DEPLOYMENT OF A LUNAR BASE – GETTING THERE, FACILITIES AND FUNCTIONS

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INTRODUCTION

A year ago US President Bush expounded a vision that may rank as the most important pronouncement he, or any leader could make. He set the USA on a permanent course beyond earth and its immediate vicinity. This vision included human exploration of the moon and mars. But it also did much more, envisaging the search for life in our own system and on earthlike planets around other stars and scientific investigations made on the moon. These are among the most exciting scientific challenges ever – challenges that will draw the best minds of the next generation into science.

Yet the response of the scientific community has been lukewarm at best. Their concerns are typified by the November, 2004 report from the American Institute of Physics, warning of serious negative impacts on NASA scientific programs due to competition for funds between science and exploration. Skepticism over uncertain costs and where the necessary resources might be found is the reason for less than enthusiastic support for the new exploration program. The lack of enthusiasm arises because the vision has not yet evolved into enduring directions and goals needed to assure consistent support over the decades and many Administrations needed to see fulfillment. What scientist would want to give up on a well thought plan for continuing strongly motivated and supported robotic missions for a program that could quickly vanish?

The International community too has been slow to sign-on to the exploration program. In a late 2004 meeting between NASA's Exploration Office and potential international partners the constantly repeated refrain was a plea to define what it is we will do on the moon and Mars and not just how we will get there.

To date the exploration programs focus has been on engineering. First up has been discussion of how to replace the Space Shuttle. NASA's primary focus in the exploration program to date has been on a Crew Exploration Vehicle – the means of getting people to and from space. Significant additional work has focused on exploration hardware. To date NASA's program is single-mindedly focused on getting people to and from Mars, with lunar efforts primarily revolving around checking out Mars exploration hardware. Current US space launch systems are inadequate and too expensive for any lunar program. While some new options may be available they are unlikely to be available in the near future. Conversely, foreign launch systems could assist in an international lunar program. But these non-US options have political problems that need to be addressed carefully.

POTENTIAL ISSUES AND APPROACHES – FUNCTIONS AND FACILITIES

LIFE ON MARS?

The evidence from recent Mars robotic spacecraft now seems firm that Mars once hosted substantial bodies of water – perhaps as recently as a few million years ago. This enhances the possibility that life once arose on Mars. Moreover, recent observations of life-related (but not necessarily life-unique) compounds such as methane and formaldehyde raise the possibility that some form of life may currently exist on Mars. The real prospect of current life on Mars forces us to re-think the entire exploration program. Indeed the program may now have a much better set of justifications. The discovery of and ability to study alien life represents one of the most fundamentally important scientific opportunities possible.

The real possibility of extant life on Mars means we must rethink our entire exploration program. First, it is essential that we do not contaminate Mars inadvertently. The discovery that terrestrial microbes can live for years in a vacuum environment on a spacecraft indicates that extreme caution is necessary to ensure that robotic missions to Mars are sterile. Moreover, until the existence and then sensitivity of Mars life to terrestrial is confirmed it makes little sense to consider human expeditions to Mars. Not only might humans and the microorganisms we bear contaminate Mars, but Mars life could contaminate us. For the latter reason it would appear than Mars sample return to earth must be deferred. The risk of incompatible Mars life contaminating, and perhaps dangerously altering the earth's biosphere is a real and serious danger. Some might claim that Mars life probably already got to earth on meteors, and may even be the origin of terrestrial life – but this doesn't alter the need for extreme caution. Conversely, Mars life has great value. Beyond the obvious scientific implications of genetic material formed and evolved in an alien environment, the genetic coding could lead to a plethora of new genetic-based products – especially if Mars life was the genesis of terrestrial life. For these reasons a new exploration program based on what's now being called astrobiology is essential.

THE ROLE OF THE MOON

An astrobiology-based exploration program must begin with the moon – indeed for the foreseeable future most activity should focus on that body. The moon should perform several key functions. First, it is the ideal laboratory for perfecting our ability to permanently reside off earth. Second, the moon represents the ideal location for robotic scientific research – particularly that which may prove too dangerous to perform on the earth.

UNDERSTANDING HOW TO LIVE OFF EARTH

Very little discussion has occurred on long-term human habitation off earth. But this is the underlying rational for human space exploration. Long-term habitation, indeed colonization of other worlds has long been a primary dream of humans. The two approaches tried to date are orbiting space stations and the "biosphere" concept. For a variety of reasons, including the inability of the human organism to survive for long periods in weightlessness, living on orbiting space stations has become a short-term prospect. Space stations and space ships, even with all necessary consumables are simply not a reasonable long-term solution for permanent life off earth. Yet this is the current focus of human exploration to both the moon and Mars. The alternative biosphere approach attempts to encapsulate a large enough cross section of terrestrial life that the "biosphere" so created can adjust to a new state capable of supporting higher forms of life, including humans indefinitely. The large scale experiments performed under private funding in Arizona during the 1990s were only partially successful. A key need was to allow the biosphere to "consume" some inputs and eject some "wastes" from time to time. The biosphere approach thus clearly warrants more attention.

In order to efficiently make a biosphere or even a close habitat of any scale work for long periods is thus In Situ Resource Utilization (ISRU). Long-term human habitation off planet, particularly at distant locations such as Mars will simply be too expensive if all facilities and consumables must be sent from earth. With the likely presence near the lunar poles of substantial volatiles, including water in permanently shaded craters, the moon has most of the potential ISRU material needed to support long-term human and robotic presence. Thus, the moon could be an ideal testing ground for researching and building a permanent human habitat, largely supported with ISRU. This would enable us to perfect the relevant technologies and methods before venturing further, and to potentially more complicated environments such as Mars.

ROBOTIC FACILITIES

A primary order of business is to construct on the moon robotic laboratories to resolve critical issues. The objective of these robotic laboratories is to pave the way for human "biospheres" on the moon. Key to cost-effective development is to aim at increasingly self-reliant and self-sustaining facilities, including use of in-situ resources.

LABORATORIES FOR DANGEROUS TECHNOLOGIES

The moon is the ideal location for handling dangerous materials and developing dangerous technologies. With no hydrologic or atmospheric processes to transport materials a facility is relatively easy to isolate. The poles in particular are an ideal location – with benign, almost uniform temperatures, thermal and other environmental control systems are straight-forward. Additionally both poles appear to contain volatile deposits, including water ice in permanently shaded craters. Not only is this key for in-situ development but the associated cold traps – probably only a few tens of degrees Kelvin is an important resource for heat engines, sensor cooling and preserving samples. Conversely, at least the lunar South Pole is surrounded by a high crater rim (the Shakleton Crater) that spends most of the lunar day-night cycle in sunlight. Consequently solar power systems can be constructed to supply continuous power in a manner similar to orbiting satellites. Indeed, one of the early manufacturable products from the moon might be silicon-based solar panels.

Perhaps the most urgent development for a robotic laboratory on the moon would be to construct a Mars sample receiving laboratory. As the possibility of current life on Mars grows, so too will the realization that off-world labs will be essential. Constructing such a laboratory on Mars would be more expensive than the moon. Moreover, one of the key experiments needed is to determine the inter-compatibility of earth and Mars life. Before any human or even extensive robotic exploration of Mars will occur should Mars life exist this compatibility determination must be made. With the atmospheric circulation on Mars introducing earth life to Mars, even in a close laboratory runs an acceptably-high risk of contamination. An alternative of an orbiting receiving facility is of course possible. However, all of the terrestrial biological procedures are based on gravity-driven processes. While a rotating, artificial space station is feasible, it is probably prohibitively expensive. Moreover, the risk of a station carrying dangerous life returning to earth would necessitate it being deep in space, adding additional cost. The moon is an ideal alternative as failed or disrupted experiments would stay put – and in an environment very hostile to life, a high-quality natural isolation feature.

The moon is expected to become a development site for in situ resource development. The most exciting possibility is to pursue self-replicating robots. The objective would be to build an off-world robotic colony capable of itself constructing other facilities for research and eventually human habitation. Of course the robotic manufacture of some high technology components, such as integrated electronics is a distant goal. Conversely, 80-90% of an advanced machine is components such as metal casing and structure basically using 19th Century technology. The first step in self-replicating robotics on the moon would be to construct the 19th Century technology components and bring only the high-tech pieces from earth. Over time, as infrastructure on the moon matures more and more advanced components could be manufactured there. Eventually, the robotic colony could be self-sustaining.

The development of self-replicating robots would be a major breakthrough, both technically and philosophically. It's probably the key for human expansion into the universe. However, this development also holds dangers. The run-away expansion of robots is the source of innumerable science horror scenarios – possibly resulting in the extinction of all humankind. The scenarios become even bleaker when the robots include some form of artificial intelligence (AI). The possibility of "strong AI" – human levels of intelligence in machines is highly controversial, but what many believe to be a real possibility in the next few decades. Yet, true AI could enhance and extend human capabilities and even life in unlimited and wonderful ways. As with the possibility of Martian life AI is a possibility of great potential as well as great peril. The use of the moon as a reservation of studying and developing these dangerous technologies could provide a way to move forward and protect life on earth, and perhaps even Mars from unforeseen consequences. Of course no isolation scheme, even on the moon is perfect. It may be that one long-term purpose of terrestrial military forces would be to monitor and devise mitigation schemes for worse case scenarios.

The moon may prove an ideal location for laboratories for other, less dangerous purposes. It could prove an ideal location for more “standard” biological development. Its isolation could make genetic engineering easier, as well as of less concern for mistakes escaping into the environment – an increasingly limiting factor for terrestrial genetically-engineered product development. Similarly, robotic lunar laboratories may prove ideal for developing new energy sources such as nuclear fission and fusion – another technology limited by concerns over inadvertent release of material into the earth’s environment.

The moon may also turn out to be an ideal location for advanced astronomical observatories. While free-space systems have certain advantages such as the possibility of very great apertures in optical and other wavelengths using gossamer structures, the presence of gravity may also hold advantages. One such advantage is the possibility of constructing very large optical reflectors (10s of meters in diameter) as rotating liquid mirrors. Moreover, a fixed facility on the moon has the advantage of staying put when it’s turned off. Operations similar to traditional observatories on earth, with which we have great familiarity, could be possible on the moon. The difficulties with our inability to service Hubble threatening the entire mission might not occur with a surface lunar observatory. Large ground telescopes have the advantage that they can easily evolve to be useful for a century or more. A lunar observatory might have similar advantages over free-flying space observatories. The moon could prove to be an ideal location for advanced scientific laboratories in biology and astronomy – but we must fully understand the pluses and minuses of the moon for such laboratories and not be driven to costly compromises between science and human exploration. Conversely, the presence of substantial robotic, and in-situ resource utilization infrastructure on the moon might make lunar observatories an appealing option.

THE PRIVATE SECTOR

The current space exploration vision places a high premium on private sector development. Indeed, without both private sector investment and new private-sector oriented cost-discipline it’s unlikely that the exploration programs ambitious goals will be met. Of course this raises the issue of why the private sector should be involved. What’s the profit motive? Second, just who is the private sector we are interested in?

The traditional aerospace companies perform Government functions as directed by the Government. This is the mode that NASA has operated in and appears focused on today. However, this is not what many believe the Administration means by private sector. There are two other modes possible. The first is akin to how roads and other infrastructure are built. The Government lets out a bid for a specific capability without specifying how it is to be done. For the moon this model suggests the Government might ask the private sector to provide infrastructure to support diverse functions on the moon – infrastructure such as communications and power systems. This infrastructure in turn would be available for other functions such as scientific laboratories as outlined above or scientific installations. This should probably be an early step in developing the moon.

An alternate mode of private sector development is that devoted to producing products. This is where an extensive robotic and other infrastructure on the moon could be the necessary precursor. Some of the products from the high-risk laboratories – such as self-replicating, possibly intelligent robots and/or mars life investigations could more than justify the expense of working on the moon. If the Government had provided basic infrastructure, these costs could be lower and true private sector development even more appealing. As we consider how to use the moon this approach could be an interesting alternative.

HUMAN HABITATION

The permanent presence of humans in a suitable environment on the moon offers significant appeal. From a strictly functional standpoint the robotic facilities outlined above are far easier to build and maintain if they do not need to be fully autonomous. Tele-robotic operations have proven to be far more feasible than fully autonomous robotic operations. Indeed, the only reason a robotic Hubble Telescope servicing mission is possible is through tele-robotic operations with human operators managing most functions. Such an operation is difficult on the moon if conducted from the earth due to the light travel delay of some seconds. Thus, the presence of humans on the moon to tele-robotically operate facilities is highly desirable. Moreover, the possibility of direct human intervention in emergencies becomes feasible.

Humans living for long-term on the moon are important for other reasons as well. The moon represents a much easier laboratory for perfecting the technologies and techniques for long-term living off planet. At only a few days journey from earth, providing emergency supplies and even evacuation is far easier than mars, for example. From the long-term perspective of human survival should life on earth become impossible developing the technology and means for permanent human habitation off earth becomes an imperative.

Experience on the International Space Station and MIR Space Station have shown us that a strictly engineering approach to human life off earth is difficult, expensive and unlikely to succeed for long-periods of time. One of the most interesting experiments in the past few decades has been the “terrarium” concepts applied in the Biosphere II project. Interestingly, this project was wholly supported with private money – a useful template for further space development. The Biosphere II concept was to place a wide diversity of life in a close system and allow it to self-adjust. The concept was that a closed system, including humans could survive indefinitely. The Biosphere II experiment, while not conducted along a strictly scientific basis, did provide a useful starting point for further work. Among other results was the necessity to provide a facility for some inputs and waste removal to maintain stability.

We propose that the work done in Biosphere II be expanded with the aim of building a permanent human-qualified habitat on the moon. Such a habitat should de developed in concert with robotic laboratory facilities on the moon for diverse purposes.

POTENTIAL ISSUES AND APPROACHES - GETTING TO THE MOON

The US launch infrastructure is at a crisis point. It is in no state to support a renewed space exploration program as envisaged by US President Bush. US human access to space embodied in the Space Shuttle is due to be phased out by the end of the decade. We currently have no heavy lift (100 ton class) launcher to support the President's space exploration needs. The US medium and large expendable launch providers, Lockheed's Atlas and Boeings Delta Evolved Expendable Launch Vehicles (EELV) have become so expensive that they no longer carry commercial payloads and represent a significant brake to future use of space for national security or exploration. If we are going to mount any mission to the moon we must find a solution – nationally or internationally to getting there.

COST, RELIABILITY, INDUSTRIAL BASE

The root cause of many of the US industry's problems lies in an aging infrastructure, and more to the point ageing human capital resource. While not unique to launch, or even space the ageing technical expertise base is at the root of many problems. With the average age of US aerospace engineers into their 50s, all space programs are costing more and leave long-term sustainability in question for any system (after all old engineers soon retire).

The most visible result from our growing launch problems is the accelerating cost of space access with US boosters. For example, the EELV was supposed to cost significantly less per launch than predecessor systems. In fact EELVs cost considerable more that what they replaced – with no real increase in capability or operability. Even small boosters such as Orbital Sciences Pegasus launcher have suffered. When developed 20 years ago each flight was to cost $6M (about $10M in current dollars). Yet Pegasus now costs over $25M per launch – at least double its original cost with no increase in capability. As human capital further evaporates the cost will only continue to rise. More serious is that reliability may also suffer.

POTENTIAL APPROACHES

For the purposes of this discussion we will focus on medium, large and heavy lift options needed for lunar exploration. There are three potential approaches, with corresponding pluses and minuses, to meet our needs. The first approach is to derive new capability from existing US systems – the Space Shuttle and EELV. The second approach is to develop a new US launch capability. Finally, we consider capabilities, components and technologies developed outside the United States.

DERIVED LVS

Deriving new capabilities, either heavy lift or new human space access from existing US large boosters is an appealing option. This approach has the advantage of existing infrastructure and tooling (and the political support that goes with that). For NASA with an urgent need to support the International Space Station and get a start on space exploration, deriving new capabilities from existing US ones holds the least apparent schedule risk.

One of the key decisions to be made is whether to pursue EELV-derived or Shuttle derived options. Shuttle components were originally designed for heavy-lift and human spaceflight. Thus Shuttle derived launch capabilities would appear better suited that EELV-derived. The latter, after all is an evolution from ICBM systems and is most effective for medium payloads. However, the national synergy between a civil EELV-derived set of systems and security requirements could argue for an EELV-based approach. The recent "merger" of EELV providers may add impetus to this argument.

Against these considerations are some negative aspects of the derived launch vehicle approach. Unless considerable increases in launch rates are envisaged it's unlikely that deriving new launch vehicles from old will save any money. After all, the primary cost of launch (or any other aerospace capability) is in the people that support it. The current systems are all human manpower intensive. Political pressure alone could ensure that most often the existing people would remain employed. Since the resources to support new missions such as space exploration will come from re-direction of old much more than new Government resources, spending the money "saved" by phasing out the Space Shuttle could simply flow back into an equally expensive derived capabilities. An additional consideration is that relying on the current aging human infrastructure calls into question the sustainability of whatever derived approach is taken. Maintaining an existing system is also unlikely to attract the best of the new generation – most of whom will be more attracted to fields where new technology is being developed.

NEW US CAPABILITIES

The United States has a history littered with failed new launch vehicle programs. Each new program, whether it is the National Aerospace Plane (NASP), National Launch System (NLS) or a host of others has failed. Nonetheless most experts agree that a healthy long-term US space strategy mandates that we develop new launch capability – whether for affordability, reliability or sustainability reasons.

New capabilities fall into several categories. First are new capabilities developed in a more or less conventional way by our large aerospace firms. Second are capabilities developed by an emerging new aerospace industry – partly or wholly funded by wealthy private concerns with a diverse, often philanthropic set of interests. Third is the class of capabilities which would make use of foreign-developed technology or hardware.

US DEVELOPED SYSTEMS – TRADITIONAL PLAYERS

The large aerospace firms have frequently studied "start from scratch" systems. Lower-cost concepts such as the oft-discussed "big dumb booster" or a reconstruction of Apollo era hardware have frequently been proposed. However, most of their recent concepts rely on significant legacy from current systems for affordability reasons. Unfortunately, only a new booster approach incorporating newer materials and manufacturing methods has any possibility of competing with foreign launch capabilities – an essential objective if we are to maintain space leadership. Developing a new booster by the traditional aerospace houses has the benefit of higher confidence in their ability to do so. Moreover, a major launch development program, particularly involving the traditional aerospace contractors could be a key impetus in revitalizing this essential industry.

To finance a completely new booster family from existing aerospace firms is an expensive proposition. Including heavy lift options a new, modern booster development would probably cost between $10-20B based on recent corporate estimates.

US DEVELOPED SYSTEMS – NEW PLAYERS

Consternation with traditional aerospace firms has given rise to a significant number of new players in the launch business. These firms, entrepreneurial and often composed of young, aggressive technical and management personnel offer a totally new approach to launch vehicle development. Estimates of the cost to develop medium and heavy lift vehicles vary widely – but development costs of as low as a few hundred million dollars for such development have been put forward with some credible back up.

Of particular interest is a special class of new launch vehicle developers. These are the independently wealthy individuals such as Paul Allen, Elon Musk, and Jeff Bezos. Unlike many new, private sector approaches which often involve little more that "three guys in a garage" seeking hundreds of millions in Government resources, these independently wealthy individuals want little, often nothing other than to be left alone, from the Government. These individuals are often not motivated by near-term monetary gain – and in some cases are not motivated by monetary gain at all. As such they fit a traditional mold of explorers – privately financed and supported. Much of the polar exploration of a century ago was supported by such individuals. Such individuals are generally not interested in new technology development. Some, such as Elon Musk's Space-X corporation are already developing heavy lift concepts such as his "BFR" (Big Fun Booster?) with 100 ton to LEO or more capability. Others, such a Jeff Bezo's Blue Origin aims at human flights to LEO within a few years. It is possible that most of what the US needs, particularly in its civil space program might be available from this special private sector in a few years.

While true private sector launch initiatives – the so-called "alt.space" movement is appealing – and quintessentially, even uniquely American – its success rate is low. Despite many efforts, the only significant success from this community so far has been the Ansari X-prize. Elon Musk's Space-X endeavor could show some successes in 2005. Nonetheless, relying on true private investors is not likely to produce heavier lift of human space transport in the near to mid term. Long term potential is quite high however and should be encouraged as much as possible by the US Government. The passage of the US Space Launch Amendments act of 2005 placed a firm and supportive regulatory regime under this industry.

FOREIGN TECHNOLOGY AND SYSTEMS

The impressive progress of European space endeavors, particularly with smaller payloads rests in part with their access to low cost Russian boosters. Indeed, the Europeans have the nucleus of a substantial human space access capability with their development of a Soyuz booster pad at the European launch site in French Guiana.

Direct use of Foreign launch capabilities – except as a barter arrangement as with the use of Soyuz for human access to the International Space Station or joint projects such as the possible use of the European Ariane to launch the James Webb Space Telescope is difficult if not impossible for the US. Political forces generally make it extremely difficult to directly purchase foreign launch services. There are however many successes in using elements of foreign launch systems. For example one of our two US EELVs (Lockheed-Martins Atlas V) rides on Russian designed and produced engines. The latter are currently produced wholly in Russia, but have provisions for co-production within the US - an option that has not been exercised due to US Air Force inability to fund this development.

Essentially all US commercial satellite launch is contained in two joint ventures, ILS and Sea Launch. Both are partially owned by the big US aerospace firms Boeing and Lockheed. Both use Russian boosters but rely on western payload handling and integration. These efforts are among the few money making commercial space ventures today.

Perhaps the most interesting alt.space approaches are those which rely on combinations of US and foreign payloads. These efforts are wholly commercial and offer capabilities ranging from resupply of the space station to human space transportation including even lunar human swingbys! These groups are creative and have great promise. Unfortunately none of them seems to have the necessary capital to get very far independent of the US Government.

PROPOSED WAY AHEAD FOR LUNAR ACCESS

The United States does not have the luxury of suspending current space programs to divert resources to new launch development. The Space Station must be supported and national security payloads delivered and maintained. Conversely there's little likelihood of substantial new resources for new launch vehicle development. Thus, tens of billions of dollars "start from scratch" launch vehicle development is unlikely.

Launch vehicles derived from existing US boosters offer a near term, albeit somewhat expensive option. Relying as they would on existing, and aging (particularly human) infrastructure these options will start expensive and probably grow in cost with time. Pursuing them to the exclusion of other, more appealing options could further lower US long-term competitiveness in this critical area.

Privately funded launch options offer an appealing, but largely unproven alternative. An interesting alternative which can preserve US competitiveness involves creative use of foreign technology and capabilities. Taking advantage of political opportunities such as US interest in supporting a democratic Ukraine, for example, could enable us to use the efficient and well designed Zenit booster as a building block for human, cargo and even security access to space. However, if these options are to be pursued they would need to have US concerns clearly in the lead as well as involve mandatory co-production features – something that the Atlas V EELV has not yet faced up to. These options might best be pursued by NASA, an agency with immediate space access needs and a tradition of international cooperation. This approach could provide the necessary near-term capability to get a lunar base up and running.

SUMMARY

NASA's current plans for space exploration are focusing largely on engineering and transportation systems. We believe this focus should be expanded to include development of permanent human habitats on the moon as well as extensive robotic facilities. Much of the criticism of NASA's exploration program stems from the lack of coherent rationale for what we will actually do on the moon and mars. The construction of permanent human and robotic facilities on the moon could begin to answer this question.

Using the moon to perfect the means for humans to permanently live off planet is an essential first step. The Biosphere II terrarium approach could provide one interesting starting point. Simultaneous with working on human habitation of the moon, we should construct robotic facilities for developing in-situ lunar resources. More to the point we should construct robotic facilities to explore technologies too dangerous to consider on earth. Among the most critical would be a receiving laboratory for possible life-containing Mars samples. The presence of humans directly on the moon is critical to enable efficient tele-robotic operation of these facilities as well as to monitor status and assess problems before they become critical.

NASA has yet to fully engage the international community or the scientific community in its exploration programs. A focused program to develop permanent human habitats and robotic laboratories on the moon could address both communities. The science and engineering challenges and opportunities of such a program are large and very appealing. The fundamental question of how life exists and adapts to its environment could be a significant outcome of this approach. Private sector resources and development would likely be attracted and attractive.

We urge NASA to focus reasonable investment in exploring these possibilities. There are clearly many promising approaches such as the Biospheres II concept waiting for such a positive signal. Without a focus such as we propose the exploration vision may not get off the ground.

Of course we will not succeed in any lunar exploration program if we don't have the means of getting there. This is another area that foreign cooperation could help address. There is little likelihood that the United States will have an affordable means to access the moon with derivatives of its current Space Shuttle and EELV programs. Conversely, simply purchasing foreign launch services is unlikely from political perspectives. However, a joint venture managed by US concerns and utilizing elements of foreign launch vehicles such as the Ukrainian ZENIT could provide a near-term solution to space access for lunar exploration.