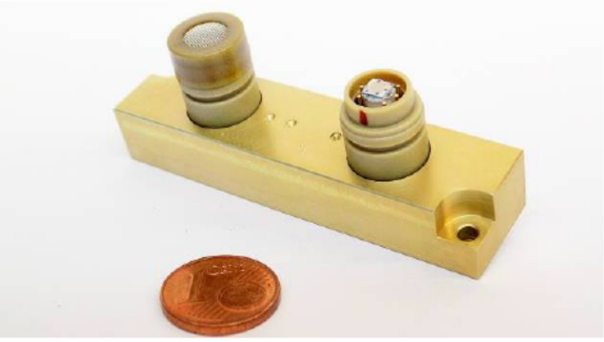

FIGURE 6. System configuration 3 after final assembly, front sensor shown without sensor cover

FIGURE 7. System configuration 3 rear view

To ensure a late replacement of the FIPEX Sensors, just the two screws of the sensor housing need to be removed and the complete system configuration 3 including both FIPEX Sensors are able to disconnect from the spacecraft and a new one can be replaced and fixed with both screws. The length, routing and design of the harness depends on the spacecraft and available envelope.

4. TESTS AND RESULTS

4.1. General

The test campaign of the APOLLON EM started with physical properties measurement and electrical interface test, followed by vibration test, thermal cycling test and atomic oxygen exposure test. In order to ensure the functional integrity of the system between the steps of the test campaign, visual inspections as well as functional tests were performed.

Physical properties measurement includes the measurement of the system configuration 1 weight as well as the measurement of the dimensions. The overall dimensions are 100 x 100 x 45 mm^3 without sensor protection cap. The total mass of system configuration 1 is 255 g. The dimensions a well as the weight of APOLLON stays in line with the requirements.

Two different test procedures were defined for the electrical interface tests. The long functional test should execute all possible commands, test the limits of the parameters that can be adjusted and perform all state transitions that are possible. The second test is the short functional test, that turns on both sensors and thus is able to prove the functionality of the electronics and the sensors during the different phases of the other tests. The long functional test was performed at facilities at Dresden University of Technology, where APOLLON was connected to a power supply and a computer running the programme HTerm, that can send and receive commands of the system. The system behaved correctly to all for all commands that were sent to it, responded with the right packets and performed all state transitions as expected. The current consumption stayed within the expected limits. The short functional test was used between all the different phases of the later tests and was able to prove the functionality of the electronics throughout the whole test campaign.

4.2. Vibration Test

In order to simulate the launch environment of the APOLLON unit a sinus and random vibration test has been performed. These tests were performed at IMA Materialforschung und Anwendungstechnik GmbH (IMA) test facility, see Fig. 8 for the setup. The vibration test was done axis by axis in the sequence sine sweep, sine vibration, random vibration, sine sweep. During sweep the natural frequencies were determined and compared to test prediction values. The functional integrity of the APOLLON unit was tested by means of short functional performance test between, before and after every vibration direction in order to detect failures.

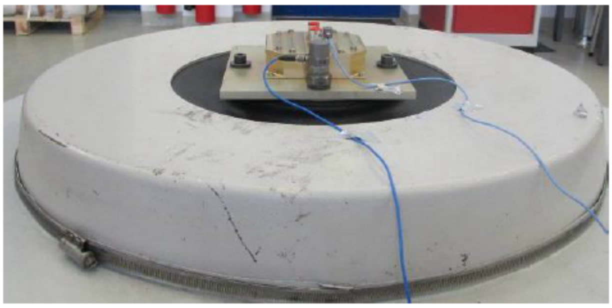

FIGURE 8. APOLLON mounted on shaker adapter, arrangement for testing z-direction

The APOLLON Unit was tested successively in test directions y, x and z. No significant changes of the main resonance frequencies were detected. No damage or other failures appeared at all inspection points of the APOLLON unit during and after the vibration tests.

4.3. Thermal Test

In order to simulate the thermal environment during a mission, the APOLLON unit was exposed to thermal cycling's followed by visual inspection and functional performance test. The thermal cycling test was performed at Dresden University of Technology, Bitzer-Stiftungsprofessur für Kälte-, Kryo- und Kompressorentechnik (KKT), see Fig.9 for the setup. The temperature has been measured and monitored on six different positions inside and outside of APOLLON.

FIGURE 9. APOLLON prepared for testing in the thermal cycling chamber

The general conditions of the thermal cycling test were normal pressure, maximum temperature gradient dT/dt of 2 K/min and dwell time of minimum 2 hours. The temperature regime consists of 10 cycles starting at room temperature (RT) then rise to +70°C and drop to -40°C, ending at RT. The humidity during test were measured and monitored by means of a hygrometer allocated inside the thermal chamber.

There were no changes between the functional test before and after the thermal cycling test. Furthermore no failure was detected during the visual inspection. Based on the test results, the APOLLON unit is able to withstand the temperatures between -40°C to +70°C without significant changes or failures.

4.4. Atomic Oxygen Test

The test was performed at the ATOX facility (see Fig. 10) at Dresden University of Technology, Institute for Aerospace Engineering in Dresden and proves the ability of the sensor elements to detect atomic and molecular oxygen and measure it at pressure ranges that are similar to the upper atmosphere.

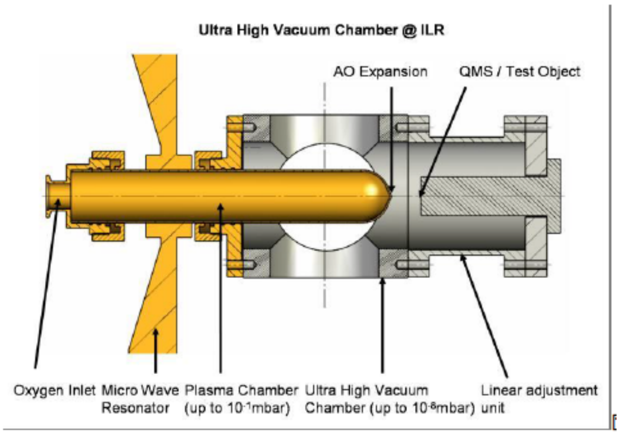

FIGURE 10. ATOX test chamber schematics

The sensors were put into an ultra high vacuum chamber that was evacuated under pure oxygen. The sensor current showed a pressure dependent behaviour as nearly linear function in a double logarithmic display. The sensors were than mounted on a movable mimic, which is able to vary the distance of the sensor to a plasma chamber, that can produce a stream of either atomic or molecular oxygen. The different distances simulate different partial pressures of those gas species. The sensors clearly showed a behavior sensor current that is dependent to the distance and therefore to the partial pressure of oxygen. The following figure shows the sensor current of a gold sensor in stream of molecular and atomic oxygen.

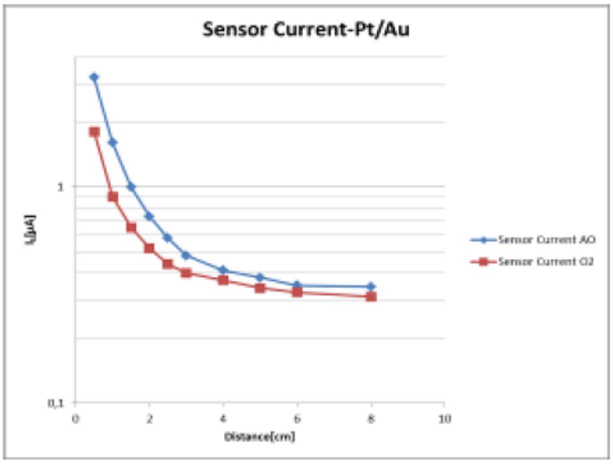

FIGURE 11. Sensor current in a stream of atomic and molecular oxygen

5. SUMMAYR AND OUTLOOK

As a result of two years development by HTS GmbH and Dresden University of Technology, Institute for Aerospace Engineering, a system named APOLLON was developed in three configurations, able to be accommodated onto a wide range of spacecraft as a secondary payload for multi-point time resolved measurement of atomic and/or molecular oxygen. The paper describes the general APOLLON system configuration based on the requirement specification generated by user needs. Furthermore the vibration test, thermal test and atomic oxygen test of APOLLON are described.

The project resulted in a well working system, however, some possible improvements were identified. To achieve high reliability a double bonding of the sensor plates is necessary. In order to handle residual buckles, the fixation of the common plate can be changed from four to eight screws with the objective to increase the force distribution between the common plate and the housing or spacecraft interface.

Within the finalized APOLLON project, a science unit was developed ready to be placed on the market. There will be the possibility to have a full qualified system with space qualified parts and software for earth observation or other missions on large spacecraft and a low cost version (e.g. industrial off the shelf material with space heritage) to be applicable for student space program like CubeSat. In order to increase the possibility of flight-improvement the steps listed hereafter need to be met:

- Reach TRL 8
- Implementation of the “Lesson Learned” to the APOLLON design
- Investigate flight opportunities with spacecraft project and space program managers
- Investigate flight opportunities for CubeSat missions

6. ACKNOWLEDGEMENT

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