A Sensor-Rich Solution for Lunar/Cislunar Space Domain Awareness

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ABSTRACT

This paper describes a sensor-rich solution to explore, map, and characterize the lunar/cislunar domain to support future human journeys to the moon, other moon exploration activities, and Space Domain Awareness. The solution addresses lunar orbital, surface, and subsurface domains.

The solution is designed to provide:

- Detailed mapping of the lunar surface and the top layers below the surface
- Lunar resource identification
- Natural shelter identification on or below the lunar surface
- Remote and proximity sensing and situational awareness of the lunar surface and cislunar orbital domain
- Navigation support for vehicles on the lunar surface and cislunar orbital domain
- Local and backhaul communications support for lunar surface and cislunar orbital domain

The paper covers the following topics:

- **Ground Penetrating Radar:** A software-defined radar for profiling surface and sub-surface features of the moon and differentiating among various in situ resource utilization requirements such as deposits or surface characteristics (e.g., potential water/ice deposits).
- **Multi-Spectral Telescope:** Provides 6 bands in visible and 4 bands in MWIR range for detailed characterization of the lunar surface and resource content.
- **Wide-Field-of-View Sensor:** Provides wide-field-of-view imagery for navigation, situational awareness, and tracking.
- **Precision Navigation Software without Need for Continuous Earth Ground Station Contacts:** Utilizes the asymmetric gravity field in cislunar space to solve for the absolute state of the ESPA host and additional lunar/cislunar objects using relative ranging observations. That is, without earth ground station support, it can determine where the ESPA host is, as well as anything else around it providing robust Space Domain Awareness. This can provide navigation support and enhancement for approaching and operating crewed lunar missions, as well as lunar surface operations such as a rover.

1. SOLUTION CONCEPT

Mission goals addressed by this concept include superior awareness of the orbital and surface domain and natural shelter and resource identification. To satisfy these requirements, a versatile sensor suite is assembled combining ground-penetrating radar and electro-optical sensors. Given the limitations of size, weight, and power (SWaP) and budget typical for space exploration, each sensor is chosen for its multi-purpose, multi-mode capability in supporting various aspects of the mission.

The solution is based on exploiting high technology readiness level (TRL) sensors that are at least at TRL 6, i.e. have demonstrated performance and applicability for the lunar/cislunar domain exploration. Some of the sensors have gone through the full development cycle and acceptance tests achieving TRL 8 and some are in advanced stages of development and being tested and demonstrated at TRL 6 and 7.

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The solution concept is illustrated in **Figure 1**. The payload in the lower-orbit lunar satellite(s) ❶ includes a ground penetrating radar, a multi-spectral telescope, and a wide-field-of-view sensor. A higher-orbit lunar satellite ❷ includes the precision navigation solution and more sophisticated communications links.

The higher-orbit lunar satellite is able to communicate with lunar ground assets such as surface sensors ❸ and surface vehicles ❹ to collect data as well as potentially provide navigation assistance. Various types of ground sensors are possible including robust and hardened sensors dropped through the relatively low gravity of the moon onto the relatively soft surface of the moon. These unattended sensors self-initialize, self-organize, and provide various types of services (sensing, communications, position, navigation, timing).

Communications with other space assets ❺ are established to exchange data as well as to provide navigation and other assistance to other space assets.

Data is selectively transmitted to earth ❻ for additional data processing, data fusion, and archival.

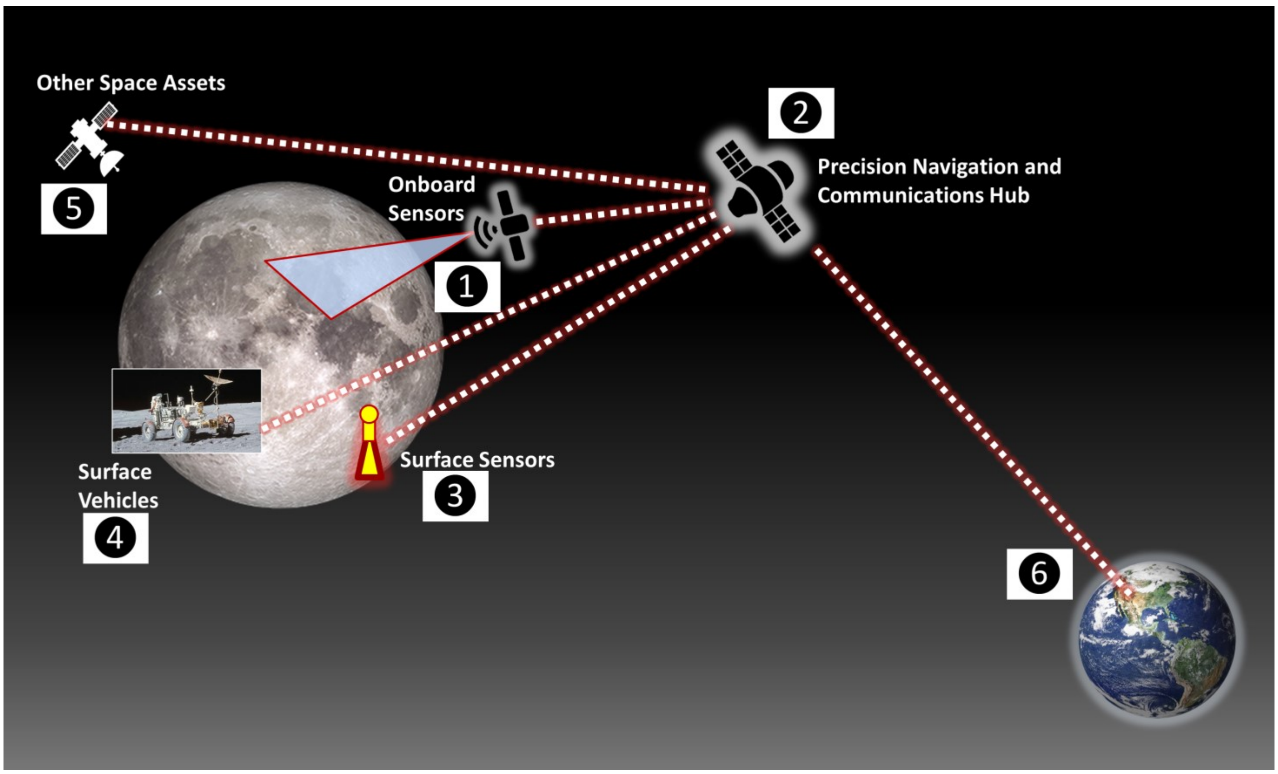


Figure 1: Solution Concept. (Notional diagram.)

2. GROUND PENETRATING RADAR*

A radar-based sensor is included because of the multiplicity of capabilities that a radar can provide, and because of the technical maturity associated with typical radar payloads. SRI International's ground penetrating radar (GPR) and synthetic aperture radar (SAR) heritage makes possible to field a compact, software defined radio (SDR) implementation of radar well suited for lunar and cislunar operations [1], [2]. The maturity of the SRI radar electronics and processing stems from over 40 years of radar development and processing experience, and more recent developments intended for CubeSat scale applications.

* SRI Ground Penetrating Radar is based in part upon work supported by NASA under award No. NNX17AC20G.

In the lunar application, at much shorter range (70-100 km) than typical terrestrial applications (500-600 km), a much smaller body-fixed antenna can be utilized than the typical large area deployable antenna required for terrestrial applications. Hence, leveraging existing development heritage, software defined radio flexibility, and simpler aperture and lower power operations at shorter range, makes the SRI radar ideal for lunar applications.

The SRI radar can serve as a multi-function payload – providing radar ranging to the surface, profiling the surface, profiling sub-surface features and structures, and differentiating among various in-situ resources (e.g. deposits, surface characteristics, potentially identify water and ice deposits, and differentiating between different sub-surface constituents). Such a multi-function capability allows the same hardware operating in different modes to image surface features and objects, map the surface, provide change detection on subsequent passes, provide radar functionality, and in certain modes also provide near-range and long-range communications, timing, and synchronization functions. In short, a compact SDR radar becomes a highly flexible and multi-purpose tool to explore and support operations even from a compact platform, such as the ESPA-class platform proposed for lunar exploration.

The SRI radar was designed as a payload for a 6U-16U sized bus, and the electronics occupies approximately 4U of volume (approximately 20cm x 20 cm x 10 cm), ideally suited as one of several payloads in an ESPA class bus, or smaller. In addition, with a body-mounted antenna, whose size will be dominated more for the lunar mission by the center frequency of operation, the radar system avoids the complexities of a large deployable antenna, and can, if desired, switch between two or more body-mounted antennas for different operating modes (limited only by external surface utilization constraints). The antenna size can be reduced to a small fraction of a square meter depending on available power, and will be more dominated by the tradeoffs associated with wavelength for various mission functions than the need for aperture gain. From this perspective, lower frequencies such as UHF will provide greater regolith penetration depth, potentially down to 10 m, while higher frequencies that have already been field tested with SRI radar prototypes such as S-band might only penetrate down to 1-2 m depth, L-band possibly down to 3 m, while also providing greater image and range resolution. C-band and X-band, for which there are SRI CubeSat radar designs that have not been field tested, are possible, but less desirable, since they would provide greater SAR and ranging resolution, but at substantial degradation of GPR functionality.

The final RF amplifier and antenna design will be guided by selection of the appropriate mission balance, while remaining able to leverage the core electronics and processing developed by SRI for prior programs. Ground penetrating interest will drive to lower frequencies and larger amplifier and antenna size, while imaging or mapping resolution will drive to higher frequencies and smaller amplifier and antenna size. However, the compactness of the core electronics already achieved also enables a novel approach of possibly including two variants to support both general mission categories well. Either two variants in one ESPA class payload or two distinct payloads flown in two smaller busses could be utilized to achieve both mission types, as well as a measure of redundancy and multi-perspective operations. For example, while one payload/antenna complement might be optimized for ground penetrating radar, and the second for surface or object imaging, both will be able to leverage their SDR nature to carry out either mission, potentially providing added insight and information that will be of great value in differentiating amongst deposit types, water and/or ice variants, or other differentiation not anticipated at this time.

Compact SDR Radar Development Background

SRI's small form factor software-defined radar system was recently developed using NASA ESD (Earth Sciences Directorate) funds, and intended for CubeSat-scale Earth observation missions. It is at TRL 6 having experienced substantial testing on terrestrial vehicle and airborne platforms and exercising of all aspects of operations and data processing in anticipation of on-orbit flights. Since the initial development and demonstration of the software-defined radar technology for earth-observing applications, it became clear that the software-defined nature permitted straightforward application of the radar for lunar ground penetration studies. When adapted to lunar applications, the SRI radar can enable profiling of sub-surface structures and potentially profiling of water/ice deposits as well as application for precision lunar surface mapping and surface change detection (e.g. to document changes resulting from human or machine activity). This capability is enabled not just by the software-defined nature of the SRI radar, but also by the closer proximity possible from a lunar orbit, i.e. instead of a reference 500km intended for Earth orbit, a 70-100km lunar orbit. Since radar (depending on operating mode) has a range cubed ($1/r^3$) or range to the fourth power ($1/r^4$) dependence, this much lower altitude operation results in substantial benefits, either in reducing power requirements or in reducing antenna size. The SRI radar payload was already designed for as low as 60 Watt orbit average power at 10% duty cycle, allowing the trade for lunar application to be made in the direction of substantially reducing the antenna size, reducing the technology risk associated with typical large deployable radar antennas, while still retaining excellent radar performance. The radar has also been instantiated with 50 MHz and 200 MHz bandwidths for different performance features, allowing tradeoffs to be made on desired resolution and processing requirements. An additional tradeoff associated with the lunar altitude might be for greater duty cycle. But this comes with added considerations of data volume and processing, and thermal design considerations – but all well understood tradeoffs. These performance and form-factor considerations make the SRI radar ideally suited for lunar applications as a separable payload delivered to lunar orbit for exploratory and operational mission roles.

SRI's SAR payload internally handles the high-power capacitance required for the 600W RF peak pulse, the high-speed data storage, and the on-board processing that a satellite bus would typically provide, thereby greatly simplifying integration. The simplified interfaces between SRI's payload, antenna and a bus, make it possible to do rapid development and test, as well as integrated testing. The mechanical interfaces to a lunar bus for the payload and antenna would still have to be defined; but the electrical connections to the bus power and data system are rather straightforward. A single RF coax cable can connect the SAR payload to the antenna's feed system. An Ethernet cable between the SAR payload to bus supports payload commanding and raw data transfer. The remaining electrical interfaces include a bus-to-payload 1PPS signal and DC voltage power transfer to the electronics. In addition, if the bus is capable, SRI has also developed designs for up to 2 kW peak power operation, which could also be considered for a lunar mission if mission objectives end up suggesting such power levels.

Modifications Needed for Lunar Operation

By virtue of its SDR nature, the existing radar hardware is readily tailored for missions other than the precision Earth Science mission for which it was designed. Obvious changes associated with frequency selection require modifications to the amplifier, antenna and RF connection between the antenna and SDR; but the modular architecture allows the majority of the hardware stack to be re-used from the SDR interface back through the data processing end – that can be used to yield directly usable imagery or data products. As such, changes related to specific mission processing, and not related to frequency changes, are handled principally in software. This allows software updates to be carried out with rapid iteration, during payload test and calibration, as well as during actual mission operations. This latter capability is viewed as specifically relevant to a lunar mission, during which new capabilities, processing or operational changes are expected to be likely as the mission proceeds.

A further value of the software defined nature, and heritage of the software is that use of the SRI GRP/SAR capability brings with it low risk, as well as significant heritage from advanced processing, including algorithm development with heritage from processing of data from national systems. The specific value for a lunar mission lies in the need to differentiate between different materials and new return data characteristics that represent unknown material or lunar regolith conditions. One example of how to leverage the signals from such a radar for lunar exploration might be consideration of circular polarization ratio – i.e. the difference in reflectivity from different regions to different signal polarizations. Hence, changes in polarization ratio might be a significant tool for differentiating water or various ice deposits from other types of regolith materials. In addition, in the case where two spacecraft might be used, the differences between bi-static and mono-static viewing configurations will additionally provide added mechanisms for differentiating between materials. Another example might be the use of algorithms and understanding developed with terrestrial programs to differentiate between natural and manmade objects in a scene, allowing more rapid and definitive identification of human activity and change detection.

Operational Issues and On-board processing

Operationally, the radar's ability to be used in different modes includes such differences as changing viewing geometry to pursue different measurement or observation types without any change to electronics. In the GPR mode, direct to nadir illumination is most likely to provide the best geometry for ground penetration, and discovery of underlying structures. In SAR or alternate GPR modes, side-looking geometries are mostly used to generate terrain maps and object images, as well as for exploring 3D-structure of underground cavities, deposits, or formations. As such, even if flying a single spacecraft mission, one can anticipate pointing a single radar to nadir or in side-looking mode for various mission phases, or even having two side by said radar payloads pointing in different directions – nadir and side-looking respectively - to enable greater richness and quality of data products from correlated radar operations.

Another example innovation developed by SRI, with potential value to lunar exploration has been the development of analysis capability enabling the use of SAR techniques from slow moving platforms, i.e. UAVs. Traditionally, SAR has leveraged fast moving aircraft or satellites from which to create a synthetic aperture. With algorithms developed for slow relative motion, our techniques allow new modes of analysis or operation, potentially of value in lunar exploration where the orbital velocity is about 1/4th that of LEO satellites. In short, the switching of software and waveforms by the radar can result in novel mapping, ground profiling, resource identification, underground formation discovery, resource differentiation, change detection, analysis of patterns of life, differentiation between human and natural objects, and water/ice exploration – all functions potentially useful in future lunar exploration.

Water and Ice Detection

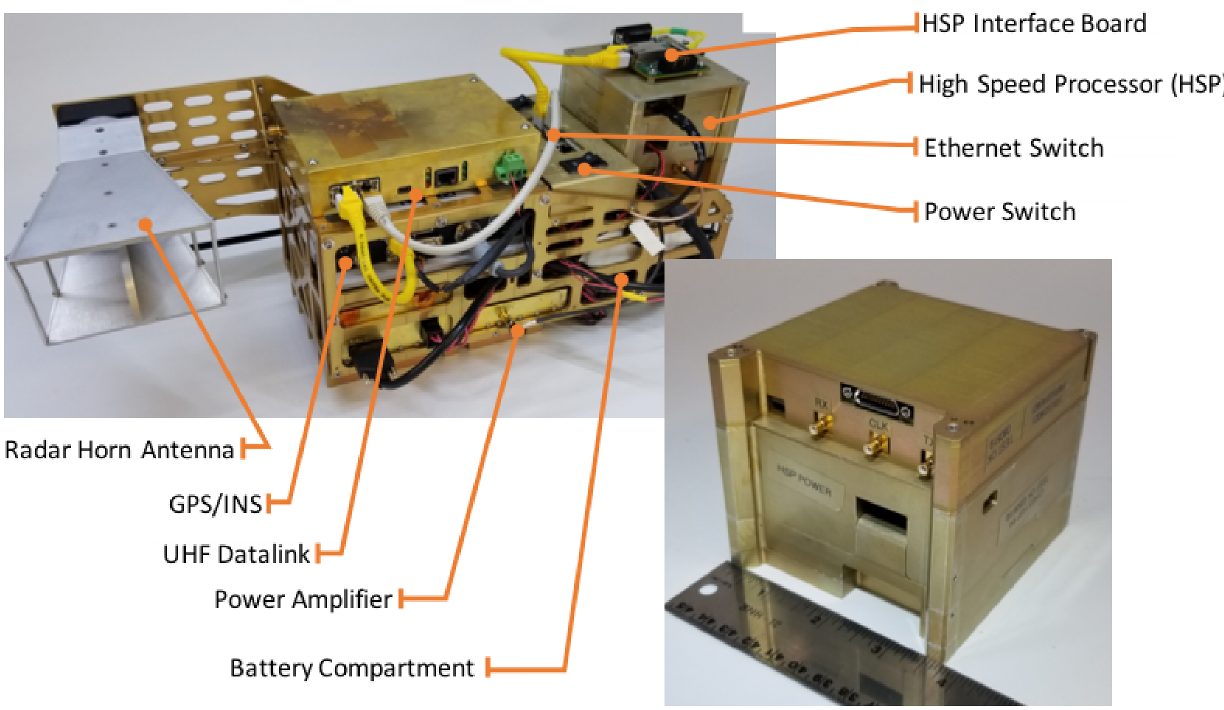
In the specific case of searching for water or ice deposits, it is hypothesized that measurements such as the circular polarization ratio differences between different regions may be sufficient to indicate or suggest water or water-ice mix in the regolith. Scatter signals from multiple angles could also provide differentiation between different materials, such as between water-ice and regolith. For the case of two satellites in a bi-static configuration, scattering from multiple angles received on both satellites simultaneously should show different scattering curves for regolith and water-ice, allowing high confidence identification. Characterization and test of this hypothesis should be conducted before launch to better quantify the expected quality of the result and to support trades associated with optimal frequency selection, and mission balance.

Additional Functionality Possible

As alluded to earlier, additional functionality can be enabled through the SDR nature of the SRI radar. The same RF subsystem components, using software updated waveforms and processing, can be utilized for various additional functions. These include:

- **Position, navigation, and timing functions** – Specific RF waveforms and processing can be used to provide navigational aid and relative motion guidance to objects at a distance. A set of satellites providing such signals can also provide a GPS-like navigational reference for other maneuvering satellites. These are well understood techniques and possible secondary functions that can be provided by the RF radar payload.
- **Communications** - The RF subsystems can be used to implement communications, where messages are encoded on the RF signal stream, just as synchronization, ranging, or timing signals. Variations of this technique can be tuned for local area communications, long range communications, or even broadcast unidirectional communications.
- **Ranging and Space Domain Awareness** – The radar functions can be utilized for standard RF-based ranging to objects – an important capability as more and more objects are placed in orbit around the moon. In fact, frequent lunar situational awareness updates that help identify the location or orbital parameters of non-functioning satellites may become a necessary local traffic management function.

Figure 3: Antenna, Power Electronics, Tx/Rx Module, and Processor for existing radar.



- 1.5 kg total Mass, 1.25 U total Volume
- 600-700 W peak power, 10% duty cycle,
- Currently supports 60 to 200 MHz bandwidth,
- 2.9 GHz center frequency (scalable to other frequencies),
- >300 GFLOPs on-board processing (future: 1 TFLOP)

Figure 4: Integrated sensor electronics stack as assembled for UAV test, i.e. not yet optimized for space.

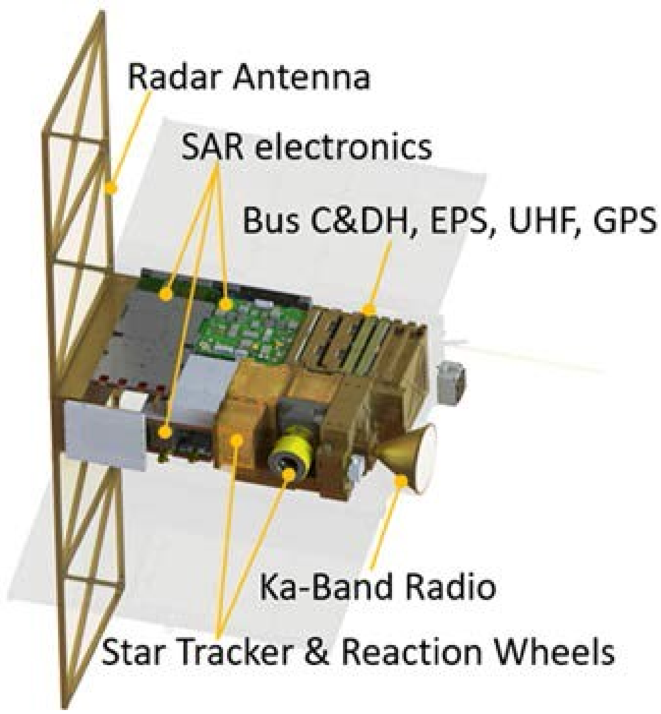


Figure 5: Rendering of the hardware integrated into a standard 6U bus for an example terrestrial prototyping validation and test activity.

3. MULTI-SPECTRAL TELESCOPE

The Leidos Multi-Spectral Telescope (MST) design and performance characteristics are highly relevant to evolving lunar/cislunar exploration and mapping needs. **Table 1** presents a summary of the Leidos MST design and performance characteristics. The visible sensor is a 1024 x 1024 pixel, radiation hardened CMOS Active Pixel Sensor and the MWIR sensor is a 256 x 256 pixel InSB focal plane array. Larger format arrays are available and could be used to increase the sensor FOV or reduce the IFOV. For example, for a given IFOV, larger format arrays reduce the time to map or survey larger fields of regard, improving the utility and efficiency of the sensor for the mission. The MST fits into a 50U internal space on an ESPA-class bus, with the telescope extending outside one side of the spacecraft by about 6". We also use a radiator along one side of the spacecraft to help cool the IR optics and dissipate excess heat from the sensor electronics.

Table 1: Multi-Spectral Telescope Design Specifications

Parameter	Value
Operational Bands	Vis (6 bands) and MWIR (4 bands)
Aperture Diameter	15 cm
Coverage at 1 km	10 m (visible); 24 m (MWIR)
Mass	≤ 14 kg
Envelope	18" x 14" x 14"
Power	55 W Peak; 35 W Average
Input Voltage (SC power)	22 to 32 V
Design Lifetime	1 - 3 years

All payload hardware, with the exception of the payload electronics, is mounted on an optical bench that also serves as a structural component of the spacecraft. The telescope output is split between visible and MWIR channels by a dichroic beam splitter. The MWIR focal plane is cooled to cryogenic temperatures by a split-Sterling cryocooler. Narrow spectral bands are selected using a motorized filter wheel assembly in each optical path. The spectral bands provide the capability to image and map specific resources of interest on the moon; typically, these bands are specified by the customer's science team. Both the visible and MWIR paths feature a motorized focus mechanism for fine focus adjustment on orbit. The visible and MWIR images are acquired and read out simultaneously for transmission to the ground. The imagers are supported by an electronics module that can be mounted remotely from the optical bench. Sensor thermal control utilizes spacecraft radiators to passively radiate excess heat from the sensor electronics and cryocooler.

The MST has been fully qualified for space and has a TRL of 8. This level of technical maturity provides a low risk path to acquisition of high-quality multi-spectral imagery for a number of lunar/cislunar missions. Its low mass, low power and small size facilitate its integrations as a primary or secondary sensor on small spacecraft platforms. Mission life is 1-3 years, depending on parts selection and the level of redundancy implemented in the payload electronics.

4. WIDE-FIELD-OF-VIEW SENSOR

Hosted in close proximity to the Mullti-Spectral Telescope, the Leidos Wide Field of View (WFOV) Sensor (**Figure 5**) provides visible imagery that is co-aligned with the narrow field of view of the MST. The WFOV imagery is used to provide guidance and navigation for the satellite and to assist in pointing the MST to a desired area for acquisition of detailed multi-spectral imagery. The sensor incorporates refractive optics and the same 1024 x 1024 pixel imager utilized in the MST. The sensor electronics are housed with the main body of the sensor. As with the MST, larger format imagers can provide a larger FOV or smaller IFOV, depending on the demands of the mission. **Table 2** presents a summary of the design specifications for the sensor.

Like the MST, the WFOV sensor has been fully qualified for space and has a TRL of 8. The size, weight and power of the sensor is compatible with nearly all small spacecraft platforms. Mission life is 1-3 years, depending on parts selection and the level of redundancy implemented in the payload electronics.

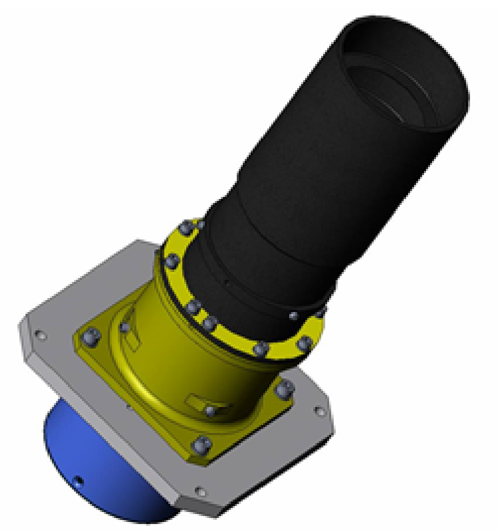


Figure 6: The Leidos Wide-Field-of-View Sensor

Table 2: Wide Field of View Sensor Design Specifications

Parameter	Value
Operational Band	Vis
Aperture Diameter	22.5 mm
Coverage at 1 km	166 m x 166 m
Bright Object Exclusion	≥ 20° from the boresight
Mass	≤ 1.2 kg
Envelope	9" x 4" x 4"
Power	≤ 2.5 W
Input Voltage (SC power)	22 to 36 V
Design Lifetime	1 - 3 years

5. PRECISION NAVIGATION SOFTWARE

In addition to having the required sensors tested and ready to support lunar exploration, our solution concept utilizes a novel approach to navigation developed by Hill [3] at the University of Colorado, and implemented by SpaceNav into their Advanced Orbit Determination Software tool that an ESPA host could leverage. The SpaceNav software leverages the asymmetric gravity field in cislunar space to solve for the absolute state of itself and additional

lunar/cislunar objects using relative ranging observations. That is, without ground station support and without need for continuous earth ground station contacts, it can tell where the ESPA host is, as well as anything else around it. SpaceNav Advanced Orbit Determination Software is currently implemented as a working prototype (TRL 3-4).
By leveraging an innovative navigational technique on the ESPA host, the solution enables persistent local and backhaul communication, situation awareness, and navigation capability for the orbital and surface domain in cislunar and lunar space. The proposed methodology can provide navigation support and enhancement for approaching and operating crewed lunar missions, as well as lunar surface operations such as a rover.

Navigation

The accurate navigation of spacecraft in cislunar and lunar space has historically required large, expensive networks of sensors on the earth, demanded a frequent observation schedule, and encountered difficulties such as limited options on the far side of the moon. For spacecraft in low lunar orbits (LLOs) and libration point orbits (LPOs) such as near rectilinear halo orbits (NRHOs), successful navigation requires consistently high accuracies due to perturbations caused by large mass concentrations ("Masscons") and the natural sensitivity of three-body orbits to small perturbations. Therefore, it is of interest to reduce cost and complexity of cislunar and lunar space navigation, while maintaining operational accuracy.

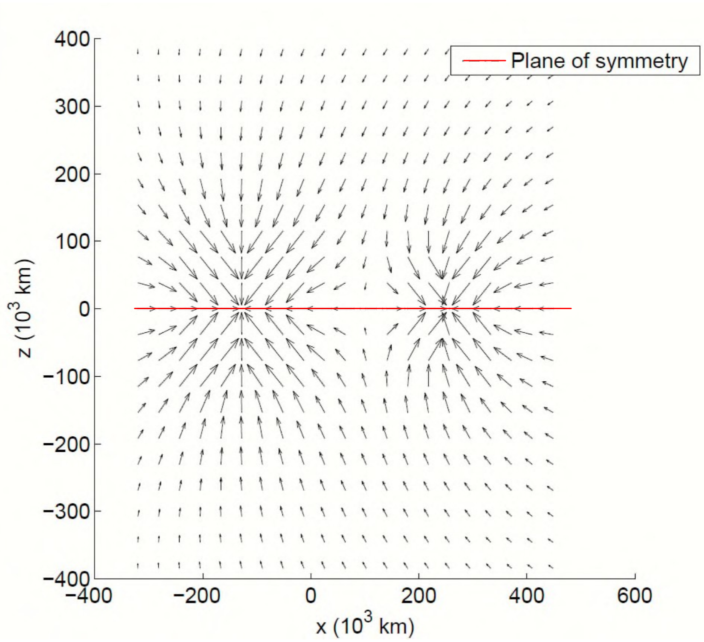


Figure 7: : An exaggerated gravity field map between the Earth (left) and the moon (right). The direction of the moon's orbital velocity is in the y-axis direction. From Hill Error! Reference source not found..

Coincidentally, the non-uniform gravitational field of the earth-moon system, which is responsible for some noted navigational difficulties, also enables a peer-to-peer navigational methodology known as Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON). Typically, satellite-to-satellite tracking (SST) is incapable of absolute positioning due to the nonuniqueness of solutions, e.g., the geometry of a satellite pair in low earth orbit (LEO) is exactly replicable on the opposite side of the earth. When considering the effects of the earth's gravity in cislunar and lunar space, however, the gravitational dynamics become asymmetrical, and orbit shape, size, and orientation becomes unique [3].

Figure 6 illustrates the complex gravity field between the moon and earth. Therefore, LiAISON enables absolute positioning for navigation purposes based on relative SST. Specifically, as long as one satellite is positioned in an orbit based on third body dynamics, the orbit of both this and another satellite can be determined via traditional orbit determination (OD) process such as the Kalman filter. Since NRHOs leverage the third body effects of the earth-moon system, they are candidates for a LiAISON enabled mission.

LiAISON has received extensive attention in literature, with research spanning LLO tracking, crewed mission navigation and support, and rover positioning [3], [4], [5], [6]. In all cases, LiAISON has provided a powerful and stable method of navigation that is possible to be used as a fully autonomous methodology, as well as an enhancement to more traditional navigation approaches such as the Deep Space Network (DSN). Specifically, applying LiAISON to a cooperative pair of a lunar L2 (LL2) halo orbiter and a LLO in a 100 km circular polar orbit resulted in state estimates within 10 meters in position and 1 cm/s in velocity for the LLO orbiter and 100 meters and 1 mm/s in position and velocity for the L2 halo orbiter [3]. In our concept, LiAISON methodology is selected for cislunar and lunar absolute position navigation. LiAISON enables persistent local and backhaul communication and navigation capability for the orbital and surface domain in cislunar and lunar space.

6. DESIGN CONSIDERATIONS

There are various design tradeoffs that will be decided based on mission objectives. Ground penetrating radar and electro-optical sensors, for instance, perform better in an orbit closer to the lunar surface. As a result, and enabled by a negligible atmosphere on the moon, the operating altitude for the ground penetrating radar is lower than for a similar earth-bound radar, allowing for a much less complex and lower risk antenna and power level design. Hence, for the lunar mapping and resource and natural shelter identification applications, an altitude of approximately 100 km is selected to result in a more stable orbit (than possible at even lower lunar orbits) and to allow use of the same SRI electronics with a non-deploying antenna (i.e., lower risk than a deployable).

Around earth, the atmospheric drag when traded against the antenna size requires a minimum altitude of 500-550 km, so that the drag is not so large as to limit the mission life. Since there is negligible atmosphere on the moon, the radar can be operated at much lower altitude (~5x lower) in lunar missions than earth-bound missions, and hence use even lower power and smaller antenna.

For ranging applications (finding the distance to an object) the operating distance of the same radar can be more than 10,000 km.

SpaceNav's relative navigation solution needs an orbit thousands to tens of thousands of kilometers from the lunar surface so that there is significant interaction between the gravitational fields of the moon and the earth because the relative navigation method depends on the asymmetry created by the two interacting gravitational fields.

Therefore, for lunar mapping and resource identification applications, as illustrated in **Figure 1**, the solution would involve multiple vehicles: sensors in a vehicle in a lower orbit (~100 km) and the precision navigation solution in a different vehicle in a near rectilinear halo orbit at a much higher altitude (~10,000 km). Taking into consideration the broader lunar asset arsenal including other lunar space assets, the optimal placement of the described payloads can be determined.

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