i-DRILL: AN INSTRUMENTED DRILL FOR SURFACE AND SUB-SURFACE GROUND TRUTHING OF LUNAR VOLATILES AND RESOURCES. S. J. Barber[1], S. Sheridan[1], M. Anand[1], P. Harkness[2], R. Timoney[2], K. Worrall[2], N. J. Murray[3], R. Trautner[4] and C. J. Howe[5]. [1]School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK simeon.barber@open.ac.uk [2]School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK. [3]Dynamic Imaging Analytics, Milton Keynes, MK14 6GD, UK. [4] ESA ESTEC, Keplerlaan-1, Noordwijk, The Netherlands. [5]STFC RAL Space, Harwell Campus, Didcot, OX11 0QX, UK.

Introduction: The nature and occurrence of water and other volatiles on and below the surface of the Moon is an important scientific topic, bearing upon the history and evolution of the Earth and its satellite and the wider consequences throughout the Solar System. It also has ramifications for lunar exploration, through the concept of in-situ resource utilization (ISRU), in which for example water could be harvested at the Moon for life support or rocket propulsion purposes. Yet our knowledge of lunar water and related resources is far from complete. We do have an increasingly detailed understanding of the lunar samples, including more recent discoveries of elevated concentrations of OH in certain minerals [1, 2]. But these samples are from geographically limited lunar regions notably distant from the poles, and were collected under conditions not conducive to the preservation of the most volatile components. Meanwhile we also have an increasing body of evidence supporting the presence of elevated levels of water ice in colder, high-latitude regions of the Moon [3, 4]. But the remote nature of these measurements and the associated complications in data retrievals/processing, mean that these data are insufficient either to fully test scientific hypotheses or as a firm basis for planning ISRU.

Lunar volatiles are therefore at the convergence of lunar science and exploration, and both fields require new landed missions to provide ground truth data to fill in the knowledge gaps. Data are required *across the surface*, adding detail to the broad-brush picture obtained from orbit. And crucially, data are required from the *sub-surface*, particularly within the upper ~1 m i.e. those depths probed by remote sensing techniques such as neutron spectroscopy [5]. Finally, the measurements should be *specific* i.e. providing unequivocal identification of individual volatiles, and *quantitative*.

i-Drill Overview: i-Drill is an integrated suite of drill and scientific instruments, and provides a tool for answering current scientific and exploration knowledge gaps outlined above. It is readily accommodated on a mobile platform to enable rapid acquisition of volatiles identity, concentration and distribution to a depth of ~1 m below the lunar surface. The drill is optimized for rapid penetration into the regolith surface. The mechanical perturbation and heat generated by the drilling is utilized to release volatiles from the regolith and to convey them upwards within the drill string to a mass spectrometer for real-time identification and quantification as a function of drilling depth. A borehole camera (BoreCam) captures a depth-correlated, (radial) 360-degree movie of the borehole as viewed from within the string as it is advanced, providing geologic context. A permittivity sensor (PerSen) surveys any ice content in the surrounding regolith. The surface camera (SurfCam) records a multispectral 3D movie of the evolving cuttings pile enabling insight into regolith geochemistry, geotechnical properties and hydration state with depth.

i-Drill would optimally be deployed upon a small or medium class lunar rover where it could quickly survey volatiles (as outlined above) at waypoints during the rover's traverse across the lunar surface. During the traverse itself, SurfCam would be operated to record a multispectral 3D movie of the lunar surface, with the rover wheel tracks within field of view to study surface geotechnical properties. i-Drill could also be deployed on a static lander, enabling proof of concept and the coordinated measurement of volatiles content versus depth together with geologic context. Added value would be achieved through incorporation of a simple lateral translation mechanism to enable i-Drill to obtain a number of discrete borehole surveys.

i-Drill Status, Heritage and Instruments: i-Drill is a powerful tool for lunar volatiles science and prospecting, at a resource requirement (mass, power, volume, data, development cost and interface simplicity) compatible with multiple rover and static platforms.

The Drill seeks to reach its full depth in approximately one hour, using a relatively high power setting for this short period of time. The drill cycle will proceed under autonomous control, managing auger torque and weight-on-bit according to the desired power setting, rate-of-progress, and local geotechnical considerations. A rotary-percussive system largely decouples the augering and rock-fracturing efforts, which provides the flexibility required to deal with different target materials, and the bottom of the drill-string provides an aperture (with dust filter) so that volatiles may be drawn up into the instrument casing for mass spectrometry. The architecture overall will be arranged so that there is a clear line-of-sight (e.g. through an in-bit optical element) through the drill string, rotation, and percussion mechanisms, allowing the BoreCam to remain above ground while still imaging the very bottom of the hole.

Mass Spectrometer: the Ion Trap Mass Spectrometer (ITMS) is a very compact and lightweight device, capable of detecting volatiles up to m/z ~150 (so including e.g. water, xenon and light organics). It is derived from ongoing developments with ESA's PROSPECT program [6] including the development of the Exospheric Mass Spectrometer (EMS) within the PITMS instrument for NASA Artemis/CLPS [7]. The EMS program will develop an ITMS mass spectrometer with associated power, control and data electronics by 2020 that serve as a basis for re-use in i-Drill with addition of further electronics and code as required.

BoreCam and SurfCam: These imagers utilize plenoptic (light-field) optics which capture both the intensity and direction of photons emanating from a scene. Each output frame therefore provides the conventional 2D (*x*,*y*) view of the scene, with the added advantage that the depth (in *z*) of any feature in the scene can be calculated accurately. Thus 3D images can be achieved from a single exposure. Optionally one or both cameras may operate in multiple spectral bands to achieve a snapshot 3D multispectral camera configured to observe for example characteristic absorption of O-H bonds. BoreCam is configured to record a 3D movie of the borehole as it is cut by the drill; SurfCam records in 3D the evolution of the related cuttings pile. Each has heritage from the Sample Camera (SamCam) [8] being developed within ESA PROSPECT [6]; SurfCam development is presently under EU Horizon 2020 funding.

Permittivity sensor (PerSen): a small electrode integrated in the drill rod surface emits an AC signal. This enables the dielectric constant of the surrounding regolith to be measured accurately. The dielectric constant of lunar regolith varies with depth, and can be expected to lie in the range of about 1.6 (low density regolith) to 10 (dense rocks or pebbles). It would also be strongly influenced by the presence of water ice in the surrounding regolith. Thus PerSen enables compilation of an electrical subsurface image and contextual information on the presence of permittivity trends, density changes and water ice presence to be interpreted in conjunction with the other i-Drill sensors. PerSen benefits from heritage within ESA's PROSPECT [6].

Conclusion: i-Drill would address key scientific and exploration knowledge gaps through identification, quantification, and mapping of volatiles in the upper 1 m of lunar regolith. Compatible with various platforms, it leverages on ongoing development programs and targets flight opportunities from 2021.

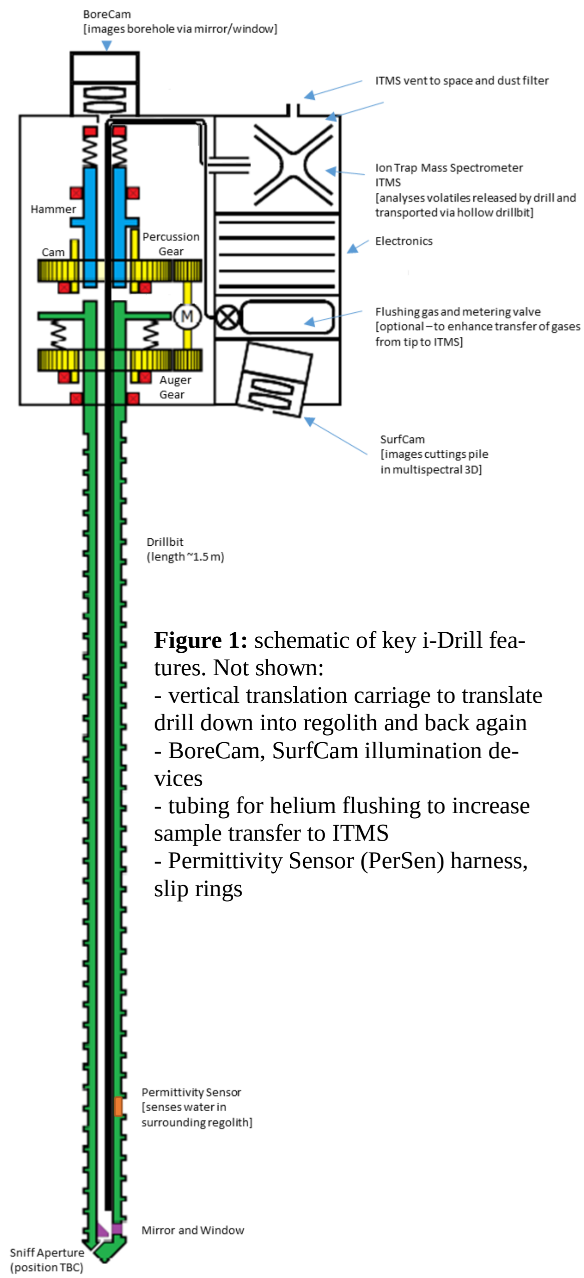

Figure 1: schematic of key i-Drill features. Not shown:
- vertical translation carriage to translate drill down into regolith and back again
- BoreCam, SurfCam illumination devices
- tubing for helium flushing to increase sample transfer to ITMS
- Permittivity Sensor (PerSen) harness, slip rings

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