Resources Prospecting & Mobility Beyond Earth

Martin Picard, Taryn Tomlinson, Régent L'Archevêque, Daniel Lefebvre, Steeve Montminy *
Gerald B. Sanders **, Jacqueline Quinn, William E. Larson ***,
Anthony Colaprete, Richard C. Elphic, Daniel R. Andrews ****, Donald G. Chavers *****

*Space Exploration, Space Technologies, Canadian Space Agency, Canada
martin.picard@asc-csa.gc.ca, taryn.tomlinson@csa-asc.gc.ca, régent.larchevêque@asc-csa.gc.ca, daniel.lefebvre@asc-csa.gc.ca, steeve.montminy@asc-csa.gc.ca

** Johnson Space Center (JSC), NASA, TX, USA
gerald.b.sanders@nasa.gov

*** Kennedy Space Center (KSC), NASA, FL, USA
jacqueline.w.quinn@nasa.gov, william.e.larson@nasa.gov

**** Ames Research Center (ARC), NASA, CA, USA
anthony.colaprete-1@nasa.gov, richard.c.elphic@nasa.gov, daniel.r.andrews@nasa.gov

***** Marshall Space Flight Center (MSFC), NASA, AL, USA
greg.chavers@nasa.gov

Abstract

Building on its past robotics space heritage, the Canadian Space Agency (CSA) has continued expanding its international space contribution to surface mobility systems and related technologies. Since 2007, the CSA has funded and supported numerous advanced concept studies, prototypes, deployments, testing and simulations to further develop exploration enabling technologies. These investments targeted different exploration scenarios including significant advancements in the field of lunar and planetary In-Situ Resources Utilization (ISRU) technology and scientific development.

Since as early as 2005, ISRU has been an on-going field of collaboration between NASA, CSA, the Canadian industry and Academia. From 2008 to 2012, three very successful international analogue deployments occurred at the Mauna Kea Volcano, Big Island Hawaii focusing on integrated ISRU technology demonstrations and simulations. The last deployment in July 2012 demonstrated a proof of concept and simulation of a Lunar ISRU mission at the lunar pole. As a result of this successful initiative, NASA and CSA have taken steps working towards eventual lunar resources prospecting and science mission opportunities.

1 Introduction

Building on its past history and on-going programs involving a number of technologies such as satellite communication, imagery, remote sensing, specialized scientific equipment and robotics systems, the CSA has expanded its international space contribution to surface mobility systems and related technologies over the last 8 years. As an International Space Exploration Coordination Group (ISECG) member [1], the CSA is actively participating in defining the future space exploration systems as well as developing, integrating and deploying ground prototypes to advance the Technology Readiness Level (TRL) of these systems on Earth. Since the beginning of the CSA Exploration Core Program (ExCore) in 2007, the CSA has funded and supported numerous advanced concept studies, prototypes, deployments, testing and simulations to further develop many diverse exploration enabling technologies. These investments targeted different exploration scenarios including significant advancements in the field of lunar and planetary In-Situ Resources Utilization (ISRU) technology and scientific development.

Since as early as 2005, ISRU has been an on-going field of collaboration between NASA, CSA, the Canadian industry and Academia. NASA and CSA signed a collaborative agreement in 2008 focusing on joint technology development and analogue deployment activities. Since then, three very successful international deployments occurred at the Mauna Kea Volcano, Big Island Hawaii focusing on integrated ISRU technology demonstrations and simulations. The last deployment that occurred in July 2012 demonstrated a proof of concept and simulation of a Lunar ISRU mission at the lunar pole. The simulation was based on a 6 days mission and was used to assess the feasibility and readiness to proceed with the subsequent phases towards a lunar mission.

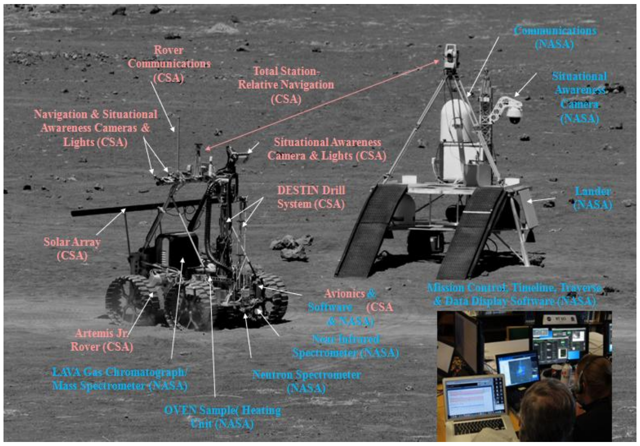

Figure 1: Field deployment Mauna Kea, July 2012

Initiated earlier under the RESOLVE (Regolith & Environment Science Oxygen & Lunar Volatile Extraction) project and as a follow-up to this very successful deployment, during the fall of 2012, NASA and CSA renewed their joint efforts to work on subsequent development phases leading toward an eventual lunar flight opportunity. In parallel with these activities, the ISECG released the Global Exploration Roadmap (GER) [2] indicating a mission opportunity that could fulfill these objectives by 2018-2019 referred as the Resource Prospector Mission (RPM), previously known as RESOLVE. Under the direction of the Advanced Exploration Systems Program in NASA's Human Exploration and Operations Mission Directorate (HEOMD), the RPM initiative office led by the Ames Research Center (ARC) involves a number of NASA centers and organisations in addition to NASA HQ and ARC: KSC, JSC, MSFC, GRC, and JPL. From fall 2012 to spring 2014, a CSA team worked closely with the NASA team on establishing mission concepts, requirements, operational scenarios, establishing potential contributions to advance the technology, as well as perform complementary science. Two main concepts studies were completed by Canadian Industry in addition to specific studies performed by the CSA involving on-going technology testing and development that would apply to such endeavour.

Figure 2: Resource Prospector Mission Concept

Figure 3: ISECG global exploration roadmap [2]

This paper provides an overview of the overall targeted needs for ISRU and a status on the continuing developments in this field of space exploration. It will then expand on the technology development and simulations performed over the last 6 years. It will focus mainly on the evolution of the systems with respect to the last field deployment and move towards eventual mission development phases and the upcoming steps of technology maturation. The benefits acquired from the joint development and deployment activities were crucial elements in advancing this initiative. Early mission phase studies, in addition to the outcomes of the field deployments, have significantly contributed to understanding the implications of such a mission and how it could be adapted to different lunar, planetary and even asteroid exploration scenarios. Overall results, lessons learned and recommendations will be addressed for eventual up-coming flight opportunities focusing on the required technology development and maturity.

2 Needs for Space Resource Prospecting

In order to enable the next steps in Planetary Exploration, key fundamental elements must be addressed:

a. Human Planetary Exploration: To sustain human presence on a distant celestial body, access to oxygen, hydrogen, water, electricity and habitats building are fundamental.

b. Challenges & Cost of Space Propulsion: Considering that flying hardware to space is very complex and expensive; there is a need to reduce the cost of transportation, establish space depot and refueling options for longer term destinations.

c. Science: Understanding of lunar and planetary surface and sub-surface composition is key to establish the genesis of a celestial body and qualify its evolution and its impact on our planet.

d. Growing Need for Resources: There is a need to seek resources to complement the diminution on Earth.

From these elements emerges the field of In-Situ Resource Utilization (ISRU) and in particular space resources prospecting.

This initiative has been formulated and pursued by scientists and engineers from many countries and in particular by a NASA-led team from multiple centers for many years [3]. As a results of these efforts, in October 2009, the impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) showed that the Moon's Cabeus crater contained water ice; additionally, instruments aboard the Lunar Reconnaissance Orbiter (LRO) showed evidence that the water ice may not be limited solely to the Permanently Shadowed Regions (PSRs) [4]. These results led to a set of questions to be answered. There are potentially substantial hydrogen rich resources on the Moon, thus we must gain the necessary knowledge to guide future mission architectures to allow effective utilization of in-situ resources to their full extent and optimum benefits:

a. **Understand the resources**
   - What resources are there?
   - How abundant is each resource?
   - What are the areal and vertical distributions and hetero/homogeneity?
   - How much energy is required to evolve/ separate the resources?

b. **Understand environment impact on extraction and processing hardware**
   - What is the local temperature, pressure, radiation environment?
   - What are the physical/mineralogical properties of the local regolith?
   - Are there extant volatiles that are detrimental to processing hardware or humans?

c. **Design and utilize hardware to the maximum extent practical that has applicability to follow-on ISRU missions**
   - Can we effectively separate and capture volatiles of interest?
   - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?
   - Are the proposed mission architectures and capabilities feasible, and can we build infrastructure and maintain a human presence as demonstrated in the Figures 4 and 5? [5]

Figure 4: Uses of space resources

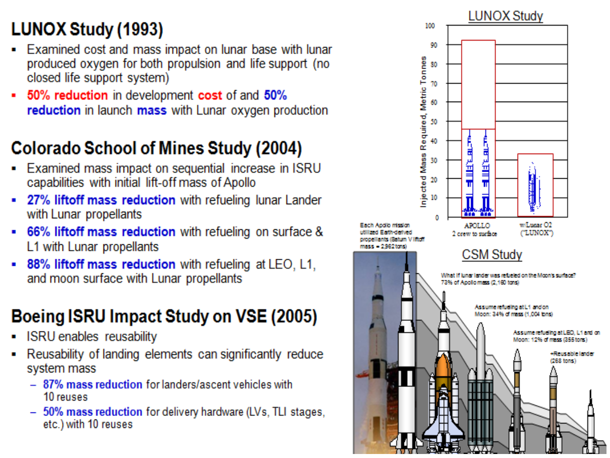

Figure 5: ISRU propellant use studies

3 Lunar Resource Prospecting Mission

Starting with the closest celestial body to Earth: the Moon, missions such as the NASA-led Resources Prospector Mission (RPM) are being planned. RPM is aiming at delivering a rover and an ISRU suite of instruments to the North or South Pole of the Moon prospecting for presence of water-ice contained regolith; targeting a number of Scientific Knowledge Gaps (SKGs) summarized in Figure 6. This is a logical step to take as a follow-up to the LRO and LCROSS orbiter missions.

Lunar Exploration Strategic Knowledge Gaps		Instrument or Activity	RPM Relevance
I. Understand the Lunar Resource Potential			
B-1	Regolith 2: Quality/quanity/distribution/form of H species and other volatiles in mare and highlands	NSS, NIRVSS, OVEN-LAVA	VH
D-3	Geotechnical characteristics of cold traps	NIRVSS, Drill, Rover	H
D-4	Physiography and accessibility of cold traps	Rover-PSR traverses, Drill, Cameras	VH
D-6	Earth visibility timing and extent	Mission Planning	VH
D-7	Concentration of water and other volatiles species within depth of 1-2 m	NSS, NIRVSS, OVEN-LAVA	VH
D-8	Variability of water concentration on scales of 10's of meters	NSS, NIRVSS, OVEN-LAVA	VH
D-9	Mineralogical, elemental, molecular, isotopic, make up of volatiles	NIRVSS, OVEN-LAVA	VH- Volatiles L-M-Minerals
D-10	Physical nature of volatile species (e.g. pure concentrations, intergranular, globular)	NIRVSS, OVEN-LAVA	H
D-11	Spatial and temporal distribution of OH and H2O at high latitudes	NIRVSS, OVEN-LAVA	M-H
D-13	Monitor and model movement towards and retenion in PSR	NIRVSS, OVEN-LAVA	M
G	Lunar ISRU production efficiency 2	Drill, OVEN-ROE, LAVA-WDD	M
III. Understand how to work and live on the lunar surface			
A-1	Technology for excavation of lunar resources	Drill, Rover	M
B-2	Lunar Topography Data	Planning Products, Cameras	M
B-3	Autonomous surface navigation	Traverse Planning, Rover	M-L
C-1	Lunar surface trafficability: Modeling & Earth Tests	Planning, Earth Testing	M
C-2	Lunar surface trafficability: In-situ measurements	Rover, Drill	H
D-1	Lunar dust remediation	Rover, NIRVSS, OVEN	M
D-2	Regolith adhesion to human systems and associated mechanical degradation	Rover, NIRVSS, OVEN, Cameras	M
D-3	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism: Modeling	Landing Site Planning, Testing	M
D-4	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism	Lander, Rover, NIRVSS	H
F-2	Energy Storage - Polar missions	Stretch Goal: Lander, Rover	H
F-4	Power Generation - Polar missions	Rover	M
VH=Very High, H=High, M=Medium, L=Low			

Figure 6: Lunar exploration SKGs

The Design Reference Mission (DRM) for such a mission is significantly evolving and an initial core set of requirements was identified as well as complementary ones and alternatives considered by CSA for eventual future RPM like missions. [6]

a. NASA RPM Mission-Level requirements:

- RESOLVE shall land at a lunar polar region to enable prospecting for volatiles.
- RESOLVE shall be capable of obtaining knowledge about the lunar surface and subsurface volatiles and materials.

b. CSA Science Complementary Requirements:

- Lunar science multi-band camera sensor for lunar geological prospecting
- Measure and characterize wheel/regolith interaction and soil pressure in reduced gravity
- Measure While Drilling (MWD) enhanced capabilities to characterize the regolith composition and temperature variation from the lunar surface down to 1m below the surface.

c. Extended Lunar Night Survival Target Requirements:

- Extend the base mission of 7 days at the lunar pole through the lunar night and multiple nights to prove survival capability for future ISRU missions.

To fulfill these requirements, a proposed architecture is demonstrated in Figure 7 and includes the following components:

a. **Lunar ISRU Rover (LIR):** Lunar rover including a Direct To Earth (DTE) communications system, sensors, to provide mobility, power and thermal services to the suite of on-board payloads.

b. **RESOLVE payload instrument suite** that includes:

- The *Neutron Spectrometer (NS)* Subsystem: used to verify the presence of hydrogen rich materials and then map the distribution of these materials to assist in sample site selection and better understand the morphology of the resource.
- The *Near Infrared (NIR)* Spectrometer instrument: to be used to scan the immediate vicinity of the drill site before and during drill/auger operations to look for near real-time changes in the properties of the materials exposed during the drilling process
- The *Drill Subsystem*: to physically excavate/ extract regolith from the lunar surface to a depth of 1 m and perform any type of preparation necessary (grinding, crushing, sieving, etc.) before delivering the sample to one or more reactor chambers for further processing by the Reactor Subsystem.
- The *NIR Volatile Spectrometer System (NIRVSS)* that includes the NIR spectrometer, the drill operations camera and the Longwave Calibration Sensor.
- The *Oxygen and Volatile Extraction Node (OVEN)* Subsystem to accept samples from the Drill Subsystem and evolve the volatiles contained in the sample by heating the regolith in a sealed chamber and also extract oxygen from the remaining regolith sample. Each sample will be sealed in the OVEN chamber and heated up to 150 C to evolve volatiles (H_2O, CO, etc.). At most one sample from each core will continue to be heated up to ~900 C and be subjected to hydrogen reduction processing
- The *Lunar Advanced Volatile Analysis (LAVA)* Subsystem: to accept the effluent gas/vapor from the OVEN subsystem and analyze that effluent gas using gas chromatograph and/or mass spectrometer sensor technologies. The LAVA subsystem will provide all of the fluid system hardware and will measure constituents below atomic number 70 (including H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2, etc.).

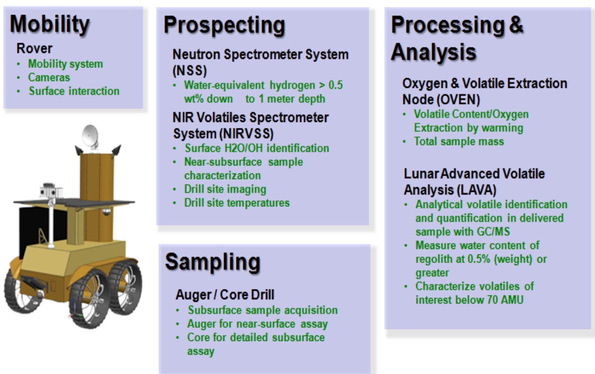

Figure 7: ISRU Tool box

In addition to these core ISRU components, science instruments options have been considered by CSA: enhanced rover science camera with multiple filters, regolith interaction wheel sensors [7] and Measure While Drilling (MWD) instrumentation [8]. Night survivability options are also being envisaged by CSA, some initial studies were conducted and planned to be pursued to expand the capability of a lunar polar rover beyond the current RPM 7, 14 day mission. To bring this hardware to space, the current DRM has identified a launch vehicle such as Falcon 9, Atlas or SLS class vehicle to be provided by NASA and a lander to be either provided by NASA/commercial partners or an international partner (TBD). The results of a proposed lander study [9] conducted by NASA was presented at the Mission Concept Review (MCR) in September 2013 is illustrated in Figure 8 and 9.

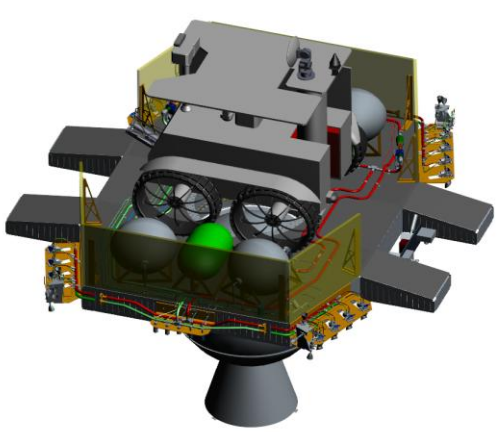

Figure 8: Lander-rover NASA concept

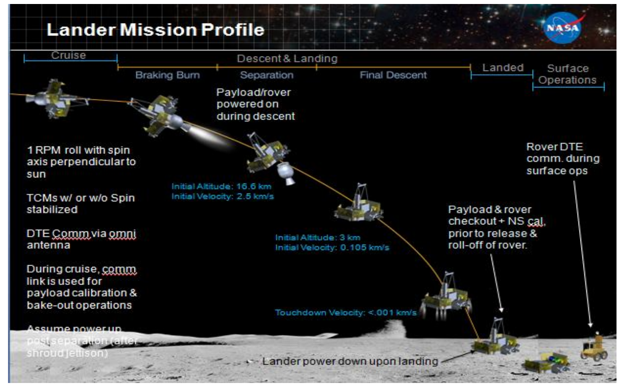

Figure 9: Mission landing profile

4 Canadian Contributions

As introduced in Section 1, the involvement of CSA with NASA in the field of ISRU was initiated a number of years ago. CSA first concentrated its efforts in defining potential scenarios and concepts with NASA. These resulted in a number of studies, prototypes, terrestrial testing and analogue deployment activities. These initiatives address many scientific and technological needs such as rovers, tele-operations, rover navigation autonomy, camera and laser-based sensors (LiDAR), compliant wheels, test beds, drilling, sampling and capturing systems and power systems (advanced battery and fuel cell technology). The 2008, 2010 and 2012 field deployments are considered as three important international deployments that took place at the Mauna Kea Volcano. This area is well-known for its tephra rich soil, a very good terrestrial analogue for the moon that was used back in the Apollo days for geological crew training. The two initial deployments focused on proof of concept and advanced technology development on elements required to form an ISRU complete food chain on the Moon that could eventually be used for a human-base as illustrated in Figure 10. [6]

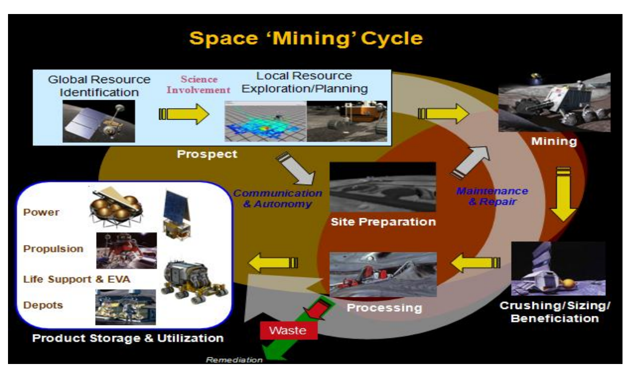

Figure 10: Space mining cycle

Between 2008 and 2012, a minimum of three generations of hardware were built for the core systems described in section 3. In addition to these, solar based sintering was exercised, TriDAR based rover navigation, tele-operated rover based transport of tephra to a central reactor, creation of water from regolith, fuel extraction, rover landing pad construction, thruster demonstration and fuel cell based rover mobility were completed. The ISRU RESOLVE processing plant and rover hardware evolved from a rover/trailer system to a tandem rover and to its latest configuration of a single rover as illustrated in Figure 11, 12 and 13. [10]

Figure 11: ISRU technology development 2008, 2010

Figure 12: ISRU and mobility development 2010

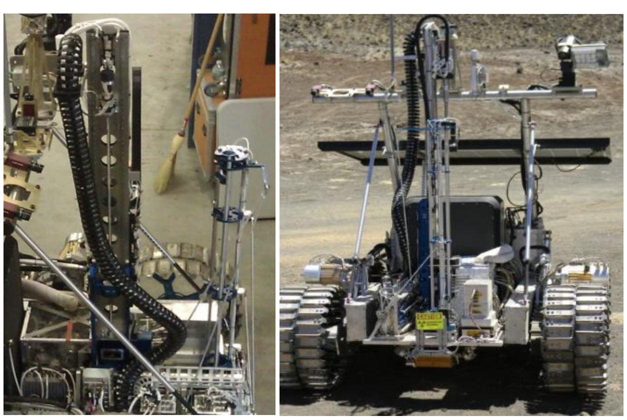

Figure 13: ISRU and mobility development 2012

During the July 2012 deployment, the CSA provided the Artemis Jr rover and the DESTIN drilling system and successfully performed the planned operations. [11] The tele-operated Artemis Jr rover drove off the lander mock-up and either in a semi-autonomous mode or tele-operated completed a total roving distance of 1140 m over a 6 day simulation. The scenario involved seeking simulated hydrogen 'hot spots' using the NASA provided NS system controlled from multiple remote locations: the Mauna Kea based control center and the CSA Exploration and Development Center (ExDOC) located in St-Hubert, Canada. The CSA-provided DESTIN drilling system was also used to perform a total of 4 augering operations analyzed by the NIRVSS and 4 core sample acquisition and transfer to the OVEN for sample processing and analysis. In addition to the rover and drill, CSA also provided core processing cards to the NASA RESOLVE central avionics via a set of Q6 cards and I/O interfaces as well as remote operations control and support from its CSA St-Hubert located ExDOC.

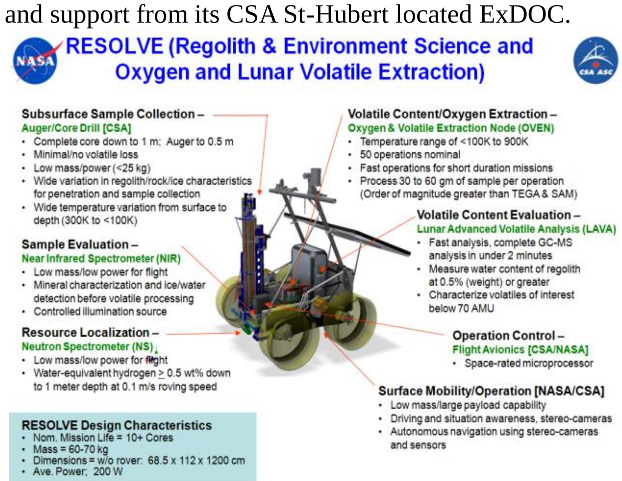

Figure 14: ISRU mission simulation 2012

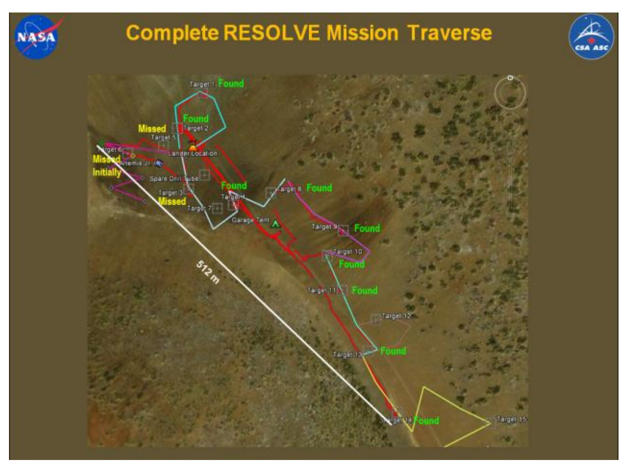

Figure 15: NASA/CSA 2012 complete traverse

During the fall of 2012, following-up on the very successful deployment, NASA and CSA joined the path towards maturing the lunar resources prospecting concept and hardware TRL towards flight. As a result, CSA initiated two external concept studies at the end of 2012 (Lunar Tele-Operated ISRU Platform (LTOIP)) based on the RPM DRM 2.2. These two studies were completed by the fall of 2013, delivering each a drill and rover concept. Each provided detailed information on the technical and programmatic challenges of Canadian contributions to the RPM mission, which at the time was planned for a 2017 launch. The two concepts addressed the drill and the rover contribution as well as the impacts and approach to accommodate three classes of missions: a minimum RPM DRM, the complete RPM DRM and an augmented mission concept which targeted lunar night survival. In parallel with these contracted studies, CSA conducted internal and join analyses with NASA that fed into these contracts. The outcomes of these initiatives were iterated, discussed and presented by CSA at the RPM MCR in September 2013. Key challenges for the rover and drill were identified, in particular:

1. Challenges related to the extreme temperature at the South and North Pole of the moon;
2. Dust challenges, and the behavior of the regolith in these PSRs both for roving and sample capture;
3. The low solar and Earth angle - a challenge for power and communications requiring a rover DTE system over a lander relay with the rover and its suite of instruments; and
4. Maintenance of sample temperature while transfer and volatile lost mitigation.
5. Proper tool selection and reduction of moving parts and complex assemblies.

From these studies and conclusions, the CSA team elaborated a plan and has initiated a suite of risk mitigation activities since summer 2013. From these emerged a Rover Direct To Earth Communications System (RDCS) contract, a critical components and assembly lunar dust mitigation contact as well as TRL advancement for the compliant wheels, drilling module and tools maturity. Complementary to this, CSA is also investing in a higher TRL LiDAR navigation sensor and performed analogue field trials in the vicinity of the CSA using its Juno rover platform and developed a rover Tele-operations Test Bed (TRT) to address tele-operations and autonomy challenges on the Moon. The contracts are currently in place and target anywhere from lunar prospecting critical TRL 5 to TRL 6 subsystems, and the TRT initiative phase 1 is complete.

Requirement	Value
Volume Enveloppe	2m x 1.4m x 1.6m (H x L x W)
Mass	~300 Kg (including main plds) (TBC)
Speed	10 cm/s (nominal) .. 50 cm/s (max)
Maximum Range	3 Km max traverse
Maximum Gradient/Side Slope	15 degrees / 10 degrees
Localisation	10 m over 100m traverse (TBC)
Ground Clearance	35 cm
Payload bay	Payload to be integrated and then to rover
Bandwidth limits	~2 kbits/s (low rate), ~400 kbits/s (high rate)
Sun Shadow Operations	6 hours
Lunar Night Survivability	Under investigation

Requirement	Value
Drill depth	1m below the surface
Sample size	16 mm diameter X 0.75 m length
Core sections	12.5 cm lengths (sub-samples)
Drill Mass	~ 40 Kg
Power Consumption	less than 75W (average)
Volume	less than 1.35 m x .75 m x 1 m [height x length x width]
Cross contamination	Minimized
Sample time	Acquisition of sample within 1-2 hours

Figure 16: Rover and drill concepts requirements

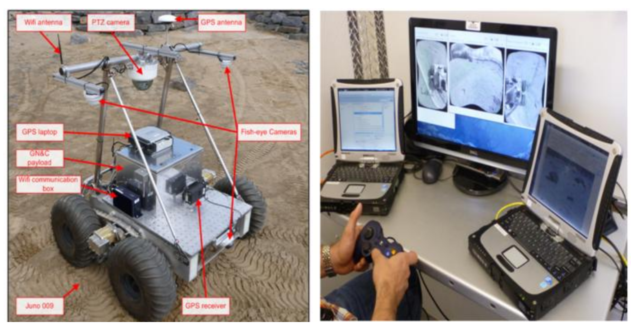

Figure 17: CSA Tele-operations Rover Test bed (TRT)

From these initiatives emerged a CSA proposed concept that is evolving along with the technology development towards flight. Upcoming development will help refine this concept and keep developing the required technologies and concepts of operations towards ISRU prospecting and scientific missions. Critical elements such as sample capture and transfer of regolith via the drill remains a challenge with the unknown nature of the regolith in these PSRs area where the rover will have to navigate and the drill capture samples and minimize lost of volatiles.

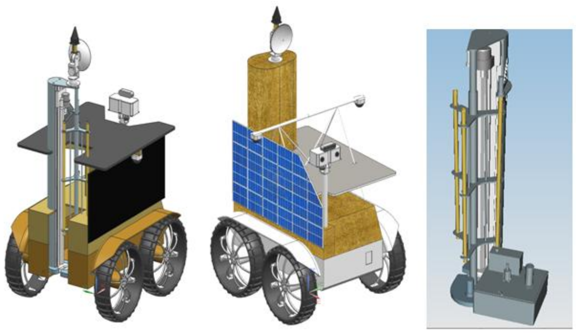

Figure 18: CSA proposed rover and drill concepts

5 Acknowledgment

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6 Conclusions

Planetary ISRU and mobility is an important enabler for long term space exploration. It has been identified as a key area by the ISECG GER and missions such as the Resource Prospector Mission (RPM) are being defined by the community. CSA, its Canadian team of contractors and academia engineers and scientists have contributed in advancing this field and are still pursuing this long term objective. At this point in time, the CSA is to pursue scientific and engineering advancements for lunar and planetary mobility, payload including ISRU and scientific instruments development.

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