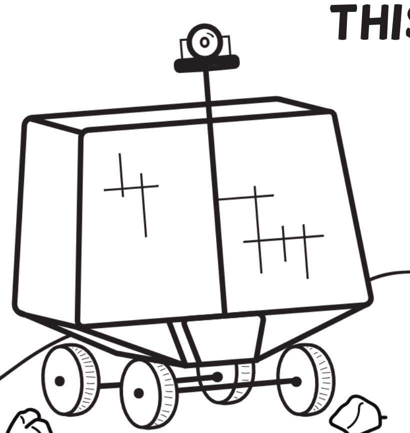
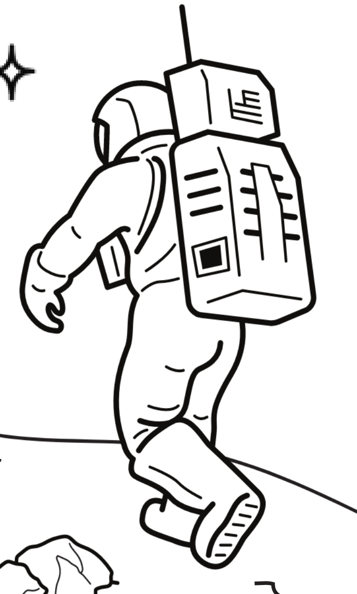
THE MYSTERY OF LUNAR WATER

HELP SCIENTISTS UNCOVER WATER ICE ON THE MOON

PART 1

THIS ACTIVITY IS DESIGNED FOR AGES 9 AND UP.





INSTRUCTOR GUIDE

INTRODUCTION

We want to send astronauts back to the Moon to areas near the south pole that have water in the form of ice. But first, we need to discover where water, or water ice, is the most plentiful. To do this, we need to compare information from many of the instruments on the Lunar Reconnaissance Orbiter (LRO) to find out which areas show water ice in all the datasets. Scientists are doing analyses very similar to this to answer the same question! Help scientists locate where water ice exists on the surface in the form of surface frost. Locations of surface frost will help scientists search for water ice and other frozen resources that are buried beneath the surface.

BACKGROUND INFORMATION

Do craters at the Moon's poles hold water ice?

There are regions near the Moon's poles that never receive sunlight because the poles are not tilted directly towards the Sun. On Earth, we experience seasons (where each pole experiences six months of daylight during its summer and six months of darkness during its winter) because of Earth's tilt (23.5°) on its axis of rotation.

Because the Moon is only tilted 1.5°, there is little seasonal change and some craters at the poles remain in permanent shadow (Figure 1). Permanent darkness means that such regions can maintain very cold temperatures (down to -415°F or -248°C!). As such, frozen materials such as water can be captured for billions of years. At these cold temperatures, there can be ice made from many other frozen substances, which is why we refer to frozen water as water ice in this guide.

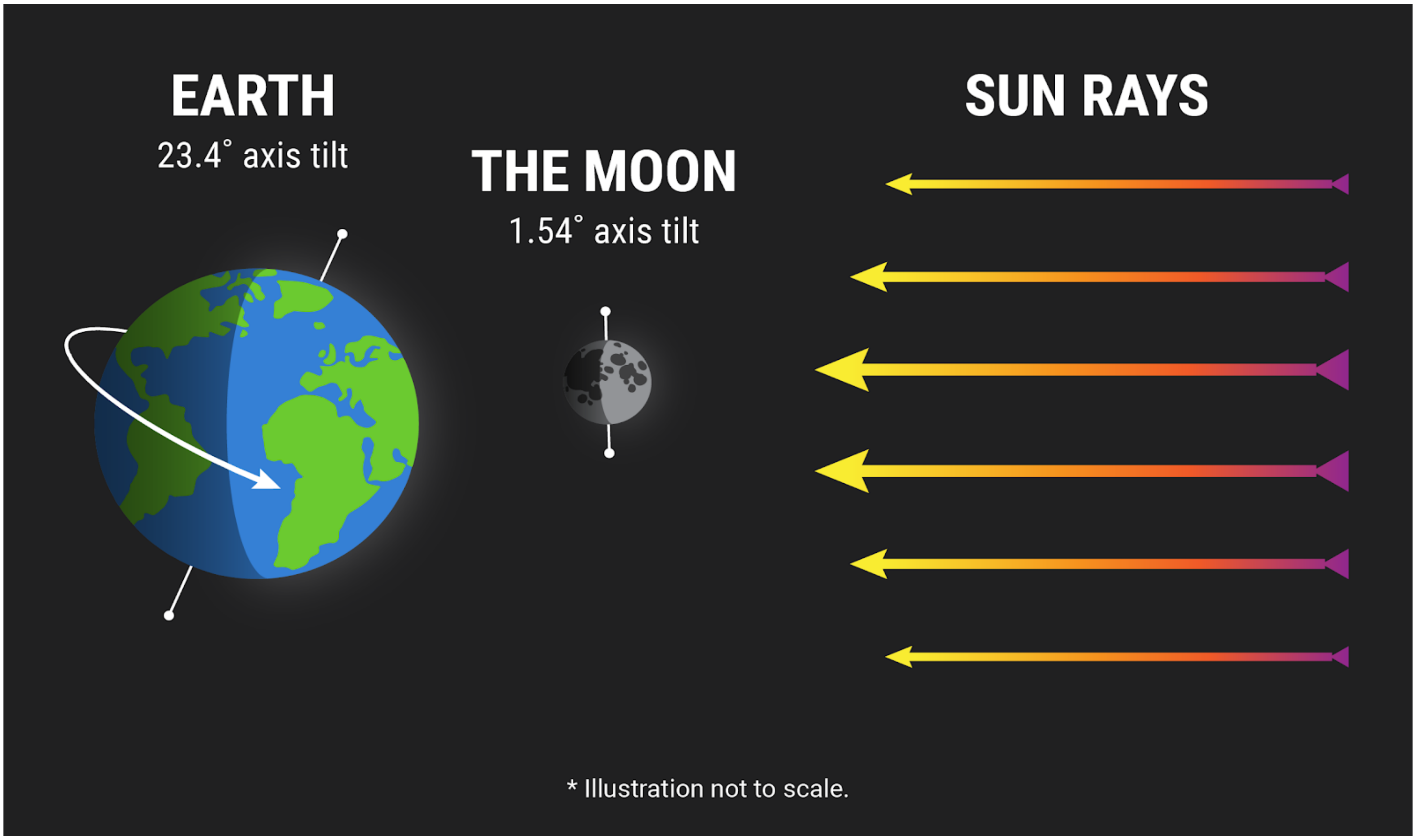


Figure 1: Image showing how the Sun's rays illuminate the Earth and the Moon. The small tilt of the Moon means there are some areas near the poles that never receive direct sunlight.

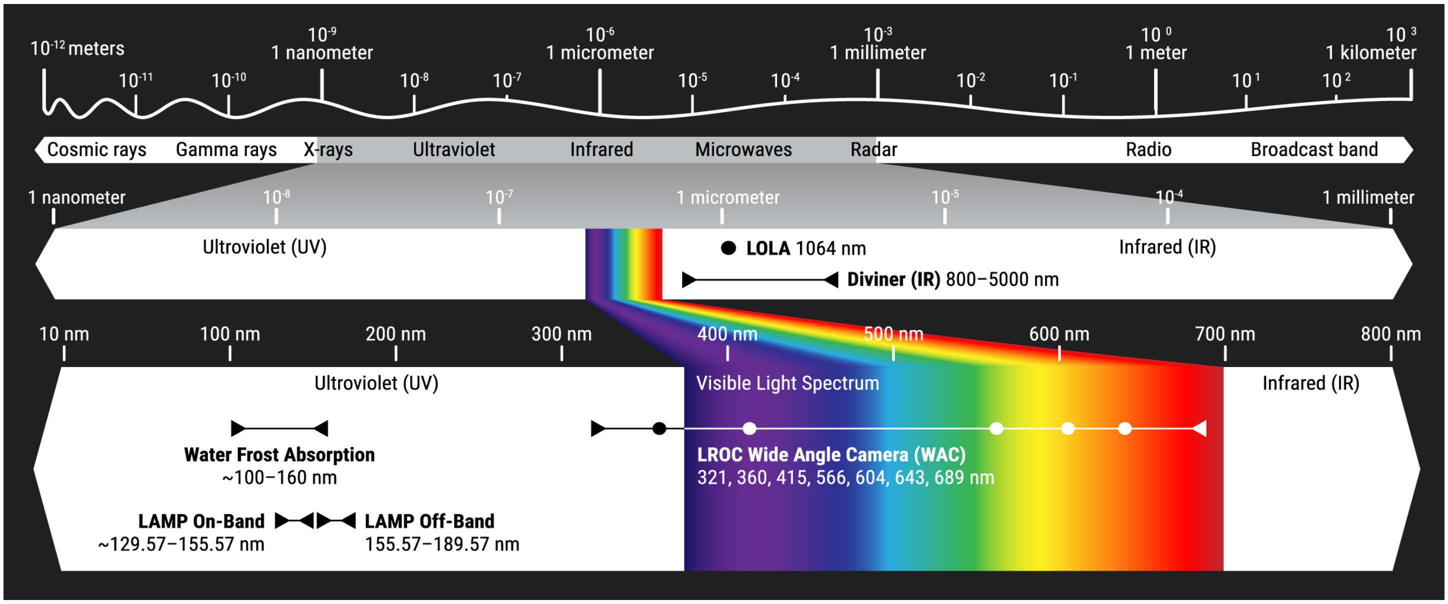


Figure 2: Electromagnetic (EM) spectrum showing the various wavelengths of light detected by instruments on-board the Lunar Reconnaissance Orbiter. Each instrument can only measure a specific wavelength range, and each provides a different type of information: Diviner measures surface temperature using infrared emission (from 2500 to 4000 nm), the Lyman-Alpha Mapping Project (LAMP) identifies water frost using far-ultraviolet reflectance (from 130 to 190 nm), and the Lunar Reconnaissance Orbiter Camera (LROC) takes pictures of the land around PSRs in visible light (400 nm to 689 nm) with the Wide Angle Camera (WAC). The Lunar Orbiter Laser Altimeter (LOLA) uses a laser to measure the height of the ground, and how reflective it is at the near-infrared wavelength of the laser (1064 nm).

Seeing in the dark

Much like the Moon is gravitationally bound to Earth, a human-made spacecraft, the Lunar Reconnaissance Orbiter, is in orbit around the Moon. Onboard the spacecraft are multiple instruments that act as camera lenses that can "see" in various waves that make up the electromagnetic spectrum (Figure 2). Observations from these instruments tell us that frozen substances, such as water ice, likely exist in some of the Moon's permanently shadowed craters. Even with the variety of data available, determining how much water ice is present, what other frozen resources exist, and the exact locations and depths of the frozen materials remain uncertain.

Water is important for future space exploration because water (H_2O) can be broken apart into hydrogen and oxygen, which can be used as rocket fuel. Rocket fuel mined from space would enable the development of a space "highway" between the Earth and Moon, and possibly beyond. And of course, water could quench the thirst of space travelers!

Next Steps?

However, to choose a landing site for future missions additional observations are needed to interpret where the water ice actually is, particularly in the subsurface, and how much of it can be used for rocket fuel.

ShadowCam, set to launch in 2022, will map terrain and search for features on the surface that may be related to water ice. ShadowCam will be 800 times more sensitive than the camera it is modeled after (the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC)), and will identify features on the ground that are > 1.7 m (5.6 feet) (or objects the size of a small car).

Improved imaging of what the surface looks like inside permanently shadowed craters will enable scientists to map obstacles such as boulders and craters, reducing travel risk for future landers and rovers. ShadowCam images of the surface will also be compared with instruments that probe the subsurface, helping scientists to interpret the locations of water ice more precisely.

At the current pace of scientific invention, humankind could be visiting the Moon's south pole in as little as a decade. But for now, mysteries remain frozen right in our backyard.

INSTRUCTIONS

Supplies:

- ***Colored pencils or other colored writing implements.***
- ***Printouts of the Coloring Page (hillshade) to color on for each participant***
- ***Digital or Printouts of the maps***

The goal of this activity is for students to identify the most likely locations of water ice on the surface. Compare each of the provided maps to find where all four maps (WAC Summer Mosaic with permanently shadowed regions (PSRs), Diviner Maximum temperature, LOLA 1064 nm albedo, and LAMP UV off/on-band ratio albedo) show results consistent with surface water ice.

Each map has a different legend, but results that are consistent with water ice are indicated by the dark blue color in each map. The PSRs are outlined in Dark Blue.

Students should try to find at least one location where astronauts should go to search for water ice. To make the activity more challenging, students can identify multiple locations where scientists suspect water ice may be. Colored pencils can be used to shade in the area(s) most likely to have water ice on the Coloring Page.
There is an answer sheet provided to check their work.

MAP DESCRIPTIONS

- ***Each map represents a different dataset from LRO, including some from instruments other than LROC.***
- ***Each map extends from 86°S to 90°S.***
- ***Latitude lines are at 1° increments and Longitude lines are at 45° increments.***

LOLA DTM Hillshade - Coloring Page

This is the image for the coloring sheet. It is a hillshade created from a 150 m pixel scale Lunar Orbiter Laser Altimeter (LOLA) digital terrain model (DTM). LOLA is the instrument on-board LRO that measures elevation by shining a laser at some spot on the surface and recording how long it takes for the reflected light to return. By combining all the measurements of reflected light, we can make maps of the Moon's topography, such as a Hillshade.

LROC WAC Summer Mosaic with PSRs

This is a mosaic of images from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) (about 100 m pixel scale) taken during the summer from 21 September 2010 to 23 October 2010. The summer is when the south pole receives the maximum amount of sunlight. Overlaid on this mosaic are outlines of the areas which are permanently shadowed. Because these areas never receive direct sunlight, it is possible that there might be water in the form of ice there.

Diviner Annual Maximum Temperature

This map shows the maximum temperature in degrees Kelvin (K) over the entire year as measured by the Diviner Lunar Radiometer Experiment (Diviner, for short) at a pixel scale of 250 m. Water ice evaporates into gas at warm temperatures, so ice can only exist in regions that stay very, very cold. In the vacuum on the Earth's surface, it takes temperatures < 110 K (< -262°F; dark blue on the map) to trap water ice and keep it from evaporating. For comparison, the coldest temperature ever recorded on Earth's surface, at Vostok Station, Antarctica, was ~184K (-128°F or -89°C).

LOLA 1064 NM Albedo Map

This map is a color-coded version of the albedo map from the Lunar Orbiter Laser Altimeter (LOLA) instrument at a 500 m pixel scale. Albedo is a measure of how much a material reflects light. So, a surface that appears brighter has a higher albedo than one that appears darker. One material that is very reflective and can appear bright is ice in the form of surface frost, so this map can help us tell where surface frost might be located. Values of >0.37 (dark blue) are bright enough to indicate surface frost.

Another kind of surface that appears bright is the walls of steep craters. So to help with interpretation, steep crater walls have been removed from this map (white).

There is some striping at the edges of this image. These are artifacts (errors) in the data. While we try very hard to understand and correct for all the factors that affect the data (like where the spacecraft is during observations) when producing maps like this, there is still sometimes uncertainty in the data that isn't yet understood, and this can show up as minor glitches in the final product.

LAMP UV Off/On-Band Albedo Ratio Map

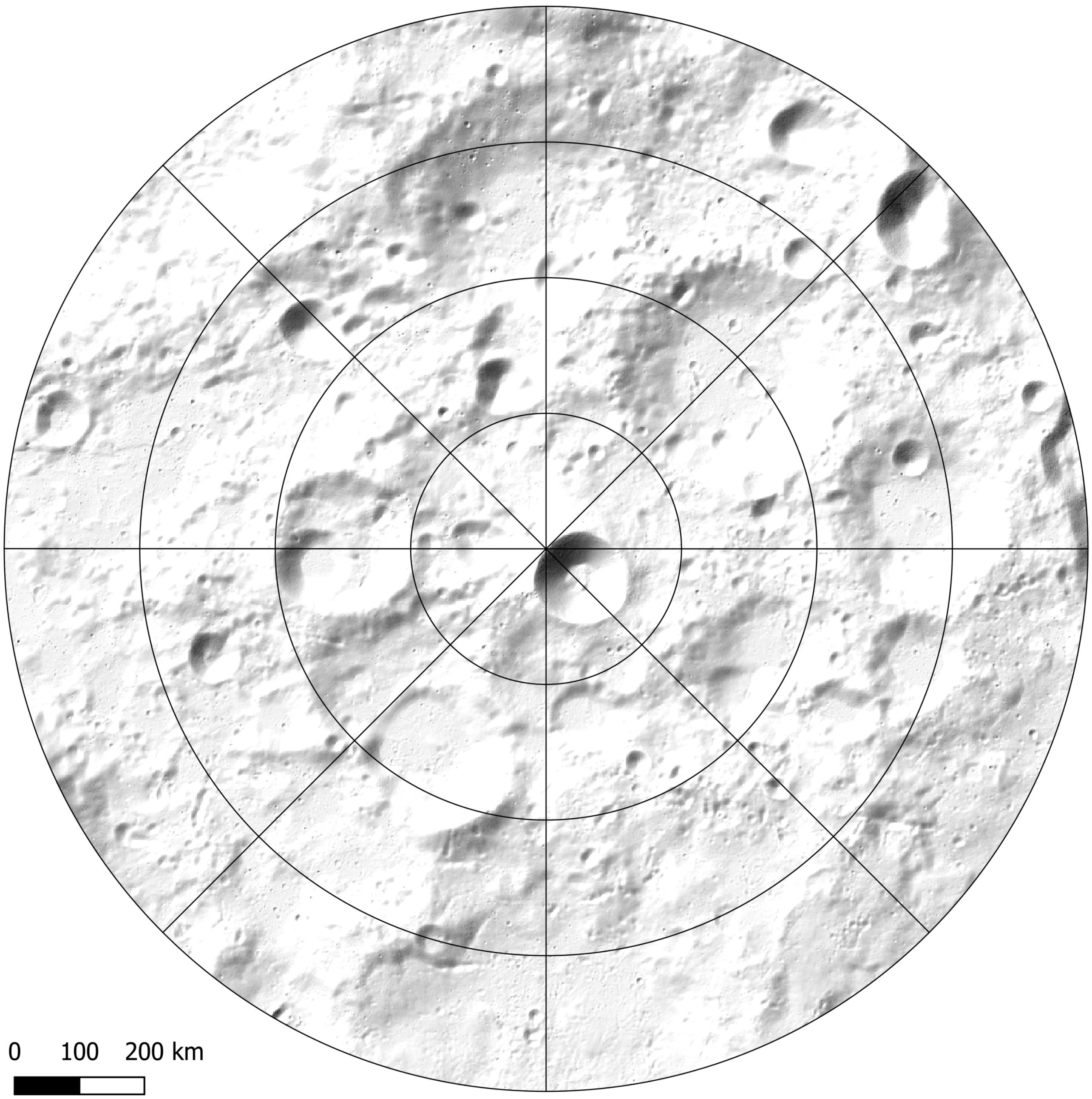
This map shows the reflectance (or albedo) in the ultraviolet (UV) spectrum, measured by the Lyman-Alpha Mapping Project (LAMP) instrument at a pixel scale of 250 m. The 155.57-189.57 nm wavelength range (also called the "Off-band) is a near-perfect reflector of water ice, while the 129.57-155.57 nm wavelength range ("On-band") is not. To see the differences between the two wavelengths, the LAMP team divided the values in the Off-band map by the values in the On-band map to make a ratio map. The Off/On-band ratio map is used to easily detect water frost absorption, which occurs at ~100 -160 nm. The ratio map shows that at temperatures below 110 K, PSRs increase in UV reflectance. Water ice is not the only highly reflective feature within PSRs though, so bright features like crater rims are removed from the ratio map where temperatures are too high for ice to be stable on the surface.

Water Ice Map (Answer Sheet)

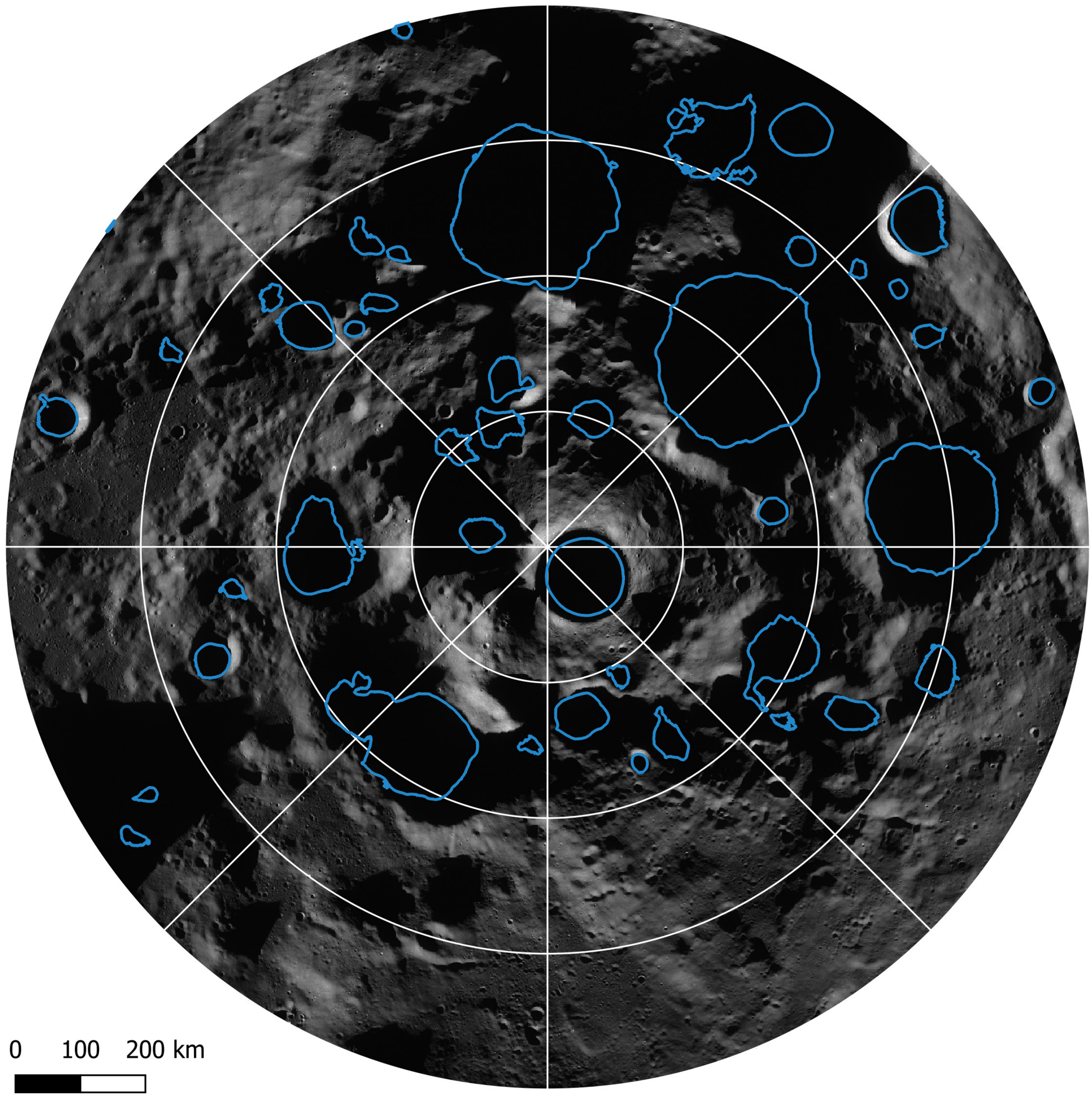
Surface frost extents. Dark blue indicates locations where LAMP UV albedo (values >= 1.2) and LOLA albedo (values >= 0.35) intersect in craters where average annual maximum temperatures never exceed 110 K.

The distribution of water ice in the subsurface is still unclear to scientists!

COLORING PAGE - HILLSHADE

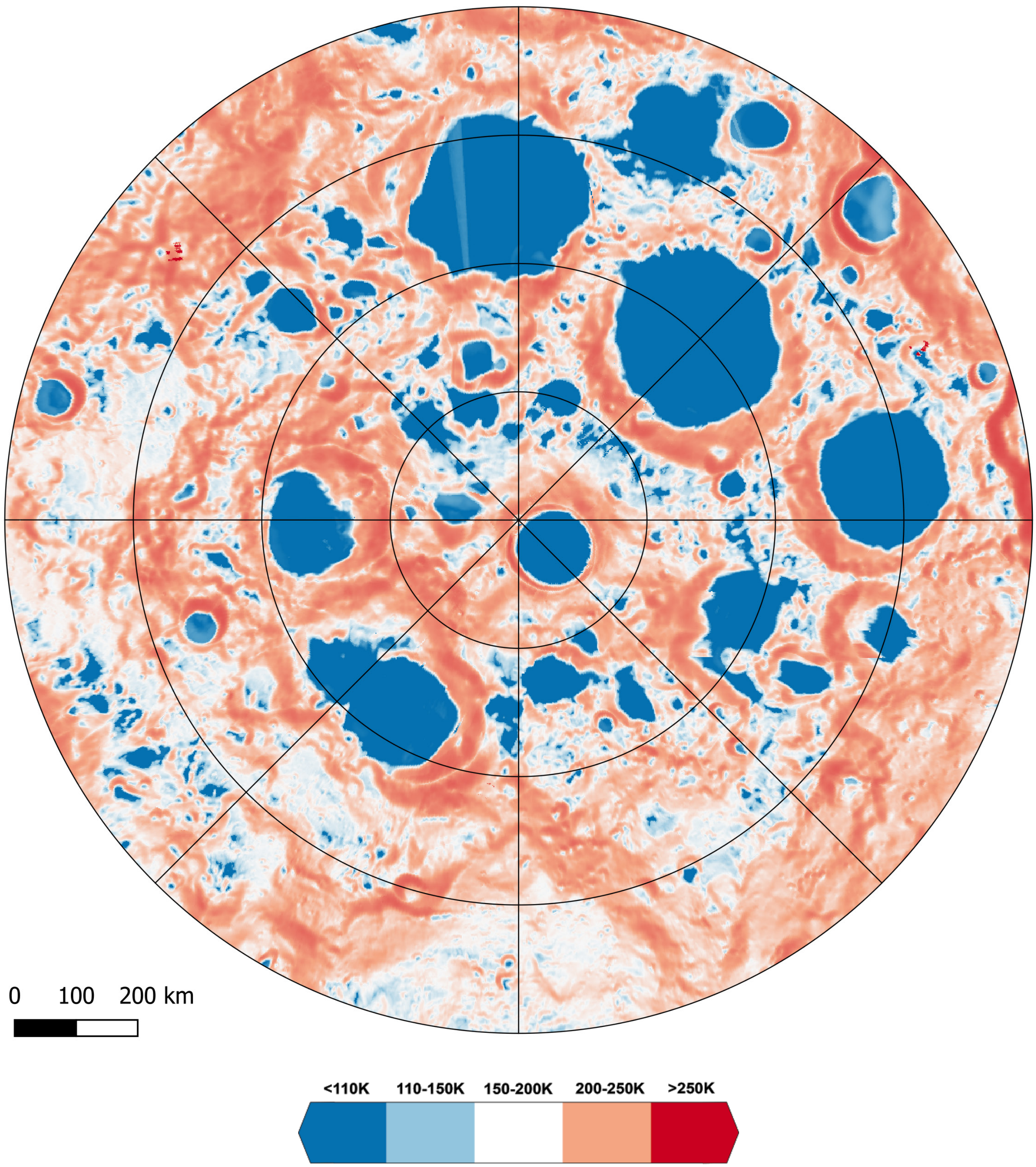


LROC WAC SUMMER MOSAIC WITH PSRs



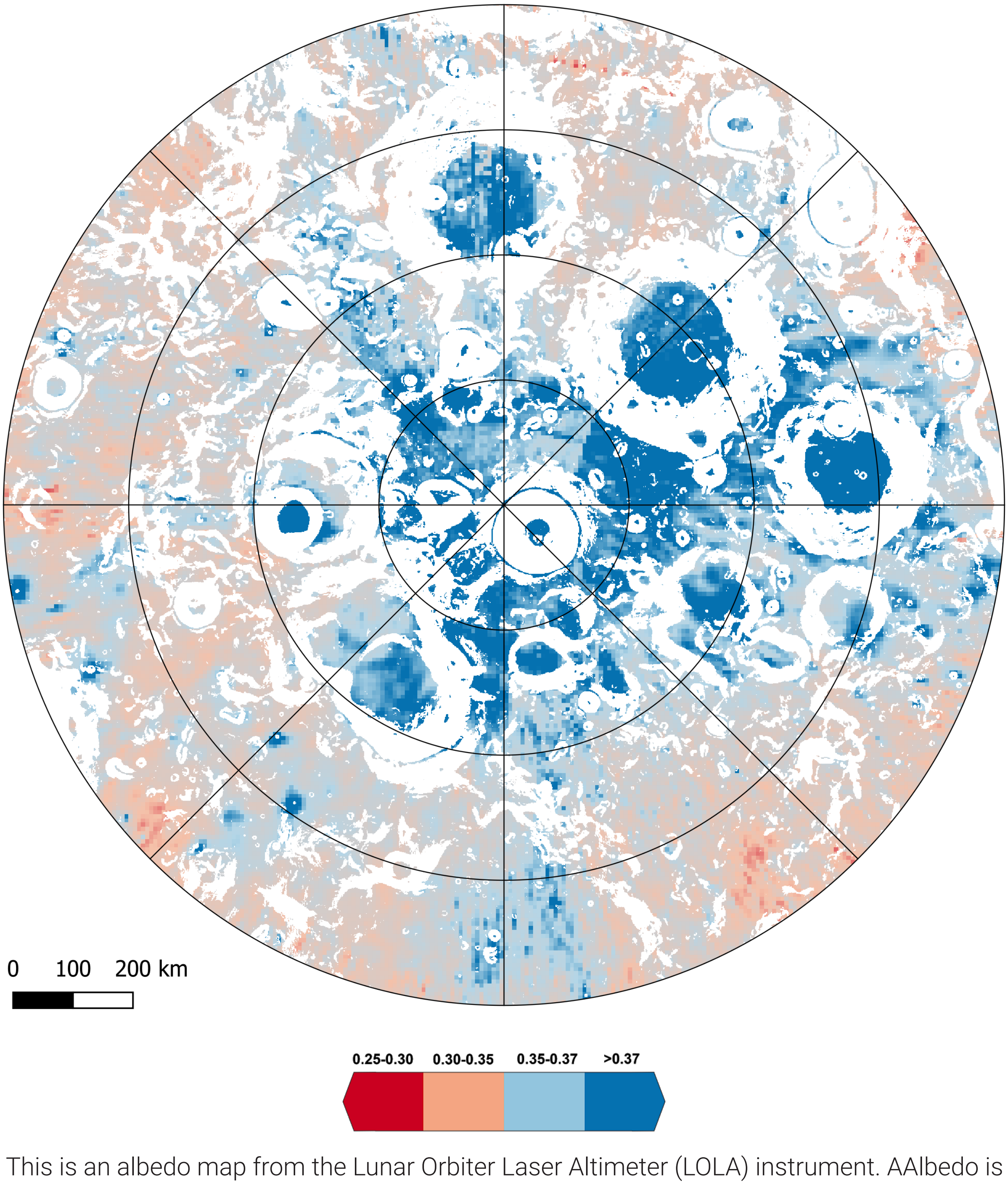
This is a mosaic of images from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) taken during the summer (from 21 September 2010 to 23 October 2010). The summer is when the south pole receives the maximum amount of sunlight, but still not enough to light up the insides of most craters. Outlined in dark blue are the areas which are permanently shadowed. Because these areas never receive direct sunlight, it is possible that there might be water in the form of ice there.

DIVINER MAXIMUM TEMPERATURE



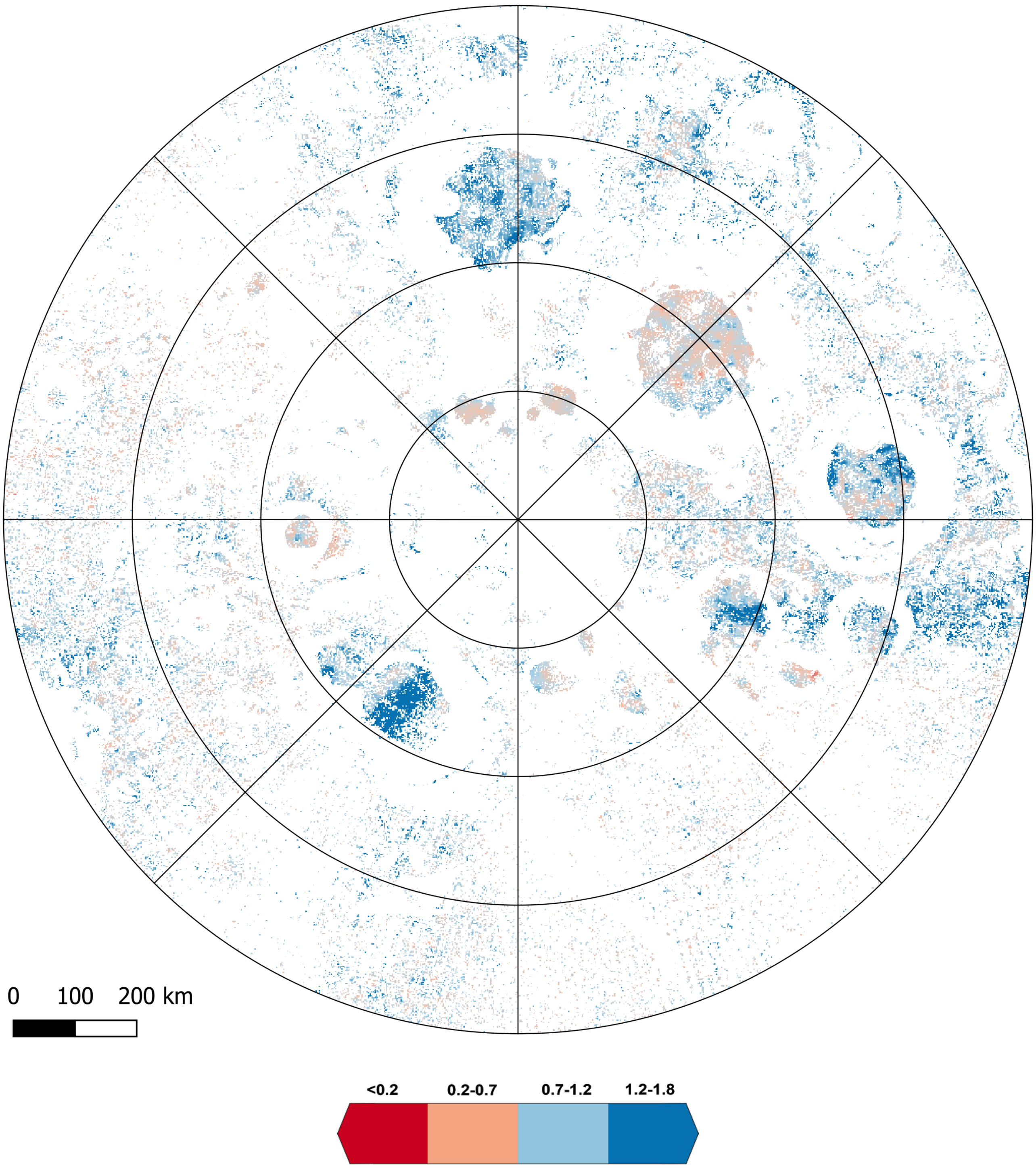
This map shows the maximum temperature in degrees Kelvin (K) over the entire year as measured by the Diviner Lunar Radiometer Experiment (Diviner, for short). Values < 110 K (dark blue) are cold enough to trap water ice.

LOLA 1064 NM ALBEDO MAP



This is an albedo map from the Lunar Orbiter Laser Altimeter (LOLA) instrument. AAlbedo is a measure of how much a material reflects light. So, a surface that appears brighter has a higher albedo than one that appears darker. One material that is reflective and can appear bright is ice in the form of surface frost, so this map can help us tell where surface frost might be located. Another surface that appears bright is crater walls, so to help with interpretation, the steep slopes have been removed from this map (White). Values of >0.37 (dark blue) are bright enough to indicate surface frost.

LAMP UV OFF ON-BAND RATIO UV ALBEDO MAP



This map shows the reflectance (or albedo) in the ultraviolet (UV) spectrum, measured by the LAMP instrument. LAMP's Off-band is a near-perfect reflector of water ice, so the LAMP team took the ratio of the "On-Band" and "Off-Band" maps to more easily detect water frost absorption. Values >1.2 (dark blue) are consistent with surface water ice.

STUDENT GUIDE

INTRODUCTION

We want to send astronauts back to the Moon to areas near the south pole that have frozen water (referred to as water ice in this guide). But first, we need to discover where water ice is the most plentiful. To do this, we need to compare information from many of the instruments on the Lunar Reconnaissance Orbiter (LRO) to find out which areas show water ice in all the datasets. Scientists are doing studies very similar to this to answer the same question! Help scientists locate where water ice exists on the surface in the form of surface frost. Locations of surface frost will help scientists search for water ice and other frozen resources that are buried beneath the surface.

BACKGROUND INFORMATION

There are regions near the Moon's poles that never receive sunlight (Figure 1). Such regions, known as permanently shadowed regions (PSRs), can maintain very cold temperatures (down to -415°F or -248°C!). At these cold temperatures, there can be ice made from many frozen substances, including water, carbon dioxide (CO^2), sulfur, and hydrogen.

INSTRUCTIONS

Supplies:

- ***Colored pencils, markers, or other writing tools.***
- ***Printouts of the Coloring Page - Hillshade to color on for each student***
- ***Digital or Printouts of the maps***

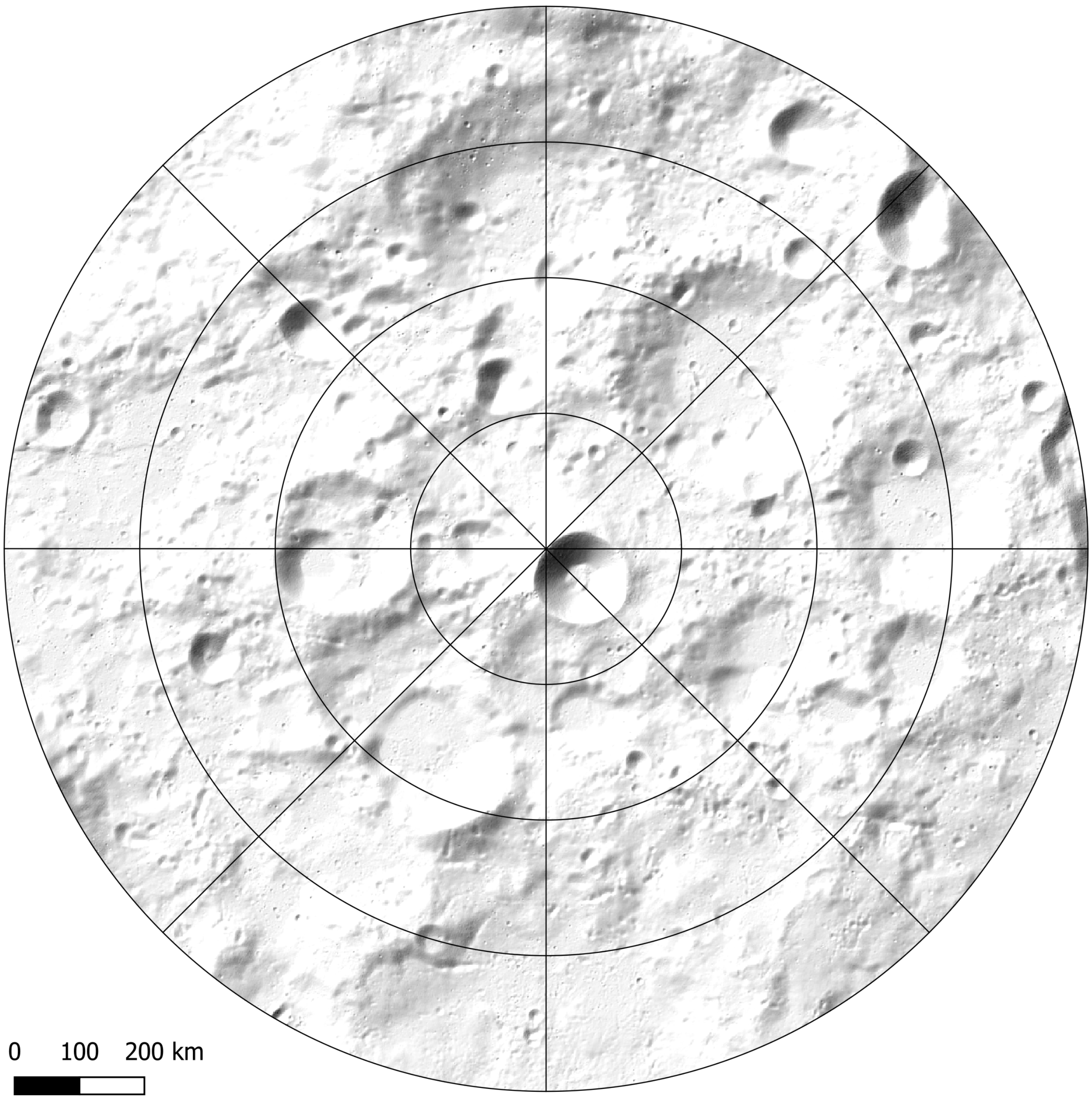
The goal of this activity is to help scientists figure out where water ice might be on the surface. Compare each of the maps to find where all four maps (WAC Summer Mosaic with PSRs, Diviner Maximum Temperature, LOLA 1064 nm albedo, and LAMP UV off/on-band ratio albedo) show results consistent with surface water ice.

Each map has a different legend, but results that are consistent with surface water ice are indicated by the dark blue color in each map. The PSRs are also outlined in dark blue.

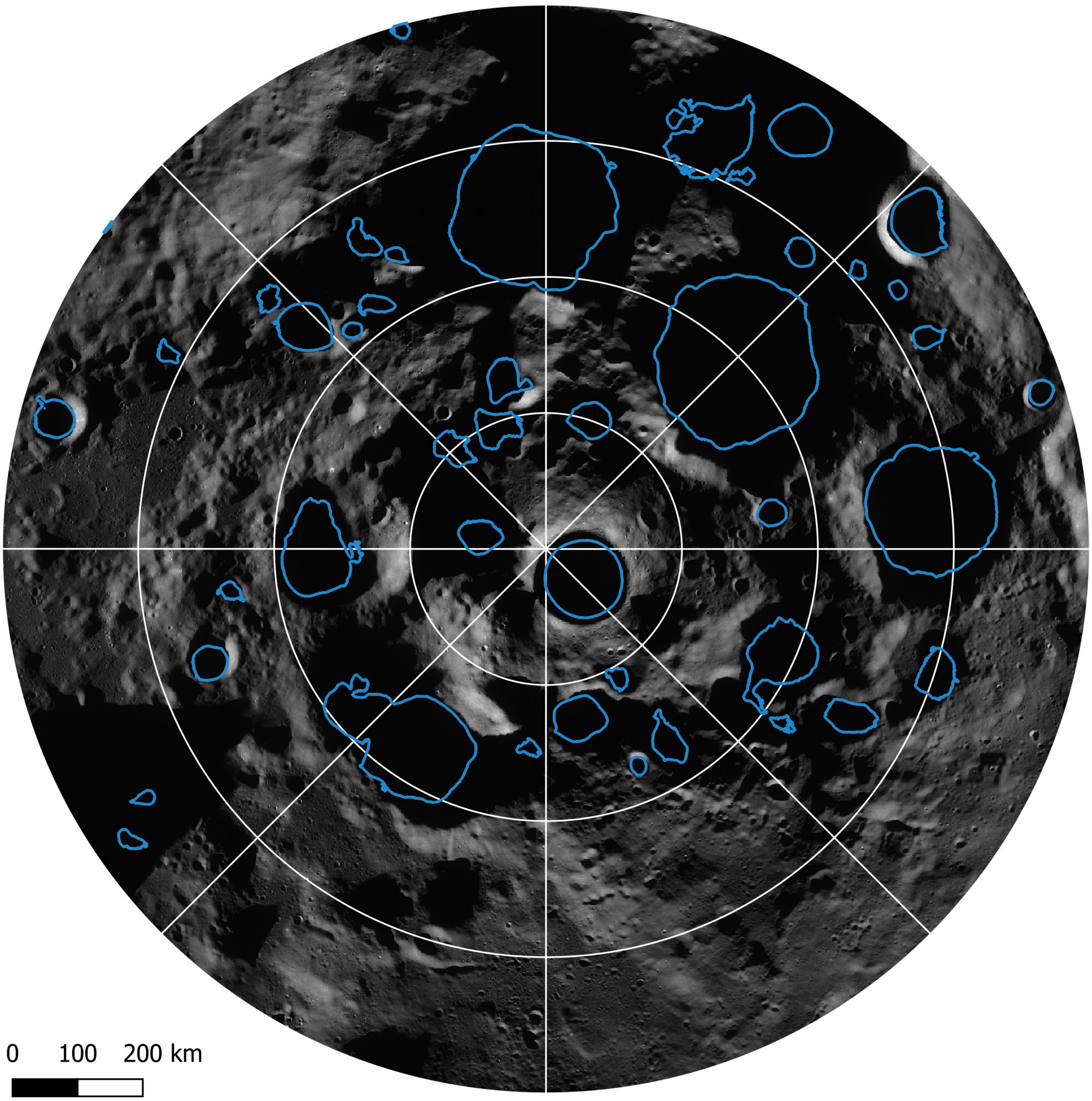
Try to find at least one location where astronauts should go to search for water ice. There are several locations that might contain water ice, so to make the activity more challenging, identify multiple locations where scientists suspect water ice may be. Colored pencils can be used to shade in the area(s) most likely to have water ice on the Coloring Page.

There is an answer sheet provided in the instructor packet so you can check your work.

COLORING PAGE - HILLSHADE



LROC WAC SUMMER MOSAIC WITH PSRs



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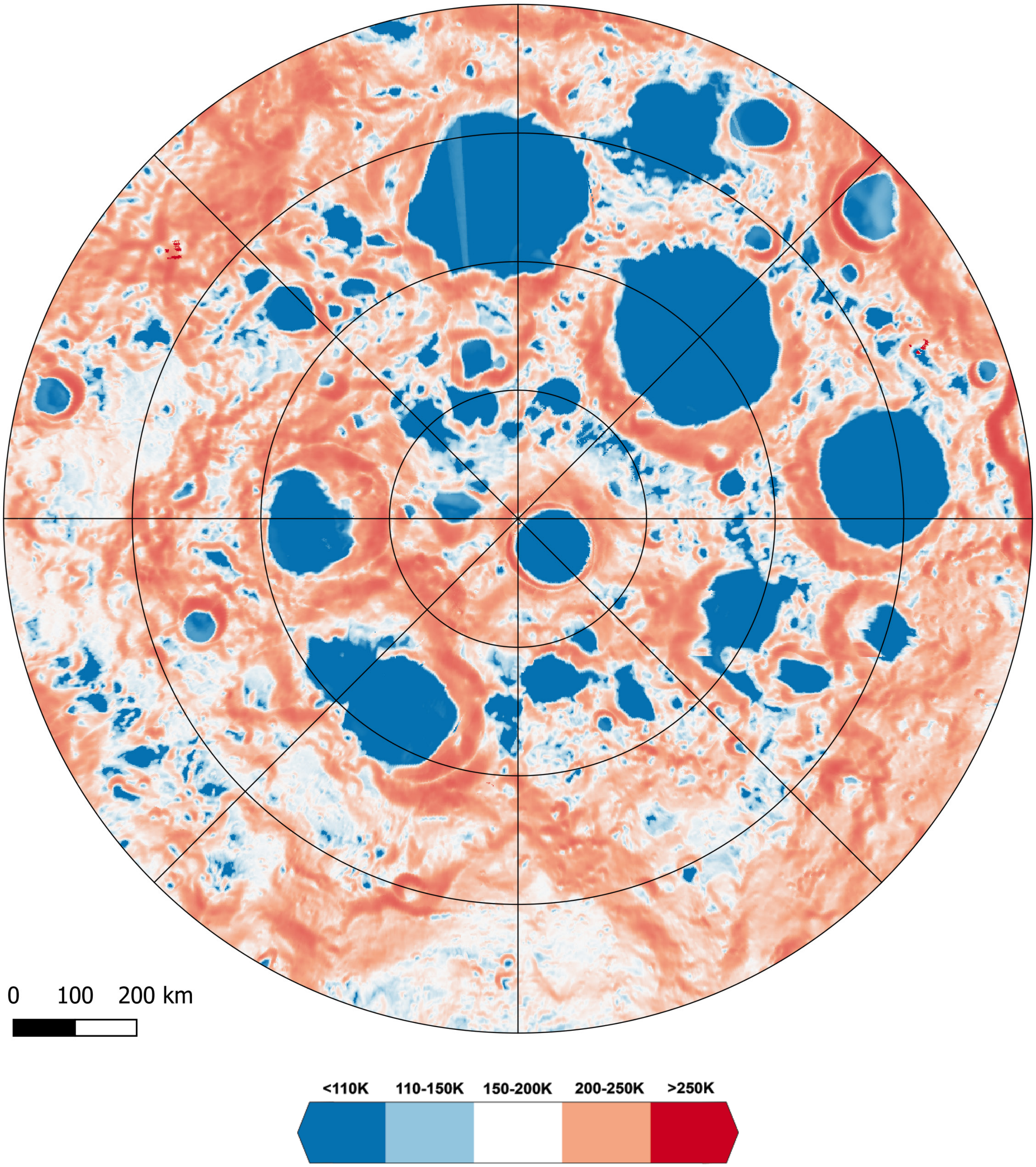
DIVINER MAXIMUM TEMPERATURE



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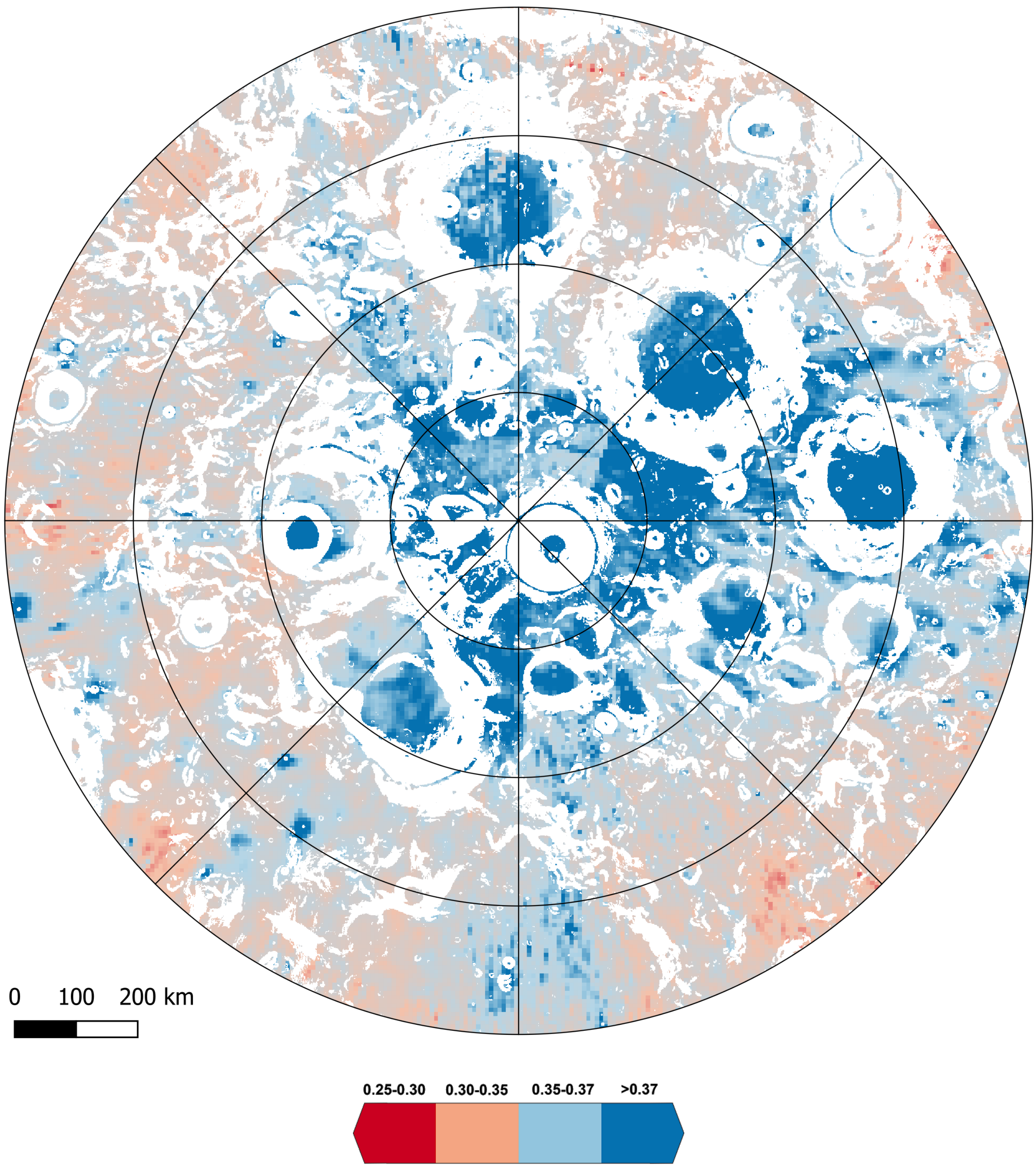
LOLA 1064 NM ALBEDO MAP



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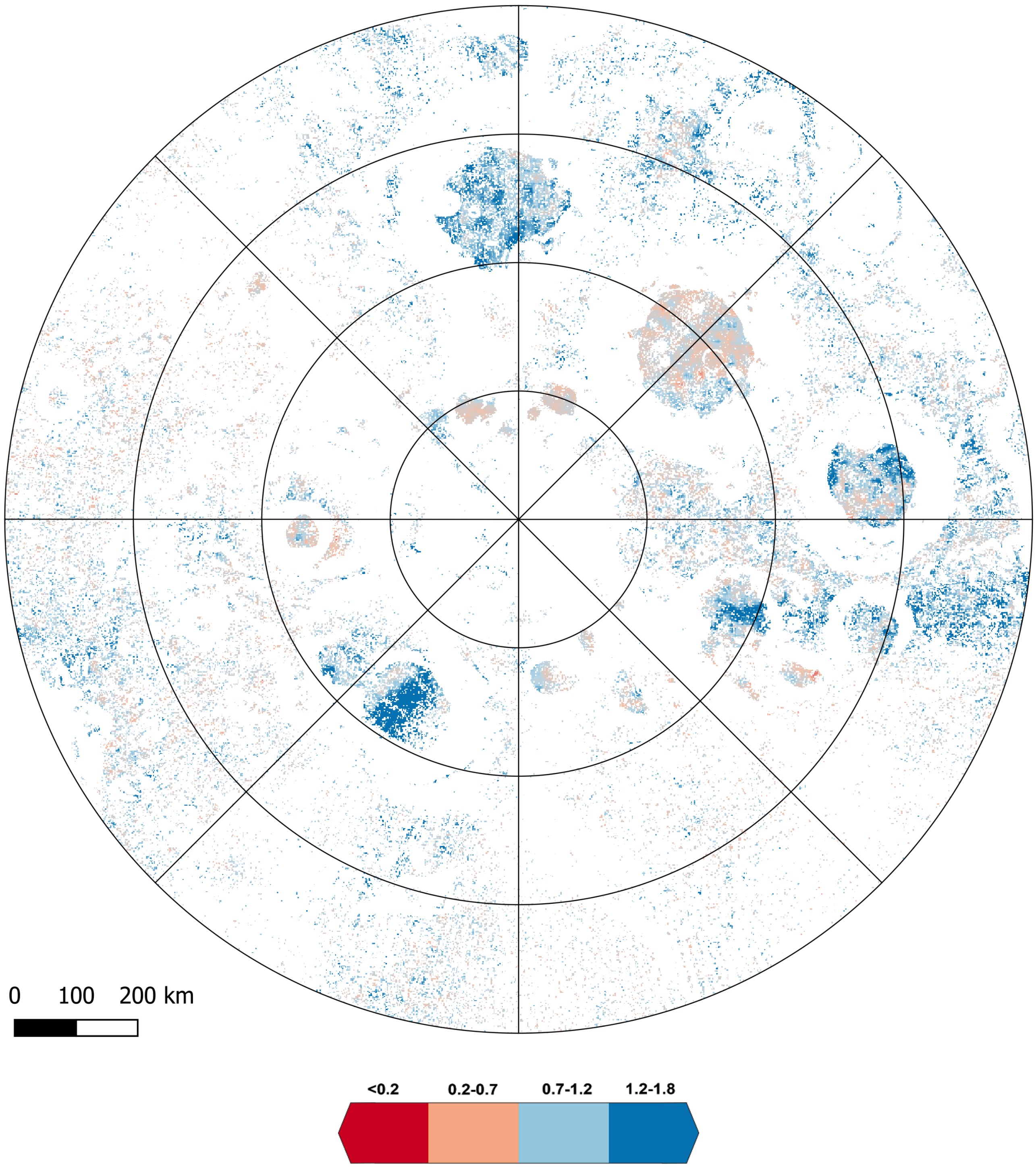
LAMP OFF ON-BAND RATIO UV ALBEDO MAP



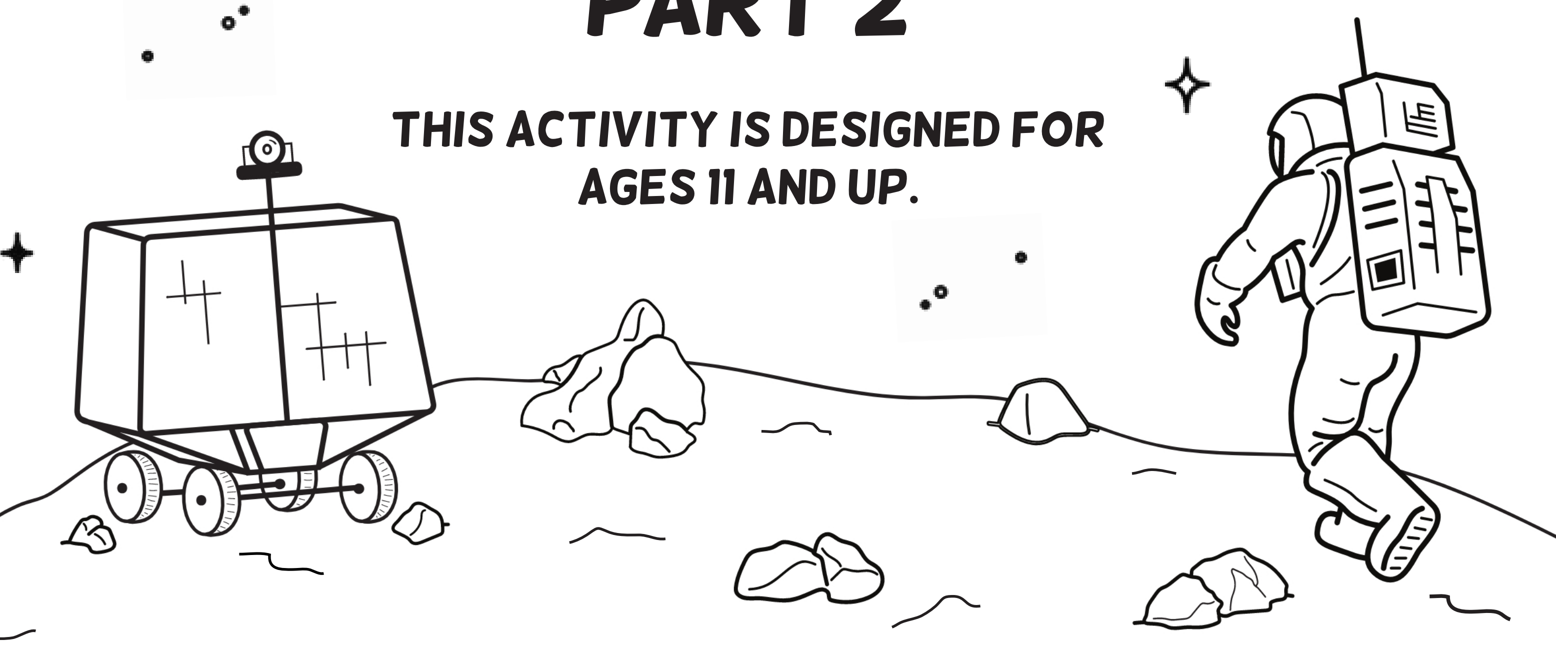
This map is an albedo map from the Lunar Orbiter Laser Altimeter (LOLA) instrument. Albedo is a measure of how bright or dark materials are. One material that is reflective and can appear bright is ice in the form of surface frost, so this map can help us tell where surface frost might be located. Values of >0.37 (dark blue) are bright enough to indicate surface frost.

THE MYSTERY OF LUNAR WATER

HELP SCIENTISTS UNCOVER WATER ICE ON THE MOON

PART 2

THIS ACTIVITY IS DESIGNED FOR AGES 11 AND UP.



INSTRUCTOR GUIDE

INTRODUCTION

Identifying locations with water ice on the surface is only part of the puzzle scientists and engineers are trying to solve. Many of the conditions that are ideal for preserving water ice are not very safe for human exploration. Ideal exploration conditions involve relatively flat surfaces (<15 degrees), plenty of sunlight for power, and good line-of-sight communication with Earth. To safely find and use any water ice resources on the Moon, we need to plan a mission that lands somewhere much safer, then traverses with a rover to the water ice. Scientists and engineers at NASA, commercial spaceflight organizations, and non-NASA governmental organizations are currently examining datasets like these to plan future missions to the lunar south pole! Help them to plan a mission by choosing a safe landing site, then planning a traverse that takes them to a surface water frost location identified in Part 1 of this activity.

BACKGROUND INFORMATION

Mission Requirements

Robotic missions to the Moon are a combination of engineering and science considerations. From an engineering point of view, flat areas with a clear view of the Earth for communications and abundant energy from the sun is an ideal place to be. However, scientists want data from under boulders, inside craters, and along boulder-strewn debris paths. The job of mission planners is to reconcile these differing requirements to achieve the most science goals possible with a realistic and safe rover design.

Communication with Earth

The Moon is tidally locked with Earth, which means that the same side of the Moon always faces the Earth (we call this the nearside). This creates a challenge when planning a rover mission at the pole because about one half of the pole does not have a direct line of communication with Earth. Rovers need to communicate with Earth to upload all the data they collect on the surface. Also, for manned missions, this means that astronauts do not have the support of the operations team on Earth, and for unmanned missions, this means that the rover cannot receive any commands.

To overcome this challenge, NASA could put a communications satellite into orbit, similar to Queqiao, the satellite used for Chang'e 4, the first lander on the far side of the Moon. NASA is also developing the Lunar Gateway, a deep space habitat that will not only serve as a base and communications hub for lunar missions but also will be a science lab.

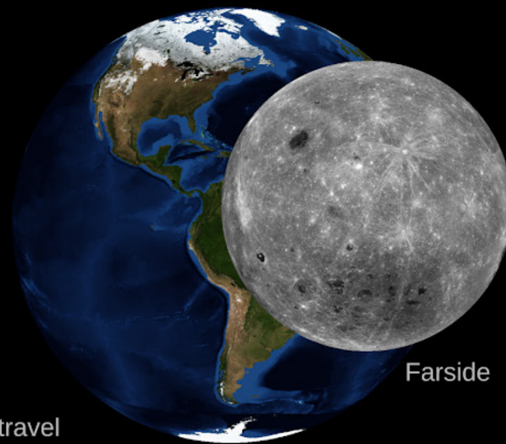
Direct communication with Earth during and immediately after landing is especially important because data sent by the spacecraft can be monitored and commands can be sent if needed during touch-down. Also, the rover will need to communicate with Earth during its initial start-up and checks. The lag time for radio signals from the rover to reach engineers on Earth (called latency) is about three seconds for a round-trip from the Earth to the Moon and back (Cooper et al. 2005). When engineers send a rover to Mars, the lag in communication time will be even greater (minimum of three minutes).

Abundant Sunlight for Power

Lunar rovers will likely be solar-powered, as sunlight is, in general, a readily available and reliable power source on the Moon. However, solar energy becomes more difficult at the poles, as the shadowed regions that allow ice to exist also prevent solar panels from charging the batteries. Traverses will need to be carefully planned and rovers carefully designed with solar power constraints in mind. When scientists plan missions to the south pole, they will pay close attention to the available light and how it changes every day over the entire mission. For a 30 day mission, like the one the students are planning here, just over one day will happen on the Moon.

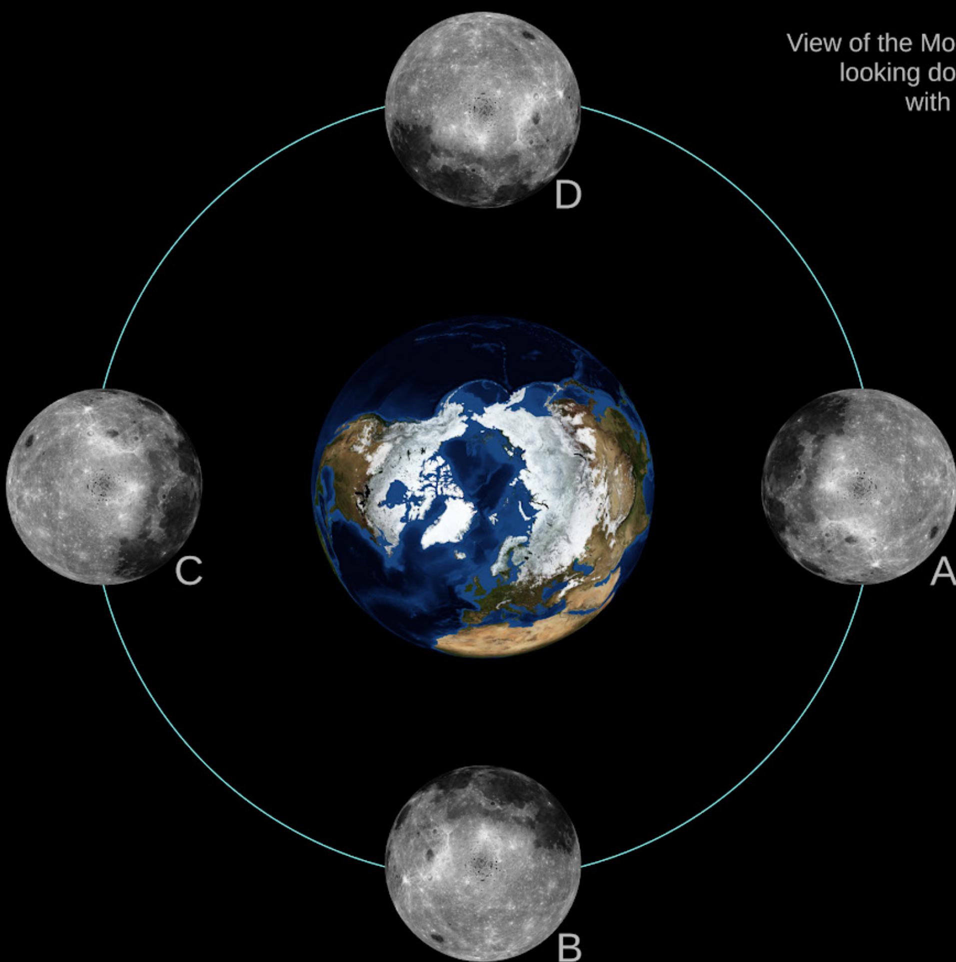
Since available light will change throughout one lunar day, a successful mission would land in terrain that stays consistently illuminated throughout the year. Once the rover has landed, direct sunlight for power is essential for the rover to undergo its initial checks, which allow engineers to make sure the rover is healthy. Additionally, having access to lots of solar power ensures that the rover doesn't unexpectedly run out of power and that it can begin its traverse with full batteries.

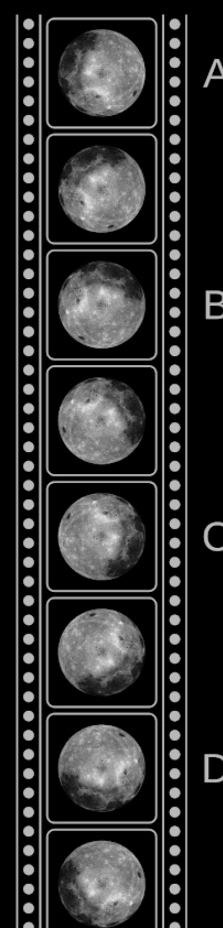
The LROC WAC Polar Illumination map provided in this activity was initially created to help scientists plan missions and find sites that have the most abundant sunlight year-round.



From the Earth, we can only see the nearside of the Moon.
To see the farside of the Moon, a spacecraft would have to travel beyond the Moon and look back towards the Earth.

View of the Moon's orbit around the Earth looking down towards the North Pole with a "filmstrip" of the rotation.
(Not to scale)





The Moon rotates once every orbit around the Earth.
This is called "tidal locking" and means only the nearside of the Moon has a clear path for radio signals to reach the Earth.

Hazard Avoidance

Landing site selection is one of the most important decisions for any rover mission. While during the course of a rover mission the rover can drive into dark areas, or climb up a steep slope, the landing site must have direct communication with Earth, abundant sunlight for energy, and avoid surface obstructions.

To avoid topographic obstructions, the landing site must have slopes <5° within an oval of space called a landing ellipse. For the Apollo missions to the Moon, the landing ellipse was 15 km by 5 km in diameter, which gave engineers a margin of error when landing the spacecraft. The area must be relatively free of boulders and craters. To identify obstructions and potential hazards, scientists spend a lot of time looking at surface roughness maps, and high-resolution images of the potential landing zones, such as those taken with the LROC Narrow Angle Cameras (about 0.5 meters per pixel resolution at the South Pole).

Lunar Rovers

To safely traverse on the uneven lunar terrain, engineers must give special consideration to a rover's suspension and drive systems. The suspension system provides control and stability, allowing the rover to drive over obstacles (such as craters and boulders) by minimizing tilt. A simple, light weight, yet sturdy as possible suspension system is ideal. When the rover encounters an area with obstacles its suspension is unable to handle, it must either drive around (perhaps many kilometers out of its way), or be able to carefully maneuver between the obstacles.

Older rovers such as the Apollo Lunar Roving Vehicles (LRVs) accomplished obstacle avoidance by providing car-like steering on both the front and rear ends. This steering capability allowed the LRVs to have a tight turn radius (in comparison to traditional vehicles that steer with the front wheels only). For future rovers, engineers look to improve upon this drive system design by providing independent steering to each wheel. The four-wheel steering system will allow the rover to turn in place and drive sideways.

Successful Landed Lunar Missions

There have been seven successful landed lunar missions with rovers; the Apollo Lunar Roving Vehicle (LRV) used during the United State's Apollo 15, 16, and 17 missions, Soviet Union's Lunokhod 1 & 2, and Chinese landers Yutu and Yutu 2.

The Apollo LRV was used to transport astronauts, tools, scientific equipment, communications gear, and lunar samples across large distances, allowing the crew to explore more of the Moon than on previous missions. The LRV could operate for 78 hours and travel up to 65 km (40 mi) during the lunar day. The rover is 3.1 meters long, 2.3 meters wide, and 1.14 meters tall, and was capable of carrying more than twice its own weight, or 490 kg (1080 lbs).

The Lunokhod rovers were the first robotic rovers landed on the Moon.They were designed to support the planned Soviet crewed lunar missions before those missions were canceled shortly after the success of the Apollo missions. Lunokhod 1 drove 10.5 km (6.5 mi), and Lunokhod 2 drove 39 km (24 mi) on the Moon.

Yutu (Jade Rabbit) and Yutu 2 landed on the lunar surface as part of China's Chang'e 3 & 4 missions. Chang'e 3 landed and deployed Yutu in 2013 and Chang'e 4 landed and deployed Yutu 2 in 2019. The objectives of the Chinese Lunar Exploration Program that launched the Chang'e missions is to help pave the way for future human exploration missions.

No lunar landed missions have yet been attempted at the poles or in permanently shadowed craters. However NASA is planning the Volatiles Investigating Polar Exploration Rover (VIPER), which will explore the south pole in late 2023 in search of water ice and other potential resources.

For a complete list of rovers, see our activity, Rovers of the Solar System!

INSTRUCTIONS

During the first part of this activity, the most interesting locations to gather scientific data for water ice on the surface were identified. Using the rover's capabilities, how many of those areas can be visited by the rover during its limited time? Where will the rover land? Where will it go? What PSRs will it study? If students want more of a challenge, encourage them to consider possible extended missions; can the rover explore the most interesting areas, and be in a good position to continue exploring other targets if it survives longer than planned?

For this exercise, there is a small number of important engineering constraints to design the mission around:

Rover design:

- ***The rover can travel 60 km on a full battery charge.***
- ***The rover travels at up to 15 km/h***
- ***The rover can operate for 78 hours before needing to recharge.***
- ***The rover may survive longer and have extended missions, but has been designed to operate for a minimum of 1 lunar cycle (27.5 earth days).***

Landing site constraints	Traverse constraints	Associated LRO maps
The site must have exposure to Sun to maintain power during initial rover checks	Rover must be in sunlight to transmit high-speed science data and to receive battery recharge	LROC WAC Polar Illumination Map
Slope <5°; flat terrain is best	Rover can climb slopes up to 15°	LOLA Slope Map
Means of communicating with Earth	Rover must have a view of Earth to return data	LOLA Earth Visibility Map

Table 1. Engineering constraints for a safe landing site and successful rover traverses.

Slope (°)	Speed	Power Requirements (Watts)
Relatively flat (+/- 2°)	15 km/hr	646 W
5°	15 km/hr	893 W
10°	15 km/hr	1303 W
15°	15 km/hr	1693 W

Table 2. Engineering constraints for how much power a rover has during its traverse based on slope of surface and speed travelled.

Landing site constraints:

- ***The landing area must have a slope <5°***
- ***The landing area must have a view of the Earth for communication during the landing sequence.***
- ***The landing area must be relatively free of large boulders.***
- ***The landing area must have exposure to the Sun to maintain power during initial rover checks.***

Traverse constraints:

- ***The rover must have a view of the Earth to return data.***
- ***The rover must be in sunlight to transmit high-speed science data.***
- ***The rover can climb slopes up to 15°.***

If students would like more of a challenge, encourage them to consider the following questions:

- ***Using the rover's capabilities, how many water ice deposits can be visited by the rover during its limited time?***
- ***If the rover were on an extended mission, could it explore the most interesting areas, and be in a good position to continue exploring other targets if it survives longer than planned?***

Students can use Table 2 to consider how the slope of the surface affects the speed in which a rover can travel. Speed plays an important role in how far the rover can explore before needing a battery recharge.

Students can consider rover power constraints, assuming that on the Moon the rover weighs 116 kg:

- ***The battery capacity of the rover is 8700 watt hours.***
- ***A 1300 W load would last about 6 hours.***
- ***Half the speed would use half the power.***
- ***Given a solar panel that could output 300 W, the rover could recharge 300 W of battery per hour assuming full illumination.***
- ***It would take the rover approximately 29 hours (or a little over one day) to fully recharge.***

Supplies:

- ***Something to write with: pencil, pen, markers, colored pencils, etc.***
- ***Printouts of the Planning Sheet (Hillshade) to write on for each student.***
- ***Digital or Printouts of the maps.***
- ***(Optional) Ruler to help more accurately measure distances. There are many free, printable rulers online and they are available in most graphics programs.***

Map Descriptions:

- ***Each map represents a different dataset from LRO.***
- ***Each map extends from 88°S to 90°S.***
- ***The grid has 10 km by 10 km squares.***

LOLA DTM Hillshade - Planning Sheet

This is the map to print for planning the manned rover mission. It is a hillshade created from a 150 m pixel scale Lunar Orbiter Laser Altimeter (LOLA) digital terrain model (DTM) with the results from the surface-frost analysis overlaid in black. LOLA is the instrument on-board LRO that measures elevation by recording how long it takes to bounce 5 laser spots to the Moon and detect it on the spacecraft. By combining all the spots, we can make maps of the Moon's topography.

LROC WAC Polar Illumination Map

This map is created from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) taken over an entire year, and the values in it represent the percentage of time that each pixel was illuminated during that year. Areas with surface frost are indicated by gray. While the slight tilt of the Moon creates areas that never seen any illumination (0%), it also means there are areas that see sunlight more than half the time (up to 71.7% of the time) - more than anywhere on Earth. This is good news for polar explorers since most of the equipment sent to the Moon is solar powered. Any areas that are blue are illuminated more than 45% of the time, with areas that are dark blue having the most sunlight. Any planned traverses should try to stay in illuminated areas as much as possible, and must not be in shadowed areas for more than 30 hours.

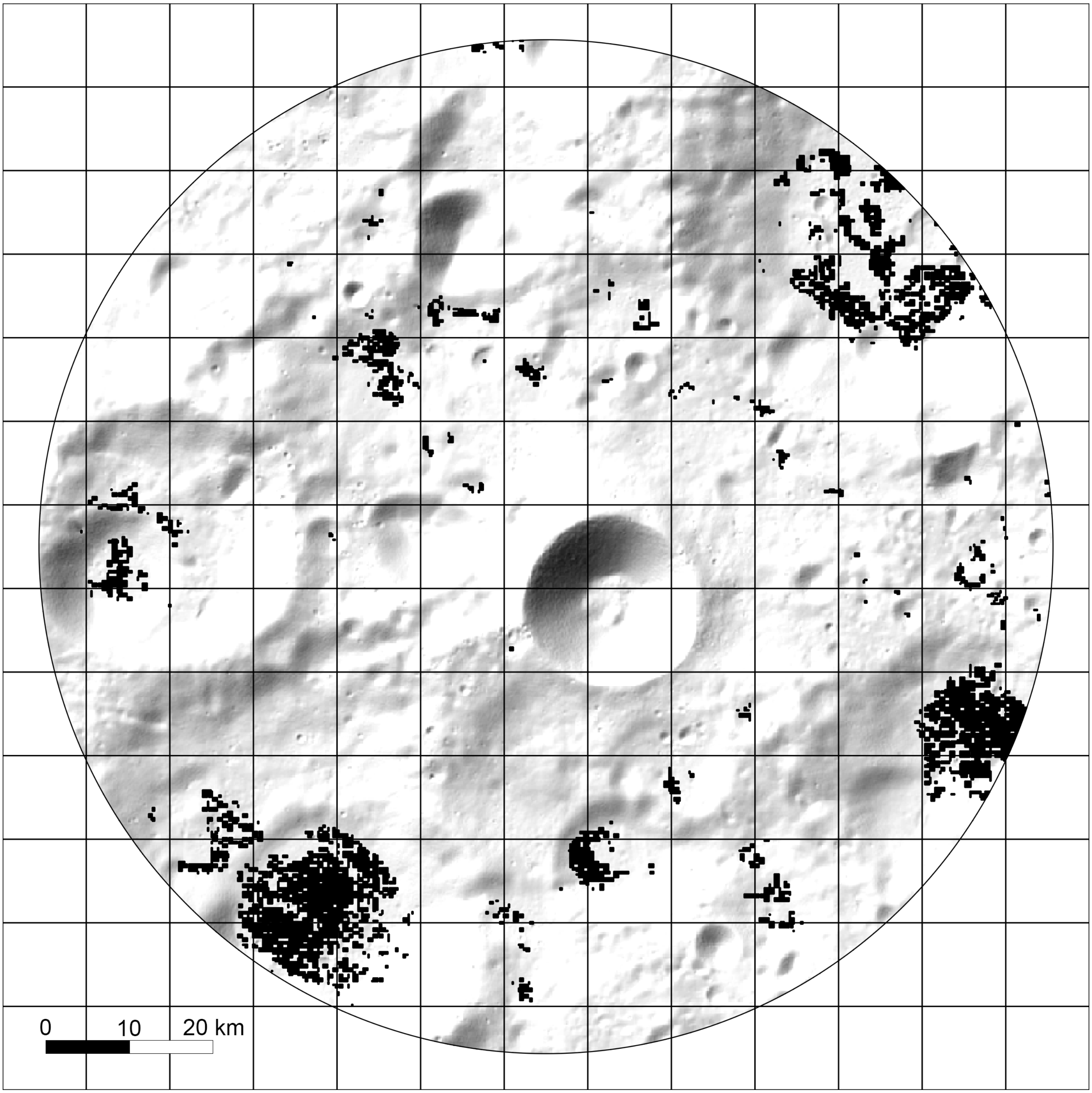
LOLA Slope Map

This map shows the angle of the surface, or slope, for the lunar surface. It was created from a 25 m/px LOLA digital elevation map, similar to the one used to create the hillshade. Slope is a very important consideration when planning rover traverses, as slopes must be less than 15 degrees to be traversable. If they are 15 degrees or larger there is a serious risk of the rover tipping or sliding downhill. These are indicated by shades of blue. Landing sites must be even flatter, with slopes <5 degrees (indicated by dark blue). Areas with surface frost are indicated by dark gray.

LOLA Earth Visibility Map

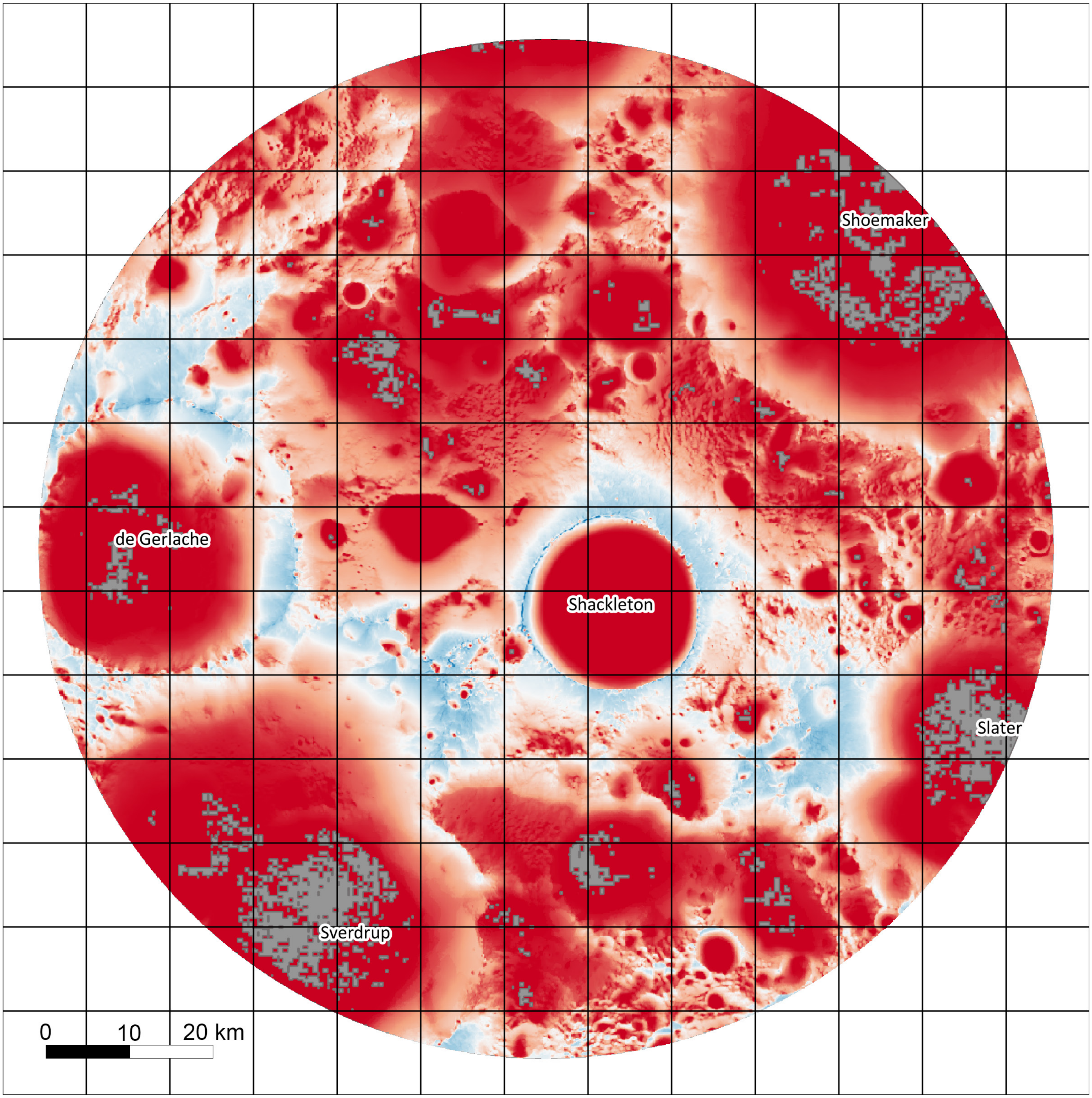
This map shows the average visibility of Earth from the lunar south pole. The Moon is tidally locked, so the same side, called the nearside, faces the Earth. To communicate with Earth, rovers need direct line-of-sight communication with Earth. This map shows the average percent of the Earth is visible with direct line-of-sight communication. Areas that are blue have enough visibility to send data back to Earth. It is also safer to stay as much as possible in areas with line-of-sight communication with Earth. Areas with surface frost are indicated by gray.

PLANNING SHEET - HILLSHADE



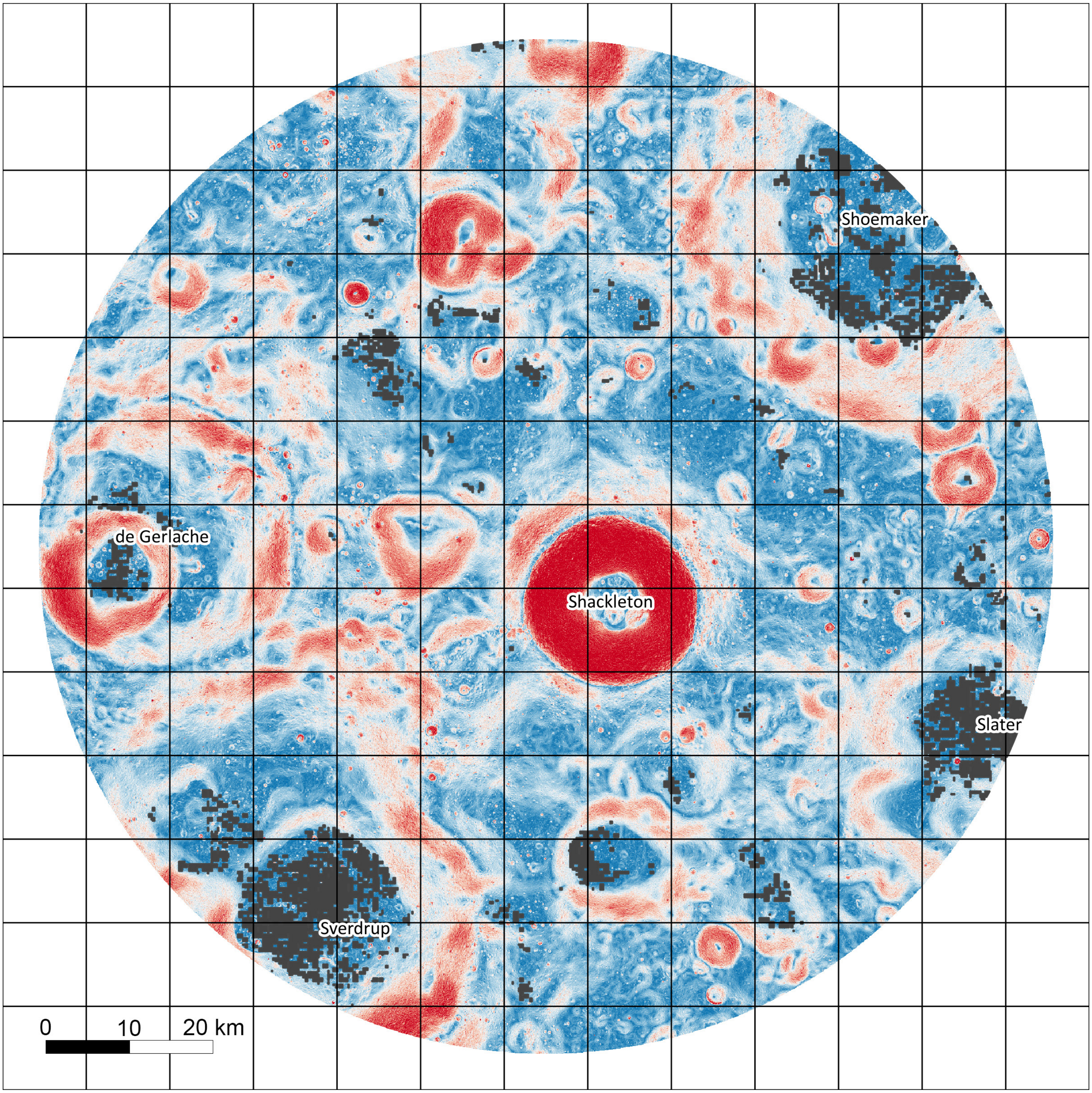
This is the map to print for planning the manned rover mission. It is a hillshade created from a 150 m pixel scale Lunar Orbiter Laser Altimeter (LOLA) digital terrain model (DTM) with the results from the surface-frost analysis overlaid in Black.

LROC WAC POLAR ILLUMINATION MAP



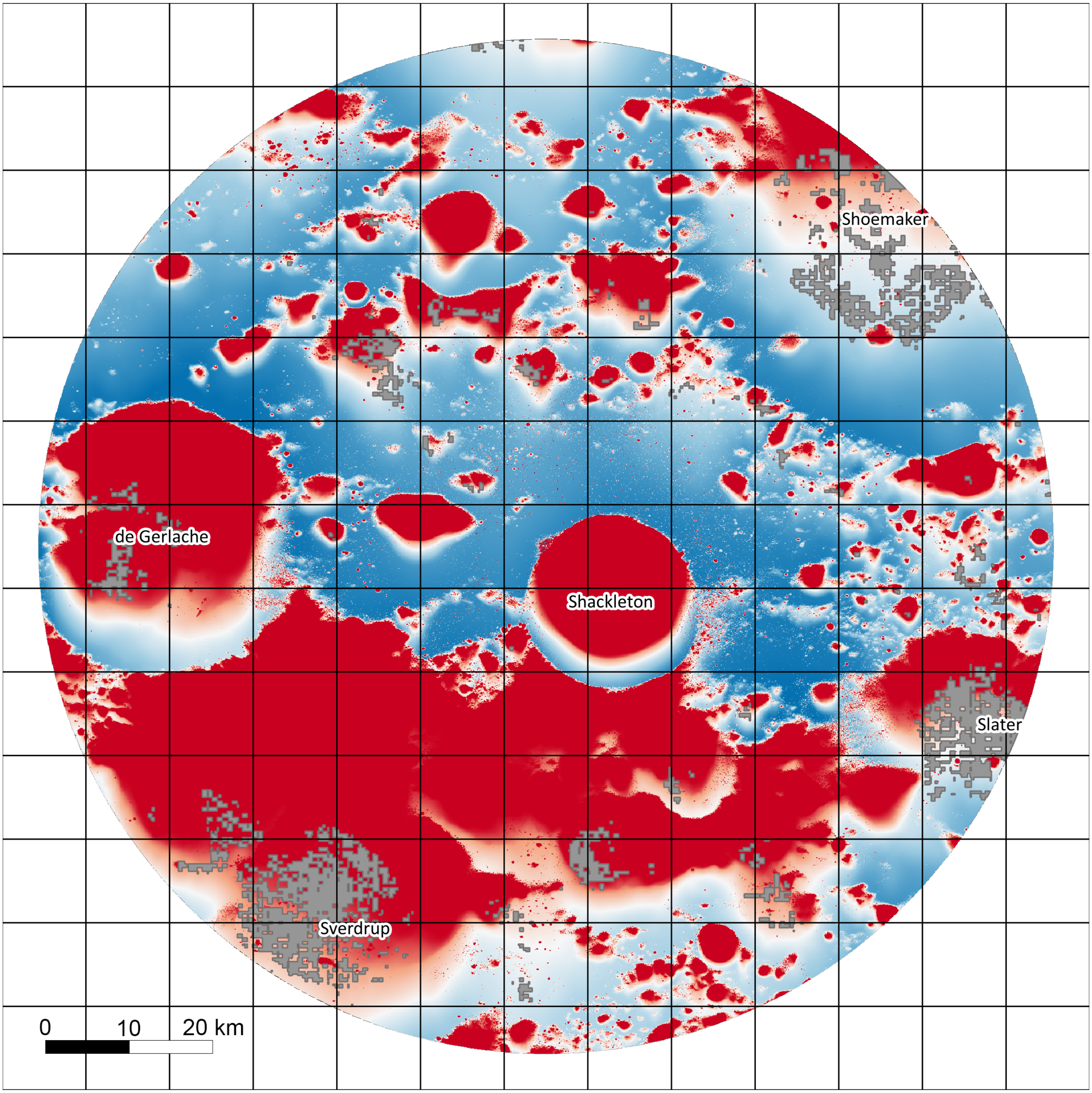
This map is created from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) taken over an entire year, and the values in it represent the percentage of time that each pixel was illuminated during that year. Areas with surface frost are indicated by gray. Any areas that are blue are illuminated more than 45% of the time, with areas that are dark blue having the most sunlight.

LOLA SLOPE MAP

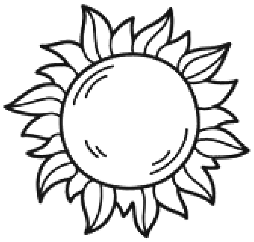


This map shows the angle of the surface, or slope, for the lunar surface. If slopes are 15 degrees or larger the rover cannot traverse them. These are indicated by shades of blue. Landing sites must be even flatter, with slopes <5 degrees (indicated by dark blue). Areas with surface frost are indicated by dark gray.

LOLA POLAR EARTH VISIBILITY MAP



This map shows the average visibility of Earth from the lunar south pole. The Moon is tidally locked, so the same side, called the nearside, faces the Earth. To communicate with Earth, rovers need direct line-of-sight communication with Earth. This map shows the average percent of the Earth is visible with direct line-of-sight communication. Areas that are blue have enough visibility to send data back to Earth. Areas with surface frost are indicated by gray.



STUDENT GUIDE

INTRODUCTION

Identifying locations with water ice on the surface is only part of the puzzle scientists and engineers are trying to solve. The harsh environments that host water ice are not very safe for human exploration. Robots and humans have to find a way to survive where there is no sunlight, extremely cold temperatures, and hazardous travel kilometers deep in a crater. A safe and successful mission would have conditions such as plenty of sunlight for power, relatively flat surfaces (<15 degrees slope), and be able to see and communicate with Earth (good line-of-sight communication).

To safely find and use any water ice resources on the Moon, we need to plan a mission that first lands somewhere much safer and sets up a lunar outpost, then travels with a rover to the water ice. Scientists and engineers at NASA as well as other commercial spaceflight organizations are currently using datasets like these to plan future missions to the lunar south pole! Help them to plan a mission by choosing a safe landing site, then planning a traverse that takes them to a surface water frost location identified in Part 1 of this activity.

INSTRUCTIONS

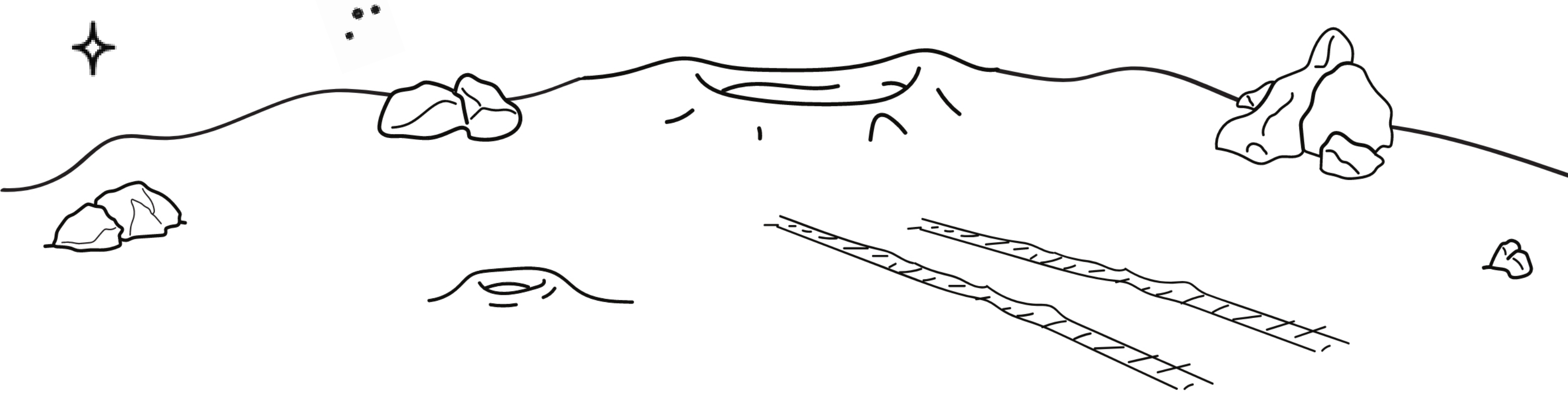
Now that you have found at least one location where you think astronauts should go to find water ice, help scientists plan a mission to send a manned rover to confirm the findings! Where will the rover land? Where will it go? What PSRs will it study? Using the three provided maps (WAC Polar illumination, LOLA slope, and LOLA earth visibility), identify the safest landing site and traverse path for the rover to travel to find water ice. Use the LOLA DTM hillshade map to plan your mission!

To choose a safe landing site and plan a traverse path for your rover, the following engineering hazards must be considered:

Rover Design:
- ***The rover can travel 60 km on a full battery charge.***
- ***The rover travels at up to 15 km/h***
- ***The rover can operate for 78 hours before needing to recharge.***
- ***The rover may survive longer and have extended missions, but has been designed to operate for a minimum of 1 lunar cycle (27.5 earth days).***

Landing site constraints:
- ***The landing area must have a slope <5°***
- ***The landing area must have a view of the Earth for communication during the landing sequence.***
- ***The landing area must have exposure to the Sun to maintain power during initial rover checks.***

Traverse constraints:
- ***The rover must have a view of the Earth to return data.***
- ***The rover must be in sunlight to transmit high-speed science data.***
- ***The rover can climb slopes up to 15°.***



- Use the table below to help you design a safe and successful mission to search for water ice and other resources:

Landing site constraints	Traverse constraints	Associated LRO maps
The site must have exposure to Sun to maintain power during initial rover checks	Rover must be in sunlight to transmit high-speed science data and to receive battery recharge	LROC WAC Polar Illumination Map
Slope <5°; flat terrain is best	Rover can climb slopes up to 15°	LOLA Slope Map
Means of communicating with Earth	Rover must have a view of Earth to return data	LOLA Earth Visibility Map

Table 1. Engineering constraints for a safe landing site and successful rover traverses.

If you would like more of a challenge, consider the following questions using table 1 and 2:

- ***Using the rover's capabilities, how many water ice deposits can be visited by the rover during its limited time?***
- ***If the rover were on an extended mission, could it explore the most interesting areas, and be in a good position to continue exploring other targets if it survives longer than planned?***

Power constraints, assuming that on the Moon the rover weighs 116 kg:

- ***The battery capacity of the rover is 8700 watt hours.***
- ***A 1300 W load would last about 6 hours.***
- ***Half the speed would use half the power.***
- ***Given a solar panel that could output 300 W, the rover could recharge 300 W of battery per hour assuming full illumination.***
- ***It would take the rover approximately 29 hours (or a little over one day) to fully recharge.***

Slope (°)	Speed	Power Requirements (Watts)
Relatively flat (+/- 2°)	15 km/hr	646 W
5°	15 km/hr	893 W
10°	15 km/hr	1303 W
15°	15 km/hr	1693 W

Table 2. Engineering constraints for how much power a rover has during its traverse based on slope of surface and speed travelled.

Supplies:

- ***Something to write with: pencil, pen, markers, colored pencils, etc.***
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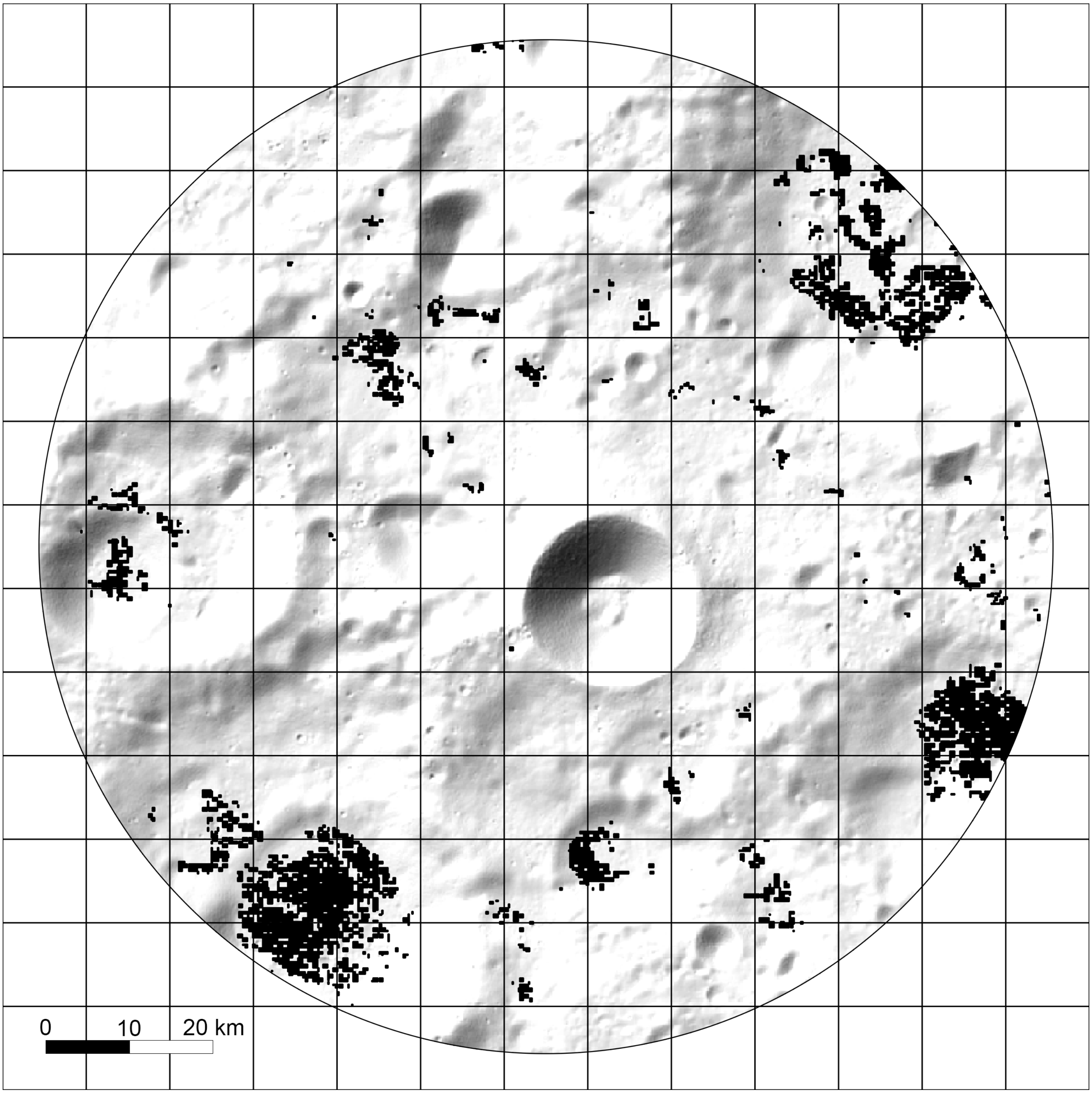
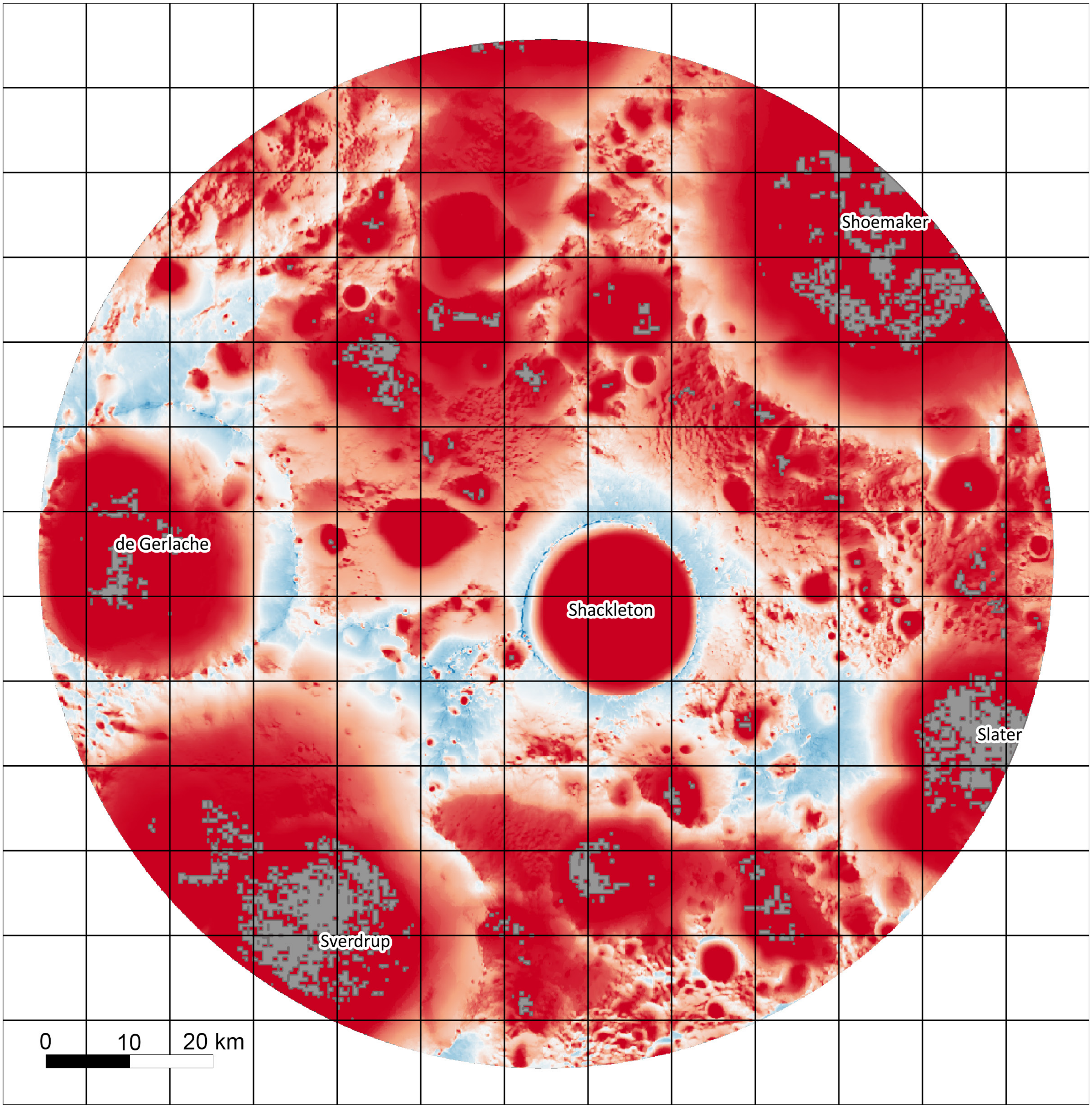
- ***Digital or Printouts of the maps.***
- ***(Optional) Ruler to help more accurately measure distances. There are many free, printable rulers online and they are available in most graphics programs.***

PLANNING SHEET - HILLSHADE



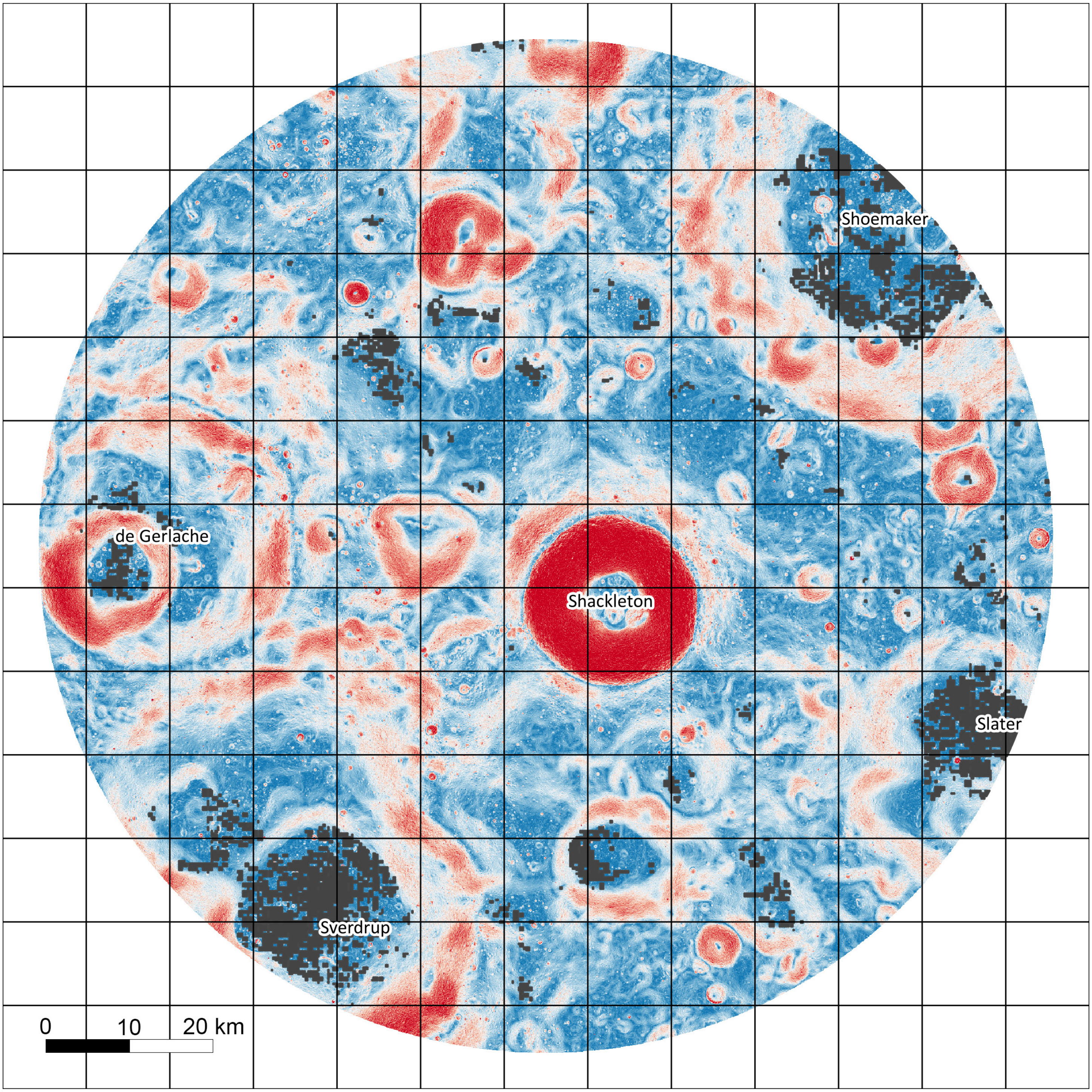
This is the map to print for planning the manned rover mission. It is a hillshade created from a 150 m pixel scale Lunar Orbiter Laser Altimeter (LOLA) digital terrain model (DTM) with the results from the surface-frost analysis overlaid in Black.

LROC WAC POLAR ILLUMINATION MAP



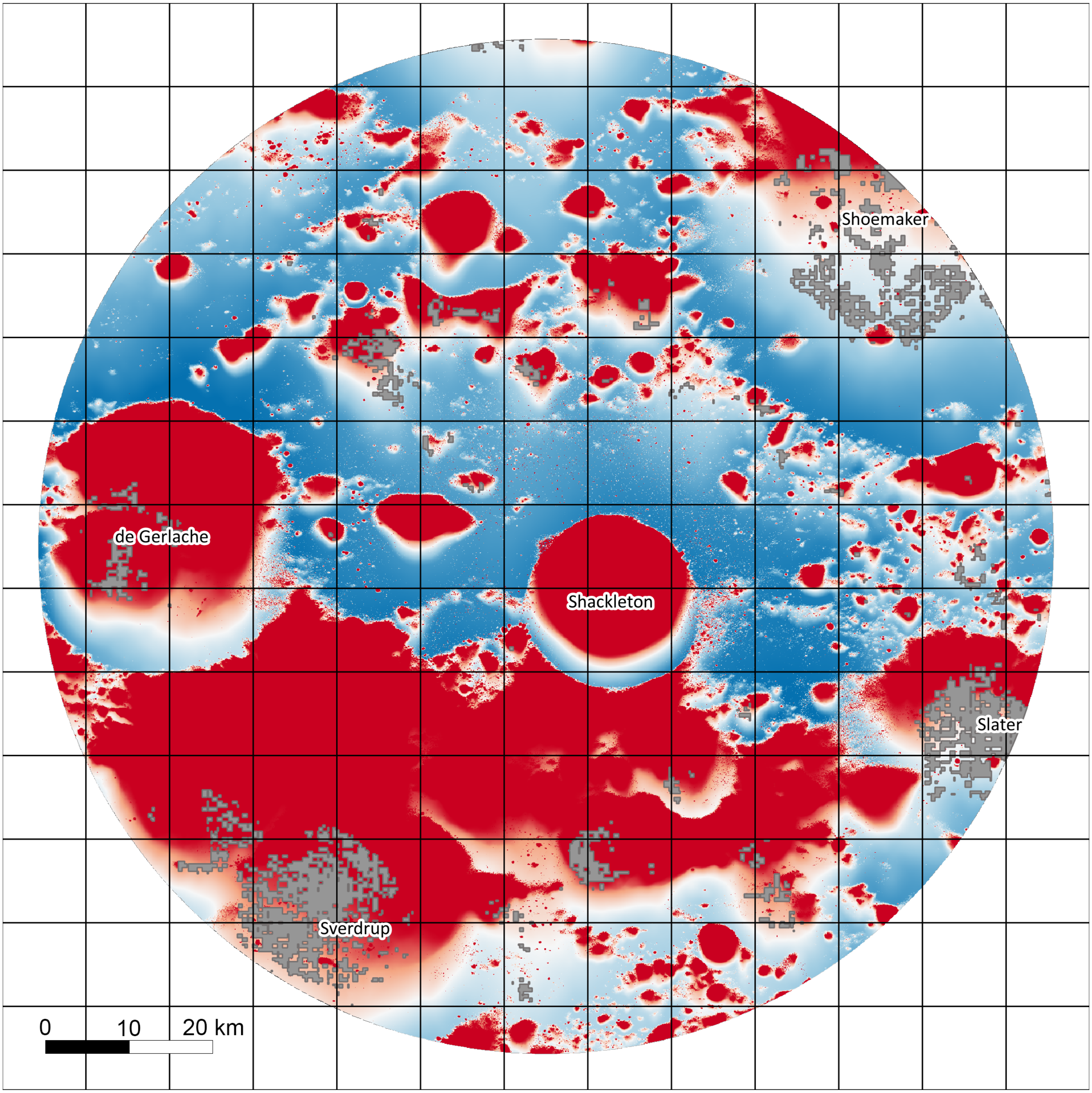
This map is created from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) taken over an entire year, and the values in it represent the percentage of time that each pixel was illuminated during that year. Areas with surface frost are indicated by gray. Any areas that are blue are illuminated more than 45% of the time, with areas that are dark blue having the most sunlight.

LOLA SLOPE MAP



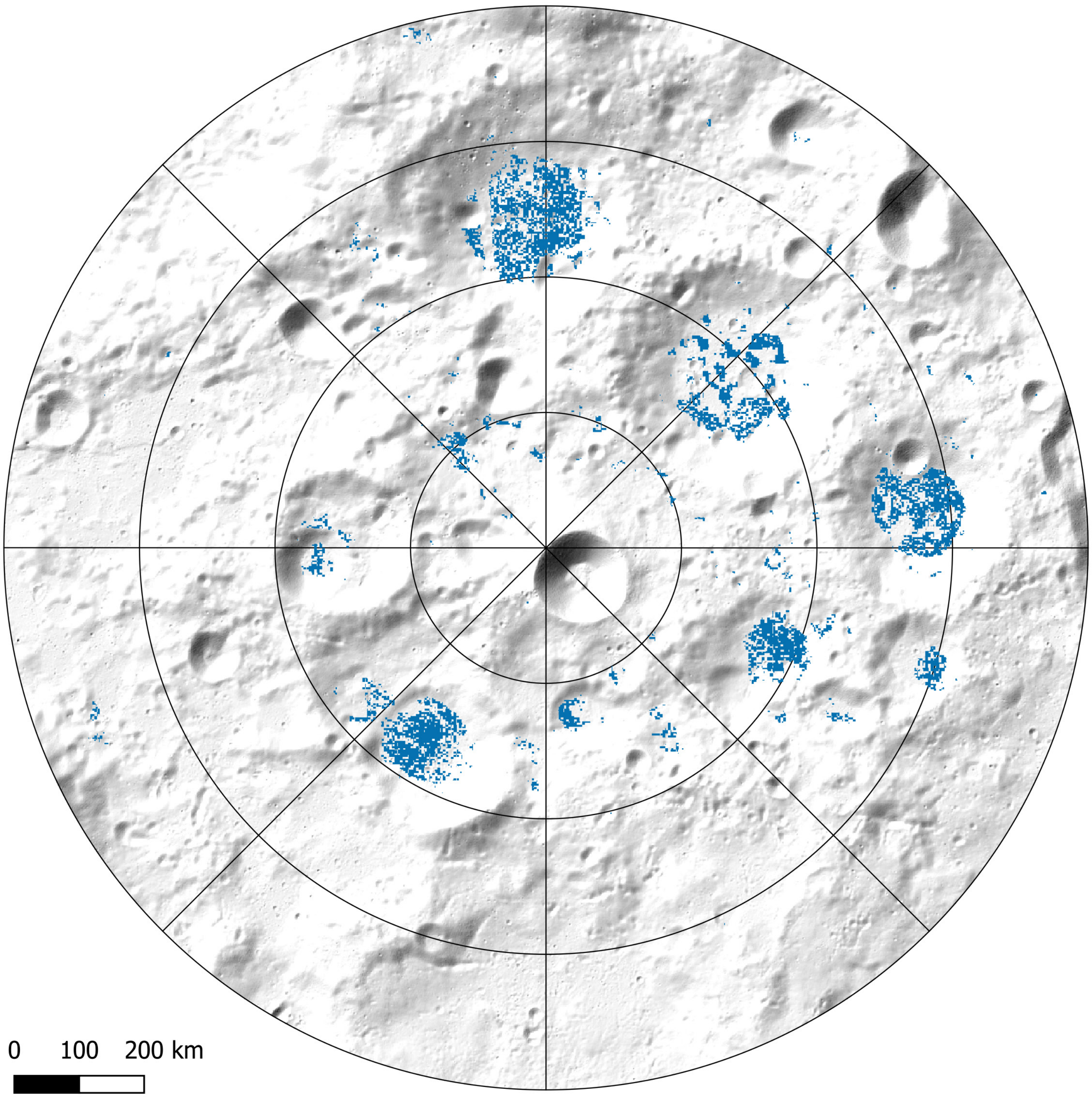
This map shows the angle of the surface, or slope, for the lunar surface. If slopes are 15 degrees or larger the rover cannot traverse them. These are indicated by shades of blue. Landing sites must be even flatter, with slopes <5 degrees (indicated by Dark Blue). Areas with surface frost are indicated by dark gray.

LOLA POLAR EARTH VISIBILITY MAP



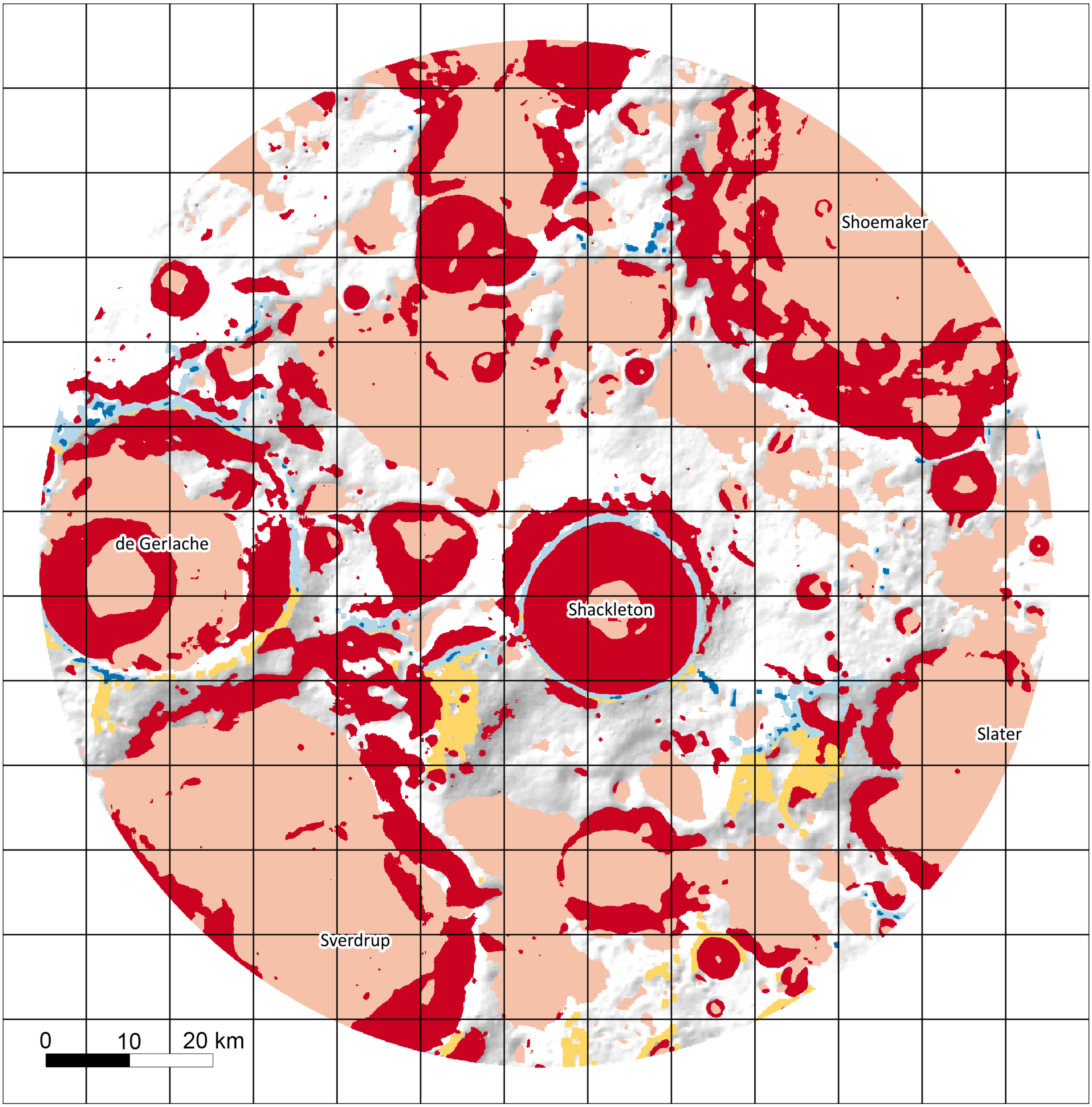
This map shows the average visibility of Earth from the lunar south pole. The Moon is <u>tid-ally locked</u>, so the same side, called the <u>nearside</u>, faces the Earth. To communicate with Earth, rovers need direct line-of-sight communication with Earth. This map shows the average percent of the Earth is visible with direct line-of-sight communication. Areas that are blue have enough visibility to send data back to Earth. Areas with surface frost are indicated by gray.

ANSWER SHEET FOR PART 1



Surface Frost is overlaid in blue.

ANSWER SHEET FOR PART 2



Ideal exploration conditions for sustained surface activities involve relatively flat traverse surfaces (<15°), plenty of sunlight for power (>50%), and good line-of-sight communication with Earth (>50%), all within a reasonable distance from water ice deposits. Impassable terrain (>15° slope) is indicated by red, >45% sunlight is indicated by yellow, ideal landing sites (<5° slope, >50% communication and sunlight) is shown in dark blue, and communication and recharge zones (>45% sunlight and communication) are indicated by light blue. Surface-frost analysis is overlaid in black.

GLOSSARY

Albedo - A measure of how bright or dark materials are.

Commercial spaceflight organizations - Nongovernmental companies that provide space goods, services, or activities. Some American commercial spaceflight organizations that work with NASA include Boeing and SpaceX.

Drive system - A system that controls speed, rotation, and direction of a motor in a machine.

Earth line-of-sight communication - Communications between Earth and rover are made possible because Earth is in constant view. Only the nearside of the Moon is in constant line-of-site.

Electromagnetic spectrum – Made up of waves (wavelengths) that travel through space at the speed of light. Waves differ in frequency (long vs. short waves).

Elements – Chemical elements that are matter in the universe. Elements are atoms with a specific number of protons.

Engineering - Designing and building new products, machines, or systems using chemistry, physics, and math to solve problems. Different kinds of engineering are often used together when designing something. Building a rover for example uses a combination of electrical engineering (designing how the machine is powered), mechanical engineering (the design, construction, and use of the machine), and materials engineering (designing and building new materials).

Farside - The face of the Moon that faces away from Earth. Sometimes inaccurately called the "dark side". During a New Moon on Earth, the Farside is illuminated by the Sun.

Kelvin - K, the abbreviation for Kelvin, is the base unit of temperature in the International System of Units.

Nearside - The face of the Moon that we see from Earth is called the nearside.

Pixel scale - A pixel (short for picture element) is one of many small squares that make up a picture. The number of small squares in a picture is referred to as resolution. In a satellite image, how much ground is covered by one pixel is referred to as the pixel scale.

Power - In physics and science power refers to the rate, or how fast, energy is used. Power comes from work, or heat or energy transferring to an object.

Surface frost - On Earth, frost is a thin layer of ice on a solid surface. Frost forms when water vapor (a gas) comes into contact with a frozen surface, thus changing the water vapor into ice (a solid). On the Moon, surface frost is not only water, other elements such as sulfur and nitrogen are thought to exist as well.

Suspension system - How the wheels are connected to the rover; provides control of how the rover interacts with the terrain.

Tidal Locking - The Moon rotates about its axis in about the same time it takes to orbit the Earth, resulting in the same side of the Moon always facing towards Earth.

Traverse - Planned path that rover will travel during mission duration.

Vacuum - The vacuum of space is empty and cold; the vacuum of space is nothing.

Water ice - Frozen materials such as water can be trapped in the permanently shadowed regions on the Moon because of such cold temperatures. There is no liquid water on the Moon.

Watts - Unit used to measure how fast energy is used. Power is measured in Watts.