MINERVA: A 6U Nanosatellite with an Autonomous Intelligent Biological Operating System (AIBO) for Deep-Space Experiment

The demonstration of anti-mutation technology with the ability to inhibit DNA damage against space ionizing radiation by using genetic modification

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(**Yes**) **We apply for Student Prize.**
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Need

The ideas of long-term space exploration, interplanetary travel, and space civilizations are starting to become a reality. However, there are still many challenges we have to cross before we could accomplish such a feat, one of these being space ionizing radiation. Each year, a person receives roughly 2.4 to 3 milliSievert (mSv) on earth. On the contrary, an astronaut receives an average of 160 mSv with a six-month mission on a space station. Space radiation has become the most hazardous health risk for space missions, as long-term chromosomal damage occurs at 50 mSv. Furthermore, for deep space exploration and living on Mars, we would be exposed to more than 1000 mSv over the span of three years-causing much more severe symptoms. [1]
To date, the most reliable and proficient way to protect against space ionizing radiation is to use heavy shielding, for example, 15 centimeters of steel. In outer space, we will be bombarded with galactic cosmic rays (GCRs) and proton from solar particle events (SPEs) that make the current shielding method obsolete. Consequently, colonization on Mars would be forced to live underground, provoking possible ramifications regarding psychological illnesses. In addition, we cannot test the feasibility of habitat builds on earth, as no terrestrial facilities can replicate the unique properties of the space environment. Leading to the idea of genetically modifying an organism, fit for future development and integration into medicine, as a new alternative to manage space ionizing radiation. [2]

Mission objective

The primary objective of Minerva is to create a 6U nanosatellite platform that can sustain and culture a microorganism for 4 months in the cis-lunar orbit. The experiment must be carried out into deep space as it best represents GCRs that would be received during long-term space exploration. The international space station (ISS) or Low earth orbit (LEO) is not suitable for our mission since LEO or ISS cannot replicate the nature of deep space radiation within Earth magnetosphere protection. Minerva will provide an autonomous system for future missions planning to conduct experiments under space conditions in a nanosatellite. The concept of the experiment is to create a radiation-tolerant transgenic organism from a creature with radiation-intolerance. In this experiment, we will be using *Caenorhabditis elegans* (*C. elegans*) as a model organism. The *C. elegans* will be genetically modified with a protein-coding gene associated with DNA damage protection called Damage suppressor (Dsup) protein (**Figure 1**). The onboard experiment will serve as a proof of concept that the genetically modified *C. elegans* can tolerate more radiation than wild type *C. elegans*. In addition, Minerva will be equipped with an autonomous biosensor system capable of working under the space environment condition, suitable to sustain the optimal environment for growing the subject, to obtain the most accurate information possible.
Our mission will set in motion a paradigm shift corresponding to future space medicines and how they will be developed in the future, introducing a platform suitable for future experiments in the fields of space biology. Ultimately, the paramount objective of Minerva will be to test the limits of genetic engineering and incorporate it into the arduous journey of human perseverance to overcome the boundaries of space exploration—a vital step in making Mars colonization safe.

Primary objectives

1. Provide a platform to study the biological effects of transferring a protein-coding gene, with an ability to protect against DNA damage from space ionizing radiation, into *C. elegans*.
2. Develop a CubeSat platform with autonomous biosensor technologies, capable of sustaining life support for the *C. elegans* throughout the mission and collecting the DNA protection response data.

Secondary objectives

1. Establish a learning foundation corresponding to the transferring of genetic material from a low-level organism to a more sophisticated organism
2. Examine the radiation dose received while travelling through the Near-rectilinear halo orbit, possibly providing fundamental information on human space exploration in this orbit
3. Provide a rudimentary basis for developing space medicine that protects astronauts from radiation in the future

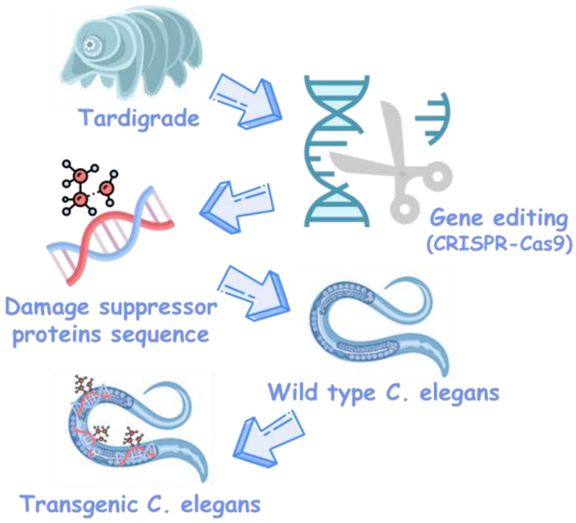


Figure 1. Gene transfer process

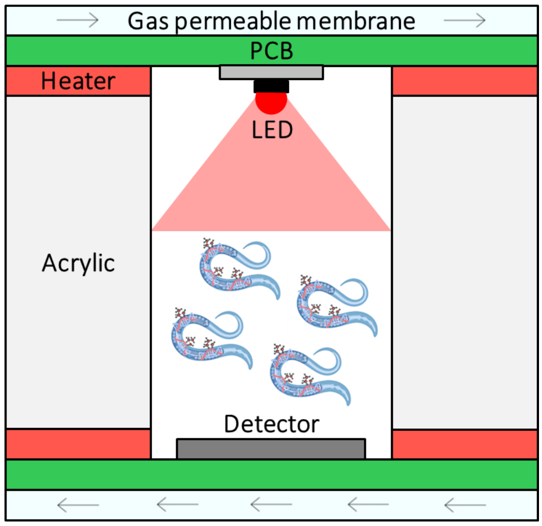


Figure 2. AIBO biosensor

Concept of Operations

The experiment will be using the animal, *C. elegans*, as a model organism. The reason being, *C. elegans* genome has up to 83 percent human homologs genes; showing promise for being appropriate to develop into space medicine. We plan to transfer a protein-coding gene associated with DNA damage protection called Dsup protein into our subject. The Dsup protein is the key component that makes the tardigrade species able to withstand 1000 times more radiation than other animals. We will extract it from the extremophile *Ramazzottius varieornatus*, one of the most tolerant tardigrade species. [3]

A key segment in our experiment is loading the *C. elegans* into the nanosatellite while it is in hibernation-specifically the Dauer state. The intriguing thing about *C. elegans* is that they can hibernate through controlled starvation. If the eggs of *C. elegans* hatch in the absence of food, they will enter the L1 arrest Dauer state to prolong survival of starvation for up to 4 months. The idea of the experimenting *C. elegans* within the Dauer state in space has been performed successfully during the Shenzhou-8 (SZ-8) mission in 2011. [4] L1 arrest ensures that post-embryonic development is not initiated without adequate nutrition. It is advantageous for our experiment, as we are able to experiment with a living organism for over 4 months. Moreover, we can stimulate the *C. elegans* to continue growing by flooding it with nutrients. Consequently, we can control and observe the growth rate of *C. elegans* closely in space with AIBO platform (**Figure 2**). [5]

Phase 0: Gene identification and implantation (L-14 months to L-8 months)

Locate and identify the protein-coding gene for Dsup protein. Once the gene is isolated, it will be implanted into the reproductive cell of *C. elegans*, with a method called Bacterial Plasmid Microinjection.

Phase I: Testing of the modified C. Elegans (L-8 months to L-4)

After the implantation is complete, the modified *C. elegans* will be tested under lab conditions to ensure that the ability from the Dsup protein is transferred to the *C. elegans*. Afterwards, the *C. elegans* will be instigated to enter L1 arrest and then activated to exit the L1 arrest state, to certify that the *C. elegans* can exit the L1 arrest state after being genetically manipulated.

Phase II: Assembly and Launch (L-4 months to L)

The *C. elegans* will be loaded into the microfluidic system of AIBO while in the L1 arrest state. The Minerva payload will be separated into 8 sets of the AIBO platform. Each set of AIBO will contain two models of *C. elegans*; one will be a wild type, and the other will be the transgenic type. Microfluidic and optical sensors will be integrated into the AIBO platform. After integration, AIBO must be tested for their function as a primary measuring system to make sure that they can operate correctly in space.

Once the payload testing is complete, it will be integrated with other subsystems and continue testing as an engineering model. After all testing is done, we will build the flight model and launch it into space. We plan to launch Minerva to space in early 2025 during the next solar maximum.

Phase III: Early Orbit (L to L+2 weeks)

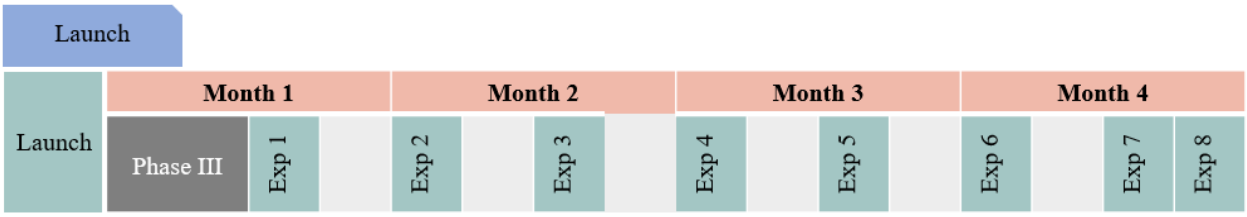
During the launch state, AIBO will be operating in order to keep *C. elegans* alive. After the separation from the launcher, Minerva might be in tumbling mode until it can maintain its orbit. It will deploy the solar panel to recharge the battery. Then, the satellite will run a series of diagnostics to make certain that all systems are online and operating smoothly.

Phase IV: Near-rectilinear halo orbit Experiment (L+2 weeks to L+16 weeks)

AIBO 1 - 8 will be conducted for a total of 16 weeks, with a 2-week gap between each experiment (1st to 6th). Each experiment will compare the different radiation responses of the two model organisms in space and one ground control wild-type *C. elegans*. The results will be quantified and examined to determine if the transgenic *C. elegans* can withstand the space ionizing radiation and continue growing normally as it would on earth. AIBO 7 and 8 will be activated during the solar maximum of SPEs. This experiment is conducted to monitor how modified *C. elegans* respond to SPEs, as SPEs are the most harmful risk of space exploration and colonization. The 7th AIBO will be activated right after the CubeSat is exposed to SPEs. While the 8th AIBO will be activated a week after to compare the sudden response and side effects after a week of absorption.

Phase V: Observe the radiation and End-of-life (EOL)

After all, the primary goal of Minerva is completed. In the final phase, the CubeSat will continue to observe the radiation dose in the near-rectilinear halo orbit until the EOL state. Finally, the CubeSat will deorbit into the Moon at EOL.



Key Performance Parameters

Biosensors (AIBO) – Fully automated in-situ experiment platform using a microfluidic and optical detection system that provides real-time insights on the growth rate and metabolic activity of transgenic *C. elegans* with exposure to space radiation.

Radiation dosimeter – Provide radiation dose measurements during travelling in Angelic halo orbit that allows the CubeSat to study the relation between the biological response and the dynamic nature of the space radiation environment throughout the entire mission.

Payload environment – The payload inside must maintain the ambient temperature within an optimal range at 20 °C and 1 atm of pressure to sustain the lifespan of *C. elegans* during the entire mission.

Ground Segment Description

In this mission, we will use the Deep Space Network (DSN) as the ground segment. DSN is an international array of massive antennas that supports interplanetary space missions. The DSN consists of three main facilities around the world: 1) Goldstone, Barstow, California 2) Madrid, Spain 3) Canberra, Australia. This ground station network allows us to communicate with Minerva as the Moon rotates around our planet. [6]

Space Segment Description

Minerva is a custom 6U nanosatellite with a mass of approximately 9 kg. Minerva will be placed in a near-rectilinear halo orbit within cis-lunar space. It will have two deployable solar cells embedded over 2-side of satellite 2U surfaces and wings that can pivot on a single axis of rotation using a modification gimbal to span across the 1U x 2U face. The electrical power subsystem (EPS) can generate power up to 84W BOL with 4 deployable solar panels. The total average and peak power consumption of Minerva is approximately 31W and 79W, respectively, which satisfies the power balance of Minerva (**Table 1**). Minerva will contain two scientific payloads that are AIBO (biosensors) and radiation dosimeter (**Figure 3**). The onboard data handling (OBDH) subsystem & Telemetry, Tracking and Command (TT&C) subsystems are responsible for establishing communication with the ground station and sending the experiment data from both payloads via X-band communication. Attitude determination and control subsystem (ADCS) of Minerva requires precision of less than 1 degree. Hence, ADCS will consist of one inertial measurement unit (IMU) sensor, two star trackers, two fine sun sensors, ten coarse sun sensors, three momentum wheels, and one 6DOF cold gas thruster.

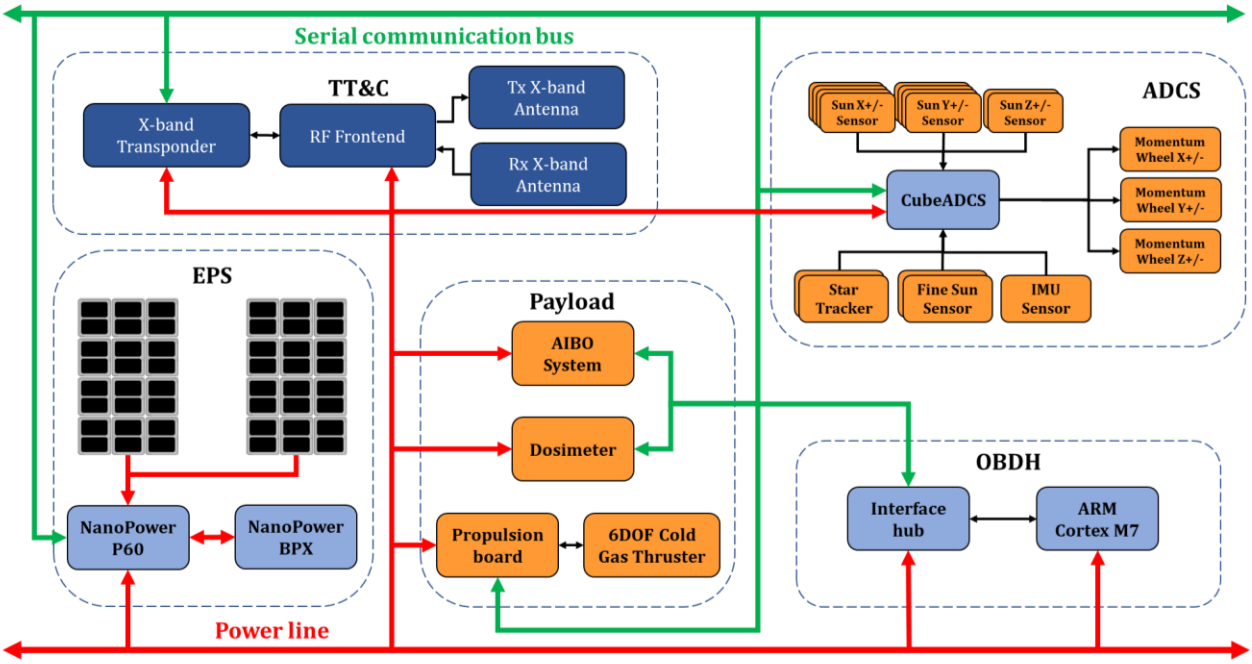


Figure 3. System diagram of Minerva

Orbit Description

Our mission concerns the radiation effect on our microorganisms. Therefore, we have chosen the Near-rectilinear halo orbit (NRHO), as our pathway since this kind of path meets our requirements: 1) the effect of the magnetic field will be greatly reduced. 2) its time frame according to this orbit could reduce the number of eclipses in which the Minerva is shrouded by the shadow Earth or Moon. 3) the satellite temperature will never be too high or too low (in contrast to normal L2 Halo orbit). This orbit has an elliptical shape trajectory by making use of the special case of the L2 Halo family orbit. From the literature, the NRHO has a distance between the satellite and the lunar surface of 3,000 km to 70,000 km and takes approximately 7 days for a period. However, this type of trajectory requires little thruster control effort to become dynamically stable.

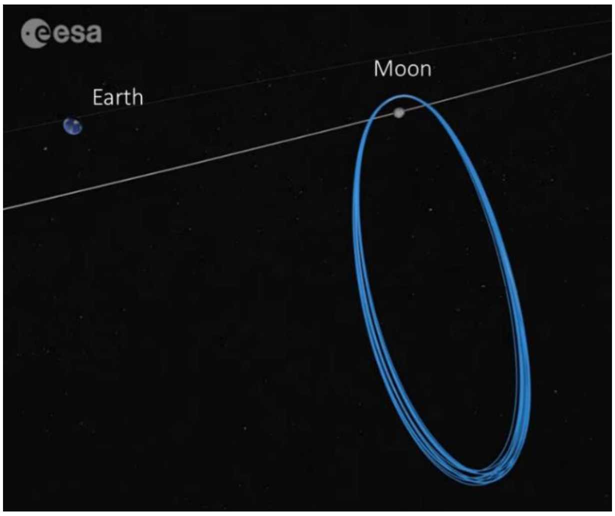


Figure 4. Near-rectilinear halo orbit (NRHO)

Orbital trajectory control

In order to maintain the orbit, the cold gas thruster is used to stabilize using PID control law which tries to bounce the satellite back to its orbit due to the quasi-static nature of NRHO. However, the satellite has to know its position accurately in space. The navigation tracking method will be utilized radio transmissions from Deep Space Network (DSN) to obtain the satellite position via Iris transponder. The orientation of the satellite will be controlled using nonlinear control law based on the modified Rodrigues parameters (MRP), a parameterization system that is renowned for singularity avoidance. Momentum wheels will work as the primary actuators to maintain the orientation, while the thruster will be used to desaturate the wheel speed. Static attitude determination uses the optimal linear attitude estimator (OLAE) algorithm, with the input from star trackers and fine sun sensors. Then, the calculated attitude will be utilized as information for the sensor measurement part of the extended Kalman filter (EKF) algorithm, where the gyroscopic data from IMU is used in the updating process. The trajectory schemes to maneuver the solar panel to face the sun as much as possible. There are 4 modes of operation: detumbling mode to control the satellite to zero angular velocity, earth-pointing mode to transmit and receive the signal from the earth, orbit maintenance for adjusting the orbit for every 7 days, and sun-pointing mode to maximize the generated power.

Table 1: Power budget & Mass budget analysis

Subsystem	Component	Part description	Mass (g)	Average Power consumption (W)	Peak Power consumption (W)	COTS/ Custom
TT&C	X-band transponder	Iris V2.1 CubeSat Deep Space Transponder	1200	12.6	35	COTS
	Tx/Rx X-band antenna	IQspacecom X-Band Patch antenna	40	-	-	COTS
Structure	6U structure	EnduroSat 6U CubeSat structure	1000	-	-	COTS
EPS	Battery+Heater	GOMspace NanoPower BPX	500	6	6	COTS
	Power module	GOMspace NanoPower P60	191	0.6	0.6	COTS
	Solar panels	MMA design eHaWK (84W BOL)	600	-	-	COTS
ADCS	3-axis ADCS	Cubespace CubeADCS	554	0.571	2.295	COTS
	Fine sun sensor	Cubespace Cubesense	0.03	0.1	0.2	COTS
	Star sensor (x2)	Cubespace CubeStar	111	0.284	0.528	COTS
OBDH	Onboard Computer	EnduroSat Onboard Computer	130	0.783	11.9	COTS
Payload	Biosensor	AIBO	<5000	<10	<20	Custom
	Dosimeter	Skyfox Labs CubeSat Dosimeter	32	0.05	0.07	COTS
	Propulsion	GOMspace NanoProp 6DOF	682	-	2	COTS
Total			10040.03	30.988	78.593	

Foreseeable risks that may affect the mission

1. The model organism *C. elegans* may be affected by solar maximum to the point where it cannot exit hibernation, making our primary objective unobtainable
2. Leaking from the payload bay (AIBO)
3. *C. elegans* may not survive up to 4 months because of long exposure to solar maximum
4. Loss of leads and members due to time constraints
5. Launching failure

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