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SCIENCE, TECHNOLOGY AND SYSTEMS ENGINEERING EDUCATIONAL ACTIVITIES WITH STRATOSPHERIC BALLOONS

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Abstract

In 2021, the Space Systems Laboratory of the University of Pisa (UniPi) started a student-oriented high-altitude ballooning programme intended to provide an opportunity for hands-on experience in support of the teaching of scientific and technical courses. The programme provides mentoring on scientific, technical and management issues, along with financial support and assistance with integration and launch on a sounding balloon platform. The goal is to conduct flying experiments in the stratosphere, retrieve them after landing and process the results; by doing so, the students experience all phases of a scientific mission project, from conceptual design to realisation, operations and post-flight analysis. Following a call for proposal open to all students of the UniPi across all study areas, three experiments were selected featuring multidisciplinary teams. This paper summarises the features of the programme's first edition and presents the main lessons learned.

Keywords: high-altitude ballooning; stratospheric platform; student experiment; sounding balloon
Type of the work: research article

1. INTRODUCTION AND BACKGROUND

High-altitude ballooning is recognised as an inexpensive, yet very effective, way of bringing small payloads to a region of the Earth's atmosphere wherein the ambient conditions are very close, in many aspects, to those of space. Reaching an altitude of 25–40 km during a 2- to 3- h mission, high-altitude balloons (HABs) experience a range of different environmental parameters, such as very low pressure (down to the millibar range) and extreme cold (–70°C), together with insolation and ionising radiation conditions almost identical to those prevailing in low Earth orbit. Reaching such 'near-space' region is readily feasible for student teams using simple hardware (latex balloons filled with helium) that can be procured at low cost. Figure 1 shows the phases of a typical HAB mission.

The effectiveness of ballooning for science, technology, engineering and mathematics (STEM) educational purposes in middle and high school is widely recognised [1]. At the university level, ballooning can be a very powerful tool to perform valuable research [2]. However, the value of a HAB flight project goes beyond pure scientific instruction. When engaging in a HAB project, university students have the opportunity to experience, hands-on and in a fully immersive way, all the aspects of a flight project. Along with the issues involved in designing, instrumenting, building, testing, de-bugging and conducting a scientific or technological experiment, the student teams are confronted with the harsh realities of working

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in a team, under schedule pressure, with budgeted resources. Structured project management is readily acknowledged as a necessity and is quickly learned and willingly applied [3].

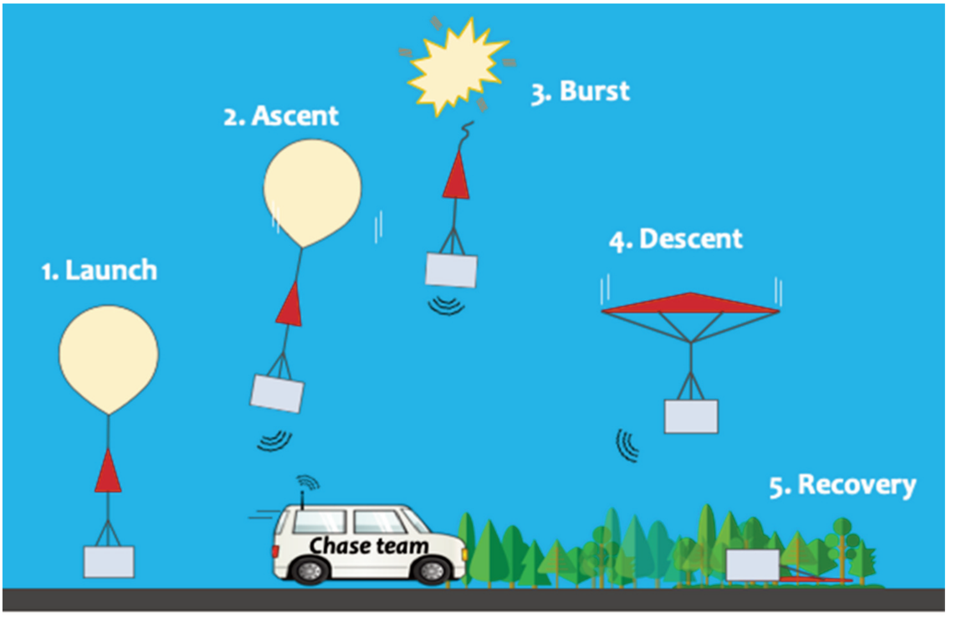

Figure 1. Phases of a typical HAB mission. HAB, high-altitude balloon.

Student-dedicated stratospheric flight programmes have been active for decades in many countries around the world at universities that use them as teaching aids for students in science and technology disciplines, from engineering to physics, astronomy and biology. As examples (among dozens of similar international initiatives), several U.S. universities[1] and several Canadian universities[2] maintain such programmes. The experiments range from the detection of cosmic rays (CRs), to the physics of the upper atmosphere (turbulence, chemical composition), to the observation of the Earth in the visible or thermal infrared range, to the exposure of biological samples to the radiative environment, to the testing of technologies for telecommunications, remote sensing, navigation and positioning, etc. The extensive literature available[3] illustrates the great potential of stratospheric flight experiments in teaching science disciplines and the great enthusiasm with which they are received by with students when offered at the university level.

2. THE STUDENT BALLOONING PROGRAMME AT THE UNIVERSITY OF PISA

Since 2018, researchers at the Space Systems Laboratory of the University of Pisa (UniPi)[4] have been carrying out sounding balloon flights at altitudes ranging from 19 km to 38 km (Fig. 2). So far, 12 flights have been performed for engineering research purposes [4, 5] with various technology experiments (telecommunications for Internet of Things, receiving automatic identification system (AIS) signals for

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[1] https://www.stratoballooning.org
[2] https://seds.ca/projects/can-sbx/
[3] https://www.iastatedigitalpress.com/ahac/
https://atpi.eventsair.com/QuickEventWebsitePortal/pac-symposium-2021/home1/ExtraContent/ContentPage?page=6
[4] http://spacelab.unipi.it

maritime detection, solar cells, etc.). In most cases, the experiments were designed, prepared and carried out with the active participation of graduate aerospace engineering students as a part of their final projects (Fig. 3).

Figure 2. Coast of Tuscany from about 30 km altitude as pictured by UniPi-HAB 01.
UniPi-HAB, University of Pisa high-altitude balloon.

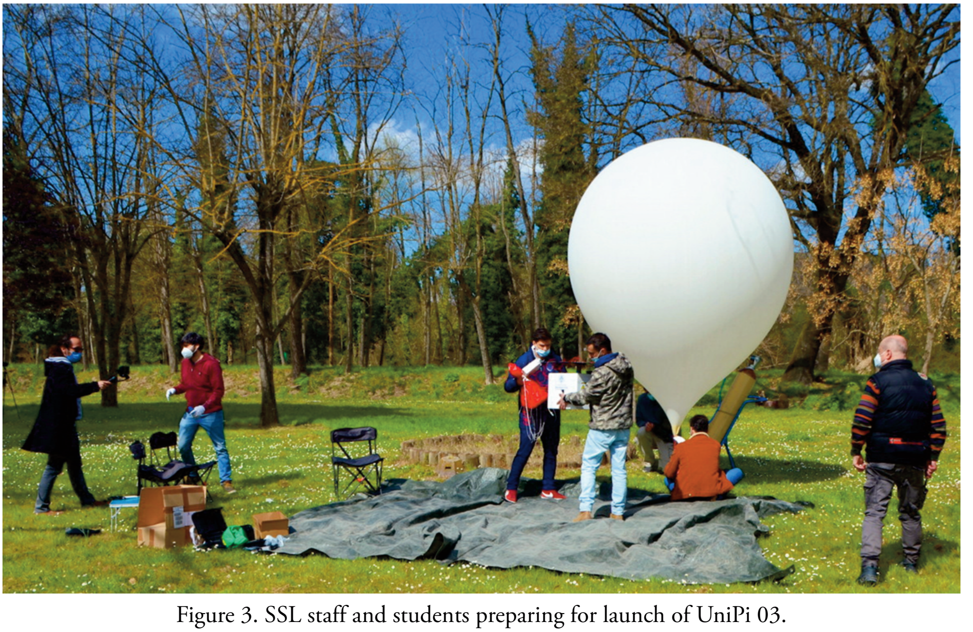

Figure 3. SSL staff and students preparing for launch of UniPi 03.
SSL, Space Systems Laboratory; UniPi, University of Pisa.

Leveraging on such experience, the Space Systems Laboratory started a student ballooning programme in 2021. The programme, internally funded by the UniPi, provides guidance, mentoring, as well as financial and logistic support to interdisciplinary teams of undergraduate and graduate students willing to undertake the process leading to the flight of a small scientific payload in the stratosphere. Services such as the procurement and management of the flight platforms (balloons, helium, parachute, tracking and telemetry, etc.), the necessary authorisation by the flight control authorities, insurance and support to operations are provided by the programme. Experiment proposals are evaluated on a competitive basis after a call for proposals open to all the students across all disciplinary areas in the University.

The objectives of the activity are to allow students to experience firsthand the following:

- the conception, realisation, testing and management of a scientific experiment in a near-space environment;
- the design and implementation of a complex system within predefined technical and economic constraints;
- the methods of group work aimed at the practical implementation of a scientific experiment, from conception to the presentation of results.

The added value at the educational level can be summarised as follows:

- 'hands-on' experience regarding flight hardware, in the laboratory and during the launch campaign;
- acquisition/improvement of direct knowledge on embedded control systems (Arduino, Raspberry and similar platforms); programming in Python and C; and simple mechanical design and fabrication techniques, such as three-dimensional (3D) printing;
- direct experience in the planning and execution of a research project.

In spring 2021, the first batch of proposals was received. After evaluation by the programme committee, the following proposals were selected:

(1) measurement of CR flux and neutron flux as a function of altitude;
(2) investigation of the effects of exposure of selected micro-organisms and other biological material to stratospheric ultraviolet (UV) radiation as a Mars surface analogue; and
(3) recording of the solar spectrum as a function of altitude.

The interdisciplinary nature of the teams is one of the most valuable aspects of the programme, allowing the participants to experience early in their student life the joys and sorrows of teamwork, having to establish effective communication and decision-making mechanisms to collaborate among specialists of different sectors. The experiments were proposed and designed by mixed teams of students from different disciplines:

- Team No. 1 (CRs): six graduate Physics and one undergraduate Mechanical Engineering students;
- Team No. 2 (UV effects on biological samples): three graduate Neuroscience and two graduate Aeronautical Engineering students;
- Team No. 3 (solar spectroscopy): one graduate and two undergraduate Physics and one undergraduate Aerospace Engineering students.

In addition to specific, albeit basic, competence on the subject of the experiment, some of the students in each group have controller programming skills and some degree of knowledge of mechanical design.

The supervisory team includes senior faculty members of the Department of Aerospace Engineering and the Department of Physics (who act as mentors and provide the necessary oversight on technical and scientific aspects of the experiments) and researchers of the Space Systems Laboratory who have several years of experience in the design, manufacture, integration, test and flight operation of stratospheric platforms and payloads. Such matters as mechanical and electrical design and integration of payloads are supported through the facilities available at the Space Systems Laboratory and at the Department of Physics.

3. EXPERIMENTS SELECTED

3.1. Miracle—study of CR flux

The Miracle project involves measuring the CR flux and separation of the charged and neutral components. CRs, elementary particles and atoms that constantly hit the upper parts of the atmosphere are usually classified into two categories: primary CRs, i.e., those particles coming from outer space, and secondary CRs, which are generated by the interactions of the primaries with the atmosphere atoms. In particular, the experiment aims to measure the vertical and horizontal flux of the CRs, which depends on the local density of the atmospheric air and therefore on the balloon altitude. To this end, three scintillators are placed perpendicularly to each other, so as to catch the vectorial components of the CR flux.

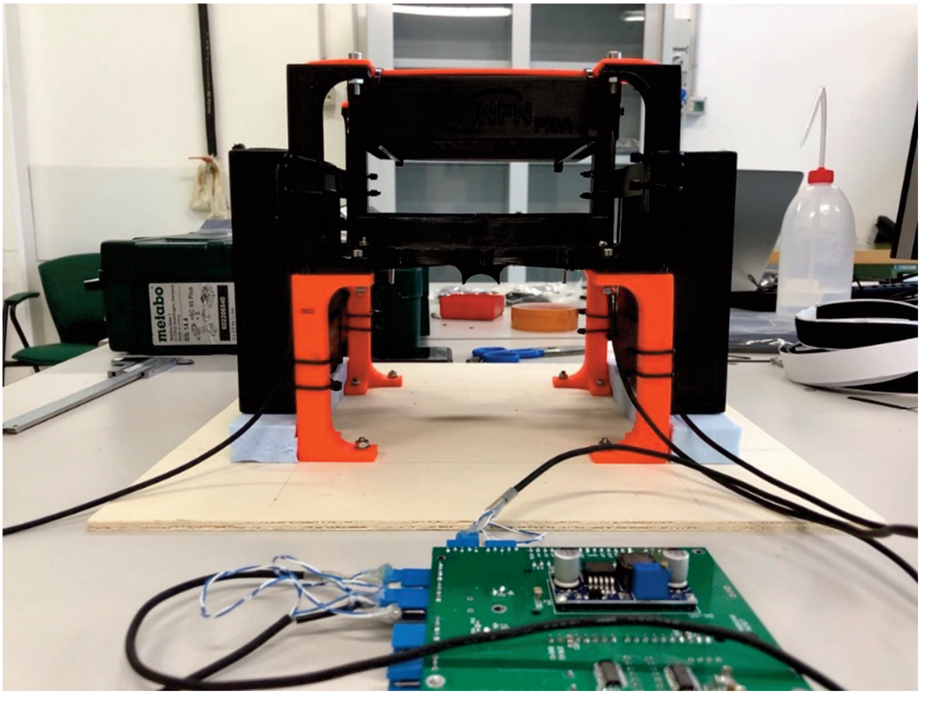

Figure 4. The payload assembly that will fly on the sounding balloon.

The payload (Fig. 4) will also host a sensor that will, during the ascent, detect thermal neutrons, produced by the interactions between the CRs and oxygen and nitrogen atoms. Finally, the Miracle experiment has also the ambitious objective to characterise, in the stratosphere, the performance of a Micromegas gas-based detector [6], specially built for this occasion at the European Organization for Nuclear Research (CERN) laboratory in Geneva (Fig. 5) and provided through the Pisa branch of the National Institute of Nuclear Physics (INFN).

Figure 5. Integration of the Micromegas at the INFN (National Institute of Nuclear Physics) laboratory in Pisa.

3.2. UV Mars — biological samples exposed to UV

The UV Mars project has the goal of sending various types of microorganisms (Fig. 6) into the stratosphere to expose them to UV radiation. Recent studies have shown how UV irradiation in the upper atmosphere of the Earth can be correlated to the irradiation conditions at the surface of the planet Mars [7]. UV radiation also interacts with biological material, inducing damages of varying degrees in the different cellular regions. The harmful biological effects of UV are almost completely attributable to photochemical reactions, in which the energy carried by the radiation is able to catalyse a chemical reaction that could not have occurred under other conditions. For this reason, UV rays represent a powerful factor capable of altering genomic stability and inducing the formation of toxic photoproducts. By exposing biological samples to the unfiltered stratospheric UV radiation, it is possible to get reliable indications of what the effect would be on the surface of the red planet.

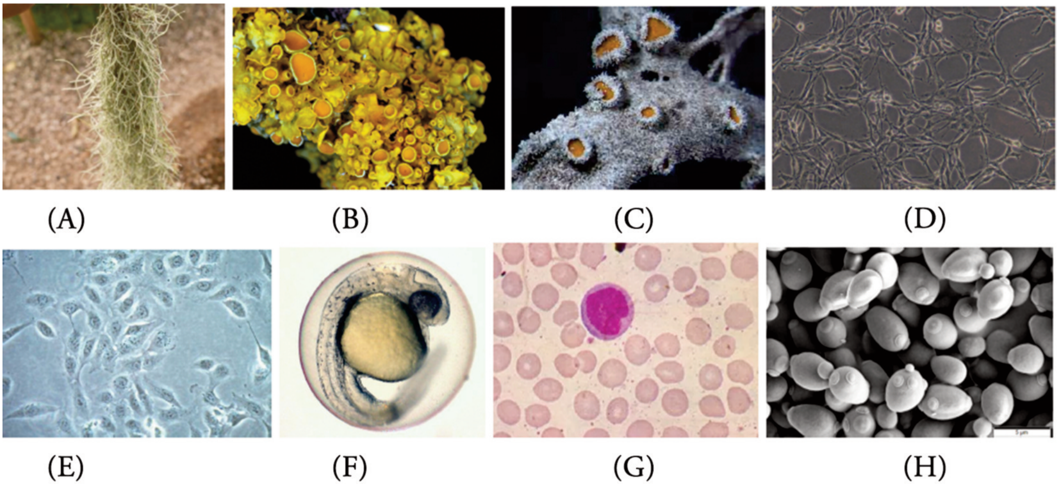

Figure 6. (A) *Tillandsia usneoides*, (B) *Xanthoria parietina*, (C) *Seirophora villosa*, (D) C6 cancer cells, (E) insulinoma (INS)-1 cells, (F) zebrafish embryos, (G) human peripheral blood lymphocytes and (H) *Saccharomyces cerevisiae*.

For this particular payload, the challenge was to build a sealed chamber (Fig. 7), which is transparent to UV radiation and also able to maintain the temperature and pressure within the optimal ranges for the survival of the biological species. It will also host a whole set of sensors to measure the variation in the incoming UV radiation while ascending through the atmosphere in order to be able to correlate, in post-processingstage, these measurements with the damage induced to the microorganisms.

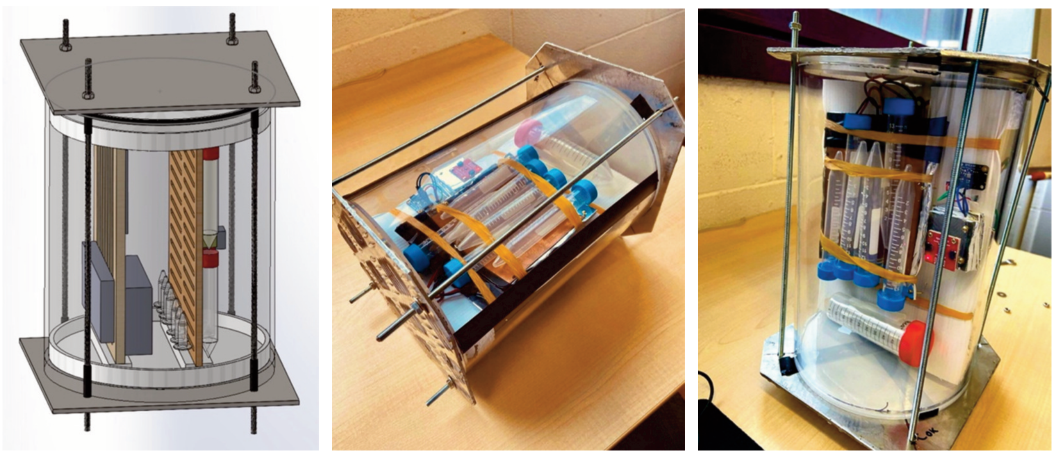

Figure 7. CAD drawing and pictures of the flight hardware of the UV Mars payload. CAD, computer-aided design; UV, ultraviolet.

3.3. Solar spectroscopy

The purpose of this experiment is to analyse the spectrum of the radiation emitted by the Sun in the optical and infrared bands at different altitudes, by making measurements during the ascent and descent phases of the balloon. The uniqueness of this experiment is the sun-tracking system based on low-cost commercial off-the-shelf (COTS) components that will point the light collector towards the sun during the ascending part of the flight (Fig. 8), counteracting the residual angular motion of the balloon gondola.

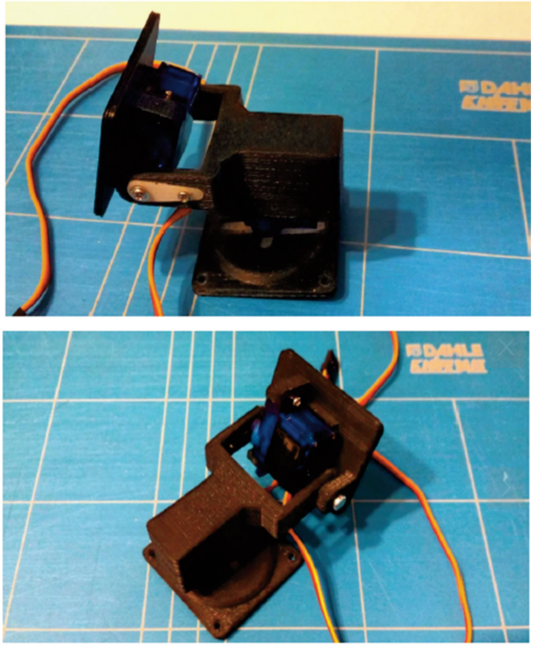

Figure 8. View of the tracking system that makes use of servo motors to follow the Sun.

The tracker will contain an optical fibre that will capture sunlight and channel it into a spectroscope. The latter was manufactured from an open source design using 3D printing, resulting in a very compact (approx. 13 cm × 13 cm × 10 cm) and light-weight component. A black filament and internal coating is used to minimise stray light. Incoming sunlight will be decomposed into its spectrum by a reflecting diffraction grating of 1,200 lines. The beam will be focussed by a parabolic mirror on a linear charge-coupled device (CCD) of about 3,700 pixels. Figure 9 shows the assembled 3D-printed chassis, while the read-out electronics are shown in Figure 10. Figure 11 shows how the optical components are placed in the lower half of the chassis.

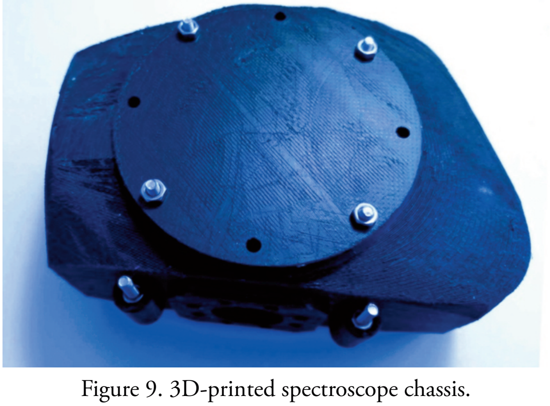

Figure 9. 3D-printed spectroscope chassis.

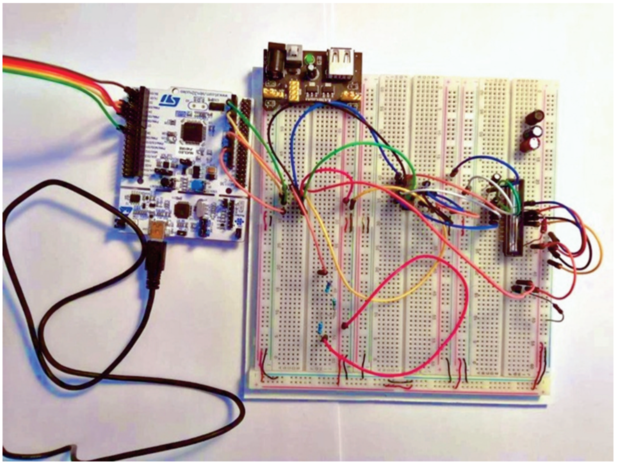

Figure 10. Breadboard of the spectroscope read-out electronics.

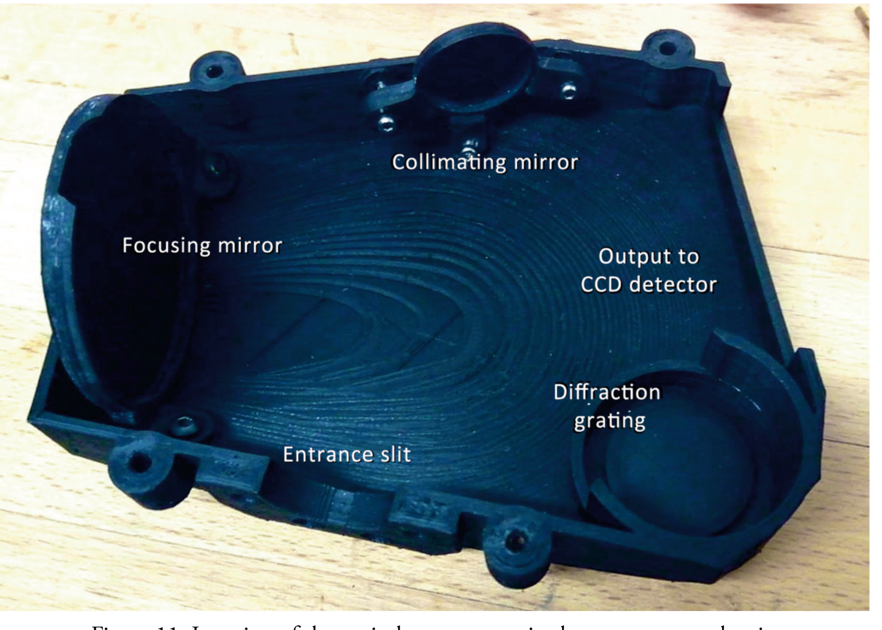

Figure 11. Location of the optical components in the spectroscope chassis.

4. LESSONS LEARNED AND CONCLUSIONS

The study teams have completed the final assembly and functional testing of the respective modules, and each of them is going to be integrated with its own balloon platform. All three launches will take place by 2022, with the actual timing depending on weather conditions and stratospheric wind patterns.
A few general considerations on the outcome of this educational experience can be anticipated:

- the opportunity to work on a near-space mission from start to end was very positively received by the student teams. The students selected ambitious scientific goals and formed interdisciplinary teams, acting autonomously and with dedication well beyond expectations. The attractiveness of HAB activities for young people and the strong educational potential of the programme is confirmed;

- along with the scientific and technical aspects of the project, the students experienced the need to establish and maintain a few formal procedures to keep work on track and proceed smoothly. In particular, basic project management tools, such as scheduling charts, interface description documents (albeit minimal) and formal meeting minutes, were used with some success;
- the three experiments selected, scientifically sound and stimulating as they are, have proven to be quite challenging for both the students and the supporting faculty. All of them required several design iterations and considerable effort by both students and mentors before reaching flight readiness. While this is partially to be ascribed to the lack of previous experience with similar projects, it eventually became apparent that simpler experimental goals may prove perfectly adequate and equally rewarding to the end of a satisfactory educational experience. More scientifically ambitious goals are probably best pursued in the frame of graduate-level end-of-study thesis projects.

In conclusion, the first edition of the student ballooning programme at the UniPi has fully met the expectations so far. A second edition has been approved for funding by the academic administration and will start in 2022. For future editions of the programme, we will concentrate on more-basic experiments aimed at selected educational topics. We look forward to making near-space student missions a regular feature of the scientific education at our University and to establish collaborations with other higher education institutions to foster hands-on scientific learning through high-altitude ballooning.

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References

[1] Cheng, Stephen, Gerhard, David, Gendron, Fifji and Ziffle, Vincent. Incorporation of High-Altitude Balloon Experiment in High School Science Classrooms. *Creative Education* Vol. 10 No. 2 (2019): pp. 262–272. DOI 10.4236/ce.2019.102021.

[2] Larson, Shane L., Armstrong, John C. and Hiscock, William A. The First Frontier: High Altitude Ballooning as a Platform for Student Research Experiences in Science and Engineering. *American Journal of Physics* Vol. 77, No. 6 (2009): pp. 489–497. DOI: 10.1119/1.3097775.

[3] Golkar, Alessandro. Experiential Systems Engineering Education Concept Using Stratospheric Balloon Missions, *IEEE Systems Journal* Vol. 14 No. 2 (2020): pp. 1558–1567. DOI: 10.1109/JSYST.2019.2917823.

[4] Gemignani, Matteo and Marcuccio, Salvo. "Dynamic Characterization of a High-Altitude Balloon during a Flight Campaign for the Detection of ISM Radio Background in the Stratosphere." *Aerospace* Vol. 8 No. 1 (2021): p. 21. DOI: 10.3390/aerospace8010021.

[5] Marcuccio, Salvo, Cataldi, Giuseppe and Gemignani, Matteo. "New Low-Cost Stratospheric Balloon Flight Opportunities with Pisa University's MicroHAPS Platform." *Proc. 26th AIDAA Congress*. Pisa, Italy, 2021.

[6] Charpak, Georges C., Derré, Jacques, Giomataris, Yannis and Rebourgeard, Philippe C. "Micromegas, a Multipurpose Gaseous Detector." *Nuclear Instruments and Methods in Physics Research* Vol. A 478 (2002): pp. 26–36. DOI: 10.1016/S0168-9002(01)01713-2.

[7] Khodadad, Christina L., Wong, Gregory M., James, Leandro M., Thakrar, Prital J., Lane, Michael A., Catechis, John A. and Smith, David J. "Stratosphere Conditions Inactivate Bacterial Endospores from a Mars Spacecraft Assembly Facility." *Astrobiology* Vol. 17 No. 4 (2017): pp. 337–350. DOI: 10.1089/ast.2016.1549.