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Establishing lunar resource viability

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Recent research has highlighted the potential of lunar resources as an important element of space exploration but their viability has not been demonstrated. Establishing whether or not they can be considered in future plans is a multidisciplinary effort, requiring scientific expertise and delivering scientific results.

To this end various space agencies and private entities are looking to lunar resources, extracted and processed in situ, as a potentially game changing element in future space architectures, with the potential to increase scale and reduce cost. However, before any decisions can be made on the inclusion of resources in exploration roadmaps or future scenarios some big questions need to be answered about the viability of different resource deposits and the processes for extraction and utilisation. The missions and measurements that will be required to answer these questions, and which are being prepared by agencies and others, can only be performed through the engagement and support of the science community.

In answering questions about resources, data and knowledge will be generated that is of fundamental scientific importance. In supporting resource prospecting missions the science community will de facto generate new scientific knowledge. Science enables exploration and exploration enables science.

1. Introduction

If humans are ever going to live and work on the Moon or on Mars in a long-term and sustainable way then dependency on resupply from Earth must be reduced to a minimum or removed completely. To achieve this requires that maximum use is made of any local resources that are available. However, the exploration roadmaps of agencies, consolidated in the Global Exploration Roadmap (GER) [1], do not assume any dependency on in-situ resources for currently conceived mission architectures. The absence of In-Situ Resource Utilisation (ISRU) as an assumption for future missions occurs primarily due to a lack of present confidence in its viability. The GER does however recognise that local resources will be an important element in the future. Until local resource utilisation becomes a part of the way missions are planned and executed, it is unlikely that long term sustainability of human exploration of the Solar System can be realised.

New knowledge, new capabilities and new technologies will be required to make the transition to in-situ resource dependency, such that mission success is reliant on the availability and utilisation of resources extracted and processed locally. The Moon as the closest and most accessible destination for human exploration is likely to be the most feasible place to make this transition. Recent discoveries in lunar science and new technologies have changed the paradigm of what we know about potential resources on the Moon, offering new possibilities for resource utilisation to enable sustainable surface missions and develop in-situ resource dependency as an element in mission architectures and planning for missions to Mars.

2. The future of lunar exploration

In 2007 fourteen space agencies came together and agreed a common vision for robotic and human space exploration and a framework through which their activities could be coordinated. This vision and framework is recorded in The Global Exploration Strategy: The Framework for Coordination [2]. An outcome of this was the establishment of the International Space Exploration Coordination Group (ISECG) [3]; a voluntary, non-binding international coordination mechanism through which individual agencies

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may exchange information regarding interests, objectives, and plans in space exploration with the goal of strengthening both individual exploration programmes as well as the collective effort. The key product of this group is the Global Exploration Roadmap (GER) [1].

The GER represents a consolidated view of the exploration missions and plans of the ISECG participating agencies. It reflects a common long-range human exploration strategy that begins with the International Space Station and builds on this to expand human presence into the Solar System. The 'horizon goal' for the GER is sustainable human missions on the surface of Mars. The roadmap is updated periodically to reflect on-going developments in the participating agencies.

The most recent iteration of the GER was published in 2013. It focuses on the first steps in implementing this strategy: utilizing the ISS, continuing to expand the synergies between human and robotic missions and pursuing discovery driven missions in the lunar vicinity that evolve the capabilities and techniques needed to go further. The document recognises the importance of resources for future exploration and the need to characterise potential resources but explicitly defines mission scenarios that do not rely on lunar resources, stating that findings from robotic missions will inform future decisions regarding the promise of using lunar resources and their utilisation. It also states that human mission activities at the lunar surface, which it envisions from the end of the next decade, should advance knowledge that is related to the use of lunar resources and potentially provide the opportunity for advancing concepts related to use of local resources on Mars.

More recently, the Director General of the European Space Agency (ESA) has proposed the establishment of a Moon Village as a goal for the international community, following on from a human return to the lunar surface [4]. The Moon Village is envisaged, not as a discrete and predefined programme, but rather as an open architecture offering opportunities for different nations, and private sector entities, to contribute in an evolving and expanding partnership and a sustainable settlement. The Moon Village would offer multiple uses to multiple users; public and private sector, scientific and commercial. The utilisation of local resources would be an important and enabling element in the development of such a settlement and may also offer an opportunity for the commercial sector.

How then can early missions establish whether or not ISRU can be introduced as an enabling element in mission architectures?

3. The potential opportunities of lunar resources

Lunar resources have long been seen as an enabler for sustainable exploration and various schemes have been identified for their utilisation (e.g. Refs. [5] and [6]). These schemes all utilise regolith, the ground up fragments of lunar rocks that cover the lunar surface and which have resulted from billions of years of impacts by meteoroids (e.g. Ref. [7]). As well as mineral fragments regolith includes glass particles produced during impacts and particles called agglutinates, which are made up of smaller regolith particles fused together in a glassy matrix. Other particles in the regolith can be produced by volcanic events and are manifest as small glass beads (e.g. Ref. [7]). The sizes of regolith particles can vary from the nanometer scale [8] upwards, with mean particle sizes which are typically around 100 μm. The composition of the regolith is variable on both regional and local scales but any at any given lunar location is broadly related to the underlying geology, with relatively minor contributions from external sources, be they volcanic, ejecta from distant impacts or remnants of impactors themselves. The properties of regolith are also affected by the duration of its exposure at the lunar surface to impactors, cosmic radiation and solar wind particles. This exposure results in a process called space weathering, with the extent of weathering often described as a regolith's maturity [7]. Incident solar wind particles become embedded in regolith and can be extracted as a gas by heating [9].

Regolith may be utilised as a feedstock for various processes which result in the production of materials for construction and manufacturing ([10] and [11]) or in chemical consumables for life support [4] or propellants [5].

In the case of consumables, attention has generally focussed on the production of oxygen which typically makes up around 40% of all lunar materials. Most proposed oxygen extraction processes employ a reducing agent (e.g. hydrogen or methane) which is introduced at high temperatures; typically several hundred to more than 1000 °C [12]. Oxidation processes (e.g. using fluorine) have also been proposed [13]. Extracted solar wind gasses have also been identified as possible resources [14].

A potential game changer in recent years, however, has been the confirmation that large scale deposits of water ice and other volatiles are present at the lunar poles [15]. Water is a consumable in and of itself, but is also a source of hydrogen and oxygen which can be used for life-support and propellant. While the presence of water ice has long been postulated at the lunar poles [16] it is only recently, following a number of successful missions, that a strong evidence base for its presence has been available.

The first strong evidence for water ice came from the Lunar Prospector Neutron Spectrometer, which detected an enhanced hydrogen abundance within a few tens of cm of the lunar surface across the polar regions when compared with lower latitudes [17]. This enhancement was consistent with a hypothesis that water ice was present, trapped in very cold areas where solar illumination was low or zero due to shading by surrounding topography. While the intrinsic resolution of the measurements was insufficient to sufficiently correlate hydrogen abundance with topography or the illumination conditions at the surface, statistical approaches were used to demonstrate that permanently shaded areas typically contained more hydrogen than the surrounding areas [18].

More recent data sets from various instruments on the Lunar Reconnaissance Orbiter (LRO) have significantly enhanced the evidence base. The DIVINER instrument demonstrated that surface temperature across the polar regions is sufficiently low as to enable preservation of water ice in the subsurface for geological timescales [19]. Furthermore, the temperatures in permanently shaded regions are some of the coldest in the Solar System, consistent with the thermal preservation of water ice at the surface. Measurements in the UV [20] by the Lyman-Alpha Mapping Project (LAMP) instrument, and by reflected laser pulses [21] produced by the Lunar Orbiter Laser Altimeter (LOLA), are consistent with variable degrees of surface frost in permanently shaded craters. Additional neutron measurements by Lunar Exploration Neutron Detector (LEND) have indicated a complex spatial distribution for bulk hydrogen [22]. Measurements by bistatic radar on LRO, and monostatic radar on the Indian Chandrayaan mission, indicate possible blocky ice material or ice layers at different locations ([23] and [24]).

Water has been definitively measured at only one location in the permanently shaded Cabeas crater in the South Polar Region by the L-CROSS impactor mission [25]. During this mission ejecta produced by the impact of a Centaur upper stage into the crater was observed using a suite of instruments in a shepherding spacecraft, by LRO and from Earth. These measurements showed the presence at water at this location of approximately 5% within 2–3 m of the surface, assuming that the water content of the plume was consistent with that in the surface.

Lunar ice and other cold trapped volatiles at the lunar poles present a favourable first target as a resource. If present in sufficient quantities then, conceptually at least, the extraction of water from