SELECTION OF LANDING SITES FOR FUTURE LUNAR MISSIONS WITH MULTI-OBJECTIVE OPTIMIZATION.

M. Nishiyama[1], H.Otake[2], T.Hoshino[2], T. Hashimoto[2], T.Watanabe[2], T.Tatsukawa[2], A.Oyama[2], [1]University of Tokyo, [2] Japan Aerospace Exploration Agency (JAXA).

Introduction: Since lunar explorers are exposed to harsh environment, landing sites of lunar missions must be selected taking surroundings into consideration. It would be preferable to search landing sites in terms of several requirements, such as length of continuous nights, communication difficulty with the Earth, terrain roughness, and water ice distribution. However, since these requirements are often incompatible, it has been tough to meet several objectives at the same time. For example, Rosa et al.[1] investigated landing sites on the moon in terms of illumination and terrain hazards, although this research considered each conditions separately. Besides, it did not consider communication between the moon and the Earth.

This research created a database of the amount of illumination, the period to be able to communicate with the Earth and the slope angle on the moon using terrain data obtained from Terrain Camera (TC), mounted on Japanese Selenological and Engineering Explorer (SELENE), and Lunar Orbiter Laser Altimeter (LOLA), mounted on Lunar Reconnaissance Orbiter (LRO). We used this database for selecting landing sites that satisfy several objectives with multi-objective optimization[2].

Methods: This paper dealed with four objective functions: minimization of continuous night length, minimization of inclination angles, maximization of the time that can communicate with ground stations during daytime and minimization of distance between a landing site and places where the water ice exists.

This research defined two constraints: One is that the angle of inclination must be below 15 degrees, in consideration of landing safety. The other is that continuous night length must be below 14 days, considered in terms of recharging batteries. The searched scope is within a radius of 300 kilometers from the south pole of the moon, and the searched period is from January 1st in 2019 to December 31st in 2020.

SELENE surveyed the surface of the moon by various sensors, and acquired detailed moon terrain data. We created moon database of illumination, communicable time and the angle of inclination that is within 300 kilometers with 10-meter resolution by a simulator which produced from the data of SELENE.

In this paper, the amount of sunshine was binarized whether the sunlight arrives at the point or not. Communicable time was binarized whether the Earth can be seen from that point or not. Both of the amounts of sunshine and communicable time were calculated by a ray tracing method in the simulator that uses Digital Elevation Model (DEM) created from TC and LOLA data. Moreover, the maximum angle of inclination within 10 meters was defined as the inclination angle of the point. This research defined the objective value of water ice distribution as the minimum product of distance and depth of water ice refered to [3] about water ice distribution on the moon.

Result and Discussions: 174193 feasible solutions that satisfied both constraints were found by a full search, and 14141 of them were selected as the multi-objective optimal solutions. Fig.1 shows that the multi-objective optimal solutions are plotted on the indexed plan within 300 kilometers around the South Pole of the moon. Yellow dots represent feasible solutions and blue cross-shaped dots are multi-objective optimal solutions.

As the Fig.1 shows, feasible solutions distribute either on the top of mountains or level ground far away from mountains. It is deduced that the sites on the mountainsides tend not to meet the inclination constraint, while the level even grounds near mountains violate the continuous night constraint due to the mountain shadows.

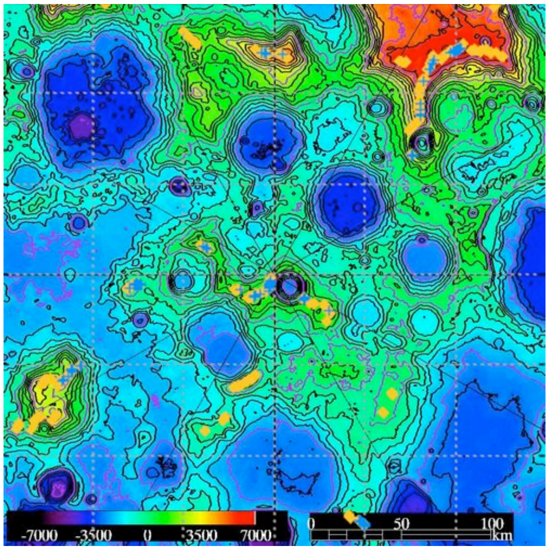

Fig.1 Landing sites distribution by full search. Yellow dots are feasible solutions that satisfied both constraints. Blue cross-shaped dots are multi-objective optimal solutions. These dots are plotted on the indexed plan within 300 kilometers round the South Pole.

Several multi-objective optimal solutions are located on the tops of mountains in the upper side of Fig.1. Its validaty is inferred from the fact that the upper side of Fig.1 is close to the Earth since the axis of the moon is inclined at 6.7 degree against the moon's path. Thus, the sites in the upper side of Fig.1 are advantageous in the viewpoint of communication between the moon and the Earth. Besides, the illuminative condition is better than other sites since there are less shadows on the peaks of mountains.

On the other hand, several multi-objective optimal solutions are located on around the South Pole. Since these sites are closer to craters that contain water ice in perpetual shadows than other landing sites, it is considered that these sites have an advantage in terms of searching water ice.

Next, Table 1 shows the multi-objective optimal solutions' the correlation coefficients between each objectives and Fig.2 shows its correlation diagrams. The better solutions that satisfy each objectives are located close to the origin.

Table 1. Correlation coefficient between each objectives

Objectives	Correlation coefficient
Nights & Communication	0.542318409
Nights & Inclination	0.114454062
Nights & Ice	-0.297914841
Communication & Inclination	0.290616518
Communication & Ice	-0.582380748
Inclination & Ice	-0.207657163

Table 1 shows the positive or negative correlateions between each objectives. Especially, there are strong correlations between the shortness of continuous night length and the length of communicable time, and between the length of communicable time and the water ice distribution. These relationships are shown in Fig.2, especially in the diagram of the correlation between continuous night length and the length of communicable time.

As the definition of the communicable time, we consider it is natural that there is a positive correlation between the shortness of continuous night length and the length of communicable time. In addition, the high score for the illuminative condition indicates that there are less obstacles near the site, which results in establishing good communication with the Earth.

As previously mentioned, the sites that have good communicable conditions also have good illumination conditions. Therefore, the negative correlation between the length of communicable time and the water ice distribution is caused by sunlight that evaporate water ice on the moon. With regards to the negative correlation between the angle of inclination and the water ice distribution, it is considered from the positive correlation between the shortness of continuous night length and the angle of inclination that slopes are exposed to sunlight that melts water ice. Besides, we suppose that water ice tend not to retain on inclined slopes.

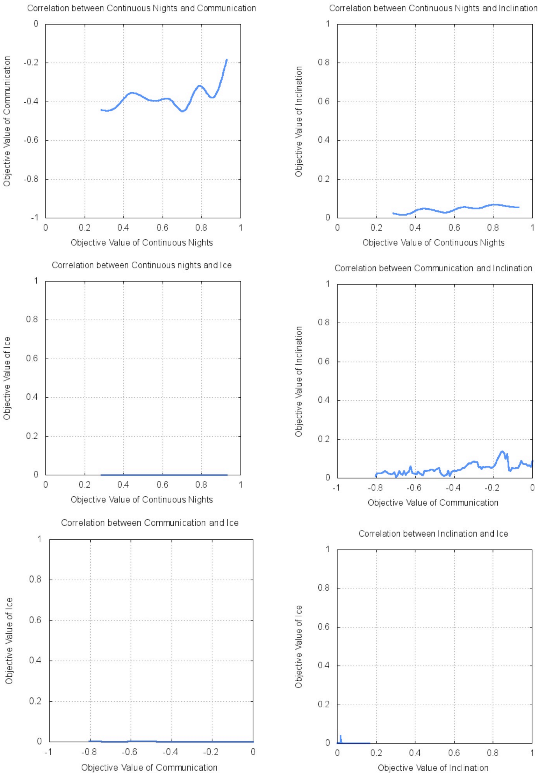

Fig.2 Correlation diagrams of each objective. The better solutions that satisfy each objectives are located close to the origin.

Conclusion: We utilized multi-objective optimization for selecting landing sites that satisfy four objectives: the continuous night length, the communicable time length, the angle of inclination and the water ice distribution. As a result, we succeeded to find several multi-objective optimal landing sites. We suppose that these selections of landing sites that consider both engineering and science aspects enable more significant lunar explorations.

References:

[1]D.D.Rosa et al. (2012) , Characterisation of potential landing sites for the European Space Agency's Lunar Lander project, *Planetary and Space Science,* 74, 224-246.

[2]K.Deb (2001) , Multi-Objective Optimization using Evolutionary Algorithms, *John Wiley & Sons, Ltd.*

[3] D. A. Paige, et al. (2010) , Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region, *Science,* 330, 479-482.