

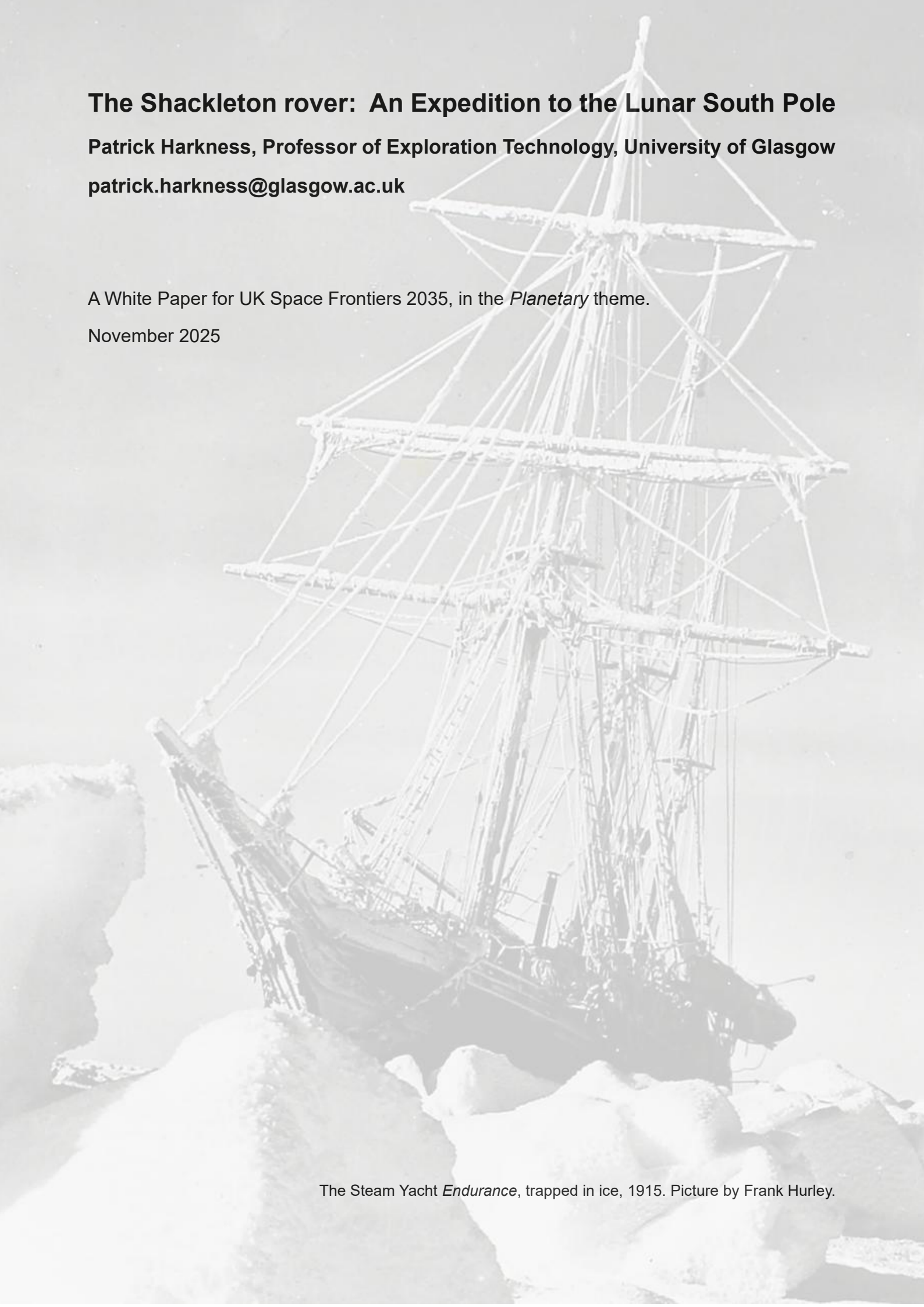
The Shackleton rover: An Expedition to the Lunar South Pole

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A White Paper for UK Space Frontiers 2035, in the *Planetary* theme.

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The Steam Yacht *Endurance*, trapped in ice, 1915. Picture by Frank Hurley.

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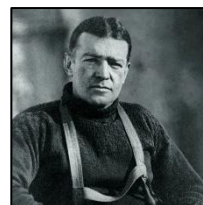
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1. Foreword by our concept sponsor, The Hon. Alexandra Shackleton:

“My grandfather, Sir Ernest Shackleton, listed the qualities required for a polar explorer thus: optimism, patience, imagination, and courage. I believe that he would recognise these qualities as motivating this proposal, and I am therefore delighted to commend it to you.”



2. Introduction: The heroic age of polar exploration ended in 1922, but the achievements remain with us today: an enduring UK presence in Antarctica that has driven global benefits for a hundred years. These efforts have helped to ensure that the continent remains a global commons, and underpin the conservation of the great whales, the protection of the ozone layer, and the defence of freedom in the South Atlantic. The value has been incalculable.

A new age of exploration is beginning. The UK, echoing this success, should ensure that the Moon becomes a new global commons with environmental protections, free navigation, and a fair balance between initiative, risk, and return. This recognises the moral responsibilities that emerge alongside the scientific, strategic, and economic outcomes which inevitably cluster towards the first movers. We have an opportunity to help create this positive scenario.

However, as in Antarctica, we must demonstrate our intent through a physical presence on the ground. We therefore propose the *Shackleton* lunar rover as an ambitious goal.

3. Science objectives: The presence of water-ice on the Moon is considered likely: ejecta generated by deliberate impacts has yielded positive signatures in permanently shadowed regions near the lunar poles.¹ This represents a key in-situ resource, because ice can be electrolysed to produce hydrogen and oxygen. These products are excellent propellants and their manufacture and sale in-space, close to an emerging customer base and above the Earth's gravity well, is a practical way to add real value to the nascent lunar economy.²

However, while many planned missions seek to obtain ground truth for this vital resource, direct contact has not yet been made. Nobody knows if the ice is distributed at a molecular level, as crystals, or in mass glaciation, nor do we know its depth or relative accessibility.

The *Shackleton* rover will help to answer these questions. *Shackleton* will be a 20kg vehicle, delivered by Commercial Lunar Payload Services (CLPS) or a similar service, landing in the south polar region with a lifetime of 14 days. The rover will traverse from the landing site to various shadowed exploration sites, prioritised by their distance, risk, and scientific potential.

At each exploration site a sonicated penetrator, with heaters and thermistors along its length, will be deployed to 20cm depth. Stepped heating will drive liberated volatiles towards an ion trap mass spectrometer. This TG-EGA experiment will (i) define the vertical distribution of H₂O; (ii) discriminate adsorbed water, pore ice, and ice-cement via evolved-gas analysis; and (iii) identify co-hosted volatiles. At the same time, thermal conductivity and heat capacity will be measured while penetration parameters and ultrasonic transducer response shall be recorded. These data will constrain bulk density, cohesion, and ice-cementation strength.

The impact will be two-fold. We will demonstrate that small rovers can interact meaningfully with the subsurface regolith, and we will obtain data on the nature, density, and accessibility of volatile resources in terms directly applicable to ISRU system design. These technological and scientific objectives are compatible with the UK's *Roadmap for Solar System Research*.³

4. Architecture: We propose a four-wheeled rover with skid-steering. Comms are S-band to the lander via a directional patch antenna on a deployable vertical mast with yaw control. The mast also provides illumination and down-looking images for path planning. The outline mass budget, set out in Table 1, is comparable to small rovers now in development by our peer nations: the Australian *Roo-ver*⁴ is 20kg, while the *Canadian Lunar Rover*⁵ is 30kg.

Table 1: Indicative mass budget for the 20 kg <i>Shackleton</i> rover concept	
Mass spectrometer suite (by comparison to MSOLO, PITMS, and similar)	4 kg
Sonicated penetrator (by comparison to non-optimised devices in literature)	3 kg
Wheels, gearmotors, etc. (750g per corner estimated)	3 kg
Structure (nominal 10%, broadly in line with standard)	2 kg
Power (outline sizing below)	1 kg
Comms (estimate includes a deployable mast such as Astromast or Rolatube)	1 kg
Thermal (estimate includes insulation and phase-change unit for shadowed operations)	1 kg
Avionics (nominal 2.5%, broadly in line with standard)	0.5 kg
Harness and fasteners (nominal 2.5%, broadly in line with standard)	0.5 kg
20% margin	4 kg

Turning to power, the outline budget is set out in Table 2:

Table 2: Indicative power budget for the <i>Shackleton</i> rover concept (mission 14d x 24h)			
Activity	Power	Duty cycle	Energy
Baseline load	5 W	100%	1680 Wh
Battery charging	5 W	96%	1610 Wh
Comms	10 W	10%	336 Wh
Mobility	20 W	20%	1344 Wh
Cameras and lights	5 W	5%	84 Wh
Mass spectrometer	25 W	5%	420 Wh
Penetrator sonicator/heater	50 W	1%	168 Wh

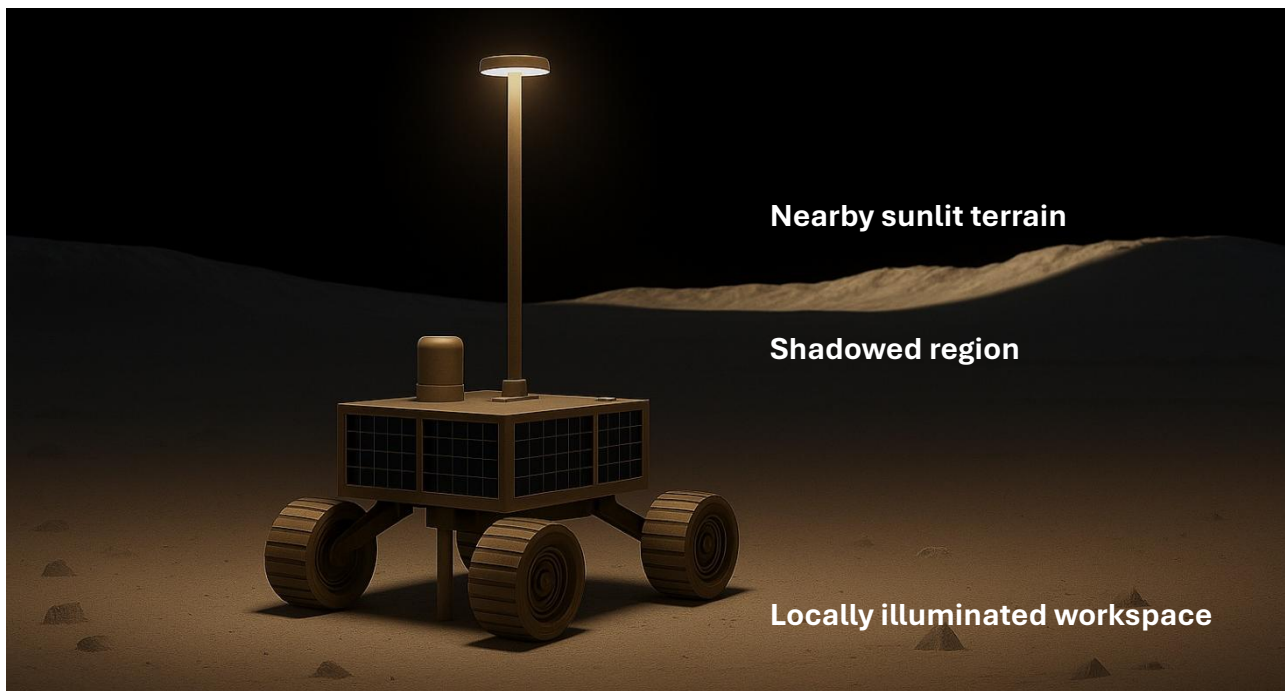
With a simple concept-of-operations (e.g., no transmission while rolling) the rolling power requirements are ~35W. The static exploration power requirements (assuming no sonication while heating) are closer to 100W. One solution is 0.25m² of solar panels, delivering ~40W, augmented by a 50Wh battery. This permits 1-hour sorties to shadowed regions with a 10-minute penetration campaign, after which the rover will return to the sunlight. Recharging will take 10 hours, permitting 20 to 25 regolith-volatile profiles over the course of the mission.

With estimates of 3kg/m² for the solar panels and 200Wh/kg for lithium-ion batteries, this balances at 0.75kg for the panels and 0.25kg for the battery. The size of the solar panels drives the size of the chassis: sides of around 0.4m long x 0.15m high will be satisfactory. The thermal system will use insulation and phase-change units during each cold sortie.

5. Cost: The cost of the *Shackleton* can be estimated by comparison to the *Roo-ver*. That Australian rover, delivered by a close peer nation, will be similar in terms of mass, delivery, and lifetime. Accordingly, our price point is £22m:⁶ less than 1% of the UK Space Agency budget over the same period. The value for money, for UK tracks on the lunar surface, is extraordinary.



UKSA announced funding of £2.8 billion to 2029/2030. The *Shackleton* rover should cost ~£22 million in the same period.



The *Shackleton* concept: An extendable mast provides lighting and down-looking for path planning. A penetrator seeks contact with ice in the regolith of a cold trap. Solar panels are side-mounted to maximise exposure to the low Sun near the lunar pole.

6. Feasibility: Many others plan to drill from static locations, sacrificing surface mobility for a stable drilling platform. *PRIME* will deploy the *Trident* drill from a ~675kg *Nova-C* lander, while *PROSPECT* will deploy the *ProSEED* drill from a ~650kg CLPS lander. Future rover concepts are also sizable: *VIPER* will be ~430kg, while *LUPEX/Chandrayaan-5* is ~350kg.

Shackleton will conduct roving subsurface operations from a platform twenty or thirty times smaller. It will be the smallest independent asset ever designed for regolith penetration, because neither *Roo-ver* nor *Canadian Lunar Rover* will attempt such operations. We will set a new standard for the capabilities of small landers, complementing our long-established strength in small satellites. Our mission intent is that our surface mobility, even over a few tens of metres, will allow us to access promising sites that the static landers cannot reach.

The main challenge is that, in reduced gravity, the weight-on-bit available for penetration is constrained. A 20kg rover will weigh only 32N on the Moon. With a ~20mm diameter probe, and a 20cm target depth, ~50N of downforce is likely required to penetrate uncemented regolith.⁷ Our penetration force requirement must therefore be very significantly reduced.

This reduction may be achieved by the sonication of the probe: a standing wave in similar probes has been shown (by UK research) to create local granular fluidisation and reduce the force required to penetrate some materials by an order of magnitude.⁸ This effect is preserved at different gravity levels.⁹ In lunar regolith simulant, in vacuum, the effect appears weaker, but remains more than sufficient to deliver the performance delta required.¹⁰ There is still work to do in the case of cemented regoliths (see §9.1), but overall the TRL is at 4.5.

The allied spectroscopy suite will be based on the UK-built Exospheric Mass Spectrometer, as flown on the *Peregrine* lander.¹¹ This provides the desired detection threshold and has a higher TRL than the penetrator assembly, and so it attracts a correspondingly lower risk.

7. Benefits: The UK benefits can be considered under multiple complementary headings.

7.1 Strategic. The importance of a physical presence on the Moon has been discussed: we will gain credibility and secure a near first-mover advantage. This will give us more influence over lunar regulation and co-ordination while these still remain tractable issues. Physical interaction with the most valuable lunar resources, in-situ, is also a convincing moral statement of intent.

7.2 Scientific. A very large part of the international exploration timeline is predicated on the presence of water-ice for in-situ resource utilisation. Contact detection of this resource is a critical step in derisking that programme, and our determination of the habit of the ice will shape all future operations. The experience of physical contact will make the UK an attractive international partner in all these activities.

7.3 Skills and sustainability. Our exploration community suffers from a degree of fragmentation, in part because the absence of a major shared goal leads to some non-strategic effort. However, a sustained objective can provide the continuity necessary to build careers, capabilities, and institutional memory. This will give us the critical mass and know-how required to deliver the partnership role above. We can make the UK an attractive location for exceptional people in the global marketplace.

7.4 Space economy. We will invest in skills. *Shackleton* will provide doctoral training alongside the design, build, and operations phases. An engineering PhD adds up to \$29k, annually, to the economy over-and-above comparable research positions.¹² The productivity of a person who earned their PhD on a lunar mission would be greater again. This mission, or one like it, is also a necessary step in fully accessing a lunar marketplace estimated to be worth \$5bn, by 2033, in Europe alone.¹³

7.5 Shackleton's spirit of optimism. The UK needs to recover its national morale. We will create an inspirational showcase that will attract more young people to STEM, while building world-leading leaders in space exploration. Our foreword captures this ethos: patience, courage, and imagination aligned towards a worthwhile goal. This mission can set an example of excellence and discovery for decades to come.

8. Proposed partnerships. There will likely be a deep relationship with the American CLPS provider at a mission systems level. At the rover level, we will have peers in Australia and Canada, and we will be well-placed to learn from their experiences because they are slightly ahead of us on the calendar. Japanese expertise in rover-regolith interactions is also renowned. More broadly, since 2010, Chinese, American, Luxembourgish, Israeli, Indian, Japanese, Italian, Korean, Emirati, European, Russian, Mexican, Pakistani, and Finnish missions and instruments have sought to reach either the Moon or its vicinity in space. These all provide international partnership opportunities.

However, the field where we can add the most technical and economic value is likely sono- or vibro-assisted regolith handling. This is most relevant for Australia, which focusses on regolith transport for beneficiation and resource utilisation. Australia is therefore our natural level-one partner, with positive outcomes in both directions. We further propose that Japan and Canada should be our key mission and hardware development associates.

9. UK leadership potential: The UK has delivered remarkable achievements at the Moon: the descent engines for the American *Blue Ghost* were tested in Westcott, and the descent engines for the European *Argonaut* are currently being designed in Belfast. The UK is a leader in the extraction of oxides from regolith simulants, which may allow us to produce both oxygen and metals for further resource utilisation in space.¹⁴ Finally, we contribute strongly to the *Moonlight* programme,¹⁵ enabling comms for partner nations.

Therefore, with a rover, we can consolidate a very broad spectrum of capabilities into a coherent and focussed lunar exploration package. At the same time, we will demonstrate a step change in the resources actually required to deliver both science and technical impact in the field. This is an important strategic clustering around an emerging international priority.

The key task headings for this mission are:

9.1 Development. The key enabler for a lightweight penetrating rover is a sonicated probe which can fluidise nearby granular material and reduce local load-bearing accordingly.⁹ The UK is well-positioned for this work: Glasgow hosts one of the largest dirty-vacuum chambers in Europe,¹⁶ and its ultrasonics research group is the largest in the world.¹⁷ Leeds is a centre for modelling the behaviour of granular materials.¹⁸ These facilities will support pre-flight tests of sonicated penetration into icy-regolith analogues under thermal vacuum, providing calibration for penetration resistance and volatile release. Should the risk profile of an ice-cemented material be raised, we can call on the icy-sediment drilling expertise of the British Antarctic Survey¹⁹ and consider other low-reaction penetration concepts, such as the pulse-elevator,²⁰ which are listed already on the UK's *Space Exploration Technology Roadmap*.²¹

9.2 Delivery. There is little doubt that the UK could deliver this rover. The small form-factor is aligned with our expertise in small satellites, while our *Beagle-2* and *Rosalind Franklin* provide heritage in planetary landers. The mass spectrometer will build on work at the Open University, in Milton Keynes. The mast could be delivered by Oxford Space Systems or Rolatube at Lymington. Teledyne e2v at Chelmsford may support cameras and instrumentation. The vibration isolation could be provided by Springco in Portadown, which provided springs for the *Curiosity* rover. Finally, with respect to surface mobility, there is a very suitable ground test facility at Airbus, in Stevenage.

9.3 Driving. The comms strategy is S-band to the CLPS lander, and then X-band to the Deep Space Network and onwards to the mission team. A dedicated command from Goonhilly Ground Station may be possible, which would demonstrate full-spectrum operations on the Moon. One interesting point is that, for maximum value on-station, two weeks of 24-hour working will be required. This creates real human resource issues. Supplementary Canadian, Japanese, and Australian driver teams, covering each others' unsociable hours, may be a way to manage this issue while adding valuable experience on all sides.

10. Suggested timeline: A four-year programme is proposed for *Shackleton*, as opposed to the roughly five-year timeline of our peers. The fifth year could be saved by eliminating any competitive phases and proceeding to tender. This timeline will be well-aligned with PhD programmes to maximise educational impact, producing a cohort of world-class personnel.

11. Some summary questions: Why should the UK choose to go to the Moon?

11.1 Why Moon? The UK is competitive on lunar descent engines, beneficiation, comms, and regulation. A rover can focus these activities, creating value-add beyond what is achievable with more distributed efforts. As ISRU proliferates, a nation with a full-spectrum capability (ideally complementing the rover activity with an orbiter such as *VOLARE*) will be a more attractive partner in this global endeavour.

11.2 Why now? We have a short window in which we retain the possibility delivering an outcome with global scientific significance and high public salience: ground truth for water-ice on the Moon. We have a science community that will benefit from a unifying goal, alongside a nation that needs a clear moral achievement alongside a route to economic growth in the future. This opportunity cluster will not arise again.

11.3 Why promptly? The most important investment is always in the development of human capital. A four-year programme, which is only compatible with a small vehicle like *Shackleton*, will facilitate doctoral training alongside every phase of the mission. The quality of our graduates will be extraordinary. Young people can do remarkable things when given responsibility. We will encourage and empower them.

11.4 Why us? Our experimental concepts provide a realistic chance of attaining a nontrivial depth using a small lander, which will leverage our proven technologies' ability to detect buried water-ice. Strategically, any physical presence will allow us to better leverage the UK's considerable convening power on the international stage. This synergy will help to create a new and better global commons on the Moon.

11.5 Why *Shackleton*? Sir Ernest's famous voyage to the Antarctic, commanding the Steam Yacht *Endurance*, is a matter of global acclaim. We will also travel south in search of ice. The echoes will not be missed, and we may be able to deliver an outcome worthy of his example. Helping to create a new Antarctica, in space, with all the protections and achievements of the old one, will be a very worthwhile outcome.

12. Conclusion: The *Shackleton* rover can represent a scientific, strategic, and economic success that will allow the UK to operate as a leading peer nation on the Moon. This is vital if we are to help recreate and extend the successes of the Antarctic Treaty. We will also address knowledge deficits, differentiating from the Australian and Canadian missions, while preparing for future ISRU applications. This will enable technology-driven growth in space, while our programme creates fungible, productive careers at home. And as for the inspiration value, a leading UK Science Correspondent has offered this comment:

"When I covered the Beagle-2 mission in 2003, I was hugely pleased and surprised at the overwhelming public response to the endeavour. It transcended even the usual high levels of public interest in space missions; it seemed to me at the time that the entire nation was gripped and enthused by this bold plan... It was exciting, inspirational and I believe attracted many young people to science, just as the Apollo missions did for a previous generation... the Shackleton mission... has the potential to possibly recreate those heady days of UK-led space exploration and inspire a new generation once again."

We therefore hope that you will be able to support the development of this concept.

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AI	Artificial Intelligence
APPG	All-Party Parliamentary Group
AROSE	Australian Remote Operations in Space and Earth
CLPS	Commercial Lunar Payload Services
CTO	Chief Technology Officer
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace
ISRU	In Situ (i.e., as found in space) Resource Utilisation
MSOLO	Mass Spectrometer Observing Lunar Operations
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organisation
NSW	New South Wales
OST	(British) OverSeas Territories
PI	Principal Investigator
PITMS	Peregrine Ion Trap Mass Spectrometer
PRL	Physical Research Laboratory
STEM	Science, Technology, Engineering, and Mathematics
SWRI	SouthWest Research Institute
TG-EGA	ThermoGravimetry-Evolved Gas Analysis
TRL	Technology Readiness Level