FRAMEWORK FOR VALUATION OF ASTEROID MINING OPTIONS, INCORPORATING STRATEGIC KNOWLEDGE GAPS, MARKET DEMAND AND TEMPORAL DEPENDENCIES OF IN SPACE RESOURCE AVAILABILITY.

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Introduction: Space resources are fast becoming a realistic and important aspect of the space industry, and the expanding human econosphere. Bank of America - Merrill Lynch, Morgan Stanley and Goldman Sachs all recently forecasted the inception of a multi-trillion dollar Space economy by the 2030s, primarily fuelled by the continuous reduction in launch costs, the proliferation of public and private activities beyond Earth's orbit, and the deployment of In-Space Resource Utilization (ISRU) capabilities to enable self-sustainable Space exploration and economic development. In the 17th century, the Dutch East India Company financially securitized the spice trade to fund their ultimately very successful trading and logistical development operations. We investigate a quantitative framework to help the Space industry valuate and securitize a Space resources based economy, detached from a fundamentally non-compatible terrestrial based currency and valuation system.

Valuation of Space Resources: Current valuation methods, based on terrestrial market demand for resources and commodities are flawed, when applied to off-Earth mining (OEM). Current valuation methods are underpinned by the assumption of resource and commodity scarcity (i.e. quantifiable supply and demand pricing), which can provide unrealistic valuations even for terrestrial mining projects.[1] Furthermore, they do not account for the multi-dimensional complexity of mining and utilizing Space resources. The utilization of Space resources requires consideration for temporal dependencies of resource extraction (i.e., asteroids that can only be travelled to/from periodically), scientific uncertainties, spacecraft and delta-v dependent capital expenditures (CapEx), and predictability in the materialization of market demand for said resources. Our quantitative framework attempts to solve the aforementioned flaws by: a) fine tuning the *Black-Scholes* based *Real-Options-Valuation* technique to discern the relative value among different Space resources, and b) adapt the options value optimization "algorithm" to account for a resource-abundant-based Space economy, underpinned by the long-term goal to maximize human settlement and economic development in the Solar System.

Black-Scholes (B-S) Real Options Valuation (ROV) Method: The Black-Scholes equation is a pricing model developed and used to determine the theoretical value for a financial option based on six variables: market volatility; type of option; underlying asset price (present); exercise price (in the future); time to exercise; and risk-free interest rate.[2] While the B-S equation is a powerful tool for valuing financial options, it doesn't yet address the aforementioned multi-dimensional Space-based complications.

The B-S equation has been adapted beyond valuing financial options to consider Real Options, and even used to consider the potential future value of technology development at NASA (<Cite Shisko, Ebble Fox>). However, these adaptations fail to consider the risks and capital requirements of OEM.

Adaptation to Space Resources Valuation: In order to normalize the Black-Scholes equation to Space Resources, it is necessary to include consideration of the cost of extraction, the probability that market demand materializes, and the uncertainties in scientific knowledge progress and market competition. These are not based on "brownian motion" equivalent stochastic movements, but real engineering needs, macro economic forces and scientific activities:

$V = V_{B\text{-}S} * P_{win} * R_{market}(t) * R_{SKG} - I_{isru}(t)$, where V is the present value of an exercisable option to mine a Space resource in a future point in time t, $V_{B\text{-}S}$ is the equivalent price of a European put option, P_{win} is the probability that the option holder will be the absolute benefactor of the resource (i.e. in the case that tenure is not possible or codified), $R_{market}(t)$ is the composite risk factor of market materialization and price sensitivity of the Space resource as a function of time, R_{SKG} is the risk factor accounting for any residual scientific knowledge risks associated with the resource (quantity, distribution, extractability), and $I_{isru}(t)$ is the time-dependent CapEx required to mine the resource.

The cost of extraction is a unique requirement of mining activities, above and beyond financial options, wherein the acquisition of the underlying asset is assumed to be (and often is) free - and instantaneous - upon execution of the option. However, mining activities carry a cost and time burden to obtaining underlying assets. This is often numerically quantified as whether or not a specific real asset is "ore-bearing," i.e., if the value of minerals extracted will be greater than the cost of the extraction. This is a particularly apropos consideration for off-Earth mining[3] where the costs are very large, and still ill-defined.

Another source of ambiguity is tied to the growth of in-Space demand for these resources. While some limited asteroid materials could be brought back to Earth and sold terrestrially, most resources will be used in Space to lower the cost of Space activities and greatly reduce dependence on resupply from Earth (i.e. self-sustainability). Water is a large driver of current and early-stage Space mining activities, due to the expected demand for propellant in orbit, human life support (hydration, sanitation, oxygen, food production) and industrial activities. Scientific uncertainty is another contributing factor to the volatility of off-Earth mining activities, most notably with respect to mining of asteroids. The historical focus of asteroid observations on planetary science has resulted in imprecisions and unknowns in the characterization of near-Earth asteroids with respect to their minability. In some ways this can be compared to terrestrial prospecting; for example, the U.S. Geological Survey provides low-resolution estimates that would have to be refined and confirmed with in-situ data in order to provide enough confidence that a resource is ore-bearing. However, the available data set for asteroids is focused on non-resource observations and analytics, which creates a greater uncertainty in the applicability and accuracy of the underlying science with respect to the ore-bearing value of any given asteroid. This uncertainty will be reduced as more data is collected and analyzed for a given asteroid, but will continue to exist to a certain degree until in-situ prospecting, and possibly even mining activities, commence.

Finally, competition may need to be factored in. Financial options can assume fungibility in the underlying asset that is immediately available upon execution of the option. Even real options assume the guaranteed right to make use of the asset. However, in light of the unformed legal framework regulating the extraction of space resources, it is foreseeable that exclusive tenure may not be possible. This would allow competition over the same resource (e.g., a single target NEA) that could potentially devalue an entire mining project to all but the 'winning' firm.

Valuation of Space resources in the context of a Solar System wide economy: Ultimately, utilization of USD (or any other terrestrial currency) as the benchmark for Space resources valuation will become nonsensical as a Space based economy matures and eventually becomes self-sustainable. A true Space-based economy will not follow terrestrial market dynamics, especially with respect to the ways in which water and other resources would be used in Space. Water will be used primarily for life support, as well as transportation and other industrial capabilities. Along with other resources necessary to support life off-world (energy, food, habitation, &c.) codifying the underlying value of in-space resources in a *Life Support Unit (LSU), a composite measurement of all resources required to sustain one human life in Space,* would make more sense in the long-term. Consequently, the aforementioned B-S ROV method for valuation of Space resources would be tuned to maximize economic output in terms of LSUs vs. terrestrial currency.

The framework of a LSU based market can be utilized to contextualize the life supporting potential of the entire Solar System. An exemplar analysis of a sustainable Space economy[4] indicates per capita annual flows (with recycling) of 2.2 t water, 0.02 t food, 0.01 t breathing oxygen, 30 t concrete plus regolith for shielding, 0.5 t metals, 0.7 t other structural materials, 0.5 t solar PV, and 0.3 t industrial chemicals. Propellants for Space transport could dwarf these quantities, depending on assumptions about human movement and material exports; some materials trading would be necessary. Recycling of materials, particularly water, is crucial to minimize material flows and energy inputs. We estimate that 0.05% of Lunar and 0.1% of Martian land areas would provide sufficient solar energy (5.3 GW, about 40% of current final energy consumption on Earth) to support a combined surface population of 25 million plus 250 million living in Space. As such, a non-terrestrial currency almost becomes necessary; of course in tandem with the exchange of goods, services and currencies across boundaries. As further research in this area, Spacexchange and Aten are developing an economic model based on life support and industrial needs of a sustainable space-based population to further quantify the relative basis and value of the Life Support Unit.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Lane G.R. et al., (2012) *SAIMM, Platinum 2012*. [2] Black F., Scholes M., (1973) *J. Pol. Econ., 83,* 637-654. [3] Elvis M. (2013) *Planetary And Space Sci.,* http://dx.doi.org/10.1016/j.pss.2013.11.008. [4] Greenblatt J.B., (2017) Emerging Futures, http://tinyurl.com/moonvsmars.