AN ANALYSIS OF ILLUMINATION AND COMMUNICATION CONDITIONS NEAR LUNAR SOUTH POLE BASED ON KAGUYA DATA

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ABSTRACT

This paper presents the analyses of the illumination and communication conditions at the lunar South Pole based on terrain models derived from the Kaguya Laser Altimeter, and discusses the implications for the landing site selection and system design with particular reference to the European Space Agency's Lunar Lander mission and its development through upcoming Phase B1 activities. Results show that there exist some locations at the lunar South Pole offering from 6 to 10 months of quasi-continuous illumination, although they are of quite small physical extent. For the most promising locations, the influence of several parameters is assessed, as well as the communication conditions.

1. INTRODUCTION

Past missions to the Moon, including those of Apollo and their precursor robotic missions, have landed at sites on the Moon at generally low latitudes, restraining the mission durations to a maximum of one Moon-day, i.e. 14 Earth-days. However, the characteristics of the Moon's rotation, orbit and topography combine to create quite different conditions at the lunar polar regions. The Moon's rotation axis is tilted by 1.54º with respect to the ecliptic pole; due to the existence of high mountains and crater rims near the polar regions, some locations with very long continuous light exist. Even though the Sun is below zero elevation for 6 months per year, local topography at specific sites can lead to several month-long periods of continuous illumination.

The European Space Agency (ESA) intends to capitalise on these unique illumination conditions for its first contribution to the international lunar exploration effort: a Lunar Lander. With a target landing site at the Lunar South Pole, this mission will demonstrate soft precision landing with hazard avoidance capabilities, and will embark a payload to prepare for future human exploration of the Moon. Based on the outcome of Phase A studies, the mission baseline for Phase B1 activities consists of a mission launched with Soyuz from *Centre Spatial Guyanais* in the 2018 timeframe, and in a design excluding the use of Radioisotope Heater Units (RHU) in the thermal control system. This decision has been made at a programmatic level considering a number of factors including the availability of RHUs in Europe, as well as the technical and cost impact on the mission. As a result the Lunar Lander mission scenario is strongly dependent on the surface conditions at the lunar South Pole.

The locations at the South Pole with long continuous illumination periods will help to mitigate the harsh thermal environment faced by the lander on the Moon's surface. They will also provide favourable conditions in terms of power since solar arrays will be illuminated over a much longer period than the nominal ~14 days experienced at non-polar locations. However, the physical size of the favourable zones has to be considered in order not to over-constrain the requirements on landing accuracy.

Beyond the illumination aspect, communication conditions also have to be taken into account. At the poles, the Earth describes an extended-eight shape in approximately 28 Earth-days, ranging between ±6.5 degrees over the horizon in elevation in a confined narrow azimuth band. Highly-elevated obstructing lunar terrain in the Earth direction should thus be avoided to ensure sufficiently long direct-to-Earth communication windows.

Where most previous studies of lighting conditions at the lunar poles [1], [2], [3], [4] focused on the percentage of time for which the site was illuminated over a given period, the parameter driving the design of the European RHU-less Lunar Lander is rather the precise pattern of alternation between light and darkness. Because of the freezing temperatures during lunar nights, the lander can only withstand short periods of darkness without requiring substantial additional battery capacity and its associated mass. The most favourable regions of the Lunar South Pole are thus those offering the longest duration of *continuous* illumination including only short periods of darkness.

In the lunar summer, for the example site shown in Fig. 1, there is a period of continuous illumination of several weeks disrupted only by 3 short darkness periods, e.g. of durations below 60 hours. If the spacecraft is designed such that it can withstand these 60 hours in darkness, it will survive during the entire

lunar summer. However it will not survive the upcoming lunar winter as the darkness periods become too long. This long period of near unbroken sunlight is termed the *longest continuous illumination period*, even if it contains short nights.

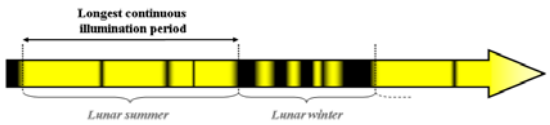


Fig. 1: Concept of longest continuous illumination period.

This study was carried out in support to the ESA Lunar Lander activity and is thus focused on this concept of continuous illumination periods filtering out short periods of darkness. It consisted of two major parts: a first global analysis at low resolution identified the most promising Regions of Interest (ROI), where higher resolution analyses were then carried out both in terms of illumination and communication conditions.

2. STUDY FRAMEWORK

The study has been performed using Satellite Tool Kit (STK) and Matlab software. The topographic data comes from the laser altimeter (LALT) instrument onboard JAXA's lunar orbiter Kaguya.

The data is a spherical-grid topographic data set around the lunar South Pole, referenced to the sphere of 1737.4 kilometres radius based on the gravity centre of the Moon. Grid resolution along latitude is 1/128 degree and for longitude is 1/64 degree. Matlab was used to convert the Kaguya raw data into PDS format files compatible with STK. For the preliminary analysis, 2 maps were created: a 500 m resolution map for latitudes further south than 85ºS, and a 1km resolution map for latitudes between 80ºS and 85ºS. Note that it is important to consider these latitudes as they contain high elevated terrain that may cast shadow on latitudes further south. For the detailed analyses, on top of the maps above, 200 metres resolution maps were created for each area of interest.

For the analyses, Matlab is used to control the STK simulation via the Connect module. Points of interest are given to STK which computes the Sun or Earth access history over one year. The condition for access is the presence of a direct line connecting the point of interest with the Sun or Earth centre, with no obstruction by the lunar terrain. The local horizon is computed by STK with a resolution of 0.5 degrees, considering the entire surrounding terrain with no range limitation. Matlab then post-processes the access history data in different relevant output figures.

The most important limitation of this study is the resolution of the input terrain data. The horizontal error of each LALT measurement is in the order of 270 m (3σ) [5]. The maps used in the study have been generated by sampling the original Kaguya terrain model, which was obtained by interpolating the LALT measurements on a predefined grid. It can be then assumed that the terrain elevation datum used for each point represents an average of the terrain elevation over the area enclosed in the corresponding grid element, with a vertical accuracy of few metres. Any large terrain feature (e.g. rocks) that is present within this area potentially has dramatic effects on illumination that could not be detected in this study.

Another limitation is the fact that the Sun's angular size is not considered. This implies neglecting partial illumination in the computation of the duration of the quasi-continuous illumination period. However, the duration of partial illumination periods should be accounted for with some conservative factor, since the incoming solar power is reduced.

3. PRELIMINARY GLOBAL ANALYSIS

3.1 Method

A first global analysis was performed using a reduced resolution in order to find potential areas with favourable illumination conditions with a reasonable amount of processing time. The analysed zone was constrained to a 300km-side square centred on the South Pole as this zone is believed to contain most of the promising terrain features of the Lunar South Pole region, see Fig. 2.

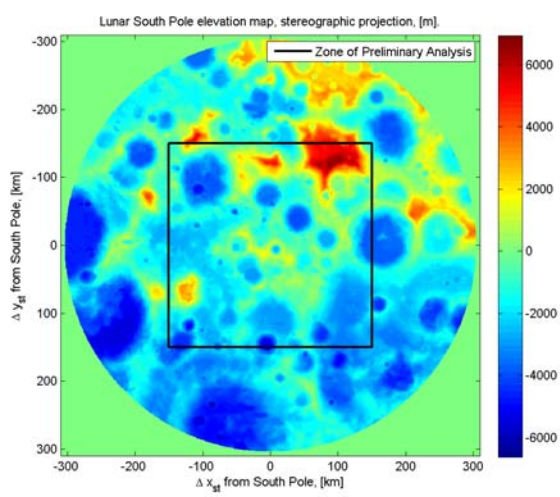


Fig. 2: Lunar South Pole elevation map with zone of preliminary analysis.

Also, locations of favourable illumination conditions are expected to be found at places where the altitude is such that it completely or partially compensates the mask induced by the sphericity of the Moon, e.g. peaks or crater rims. Only points with altitudes of -1km and higher, relative to the Moon's reference surface, were thus analysed.

The analysis was performed on a 500-metre resolution stereographic grid, which is a compromise between computation time and accuracy; any site that could be missed because of this low resolution would in any case also be too small to successfully land on. The year of analysis was set to 2018 and the height above the ground was considered as 2 metres, which reflects the height of body-mounted solar-arrays. Periods of darkness of 55 hours were filtered. This value comes from a preliminary assessment of the survivability of a lander in the lunar night, given a specific set of design assumptions which excluded the use of RHUs.

3.2 Results

The preliminary analysis revealed 6 principal ROI: 3 in the South Pole vicinity, 2 on Malapert Peak, and one on the Leibnitz Beta plateau, see Fig. 3. These sites were selected for their long continuous illumination period, and based on a first assessment of the physical size of the sites.

Other ROI were identified but classified as secondary because of a lower duration of continuous illumination or of a smaller physical extent. lists primary and secondary ROI, specifying a unique ID for each location for quick reference, the region of the Lunar South Pole, the value of the best longest continuous illumination period (in days, rounded), the location latitude and longitude, and if applicable, the corresponding literature name.

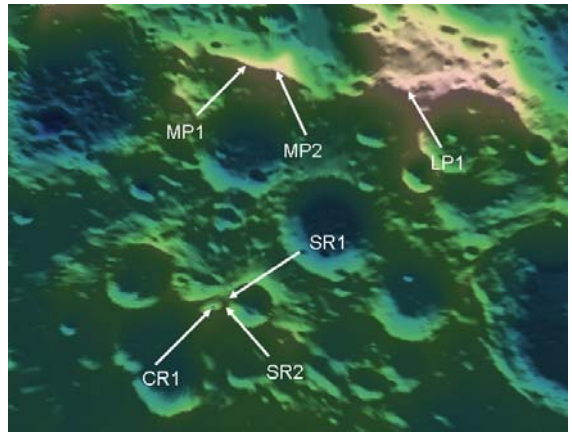


Fig. 3: Primary ROI

4. ILLUMINATION ANALYSES OF SELECTED SITES

4.1 Method

The potentially favourable areas found above have been analysed in detailed, in order to refine the assessment of the duration of the longest illumination period, as well as to estimate their physical extent over the surface. A Region of Interest (ROI) was created for each area identified in the global analysis. Each ROI is a 4km x 4km square region, centred at the central point of the area, with a gridding of 200 m.

4.2 Duration of longest continuous illumination period

 shows 3D maps of four of the six promising sites: SR1, SR2, CR1 and MP2. The colour-scale reflects the longest continuous illumination period duration calculated at the centre of each pixel. The maps

Table 1: Primary and Secondary ROI with favourable illumination conditions.

ID	Region name	Longest illumination period [days]	Location (Lat/Lon [deg])	Literature name
Primary areas				
SR1	Shackleton Rim	274	(-89.7788, -153.4349)	Site A.2
SR2	Shackleton Rim	234	(-89.6871, -161.5651)	Site A.1
CR1	Connecting Ridge	316	(-89.4632, -137.4896)	Site B
MP1	Malapert Peak	196	(-85.9756, -2.1124)	-
MP2	Malapert Peak	203	(-86.0236, 2.6133)	Site E
LP1	Leibnitz beta Plateau	203	(-85.4406, 31.8517)	-
Secondary areas				
GR1	de Gerlache Rim	203	(-88.6834, -67.9321)	Site C
GR2	de Gerlache Rim	173	(-89.0073, -94.7636)	Site G
SR3	Shackleton Rim	203	(-89.8120, 52.1250)	-
SV1	Shackleton Vicinity	175	(-88.8247, 124.1359)	Site F
LP2	Leibnitz beta Plateau	203	(-85.2934, 37.0304)	-
LP3	Leibnitz beta Plateau	203	(-85.5566, 37.4649)	-

represent the local topography which permits a better understanding of the results. The durations for the best points are consistent with the durations found in the preliminary analysis, ranging from 7.6 to 10 months for sites in the South Pole vicinity, and just above 6 months for site MP2 on top of Malapert Peak.

4.3 Extent and shape of ROI

The maximal duration of continuous illumination is not the only important characteristic to take into account: the extent and shape of the ROI also has to be taken into account. With the higher resolution adopted for these analyses, this criterion can now be evaluated.

From , the four sites can be classified into two categories. Sites located at crater Shackleton rim or at the Connecting Ridge have a relatively small extent: generally one or two pixels across. It should be recalled here that each pixel represents a square with sides of 200 metres. This could be expected as the terrain is actually the intersection of two slopes; if one slightly steps aside downhill, the ridge masks the Sun on a major part of the local horizon. On the other hand, site MP2 is located on a more regular plateau-type terrain, thus offering a wider zone of about 800 metres

The shapes of the ROI are very dependant on the local topography. It varies from a near-circular target shape such as SR1, to almost the equivalent of a landing "strip" shape such as CR1. The latter induces a preferred direction of arrival that could potentially constrain the descent orbit.

These results imply a very hard constraint on the landing accuracy that the lander should achieve to ensure a landing inside the target ROI. Furthermore, the shape of the target ROI may narrow the choice of descent orbit.

4.4 Influence of night survivability

The analyses reported to this point considered a night survivability of 55 hours both for the preliminary analysis and for the sites analyses. In order to see the influence of this parameter on the longest continuous illumination period, Fig. 5 shows 2D colour-scaled maps of the longest illumination period for sites SR1 and for different values of night survivability: 20, 60 and 100 hours. It can be seen that he darkness duration a lander can withstand has little effect on the extent of the favourable zones. Nevertheless, longer night survivability enables longer mission duration, and neighbouring peaks become interesting potentially providing alternative landing sites, albeit of small size. Maps of other sites show similar behaviour.

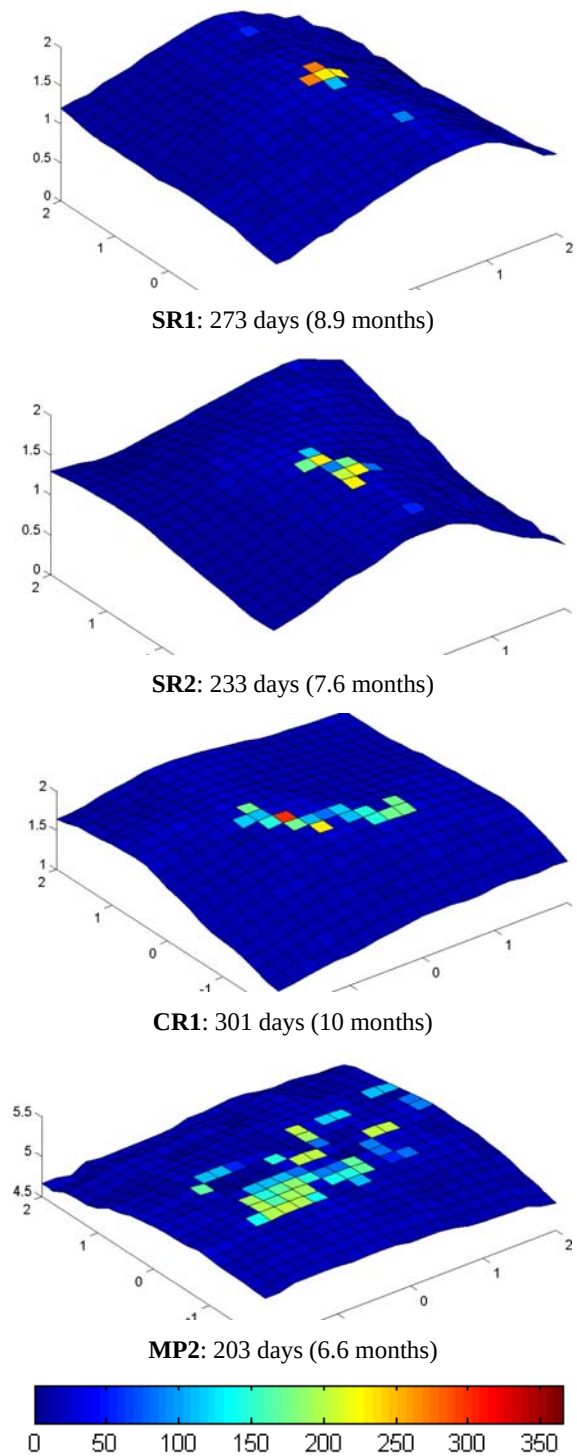
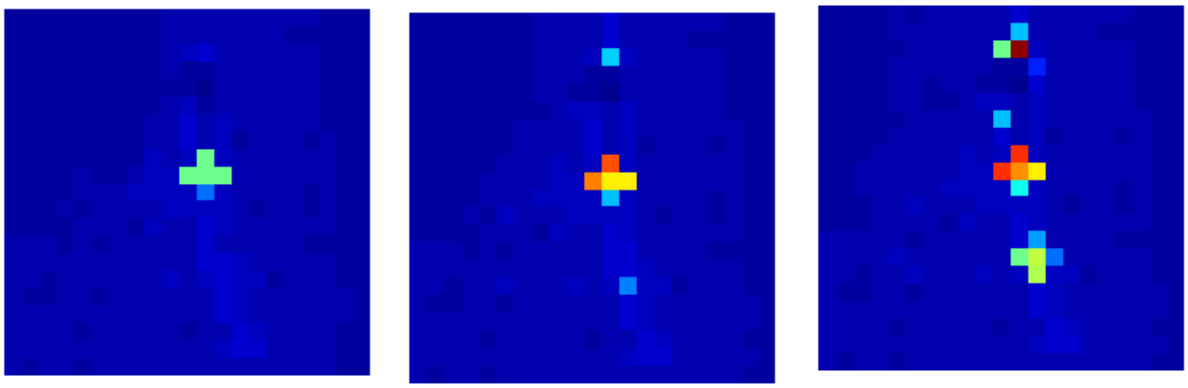


Fig. 4: Duration of the longest continuous illumination period for the 4 ROI, filtering out darkness periods shorter than 55 hours. Colour-scale in days.



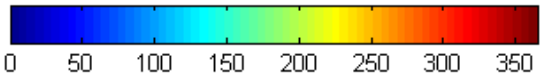


Fig. 5: Influence of night survivability on longest continuous illumination period for site SR1: 20 hours (left), 60 hours (middle) and 100 hours (right). Colour-scale in days.

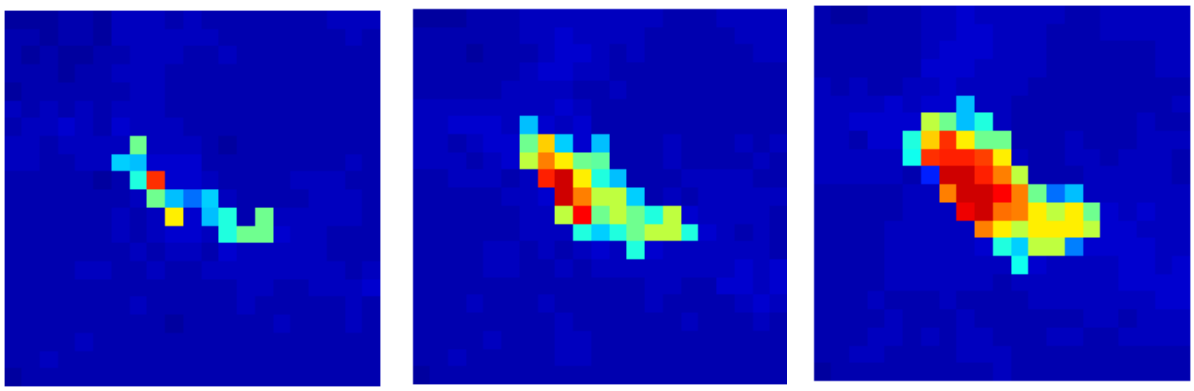
4.5 Influence of the altitude above the ground

The above reported analyses have been made for a point situated 2 metres above the local terrain to account for the height of the lander and of the solar arrays. For such an environment where the Sun is very low or even below the horizon, a concept to investigate would be a tower-mounted solar-array. This means investigating the illumination conditions at higher (vertical) altitudes above the local terrain.

To this aim, analyses were performed at different altitudes above the ground. shows site CR1 with height above the ground of 2 meters as before (left), 10 meters (middle) and 20 meters (right). The first effect to observe is that the extents of the zones increase as the height increases. This is due to the fact that the tower mitigates close-proximity terrain effects. Combined with longer night survivability, some locations offer the possibility of completely uninterrupted illumination. A tower-mounted solar-array thus provides a significant increase to the duration of the mission and, importantly, to the extent of the landing zone by mitigating the effect of close-proximity terrain. The actual benefits however strongly depend on the vertical resolution of the available terrain data.

4.6 Variation with the year

The global analysis of the previous chapter and the detailed analyses of this chapter were all conducted on a 1 year period, from 1st January 2018 to 1st January 2019. However, because of celestial mechanics effects, the results of a year cannot be exactly applied to any other year. The cause is a complex combination of the Moon's rotation and sidereal periods, the regression of



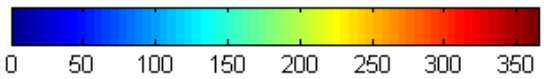


Fig. 6: Influence of the height above the ground on the longest continuous illumination period for site CR1: 2 meters (left), 10 meters (middle) and 20 meters (right). Colour-scale in days.

Moon's orbit ascending node, and possibly the Earth orbit around the Sun. It is therefore not possible to derive a precise rule to transpose results of one year to another. Analyses were performed for years from 2016 to 2021 included. They show only a slight change in the longest continuous illumination period duration.

5. COMMUNICATION ANALYSES

Because the Moon always presents the same side to the Earth, a spacecraft positioned on the equator on the near-side will always see the Earth. However, the situation is different at the poles, where the Earth disappears under the local horizon for ~14 days. Viewed from the poles in particular, the Earth describes an extended eight-shape, ranging between ±6.5º in elevation with regard to the local horizon, and ±8º in azimuth. Without considering terrain, the Earth would be in visibility during 14 days, and hidden the next 14 days.

Fig. 7 and Fig. 8 present the average duration of the Earth visibility duration in each monthly cycle. An average value over one year is given since all the windows have roughly the same duration. Note that the colour scale has changed with regard to illumination analyses.

It must be understood that Earth visibility means a line of sight between the lander and the centre of the Earth, no specific ground station is yet taken into account. Also, effects due to partial occultation of the antenna beam by the terrain are neglected.

As could be expected, Earth-visibility window duration is around 14 days for sites in the South Pole vicinity, and a little longer for Malapert Peak which is at lower latitude and sited towards the near-side.

Fig. 9 presents together the Sun and Earth visibility patterns. Obviously, the two patterns are independent. In this case, if the landing occurs just when the illumination window opens, the site is in view of the Earth, so a direct-to-Earth link can be expected. However, the Earth disappears after 3 days for a duration of 15 days. If these 3 days are not sufficient to conduct post-landing operations, the landing should be delayed until the next communication window opens, which shortens the mission by about 20 days.

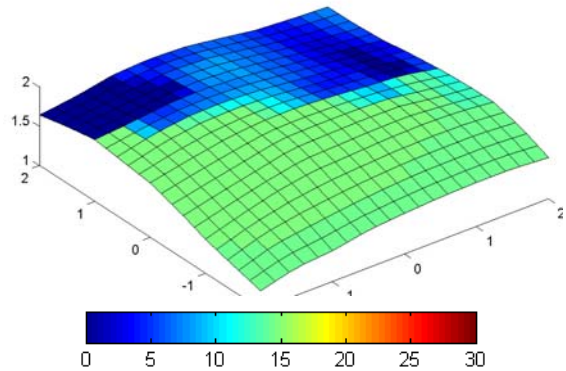


Fig. 7: Duration of average visibility for site CR1, colour-scale in days.

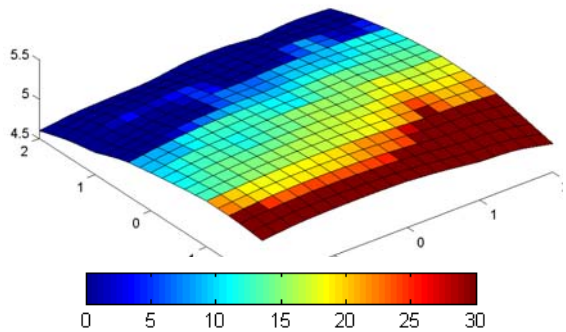


Fig. 8: Duration of average visibility for site MP2, colour-scale in days.

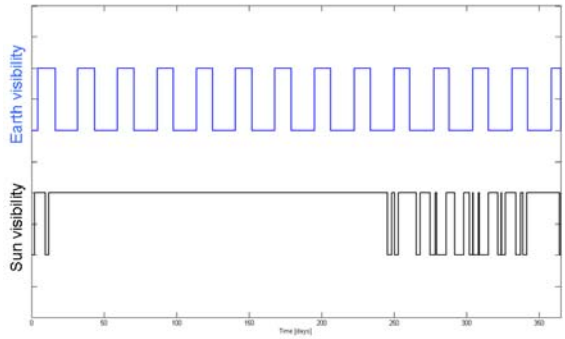


Fig. 9: Combined Sun (filtered) and Earth visibility patterns.

6. CONCLUSIONS

The analyses which have been performed through the work described here are considered significantly representative of the real conditions at the Lunar South Pole, however the effects of certain limitations including the resolution of the Kaguya data used may still be significant for the results. Despite this, several important conclusions can be drawn from the analyses performed.

One of the most important conclusions, indicated also by parallel studies, is that so-called 'peaks of eternal light' offering year round illumination on the Moon, do not exist. Rather, when filtering out periods of darkness, e.g. those less than 55 hours, continuous illumination periods of 6 to 10 months exist at certain locations at the lunar South Pole. Several ROI were identified: 2 at the Shackleton crater rim, one at the ridge connecting craters Shackleton and de Gerlache, and one at Malapert Peak. These ROI can be separated into two categories: ROI in the close vicinity of the South Pole, with longer illumination periods but with smaller physical size, and ROI at lower latitudes, offering shorter illumination periods but with larger physical size. It can be expected that analyses conducted with more accurate topographic data may highlight different ROI.

Considering longer periods of darkness survivability directly results in an increase in the length of the longest quasi-continuous illumination period.

An important effect identified was the increase in longest quasi-continuous illumination period, as well as to a certain extent the physical size of the ROI, when the analysis was performed considering a point at increasing height above the surface, i.e. considering a form of solar tower concept. Finally, illumination conditions vary slightly depending on the year.

Continuous direct-to-Earth communication is not possible at Lunar South Pole. Around 14 days of Earth visibility can be expected every lunar month. Earth visibility windows are not synchronised with illumination and darkness periods, this may delay the landing for up to ~14 days.

For a specific landing site, there is only one favourable illumination window per year. The landing shall occur as soon as possible after the opening of the window. The mission planning shall introduce a sufficient buffer time to allow for launch delays. In case of nominal launch date, the spacecraft will have to wait in LLO.

The analyses reported here shall be improved upon in further work, which intends to use more precise surface topographic data, and shall be used to inform further mission and technology activities on the European Lunar Lander.

7. REFERENCES

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