GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 9, PAGES 1187-1190, MAY 1, 1999

Illumination conditions at the lunar south pole

D. Ben J. Bussey
ESA/ESTEC, Noordwijk, The Netherlands

Paul D. Spudis
Lunar and Planetary Institute, Houston, Texas

Mark S. Robinson
Northwestern University, Evanston, Illinois

Abstract. Recent remote sensing data strongly suggest that deposits of ice occur in permanently shadowed regions at the lunar poles. Clementine, by providing the first contiguous coverage of the Moon, has enabled the production of an illumination map of the south pole. This map shows the extent of the areas of permanent darkness during winter in this region as well as identifying places on the lunar surface that receive illumination for more than 50% of the lunar day. The permanently dark areas are prime candidates for locations of ice deposits while regions that are illuminated for anomalous periods are possible sites for lunar bases. In this paper we study in detail the illumination history during a lunar day of some of these sites. While we find no area that receives permanent illumination, we do find two areas, only 10 km apart, which collectively receive sunlight for over 98% of the time.

Introduction

The lunar poles are of great interest for both scientific and operational reasons. The discovery of permanently shadowed regions inside craters close to the poles, which are prime candidates for locations of deposits of water ice [*Watson et al.*, 1961; *Arnold*, 1979; *Ingersoll et al.*, 1992; *Shoemaker et al.*, 1994; *Nozette et al.*, 1996; *Feldman et al.*, 1998], has important ramifications for a human return to the Moon. Similarly, regions that receive near-constant solar illumination are possible sites for future lunar bases. Not only do these areas permit operations in a relatively benign thermal environment, but also a lunar base could be supported by solar power without the need of additional power sources. The location of the south pole, on the floor of the giant South Pole-Aitken basin, is of immense geological interest because of the possible presence of material from both the deep crust and upper mantle of the Moon either on, or close to, the surface.

The Moon's poles are nearly perpendicular to the ecliptic plane, with an inclination of 1.5°from the vertical. The significant consequence of this is that the Sun will always appear close to the horizon near the poles, as the Moon slowly rotates on its axis every 708 hours (about 29 Earth days). Thus, topographically high and low points in the vicinity of the poles are potentially permanently illuminated or shadowed, respectively [*Watson et al.*, 1961; *Arnold*, 1979; *Ingersoll et al.*, 1992]. An initial examination of new Clementine images of the south polar region did indeed suggest that some areas were in near-permanent darkness and illumination [*Shoemaker et al.*, 1994; *Spudis et al.*, 1995; *Nozette et al.*, 1996; *Bussey et al.*, 1998].

The Clementine spacecraft, launched in January 1994, mapped the Moon in a near polar orbit for a period of 71 days. In doing so, it provided the first digital data set with which to analyse the lunar poles at medium-high resolution (250-500 m/pixel) with contiguous, consistent coverage. In addition, a cartographic control grid for the Moon has been produced from the Clementine data by the USGS and RAND [*Lee et al.*, 1997] such that positions on the lunar surface are known to an accuracy of better than one kilometer in mid-latitudes. With these new data it is possible to investigate how the lighting conditions at the poles vary over the course of a lunar day.

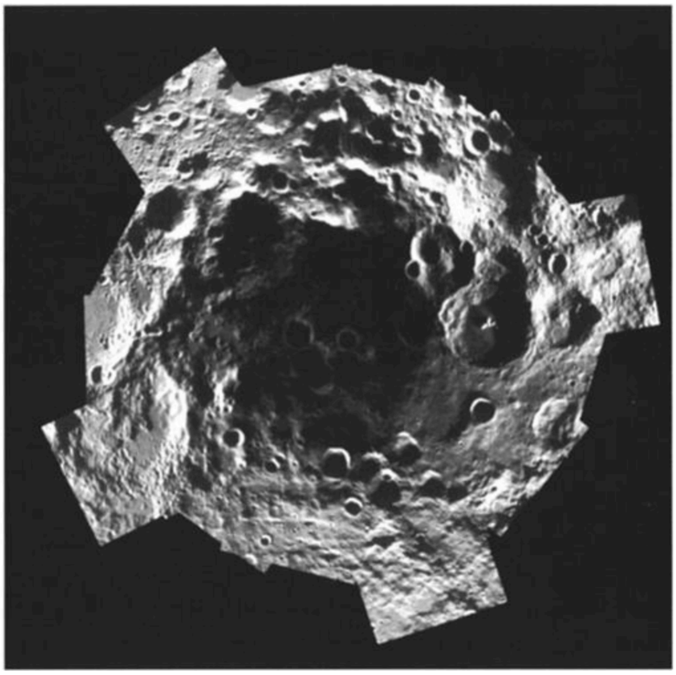

Figure 1. A mosaic, made up of second month Clementine images, showing the south polar region of the Moon. It extends from 85°S to the pole at a resolution of 500 m/pixel. 0°longitude is located at the top of the image.

Paper number 1999GL900213.
0094-8276/99/1999GL900213$05.00

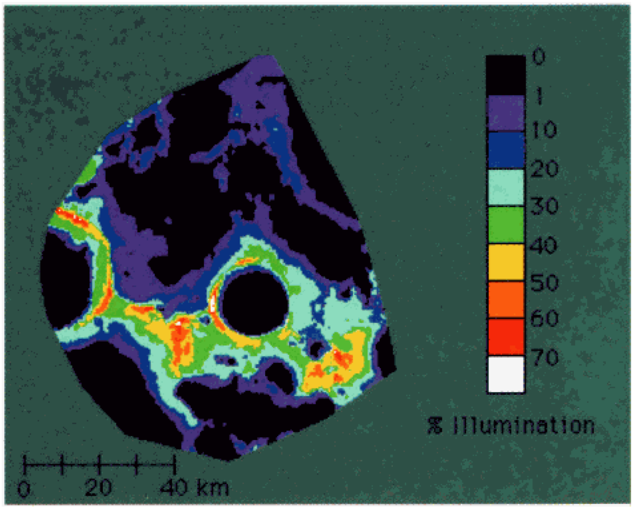

Figure 2. The illumination map, which shows the percentage of time that a place on the lunar surface receives illumination during a lunar day.

Method

Approximately two months (two lunar days) of Clementine data are available for analysis [*McEwen and Robinson*, 1997]. Although the resolution is about a factor of two poorer than the first month data (500 m/pixel instead of 250 m/pixel), we used second month Clementine data because the area of contiguous coverage of the lunar south polar region is twice as great. During construction of a mosaic of the south pole region it was found that the USGS-RAND control network was unreliable within a few degrees of the pole. To improve the control grid near the south pole an Arecebio radar image [*Stacy et al.*, 1997] that covered the polar region from 80°S to the pole on the nearside (with lesser coverage on the farside) was used. This radar image was controlled to the USGS basemap in the vicinity of 80°to 85°where the control is reliable. Closer to the pole the Clementine images were tied to the newly controlled radar image. From this new control net we produced a 750 nm Clementine basemap for the south pole from month two images (Figure 1) that has an average geometric accuracy of better than 500 m overall, and a maximum error of ~1 km (estimated from observations of geometric mismatches from frame-to-frame). This basemap is formed from approximately one hundred individual Clementine frames and gives a first order impression of the lighting conditions at the pole. It is clear that several areas of permanent darkness exist in the environs of the south pole. These data were collected during wintertime at the south pole so the areas of darkness are at their maximum extent.

To better visualize how the lighting conditions change as a function of illumination direction a movie was produced from the frames in the basemap. All second month images covering the south pole were projected to the same latitude/longitude boundary (-85°to -90°S, -180°to 180°E) forming the frames of the movie. Clementine imaged the south pole approximately every 10 hours, so the change in illumination direction between consecutive images is about 5 degrees. The south pole movie dynamically shows how the lighting conditions change as a function of illumination direction.

To quantitatively map the areas of illumination and non-illumination the movie was collapsed into an illumination map which shows the percentage of time that a point on the surface is illuminated during a lunar day (Figure 2). Of particular interest are regions that experience lighting extremes, both areas that appear to be in constant darkness as well as regions that receive large amounts of sunlight. The illumination map was made by converting the Clementine movie frames into binary images (by choosing a threshold dn value that represents the dark/light boundary) which show whether a point on the surface is in light or darkness. Averaging the number of 1's and 0's of all the binary images provides the illumination statistics. The nature of the available data means that assumptions have to be made in the production of the illumination map. Clementine took a snapshot of the lighting conditions at the poles every 10 hours. In making the map, if a place on the surface is lit in consecutive images then it is assumed to be continuously lit for the 10 hours in-between images. Unfortunately the illumination coverage of the south pole is not complete. Ideally there should be 72 images, equally spaced in subsolar longitude. In fact only 59 images exist resulting in gaps in the illumination coverage. These gaps were filled using approximation images formed by taking averages of the images preceding and following the gap.

The spatial extent of the illumination map is constrained by the condition that for a point on the surface to be in the map, it must be covered in every image. The map considers a region centered at the pole and extending out to approximately 88.5°S (within 45 km of the pole), covering about 7000 km^2 of the lunar surface.

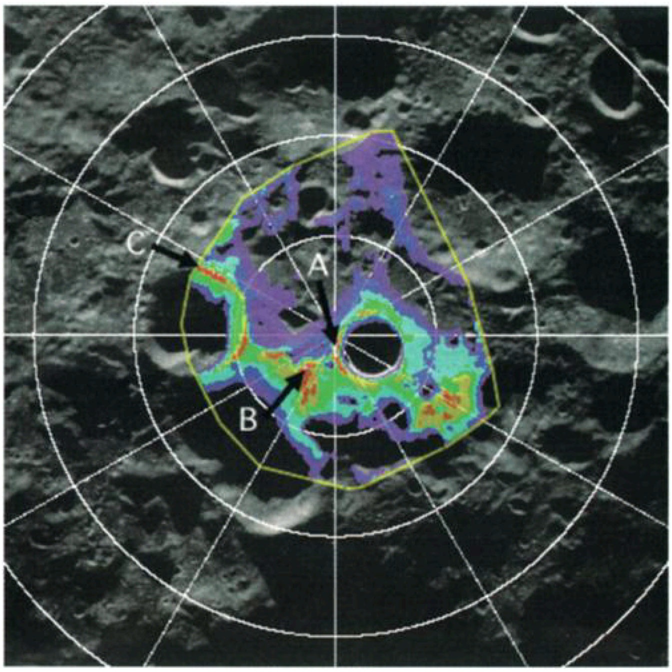

Figure 3. The illumination map from figure 2 is shown overlaid on top of an Arecibo radar image [*Stacy at al.*, 1997] in order to better show how the map corresponds to places on the lunar surface. The spatial extent of the map is indicated by the thick yellow line and regions which receive no illumination are transparent to reveal the lunar surface to which they correspond.

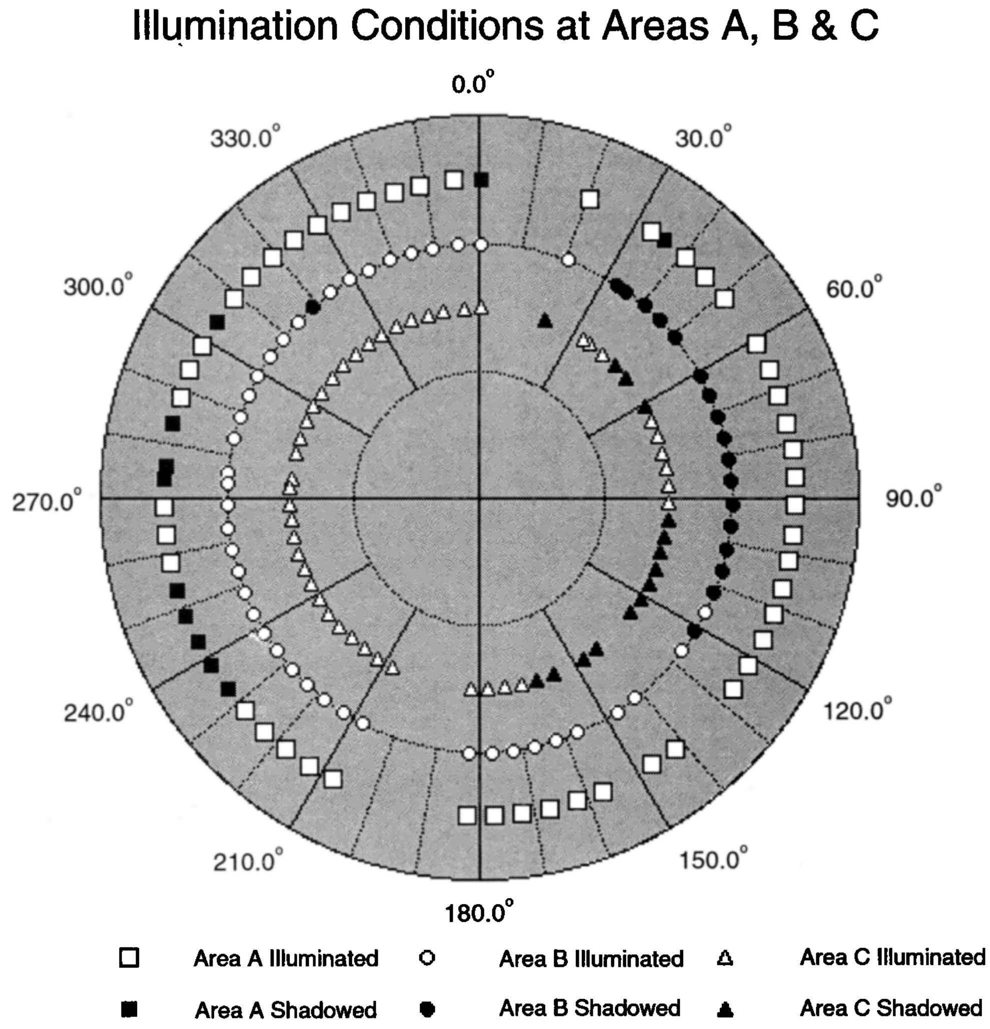

Figure 4. This diagram shows the illumination history during a lunar day at three places on the lunar surface. They indicate whether the area receives sunlight (white symbol) or not (black symbol) as a function of illumination direction.

Illumination conditions

Extremely well illuminated regions

Areas that receive excess amounts of illumination (more than half a lunar day) are of interest as potential landing sites and possibly, future outpost sites. Not only do they offer a near continuous availability of solar energy (possibly negating the requirement of other power sources, such as nuclear), but they would also permit surface operations in relatively benign thermal conditions (it has been estimated that temperatures in permanently lit areas near the lunar poles are on the order of -53°± 10°C, [*Heiken et al.*, 1991]). Figure 3 shows the illumination map overlaid on top of an Arecibo radar image. It can be seen that a number of regions with greater than 50% illumination (orange, red and white areas in Figure 3) exist in the south polar region. We have chosen three regions that receive the largest amounts of sunlight for a more detailed illumination study. These locations are marked as A, B, and C in Figure 3.

Area A lies on the rim of Shackleton crater and is the most illuminated region near the south pole, approximately 80 % of the lunar day in southern winter (it would be in sunlight even more during the southern summer). Figure 4 shows in detail how the illumination conditions vary by indicating its illumination as a function of subsolar longitude: there are five periods of light and darkness during a lunar day. The longest period of illumination has a duration of about 378 hours and the longest stretch of darkness lasts for approximately 50 hours. The total period of illumination at Area A is 591 hours (recall a lunar day is 708 hours)

Areas B and C are both illuminated for more than 70 % of the lunar day. Area B lies on a ridge that originates along from the rim of Shackleton crater and roughly trends along the 124°W meridian. The "illumination map" for area B is shown by the circle symbols in Figure 4. It has a more standard lighting profile with essentially one long period of sunlight followed by a shorter period of darkness. The sunlit duration is 520 hours (except for one 10 hour eclipse period) followed by darkness for about 188 hours (this time with one illuminated period of about 10 hours). The lighting profile for area C, on the rim of the 30 km diameter crater centred at 88.5°S, 90°W, is shown by the triangle symbols in Figure 4. It consists of a "daytime" illumination lasting approximately 358 hours, followed by a number of illuminated and dark periods. The longest duration of darkness is approximately 140 hours. The total illumination time for area C is 510 hours.

At the spatial scale of the Clementine data there are no regions in the south pole area that receive permanent illumination. However, areas A, B, and C all have the potential to receive continuous sunlight during a lunar summer day. It is still possible for a lunar base in this region to have its energy provided solely by solar power; by using a link. Consider the illumination profiles for areas A and B shown in figure 4. There is only a period of 10 hours when neither A or B are in sunlight. Therefore if solar arrays were placed in both areas and connected by a link (either microwave or cable) then a base at either site would receive near constant solar energy.

Permanently shadowed regions

The Clementine bi-static radar experiment located regions near the lunar south pole with properties highly suggestive of ice [*Nozette et al.*, 1996]. This discovery has been subsequently supported by the neutron spectrometer onboard the Lunar Prospector [*Feldman et al.*, 1998]. The deposits detected by Clementine and Lunar Prospector are present in the cold traps that exist in the permanently shadowed regions. The temperature within these regions has been estimated to be approximately 40 K [*Watson et al.*, 1961; *Arnold*, 1979; *Ingersoll et al.*, 1992] and so any water molecule entering a cold trap (probably by random walk migration after a cometary impact somewhere on the lunar surface) will not have the thermal energy to escape the trap. Over a time span of hundreds of millions of years, a sizeable deposit of ice can build up.

Figure 3 shows that the permanently shadowed areas are not confined to the floors of craters. Several zones of darkness occur in the environs of the south pole sheltered by basin massifs. The total area of all the permanently shadowed regions covered in the illumination map (i.e. within roughly 1.5 degrees of the pole) is approximately 3300 km^2. This differs from the previous estimate of 6681 km^2 [*Nozette et al.*, 1996] because they considered a larger region, we are only considering the area that is imaged by all second month Clementine frames. It is obvious that regions outside our area have the possibility of being permanently shadowed, e.g. the illumination map only covers half of the crater at 88.5°S 85°W, the entire floor of which is likely to be in permanent shadow. Our number therefore reflects a minimum value for permanently shadowed locations during winter.

It is important to stress that these data were collected during winter in this region. The actual extent of permanently shadowed regions can only be calculated using data acquired during a lunar summer day at the south pole or by knowing the local topography (e.g., *Spudis et al.* [1998]).

Conclusions

Clementine data have allowed us to produce the first detailed illumination maps of the south polar region of the Moon. We find no areas that receive permanent illumination. However several places are illuminated for greater than 70 % of the time during a winter day. One area, on the rim of Shackleton crater, appears to be illuminated for more than 80 % of the day. Between two areas, only 10 km apart, solar illumination occurs for 98 % of a lunar day: an important discovery for locating future bases. We have also located the whereabouts of several regions that were in constant darkness during the period that the imaging took place. These total 3300 km^2 in area and are likely locations of deposits of water ice. Mapping the location and extent of permanently dark and near-continuously sunlit areas in the south polar region is an important discovery for locating sites for future missions to explore and confirm the presence of water ice and positioning future lunar bases.

Acknowledgments. We thank N Stacy for providing the digital radar image used in Figure 3.

References

Arnold, J. R., Ice in the lunar poles, *J. Geophys. Res., 84*, 5659-5668, 1979.

Bussey, D. B. J., P. D. Spudis, and M. S. Robinson, Analysis of the lunar polar lighting conditions as seen by Clementine, in *Lunar and Planetary Science* XXIX, Abstract 1373, Lunar and Planetary Institute, Houston (CD-ROM), 1998.

Feldman, W. C., S. Maurice, A. B. Binder, B. L. Barraclough, R. C. Elphic, and D. J. Lawrence, Fluxes of fast and epithermal neutrons from Lunar Prospector: Evidence for water ice at the lunar poles, *Science 281*, 1496-1500, 1998.

Heiken G., D. Vaniman, and B. M. French (Eds.), *The Lunar Sourcebook*, 736pp., Cambridge University Press, 1991.

Ingersoll A. P., T. Svitek, and B. C. Murray, Stability of Polar Frosts in Spherical Bowl-Shaped Craters on the Moon, Mercury, and Mars, *Icarus, 100*, 40-47, 1992.

Lee, E.M., and 10 others, Clementine UVVIS Multispectral Processing, in *Lunar and Planetary Science* XXVIII, Abstract 1705, Lunar and Planetary Institute, Houston (CD-ROM), 1997.

McEwen, A. S. and M. S. Robinson, Mapping of the Moon by Clementine, *Adv. Space Res. 19*, 1523-1533, 1997.

Nozette S., C. Lichtenburg, P. D. Spudis, R. Bonner, W. Ort, E. Malaret, M. S. Robinson, and E. M. Shoemaker, The Clementine bistatic radar experiment, *Science 274*, 1495-1498, 1996.

Shoemaker, E.M., M. S. Robinson, and E. M. Eliason, The South Pole region of the Moon as seen by Clementine, *Science, 266*, 1851-1854, 1994.

Spudis P.D., K. R. Stockstill, W. J. Ockels, and M. Kruiff, Physical environment of the lunar south pole from Clementine data: Implications for future exploration of the Moon (abstract), *Lunar Planet. Sci. XXVI*, 1339-1340, 1995.

Spudis P. D., T. Cook, M. S. Robinson, D. B. J. Bussey, and B. Fessler B, Topography of the south polar region from Clementine stereo imaging, *Workshop on New Views of the Moon*, Lunar and Planetary Institute, Houston, TX, 79-80, 1998.

Stacy N. J. S., D. B. Campbell, and P. G. Ford, Arecibo Radar mapping of the Lunar Poles: A Search for Ice Deposits, *Science 276*, 1527-1530, 1997.

Watson K., B. C. Murray, and H. Brown, The behavior of volatiles on the lunar surface, *J. Geophys. Res., 66*, 3033-3040, 1961.

D. Ben J. Bussey, Space Science Department, ESA/ESTEC, 2200 AG Noordwijk, The Netherlands. (email: bbussey@estec.esa.nl)

Paul D. Spudis, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058.

Mark S. Robinson, Northwestern University, 1847 Sheridan Road, Locy Hall 309, Evanston, IL 60208.

(Received February 3, 1999; revised March 3, 1999; accepted March 5, 1999.)