DEVELOPMENT OF AN EXTERNAL SECONDARY PAYLOAD UNIT FOR TIME RESOLVED ATOMIC OXYGEN MEASUREMENT

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Abstract

This paper describes the development of the external secondary payload unit APOLLON (Atmospheric Portray of Oxygen Level with Low Orbit Network) for multi-point time resolved measurement of atomic and/or molecular oxygen as a key parameter of the lower thermosphere. The measurement is based on solid oxide electrolyte micro-sensors which operate at an elevated temperature of 600-700°C, heated by an electrical resistance. Oxygen is “pumped” from one electrode to the other by an applied direct voltage and in accordance with Faradays’ law. The measured current is proportional to the mass flux by electrolysis. APOLLON consist of sensor itself, the necessary electronic I/F circuitry, harness and the mechanical platform/housing and will be placed on a satellite platform in free flow. Details of the technology and design of the external secondary payload unit as well as market analysis will be presented.

1. INTRODUCTION

Space based measurements of atomic and molecular oxygen in the thermosphere are key measurements that may potential 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 spacecraft (S/C) surfaces.

A small sensor system designed by Dresden University of Technology based on solid oxide electrolyte micro-sensors 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 in these regions and therefore its measurement is crucial in the correlation and validation of atmosphere models. Moreover, erosion of S/C surfaces due to interaction with atomic oxygen is a serious concern. In principle, this sensor system can be attached as a small secondary payload at the outside of a spacecraft/satellite.

In order to focus on the further development of this sensor system secondary payload for space applications ESA has commissioned Hoch Technologie Systeme (HTS) GmbH, located in Coswig, Germany and TU Dresden, Institute for Aerospace Engineering in Dresden, Germany, to undertake the assessment study.

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, because 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 Concept

The working principle of the Dresden University of Technology developed oxygen sensors called FIPEX (ϕ-(Phi=Flux)-Probe-Experiment) 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, e.g. in Low Earth Orbit (LEO) 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.

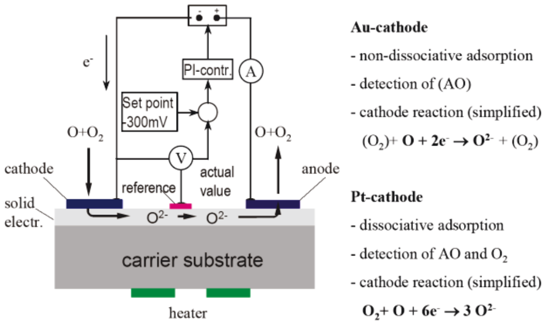

FIGURE 1. Sketch of the amperometric measurement principle

3. MARKET ANALYSIS

One work package of this study is to critically assess the potential users (science and satellite prime) and user needs, concentrating mainly on the European market. As part of the study the team contacted 25 to 30 companies and research institutes in the European space community, in order to gather a preliminary set of generic and specific technological requirements for the small sensor system. Based on this information a baseline design for three types of sensor system secondary payloads were selected for detailed design and engineering model manufacturing in order to pave the way for a secondary payload atomic oxygen sensor system for future space missions.

3.1. Potential Applications

The potential market for an oxygen sensor unit for space includes the following aspects:

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

3.1.1. Knowledge of Atmosphere

The lower thermosphere is the least explored layer of the atmosphere. Satellites exploring the lower thermosphere were flown in the past in highly elliptical orbits (typically 200 km perigee, 3000 km apogee); they carried experiments for single-point and in-situ measurements but the time spent in the region of interest was only a few tens of minutes per orbit. APOLLON has the potential to perform in-situ measurements for a time period in the order of months, instead of minutes.

All atmospheric models and users of these models can benefit from the measurements obtained by APOLLON in the lower thermosphere as APOLLON shall provide 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. It is well documented in the literature that the main models of the upper thermosphere (e.g. NRLMSISE, DTM, METM) show significant deviations in the prediction of the gas species over time, altitude, latitude and longitude of up to 470 percent.

The measurements as planned have the potential to give enough experimental data to correlate these models. Another potential application could be the use of APOLLON on missions that objective is to conduct vacuum or plasma experiments. The in-situ environment mainly influences such experiments. The AO and O2 measurements of APOLLON can be used to process the scientific data of these experiments and to improve the scientific output.

3.1.2. Knowledge of Satellite Drag

Due to atmospheric drag, the orbits will decay. So, one important aspect to gain the knowledge of atomic oxygen is the deceleration of S/C due to atmospheric drag. Different papers [2] have implied that the coefficient of drag is significantly mis-modeled by current orbit determination approaches and that by simply using thermospheric models [3].

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 AO oxygen by APOLLON, 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.

For the aspect of space debris mitigation, even small satellites in LEO or in high elliptical orbits could estimate their own decay of their orbits due to atmospheric drag with limited access to a tracking station until they burn up in the atmosphere at ~100 km altitude. The atmospheric drag perturbations satellites experiences to their orbit are leading to an increase in the eccentricity, which has implications for the satellite orbit and attitude-keeping activities.

3.1.3. Knowledge of Degradation

Atomic oxygen shows several interactions and erosion effects on S/C materials, e.g.:

- Erosion of space exposed structural materials (limited),
- Degradation of thermal-optical properties, Degradation of solar cells
- Degradation of optical measurement devices (Sun sensors, telescopes, star trackers, thermal radiators)

Consequently, the prediction of these erosion effects is very important for the mission of a satellite. However, it is very difficult to get exact results as there are a variety of thermospheric models that are based on three different modelling constrains:

- satellite drag
- modelling from temperature and composition measurements from ground (and limited in-situ measurements)
- General circulation models.

The main thermospheric models used for satellite atomic oxygen and molecular oxygen based erosion predictions are categorised in figure below [3]. Further, the flow of information among the three overall categories is very limited.

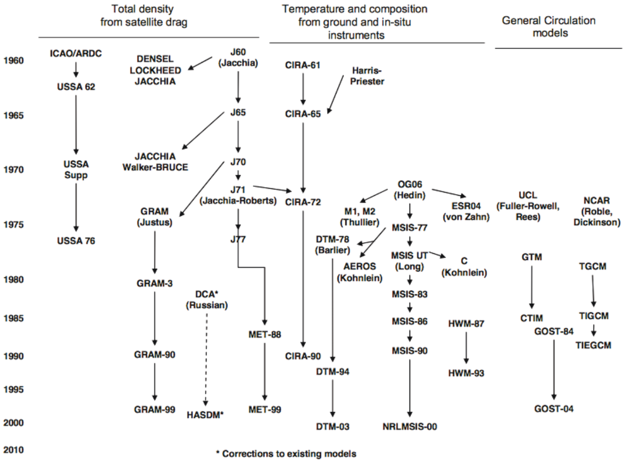

FIGURE 2. Development and categorisation of Atmospheric Models used also for drag and erosion effects on space vehicles. Notice the variety of the models and the limited flow of information between these models. [3]

To predict the atomic oxygen and the degradation of material properties, three models are widely used even the deviation is high. The main models in use are the NRLMSIS-00; Drag Temperature Model (DTM), Marshall Engineering Thermosphere (MET), the Russian GOST and general circulation models.

The table below shows selected AO induced erosion rates of different materials measured during different space missions [4, 5].

Material	Erosion rate [cm³/Atom]
PEEK	$2.0\text{-}4.0 \cdot 10^{-24}$
Kapton®H	$3.5\text{-}3.9 \cdot 10^{-24}$
Black Kapton®	$2.1\text{-}2.7 \cdot 10^{-24}$
Copper	$0.87 \cdot 10^{-26}$
Titanium	$0.39 \cdot 10^{-26}$

TAB 1. AO induced erosion rate measured from different missions

3.2. Market Survey

As part of this project a dedicated questionnaire has been elaborated and implemented. The questionnaire has been implemented in close cooperation with ESA in order to cover an as wide as possible range of questions, however keeping the extent and depth of questions in a reasonable frame. The background for implementing this questionnaire was to gain a broad overview of the current situation in terms of secondary payload unit based on atomic oxygen sensors at the major users of this technology for space applications. In essence the questions address the current situation at the potential users side in terms of applications, performance requested and problems observed. Furthermore the questionnaire covers technical requirements in terms of performance, mechanical, thermal and electrical interfaces, life time and environmental requirements, in particular in terms of operational/ non-operational temperature ranges and radiation levels, the science unit needs to sustain.

In order to design a system applicable on a large range of space missions, from CubeSat up to large S/C the conclusions of the market assessment leads to important design requirements addressed to the APOLLON System. Hereafter the conclusion and main results necessary to be considered in the further steps of the project are described.

To find out if the requirements of the APOLLON stay in line with the possibilities of the payload (P/L) questions about the mounting conditions, view direction, mass, power duty cycles, attitude control, assess before launch and data rate were created. Basically all the requirements of the APOLLON system addressed to the P/L were considered as “No Problem”. Based on the individual design of each S/C it is strongly mission-depending if the APOLLON system fits with the P/L and the APOLLON design shall provide the ability for mission specific modifications.

In order to figure out the environmental conditions needs to be handled by the system questions regarding the mission environment were assessed to get an impression of the temperature range, radiation level, outgassing values, launch loads and lifetime. Based on the heritage of the consortium and the input from the market survey an impression of the worst case mission scenario shall be provided. This scenario shall be split into requirements addressed to the system. The estimated values of the project team basically fits with the environment and requirements of the potential users.

The mechanical interfaces shall be designed to fit with a large range of S/C. Therefore the three system configurations were discussed with the potential customers within typical volume and typical mechanical interfaces. In summary the “Self standing Unit” System 1 is the preferred system of the large S/C contractor, based on the accommodation effort of the system. The “Unit with Adapter Plate” System 2 is the preferred system of the CubeSat developer based on the size and accommodation effort on CubeSats. System 3 “System without Housing” was in discussion based on the easy modification and individual accommodation possibilities.

To stay in line with the electrical design of the P/L the standard interfaces, I/F protocols, typical bus voltage data transmission, self diagnostic functions, typical used standards etc. were accessed. The Table 2 give an overview about the interface requirements resulting from the market assessment.

I/F requirement	Result
Max accommodation area	Depends onto the P/L. Cube Sat payloads are restricted to (100x100) mm²
Volume	The envelope shall not exceed (100x100x25) mm³
Mass	The mass shall be ~180 grams
Mechanical I/F	The mechanical I/F shall be established by means of screws between M2,5 and M5
Sensor position	The sensor shall be installed in RAM direction of the P/L
Power duty cycle	The power consumption shall be below 3000 mW
Data rate	The data rate shall be ~1.5 Mbits per day
I/F Protocol	A standard I/F Protocol shall be used : EIA-RS422 / RS433; LVDS 3.3V (refer to ANSI/TIA/EIA-644); I2S; MilBus 1553
Bus Voltage	If the bus voltage is not 5V, a power converter shall be used to convert the provided voltage to 5V.

TAB 2. Requirements of the questionnaire addressed to the APOLLON interfaces

4. APOLLON SYSTEM

APOLLON (Atmospheric Portray of Oxygen Level with Low Orbit Network) is the general name of the Science Unit in three different configurations which is able to measure the density of atomic and molecular oxygen in low earth orbit.

4.1. System Configuration

There are three configurations of the science unit consisting of sensor unit and mechanical support structure. System 1 is a self standing unit consisting of sensor unit, electronic circuit and housing with defined mechanical I/F 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 an S/C. This system will have integrated electronics and either harness with connectors or a pigtail harness. System 3 is a small sensor unit with a mechanical adapter and without integrated electronics having either harness with connectors or a pigtail harness. The electronic circuitry is to be separately integrated into the satellites electronic.

4.1.1. Unit with Adapter Plate

The system configuration 2 shown in Figure 3 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 (chapter 4.1.2) without changes. In this configuration the system can be implemented onto the outer wall of the S/C by means of the common plate, e.g. CubeSat. The PCB unit is allocated inside the S/C, connected by means of a wire with a D-Sub connector to the on board control and power system and four screws to install the system onto the S/C. To ensure the late replacement of the FIPEX sensor and sensor cap, the sensor cover needs to be removed. After removing that cover, the both sensor covers are able for removing and the new sensors can be installed and fixed by means of the sensor cover and the two screws.

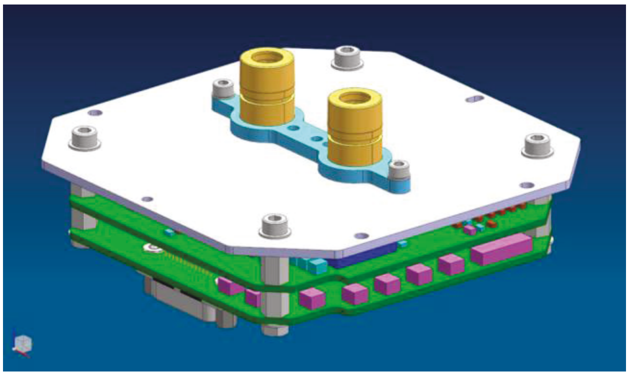

FIGURE 3. CAD design of system configuration 2

4.1.2. Self standing Unit

The system configuration 1 is designed to be compatible with the setup of the system configuration 2 described in chapter 4.1.1. Basically the system shall be an assembly consisting of the APOLLON System 2 with an additional housing designed to ensure a “Self standing Unit”. The System 1 is designed to be easily manageable and adaptable onto a large range of S/C. 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 S/C. To find a suitable electrical connector position a trade off by means of a matrix were used. Basically the connector of the APOLLON system is be allocated on the back side (between S/C and housing).

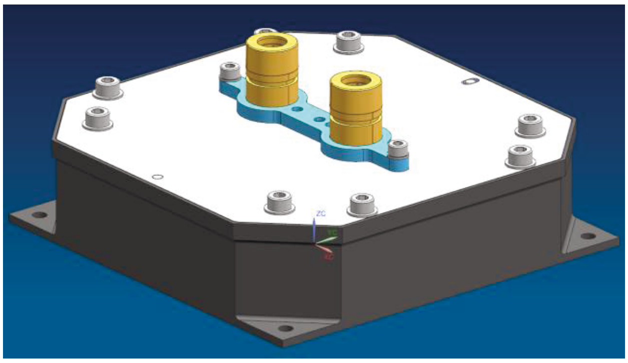

FIGURE 4. CAD design of system configuration 1

In order to ensure that the electronic components like transistors and diodes are capable to survive the radiation environment a generic analysis was performed. A detailed EMC analysis was not foreseen in scope of the project. The shielding parts of the APOLLON System are mainly the Housing and the cover plate made of aluminum. In case of the APOLLON system 2 housing thickness of 2 mm the dose of radiation will be reduced from $3 \cdot 10^6$ rad down to $3 \cdot 10^3$ rad. Commercial, off the shelf electronic components survive a radiation level between $5 \cdot 10^3$ to $1 \cdot 10^4$ rad but the manufacture of such parts will not give a guar-anty for that. “Radiation harded” components are able to survive a guaranteed radiation level up to $3 \cdot 10^5$ rad and “strategic rad harded” parts up to $1 \cdot 10^6$ rad. However, a large range of further analysis need to be met to ensure a full qualified EMC assessment, the preliminary analysis of the APOLLON system shows that the design will survive the radiation environment of the worst case orbit. Also in addition with a typical design margin factor the radiation values are in-between the permitted limits.

4.1.3. Unit without Housing

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

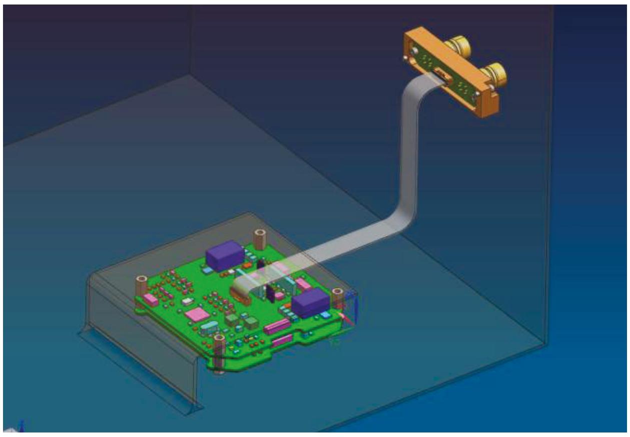

FIGURE 5. CAD design of system configuration 3

4.2. Sensor Unit

The sensor unit is used to connect the FIPEX sensors with the PCB unit. Furthermore, this sensor unit is needed to fix the sensors in their position. The data and power interface is established by means of the 14 pin Microstac connector. The FIPEX sensor is the main part of the system. This sensor is able to measure the oxygen density in its molecular and atomic condition as described in chapter 2.2. The FIPEX sensor 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.

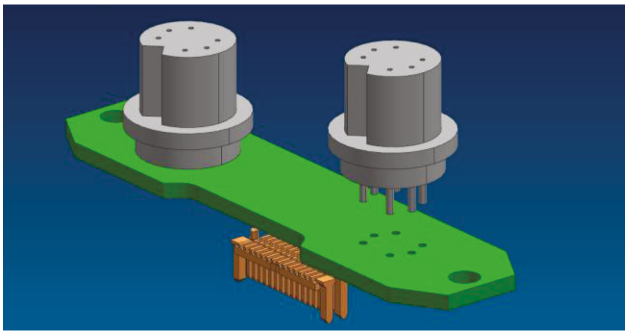

FIGURE 6. Design of Sensor Unit

The design of the oxygen sensor element is straight forward for small size, low power consumption and high sensitivity in high vacuum conditions. The sensor plate geometry is 3.0x3.0x0.5mm, resulting in a reduced heater power of less than 1 Watts at 660°C. Figure 7 shows the oxygen sensors embedded in the sensor housing and protected with the sensor cap.

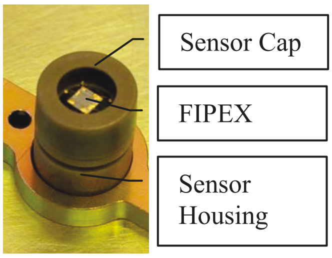

FIGURE 7. Oxygen sensor element with sensor housing

4.3. Electronic Unit

The PCB unit shown in Figure 8 is designed to ensure a small envelope necessary to be adaptable onto a large range of S/C. The electronic is distributed over two PCBs, the main PCB, containing the sensor control and measurement electronics, and the Interface PCB, containing the MDM25 connector. The sensor unit and the PCB unit data and power connection is established by means of a microstac connector. The connection to the S/C shall be established by means of a Norcomp D-Sub connector allocated on the back side of the second PCB. In summary, the PCB unit can be considered as the heart of the system, designed to be a part of all three APOLLON System configurations without changes.

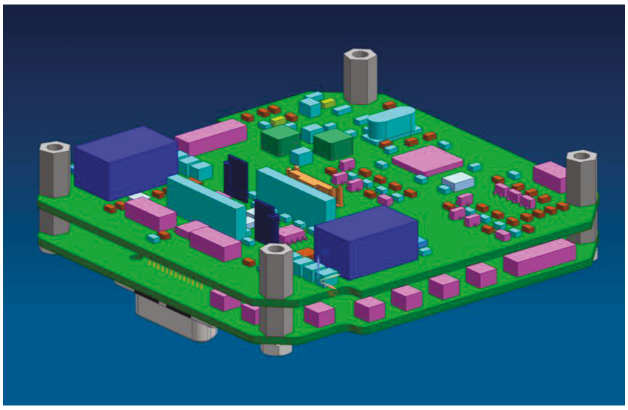

FIGURE 8. PCB Assembly Design

5. SUMMAYR AND OUTLOOK

HTS GmbH and TU Dresden, Institute for Aerospace Engineering, developed an external secondary payload unit named APOLLON for multi-point time resolved measurement of atomic and/or molecular oxygen on different S/C. The paper describes the general design of APOLLON based on the requirement specification generated by user needs. Furthermore the atomic oxygen measurement and potential applications of sensor unit are described.

After manufacturing and assembly of the engineering model (EM) for system configuration 1 there are further topics to deal with. Some of the fields of activity are listed below:

- Functional test of EM
- Vibration test including test prediction of EM with defined load of requirement specification
- Thermal test including test prediction of EM with defined load of requirement specification

Based on the market assessment and the merits of the APOLLON system there is a market potential for a large range of space missions. 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 S/C and a low cost version (e.g. industrial off the shelf material with space heritage) to be applicable for student space program like CubeSat.

6. ACKNOWLEDGEMENT

The authors would like to thank the involved team for their contributions during the initiation of this project and their continuous support. Additionally we thank all participants of the survey who took the time to fill in our questionnaire. This work is supported by the European Space Agency under contract #4000111393/14/NL/CBi/fk

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