Building a robust commercial microgravity economy in Earth's orbit: *Economic Readiness* considerations

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The reduced gravity environment of space provides a unique opportunity to further our understanding of various materials phenomena involving the molten, fluidic and gaseous states as well as life science applications where, contrary to earlier beliefs, microgravity induces changes in single cells and simple organisms; not only in large organisms with a complex overall response to gravity (or lack thereof). The potential breadth of commercial opportunities in microgravity thus spans over many verticals of the private sector with applications ranging from fiber optics, high-resolution crystals, microencapsulation, 3D organs to perfume and color dyes. Overall, products manufactured in microgravity hold the promise to have key properties surpassing their best terrestrial counterparts.

Figure 1 Concept of a robust Earth's orbit economy building upon Microgravity Verticals and Economic Readiness Level

Commercialization, also known as "taking a new technology to market", is a journey in itself where the business, economic, market and technological components must align to generate a successful outcome. A business perspective is very different than technology maturation. In order for a technology to be ready for commercialization, it must not only be mature, but it must also have a compelling business case, and the means to scale up production must be identified and practical. Creating a robust economy in Earth's orbit (Fig 1) is especially challenging because of the complexity (high risks, lack of standardization) involved in predicting future growth. This complexity can easily overwhelm the fact that many of the products have an attractive "touch of space" which aids with branding and marketing.

This paper reviews the types of added value that can be extracted from space, with an emphasis on the microgravity environment. In addition, lessons learned from past commercialization efforts will be reviewed. While past efforts have yielded some point successes, they have as a whole failed to precipitate a sustainable LEO based market (Fig 2).

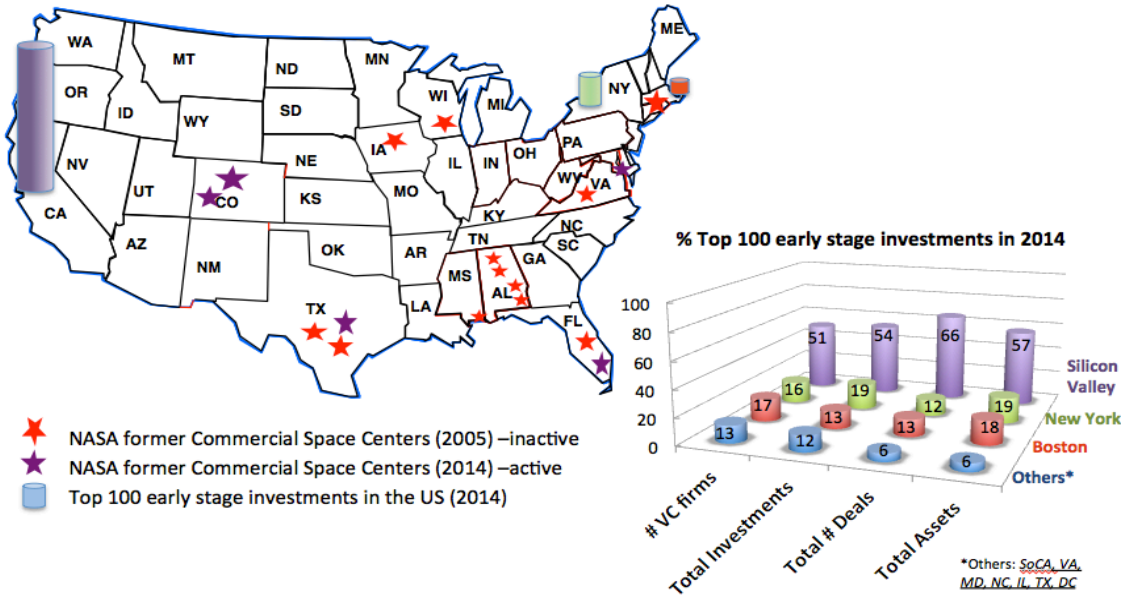

Figure 2 Stars: NASA Commercial Space Centers (17) operated at approximately $1M a year: inactive as of 2005 (red stars) and active as of 2014 (purple stars). Total 2014 early stage investments per regions from top 100 venture capital firms are also mapped: ~$14M and 914 deal count in Bay Area California (purple cylinder); $5M and 164 deals un New York (green cylinder) and $3.6M and 185 deals in Boston (orange cylinder). The inset provides additional information on the number of VC firms, total investments, total number of deals and total assets.

Microgravity results have traditionally been categorized based on fundamental scientific or engineering disciplines. While this approach can be effective at highlighting research in a given field, it results in discipline level stove-piping, making it more difficult to see how microgravity can impact a multidisciplinary advance to current technology. In order to overcome this limitation, the concept of *Microgravity Verticals* is introduced where existing microgravity results have been binned across multiple disciplines based on their relevance to a sector of private industry. The Microgravity Verticals are developed to capture in a compressed manner a mix of very diverse values (knowledge, processing) of the microgravity environment as well as companies who have self identified their interest or intent to mature those technologies for commercial applications. To improve our understanding of the current potential of microgravity commercial R&D, the Verticals extend into the future to make predictions of microgravity-based solutions relevant to a sector of the private industry as identified in current industry specific roadmaps.

Figure 3 Concept of a free flying laboratory for private sector utilization

To construct the Verticals, technologies were initially sorted using the government standard Technology Readiness Level (TRL) scale. An important finding of this work is that the TRL scale is insufficient for this purpose. While the TRL scale provides a simple, standardized measure of *maturing a technology from a fundamentally new idea (research) to design maturity,* it does not take into consideration nor does it capture economic intelligence, investment strategies and existing market pull. A new scale, the *Economic Readiness Level (ERL)* is proposed that merges on the same scale technology and investment considerations to bridge between supply, demand and capital. To advance on the Economic Readiness Level scale, the technology itself may not necessarily need to mature but the understanding of its economic potential does.

Building on these new concepts of Microgravity Verticals and the Economic Readiness Level, this paper further captures and describes key aspects and elements of the machinery of commercialization that ultimately leads to the creation of pathways for infusion of private capital that could harvest the resources of space through a robust economy in Earth's orbit and beyond and return value to Earth.