Concept Name: Lunar Manual Orientation And Positioning System (LMOAPS)

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Brief description of your device and how it will best achieve the goals of Challenge 1:

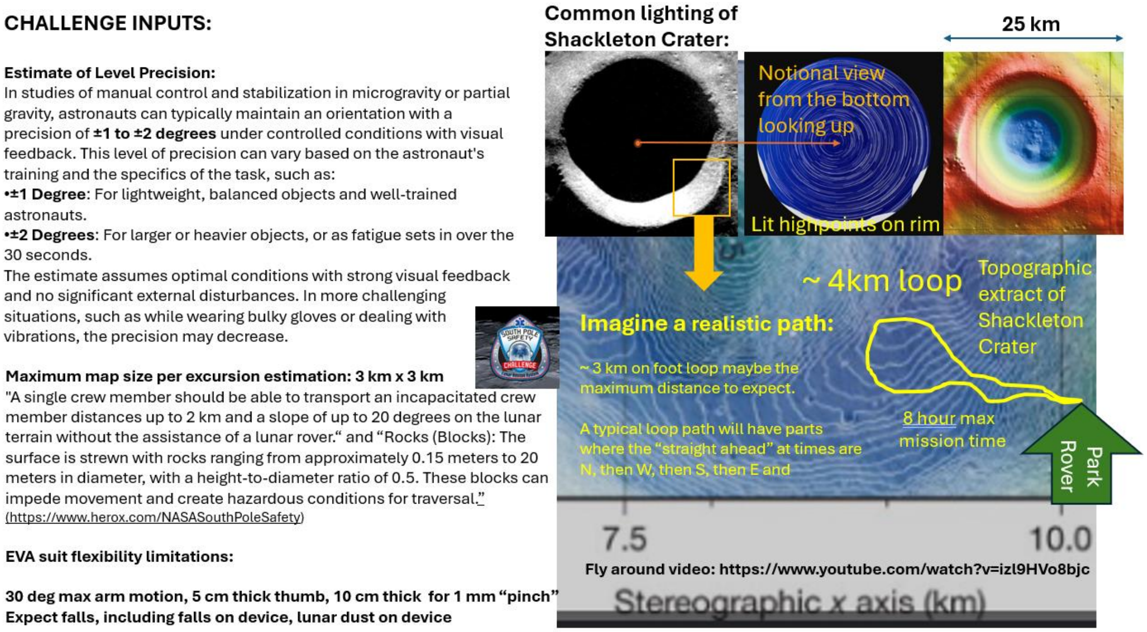
Orientation and positioning are much different problem on the Moon than on Earth, but we do have an advantage on the Moon of having little variations in the "near vacuum atmosphere" (no clouds, constant stars) so for any point on Moon, you can simulate what your surroundings at the local horizon and above should look like in high resolution. Orientation can use Stars and Sun-Earth (when available) positions, positioning can use a combination landmarks, rock high estimation and detailed maps.

LMOAPS-On Surface Device consists of a 30cm (across chest) x 60cm (away from chest) x 10cm (high) ~1.6 kg device that mounts to a 20 cm x 20cm x 1 cm EVA suit chest plate and precalculated physical inserts that are customized for the user location and use date(s). No electricity is needed, and no information processing will occur during device use. LMOAPS uses three complimentary ways to establish orientation (all methods require the device to be level, and a micro plum line and level bubble will indicate this). When the sun and/earth are in view, the inserts will reflect in specific locations on the device to indicate N (or S depending on mission). Otherwise, a half sphere with a specific pattern of small, drilled holes will allow light inside only when the device is oriented to the desired heading. With that desired heading set with the glove, the astronaut should turn the body/EVA suit slowly with the device as level as possible until a dot of concentrated starlight appears in the alignment indicator. At that point a mirror reflects a destination reference that the user can walk toward. Since walking is uneven, step counting will often not help with positioning.

The mechanical position estimator uses 3 location-date specific inserts, one a 16cm x 16cm X 1mm 20 g map and 2 horizon-high-point-shape-templates (10cm X 1cm X 2mm 20 g each). When the user is stopped, and a North is found, the turning of 3 position knobs will bring the high points into alignment, which is visible to the user 's right eye via mirrors. Through triangulation the device will show an estimate of the current X and Y position of the user, which is refined with the map.

When not in use the device can be flipped down, leaving the end of the device just above hip level. The rotation bars, 2 fine rotation knobs and 4 position knobs are large enough to allow movement even with thick gloves. With practice is estimated that a good orientation and position can be determined in less than a minute. If level can be determined within 5 degrees, the rest of the components can be engineered to provide orientation within 10 deg and positioning with 150 m, in the dark or in light. Components that need to rotate will use materials that do not fuse at 90K, although it is likely that the connection to the EVA suits and initial 20C temperature will persist for some time in a vacuum. Materials used are common and only require basic machining. It is assumed that the EVA suits have minimal flexibility, thus the device uses many mirrors designed for the user's right eye position to bring the alignment dot and landmark images to the user.

Additional informative research for this challenge:



CHALLENGE INPUTS:

Estimate of Level Precision:
In studies of manual control and stabilization in microgravity or partial gravity, astronauts can typically maintain an orientation with a precision of **±1 to ±2 degrees** under controlled conditions with visual feedback. This level of precision can vary based on the astronaut's training and the specifics of the task, such as:
- **±1 Degree**: For lightweight, balanced objects and well-trained astronauts.
- **±2 Degrees**: For larger or heavier objects, or as fatigue sets in over the 30 seconds.

The estimate assumes optimal conditions with strong visual feedback and no significant external disturbances. In more challenging situations, such as while wearing bulky gloves or dealing with vibrations, the precision may decrease.

Maximum map size per excursion estimation: 3 km x 3 km
"A single crew member should be able to transport an incapacitated crew member distances up to 2 km and a slope of up to 20 degrees on the lunar terrain without the assistance of a lunar rover." and "Rocks (Blocks): The surface is strewn with rocks ranging from approximately 0.15 meters to 20 meters in diameter, with a height-to-diameter ratio of 0.5. These blocks can impede movement and create hazardous conditions for traversal." (https://www.herox.com/NASASouthPoleSafety)

EVA suit flexibility limitations:

30 deg max arm motion, 5 cm thick thumb, 10 cm thick for 1 mm "pinch"
Expect falls, including falls on device, lunar dust on device

Common lighting of Shackleton Crater:

Imagine a realistic path:

~ 3 km on foot loop maybe the maximum distance to expect.

A typical loop path will have parts where the "straight ahead" at times are N, then W, then S, then E and

Fly around video: https://www.youtube.com/watch?v=izl9HVo8bjc

Figure 1. Additional Informative Research

While some environment variables were provided for the Challenge (such as 90K), when considering a solution, one needs to factor in some background research and bounding observations. Figure 1 shows some key challenge inputs. The proposed solution, LMOAPS, uses the research findings on the ability of an astronaut to level a light object within 2 degrees as a foundational input, since this enables the use of the stars, sun and earth (often only one) to provide a heading estimate. Lit peaks on the crater rim can be used in conjunction with a map to provide position estimates (https://www.youtube.com/watch?v=hbjbH-LOPtk). The proposed system LMOAPS is the result.

Description of the system (including On Surface Device: OSD)

The overall LMOAPS system has three components and five mission-day(s) inserts for the on-surface device (LMOAP-OSD). Note that mission-day(s) inserts have the highest resolution for a use over a few consecutive days, so it is possible that a few sets might be best for a 10 day Lunar surface stay. Namely:

1. Earth based mission design software (LMOAP-MDS)
2. Earth based test rig driver software (LMOAP-TRD)
3. On-surface device (LMOAP-OSD)
4. Mission day(s) specific inserts for (LMOAP-OSD):
    a. Star-Sun-Earth Sphere (and mirrors)
    b. Mission Maps (10 10 x 10 cm for 1 mission)
    c. Left Position Triangulator (X estimation)
    d. Right Positioner Triangulator (X estimation)
    e. Top Positioner Triangulator (Y estimation)

Methodology

Designing the Star Hemisphere with Sun Earth Reflective Projections

Select the brightest stars centered on the Lunar south pole that don’t fill another star’s light pit when turned:

Star Name	Apparent Magnitude	Color	AOH (Angle Off Horizon, degrees)	DFN (Degrees from North)
Sirius	-1.46	Blue-white	30	160
Canopus	-0.72	White-yellow	45	180
Rigil Kentaurus	-0.27	Yellow-white	40	210
Arcturus	-0.05	Orange	25	270
Vega	0.03	Blue-white	28	300
Capella	0.08	Yellow	32	320
Rigel	0.13	Blue-white	50	[illegible]
Procyon	0.34	White	35	[illegible]
Achernar	0.46	Blue-white	60	[illegible]
Betelgeuse	0.50	Red	42	85
Hadar (Beta Centauri)	0.61	Blue-white	55	200
Altair	0.76	White	29	310
Acrux	0.76	Blue-white	48	195
Aldebaran	0.87	Orange	27	70
Antares	1.06	Red	33	245
Spica	1.04	Blue-white	37	220
Pollux	1.14	Orange	31	115
Fomalhaut	1.16	Blue-white	45	165
Deneb	1.25	White	24	325
Mimosa	1.25	Blue-white	54	210

Drill holes in Star Hemisphere at these coordinates

H (Horizon Angle) needs to be great enough to block non-starlight from the lit lunar surface, but not too high as that will reduce the collected light. Lower H stars also improve heading resolution. This design set H = 20 deg to include Arcturus at 25 deg. **HR (Hole Radius)** need to be large enough to allow light in even if not perfectly aligned. **D (Hole Depth)** needs to be deep enough to block the light from other stars. HR is set to 2 mm and D = 10 mm. **IR (Inner Sphere Radius)** need to the large enough to allow easy operation but not so large to impair other astronaut operations. IR is set to 10 cm in this design.

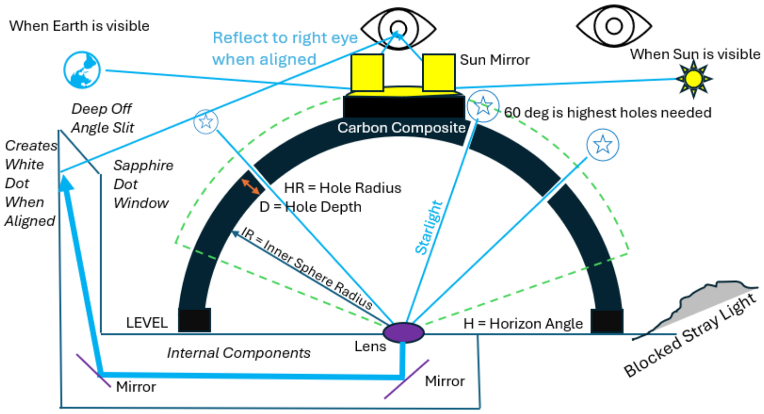


Figure 2. Star Hemisphere and Sun – Earth Mirror concept

Figure 2 shows the stars available for heading orientation at the Lunar south pole. Although the Sun and Earth are often below the local horizon at the Lunar south pole, they are occasionally available for positioning in crater, and often out of crater, and this is supported as the dominate mode of finding a heading when available. This requires that this Sun-Earth mirror device insert is machined for specific mission dates. Note that at any time only 60% of these stars are not blocked by the map frame that blocks stray light from the astronaut. Heading determination should be available at least 95% of the time, as figure 2 indicates few points in Shackleton where the sky is blocked. Figure 3 depicts a 3-D model of Shackleton Crater (using unrealistic lighting to perform analysis) with some visibility cones superimposed. The red cones have 30-degree horizon angles, yellow is 40 degrees and green is 50 degrees. Analysis has shown that even 30-degree cones should work in at least 95% of the area.

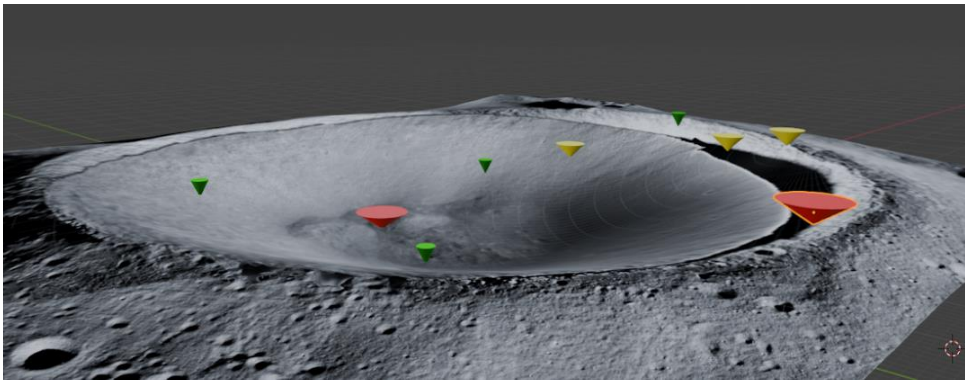


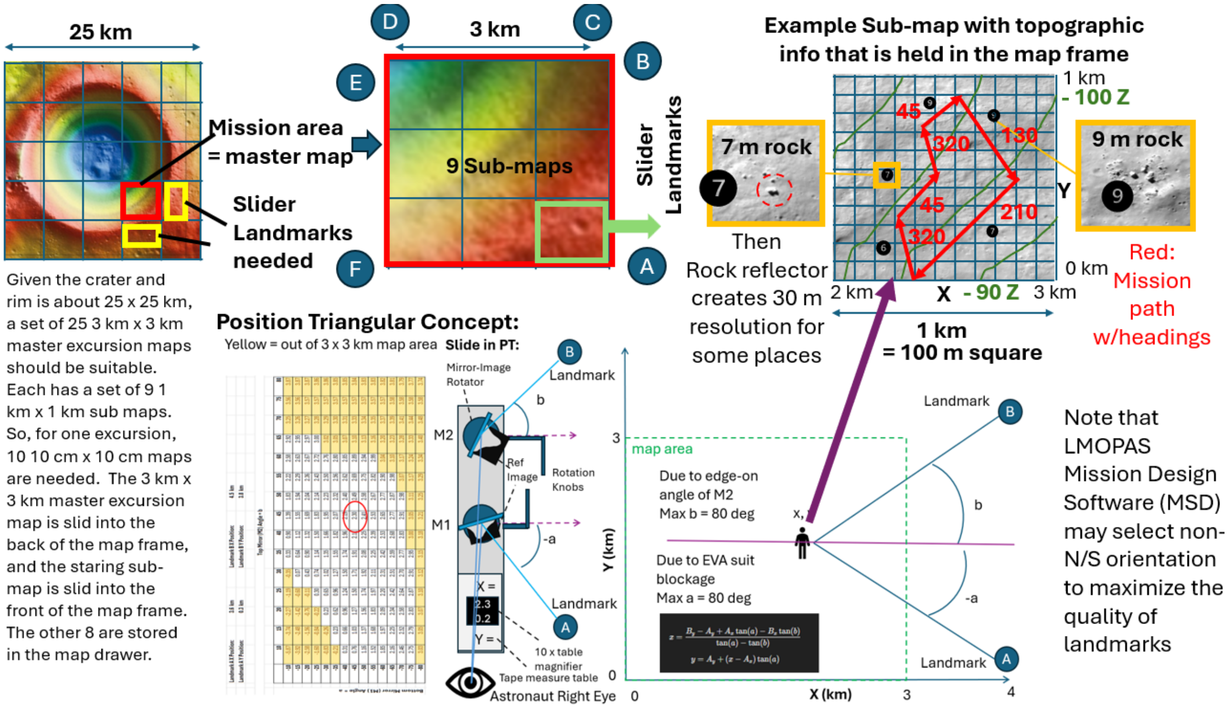
Figure 3. Sightlines inside Shackleton Crater (false light for detail)

LMOAP-MDS

The mission design software uses the highest resolution data for the mission area, then combines it with illumination projections for the mission date which variations are shown here: https://www.youtube.com/watch?v=hbjbH-LOPtk. Open source and free use software such as Bender can be used if cost is an important factor via the coding of custom Python scripts. But the key development cost will be turning key geometry into machine ready CAD models.

LMOAPS-OSD

Positioning is far more of a challenge than heading determination. Less than 150m resolution positioning will require a combination of techniques to be used together. First, custom position triangulators (PT) are machined on Earth for the mission area that uses 2 distant landmark (or constellation) points for X positioning and 4 points for Y positioning. This allows for position determination through triangulation. LMOAP-MDS will simulate the lighting in the mission to find 2 landmarks where the reference image on a PT can match an image reflected on a mirror into the user's eye. The mirrors are slid with a rotating lever that corresponds to 1 degree per rotation. This also advances a "tape measure" type lookup table with a magnifying lens above it that shows the X or Y position estimate. This will triangulate a rough location in the mission area. If the angle between the two points can be determined within 4 degrees, then the position on each axis can be determined to about 60m if the landmarks are 1 km outside of the map area, and about 90 m for 2 km or 130 m for 3 km. All three PT are used to create an X – Y location estimate that corresponds to a point on the active mission map. Although 1 may work, 3 provides redundancy, mission flexibility and additive resolution. Figure 4 shows key parts of the concept.



Given the crater and rim is about 25 x 25 km, a set of 25 3 km x 3 km master excursion maps should be suitable. Each has a set of 9 1 km x 1 km sub maps. So, for one excursion, 10 10 cm x 10 cm maps are needed. The 3 km x 3 km master excursion map is slid into the back of the map frame, and the staring sub-map is slid into the front of the map frame. The other 8 are stored in the map drawer.

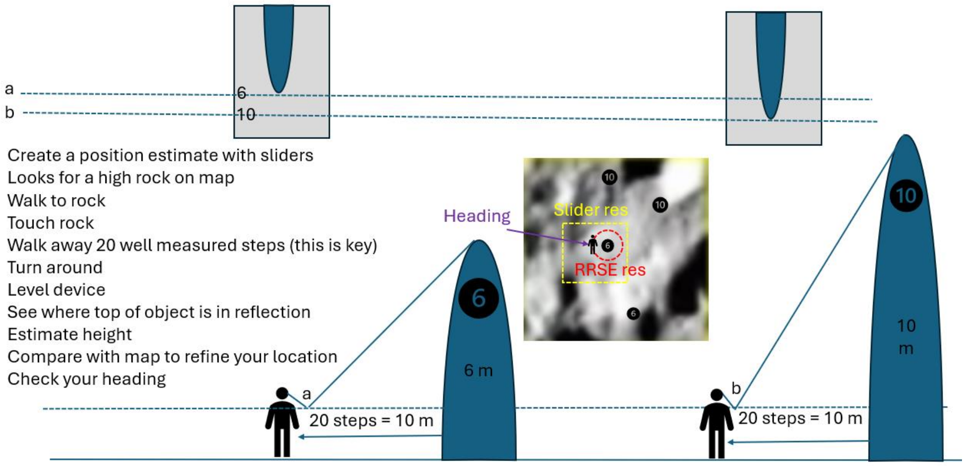
Then Rock reflector creates 30 m resolution for some places

Note that LMOPAS Mission Design Software (MSD) may select non-N/S orientation to maximize the quality of landmarks

Figure 4. Maps, landmarks, positioning and the positioning triangulator

Next, a map for one of the parts of mission area is used to look for extra large rocks conceptualized in Figure 5. In conjunction with the Reflecting Rock Height Estimator, large rocks that have imaged with visible or radar imagers can anchor the position estimation. By walking up to a large rock, then turning around and walking measured steps away to create a 20 m baseline, turning around, leveling the device, then looking down at the mirror should help to estimate the rock height. This is compared to the map. This established a circle inside the slider estimated box. Finally, the header can be used to establish a point on the circle. This combination should create a 100m resolution for most of the mission area (within the 150 m requirements), but there are potentially some pockets that may not achieve this.

Reflecting Rock Size Estimator (RSE)
count steps, the faster the reflection grows the taller the rock



Create a position estimate with sliders
Looks for a high rock on map
Walk to rock
Touch rock
Walk away 20 well measured steps (this is key)
Turn around
Level device
See where top of object is in reflection
Estimate height
Compare with map to refine your location
Check your heading

Figure 5. Rock Size Estimator concept

Figure 6 depicts the LMOAPS-On Surface Device (OSD) which consists of a 20cm (across chest) X ~60 cm (away from chest) X 10cm (high) ~1.6 kg device that attaches to an 20cm X 20cm X 1 cm EVA suit chest plate and precalculated physical inserts that are customized for the user location and use date(s). The device is engineered to right eye position of a given user. The mounting to the chest plate allows for hand free use. It also improves the ability to level the device vs holding in hand. The vertical position on the chest plate needs to be calibrated to the height of the user's eyes when slightly titled down to look at the device. No electricity is needed, and no information processing will occur during device use. LMOAPS-OSD uses three complimentary ways to establish orientation (all methods require the device to be level, and a micro plum line and bubble level will indicate this. The lights projected and reflected from the Lunar surface space suit must be blocked from illuminating the Star Hemisphere. The levers on the device are positioning for the astronaut to manipulate them from below to prevent reflected lights from the gloves getting into the Star Hemisphere. The polished Aluminum mirrors may be slightly concave (testing needed).

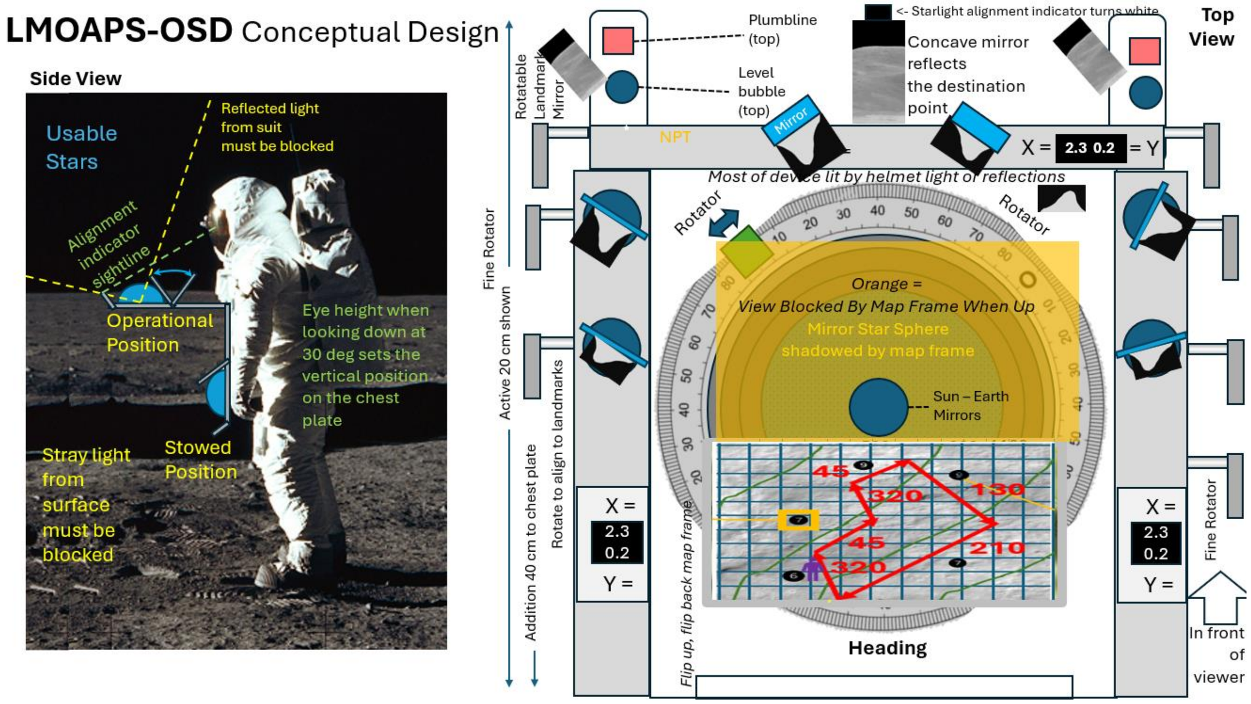


Figure 6. LMOAPS-OSD Conceptual Overview Diagram

Now that a conceptual solution to challenge requirements has been proposed, one needs to look at designing a useful device that does not impede astronaut operations. Figure 7 suggests a design (CAD designed) that provides the needed functionality.

Component	Name	#	Total CC	Mass (g)
Degree	Plate	1	40.2	**108.6**
Star Hemisphere (CC)		1	126.7	**342.1**
Main	plate	1	64.5	**174.1**
Map	Hinge	1	1.7	**4.6**
Map	Frame	1	20.0	**54.1**
West	Positioner	1	16.0	**43.2**
East	Positioner	1	16.1	**43.4**
North	Positioner	1	20.4	**55.1**
Rotator		2	6.8	**18.4**
Level	Bar	2	4.2	**11.3**
Map	Insert	1	7.7	**20.8**
Alignment	Indicator	1	2.5	**6.8**
Lever		8	11.1	**30.0**
Destination	Mirror	3	0.8	**2.3**
North	Mirror	2	0.0	**0.0**
Sun	Earth Base	1	0.3	**0.8**
Sun	Mirror	1	0.2	**0.6**
Earth	Mirror	1	0.3	**0.8**
Hinge		1	13.4	**36.0**
Chest	Plate	1	68.0	**183.6**
Frame	Stiffener	2	36.0	**97.1**
YMirrors	Left	2	0.6	**1.6**
YMirrows	Right	2	0.5	**1.3**
Xmirrows		2	0.7	**1.8**
Rock	Mirror	1	16.8	**45.4**
Drawer		1	33.7	**90.9**
Drawer	Hinge	1	3.0	**8.2**
Drawer	Door	1	3.1	**8.4**
Fall	Protection	1	1.2	**3.2**
Fall	Protection	1	25.8	**69.6**
Y	Position Rot	2	5.6	**15.2**
X	Position Rot	4	6.3	**17.0**
Window (Saphire)		1	6.0	**24.0**
Value Magifier (Saphire)		3	6.4	**17.4**
Lens (Saphire)		1		**6.3**
Internal Mirror (Saphire +		3	0.3	**1.2**
		TOTAL (g):		**1545**

Mostly made from aluminum
~1.6 kg with maps

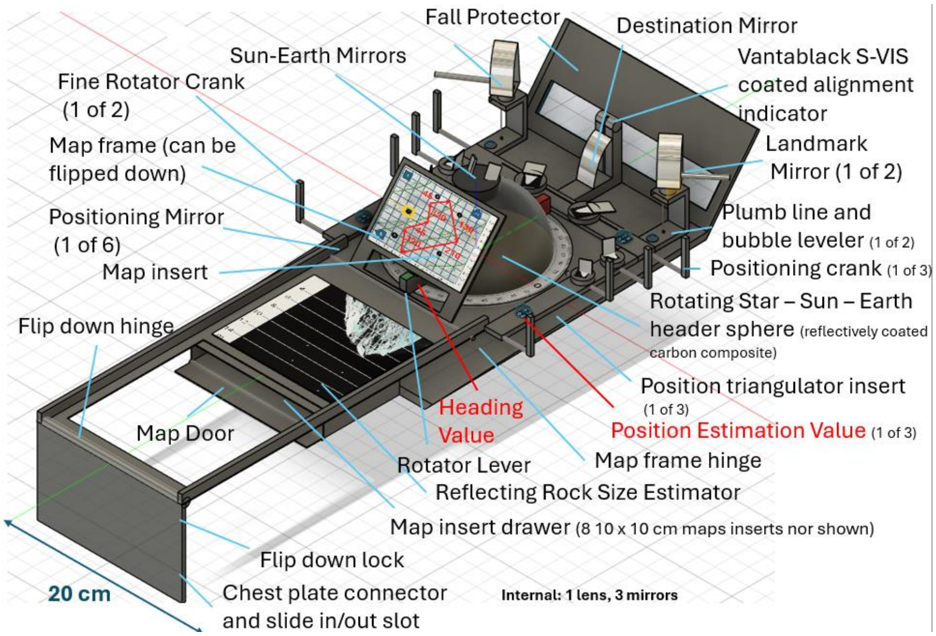


Figure 7. LMOAPS-OSD: Putting the components together

In this design leveling is key to operating this device, and both a visual plumbline type leveler and a bubble type leveler (optional) is provided. While an astronaut can probably level a device to +/- 10 degrees without feedback, a level between 2-3 degrees is needed to align the Star – Sun – Earth sphere. The plumblines drop around a 1 mm needle that indicates level within 2 degrees if the "needle like" plumbline "weight" is touching the level needle. Research has shown that an astronaut trained with a device that has level feedback can level a device within 2 degrees. When the user is stopped, and a N is found, the turning of 6 positioning cranks will bring the uniquely shapes lit high points into alignment, which is visible to the user via a mirror. Through triangulation the device will show an estimate of the current X and Y position of the user. When not in use the device can be flipped down, leaving the end of the device just above hip level. The 2 rotation levers, 2 fine rotation cranks 6 position cranks are large enough to allow movement even with thick gloves. With practice is estimated that a good orientation and position can be determined in less than a minute. If level can be determined within 5 degrees, the rest of the components can be engineered to provide orientation within 10 deg (in 99% of locations) and positioning within 150 m (in 90% of locations). Figure 8 depicts the device mounted on the EVA suit chest plate.

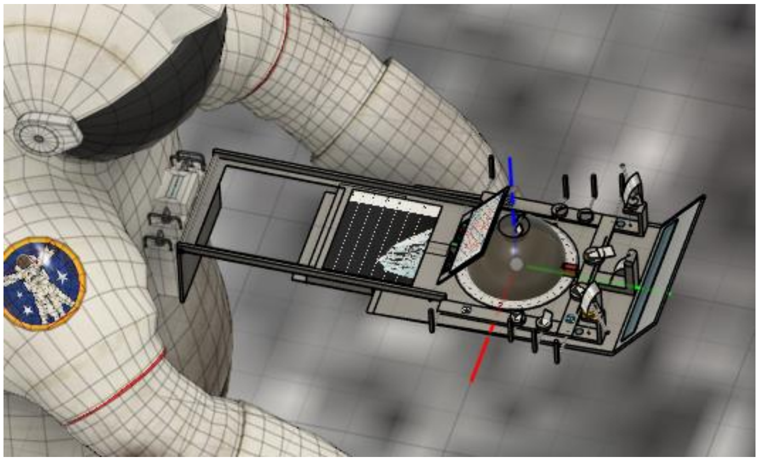


Figure 8. LMOAPS – OSD mounted to chest plate

Meeting Environmental Challenges

1. **90K potential low temperature can make some materials brittle or fused:** This device uses pure or lightly alloyed Aluminum, Carbon Composites, and Apollo proven coated paper inserts.
2. **Nearly compete darkness in some operational areas:** This device uses darkness as an advantage to isolate lit landmarks with unique shapes, although it can operate well in highly lit areas with good landmark opportunities.
3. **Lunar dust can get into gaps and coat electro-static surfaces:** Precision machining is recommended to minimize gaps. The device can be put in a down position to shed dust after a fall and then set back into operational position. The device can be detached and banged hard against a metal object to dislodge dust between missions.
4. **Uneven terrain will lead to falls in many directions:** the fall protection plate can protect the device and potentially protect the EVA front and help with fall recovery.

Next, we need to confirm the design geometries work with the EVA suit and lighting, and the positioning of the astronaut's eyes. Figure 9 shows side and top sightlines to various components. It appears that the positioning of all the components should work well for the functionality. Note that the Star Alignment Indicator is in a deep pit aligned to the right eye that absorbs all external light with its Vantablack S-VIS coating.

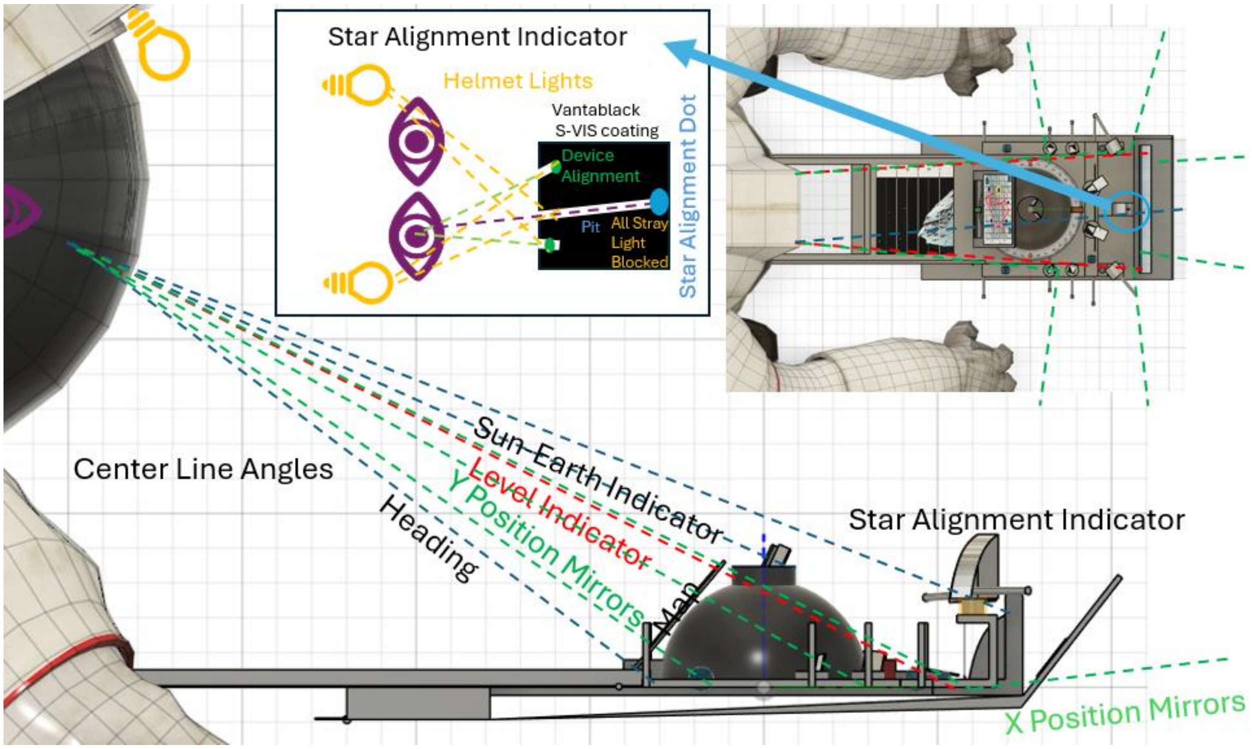
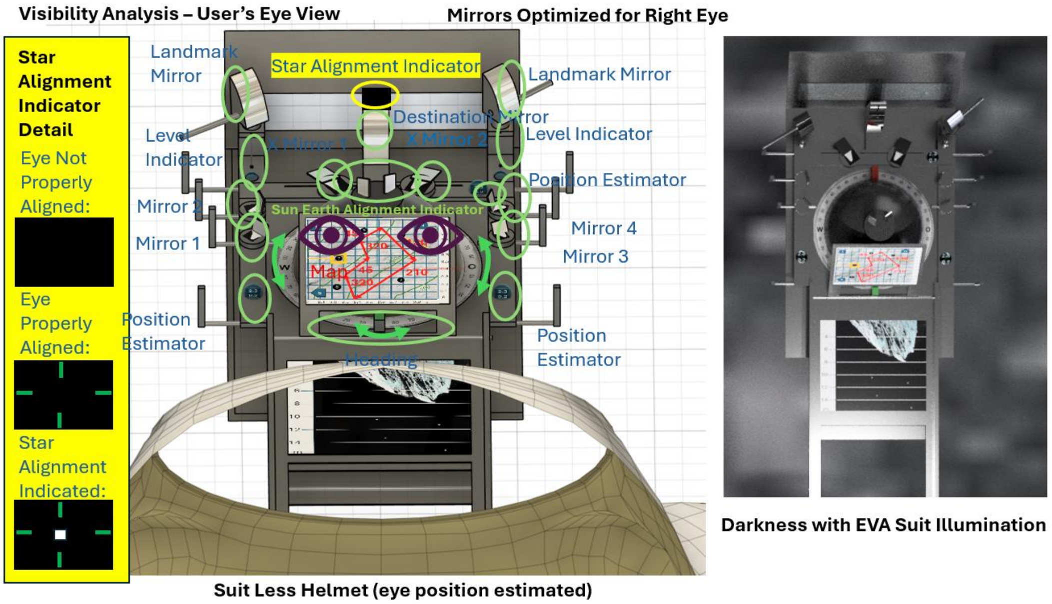


Figure 9. Astronaut Side/Top LOS and Stray Light Analysis

Figure 10 simulates the position of the astronaut's eyes to confirm that everything that needs to be seen, can be seen. It also depicts what the device should look like from the astronaut's eyes in dim conditions. The Star Alignment Indicator needs to first show green dashes before alignment.


Visibility Analysis – User's Eye View

Mirrors Optimized for Right Eye

Suit Less Helmet (eye position estimated)

Darkness with EVA Suit Illumination

Figure 10. Astronaut LOS and dark conditions estimation

Instructions for using the system:

1. On Earth
    a. use software to design the inserts for the device, based on range of operational dates and the location(s) of Lunar surface excursions. This creates several CAD files
    b. Have the aluminum inserts automatically machined
    c. Screw together OSD
    d. Test parts in cold vacuum on a custom test rig, refine if they don't pass test
    e. Configure inserts for first use on Lunar Surface
2. On Lunar Surface (inside hab or spacecraft)
    a. Attach to chest plate, ensure the OSD performs well inside
    b. Lower OSD into down position for exit to Lunar surface
3. On Lunar Surface
    a. When at OSD use area, relock OSD into chest out position, perform a sequence of heading estimations and positioning estimations
        i. In all cases ensure device is level within 5 deg using the micro-plum line indicators and bubble level indicators
        ii. Heading estimation:
            1. If Sun and/or Earth is visible, then turn the rotator to desired heading then turn the body/EVA suit to have Sun or Earth point to reflecting into the user eye.
            2. If Sun and/or Earth are not visible, then turn the rotator to desired heading then turn the body/EVA suit until the star alignment indicator lights up.
            3. In both cases turn the landmark mirrors to a unique view of an object or star and try to walk toward the object in the destination mirror, which will probably require leaving the strait line path occasionally.
        iii. Positioning estimation:
            1. Ensure device is pointing North
            2. Turn the knobs on the three positioning sliders until the lit shapes on the reference match the lit shapes in the mirror. Each slider should show a number that indicates the X or Y of your position. Then refer to the map to estimate your position on the map. Use local large rock references (if available) to refine your position estimate on the map. Finally use a heading estimate to get within 10 m.
    b. When exiting OSD use area, remove OSD and tap upside down again rover or outside of hab or spacecraft to remove lunar dust particles.

Creating the components of LMOAP:

Software used

1. Earth based design software (LMOAP-MDS), produces location and date specific CAD files for inserts for on-surface device (LMOAP-OSD) based on 3-D mission simulation for a given range of dates.
2. Test rig driver software (LMOAP-TRD).

Materials

1. Pure or lightly alloyed Aluminum (If testing indicates issues with rotating and sliding at 90K, then alternatives such as copper or stainless steel should be built with the same CAD files and tested). Polished Al can be used for mirrors.
2. Sapphire for the single positive meniscus lens (focuses the starlight: $1000), 2 cm wide level bubbles filled with Xenon and Helium (optional: $500 - 1000)
3. Carbon Composite for the Star Hemisphere, which is coated to be reflective with Physical Vapor Deposition (PVD) of aluminum ($300 -$700). CC work well at 90K (often used for cryogenic fluid storage)
4. Vantablack S-VIS coating of key elements ($1000)

Costs

5. Software (all Earth based) may cost $300K to made robust and well tested
    a. Map to 3-D model loader, uses best available Lunar surface maps
    b. 3-D mission model, factors in the exact dates to predict bright, high, separated and uniquely shaped areas that surround the map area for triangulation for positioning. This creates CAD models for machining.
    c. Star-Sun-Earth position vs date optimizer. The Star Sphere needs to be calculated to maximize the number of stars used but must reject some stars if the rotation can lead to false positives. This creates CAD models for machining.
    d. Test rig driver, that rotates all control surfaces in a cold vacuum testing facility, also inducing some vibrations and shocks that might happen during the mission.
6. Materials should be minimal as this is Aluminum based. If testing indicates issues with rotating and sliding at 90K, then alternatives such as copper or stainless steel should be built with the same CAD files and tested. Some Carbon Composite and Sapphire components adds ~$3000.

Build requirements

1. High quality aluminum small device machining facility. At $100/hr for labor the cost is estimated at $50,000

Size: 60 cm (long) x 30 cm (wide) x 10 cm (highest point) + 20 cm (high) x 20 cm (wide) x 1 cm (deep) chest plate.

Weight: ~1.6 kg

Requirement Trace

REQUIREMENT	**LMOAPS**
Accuracy Ability to locate: Absolute heading within 10 degrees Absolute 3-D position within 150 meters	Heading: combination of Sun, Earth reflector and starlight collector. Position: Position sliders, with fine tuning knobs in conjunction with high resolution map with topographic contours and rock reflection refinement.

Ease of Use Can be used by an astronaut wearing pressurized gloves Easy to understand/operate Quality of instructions	Chest plate mounted with bar projections and levers to rotate and slide parts of the device as needed. The right thumb can flip the map frame and lock up or down the device on the chest plate. With training a heading or positioning event may only take 1 minute.
Mission Capable Ability to function under the constraints found on the lunar south pole	Aluminum has been proven to operate in Lunar conditions with Apollo rovers and Yutu-2. CC is being considered for future rovers. Of course, cold vacuum testing on Earth with a test rig is recommended. Sticking may be fixed with larger gaps or a Teflon seal.
Impact on Mission Size, Weight, Manufacturing costs	30 cm x 60 cm x 10 cm, 1.6kg, $50K LMOAP hardware, $300K LMOAP -MDS, -TRD software (mainly labor)
Manufacturability/Usability Ease of construction Robustness Durability Reproducibility	Mostly common Aluminum based milling with a few specialty components source-able in the $1000 range. Stiffening components have been added to make this fall resistant, although with anything with moving parts Lunar dust contact should be minimized. As this is CAD driven, reproducibility should be good.

Conclusion

Although this analysis has emphasized the Shackleton Crater region the LMOAPS design is intended to generally useful across the Lunar surface. Orientation should be universal, with a Star-Sun-Earth Sphere made for the area, but positioning needs well placed landmarks that are somewhat unique. LMOAPS-MDS should aid in maximizing the areas that can be covered.

While this design has good potential to meet challenge goals in many areas, it has made some assumptions about the EVA suit and EVA procedures that may be refined before the mission (the Axios suit is still in development). There is no substitute for refining this design with prototypes with the actual Axios EVA suit (or whatever suit is selected). A slightly larger design may work better, but that may hinder other EVA operations and goals. An Earth based test facility that involved the use of simulated background 20 m from the astronaut (all around the astronaut) and a projected starfield overhead in an otherwise dark environment and may give the astronaut and intuitive sense of rough heading and position that can make the work of heading determination and positioning much faster and more reliable. This design attempts to manage the very challenging workload for the EVA astronaut by not demanding too much precision yet yielding useful information. The real outcome will integrate both the limits of the device, and the ability of the astronaut to maintain situational awareness, which can be boosted with simulation and training. Current projection technology is now quite affordable, and the LMOAPS software can create the needed background throughout the mission area to practice the excursion.