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Hyper Datacube for a Digital Twin of the Moon to plan and support operations

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Abstract

The lunar ambitions of NASA's Artemis program spell out multiple crewed missions to the Moon and later to Mars. The ESA Terrae Novae 2030+ exploration strategy roadmap aims to enable Europe's participation in the first crewed exploration mission to Mars. Yet, missions to deep space still pose significant challenges in terms of crew autonomy. As missions will become longer and more distant, the operations and sustainability of such structures in stressful isolation conditions constitute a high level technological and human challenge. The objective of Spaceship FR team at CNES (Centre National d'Etudes Spatiales - FRANCE) is to develop innovative technological bricks for the future Moon and Mars bases, thanks to technologies and skills of its network of partners: academia, laboratories and industries. To prepare, plan and design the future missions, Spaceship France project develop a digital twin of the Moon. With this software, the future operation teams will plan the exploration activities, for example to find the shortest illuminated path for rovers, or the base placement near in-situ resources according to environmental constraints. Once the various digital equipment are integrated in the tool, operational teams and astronauts will be trained thanks to virtual reality for surface exploration and management of the base. This tool will also be used to support the lunar operations. It will be used for assistance to satellites involved in the lunar missions for efficient communication, navigation, mission and infrastructure support, or for alarm systems involved in radiation and micrometeoroids alert. Finally, for surface operations, this tool will support rover handling and human operations and automatic rover exploration. Hypercube, use by this tool, is a cube of data gathering various information to feed the digital twin. These data can be provided by Digital Elevation Models (DEM), catalogs, for example of ephemeris, dynamic maps like illumination maps, static maps like materials location or slope map, digital twin of buildings and equipment, and results of various simulations. This paper aims to present the strategy of development of such a digital twin and the Hyper Datacube to feed it. It also gives a status of the development and tests done with the first version the tool.

Keywords: Spaceship FR, Datacube, Digital twin, Moon.

Acronyms/Abbreviations

2D/3D	Two Dimensions/3 Dimensions
CNES	Centre National d'Etudes Spatiales
CSV	Coma-Separated Value
DEM	Digital Elevation Model
ESA	European Space Agency
ExPeRT	Exploration Preparation, Research and Technology
GDAL	Geospatial Data Abstraction Library
JSON	JavaScript Object Notation
JPL	Jet Propulsion Laboratory
LISE	Lunar Integrated Shelter for Exploration
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
IMG	Image format
NASA	National Aeronautics and Space Administration

PNG	Portable Network Graphics
TIFF	Tag Image File Format
VR	Virtual Reality

1 Introduction

The goal of NASA's Artemis program [1] is to send multiple crewed missions to the Moon beginning in 2028, to build a permanent base. After testing the various technologies necessary to live on the surface of the Moon, the objective is to transfer them to Mars. France signed the Artemis Accords on June 7, 2022 [2]. France is also member of ESA and participates in the Terra Novae 2030+ program [3]. In this program, the ExPeRT (Exploration Preparation, Research and Technology) team integrates, coordinates, and manages the development of studies and technologies for future Exploration missions to low Earth orbit, Moon and Mars destinations. In the ExPeRT program, the Spaceship projects teams network work on innovative technological components for future Moon and Mars bases [4]. As part of this network, CNES created the Spaceship France project [5]. The French team works on seven technical areas: Habitat, Robotics, Life Support Systems, Human Health & Performance, Energy, In-Situ Resource Utilization, and Digital Technologies [5]. The objective is to provide a portion of the landed assets as well as innovative systems to CNES space partners starting in 2025 anticipating the return of humans to the Moon. CNES aligns with NASA’s strategy to offer technologies and landed systems for Moon missions, allowing thorough testing before their eventual transfer to Mars.

To help teams to design missions and execute operational activities, Spaceship France team envisions to develop a digital twin of the Moon. This first version of digital twin of the Moon is a virtual and interactive imitation of lunar surface and its characteristics. This numeric model gathers geographic, topographic and environmental data to analyze and simulate lunar environment. This digital twin can be used for several concrete situations as location of lunar infrastructures or plan missions. These missions could be either robotic exploration or human exploration.

To create a digital twin of the Moon is a complex task. The first step was to build a numerical Moon at a scale of 1:1. Such a model is useful to know what the terrain and landscape looks like at a given location to anticipate where LISE (CNES lunar habitat) [7] will be deployed at the South Pole of the Moon around Shackleton Crater.

One way to create such a simulation is to use graphics engines, which are well known and used in the gaming industry. However, these engines are increasingly being used in other sectors such as cinema, aeronautical simulations and space. For space, the best example [8] is what a NASA team has done with Unreal Engine 5 (a graphics engine) to model the South Pole of the Moon. There are many graphics engines, but not all of them are capable of this kind of simulation. Spaceship France team has developed a first mock-up based on Unity graphics engine.

2 Generation of a twin of Moon

The three main functionalities of the tool are:

- A 3D model of lunar terrain with a precision of 5 meters per pixel at the poles (latitudes between [87.5, 90] and [-90, -87.5]) built thanks to data provided by LOLA payload (Lunar Orbiter Laser Altimeter) embedded in NASA’s LRO spacecraft (Lunar Reconnaissance Orbiter);
- Integration of ephemeris to manage Sun position at the chosen date;
- Generation of illumination maps for chosen dates to know which location are illuminated or not.

2.1 3D model of lunar terrain

2.1.1 Moon topology

LRO is a satellite orbiting the Moon to study it from space. LOLA is one of the instruments on board, responsible for laser altimetry of the Moon to collect data on the surface topography. NASA gives free access to these data [9] in the form of binary files. These images are called DEM (for Digital Elevation Model) and are available in a specific format, the IMG format, which is a binary format.

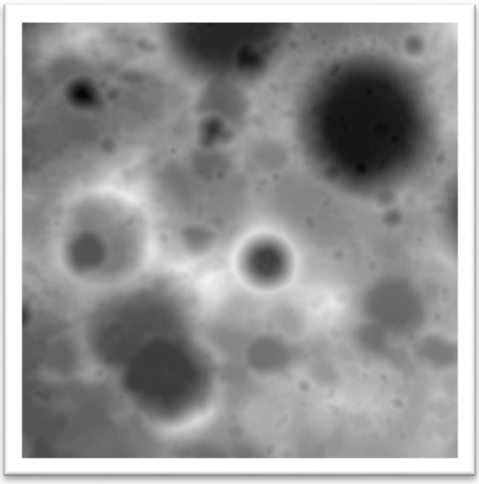


Fig. 1. Altitude data of the South pole of the Moon

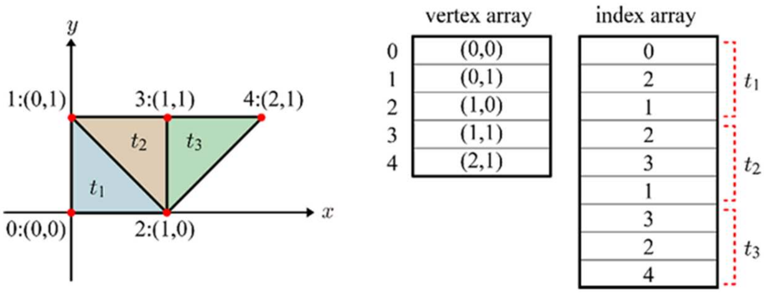
This data is divided into 2 types, cylindrical coordinates and polar coordinates. Since planets and moons are spherical, it was necessary to find a way to map them. A common method is the planisphere, but this method tends to deform the polar regions. To keep the data as close to the real world as possible, it was divided into 2 types, describing the equator and the poles. It is also important to note that the south and north poles are different in terms of coordinates, and some calculations will change due to this difference.

In order to use these data correctly, a threshold latitude had to be chosen to separate the cylindrical and polar coordinates. It was chosen according to the maximum resolution that the CNES wanted for its simulation. Since the preparation of the Artemis missions, LRO has focused on the South Pole of the Moon, collecting more data and increasing the precision of the images. At the poles, the best accuracy currently available is 5 m/pixel. In contrast, at the equator the best accuracy is 30 m/pixel. Knowing this, the threshold was set at a latitude of 60°. This means that in the best case the accuracy will be 5 m/pixel and in the worst case 60 m/pixel. This was the best compromise between distortion maps and resolution. Choosing a higher latitude would have meant more distortion and a lower latitude would have meant lower resolution.

It is also important to mention that the size of these DEMs is relatively high, around 1.7 Go for the polar ones and 900 Mo for the cylindrical ones. Since the intention is to recreate the whole moon, this means that these DEMs will have to be stored, so it is always better to compress them as much as possible without losing any data.

2.1.2 3D Mesh

To create a 3D terrain, a mesh is necessary. A mesh is an object that consists of vertices and triangles. To simplify, a triangle is the most basic shape for a graphics card to process. The triangles connect the vertices to form a 3D object. The vertices are stored in an array (known as the vertex array) of points, which can be in 2D or 3D depending on the desired rendering. The triangles are contained within an array of integers known as the index array.



	vertex array
0	(0,0)
1	(0,1)
2	(1,0)
3	(1,1)
4	(2,1)

index array	
0	t_1
2	
1	
2	t_2
3	
1	
3	t_3
2	
4	

Fig. 2. Computer representation of a mesh [10]

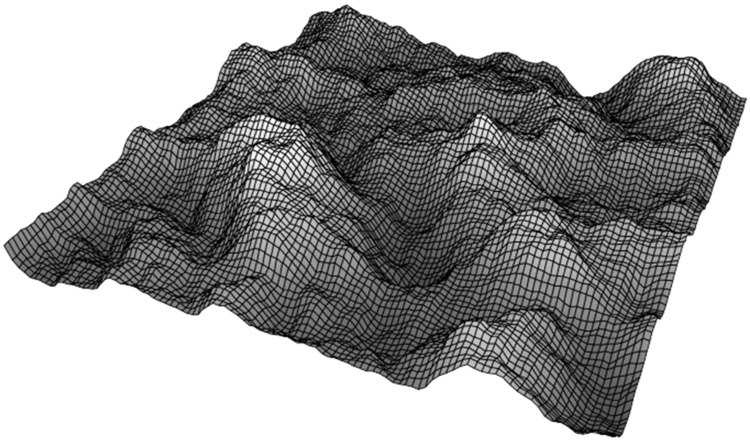


Fig. 3. 3D mesh of a terrain

Software can be used to create 3D objects with ease, and the process is often the same. As these objects are in 3D, they consist of vertices with three values x, y and z. Once created, they can be imported into a graphic engine, such as Unity, to be rendered and used as assets. Although this technique is commonly used in the gaming industry, for a project like a digital twin, it is preferable to be able to create the terrain dynamically. This would allow the user to select any coordinates on the Moon's surface and generate the corresponding terrain. Generating the entire Moon at once is possible, but it requires significant resources. Therefore, it is recommended to generate only a portion of it.

2.1.2 Unity's landscapes

Unity's landscapes provide a simple way to generate a 3D mesh terrain. This feature is easy to use and already implemented in Unity's toolset. The required data is a grayscale height-map image, where each pixel represents a height value. The Digital Elevation Models (DEMs) obtained from LOLA can be used as height-maps for Unity. However, they need to be converted from IMG to TIFF files using GDAL tool. It is recommended to use TIFF instead of PNG as the former preserves the same amount of data as the original IMG file, while the latter compresses the data and may result in data loss. Once converted to TIFF, the images can be read by Unity's landscape feature to create deformations.

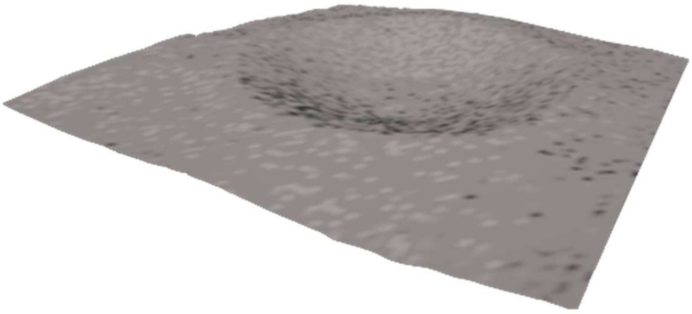


Fig. 4. Shackleton crater using Unity's landscape

The Shackleton crater has a diameter of 21 km and a depth of 4 km. To meet CNES requirement of a resolution of at least 20 cm on the ground studies, a single landscape will not suffice. Instead, a grid of landscapes can be created, with each one responsible for a specific area.

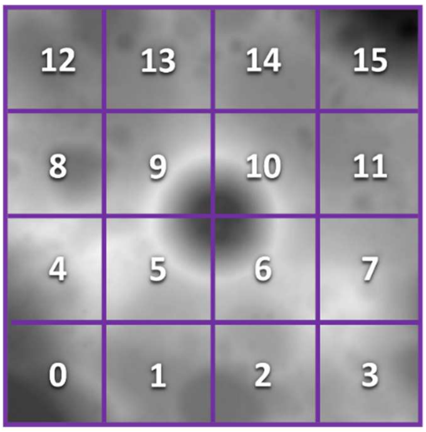


Fig. 5. Unity's landscape grid

Thanks to this type of landscape, it is possible to generate terrain with much better resolution. However, this process takes more time and comes with some issues.

2.1.3 Terrain generation

A clipmap is a method of creating a 3D terrain that maintains maximum detail near the point of interest and reduces detail in the distance. This allows for the creation of vast terrains, which is beneficial for certain studies such as sunshine analysis.

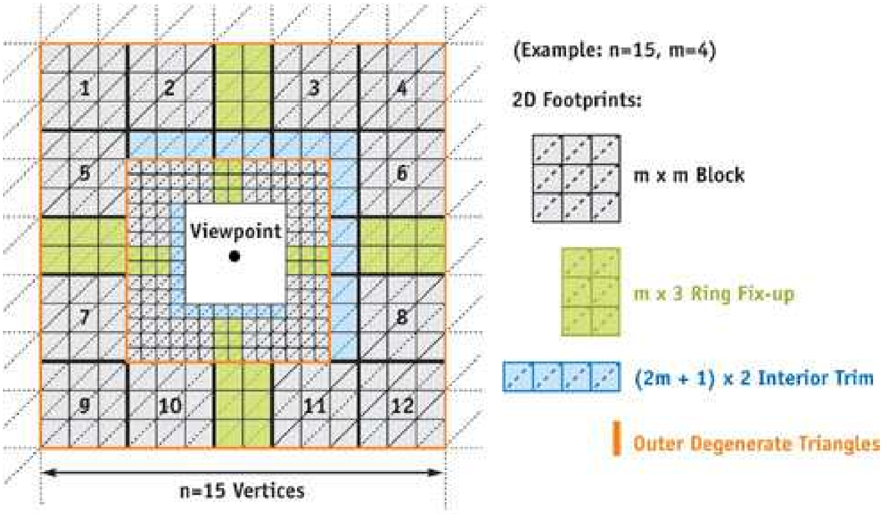
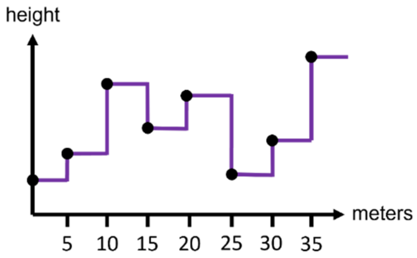


Fig. 6. Clipmap methodology [11]

Zooming in allows for a closer view of the vertices and triangles that link them together. The clipmap size grows exponentially as 2^n, with only 14 levels, resulting in a full terrain area of 655 x 655 km with a resolution of 20 cm at the centre of a 40 x 40 meters square. But blocky shapes become visible when viewed up close.



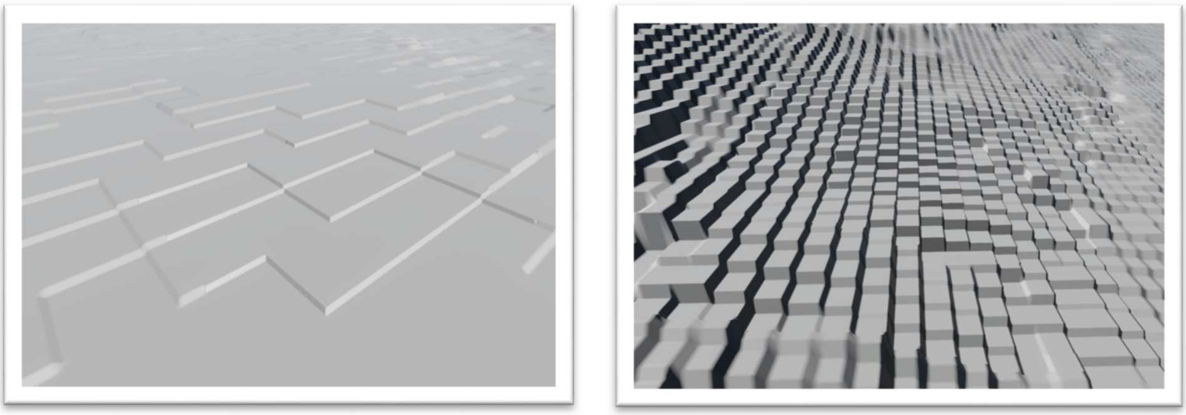


Fig. 7. Blocky shapes because no mathematics treatment

Interpolation and curvature mathematics methods are used to erase blocky shapes. As the user moves, the clipmap follows them by regenerating itself once a certain threshold is reached. This means that the user is always in the center of the highest resolution zone. The data processed from LOLA can be used to deform the clipmap to follow the Moon's surface topology.

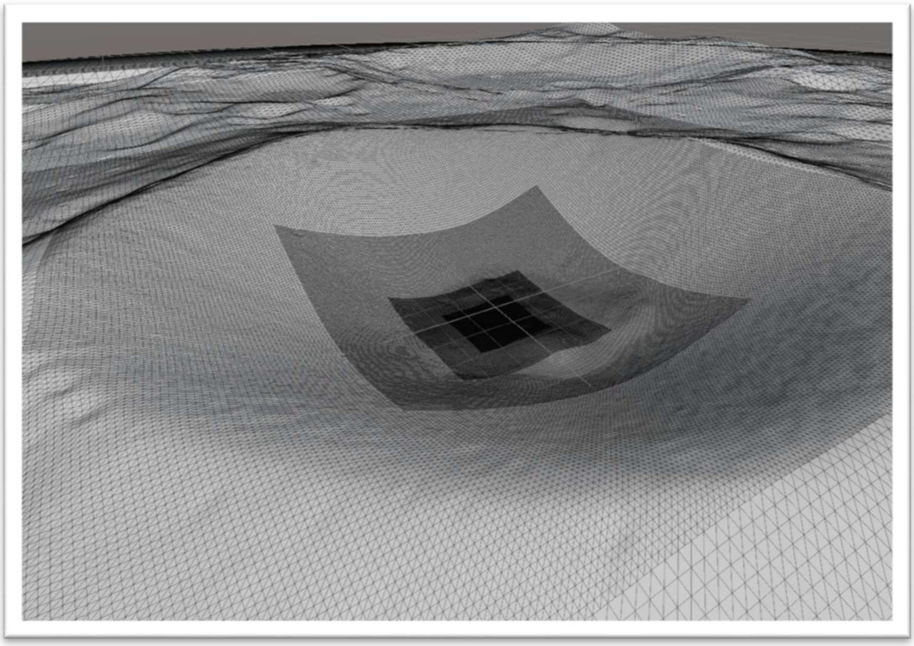


Fig. 8. Clipmap deformation from LOLA's data

Thanks to this process, the clipmap adheres to the data from LOLA. However, further work is required to obtain an accurate model.

2.2 Craters and rocks generation

The simulation requires rocks to simulate rock sampling by astronauts or obstacles for rovers. The terrain generation will include rocks based on a probability law. Due to the high number of rocks, it is not feasible to generate models for all of them. It provides the number of rocks of a certain size for a given area. For instance, an area of 1 x 1 km may contain up to thousands rocks of 20 cm and up to hundreds rocks of 1 metre. To ensure a smooth simulation, only rocks larger than 20 cm will be generated. For real-time simulations, optimization is crucial to make it possible. The 3D model optimization process took around 30 minutes, but it allows for the placement of hundreds of rocks instead of just few ones.

Fig. 9. On the left, original rock 3D model. On the right, optimized rock 3D model.

However, populating the terrain with these rocks remains a challenge that has not yet been addressed. The main challenge of this task is to maintain terrain consistency by placing rocks in the correct locations in a deterministic way. Deterministic means always generating the same rocks with the same rotation, scale and position every time the simulation is launched at the same coordinates.

On the other hand, LOLA's current highest resolution is 5 m/pixel, available only at the poles between latitudes 87.5° to 90° and -87.5° to -90°, and can go up to 60 m/pixel. For cylindrical DEMs, the resolution is 30 m/pixel. However, the surface details in these regions remains unknown. A crater with a radius of 10 meters would only be visible on a 4 x 4 pixels image in a 5 m/pixel resolution, which is a small number compared to the surface area it takes up. Simulating rovers or human exploration would benefit greatly from having craters of this size scattered throughout the lunar surface. To create craters in the simulation, three equations can be used: one for the cavity, one for the floor, and one for the crater's border.

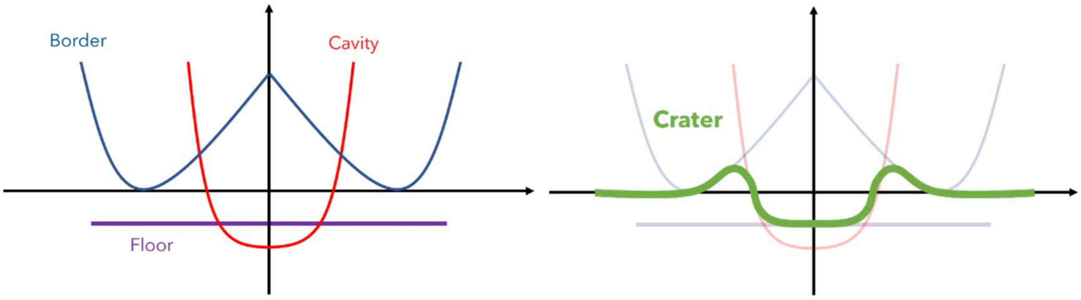


Fig. 10. Crater equations [12]

By combining equations and smoothing intersections, a 3D crater shape is formed. Parameters are used to adjust the shape of the crater to match real-life aspects such as age and size. The generated craters are then rendered in Unity on the terrain. Adding fractal Perlin noise to crater generation can break up circular shapes and create more visually interesting shapes. Fractal noise is created by combining the same noise at different scales, offsets, and amplitudes. The number of octaves determines the complexity of the noise, with each additional octave adding more complexity.

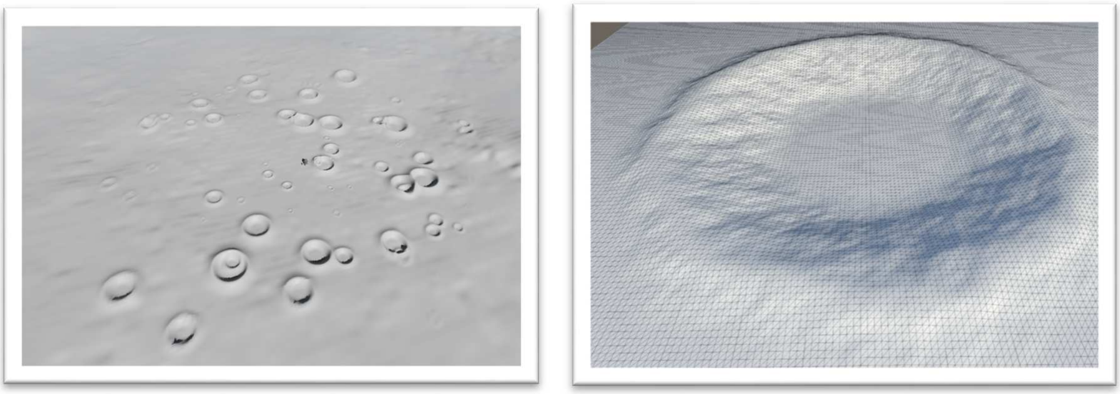


Fig. 11. On the left, craters generated with crater equations. On the right, crater render with fractal noise [13].

Currently, the craters generation is partially implemented inside the simulation. It is possible to generate them on the terrain but having them to be deterministic is also a complex task. Like the craters, it remains to find a way to save the positions and all the associated parameters of each crater during 2 sessions.

2.3 Ephemeris and illumination

The ephemeris provides the position of a celestial body in space at a given time, with the Earth as the origin of the coordinate system. To generate the ephemeris for the Earth and the Sun, CelestLab and Scilab tools were used [14], gathering data from JPL. The ephemeris is created as a text file using a stride, starting date, and ending date. By having the terrain topology, the Earth and Sun position at any given time, it is possible to generate data on the sunshine anywhere on the Moon’s surface.

By performing a simple operation, it is possible to obtain an image of the sunshine at a specific moment. This operation involves shooting a ray from the ground towards the Sun. If the ray hits an object, it indicates that the object is in light, while the absence of any hit indicates that the object is in shadow. The following image was generated using this method. As the ephemeris is spread over a period, a set of images can be generated for each stride. Using Python, a movie can be created to obtain a small animation of the Sun's rotation around the crater.

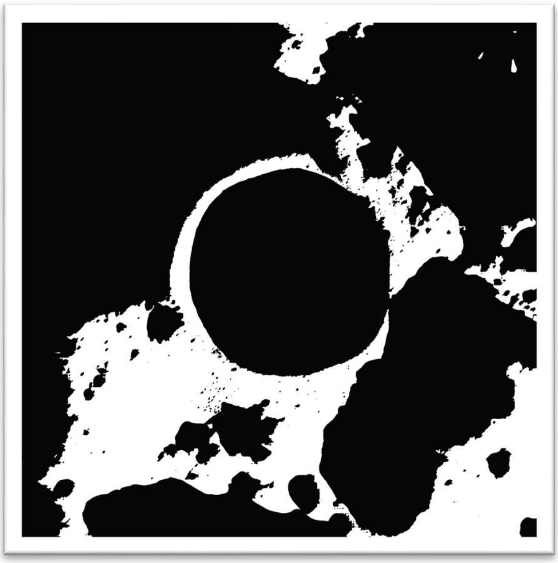


Fig. 12. Shackleton crater sunshine

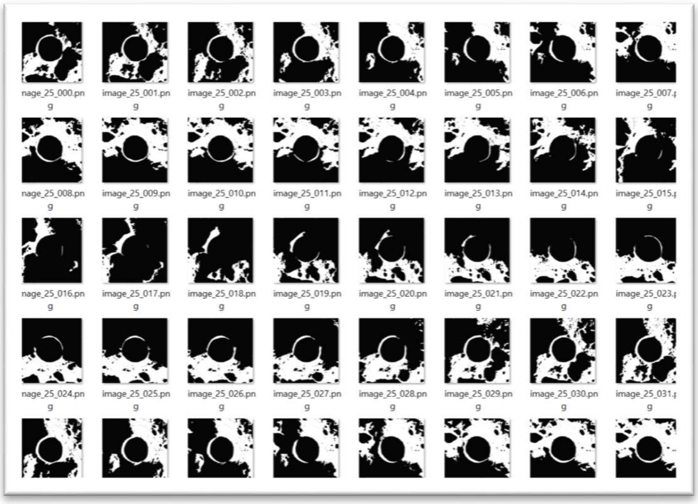


Fig. 13. Set of images of the sunshine

The following image displays the distribution of sunshine during the given ephemeris period. White areas indicate 100% sunshine, while black areas indicate 0% sunshine. The ephemeris period starts on January 1st, 2030 and ends on January 1st, 2031, with a stride of 1 day. Despite the large stride, some regions, such as the inside of the crater, appear to always be in shadow, while others, such as the border of the crater, appear to always be in the light.

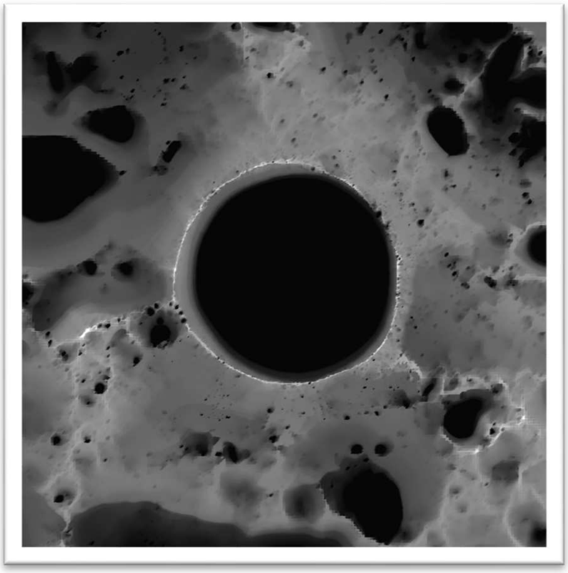


Fig. 14. Average Shackleton crater sunshine

3 Hyper Datacube

3.1 Definition

A datacube can be defined as a set of different data relative to a unique identifier, gathered in a virtual container. These data can be collected from different sources like sensors or from simulation or calculations. A line in a database can be considered as datacube, the key is the unique identifier. Datacube becomes hyper datacube when it gathers data which vary function of time. For Moon simulation each point of the surface (with coordonates x, y, z) will embed one hyper datacube. hyper datacubes can be feed with real data from:

- Satellite’s instruments, with a final resolution which can vary between 4 to 120 meters for surface mapping;

- Rover's cameras and sensors: with a final resolution which can reach few centimeters for adjustment of surface mapping and real craters and rocks mapping;
- Spacesuit's cameras and sensors: with a final resolution which can also reach few centimeters for adjustment of surface mapping and rocks mapping.

For one point of the surface, various real data collected before and during the missions can be:

- Altitude,
- Slope,
- Temperature,
- Direct link with communication means,
- Illumination,
- Radiations,
- Distance from area of interest,
- Distance from secured base,
- Characteristics of regolith
- Etc.

Visualization of these data can be added with colored maps, satellite's orbits, rover trajectory, or habitat model. Accede to these data in the tool enable creation of new functionalities.

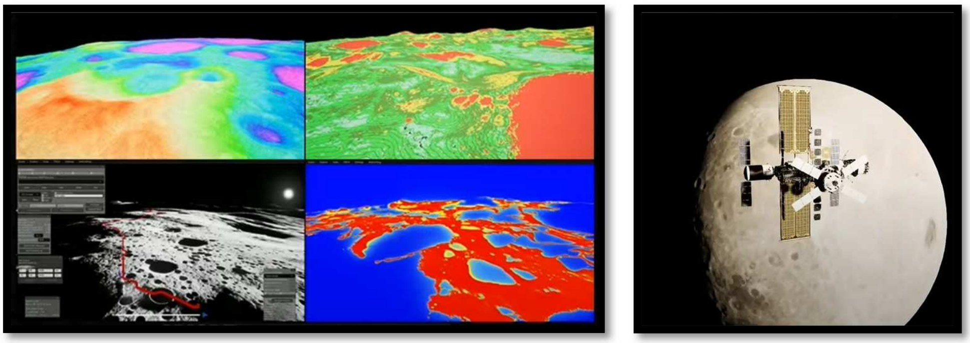


Fig. 15. Visualization of various data [15-16].

3.2 *Use of Hyper Datacube*

Spaceship France team guesses that hyper datacube integrated in digital twin of the Moon will be useful for planning and mission design, and for operations execution.

3.2.1 *Planning and Mission Design – Exploration with a rover*

Spaceship France team imagined to execute surface explorations thanks to an autonomous navigation rover with solar panels driving at 15 km/h. Tool is used to plan lunar missions for long range rover explorations. Moon digital twin tool helps to find optimal path taking into account slope, rover cannot drive if slope is more than 20°, and illumination necessary for power. As shadows are avoided, we call this functionality "Sun highway". Tool uses hyper datacube to generate illumination and slope maps and algorithm A* to compare different paths to find the shortest one between starting and final point. This chosen algorithm guaranties that the found path is the shortest one, manages very large areas, is very well documented and already used in robotics activities.

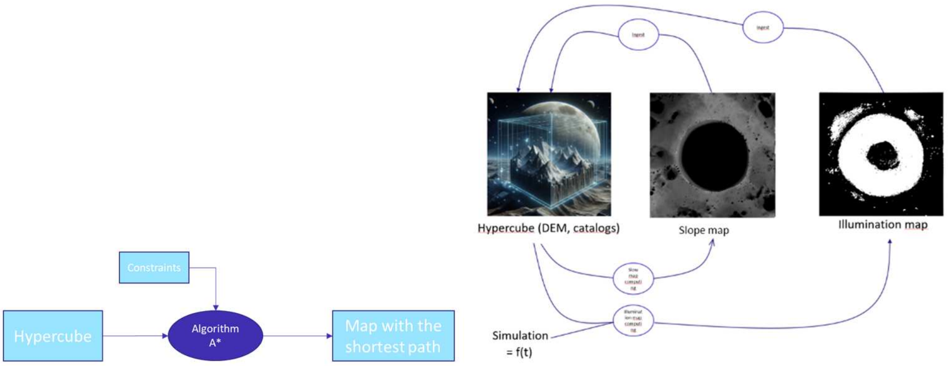


Fig. 16. “Sun Highway” functionality concept

Four principles drive the decision:

- Principle 1: slope is taken as a constraint: A* never choses a path if slope is upper than a maximum;
- Principle 2: illumination mean is taken as a constraint for a given duration: A* never choses a path if the illumination mean is too low;
- Principle 3: Slope is taken as a cost: A* choses lower slope even if distance is increased;
- Principle 4: Illumination is considered as a cost: A* choses a path with a better illumination mean even if distance is increased.

Principles 1 and 2 are always compulsory. User can chose to apply principle 3 or 4 or both for calculations. For each point of the surface hyper datacube contains slope, illumination and path data. A map can be generated (see Fig. 17). Tool’s interface enables adding intermediate points to simulate stops for Science or powering (see Fig. 18).

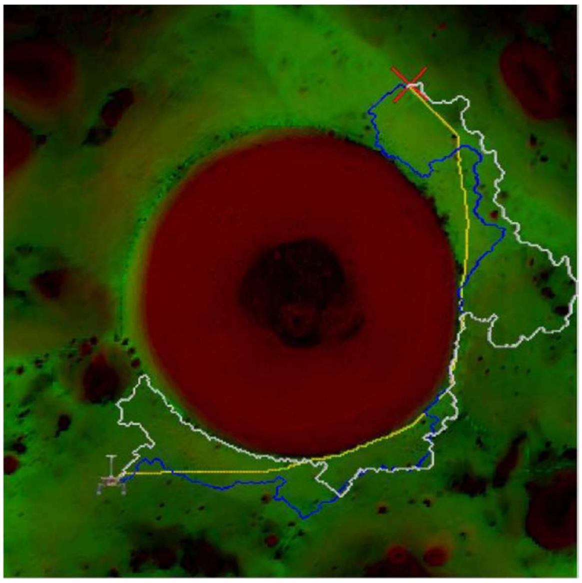


Fig. 17. Generated map containing information on slope and illumination at a given date – the greener the pixel, the higher the illumination; the redder the pixel, the higher the slope. 3 different paths are displayed: the shortest path in yellow (only principle 4 applied), lowest slope always chosen for the white path (only principle 3 applied), blue path is generated taking into account both slope and illumination costs (both principles 3 and 4 applied).

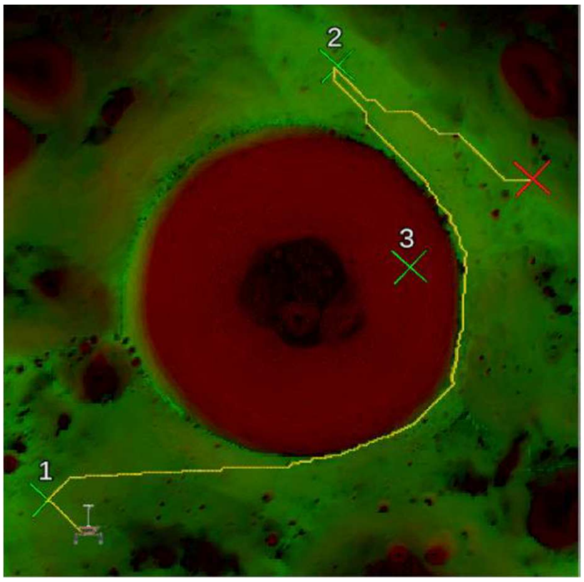
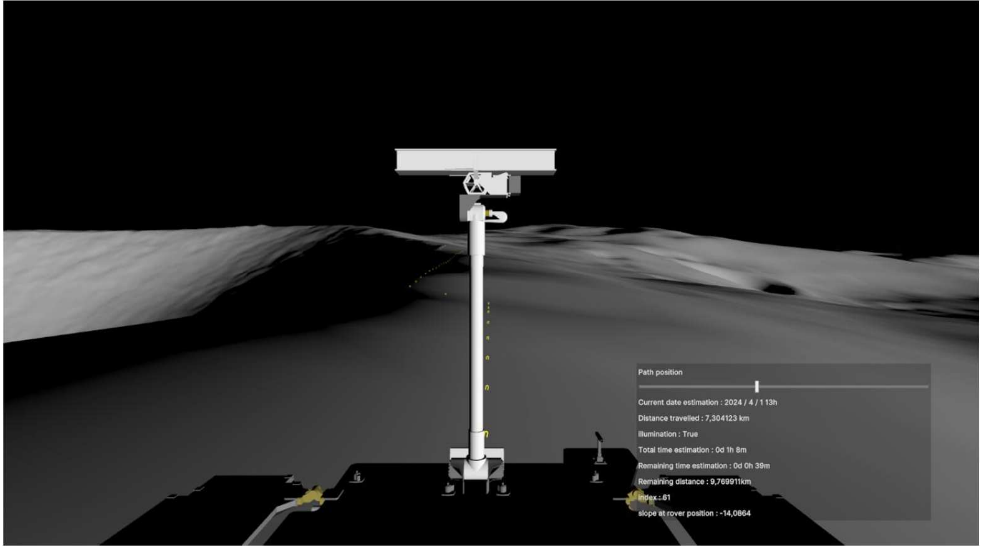


Fig. 18. Path with intermediate point – point 3 is not reachable because of too high slope

When path is generated on a 2D scene, it can be transformed into JSON format and exported to generate a 3D scene to visualize rover driving. Path is indicated on the surface and different data are displayed: local slope, number of kilometers until final point, illumination, etc. It helps mission preparation team to adjust the path if necessary.



Current date estimation : 2024 / 4 / 1 13h
Distance travelled : 7,304123 km
Illumination : True
Total time estimation : 0d 1h 8m
Remaining time estimation : 0d 0h 39m
Remaining distance : 9,769911km
index : 61
slope at rover position : -14,0864

Fig. 19. 3D model to visualize rover path

3.2.2 *Planning and Mission Design – Lunar Base location*

Sunshine simulations were used to help sizing electrical architecture of LISE habitat following its location on the surface of the Moon.

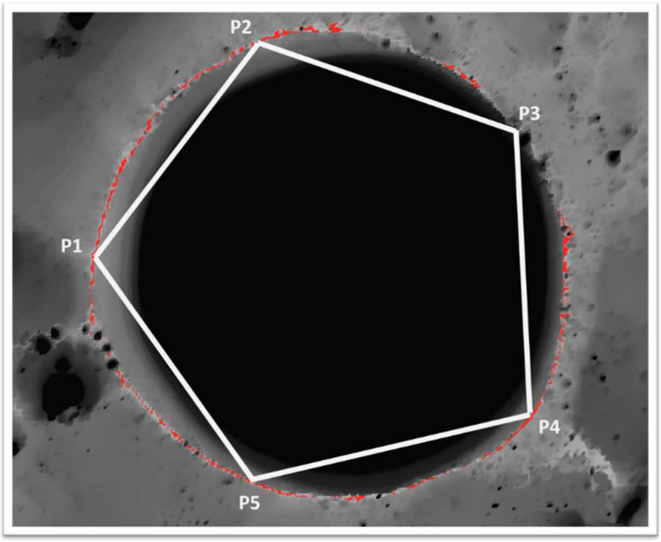
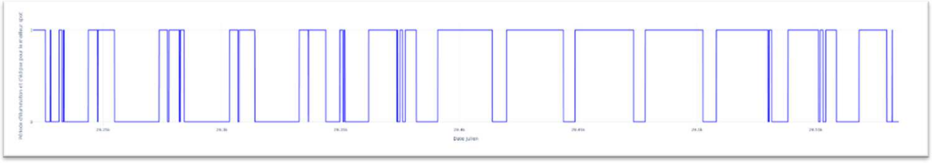


Fig. 20. Preliminary study of LISE locations

The requirement for a LISE module every 10 km resulted in the selection of five locations, as depicted in the image above. The locations highlighted in red indicate where the sunshine exceeds 70% during the year period. The selection of the five LISE locations was based on the highest sunshine level at the first point, P1. At each location, a CSV file containing all the data on the sun and its position was stored.

Worst case



Best case

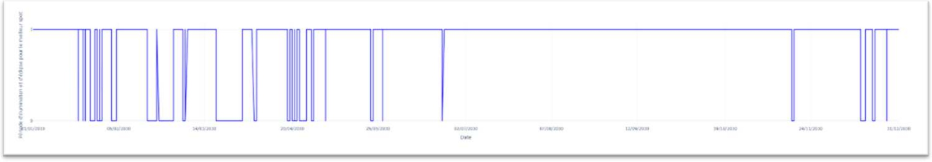


Fig. 21. Sunshine location's data

Each location corresponds to a graph representing the amount of sunshine received. In the provided image, the location P5 represents the worst case scenario while P1 represents the best. The period has been measured is one year, a 1 on the Y axis indicating the presence of light and 0 indicating the absence of light. It is worth noting that there appears to be an inversion between the first and second semesters in the worst case scenario. The first semester has less shadow in the best case than the worst one, but during the second semester, it is almost always enlightened. This makes it the ideal period for a LISE module to operate, given the cyclic nature over a year. To confirm this hypothesis, the ephemeris had been simulated over 10 years on the best case.

Fig. 22. Sun cycle over 10 years - Note that a full cycle of the Moon around the Sun is about 354 days

Thanks to this simulation, it is much easier to observe the sunshine cycle. However, it is important to note that although it appears to be cyclic, there are variations between years. This information is accurate enough for a preliminary study to begin sizing LISE's batteries and solar panels. This first step opens the door to complex mission analysis for installation placement close to area of interest (e.g. in-situ resources) according constraints (temperature, illumination, …). Hyper datacube contributes to superpose layers of data to constitute habitability map.

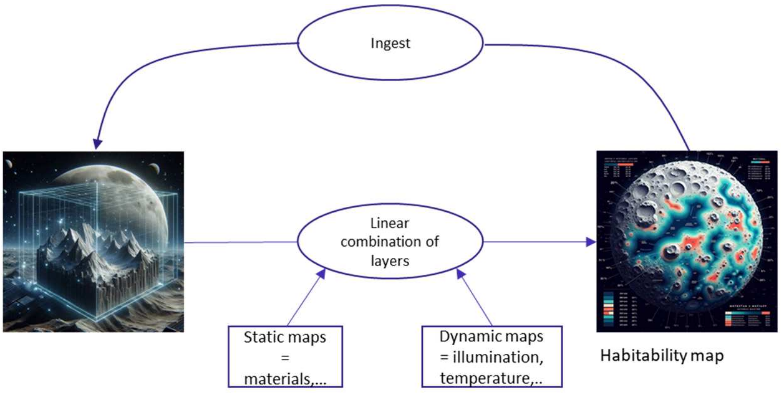


Fig. 23. complex mission analysis for installation placement concept.

4 Discussions

Hyper datacube fed by static maps, infrastructure 3D models and results from different simulation can be used to generate virtual environment for prototyping and people training.

In the context of lunar base prototyping, Virtual Reality (VR) immersion becomes important to the unique challenges and requirements of building on the Moon. Hyper datacube can contribute for:

- Enhanced visualization in a lunar environment: VR provides a realistic simulation of the lunar environment, including the low-gravity conditions, lighting, and surface textures. This allows architects, engineers, and astronauts to visualize and experience the building in its actual context. It helps in understanding how the building interacts with the harsh lunar environment, including temperature extremes, radiation, and micrometeorite impacts.
- Improved design accuracy and feasibility: VR allows for accurate spatial visualization, helping designers understand the spatial requirements and constraints of living and working on the Moon. This is crucial for optimizing space usage and ensuring functionality in a confined environment. Designers can make real-time adjustments to the prototype, instantly seeing the effects of changes, which enhances the iterative design process and leads to better, more refined outcomes.
- Early detection of anomalies: VR immersion helps in identifying potential design flaws or issues that may not be apparent in traditional 2D or 3D models. This includes ergonomic issues, accessibility challenges, and unforeseen interactions with the lunar environment. It enables thorough safety evaluations, ensuring that the design meets all necessary safety standards for human habitation on the Moon.
- Effective communication and collaboration: VR provides a powerful tool for communicating design concepts to stakeholders, including mission planners, engineers, astronauts, and funding agencies. It allows all parties to experience and understand the design, facilitating better feedback and collaboration. Teams located in different parts of the world can collaborate in a shared virtual environment, making it easier to work together on complex projects despite geographical barriers.
- Training and preparation: VR can be used to train astronauts on the layout and functionality of the lunar base before they arrive, ensuring they are familiar with the space and can operate effectively from day one. It allows for the simulation of various operational scenarios, including emergency procedures, resource management, and day-to-day activities, helping to prepare astronauts for life on the Moon.
- Cost and resource efficiency: VR reduces the need for multiple physical prototypes, which can be costly and time-consuming to produce, especially for lunar projects. This leads to significant cost savings and faster development cycles. By refining designs in a virtual environment, project teams can optimize the use of materials and resources, which is particularly important for the logistics of lunar construction.
- Psychological and Ergonomic Testing: VR allows for the testing of human factors and ergonomics in the design, ensuring that living and working spaces are comfortable and conducive to the well-being of astronauts. It provides insights into the psychological impact of long-term habitation in a confined and isolated environment, allowing for the design of spaces that promote mental health and well-being.

Virtual Reality (VR) immersion for lunar exploration training offers numerous benefits that enhance the preparation, safety, and efficiency of missions. Hyper datacube can contribute for:

- Realistic Environment Simulation: VR can create highly detailed and realistic simulations of the lunar surface, allowing astronauts to familiarize themselves with the terrain and conditions they will encounter. Trainees can interact with the virtual environment, practicing tasks such as navigation, equipment handling, and scientific experiments in a setting that closely mimics the actual lunar landscape.
- Safety and Risk Reduction: VR can simulate potential hazards such as rough terrain, dusty environment, or equipment malfunctions, allowing astronauts to practice recognizing and responding to these dangers in a safe, controlled environment. Trainees can practice emergency procedures, such as dealing with life support system failures or medical emergencies, without the risk of real-world consequences
- Operational Readiness: VR enables astronauts to rehearse entire missions, ensuring they are thoroughly prepared for each phase of the mission. Astronauts can repeatedly practice specific procedures, such as deploying scientific instruments or collecting samples, to build muscle memory and confidence.
- Enhanced Learning and Retention: The immersive nature of VR can improve learning outcomes by providing a hands-on, engaging experience that is more effective than traditional training methods. VR helps trainees develop a strong sense of spatial awareness and orientation, which is critical for navigating and working on the lunar surface.
- Team Coordination and Communication: VR can simulate team-based scenarios where astronauts must work together, improving their coordination and communication skills in a virtual environment. Team members

can train together in VR even if they are geographically separated, facilitating collaboration and joint mission planning.

- Flexibility and Cost-Effectiveness: Training scenarios can be easily modified and customized to reflect different mission objectives, challenges, and environments. VR training can reduce the need for expensive physical mockups and simulations, as well as travel costs associated with centralized training facilities
- Continuous Improvement: VR systems can track and analyze trainee performance, providing valuable data to identify strengths and areas for improvement. Trainers can provide immediate feedback and adjust training scenarios in real-time to address specific learning needs and ensure continuous improvement.
- Psychological Preparation: VR helps astronauts acclimate to the isolation and confinement of space missions, as well as the unique visual and sensory experiences of being on the Moon. Simulating high-pressure situations in VR can help astronauts develop effective stress management techniques and build resilience.

For operations we can imagine to use hyper datacube gathering data from different sensors interfaced with different model and simulation to provide continuous monitoring of the environment and infrastructure to detect and alert for potential hazards such as micrometeorites, radiations or technical failures. These data can be combined data stored in hyper datacube and with data from rovers' and spacesuits' high resolution cameras to update and improve DEM throughout the mission. This make automatic exploration possible with a fleet of rovers.

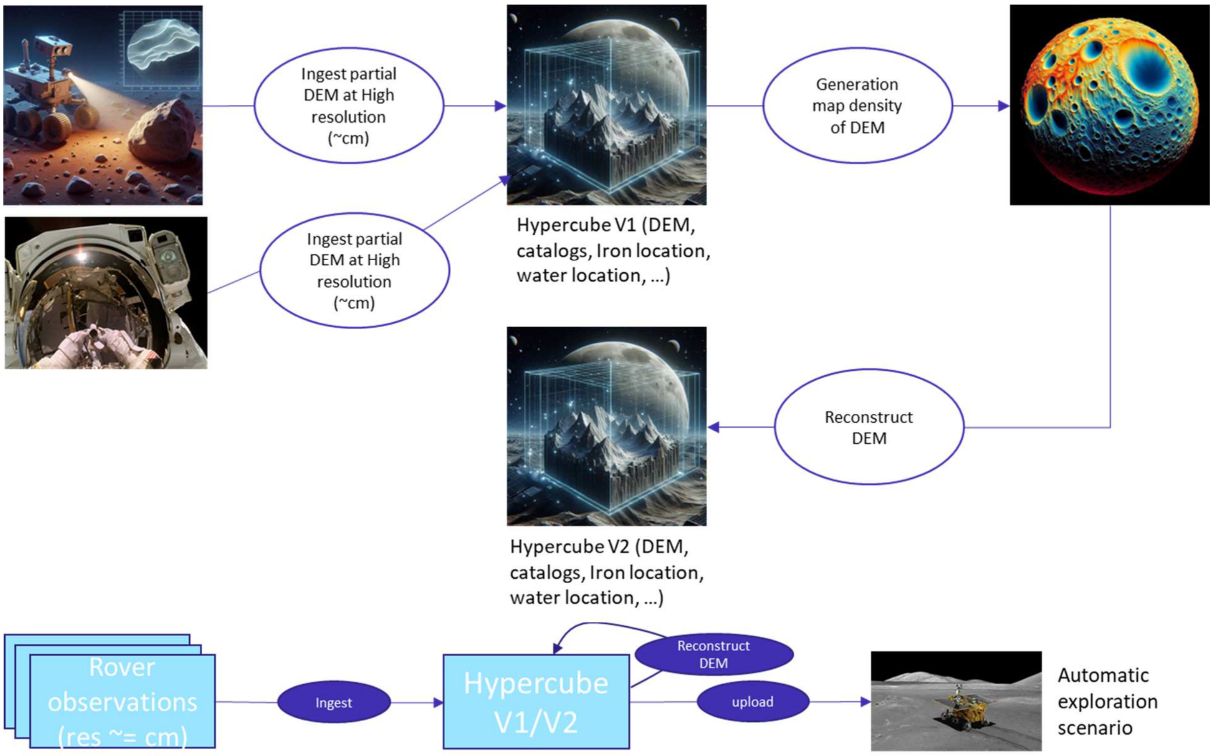


Fig. 24. Real-time updating of th hyper datacube by combining of data from different sensors and cameras.

Thanks to the hyper datacube, our project of lunar digital twin tool offers more opportunities to improve the efficiency and precision of mission preparation, and to increase the autonomy of astronauts and rovers in carrying our surface operations. It can contribute for:

- Site reconnaissance and selection: providing precise maps of the lunar surface to identify the most suitable sites for establishing a base, considering topography, soil composition, and sunlight exposure, and enabling analysis of local conditions such as temperature, radiation, and day-night cycles to choose a location that maximizes safety and efficiency for the base.
- Assessment of local resources: enabling identification and quantification of available resources, such as minerals, metals, and water ice, which can be used for construction, fuel production, and life support, and

studies of properties of the lunar soil (regolith) to evaluate its utility for building structures and growing plants using regolith-based techniques.

- Support for infrastructure: enabling installation and maintenance of sensor networks to monitor environmental conditions and the health of the base, and making it efficient to assemble and install base modules, solar panels, communication antennas, and other essential infrastructure.
- Logistics and maintenance: planning and monitoring of transportation of equipment, spare parts, and construction materials between different points of the base or to sites of interest, and supporting regular inspections and repairs on base infrastructure to ensure proper functioning and durability.
- Support for human habitation: helping preparation of the site before the arrival of human missions by building temporary shelters, storing essential resources, and testing life support systems and providing continuous monitoring of the environment and infrastructure to detect and alert for potential hazards such as micrometeorites or technical failures.
- Ongoing scientific research: supporting execution of scientific experiments to study the lunar surface, the impact of the lunar environment on equipment and materials, and the possibilities of life beyond Earth and providing data and logistical support for scientific missions conducted by astronauts or other rovers.

5 Conclusions

Spaceship France team has developed the first building blocks of a software tool with the ambition of creating a digital twin of the Moon in the near future. To achieve this objective, the concept of hyper datacube was invented to bring together data from different origins that vary over of time. A mock-up based on Unity graphics engine demonstrated its feasibility. By using a realistic 3D environment coupled with realistic ephemeris, preliminary studies become more accessible and easier to conduct. This simulation can already be used for preliminary studies, such as assessing the sunshine on the LISE module and planning exploration way for a rover.

After some feasibility tests, it was recently decided to use Unreal Engine graphics engine because it enables use of double precision which enlarge the surface of the simulation to the solar system size, use of C++ language which make easier plug to scientific tools and use of Nanite (an Unreal tool) thanks to which we can display millions of polygons without loss of performance. At the time, Spaceship France team is working on defining the roadmap for the development of this tool which will be useful for mission planning and operations support for the lunar exploration.

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