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BEING SELENE'S GUEST: ANALYSIS OF THE LUNAR ENVIRONMENT AND ITS IMPACT ON BASE LOCATION SELECTION

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In the frame of ESA's Micro-Ecological Life Support System Alternative (MELiSSA) project the German Aerospace Center's Institute of Space Systems Department of System Analysis Space Segment (SARA) conducts an investigation about the concept design of a greenhouse module for space systems and the various possible alternatives to realize such a system. As part of this investigation a review of existing data about the lunar environment has been conducted, along with a trade of selected and likely locations for lunar outposts, e.g. the Whipple crater at the lunar north pole or the Shackleton crater at the lunar south pole. Part of the analysis and trade have been issues regarding lunar illumination and so-called peaks of eternal light, which represent a valuable asset regarding power generation and thermal conditions, radiation, temperature and accessibility of the locations, referring to local topography and latitude position. The results show that the latter favours equatorial regions, which however do not support current scientific interest in the polar regions of the moon. Comparison and trade of candidate sites situated at the pole, reveal the connection ridge between Shackleton and Sverdrup at the south pole to be the most favourable location, due to lenient conditions regarding temperature and temperature history over time as well as illumination (and thus potential for power generation with solar cells). This paper reports in the course of this analysis and the need for more precise data regarding e.g. radiation at the lunar surface and other open issues necessary to be closed for the implementation of any plan for permanently inhabitating the moon or setting up autonomous systems for robotic exploration.

I. INTRODUCTION

In support of ESA's Micro-Ecological Life Support System Alternative (MELiSSA) project the German Aerospace Center Institute of Space Systems is investigating concepts for establishing greenhouse modules for space systems, e.g. on the lunar surface.

Part of the investigation is the evaluation of the lunar environment and a reasonable site location for a station. In this paper the author will present a review of the existing data about the lunar surface environment along with a trade-off regarding surface temperature, radiation, latitude and illumination. An analytical hierarchy process is then used for a numerical evaluation of the various possible sites on equatorial and polar positions.

II. LUNAR SURFACE AND SUBSURFACE TEMPERATURES

The lunar environment is coined by its orbital and rotational characteristics and the absence of an atmosphere that can affect the surface and soil [1]. Current models describe the lunar surface covered by 4 to 5 m of regolith in the mare and 10 to 15 m in the highland regions, which mostly consists of particles smaller than 1 cm. On average they are 60 to 80 μm large, generally it is a fine powder. [2]

The lunar residual heat is likely originating from the decay of radioisotopes, e.g. ^{40}K, ^{232}Th, ^{235}U and ^{238}U. Measurements of the Apollo missions revealed that the mean temperatures 0.35 m below the surface are approximately 40 K above the actual daytime surface temperatures. The first two cm of the lunar surface act as a thermal barrier, having a very small thermal conductivity (ca. $2 \cdot 10^{-3}$ W/ m K), which increases significantly (factor 5 to 10) in depths of about 12 cm, likely caused by a reduced porosity. [2]

The same measurements showed that the temperature increases significantly in the region from 50 to 100 cm, less so for deeper regions. Temperatures in regions deeper than 50 cm are approximately constant (i.e. independent of the day/ night cycle) at 250 K ± a few K. [3]

The temperatures of the lunar surface vary during the lunar diurnal cycle, caused by the heat flux from the interior and from solar illumination. Typically the lowest, equatorial temperature of the lunar night is about 135 K at sunset and 100 K before sunrise, measured. Hot-spots exist, which cool down slower and can feature a larger temperature. [2] Polar areas are cooler; down to 40 K in some ever dark craters [2], recent measurements reach even 35 K [5]. Higher latitudes than the equator can have night temperatures of ca. 80 K. [2]

During day the temperature increases from ca. 100 K at dawn to ca. 390 K at noon and then decreases again

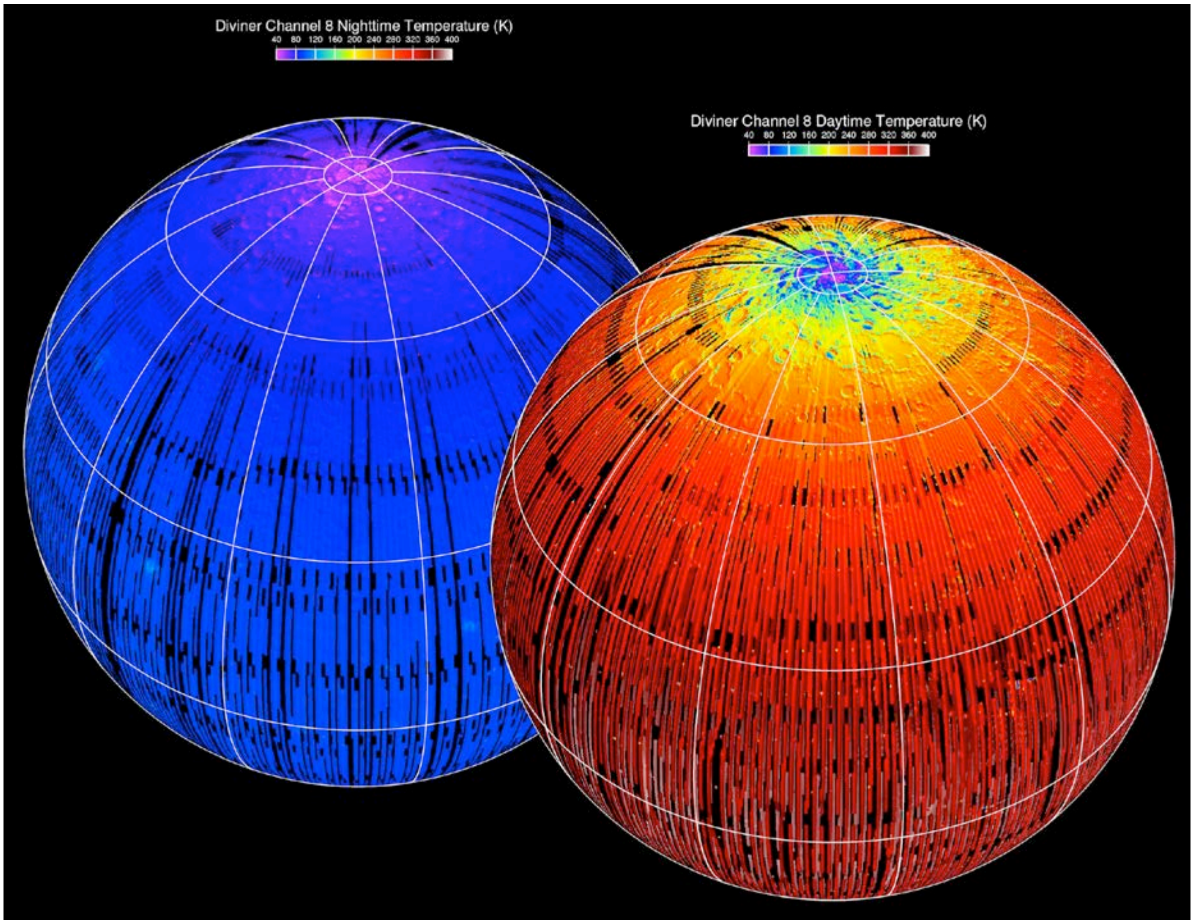

Fig. 1: Overview over the lunar day- (right) and nighttime (left) temperature distribution as measured by the Diviner Instrument of the Lunar Reconnaissance Orbiter for the northern hemisphere [4].

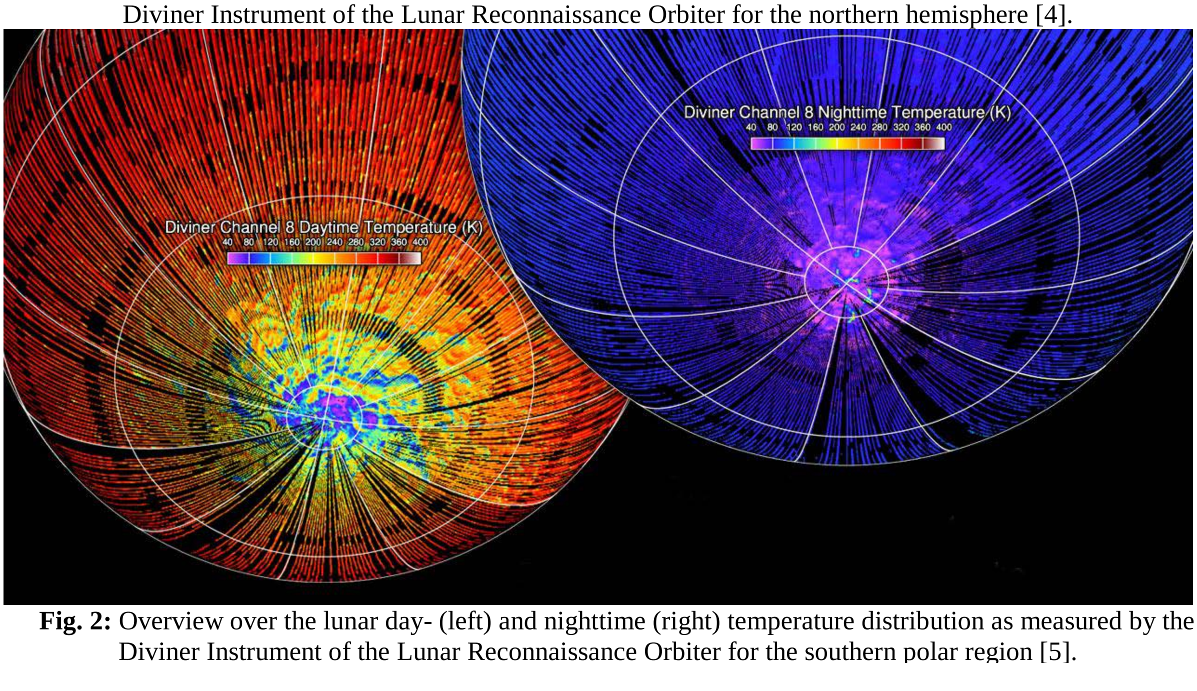

Fig. 2: Overview over the lunar day- (left) and nighttime (right) temperature distribution as measured by the Diviner Instrument of the Lunar Reconnaissance Orbiter for the southern polar region [5].

until sunset. Temperature variations caused by the elliptical Earth orbit around the Sun are in the range of 6 K. [2]

Table 1-1: Temperature properties of the lunar environment.

Parameter	Lunar Night	Lunar Day
Minimum Temperature (equator)	110 K (before sunrise)	110 K (at sunrise)
Maximum Temperature (equator)	135 K (at sunset)	390 K (at noon)
Maximum Temperature (polar)	80 K*	140 K
Mean Temperature (equator)	122 K	297 K
diurnal cycle independent parameters		
Temperature Variation due to solar orbit	ca. 6 K	
Minimum overall Temperature	35 K (within ever dark craters)	
Subsurface Temperature (at 50 cm)	ca. 250 K	

*not counting PELs

The temperature variation over the location is illustrated in Fig. 1 for the lunar northern hemisphere day and night. Clearly the polar region is significantly cooler than the equatorial region during night and day (less during the latter) and in both cases there are regions where the temperature remains at about 40 K. The temperature variation on the illuminated side of the Moon can be approximated by [2]:

$$T(\beta) = T_e \cos^{1/4}(\beta) \quad (1\text{-}1)$$

where T is the temperature at a given latitude β and T_e the temperature at the equator. Considering an equatorial temperature of 390 K at noon, this would result in a temperature of about 140 K for a region of 89° latitude, which is approximately confirmed when viewing Fig. 1.

Fig. 2 displays a similar distribution for southern polar regions, painting a comparable picture. It is worthy to note that clearly visible in the immediate vicinity of the south pole there is a region where the temperature remains approximately the same during night and day at a value of 160 K, caused by so called peaks of eternal light and is addressed in Section I.III.

The average temperature of the lunar day can be calculated with the help of a sinusoidal approximation of its history over one day and the minimum day temperature of 135 K and the maximum of 390 K. The temperature average $\bar{T}$ can then be calculated to:

$$\bar{T} = 135\text{ K} + \frac{2}{\pi}(390 - 135)\text{K} = 297.34\text{ K} \quad (1\text{-}2)$$

Using the same approximation with the minimum temperature of 100 K and the maximum temperature of 135 K for a lunar night, the mean temperature becomes 122.3 K. The previously outlined results are summarized in Tab. 1 for easier reference.

The surface temperature is depending on the solar illumination and on subsurface phenomena like heat transfer within the regolith. Besides the absolute temperatures two more characteristics are important for the process: the heat conductivity and the heat flux within the regolith.

The Apollo 15 and 17 measurements also cover heat conductivity and heat flow [14 and 15]. Probes within the lunar soil have been used to in-situ measure the temperature gradient and heat conductivity, derived from that the heat flow has been determined [6] by:

$$\dot{q} = \frac{dT}{dz} \cdot \lambda, \quad (1\text{-}3)$$

where $\frac{dT}{dz}$ denotes the temperature gradient, λ the conductivity and $\dot{q}$ the heat flow per area.

Measurements were taken at two, near equatorial sites, one probe for Apollo 15 (50 to 100 cm depth) and two probes for Apollo 17 (50 to 230 cm depth) [7]. Initial results of the measurements [6] were later revised by Langseth et al [7], whose conclusion was reviewed and supported by Grott et al [8].

The revised values, with errors estimated at 15%, are reported as a heat conductivity of about $10 \cdot 10^{-2}$ W/m K for Apollo 15 and $1.3 \cdot 10^{-2}$ W/m K for Apollo 17. The heat flow therefore is about $2.0\text{-}2.3 \cdot 10^{-2}$ W/m² for Apollo 15 and $1.5\text{-}1.6 \cdot 10^{-2}$ W/m² for Apollo 17 [7].

For the sake of completeness it shall be mentioned that, based on observational data, Jones, Watkins and Calvert have created a mathematical model for describing the temperature and thermophysical characteristics of the lunar subsurface material [9]. These models might be used to extend the measurement data into regions exceeding those actually probed during the Apollo mission. In any case it has to be kept in mind that the two regions sampled by Apollo 15 and 17 need not give a complete picture of the lunar subsurface regions.

III. LUNAR RADIATION EXPOSURE

The lunar surface is subject to electromagnetic radiation, mostly caused by the Sun (at 1 AU it has an energy density of 1362 W/m² on average), and ionizing radiation, i.e. mostly protons, electrons and some heavier nucleus particles [2]. Generally the ionizing radiation can be divided into [10]:

- Solar Wind Particles (SWP, low energy)
- Galactic Cosmic Rays (GCR, high energy)
- Solar Energetic Protons (SEP, high energy)

More contribution comes from possible interaction of these mentioned radiation sources and the lunar surface or subsurface [10], resulting in secondary radiation of e.g. helium or even heavier ions and electrons. Also as mentioned in Section II there are radioactive isotopes within the lunar soil, which can create radiation as well, contributing to about 1% of the total amount [11].

Generally the knowledge about the lunar radiation environment at the surface is limited. Measurements occurred only in various orbits around the Moon. Some models and simulations exist to evaluate the radiation exposure on the lunar surface, s. e.g. Reitz et al [11]. According to these, the hydrogen and helium nuclei are more abundant and more energetic than oxygen and iron ions.

III.I Solar Wind

The solar wind comprises mostly protons and electrons with an intensity range between 10^{10} and 10^{12} particles per cm² s sr depending on the solar cycle. The low energy (some hundred to some kilo electron volt) enables easy shielding. [11]

III.II Galactic Cosmic Rays

The galactic cosmic rays have an extra-solar system origin. They are basically atom nuclei without orbiting electrons. Due to the charge they interact with the solar wind, therefore their abundance is reciprocally depending on solar activity, i.e. their maximum correlates with the solar activity minimum. [11]

The amount of cosmic rays is reduced during times of increased solar activity, represented by the number of sunspots. Depending on this cycle, the intensity varies between 1 and 2.5 particles/ cm² s [12].

The composition is divided into atomic nuclei, which amount to 98% of the radiation, and electrons and positrons, which amount to the remaining 2%. [11]

III.III Solar Energetic Protons

During Solar Particle Events (SPE) a large amount of gamma and x-rays along with high energy particles, usually protons [11] and some Helium ions [2], are emitted from the Sun. The energy of these particles can reach some GeV [11], the particle flux is highly variable between the individual events [11]. It can reach amounts of 10^{11} particles/cm² [12]. The probability for such an event increases with the end of a solar maximum. [11]

III.IV Dependency on Location

Radiation data for the lunar surface is very limited and measurements exist only for various orbits. Derived from the Chandrayaan-1 (C1) mission and the Lunar Reconnaissance Orbiter (LRO) for three orbit altitudes measurements can be reported, s. Tab. 2. [11]

Table 2: Lunar radiation exposure (average dose) depending on orbit altitude. [11]

Orbit Altitude	Average Dose	Mission
50 km	0.22 – 0.27 mGy/d	LRO
100 km	0.227 mGy/d	C1
200 km	0.257 mGy/d	C1

It is clear that the exposure to solar radiation on the lunar surface is the same as for illumination, therefore eclipse times exclude this amount of radiation exposure. The same is not true for galactic cosmic rays, yet the actual amounts of radiation stemming from this source are unknown at the surface, they can only be estimated, s. [11]. As the exact radiation is not known, an evaluation regarding geographical variance cannot be conducted, only a qualitative assessment is possible.

Generally the amount of radiation originating from the sun can be considered to be proportional to the visible illumination, thus following a distribution similar to the heating through solar illumination as depicted in Figure 1-1 and Figure 1-2. Shaded areas, e.g. crater interiors, are also shielded from solar radiation. While the spatial angle at which the galactic cosmic radiation affects the lunar surface also depends on topography, e.g. is reduced when considering a crater interior, no location can be totally shielded from GCR as it is basically omnidirectional. On the other hand, exposed positions useful to gain a large amount of solar illumination are also more exposed to solar and galactic cosmic radiation. Therefore the need for exposition needs to be weighed with those of radiation protection. It is however possible to use lunar regolith for shielding a possible habitat [12, 13], therefore the requirements on the system itself can be lenient.

IV. ILLUMINATION OF POLAR REGIONS

The illumination of the lunar surface depends on the orbital and rotational characteristics of the Moon. The sidereal rotation period of the moon has a length of 27.322 days; a lunar synodic day is 29.531 days long. Its rotational axis has an angle of 6.58° to its orbital

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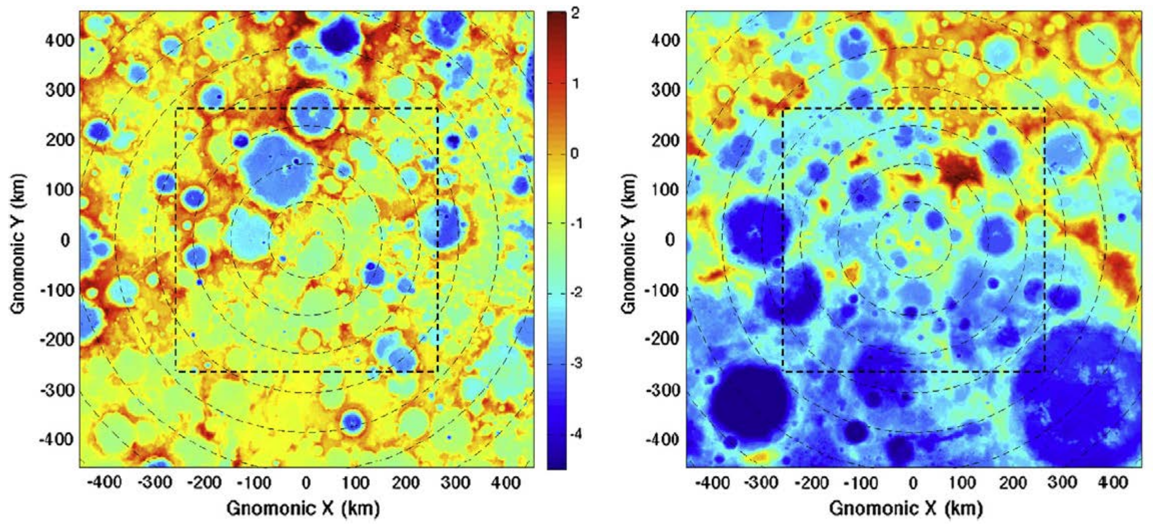

Figure 4: Topographic models with a gnomonic projection of the north (left) and south (right) pole with a horizontal resolution of 240 m. The dashed circles designate a latitude change of 2.5°. [16]

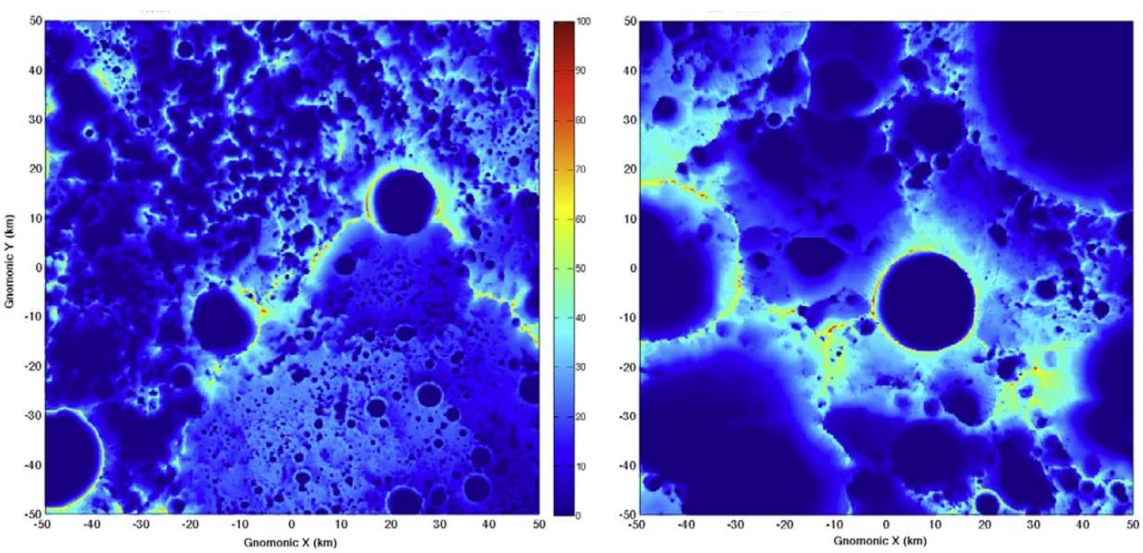

Figure 5: Average illumination over four precession cycles (4 x 18.6 yrs) of the lunar north (left) and south (right) pole. [16]

plane; the latter has an inclination of 5.14° to the ecliptic. The lunar night lasts for 14 days, the longest possible duration is even 384 h (ca. 16 days). [1] The lunar rotation axis has a tilt of 1.5° toward the normal vector of the ecliptic [2]. Its polar axis precesses on its orbital plane in about 18 years [14].

From a power generation and thermal control viewpoint a lunar night lasting 14 days is a significant obstacle for a permanent lunar outpost. Consequently it is interesting to investigate possible lunar regions where – due to topographical effects – illumination is less limited. Such regions are called Peaks of Eternal Light (PEL) and have been discussed since the 19th century [15].

Mountains (h>600m [15]) in the polar regions could exceed the horizontal line and be lit by solar illumination. Some areas might require a given height of the system to receive enough illumination for solar power generation [15]. At the same time very similar considerations, this time however the protruding topography is shielding illumination, leads to areas which are eternally dark and could therefore contain water ice. Both is addressed shortly already in Section II, where areas with temperatures below 40 K

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are reported and also areas, during night, which exceed temperatures of 150 K indicating they are illuminated by the Sun.

Based on topography data of various missions there have been several attempts to determine the positions of possible PELs on the lunar polar regions. Using data of the Lunar Orbiter Laser Altimeter (LOLA) of the LRO mission, Mazarico et al [16] have created a digital elevation model (DEM) with a resolution of 240 m, the results can be seen in Fig. 4. With this elevation model, Mazarico et al [16] have calculated the illumination for the lunar poles for four precession cycles (18.6 yrs), which is a new approach.

The results are shown in Fig. 5. It can be seen that for the left rim of the Whipple crater on the north pole (top right crater) and for parts of the Hinshelwood crater (lower left crater) locations with about 80 to 90% average illumination exist. Regions with 60% illumination are more abundant and are distributed mainly on the connections between these craters. The south pole offers even more possibilities. Along the rims and the connection between the Shackleton (center crater) and De Gerlache (left crater) craters there are several locations with average illumination exceeding 80%. In general the areas with an 80% or more illumination have a total size of 1.32 km² on the north polar region and 2.25 km² for the south polar region. The best location with an average illumination of 86.08% is located at the rim of the Aepinus crater in the north and with 89.01% on the ridge between the Sverdrup and Shackleton crater in the south. It should be marked that generally the top 50 list regarding solar illumination of the northern locations is less well performing than the southern ones, having differences of some %, s. the excerpt in Tab. 3. [16] The best location has an illumination of about 200 days of uninterrupted sunlight.

The list of ranked locations according to solar illumination changes its sequence when the illumination is investigated 10 m above the actual location – e.g. representing the possibility to create a structure of 10 m height for e.g. placement of solar arrays. [16]

Koebel et al. undertook a similar study for a duration of one year (2016) instead of four precession cycles with the help of the software Satellite Tool Kit [14]. It complements and confirms the previously reported results.

While there are changes in the ranking of the individual sites, the general layout persists with illumination periods of about 80%. If shadow periods are allowed, the duration of the shadowed period influences the possible sites. E.g. for the Shackleton crater, locations with uninterrupted sunlight exist only for periods of about 3500 h in the local summer. Including the occurrence of eclipse times allows quasi-uninterrupted sunlight for 4183 h for shadow periods of max. 24 h and 322 days for shadow periods of up to 120 h. [14]

Table 3: Top five illuminated areas (averaged over four precession cycles) for the lunar north and south poles. [16]

Longitude	Latitude	Average Solar Illumination
lunar north pole		
242.24	88.06	86.08 %
126.80	89.37	84.56 %
126.21	89.38	84.48 %
131.09	89.34	84.40 %
130.56	89.35	84.01 %
lunar south pole		
222.69	-89.45	89.01 %
222.73	-89.43	88.60 %
223.28	-89.44	87.13 %
204.27	-89.78	86.71 %
203.46	-89.77	86.70 %

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The connecting ridge between Shackleton and De Gerlache has more favourable results for shadow periods of up to 24 h, there is illumination for 5954 h. Including a 120 h shadow period, the duration is 285 days. [14] Investigations of Vanoutryve et al. [17] show similar results (for years 2016 to 2021) and also favour the Shackleton rim with a longest period of 274 days of illumination (accepting shadow periods of up to 55 h) and the connecting ridge with De Gerlache having illumination of up to 316 days of illumination (accepting the same eclipse times).

V. LOCATION TRADE

Considering the previously examined lunar environmental conditions, this section generates a trade and analysis regarding the location of a lunar landing site for a permanent base housing a greenhouse module.

For the evaluation four criteria are used and awarded scores, for each a maximum of 100 is possible. Weighting factors are found via the Analytical Hierarchy Process to relate the criterions to each other.

V.I Temperature Trade

In the previously described lunar surface temperature conditions are summarized in Table 1-4. As described the temperature development is very diverse in equatorial regions, the difference between night- and daytime temperatures can reach about 200 K. Also comparing both situations of a diurnal cycle in Fig. 1, it becomes apparent that the temperature difference for the north pole is also significant, about 60 K for the warmest regions. The south pole is more lenient. The temperature difference is only about 20 K for the best case and there are regions where minimum temperatures are about 160 K. This is advantageous for a thermal control system as it can operate in a more narrow frame than at the other two locations, i.e. power and mass constraints would be more relaxed. The south pole is therefore the better option regarding the base position from a thermal point of view.

Table 4: Temperature Trade.

Location	Best Minimum Temperature	Maximum Temperature
Equator	100 K	390 K
South Pole	160 K	180 K
North Pole	80 K	140 K

The score for this trade criterion is found by a mixture of the mean temperature with the temperature difference between minimum and maximum:

$$S_T = 50 \cdot \frac{20\text{ K}}{x_1} + 50 \cdot \frac{x_2}{300\text{ K}} \quad (1\text{-}4)$$

The score for the temperature criterion S_T regards half the effect of the temperature difference x_1, where the best found difference of 20 K has been used as baseline and the effect of the mean temperature x_2 scaled by 300 K (ca. 20° C) to favour less extreme temperatures.

V.II Radiation Trade

As outlined before currently no data exist about the radiation situation on the lunar surface, only estimates and they do not allow a precise trade regarding the location. So only general statements can be made.

During eclipse times, the solar radiation contribution is minimum, which is true for all locations. Areas like PEL in the polar regions can however be illuminated more than the equatorial regions, therefore the solar radiation is more abundant. Also Earth has a somewhat shielding effect on the Earth facing side of the moon regarding solar and galactic radiation, but considering the size of it, this is minor. The galactic radiation should be otherwise more homogeneous over the whole surface.

Consequently the radiation is stronger on the polar regions, because there is no shielding effect and the solar illumination is more abundant. Considering that radiation shielding to protect from SPEs is necessary in any case, the effort to shield the average is not more significant and therefore no design driver.

The scoring formula for the radiation criterion is set to:

$$S_R = 100 - I \quad (1\text{-}5)$$

The score regarding radiation S_R is depending only on the Illumination percentage I, which assumes that less illumination means less radiation from the Sun. Effects of Earth shielding are not regarded as they should in parts be occurring on all locations (otherwise there would be no Earth visibility and therefore no ground contact). More precise calculations could offer better insight into the shadowing effect.

V.III Illumination Trade

Regarding illumination duration, the equatorial regions are the most disadvantageous ones, being illuminated for only about 50% of the time. In terms of area size and duration the south pole, especially the Shackleton crater rim and the connecting ridge to Sverdrup and De Gerlache, outranks north pole regions, like the Whipple crater, when considering large mission durations (more than one year). The values from the previous sections are summarized in Tab. 5.

Table 5: Illumination Trade.

Location	Best Average Illumination Duration	Illuminated Area
Equator	50 %	n/a
South Pole	89.01 %	2.25 km²
North Pole	86.08 %	1.32 km²

The quasi-continuous illuminated area size on the south pole is 1.7 times larger than on the north pole, which reduces the landing accuracy needs. Also the average duration of solar illumination exceeds the north pole by several days (i.e. about 3%).

The score for the illumination simply equals the percentage of average illumination, as the area size data is not precise enough to factor in individual locations:

$$S_I = I \quad (1\text{-}6)$$

V.III Accessibility Trade

The accessibility of the locations shall be addressed from two points of view:

- Delta-V requirements to reach an orbit of an inclination equal to the landing sites latitude
- Local topography, i.e. suitability for base placement

For the former point of view, it is apparent that the equatorial regions have the benefit of being close to the likely approach trajectory and therefore resulting parking orbit inclination-wise. Also, proven by 6 Apollo landings, the terrain is obviously suitable to land infrastructure there.

The Delta-V for obtaining an orbit in polar regions, in this case assumed 89°, can be calculated with the simple formula [19]:

$$\Delta v = 2\, v_c\, \sin(\Delta i/2) \quad (1\text{-}7)$$

where v_c is the orbit's circular velocity and Δi the angular change of the inclination.

Assuming an Apollo-like orbit (for an equatorial orbit) altitude of 110 km, the circular velocity becomes:

$$v_c = \sqrt{\frac{\mu_{moon}}{r_c}} = \sqrt{\frac{4.903 \cdot 10^{12}\mathrm{m}^3/\mathrm{s}^2}{1{,}848{,}000\ \mathrm{m}}} = 1{,}629\ \mathrm{m/s}. \quad (1\text{-}8)$$

With Equ. (1-4) the Delta-V requirement for the inclination change can be calculated to:

$$\Delta v = 2 \cdot 1{,}629\ \mathrm{m/s}\ \sin(\frac{89°}{2}) = 2{,}284\ \mathrm{m/s}. \quad (1\text{-}9)$$

With the Ziolkovsky Equation and an assumed specific impulse of I_{sp} = 450 s (liquid oxygen, liquid hydrogen) this results in a fuel mass ratio of:

$$\frac{m_{fuel}}{m_0} = 1 - e^{-\Delta v/I_{sp}\cdot g_0} = 40.4\ \% \quad (1\text{-}10)$$

More than 40 % of the spacecraft entering the lunar parking orbit would have to be fuel. Although this number can be reduced by targeting a polar orbit at the beginning of the lunar injection maneuver, it still needs to be considered for the selection of a landing site. This effect needs to be regarded for base sites on the north and south pole, in fact the same orbit could be used to reach both landing sites.

Regarding local topography, only a profile for the Shackleton crater could be found in [18]. The slopes at the rim are not very steep (ca. 1 km over 6 km maximum, i.e. about 16%) and therefore do not present an obstacle to base construction. For landing operations a more flattened area might be necessary, which could be constructed prior to operation initiation.

The score regarding accessibility S_A is derived by:

$$S_A = 100 - |l| \quad (1\text{-}11)$$

The only factor relevant here, is the magnitude of the latitude; large latitudes are punished due to the increase in fuel requirements.

VI. TRADE RESULTS

The Trade evaluation is conducted with the help of the criteria of the previous subsections, i.e. illumination, temperature, radiation and accessibility. The tool for the evaluation is the Analytical Hierarchy Process (AHP) as described e.g. in [20].

VI.I Weighting of Criteria

As a first step pairwise comparisons on a scale of 1 to 10, with 10 being the most severe importance, are conducted to relate the criteria to each other. The comparison results are:

- Illumination vs. Temperature: **6** – Illumination is more important, because it is connected to the temperature (although this is also depending on the subsurface effects) and it is necessary also for power and usable for plant growth (filtering of malicious contents presumed)
- Illumination vs. Radiation: **8** – Radiation shielding is largely independent of location as it has to deal with the worst case scenario of an SPE, therefore the location is not a design driver as effects due to shadowing are minimal
- Accessibility vs. Illumination: **5** – Accessibility is more important, because the best illuminated location cannot be used if it is not reachable or not suited for base placement
- Accessibility vs. Temperature: **7** - Accessibility is more important, as non-accessibility is again a showstopper argument; stronger effect because temperature is not as important as illumination

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Table 6: Trade Scoring.

Location	S_I	S_T	S_R	S_A	S_i
(1) Aepinus	86.08	35	13.92	11.94	34.21
(2) Whipple	84.56	35	15.44	10.63	33.09
(3) Connecting Ridge	89.01	78.33	10.99	10.55	37.84
(4) Shackleton	86.71	78.33	13.29	10.22	37.13
(5) Equator	50	44.28	50	100	79.29

- Accessibility vs. Radiation: **9** - Accessibility is more important, as non-accessibility is again a showstopper argument; strongest effect because radiation is least depending on location
- Temperature vs. Radiation: **3** – Slightly more important, because of the stronger dependence on location

From these comparisons, a comparison matrix of the following form can be generated:

$$\overline{CM} = \begin{pmatrix} 1 & 6 & 8 & 1/5 \\ 1/6 & 1 & 3 & 1/7 \\ 1/8 & 1/3 & 1 & 1/9 \\ 5 & 7 & 9 & 1 \end{pmatrix} \quad (1\text{-}12)$$

Where the horizontal sequence of criteria is: Illumination, Temperature, Radiation and Accessibility and the vertical is the same transposed.

For this matrix exists only one real and positive eigenvalue, which is 4.1717, which results in the eigenvector:

$$\vec{g} = \begin{pmatrix} 0.45660 \\ 0.14711 \\ 0.07622 \\ 1 \end{pmatrix} \quad (1\text{-}13)$$

Normalized with its own sum of 1.67993, to gain a distribution of 100%, this results in a weightvector of:

$$\vec{w} = \begin{pmatrix} 0.27190 \\ 0.08760 \\ 0.04538 \\ 0.59548 \end{pmatrix} \quad (1\text{-}14)$$

So, when scoring the various locations with each other to gain a ranking, the weights for the previously defined criteria are given by this weightvector, beginning with illumination, continuing with temperature, then radiation and most strongly the accessibility. It should be noted that in this process only technical considerations are made, scientific justification is not included, i.e. this weighting could be shifted, when scientific needs for certain locations are also considered.

To check the consistency, i.e. plausibility, of the results, the consistency index CI is derived by [20]:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (1\text{-}15)$$

where λ_{max} is the largest eigenvalue and n is the number of criterions. In this case CI becomes 0.057233.

The consistency ratio CR, which is recommended to be below 10% in order to gain useful results by the AHP, can be calculated by:

$$CR = \frac{CI}{RI}, \quad (1\text{-}16)$$

where RI is the consistency index of a random matrix, which is – for four dimensions – RI = 0.9 [19]. With this the consistency ratio becomes:

$$CR = \frac{0.57233}{0.9} = 0.0636 < 0.1 \quad (1\text{-}17)$$

Therefore the above described weighting of the criteria is consistent.

VI.II Score Summary and Discussion

Due to the lack of precise data for the various possible landing sites, e.g. their topographic profile, an evaluation of the landing sites is also inaccurate and cannot be final until these data gaps are filled. The only precise data available is the average illumination of the various locations, all other data will only be considered regionally, i.e. from which pole or equatorial area.

For evaluation the following locations are picked:

- North pole: Aepinus and Whipple crater (rank 1 and 2 in Tab. 3)
- South pole: Connecting Ridge of Shackleton und Sverdrup, resp. Shackleton crater (rank 1 and 4 in Tab. 3, as ranks 2 and 3 are selenographically very close to rank 1)
- Equator: default location assuming 50 % illumination

Scoring is conducted with the help of the sums as described in the previous sections. It therefore becomes:

$$S_i = 0.2719 \cdot S_I + 0.0876 \cdot S_T + 0.04538 \cdot S_R + 0.59548 \cdot S_A \; for \; i \in \{1,2,3,4,5\} \quad (1\text{-}18)$$

The results of the scoring are summarized in Tab. 6. With these criteria the equator region is the best case. The large effort in terms of fuel mass is considerably detrimental for the polar regions. Also regarding temperature a good score is achieved for the equatorial location due to a more favourable mean temperature (245 K for a mean between night and daytime temperatures). If for scientific reasons and e.g. due to close proximity to cold traps and thus likely water ice, the polar regions are selected anyway, there is a slight favour for south polar locations. This is mostly due to the improved illumination and the difference in temperatures. It should be noted that for temperature the same value occurs among the south polar and north polar locations, because no local data exist (s. Section V.I). To improve this rating, more precise temperature measurements are required, that could be also linked to certain locations similar to e.g. the average illumination. The fact that currently no good knowledge about the temperature behaviour of the lunar surface exists and measurement also in the ground is mostly restricted to equatorial regions (due to the Apollo missions), reduces the possibility of conducting simulations identical to those used for obtaining illumination data.

Due to the lack of radiation data, the effects of Earth shielding could not be implemented into this evaluation, therefore one drawback is that the illumination is mostly considered twice within this rating.

It is obvious that within the polar locations basically the rank in mean illumination is identical to the absolute rank, which is not surprising because this is the most accurate data available. Generally the lack of data prevents a more thorough rating of the locations. One further aspect not taken into sufficient account is the local topography, i.e. the suitability of placing a base at a given location. Large slopes and instable material would prevent such an undertaking. Respective data is not available.

Another open aspect is the size of the actual illuminated area, which is a significant value influencing accessibility, because the larger the area, the easier the landing constraints. If this would have been factored in as well in the above made trade with the currently available data (s. Section IV), the south pole would have been favoured even more, because there 2.25 km² of quasi-continuous area exist, vs. 1.32 km² at the north pole. Localizing the data and link certain area sizes directly to individual locations might shift this ranking.

Another necessary step to gain more precise data is to select a mission date and duration in order to improve the illumination data, which is highly dependent on epoch. Due to various orbital influence e.g. Earth orbit precession and lunar rotation axis precession, a final analysis regarding radiation and illumination effects can only be conducted when the timeframe is set.

VII. SUMMARY AND CONCLUSION

In this paper the lunar environment regarding temperature, radiation and illumination has been described based on an extensive literature review. It has been pointed out where currently measurements and therefore precise data is still lacking.

It has been shown that with current data a south polar location is preferable to a north polar location, the best score has been gained for the connecting ridge between Shackleton and Sverdrup (disregarding equatorial default locations).

Based on the collected data this means, the requirements coming from an environmental point of view become:

- Temperature: The system should be able to obtain its operation temperature at an outside temperature of 160 to 180 K
- Illumination: The system's power supply should be able to cover lack of solar illumination for 10.99% of a year in average (40 days)

Requirements regarding radiation are highly dependent on the actual amounts of radiation, which currently are unknown for the lunar surface. A limit based on SPEs should be selected according to recent solar data and tolerances of life-forms and technology.

The current data is not sufficient to make a final statement about the lunar environment and its repercussions on system requirements.

REFERENCES

[1] S. Ulamec, J. Biele, E. Trollope; How to survive a Lunar night; Planetary and Space Science 58 (2010) pp. 1985 -1995

[2] Eckart, P.; The Lunar Base Handbook, Second Edition, Space Technology Series, 2006

[3] Heiken, G., Vaniman, D., French, B., Lunar Sourcebook – A Users Guide to the Moon, Cambridge University Press, Cambridge, MA, 1991

[4] NASA, Diviner Temperature Measurements, http://solarsystem.nasa.gov/scitech/display.cfm?ST_ID=2351, retrieved 18th December 2012

[5] NASA, New Temperature Maps Provide a 'Whole New Way of Seeing the Moon', http://www.nasa.gov/topics/solarsystem/features/diviner20090917.html, retrieved 18th December 2012

[6] M.C. Langseth, S.J. Keihm; In-Situ Measurements of Lunar Heat Flow, Proc. Of the Soviet-American Conference on the Cosmochemistry of the Moon and Planets, Moscow, USSR, 4-8 June, 1974

[7] M.C. Langseth, S.J. Keihm, K. Peters, Revised lunar heat-flow values, Proc. Lunar Sci. Conf. 7th (1976), pp. 3143-3171

[8] Grott, M., Knollenberg, J., Krause, C.; Apllo lunar heat flow experiment revisited: A critical reassessment of the in situ thermal conductivity determination; Journal of Geophysical Research, Vol. 115, E11005, doi: 10.1029/2010JE003612, 2010

[9] Jones, W.P., Watkins, J.R., Calvert, T.A., Temperatures and Thermophysical Properties of The Lunar Outermost Layer, The Moon, Vol 13, pp. 474 – 495, 1975

[10] Carpenter, J.D., Fisackerly, R., De Rosa, D., Houdou, B.; Scientific Preparations for Lunar Exploration with the European Lunar Lander; Planetary and Space Science 74 (2012), pp. 208-223

[11] Reitz, G., Berger, T., Matthiae, D.; Radiation exposure in the moon environment; Planetary and Space Science 74 (2012), pp. 78-83

[12] Pham, T.T., El-Genk, M.S.; Dose estimates in a lunar shelter with regolith shielding; Acta Astronautica 64 (2009), pp. 697-713

[13] Miller, J., Taylor, L., Zeitlin, C., Heilbronn, L., Guetersloh, S., DiGiuseppe, M., Iwata, Y., Murakami, T.; Lunar soil as shielding against space radiation; Radiation Measurements 44 (2009), pp. 163-167

[14] Koebel, D., Bonerba, M., Behrenwaldt, D., Wieser, M., Borowy, C.; Analysis of landing site attributes for future missions targeting the rim of the lunar South Pole Aitken basin; Acta Astronautica 80 (2012), pp. 197-215

[15] Kruijff, M.; The peaks of eternal light on the lunar south pole; Proc. Fourth Int. Conf. on the Exploration and Utilization of the Moon (ICEUM-4), 10-14 July 2000

[16] Mazarico, E., Neumann, G.A., Smith, D.E., Zuber, M.T., Torrence, M.H.; Illumination conditions of the lunar polar regions using LOLA topography; Icarus 211 (2011), pp. 1066-1081

[17] Vanoutryve, B., De Rosa, D., Fisackerly, R., Houdou, B., Carpenter, J., Philippe, C., Pradier, Al., Jojaghaian, Al., Espinasse, S., Gardini, B.; An Analysis of illumination and communication conditions near lunar south pole based on Kaguya data; 7th International Planetary Probe Workshop (IPPW 7), 14-18 June, 2010

[18] Smith, D.E., Zuber, M.T., Neumann, G.A., Mazarico, E.; LRO-LOLA: Measurements of Lunar Altimetry and Surface Conditions; 1st Lunar Glob. Mission International Workshop, 25-27 January 2011

[19] Prussing, J.E., Conway, B.A.; Orbital Mechanics; Oxford University Press 1993

[20] Teknomo, K. ; Analytic Hierarchy Process (AHP) Tutorial; http://people.revoledu.com/kardi/tutorial/ahp, accessed 21st December 2012