ASTROBOTIC COMMERCIAL LUNAR DELIVERY MODEL FOR SCIENCE MISSIONS. D. B. Hendrickson[1], S. A. Huber[2], K. J. P. Thornton[3], [1]Dan.Hendrickson@astrobotic.com, [2]Steven.Huber@astrobotic.com [3]John.Thornton@astrobotic.com, Astrobotic Technology, Inc. 2515 Liberty Ave, Pittsburgh, PA 15222. contact@astrobotic.com.

Introduction: Astrobotic's lunar delivery service opens access to the Moon for new science investigations from around the world. This paper outlines the market demand for lunar delivery service, an overview of the service model, and the public-private partnership that is supporting it.

Current State of Lunar Activity: Since the beginning of the space age, access to the Moon has been limited to a select few. Only three governments have landed robotic spacecraft on the lunar surface – the United States, the former Soviet Union, and China. The cost and complexity of missions to the Moon have restricted the players to large national governments that invest hundreds of millions of dollars per mission. There has been only one Moon landing since the Apollo era, despite the fact that the Moon is only a few days away. There is an enormous pent-up demand for lunar access to be served by emerging commercial lunar delivery. Three recent developments are paving the way for this new service model – reduced launch costs, innovations in electronics and robotics, and innovative public-private partnerships.

Market Demand for Lunar Delivery Service: Within the international community, numerous space agencies—both large and small—have expressed strong interest in the Moon as a destination for science and exploration. The multi-agency Global Exploration Roadmap released in 2013 converged on the Moon as an important stepping-stone for enabling future space programs. [1]

Both small and established space agencies have numerous lunar payloads and projects that have gone unserved for a variety of reasons. In some cases, agency payloads are too small or price tags are too high to justify a full mission to the Moon. Concepts for small spacecraft to host multiple payloads have been developed, but they have been confined to Earth orbit. A commercial delivery method optimized for lunar destinations enables game-changing cost reductions to deliver small payloads to the Moon. This unserved demand for lunar services is already being demonstrated by commercial sales and NASA's two successful internal calls for small satellite delivery to the lunar vicinity on the upcoming EM-1 mission on NASA's Space Launch System.

Instruments have also been built by space agencies for prior missions that were later cancelled due to programmatic issues. Some of these instruments would require little adaptation for flight on another vehicle or mission, but do not have a flight opportunity available. Moreover, there are some space agency technologies that need in-space flight demonstration, but have been grounded by risk inherent in a mission that costs hundreds of millions of dollars. Lastly, NASA's decadal survey has allowed only a once-per-decade chance to consider new missions to the Moon, constricting the very formation of new missions.

For smaller nations' space agencies, commercial lunar delivery enables sophisticated science and exploration missions without the need to invest in large infrastructure such as ground support systems, launch vehicles, launch sites, and landing craft. Commercial lunar delivery enables developing space agencies to tailor a unique lunar program to a cost that is affordable for each agency budget. In some cases, this could mean the inclusion of a small spacecraft onboard a commercial lunar delivery mission, or the outright purchase of a delivery mission for a larger dedicated science investigation.

Further demand for lunar access comes from universities, nonprofits, and other scientific entities that have the capability to do great science, but traditionally have not had the means to access the Moon. The use of CubeSats by universities and non-space agency actors has proliferated significantly since the first CubeSat was placed in orbit in 2003. About 50% of all CubeSats have a university affiliation and the National Science Foundation now has a grant program for funding these missions. Enabled by a delivery mechanism, interplanetary destinations are the next step for CubeSats, and consequently universities and non-profits. [2]

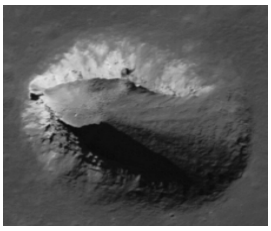
The new lower prices offered by commercial lunar companies also open the Moon to previous non-space actors that may not have considered it a possibility. The interest in space as a promotional tool is already ubiquitous. A recent National Research Council report noted that imagery of a space suit alone was used in advertisements in 2013 for soft drinks, personal fragrance, and automobiles. [3] Thanks to the low per-kilogram price of commercial delivery, companies of all sizes can carry out marketing campaigns on the Moon. For example, Astrobotic has signed a contract with a drink company in Japan to deliver a time capsule to the Moon. More than 80,000 Japanese students have participated in the marketing campaign surrounding the capsule. This is one example of many promotional campaigns and activities to come and, although they are not scientific activities, they do spread the

fixed cost of lunar missions across numerous customers.

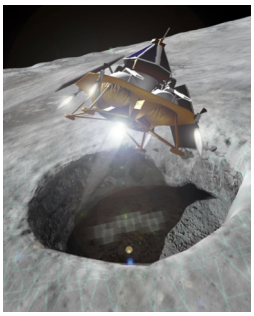
Commercial Service Model: Astrobotic delivers space missions as a service for space agencies, universities, nonprofits, and private companies. Astrobotic collects payloads from these entities around the world and integrates them into a single lunar lander spacecraft. The spacecraft not only carries payloads to their destination in the lunar vicinity, but also provides power and communications commodities as needed by the customer. Customers are offered a choice of three destinations at a cost driven primarily by mass – translunar injection ($98,000 per kg), lunar orbit ($200,000 per kg), and the lunar surface ($1.2 million per kg). The Astrobotic Griffin lunar lander has a variety of mounting configurations for payloads of diverse sizes and shapes. For instance, CubeSats could be placed on the topside deck of the vehicle for deployment in lunar orbit, volatile prospecting instruments could be placed on the isogrid deck platform, and rovers could be attached for deployment on the deck underside.

Public-Private Partnership: NASA's commitment to fostering this new commercial service is a telling indicator of its promising future. In 2014, the agency kicked off its Lunar CATALYST Program, which directly pairs agency expertise and NASA center infrastructure with commercial lunar delivery companies. CATALYST is similar to the highly successful Commercial Orbital Transportation Services (COTS) program that resulted in the development of two, independent commercial launch vehicle services now used by NASA for regular delivery of vital supplies to the International Space Station. [4] Under the CATALYST program, NASA contributes technical expertise, provides access to agency center test facilities, and loans equipment & software, and testing for three lunar focused companies. By leveraging more than 50 years of NASA spaceflight experience, the commercial sector is poised to open the Moon to commercial activity and a broader community of nations.

First Mission to a Lunar Pit: Astrobotic's Griffin Lunar Lander will fly its first lunar mission in late 2016. Its destination will be a region known as Lacus Mortis (44.96°N, 25.62°E) at a lunar pit or skylight that is believed to be an entrance to a lunar cave. Along with customer payloads, the mission will host *Andy,* a vehicle built by Astrobotic partner Carnegie Mellon University to traverse and explore the surface and win the $30 million Google Lunar XPRIZE. The potential skylight at Lacus Mortis is particularly intriguing, because one whole wall of the pit has caved in, creating what could be a natural ramp into the pit. The investigation at Lacus Mortis will be an important first step for investigating planetary pits and caves for science and exploration. For lunar exploration, pits and caves could offer a vital safe haven for astronaut crews - protecting them from micrometeorite bombardment, radiation exposure, and extreme temperature variances. In addition to providing natural protection from these elements, such techniques may reduce the cost and complexity for future planetary exploration, and the Moon offers an appropriate first destination for testing such techniques for future human missions to Mars



Orbital view of the possible lunar skylight at Lacus Mortis on the Moon.



Griffin's first mission will fly over and land near a lunar pit

Conclusion: Access to the Moon is no longer limited to the most powerful national governments. The customer base for commercial lunar delivery is large and inclusive, from companies, to universities, and space agencies. Commercial lunar delivery service makes the Moon accessible to every nation that seeks the transformational power of space to inspire its young people, grow its economy, and advance its scientific enterprise.

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[4] National Aeronautics and Space Administration, About Lunar CATALYST, 2014 http://www.nasa.gov/lunarcatalyst/#.VAh7TVY_EpE.