3D Geoinformation-Based Modelling of Interests on Space Exploration

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Abstract

Today, with the rapid development of space technologies, the number of missions and research on celestial bodies is increasing. Space missions to a number of celestial bodies, such as the Moon and Mars, are being planned by countries. In this context, studies and discussions continue on issues such as property rights related to celestial bodies and, in this context, how to use different resources such as minerals and how to regulate the restrictions needed for different purposes such as the space heritage. Today, there is a need for studies that will contribute to the interoperability between applications, researchers and institutions, based on data modelling, in order to establish an international business framework on the subject. In this direction, this study aims to initiate an approach that will allow the creation of three-dimensional (3D) digital models of physical objects and logical spaces in the context of possible interests that may exist on the surface of celestial bodies or underground, by extending the open geodata standard, namely CityJSON in this sense. A CityJSON dataset that encompasses the selected cases containing the craters and locations that cover possibly water on the lunar south pole is created, and then it is visualised in different tools. The initial results are expected to contribute to increasing the efficiency in planning of scientific research missions to celestial bodies and to the establishment of legal frameworks to be developed for the equal utilisation of space resources.

1. Introduction

There are agreements and declarations issued by the United Nations (UN) regarding space exploration carried out by different countries. The "Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space" was first published in 1963 (UN, 1963). The content of this declaration emphasizes that the exploration and use of outer space should be carried out in a way to benefit all humanity. It also states that all countries can benefit from outer space and celestial bodies equally and in accordance with international law. It is also stated that outer space and celestial bodies cannot be allocated to one nation in any way. The Declaration states that the outer space-related activities of countries can be carried out in accordance with international law in order to establish global peace and security and to maintain global unity and understanding. The "Outer Space Treaty" (OST-Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies), which was prepared for a similar purpose and published in 1967, emphasizes that exploration, including the Moon and other celestial bodies, can be carried out by all nations, regardless of their economic or scientific rank, in a manner that contributes to global benefit (UN, 1967). The 1979 "Moon Agreement" (Agreement Governing the Activities of States on the Moon and Other Celestial Bodies), also known as the Moon Treaty, contains the rules to be followed by all nations for the peaceful conduct of lunar exploration (UN, 1979). This treaty also recognized that the Moon and its natural resources are the common heritage of all mankind.

Today, there is an increasing trend for space exploration, which should be planned and carried out in line with the abovementioned declarations (ESPI, 2023). Consecutively, the amount of existing data about celestial bodies such as the Moon has increased. In addition, there is a tendency for exploiting the digital modelling approaches in the sense of planning of future missions. For example, future lunar exploration sites can be examined digitally beforehand (Bingham et al., 2023). The data resource, especially geoinformation, is highly critical to enhance the efficiency of these approaches. However, there is a lack of providing an interoperable geoinformation that can be useful for studies related to space exploration. Therefore, this research brings forward an approach that includes extending the core schema of geoinformation-based standard in a way to enable modelling of different interests on celestial bodies as reusable three-dimensional (3D) digital models.

2. Background

2.1 Modelling of Interests

As mentioned above, a long period of about fifty years has passed since the adoption of the aforementioned declarations and treaties. In recent years, however, space exploration, particularly of the Moon, has led to the study of various approaches to space law. In this context, the study of property related to the celestial bodies such as the Moon occupies an important place among the frequently studied issues (Becerra, 2017; Depagter, 2022; Yomralioglu, 2024). Research on this subject has not yet reached a consensus. The "Spurring Private Aerospace Competitiveness and Entrepreneurship (SPACE) Act", which was passed in the United States in 2015, has also been part of the debate on this issue. This is because it legally authorises US citizens to engage in commercial exploration and commercial extraction of space resources, including water and minerals, but excluding biological life.

In addition, growing awareness of the rapid depletion of natural resources on Earth has shifted the focus of scientists and investors to so-called "asteroid mining", the extraction of raw materials from asteroids and other small planets, including near-Earth objects (Iliopoulos & Esteban, 2020). Asteroids are thought to contain valuable resources as they can be rich in various elements such as neodymium, scandium, yttrium, iridium, platinum, palladium, gold and silver (Andrews et al., 2015). Various

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approaches and models have been proposed for the successful and economically beneficial realisation of such discoveries (Hein et al., 2020). There are also different perspectives on this issue in the literature, arguing that space mining is beneficial or harmful. One of the positive perspectives is that the elements mentioned are rare on Earth and have the potential to cover and even exceed the high costs of space mining expeditions.

A very important issue at this point is that there is still no consensus on who will exploit the benefits obtained as a result of mining, in what proportion and in what way, and there is no legal basis (Butkevičienė & Rabitz, 2022). For this reason, one of the needs for modelling is related to modelling of possible legal interests on celestial bodies such as the Moon and Mars. This modelling is carried out in the context of land management on Earth. More specifically, most of the countries use land administration systems to manage the cadastral works and the land registry. These systems are widely based on the use of two-dimensional (2D) data and approach. However, there is a growing interest for improving the capability of these systems in a way to manage 3D datasets in the sense of legal interests in order to overcome the challenges that are due to the increased complexity of the built environment (Guler & Yomralioglu, 2022).

Another issue that has been discussed in relation to space exploration is the preservation of cultural and historical remains in space (Walsh, 2012). Similar to the preservation of historical heritage on Earth, efforts are being made to record and preserve existing structures and remains in space exploration, and currently in lunar exploration. Although cultural heritage is not specifically mentioned in the scope of the OST, for example, a report published by the National Aeronautics and Space Administration (NASA) in the USA recommended the establishment of protected areas with a radius of 2 km around the landing sites of previous space missions such as Apollo and Surveyor, and 0.5 km around the impact areas of missions such as Ranger. It was also recommended that the Apollo 11 and 17 landing sites should be given special and strict protection as they were the first places in history where mankind set foot on the Moon (NASA, 2011).

2.2 Standards

As mentioned, the standards are highly important for enabling the interoperability, especially from the data perspective. In this sense, there are widely used data standards to create digital models of the built environment. These models are now generated in 3D to efficiently perform the decision-making mechanism from various application fields such as disaster management, land use planning, cadastre and land registry, and energy demand estimation (Lei et al., 2023). While the domain of 3D geoinformation deals with obtaining the digital representation of both physical objects and logical spaces for large scales such as districts and cities, Building Information Modelling (BIM) interests the lifecycle management of buildings/facilities through their significantly detailed digital models (Kolbe & Donaubauer, 2021).

CityGML is a well-known open data standard that provides the data schemas that include the relationships about the features to create the semantic city models (OGC, 2021). Industry Foundation Classes (IFC) is the data standard to form the Building Information Models (BIMs) in standardized and exchangeable ways (buildingSMART, 2020). The core schemas of both standards can be enhanced to enable the 3D modelling of objects and/or spaces related to the different application areas, for example, energy modelling. In this study, the use of 3D geoinformation is considered more suitable for modelling of interests on space since they might be covering highly large areas such as craters. In addition to CityGML, another standard called CityJSON is proposed as JSON-based encoding of the data model of CityGML in order to ease the usability of the 3D semantic models and improve the implementation capability in terms of software development (Ledoux et al., 2019). The standard is efficiently utilised by a number of researchers from a wide range of topics such as examining the morphology of the cities in 3D and improving the storing and usability of 3D datasets with NoSQL-based database implementation (Labetski et al., 2023; Nys & Billen, 2021). CityJSON also has an extension mechanism that is used to enhance the applicability of the 3D models for several application fields such as energy, land administration, and spatial planning (Guler, 2023, 2024). There are two levels of objects in the core model of CityJSON as can be seen from Figure 1. The relationship between first and second level objects is realized by children and the parent properties that are assigned to objects. For example, a *BuildingPart* instance should have a relation with a *Building* instance based on the core schema of the standard.

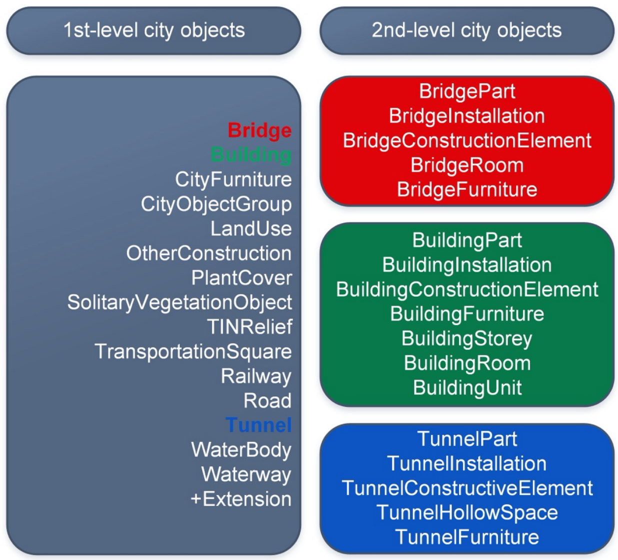

Figure 1. The city objects within the core model of CityJSON.

The core model of CityJSON can be extended in several ways, for example, by adding a new city object. In addition, the rules that are defined by the developers should be followed when creating an extension to the standard. For instance, it is allowed that the new city object should be added such that it has a new city object as a child rather than adding a new sub city object to the existing city object (OGC, 2023).

3. Developing the Extension

In this study, an initial extension is proposed for enabling the usability of datasets regarding the analyses and supporting the decision making in the sense of space exploration. This extension that is developed based on the aforementioned rules can be seen in Figure 2. There are two extra city objects, namely *+SpaceObject* and *+SpaceRestriction*. *+SpaceObject* is modelled as a subclass of *_AbstractCityObject* in which all city objects in the core schema such as *Building* are derived. First extra object can be used to model different kind of physical objects and their related logical spaces. For example, possible landing sites that are decided for planned space missions can be modelled in 3D as an instance of *+SpaceObject*. As in Figure 2, this feature has a number of attributes to store different semantics and enrich the usability of the datasets. For instance, information regarding state can be stored to show the current state of the object, such as planned or existing. *partyName* includes the information regarding who is responsible for the space object. The space agency that carries out the planned mission can be given as an example. Second one can be used to model the different restrictions with regards to space explorations. This object has a *restrictionType* attribute to store the information on various types of restriction, for example, areas that are decided to preserve as historical sites. Also, it provides the information on the value of the restriction. For example, the size of the buffer that is determined to protect the historical site can be stored via *restrictionValue* attribute.

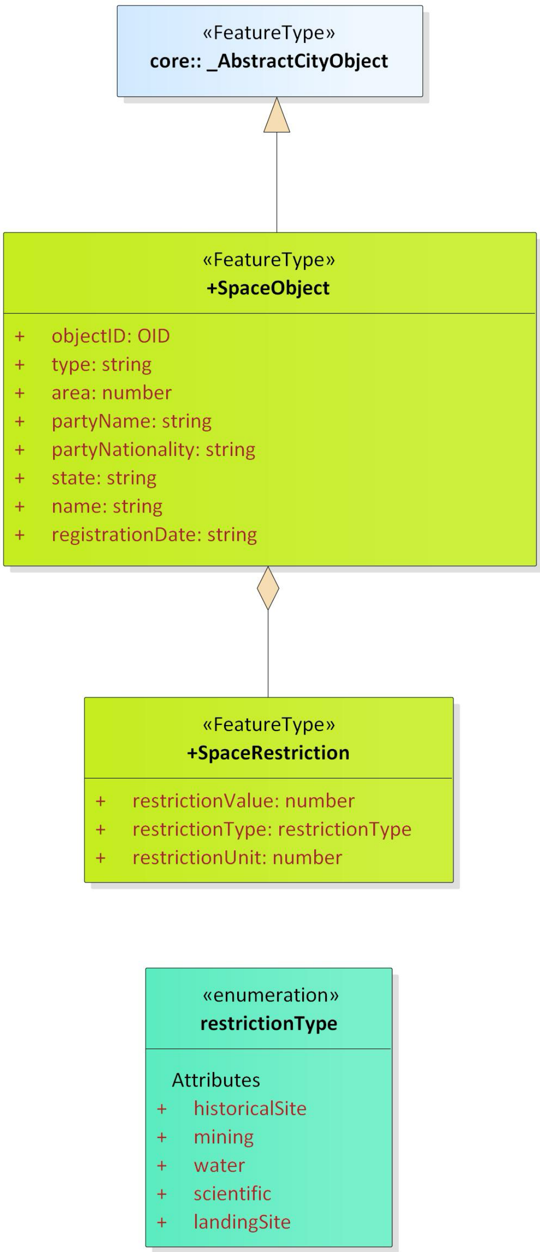

Figure 2. The content of the developed CityJSON extension.

4. Demonstration

The CityJSON dataset that covers the spatial information and semantics about the simple cases is created based on the developed extension. In this research, a part of the lunar south pole is selected as a study area. One reason for this is that there is scientific evidence that shows the existence of water in different parts of this area. The existence of several craters that can be delineated as space objects is another reason for the selection of this area. In this study, some of the locations that show the existence of water shared by Reach et al. (2023) is selected for demonstration purposes. In addition, four craters, namely Newton, Manzinus, Schomberger, and Boguslawsky, are included in the demonstration case. First, 2D spatial data that encompasses the geometry and attributes regarding the selected craters and water locations is generated. Figure 3 includes the visualization of this dataset.

The dataset that is produced based on the observations of the Lunar Reconnaissance Orbiter Camera (LROC) is used as a base map. The dataset is titled "WAC South Pole Summer Mosaic" and it can be downloaded freely (https://wms.lroc.asu.edu/lroc/view_rdr/WAC_ROI_SOUTH_SUMMER). This dataset is a mosaic that covers the south pole and is generated by using the observations from specific dates to overcome the shadowing, which hinders creating the maps (Speyerer et al., 2020).

It can be noted that the shapes of the craters are determined by the author of this paper based on the figures in the references from the literature for demonstration purposes and they should not be considered as significantly accurate (Sinha et al., 2025). Similarly, the dataset representing the water existence is formed based on the figures in the Reach et al. (2023) and it should not be accepted as correct. The coordinate system of the mosaic dataset is polar stereographic projection and it is reprojected to ESRI 103878 projection, which is titled "Moon 2000 South Pole Stereographic", in order to prevent inconsistency with regards to defining the coordinate system within the CityJSON file.

The aforementioned 2D spatial data is converted to the CityJSON dataset by using the created workflow within the Feature Manipulation Engine (FME) software, as can be seen in Figure 4. This workflow gets the 2D spatial data formatted in GeoJSON as input and then creates 3D models. It generates extrusion for craters based on provided value as an attribute and applies 3D buffering for water locations with the purpose of preserving. The workflow then writes a CityJSON file such that it contains instances from *+SpaceObject* and *+SpaceRestriction* objects. The FME Workbench 2022.1.3 is used to create the workflow. This version is able to write CityJSON v1 only. Since the CityJSON has v2 and the extension is developed based on the specifications of this version, the output CityJSON file is converted to CityJSON v2.0 using the *cjio* that is developed to manipulate CityJSON files (https://github.com/cityjson/cjio).

The created CityJSON file is first visualised using *Ninja* that is a web-based platform as the official visualisation tool of the standard (https://ninja.cityjson.org/#). Figure 5 contains the visualisation of selected instances belonging to *+SpaceObject* and *+SpaceRestriction* objects. As can be seen from the figure on the left, the attributes such as *name* and *type* are stored within the instance that expresses the Newton crater with gained extrusion. Figure on the right shows the selection of an instance pertaining to water area on lunar south pole. The attributes such as *restrictionType* can be also seen from the figure. Figure 6 presents the visualisation of created CityJSON file within QGIS through CityJSON Loader plugin (Vitalis et al., 2020). The figure on top shows the view that is close to Newton crater and nearby water locations. The view that encompasses the all objects within created CityJSON file can be seen in the figure on bottom.

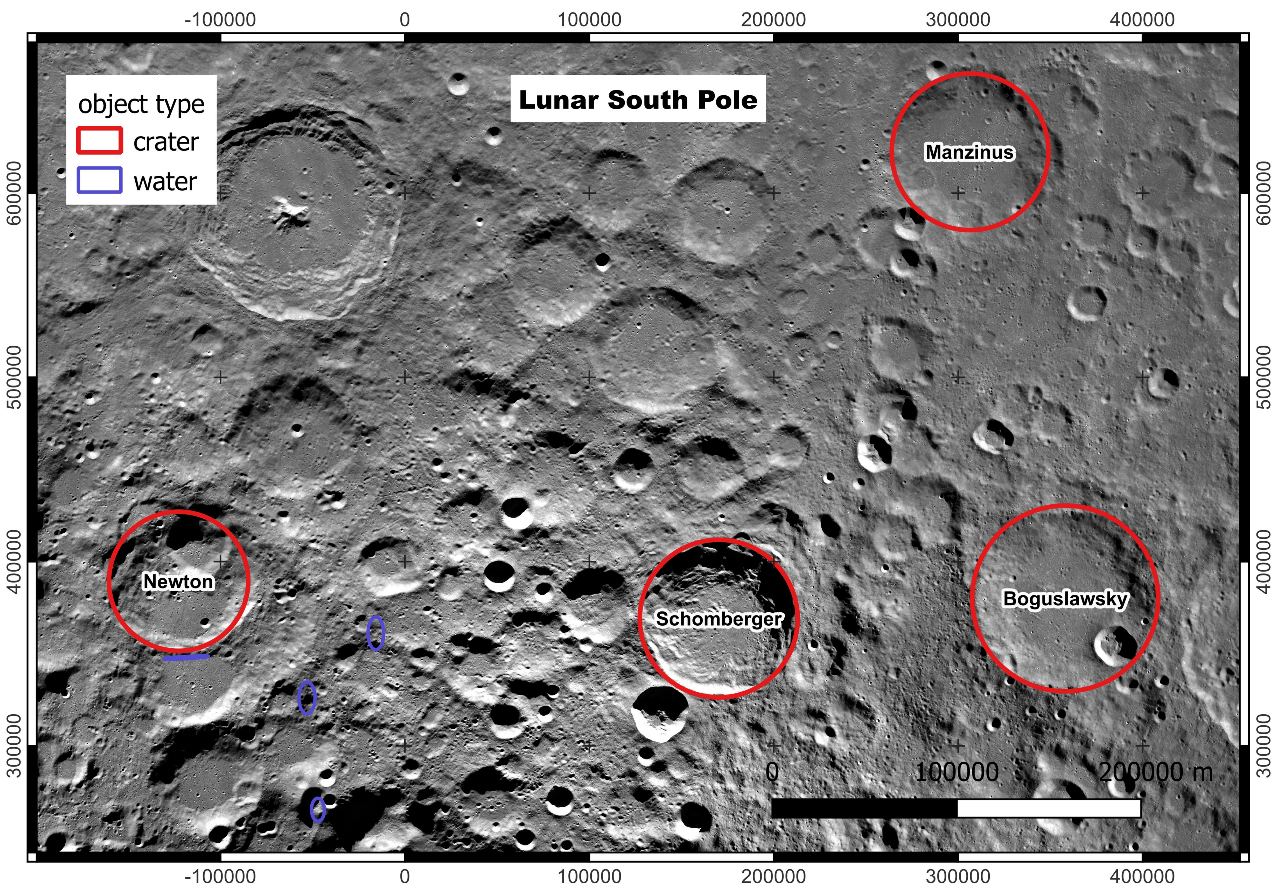

Figure 3. Map of the 2D spatial data.

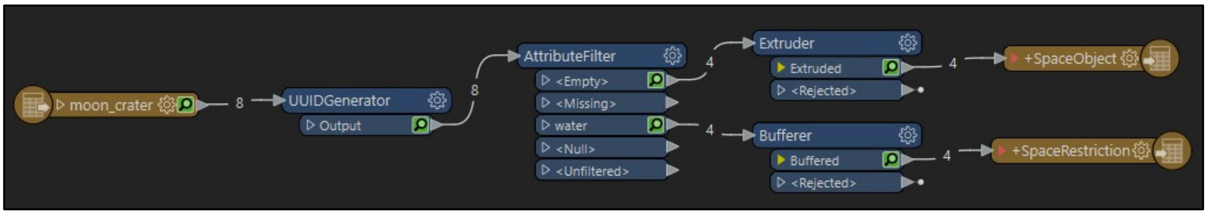

Figure 4. Developed workflow within FME.

Figure 5. Visualisation of the created CityJSON file within Ninja (left: a +*SpaceObject* instance, right: a +*SpaceRestriction* instance).

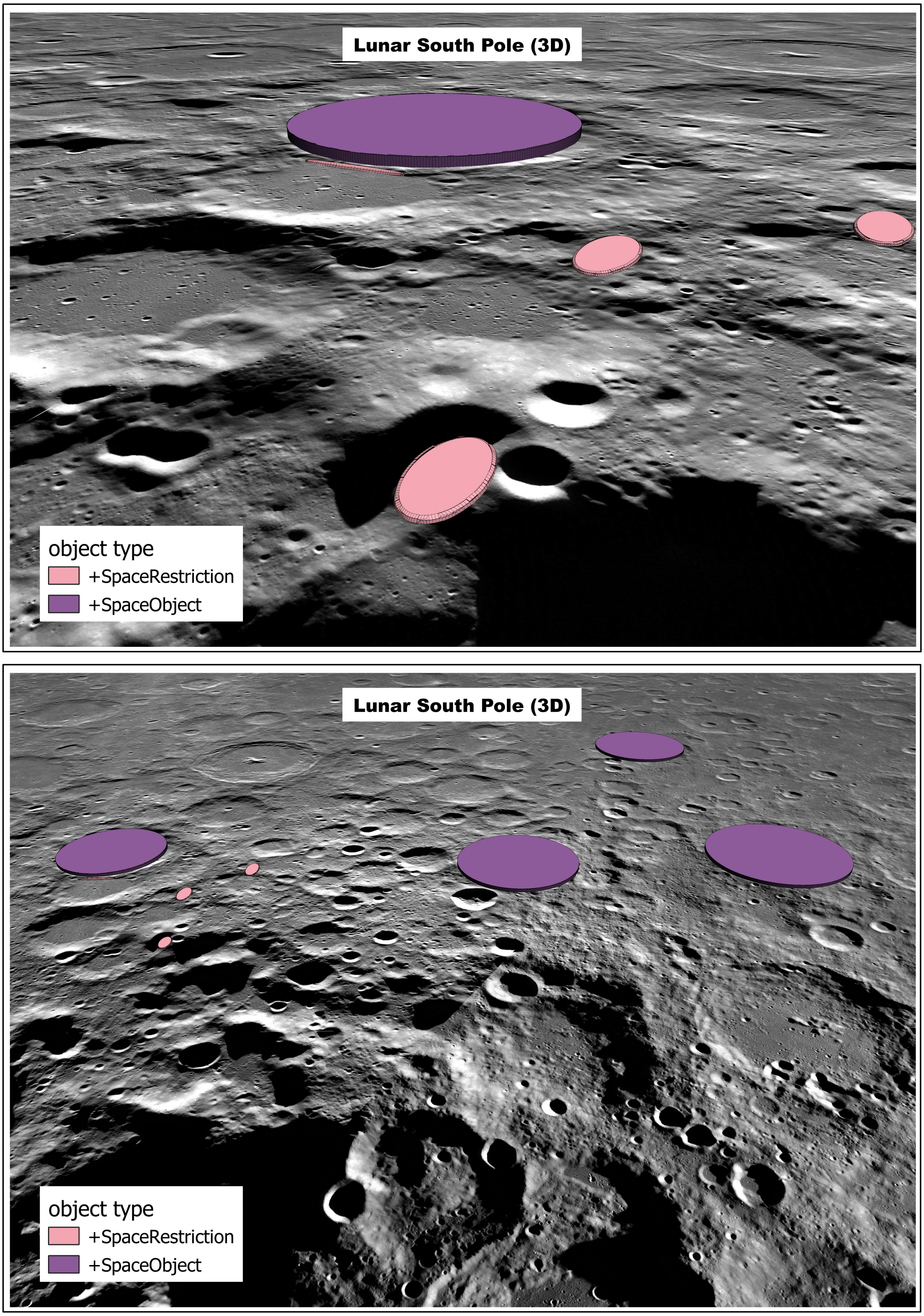

Figure 6. Visualisation of the created CityJSON file within QGIS from different camera views.

5. Discussion and Conclusions

This study extends the core schema of CityJSON standard in a way to provide a standardized data resource that can be used for 3D modelling of interests regarding space exploration. This is an important initiative because there exist recent studies that notably discuss how to manage property rights on outer space (Murnane, 2023). As provided in the literature, the extension that is proposed within this study can be further extended in this sense. Preserving space heritage is one of the significant topics that the developed extension can be beneficial since it provides a way for storing the data covering the information on heritage sites spatially, digitally, and 3D. In addition, different restrictions on these sites can also be defined and these restrictions can be modelled as 3D geoinformation, which is shown in Figure 6 as an example. Moreover, locations that possibly contain water on the Moon can be used when determining the sites for future lunar research station, for example. In this sense, a dataset that expresses these locations and that is created based on the defined data standard will be useful for decision making regarding planning of space exploration missions.

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