A NEWCOMER'S GUIDE TO THE CHALLENGES OF A COMPLEX SPACE-TO-GROUND EXPERIMENT, WITH LESSONS FROM ANALOG-1

Virtual Conference 19–23 October 2020

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ABSTRACT

An astronaut controlling a complex robot on the surface of earth from the ISS. This is exactly what we have done in ANALOG-1. Luca Parmitano teleoperated a rover in a moon-analogue geological mission scenario. On first sight the primary technical challenges seem to be the design of the robotic systems for space and ground. On a second look - with the perspective of using the system with an astronaut on the ISS in loop with an operations team in different ground centers - the scope and challenges drastically increase.

 In this paper we take a look behind the scenes, and gives insights which could guide future payload developers going on a similar endeavour. This paper outlines the Analog-1 experiment, itself, what it aimed to achieve, and how it was done, and uses it as a case study to outline the challenges and solutions a project team and particularly the payload developer - will have to overcome when designing an ISS experiment. This article may be especially insightful and a good starting point for those from a small research team at a university or other research institution with budget and time pressure. We will present it from the payload developers perspective and on concrete examples of the payloads we flown.

1. INTRODUCTION

1.1. Scope and Target Audience

This paper describes the key aspects of the process of flying a payload to the ISS, leaning on our recent mission and ANALOG-1 and its hardware for examples. It is intended to serve as a guide that could give valuable hints to future payload developers. It is written from the perspective of the payload developer. The payload was onboard the Columbus module and under an ESA umbrella so most things mentioned here apply for European payload developers of class 3 or "small payloads". This article might be most interesting for universities and research institutions that plan to fly a payload in this category. As of this moment there is also a formal difference between payloads focusing on science and technology demonstrators. In brief a science focus aims for statistic significant repetitions and allows more astronaut time and are also subject to a more complex approval. On the other side, technology demonstrators aim to study the application of new technologies in the context of space exploration. The approval is quicker but also limits the number of experiments and objectives onboard. The authors here have been involved with this technology demonstrators already in HAPTICS-1, HAPTICS-2, INTERACT, SUPVIS-Justin prior to this one named ANALOG-1.

1.2. Disclaimer

This document is written with the best knowledge from five experiments executed on the ISS from 2014-2019. Even during this time we saw changes in technical possibilities, organizational restructuring and increasing commercial initiatives which changed and eased the processes to bring a payload on board. We hope to give you an overview, but the authors encourage potential payload developers to prioritise information from your contact points at relevant space agencies.

1.3. Outline Analog-1

In November 2019 we carried out the ANALOG-1 experiment on the ISS. Luca Parmitano teleoperated a rover – a mobile platform equipped with two robotic manipulators with cameras and other sensors - in a moon-analogue geo-logical mission scenario. The mission scenario was based on a segment of the notional EL3 sample return mission, where a lunar rov-

er is operated under a time delay and operational scenario similar to an astronaut controlling it from the Lunar Gateway while being supported by rover operations and science teams on Earth. For an ISS payload, the experiment was of particularly high complexity both technically and programmatically.

On the programmatic side, the experiment connected the astronaut with a science backroom at the European As-tronaut Centre (EAC), with mission control (also at EAC), with the analogue lunar environment (in a hangar in the Netherlands) where the rover and robotics team were located. Finally a connection was made to the European Space Operations Centre (ESOC) where rover data was monitored by the rover operations centre. The project team itself was made up by the above ESA centres and groups as well as several industrial partners.

On the technical side the experiment included an agile robotic asset on the ground combined with a complex control station that had been installed on the space station, and all the associated latency, channel quality and control is-sues. The control station included the Sigma-7 haptic device, see Fig. 1. This device allowed the astronaut to feel the forces felt by the robotic arm.

Figure 1. Luca Parmitano on the ISS controlling a rover on ground during ANALOG-1

The experiment demonstrated very successfully the advantage of having an immersive control station and high level of robotic dexterity with Luca finishing all

his assigned and secondary geology targets in record time.

ANALOG-1 was the culmination of ESA's METERON project, a European initiative to help prepare for future human-robotic exploration missions to the Moon, Mars and other celestial bodies. Through 12 distinct experiments since 2014, the METERON aim is to implement an infrastructure and tools that will allow testing and evaluating communications, operations and robotic control strategies in the context of future exploration missions.

2. EXPERIMENT PREPARATION

Before starting the process the hardware and software for the experiment should already have a mature state. Of course it is possible to do it in parallel but for the involved control boards safety and guaranteed reliable operations have absolute priority and this is basically a clash (resulting in delay) between fast paced R&D and safety critical operations.

2.1. Your roles and responsibilities

There are many roles and key persons on the way to the experiment and you are one of those and it is important to have those clearly marked.

PI - principal investigator

This is the main character who has the last word on her own experiment. She is also the main contact point for all activities and where the data flows to. As in any scientific experiment the PI has primary rights on all data and scientific matters and has to be involved on all decisions.

Co-I co investigator

There are your co-investigators with rights similar to the PI's. However the PI is strictly hierarchically the leader and CO-Is come technically second. Also for any experiment data, especially if it is of a medical nature only the PI and CO-I have the right to see it. As a recommendation for good flow we recommend to have the PI as main contact point because otherwise many CO-Is cause overhead.

PD - payload developer

This is the person responsible for the development, deployment and operation of the payload. For all technical interactions it the main contact point for any interaction entity. Also note that you can be PD and CO-I or PD and PI at the same time.

2.2. The ESR/ERD

The first step for setting up an experiment is to announce it to the ISS Utilization Board (UIB). This board evaluates the experiment regarding its worthiness to be executed on the space station. The evaluation is based on the Experiment Science Requirement (ESR) Document or the Experiment Requirement Document (ERD). This document starts it all.

The ESR template is provided by ESA, and the document describes in an abstract form the envisioned experiment. We recommend to leave the basic structure as it is even if for your particular experiment flows this appears to be odd. The rationale behind is

that certain parts (chapters, articles) will be scanned and evaluated by specialists, and their job is greatly simplified if they can easily identify relevant sections. We found it very beneficial if we, in the role of PI or PD, made an effort to repeatedly communicate the bigger picture.

In short, this document contains the main goals of the experiments and the items (abstract) that are required for it. It also identifies if such items are already present on the station or if they have to be launched. For example, in ANALOG-1 we knew that we would need a laptop on board, that we would need to communicate data to ground, speak with the astronaut via voice loops and wanted the experiment session recorded in high quality video.

A good approach, to ensure the ESR is relevant, might be to introduce your experiment to the board via a presentation with the possibility of Q&A. The board meets in regular intervals and is open to hear you. But you should keep in mind that the board is
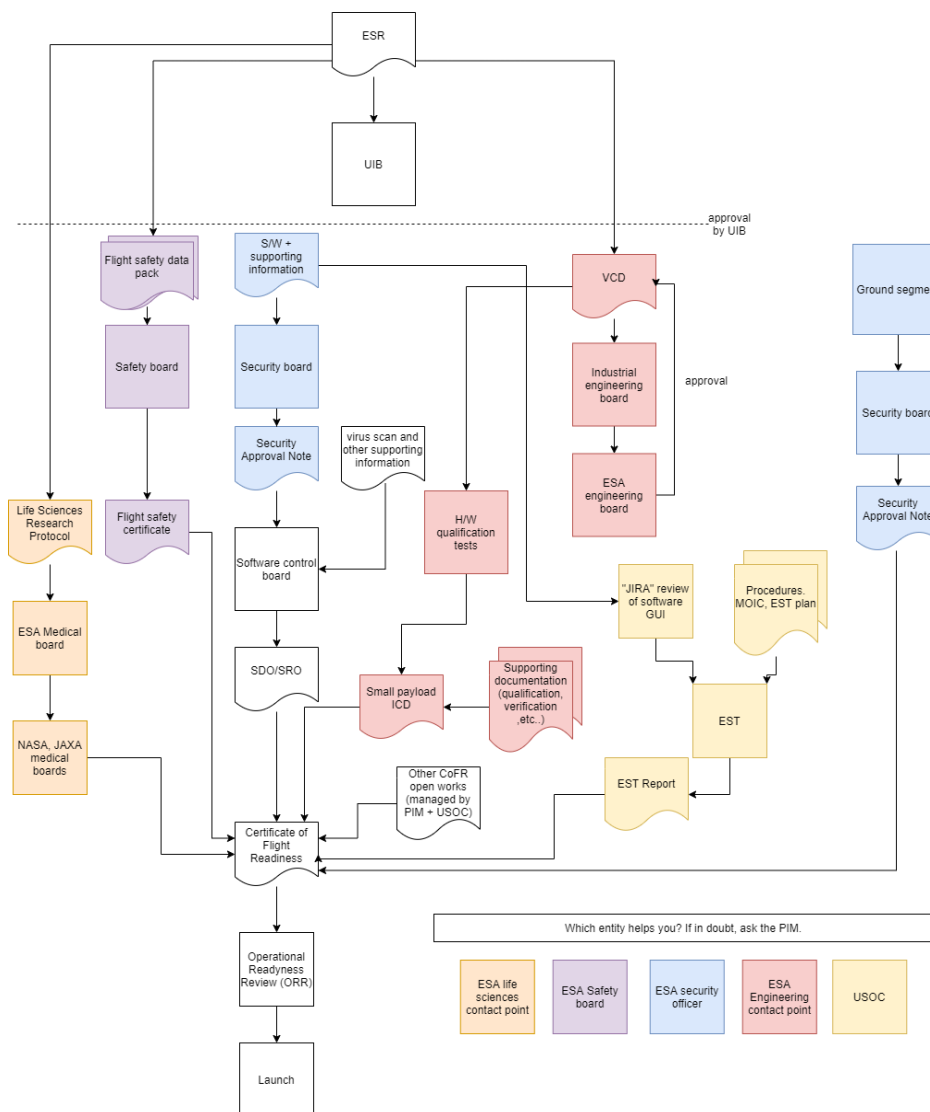

Figure 2. Flowchart for an ISS experiment including a payload

very busy, and so it is in everyone's interest that your experiment is well thought through before being presented.

In addition we recommend to already at this point have a draft ESR/ERD prepared to a high level of readiness. Such a presentation should demonstrate that you have the technical knowledge, a solid plan and also communicate what you need. From that presentation you will also get valuable feedback. The most important question, to get the "green light" to submit the full document, from the board will be:

Why do you need to perform this experiment on the space station?

For us as scientists and engineers who are working on and planning this experiment for a long time, the "curse of knowledge" applies. The board members also might see all the advantages and interesting data to be gained but have to ensure that there is a valid rationale since:

- Astronaut time is extremely scarce

- Logistics are very complex

There is no ultimate answer and as said before science payload have to undergo more reviews and pre-selections but also have the benefit of longer execution and more repetitions on board. As a rule of thumb, you should show that you will make use of the special conditions on-board (e.g. sustained microgravity) which can not be reproduced on ground.

3. YOUR PRIMARY CONTACT POINTS

3.1. The Payload Integration Manager (PIM)

If there is endorsement of the UIB then the process can begin. This is still no guarantee that the experiment will be carried out, however. From this moment on there will be a Payload Integration Manager (PIM) assigned to your project. She or he will help you with moving forward with your experiment and initiate required steps to have approval to fly to the station as well as help with logistics and to interface with (ESA) internal and external boards and experts. Like in any business relationship it is very important to keep in touch and frequent contact with your PIM. The PIM knows the required processes and has been in touch with many other payloads but is also not an

expert in your field of science, technology and the data you are interested in. We found it essential to talk, explain and aim for a very good mutual understanding. You need to understand the constraints the PIM is sitting in as well as keep him/her informed about everything and highlight the essentials. You might not be involved in all meetings and a well up-to-date PIM is the best first line of defense.

It also has to be acknowledged that your PIM has not only your experiment on her/his plate.

3.2. User center

The user center coordinates and ensures the onboard operations and execution of the experiment. The user center will provide support for developing all the procedures regarding the payload. Just see them as an additional technical support crew which also pull information from you to ensure a smooth operations. They will also need a version of your payload to operate at their facilities for them to learn how it behaves and to be able to develop the procedures. We would recommend to do reduce potential misunderstandings, see Section 4.5.

In addition the user center learns, in cooperation with the payload developer, all about the payload and its operation and is the interface point between the flight team, EUROCOM and the payload developer in the voice loops. In current regulations it is not possible for the payload developer to speak to the EUROCOM or Columbus flight team directly. Thus the user center acts as an intermediary. In addition to the procedures the user center reviews in coordination with NASA the user interface of the payload or the software.

3.3. Others

You may also have a contact point for the medical board approval, and you definitely will be interacting with the ESA safety board for the safety approval process. For software and ground segment you will be dealing with a security officer, and the qualification is guided by the Engineering contact point. However, all of this is coordinated by the PIM, and of in doubt, the PIM is always going to be your first point of contact.

4. PHILOSOPHY AND MINDSET

4.1. Explain, demonstrate, ask and involve

Even without the Space Station your payload is probably complicated and we are now adding an additional layer to it. There will be boards, documents, approval loops and it seems like a big bureaucratic machine. But in the end there are humans behind every step and besides being specialists and experts often very passionate about what they do. We want to be explicit here since this might become forgotten in the stressful process.

One general piece advice here would be to explain and demonstrate what you do. Your complex machine explained in a PowerPoint is still something abstract and might cause concerns. Live demonstrations make it so much more understandable and real. In addition the reviewers have seen many systems and you might benefit from their advice. So involve them early, listen to what they say and ask questions. Also be aware that they test many devices and might not remember yours from a documents (demonstrations are easier to). In any case be ready to explain repeatedly, and to show understanding.

4.2. Like installing an appliance in someone's home or factory

An analogy to fly a payload to the ISS could be to have your appliance installed in someone's home or factory. The instances all around are basically there to protect the home (ISS) and its inhabitant, the astronauts. In the consumer market there are authorities and markings that, at least in theory show inherent safety and user data protection. If moving into the industrial environments, several safety guidelines have to be followed. In Europe this is in general the machine directive 2009/127/EC. Depending of the nature of the payload, other guidelines might apply. More detail about the approaches are in the chapter about safety.

4.3. Tell me what you need vs. tell me what you have

As a newcomer onboard the station we did not have a lot of previous knowledge of onboard equipment and capabilities. Especially as engineers for technology demonstrators we often approached it from a point to ask for the technical limitations and go from there. When asking the answer was often: What do you need? The dilemma is that an accurate answer like "it

depends" does not move anything forward in this context. An even greater risk was to ask for too much, which can result in the request being seen as impossible with the result of having your experiment declared infeasible.

4.4. Acknowledge the Complexity even of a Small Device in the ISS context

The complexity of flying ANALOG-1 on the ISS was not only dictated by the hardware that needed to be uploaded, but in a large extent by the complicated operational scenario.

4.5. Be aware of "Chinese whispers"

When moving in an organization as big as ESA with many international partners there established processed and flows that might have historically grown and/or are enforced by contracts. That means communication is not straight and goes via multiple parties, with content potentially getting lost. We would recommend to keep an eye out for potential misunderstandings, misconceptions and communicate and rather explain one time too many than not enough. A quick chat on the phone can often go a long way towards avoiding misunderstandings.

4.6. Following the standard process is easier

The ANALOG-1 mission targeted a specific increment and astronaut (Luca Parmitano). This was done primarily for scientific reasons, as we needed someone with PANGEA (Geology) training. However, this dramatically constrained the schedule, which again put enormous pressure on all the other elements of the experiment preparation.

Being able to delay the experiment a bit when challenges arose and target another increment would have helped dramatically at almost every step on the way. Many of the steps, from safety to software security approval are done by entities that carry out their task within certain processing times which were not compatible with the timeline of ANALOG-1. The timeline meant they all therefore had to step outside their standard, and in many cases contractually agreed, processing times.

5. KEY STEPS IN THE PROCESS

5.1. Informed Consent Briefing – The Pitch

The astronauts can choose in which experiments they want to participate. Thus it is your task to convince her to subscribe and commit to your experiment. This is done in a phone call. It might even be that there is no possibility to show slides. If possible we recommend to try to speak with the astronaut beforehand and to lobby.

Treat the talk as a sales pitch or advertising an adventure try to enter into a dialog. Keep also here in mind that the astronaut hears a lot of these talks. As all persons are different and it might feel like a monologue on the phone or with the right chemistry like a good conversation, in the end also the astronauts are human beings with a very intense schedule and exposure. Furthermore the more she buys in and shows interest the more you gain during the execution of the experiment.

5.2. Medical Board & Life Science Protocol

The life science protocol describes in the experiment's medical nature in more detail. As for any experiment this description has already been endorsed by an ethics committee and has to explain your intentions methods and data to be collected. The medical board cares about the well being of the astronaut. Not only in sense of the procedure but also in sense of ethics, psychological and data protection. This board is not mandatory for all experiments. Whether it is required is a thin line and it is definitely good to check informally first.

This board is special, compared to the other boards since it concerns the astronaut and not the station. There are four governing bodies (NASA, JAXA, Roscosmos, ESA), each with their own boards. Thus when targeting a NASA astronaut there is need to get approval from the NASA medical board as well. Even though the agencies are cooperating well together these board meetings are held only every few months and have often a full agenda. So this step has the potential to take a really long time, and you should evaluate the need and if necessary start early.

In Analog-1 we went for medical board approval with NASA and ESA. In the early stages of planning the mission, we had more sessions planned and also an EEG to measure the astronauts brain activity which is undoubtedly medical data. Even though this was not used in the end, the involvement of the medical board gave us "wiggle room" in the questionnaires and collecting data on the haptic device. In other experiments from our past we did cross check our questionnaire with the medical board and adapted it so that we could go without medical board approval, thus not collecting any crew data.

Our advice is to carefully trade off the need you have to collect medical data since it takes time, requires renewal and is complicated with astronauts from different agencies. On the other hand it allows the collection of significantly more data and each data point collected on the station is valuable and might have the potential for different insights. Just plan enough time.

5.3. Safety

To get any hardware onboard the ISS the safety board has to be passed. In ANALOG-1 the hardware to be uploaded was massive, of high electromechanical complexity and had to be operated by astronauts. This made for a difficult safety and qualification process, and the high mass allocation required a close interaction with the ESA increment manager and her NASA counterpart to secure and keep our launch opportunity in face of qualification and safety process uncertainties.

The safety board follows a safety approach similar to what is present in most industrial applications. The payload developer has to make an analysis of what can go wrong in total disregard of already implemented mitigation features. For developers from academic or R&D prototyping like us this was confusing at first. You have to list everything what can go wrong, what effect this might have and how you plan to or have already mitigated it. Even if space is covered by the ECSS standards (ECSS-Q-ST-40C for safety) a good starting point is the machine directive of the European Commission and the guide to it.

It might be that besides general safety rules your experiment touches other subjects where no ECSS standards exist. In this case the safety board will orient themselves by other industry standards and or

listen to newest research and calculations. In our case with the haptic device this was ISO 10218-2.ISO/TS 15066:2016 for cobots)

A word on software safety

A special word on software. Safety in software opens an area that everyone, including the safety board, recommends to avoid. The formal process is so complex that for a class 3 payload and onboard usage this is not recommended. In practice this means you should make your equipment hardware safe in such a way that it is impossible for software to make it unsafe. In the words used by the safety panel, software should not be used as a mitigation. For example, in the case of ANALOG-1, we proved that in the extreme situation where all the drives on the sigma-7 pushed in a coordinated way, not enough force could be generated to hurt an astronaut. That way, no further software mitigations were required.

5.4. Engineering and Qualification

The qualification process is guided by ESA engineering and starts with agreeing on the requirements that apply to your payload – the Verification Control Matrix. This process, which is iterative ends with the sign-off of the draft Small Payload ICD document. The purpose of this document is to describe in detail everything that is needed in terms of station resources, and how exactly your payload interfaces with the station. In the appendix to the small payload ICD is verification matrix listing the applicable requirements, mostly taken from the Colombus Pressurized Payloads Interface Document. In order to get the final ICD signed off, all requirements need to be verified, either by test or by analysis as agreed in the beginning. The exact tests that will need to be performed depend on your payload. In case of ANALOG-1 random vibration, EMC compatibility, and EMC interface tests were performed.

When a test shows that a particular requirement cannot be met a Non-Conformance Review (NCR) is organized. The outcome of the NCR depends on which requirement is violated and by how much. In simple cases it may be that the requirement violation can be accepted. I.e. a value, for example temperature, may be outside the requirement, but still well within the safety margins. If so, a Request for Waiver (RFW) has to be raised and approved.

The verification matrix has to close every requirement with a reference to either the test report or analysis that shows the requirement is met or the RFW that shows that it is accepted as is.

In ANALOG-1 we had a major NCR related to the inrush current being far out of bounds. Since the vibration tests had already been performed it was nontrivial to modify the hardware in such a way as to comply with requirements.

As with many other examples described in this paper, the problem really stemmed from the extremely constrained timeline. This NCR was close to derailing our experiment, but would not have been a significant problem if we had had the time to go back and do the required modifications and then repeat vibration tests.

5.5. Security

All software that is run on the station requires a software delivery/release order (SDO/SRO). The SDO/SRO is released by an industrial software control board that meets every few weeks, and every version of software requires a new SDO/SRO. The biggest obstacle to obtaining the SDO/SRO is however the necessary documentation, in particular the security approval note (SAN). Even though the payload developer might think that the software release is on her turf the philosophy of the housekeeper still applies even if he will not interact with your device he still needs to know and keep track of the systems state and software running there.

The SAN is obtained by a certifying authority that checks that the software complies with all the various security requirements on the station. They basically follow the CIS-CAT scan directives. .In most cases of non-compliance the software we would recommend to fix it. However also waivers can be issued. Those waivers need to be justified and the risk accepted. The basic philosophy on board the Columbus module is that every payload connected to the Columbus network switch has to protect itself. Only on secondary priority the system should not be able to attack others (by accident). In addition the recommendation is to keep the system slim. One default requirement is to remove all unused software and provide a list of everything with a version number that is contained there.

In the case of ANALOG-1 we released a first version of the software in time to be loaded onto the launcher on a USB stick, this was subsequently updated and the update uploaded to the ISS. Each iteration required a security approval and a new SDO/SRO. The ANALOG-1 software was built on top of a custom Linux. Even though this took more time for the scanning authority this saved a lot of time and effort on our side and allowed the generation of the required documents, version and modules automatically.

Also we would advise to give as much information about your onboard software as possible. The security board and scanning authority know nothing about your payload. We would recommend to explain the used systems, software and libs. In addition we suggest to start this checking process early since the certifying authority is permitted to take quite a long time to complete one iteration of their scans.

6. OTHER THINGS WORTH MENTIONING

We can not mention everything in this paper. Other aspects are by no means less important or require less attention. This section introduces a few of them.

6.1. Packing the suitcase

In order to fly the payload to the ISS a special container called a CTB is required. The CTBs come in different sizes single, double triple. The size is defined by the payload, however as payload developer you have quite some influence on the size by designing the devices. The bigger the size the more issues might arise later since especially for launch and onboard storage there is limited possibility to accommodate triple CTBs. So make a tradeoff.

6.2. Astronaut training

The astronaut also need training on your payload. The training will be managed by the European Astronaut Center in close coordination with the USOC and PIM. The trainer might contact them and you for the preparation of the training. In might be also possible to be present during the training which we found highly beneficial to all parties. Please keep here in mind that the training is done multiple months before the astronaut launches, so you have to have at least an engineering version of the payload ready. Also keep in mind that the astronaut has many trainings and the

months between training and execution leave room to forget things. Even with a refresher lesson on board it is really important to design your payload as user friendly as possible to get maximum benefit.

6.3. Voice loop s and speaking to the astronaut

Usually only the EUROCOM can speak to the astronaut. But in special occasion it is useful to have the PD or PI talk the astronaut throughout the experiment. This can be requested but requires training. With a complex experiment, like ANALOG-1, we would definitely recommend it. Just remember all times that when you are on the loops everyone is listening. It is human to human contact but respect the medical board - e.g. asking how the astronaut feels might be a no go.

7. SUMMARY

ANALOG-1 demonstrated very successfully the advantage of having an immersive control station and high level of robotic dexterity with Luca finishing all his assigned and secondary geology targets in record time. The Sigma-7 and joystick as well as the mounts are still, as of the time of writing this paper, on-board the station, and we invite anyone who may wish to reuse it to contact the authors.

We hope that this article demystifies the process of bringing a payload onboard the ISS. On the one hand we acknowledge that it appears and still is a complicated and exhausting endeavor, on the other hand it is realistically doable. The technical challenges are only one part. The other part requires resilience, learning, patience and sometimes to push. All in all it is from a scientific, engineering and a learning standpoint a very valuable experience. There are additionally other options to fly payloads which are smaller so please check IceCubes for stand-alone experiments inside the ISS and Prometheus for the outside. The authors wish you success with your experiment!

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