HARNESSING SPACESHIP MOON FOR MOTHER EARTH
FOR THE SMALL SATELLITE SYSTEMS AND SERVICES SYMPOSIUM

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ABSTRACT

What if I built you a spacecraft? It wouldn't be a perfect spacecraft, but it would be far more capable than any that has ever been built. I would make it GIANT, so big, in fact, that it would bend the space around it and affect the dynamics of things that flew by. It could house countless people or things with an unconstrained field-of-view on the outside and secure protection from physical or radiation threats on the inside. I'd supply it with nearly limitless water, oxygen, and other valuable commodities, even equipping it with gravity, so you could tell up from down. Finally, I'd station it in a stable orbit of earth without needing any propulsion to keep it there. What if I did all of that for FREE and gave it to you TODAY?

The theme of this year's symposium is: "Information Made in Space", but we sometimes forget that concept has been around almost as long as humans have. It's not hard to imagine our primitive ancestors using Polaris to find their way home from the hunt. Once we had graduated from hunter-gatherers to farmers, the explosion of our population was fueled by our ability to exploit seasonal information from space to our advantage. However, somewhere along the way, a great divide formed between the historical Astronomer tribe and the modern Aerospace Engineer tribe, who only acknowledged the "information made from space" when it originated onboard a craft he or she had purposefully placed there. All of a sudden, navigation information from Polaris or a simple sextant was discarded in favor of "precision navigation and timing (PNT)", only to be supplied by the Global Positioning System (GPS) and its follow-on Global Navigation Satellite System (GNSS) constellations.

We have to wonder if there is a compromise between the 1.5 million years of humans that navigated without GPS and the 40 years of humans that have grown increasingly, almost exclusively, reliant upon it. This paper will explore that compromise, in the context of the most capable satellite the earth has ever "launched": Spaceship Moon. Specifically, however, it will detail how multiple small satellites and other (lunar) surface craft, built and deployed by civil, commercial, and security entities worldwide, are proliferating into the domain shaped and occupied by the Moon to serve as force multipliers to make the most out of Spaceship Moon's native resources in the interest of producing "information made in space".

1 A BIG SATELLITE WALKS INTO A SMALL SATELLITE SYMPOSIUM …

With a commitment to circle back to the theme of this symposium, it is instructive to first touch on the potential of what is, by far, the most capable satellite of earth – Spaceship Moon. A comparative resource accounting with the International Space Station (ISS) is useful to illustrate this point. ISS has up to 400 gallons of water onboard.[1] Spaceship Moon has about 600 million metric tons.[2] ISS is a structure with the area of a football field. Spaceship Moon is a structure with the area of North and South America combined. ISS can support solar arrays to produce 120KW of power. "A 400km wide solar belt constructed on the Moon could produce energy equal to 17 billion tons of oil."[3] Each day, ISS provides between 2.3 and 9kg of oxygen to the crew of six. Spaceship Moon's surface has enough oxygen to support 8 billion people for nearly 100,000 years.[4] Almost regardless of the consumer, Spaceship Moon has something for you — microgravity for biologists; radio silence for astronomers; sealable subsurface lava tubes the size of cities for settlers; and even a tidally-locked far side for those who might have something to hide.

1.1 Use Case 1: Webb 2.0 … for the scientist

Specifically, however, what services or commodities, and for what consumers, support our contention that we should pursue the Moon as a source of information made in space? Many things, but perhaps the most visible of late is the cosmological information potentially derived from systems like the James Webb Space Telescope (JWST). Launched late last year, it is already becoming identified as one of the greatest achievements of humanity, giving us an opportunity to explore the literal beginning of time and the origin of our universe, but also lighting the way to a future where humans may thrive on another planet.

NASA's JWST, built in partnership with Northrop Grumman Corporation (NGC), arrived at Earth-Sun Lagrange Point 2 (L2) recently, marking the completion of its million mile journey and the first month of its half-year long commissioning period. But despite its potential, this magnificent engineering feat took thirty years and $10 billion to arrive at a place where it can unlock these amazing mysteries of the early Universe. Unsurprisingly, scientists have already begun to ask, "Where do we go from here?" The prevailing answer is Spaceship Moon. The next "great" space observatory will not operate in the visible, nor the infrared spectrum. Rather, it will be a radio observatory with a giant aperture assembled on the radiation-quiet far side of the Moon. With breakthroughs in advanced manufacturing, could the majority of the telescope be built with in situ materials, pre-deployed to Spaceship Moon 4.5 billion years ago?

Figure 1. James Webb Space Telescope in Assembly

1.2 Use Case 2: Fusion … for the businessman

Moving beyond observational cosmology, the Moon is virtually untapped for its enormous content of minerals and the opportunities they afford. Until now, maximizing the wealth of resources on the Moon has been difficult, due primarily to our lack of knowledge of what is there and how to get it. In the last decade, however, researchers from around the world have completed detailed assessments of the sub-surface content and are developing detailed projects on how to detect, excavate, mine, extract, obtain, contain, and utilize vital minerals and resources that reside there. Some lunar resources will be used for onsite operations, while others have the added challenge of returning the materials back to earth, which involves the complexity of space transportation.

An example of the latter is Earth's need for Helium 3 (He-3). Though its requirements are somewhat debatable, it is clear that the amount of He-3 available on earth is a small fraction of what is abundant on the Moon. It is well known that He-3 is dwindling, perhaps 20 years remaining, and due to the overall shortage and current inaccessible location of remaining stores (in Russia), the US began rationing He-3 in 2010. Even before the Russian crisis, the demands and availability of He-3 were noted in open market prices - before 2010: 100,000 L/year @$200/L vs after 2010: 14,000 L/year @$2,000/L.

He-3 is a product of millions of years of our sun's rays and meteorites bombarding the surface, imparting the isotope into the Moon's regolith. The projected amount of He-3 on the Moon is estimated at one million tons[5]. The largest uses for He-3 on earth are for neutron detectors for homeland security, cryogenic systems, and medical imaging -- all information-driven systems needed on Earth. In addition, it is anticipated that He-3 will be used for future nuclear fusion power plants as their clean energy source.

Lunar exploration and mining is a new field, and other than surface regolith, no one has extracted and transported He-3 from the Moon before. It is possible that He-3 could be the first commercial "off-Earth" commodity play, and will set precedents for many more commodities to be extracted in the future. In support of that, NGC has enlisted a team from the University of Michigan to research the problem and identify methods to retrieve valuable commodities from the lunar surface. Moreover, the team is looking at cost effective ways to excavate, extract, and collect the element from the regolith.

2 IMPEDIMENTS TO REALIZING THE POTENTIAL OF SPACESHIP MOON

Assuming we have sufficiently established the potential of Spaceship Moon and recognizing this potential has existed as long as humans have occupied Earth, what has prevented us from more thoroughly realizing that potential in support of our interests? Why haven't astronomers established a radio observatory? Why haven't businessmen extracted He-3 and other natural resources? Why haven't biologists and chemists established a low-gravity laboratory? Finally, and most notably, why haven't humans migrated to what is basically an 8th continent, sitting a mere three days away, despite Krafft Ehricke's observation in 1984 that, "If God wanted man to become a spacefaring species, He would have given man a Moon"[5]?

The answers to these questions involve a complex mix of political, technical, and economic factors, well beyond the scope of this paper. However, Maslow's Hierarchy of Needs is a well-accepted recipe to achieving "one's full potential" and what will follow is a description of several small satellite efforts to establish the "support commodities" that service Maslow's "basic needs" and ultimately form the foundation that will support the full suite of human ambitions with Spaceship Moon.

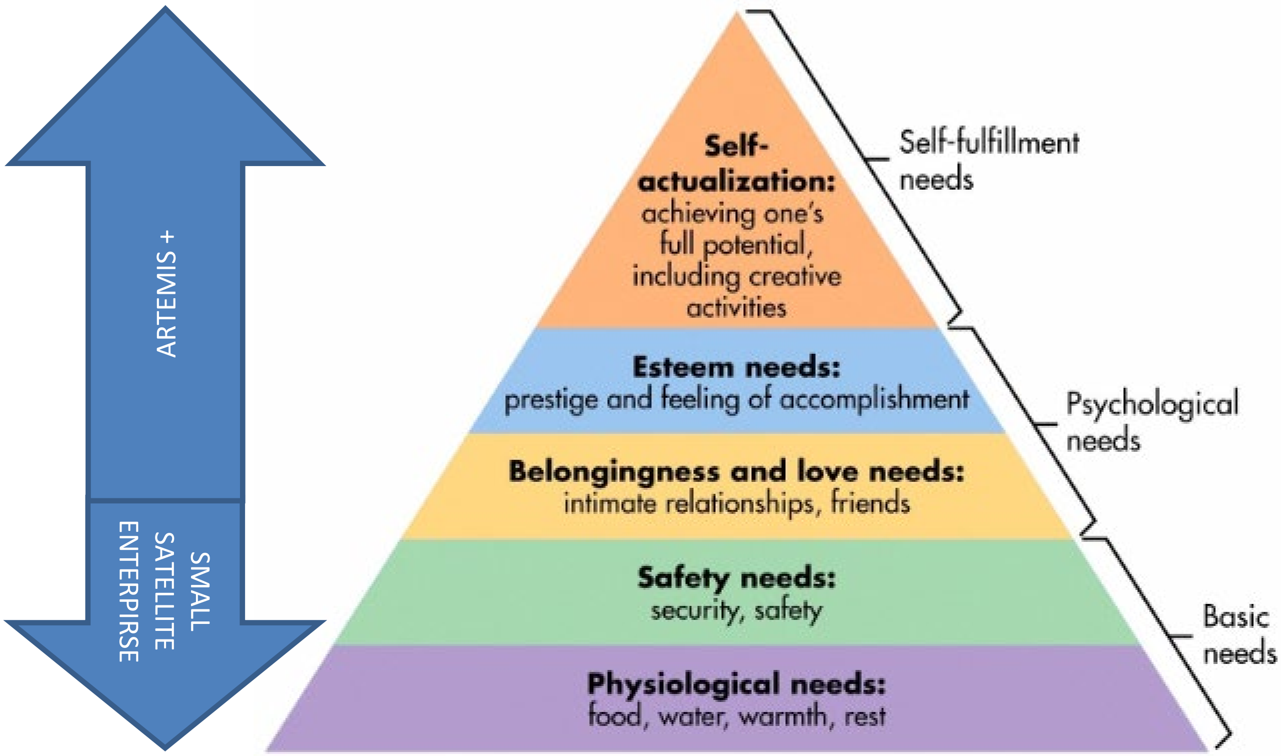

Figure 2. Maslow's Hierarchy of Needs

3 SMALL SATS OVERCOMING IMPEDIMENTS … ONE BY ONE

3.1 Commercial Lunar Payload Services (CLPS) … to get them there

Any discussion of how small civil/commercial/security satellites (to include small lunar surface craft) can serve as levers to realize the potential of Spaceship Moon needs to begin with the challenge of accessibility. Historically, small satellites are restricted to rideshare delivery and until NASA stood up the CLPS initiative, the Moon was not on the "city bus" route. NASA specifically stood up CLPS to allow rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration or commercial development of the Moon.[6] Though investigations and demonstrations launched on the commercial CLPS flights will complement the Artemis program, it is intentionally outside of that effort.

Initially welcoming nine U.S. companies to its CLPS program in November 2018, NASA added five more vendors to the list a year later, bringing to 14 the total number of eligible vendors. As science, technology demonstration and human exploration requirements for payloads develop, a request for surface task order bids will go to current CLPS contractors.

Individual task order awards cover end-to-end commercial payload delivery services, including payload integration, mission operations, launch from Earth and landing on the surface of the Moon. However, CLPS is simply a delivery service and the commercial launch provider owns the ride, so companies are encouraged to fly commercial payloads in addition to the NASA payloads.

CLPS awards continue at a furious place, opening the cislunar domain to occupants that previously had no hope of access. The current manifest, many of which still have margin to accommodate additional payloads, includes the following:

- Astrobotic will carry 11 payloads to Lacus Mortis, a larger crater on the near side of the Moon.
- Intuitive Machines will carry six payloads to Oceanus Procellarum, a scientifically intriguing dark spot on the Moon, in early 2022.
- NASA awarded Intuitive Machines a task order to deliver the PRIME-1 drill to the Moon by December 2022.
- NASA awarded a task order to Astrobotic to deliver the agency's VIPER to the lunar South Pole in late 2023.
- NASA selected Firefly Aerospace to deliver a suite of payloads to a non-polar region of the Moon in 2023.
- Masten Space Systems has one task order award to deliver and operate eight payloads – with nine science and technology instruments – to the lunar South Pole.

3.2 Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) … to learn the neighborhood

Perhaps as important as accessing the lunar surface/subsurface/orbital domain is the "made in space information" of understanding the dynamics of systems existing in that domain. To that end, NASA has partnered with Advanced Space, LLC of Boulder Colorado to develop and build the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which will serve as a pathfinder for Near Rectilinear Halo Orbit (NHRO) operations around the Moon. The NHRO, (Perilune = 3,200 km; Apolune = 70,000 km) is the baselined orbit for the NASA's Artemis Gateway lunar orbital platform.[7] The CAPSTONE mission will use a 12U spacecraft, developed by Tyvak Nanosatellite Systems of Irvine, California and expected to be the first CubeSat to fly in cislunar space, to validate simulations and confirm operational planning for Gateway while also validating performance of navigation and station-keeping requirements for the Power and Propulsion Element. Thus, this mission will provide operational experience to NASA, commercial, and international missions for operations in a demanding orbital regime.

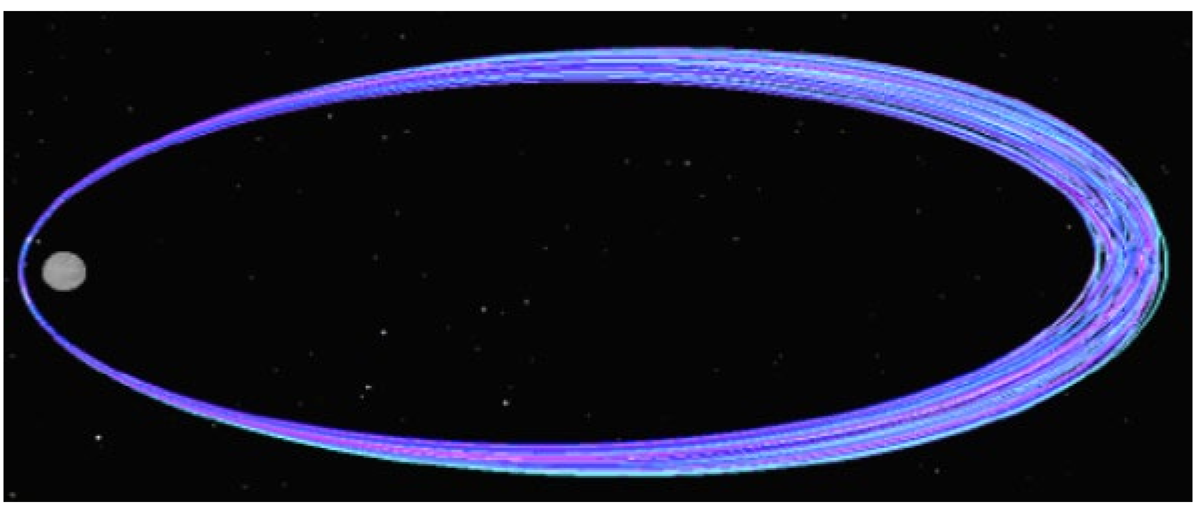

Figure 3. CAPSTONE in NRHO

Noted objectives for the CAPSTONE mission will be to demonstrate the accessibility of NHROs, validate key operational concepts in the NHRO environment, lay a foundation for commercial support of future lunar operations, and accelerate the availability of peer-to-peer navigation capabilities provided by the Cislunar Autonomous Positioning System (CAPS). However, auxiliary objectives include:

- The mission will demonstrate inter-spacecraft ranging between the CAPSTONE spacecraft and NASA's Lunar Reconnaissance Orbiter (LRO), orbiting the Moon since 2009.
- Lay a foundation for commercial support of future lunar operations.
- Gain experience with small, dedicated launches of CubeSats beyond low-Earth orbit, to the Moon.

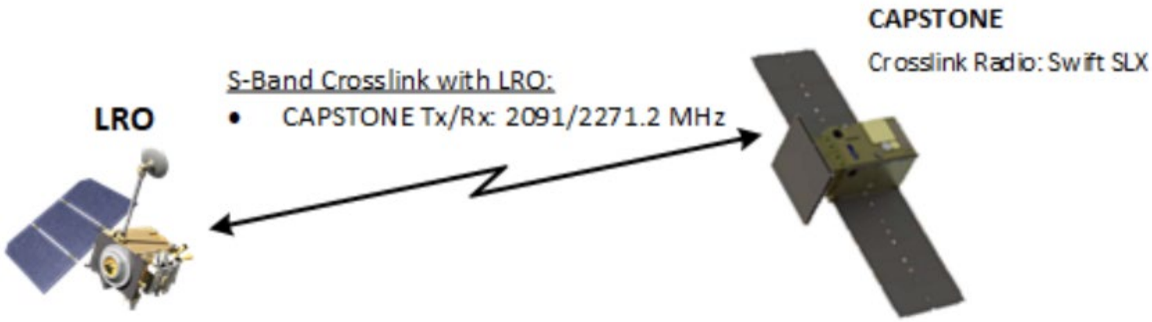

Figure 4. CAPS Peer-to-Peer Navigation Experiment

The CAPSTONE mission is funded through NASA's Small Spacecraft Technology program (SST)[8], which is one of several programs in NASA's Space Technology Mission Directorate. SST is chartered to develop and demonstrate technologies to enhance and expand the capabilities of small spacecraft with a particular focus on enabling new mission architectures through the use of small spacecraft, expanding the reach of small spacecraft to new destinations, and augmenting future missions with supporting small spacecraft. CAPSTONE is manifested for launch in 2022 aboard a Rocket Lab Electron rocket provided by Human Exploration & Operations Mission Directorate Advanced Exploration Systems Division. Coordination and acquisition of the launch is managed by NASA's Launch Services Program.

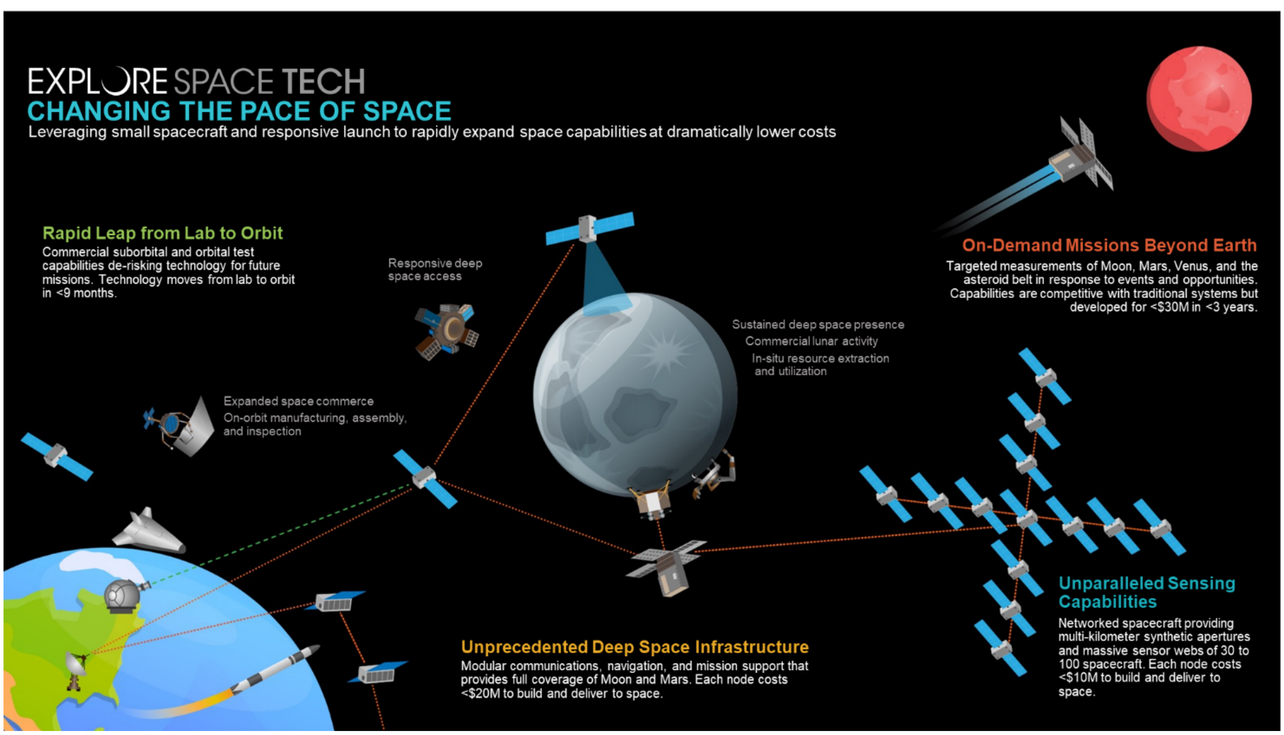

Figure 5. NASA SSTP Roadmap

3.3 Lawn Dart … to proliferate Maslow's "basic services" across an 8th continent

The Lawn Dart concept was derived from the application of connected Unattended Ground Systems (UGS) to provide security in unimproved terrestrial domains for those who rely on the services of communication, navigation, sensing, and power to accomplish their mission objectives. The program collectively labeled these services as "security commodities".

The similarity between the challenges presented in sparse terrestrial domains to those posed by the lunar surface and subsurface suggested that solutions to sufficiently secure the former might translate into solutions that support the persistent presence and ambitions of civil and commercial space. Namely:

1. The ability to remotely deploy and autonomously initialize UGS is essential in harsh, unforgiving domains.
2. The ability to autonomously connect UGS into a scalable publish-and-subscribe internet-of-things (IoT) is a capability multiplier.

The end objective of the Lawn Dart program is a proliferated mesh network around strategically valuable parts of the lunar surface, working in concert with orbital and surface assets to provide publish-and-subscribe security commodity services to civil and commercial consumers. These security commodities will allow assets and owning organizations to better understand their environment in order to safely and securely operate in it.

The Lawn Dart architecture supports NASA Strategic Goal 2: Extend human presence deeper into space and to the Moon for sustainable long-term exploration and utilization, which will require infrastructure to make "missions safer, more reliable, and more affordable". A permanent presence thriving in an undeveloped domain requires promoting a "secure and predictable space environment" as noted in the National Space Council's report, A New Era for Deep Exploration and Development. Currently, there are insufficient systems to provide security commodities to service the needs of consumers in the cislunar sphere and lunar surface/subsurface. As cislunar and lunar surface exploration and economic activities expand, these commodities will be vital in safeguarding civil and commercial infrastructure and operations.

To truly climb Maslow's pyramid, we have to abandon the current practice on the lunar surface, i.e., "bring everything you need" (… and then bring it again in 14 days, since it didn't survive the lunar night.) This leads to less payload space, increased costs, and redundant systems as the architecture scales. A forward-deployed, networked, night-enduring, and expandable solution provides infrastructure that relieves missions of the overhead burden and frees them up to focus on their mission-specific objectives.

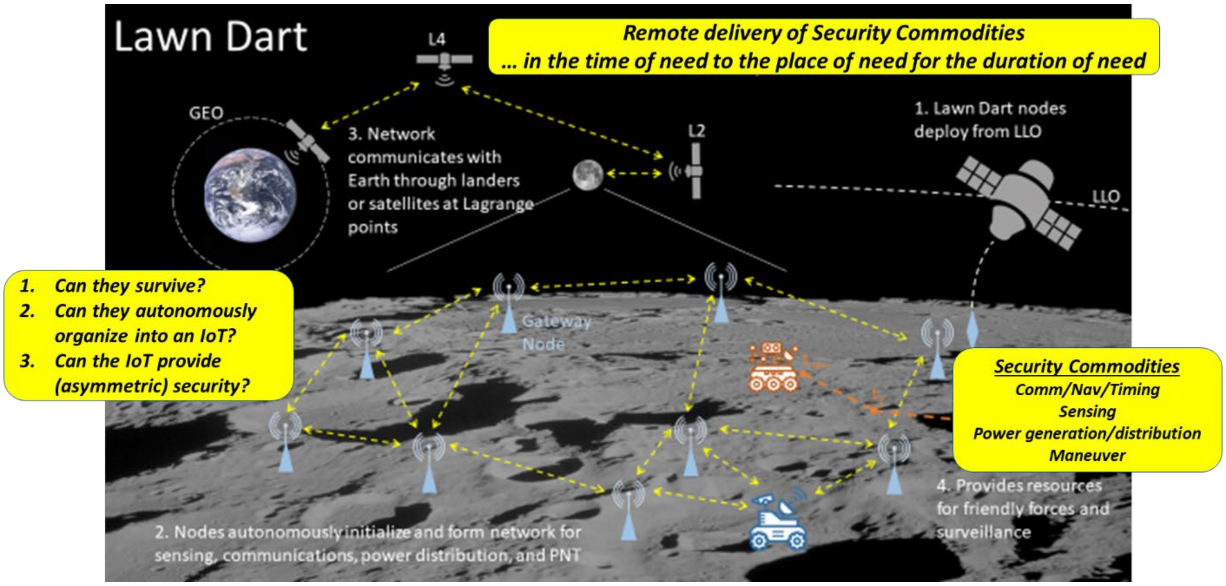

Figure 6. Lawn Dart Remotely-Delivered Lunar Surface Layer IoT

Working in concert with the NASA Flight Opportunities Program (FOP), Lawn Dart will deliver one of the first "security commodities" to the lunar surface: Masten Space System's SkyMage lunar positioning and navigation network prototype. With functionality similar to a Global Positioning System (GPS), the network will enhance cislunar security and awareness by enabling navigation and location tracking for spacecraft, assets, objects, and future astronauts on the lunar surface or in lunar orbit. As the lunar ecosystem grows, the network will also help advance lunar science and resource utilization by improving landing accuracy and hazard avoidance near critical lunar sites.

"Unlike Earth, the Moon isn't equipped with GPS, so lunar spacecraft and orbital assets are essentially operating in the dark," explains Matthew Kuhns, vice president of research and development at Masten. "As a result, each spacecraft is required to carry heavy navigation hardware and sensors on-board to estimate positioning and detect potential hazards. By establishing a shared navigation network on the Moon, we can lower spacecraft costs by millions of dollars, increase payload capacity, and improve landing accuracy near the most resource-rich sites on the Moon."

Masten is developing the PNT beacons that are equipped to survive harsh lunar conditions. They are collaborating with Leidos to build shock-proof beacon enclosures that can be deployed in lunar orbit to penetrate the lunar surface and create an autonomous surface-based network. Similar to a mesh network, the surface-based network can enable consistent wireless connectivity to lunar spacecraft, objects, and orbital assets.

Hardware is being assembled and will soon be tested aboard Masten's rocket-powered lander, Xodiac, to demonstrate payload integration and beacon operations in a terrestrial environment, enabling a path towards lunar demonstration. Masten has more than a decade of experience maturing PNT systems, including Jet Propulsion Laboratory's lander vision system that was tested on Masten's Xombie rocket to enable a successful Mars mission for the NASA Perseverance rover.

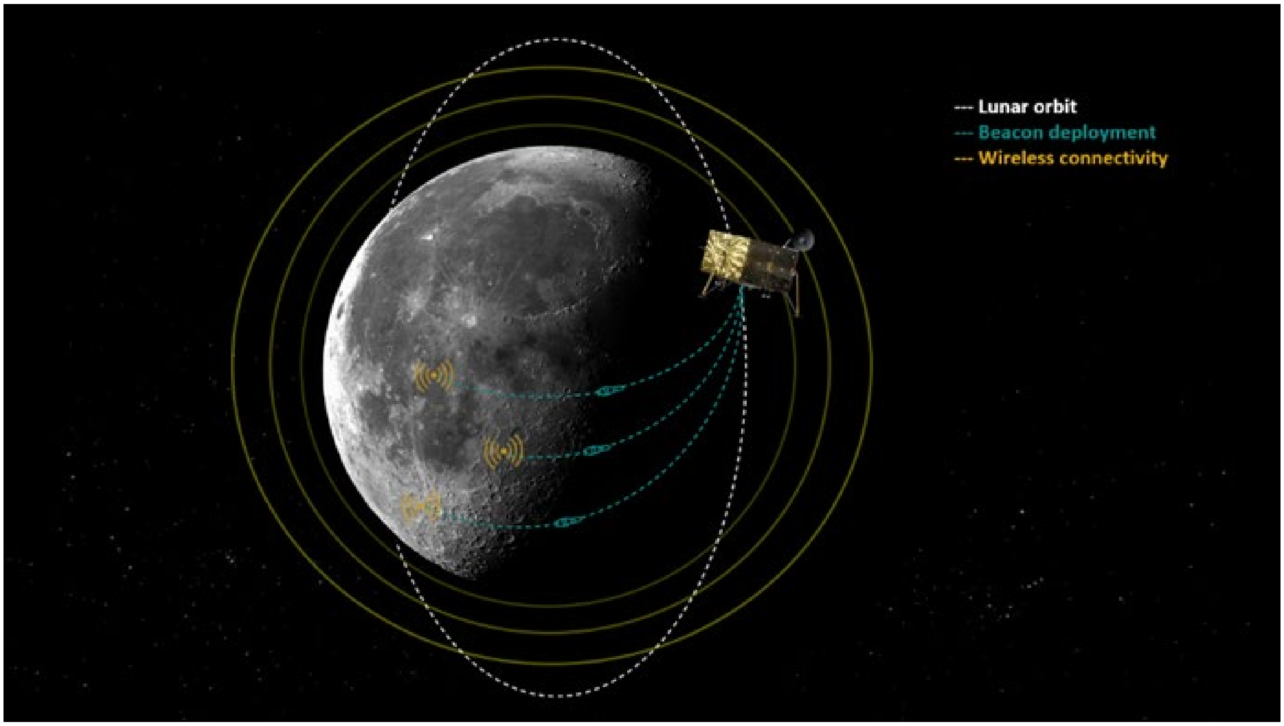

Figure 7. Masten SkyMage Lunar PNT

3.4 <u>INFORMATION</u> Made in Space

Recognizing the premise of this paper that "information made in space" can originate from the domain shaped and occupied by Spaceship Moon, there is an implied mandate to get that information to the consumers, who for the time being, are constrained to Mother Earth. But what if we attacked that problem in two pieces? The first would address the raw data … as much as possible, as often as possible, while the second would transform that data into useful information.

3.4.1 LunaNet … to connect the world(s)

Analogously to CLPS' role in getting small satellite systems into the domain, it is LunaNet that aspires to extend a very effective terrestrial communications architecture to the cislunar domain and service the need for data retrieval from any system that occupies it. In LunaNet, NASA is developing and promoting a comprehensive architecture for lunar communications and Positioning, Navigation, and Timing (PNT).[9] Based on some of the central tenets of the Internet, NASA won't own LunaNet. Rather, they will be a provider of open source services and simultaneously a user of those services. Like the Internet, everyone can participate by bringing their own networks, providing services, and using services. It's conceived in an architectural sense as a framework of frequency bands, protocols, and standard services that enable interoperability across the network-of-networks. Unlike terrestrial environment where GPS (and similar GNSS) are separate, dedicated systems, NASA envisions LunaNet to provide integrated communications and PNT services from a variety of orbiting and surface platforms to users in orbit and on the surface. It starts very small, but has scalability to grow into complete lunar coverage with unbounded capacity. The concept has been under development by a group of international space agencies for several years and has strong backing for the open, international approach.

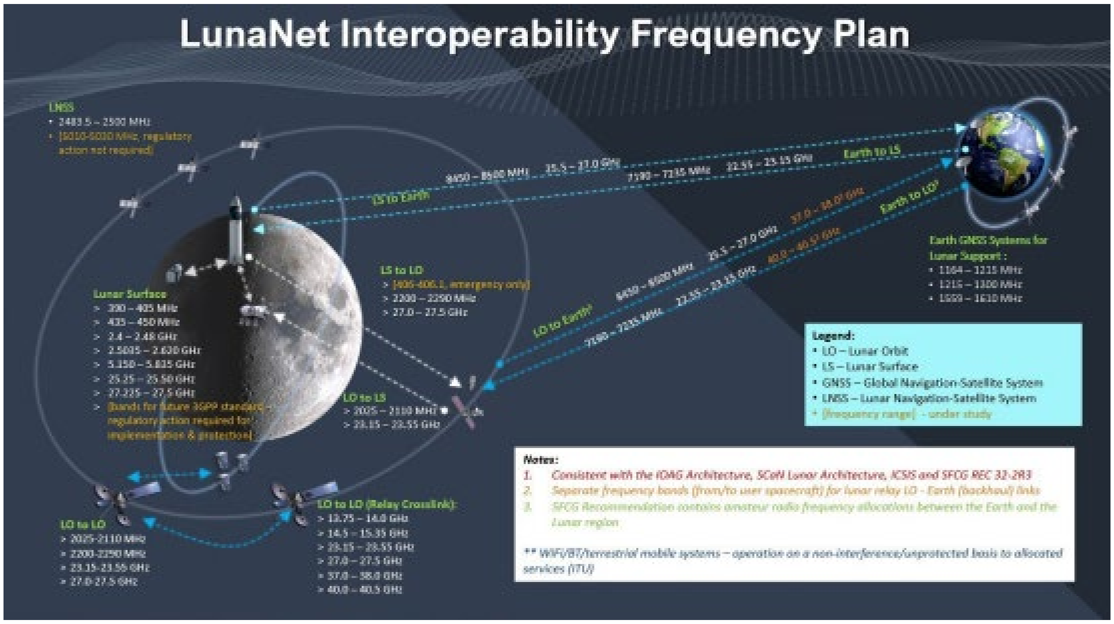

Figure 8. LunaNet Interoperability Frequency Plan

3.4.2 Celestial Mapping System (CMS) + MoonHacker™ … to make INFORMATION from data

A Lunar Decision Support System is needed for localized data gathering, processing, and determinations for optimum efficiency and safety while operating on Spaceship Moon with growing populations. This information in turn will help create the first Mother Earth Off-world Support System.

NASA Ames Research Center's (ARC) Celestial Mapping System (CMS) is a software platform to generate virtual 3D globes for celestial bodies within our solar system.[10] Various layers are built on top of the virtual globe to provide visualization of high resolution imagery, enable precise measurements, build analytical capabilities and a broad range of functionalities to assist planetary scientists and mission planners.

The present focus of CMS is on developing lunar mapping tool kits to provide features such as a 3D first person view with zoom and navigational capabilities, realistic terrain visualization based on LRO data, measurement tools, Apollo landing site annotations, stereoscopic view, elevation profiles, line of sight analysis and many more. The application is developed to provide situational and domain awareness on the Lunar surface, planning capabilities for equipment placements and traverse path optimization.

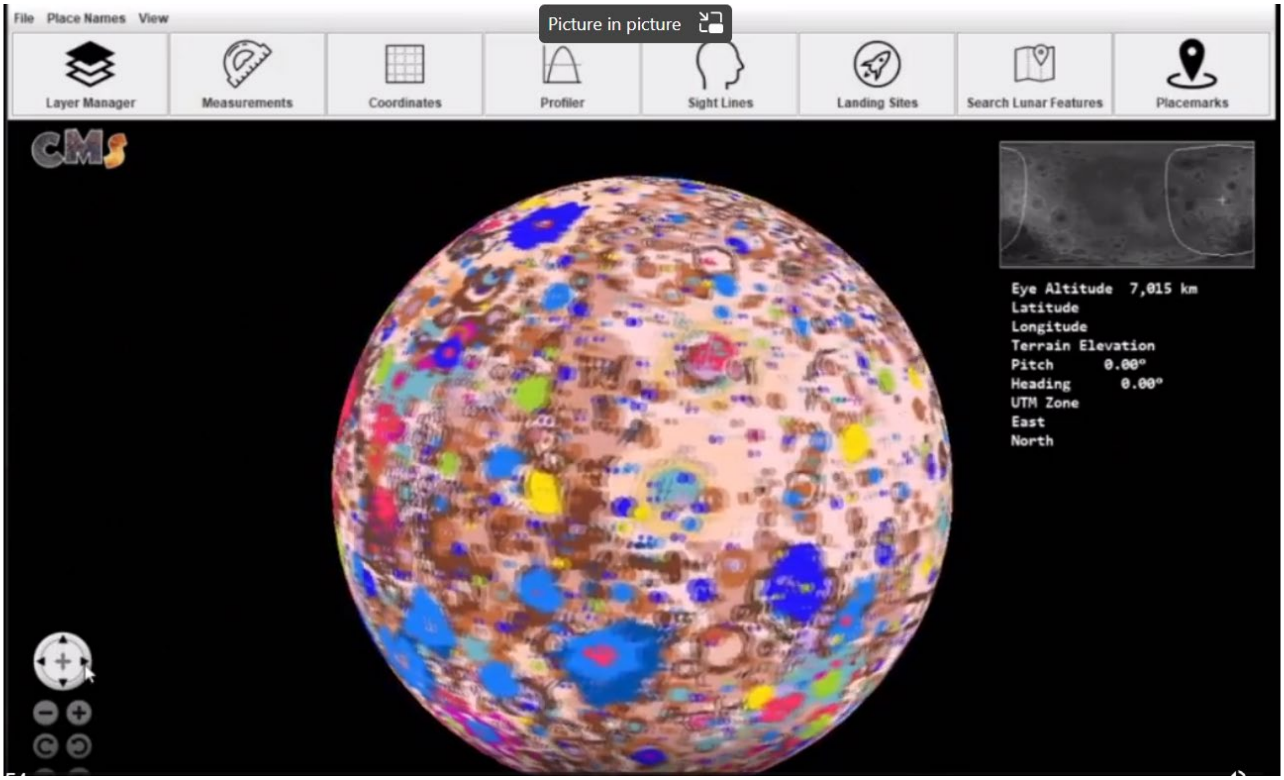

Figure 9. CMS Geologic Map of the Moon

Meanwhile, on the commercial side, Lunar Station, an MIT start/scale up at technology readiness level 9 (TRL-9) with commercial revenue, has developed a breakthrough cloud-based deep learning solution for advanced lunar environmental insight (MoonHacker™ Intelligence Platform) that retrieves and synthesizes structured and unstructured multispectral sensor datasets into foundational insights that enable scientific, governmental and commercial organizations to identify, plan, simulate and evaluate scenarios to maximize mission outcomes.

In particular, Lunar Station provides key “information made in space” with: intelligence and analytics; easy to access advanced lunar intelligence; cloud-based analytical engines for commercial, Government agencies and academia; simplified gateway for sensor companies to participate on the MoonHacker™ Intelligence Platform; and complete data lifecycle processing for data generators and insight consumers.

Recently, MoonHacker™ generated ten random locations in the SVCH-A9 area and found 90 paths between them. This chart visualizes the unique topology for the SVCH-A9 area, identifying the high and low traffic paths that could be used by Alpha Centauri Space and others who are working in this area. The best path is 106.8(km) in length and has an average slope of: 1.35(deg). The path starts at an altitude of: -1106.3(m) and ends at an altitude of: 337.5(m). The path ends at Lat: 23.795(deg) Lon: -48.595(deg). Currently 0.13% of the points along the path are outside the +/-10 deg favorability range.

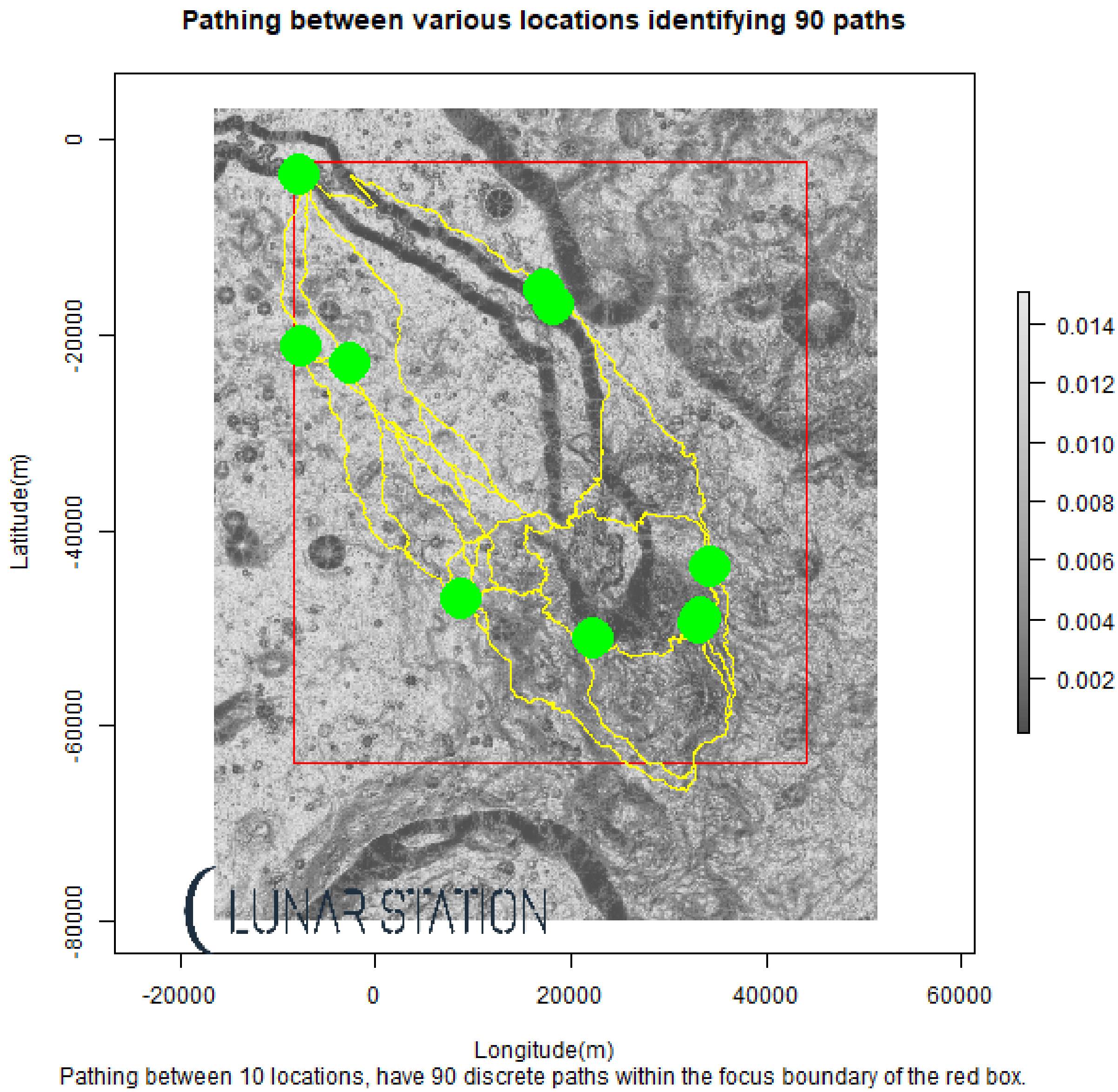

Figure 10. MoonHacker™ Lunar Decision Support System

The pathing chart above uses eight neighbors, a slope factor of four and the wheeled transport type of movement construct.

4 CONCLUDING WITH A VISION OF A REALIZED POTENTIAL

The human race is finally on the verge of transforming Spaceship Moon into a capable source of "information made in space". Unquestionably, the transformation is coming at the hands of many BIG technologies, like unprecedented mobility offered by Northrop-Grumman's Lunar Terrain Vehicle (LTV) and operational energy flowing from their recently proposed Fission Surface Power (FSP) Project to the U.S. Department of Energy. The former will allow humans and autonomous systems a level of mobility higher than all the previous rovers added together, and at speeds that will allow the first every lunar rapid response capability. The latter will produce sufficient thermal power to drive eight 7 kW_E capacity Stirling engines, resulting in 42 kW_E electrical power to finally enable a persistent human and machine presence, i.e., one that survives the lunar night.

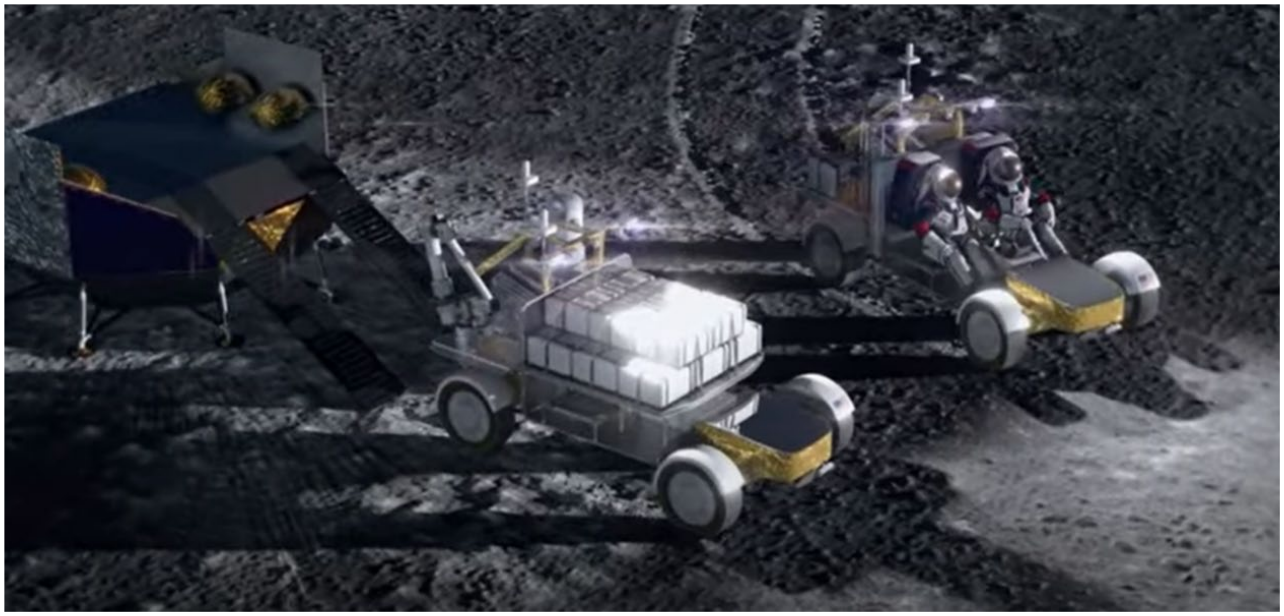

Figure 11. Lunar Terrain Vehicle

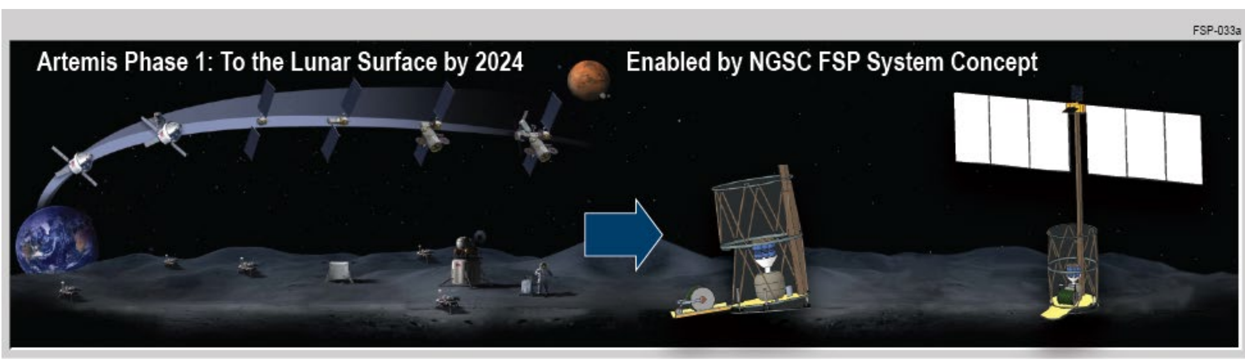

Figure 12. Fission Surface Power Reactor

However, SMALL satellites, with the networked support and security services they provide, are proliferating to the domain in parallel, but at affordable prices and responsive schedules, to almost insidiously become a critical component to the BIG picture of generating "information made in space". NASA's baseline plan is to develop and deploy a small space station, Lunar Gateway, into a low-maintenance lunar orbit to serve as a solar-powered communication hub, science laboratory, short-term habitation module for government-agency astronauts, as well as a holding area for rovers and other robots. The result will be an amazingly capable and unprecedently complex system with analogously complex cost estimates requiring multi-national budgeting. Even if estimated end-to-end costs of "$100+ billion" are exaggerated, it's tempting to imagine what a similar investment in Spaceship Moon, riding on a small satellite-enabled service and security backbone, might bring in our quest to follow Krafft Ehricke's recipe of using Spaceship Moon to climb Maslow's Hierarchy and become a spacefaring species.

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