An Analysis and Review of Measures and Relationships in Space Transportation Affordability

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The affordability of transportation to or from space is of continued interest across numerous and diverse stakeholders in our aerospace industry. Such an important metric as affordability deserves a clear understanding among stakeholders about what is meant by affordability, costs, and related terms, as otherwise it's difficult to see where specific improvements are needed or where to target specific investments. As captured in the famous words of Lewis Carroll, "If you don't know where you are going, any road will get you there". As important as understanding a metric may be, with terms such as costs, prices, specific costs, average costs, marginal costs, etc., it is equally important to understand the relationship among these measures. In turn, these measures intermingle with caveats and factors that introduce more measures in need of a common understanding among stakeholders. These factors include flight rates, capability, and payload. This paper seeks to review the costs of space transportation systems and the relationships among the many factors involved in costs from the points of view of diverse decision makers. A decision maker may have an interest in acquiring a single launch considering the best price (along with other factors in their business case), or an interest in many launches over time. Alternately, a decision maker may have a specific interest in developing a space transportation system that will offer certain prices, or flight rate capability, or both, at a certain up-front cost. The question arises for the later, to reuse or to expend? As it is necessary in thinking about the future to clearly understand the past and the present, this paper will present data and graphics to assist stakeholders in visualizing trends and the current state of affairs in the launch industry. At all times, raw data will be referenced (or made available separately) alongside detailed explanations about the data, so as to avoid the confusion or misleading conclusions that occur more often than not with complex graphs or statements when such context is lacking.

Nomenclature

CASM	=	Cost per Available Seat Mile
ELC	=	ELV Launch Capabilities Contract
EELV	=	Evolved Expendable Launch Vehicle
LEO	=	Low Earth Orbit
ULA	=	United Launch Alliance

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I. Affordability, Prices and Costs

Any discussion of the state of the US launch industry that wants to address affordability, competitiveness, capability, or productivity must recognize from the start that good data is lacking. The plural of anecdotes is not always data. The review here will not pretend to be an economic analysis either. The poor state[3] of any consensus or understanding about space economics goes hand in hand with the lack of poor data[4]; poor data being a symptom of poor incentives, lack of competition, and monopoly/monopsony conditions.

Nonetheless, some useful insights can be obtained if understanding the need for context, where cost metrics alone are only semi-useful, but their consideration alongside other measures can create “aha” moments. For example, as shown in Figure 1 and Figure 2, it is typical discussing launch costs to plot dollars per kilogram (or pounds) vs. the payload capability of different launchers.

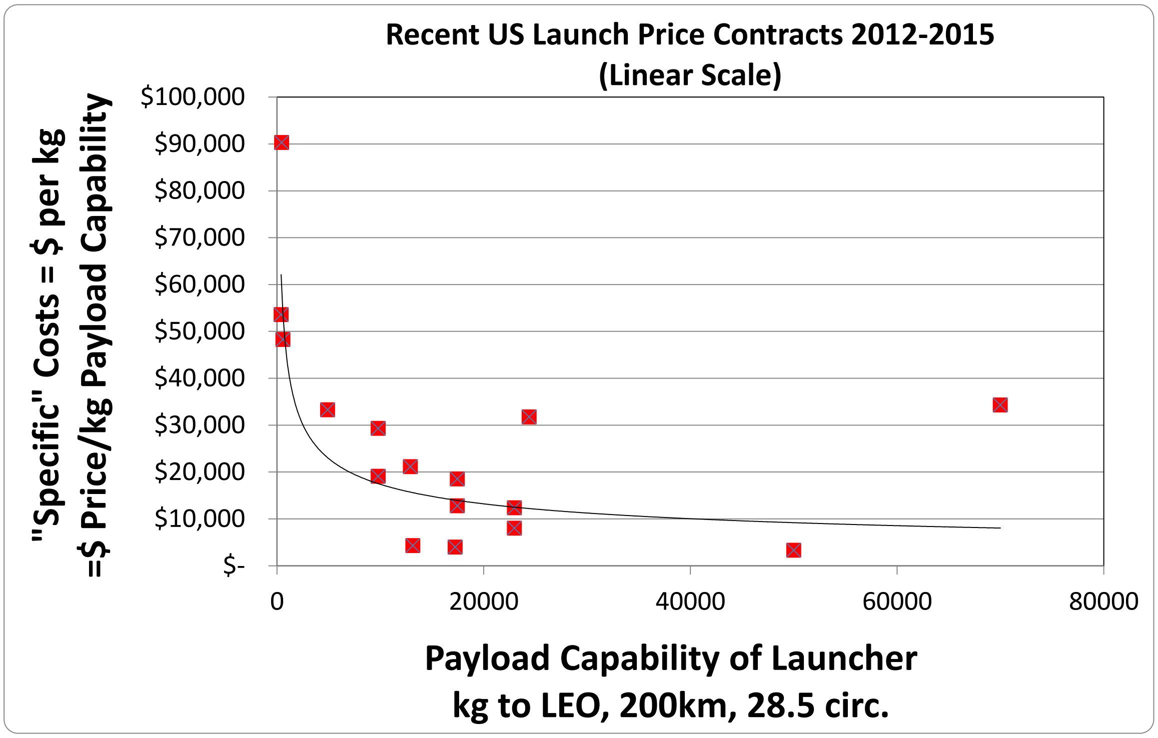


Figure 1: US Launchers and recent launch price contracts (2012-2015), using a linear scale and applying a power curve fit.

Caveats are required when adding this type of data into a discussion about US launchers, affordability, competitiveness, areas to improve or sectors ripe for investment of any sort. These caveats (and seeing the raw data[5]) help provide the most insight possible from such data while avoiding misunderstandings.

Caveats of a cost per kilogram view of US launchers include:

1. Location, location, location: The views shown in Figure 1 and Figure 2 have normalized for effort as much as possible within the data; how far is a payload being taken by that launcher? The payload may include more propulsive capability, which may fall to the customer as part of their payload, but the “ride” provided by the

[3] H. Hertzfeld, “The state of space economic analysis, real questions, questionable results,” *New Space Journal*, 2013.

[4] Futron Corporation, “Space Transportation Costs: Trends in Price per Pound to Orbit, 1990-2000,” September 6, 2002, http://www.futron.com/upload/wysiwyg/Resources/Whitepapers/Space_Transportation_Costs_Trends_0902.pdf (last visited May 27, 2014). “…many launch contracts are not made public…”

[5] The raw data for Figure 1and Figure 2 is available upon request. Contact the author at edgar.zapata-1@nasa.gov.

launcher provider has to account for a location, here low Earth orbit (LEO), at 200km, in a 28.5 degree circular orbit. This represents the delivery location up to which the launchers price and performance are compared. (Any other approach, such as comparing a price to arrive at this LEO location, in the same vein as delivering to the International Space Station, higher up at 400km, or to Geosynchronous Earth Orbit at 35,785km, would be akin to trying to compare the prices quoted from different trucking companies to deliver up the road with those prices of other companies for going cross country).

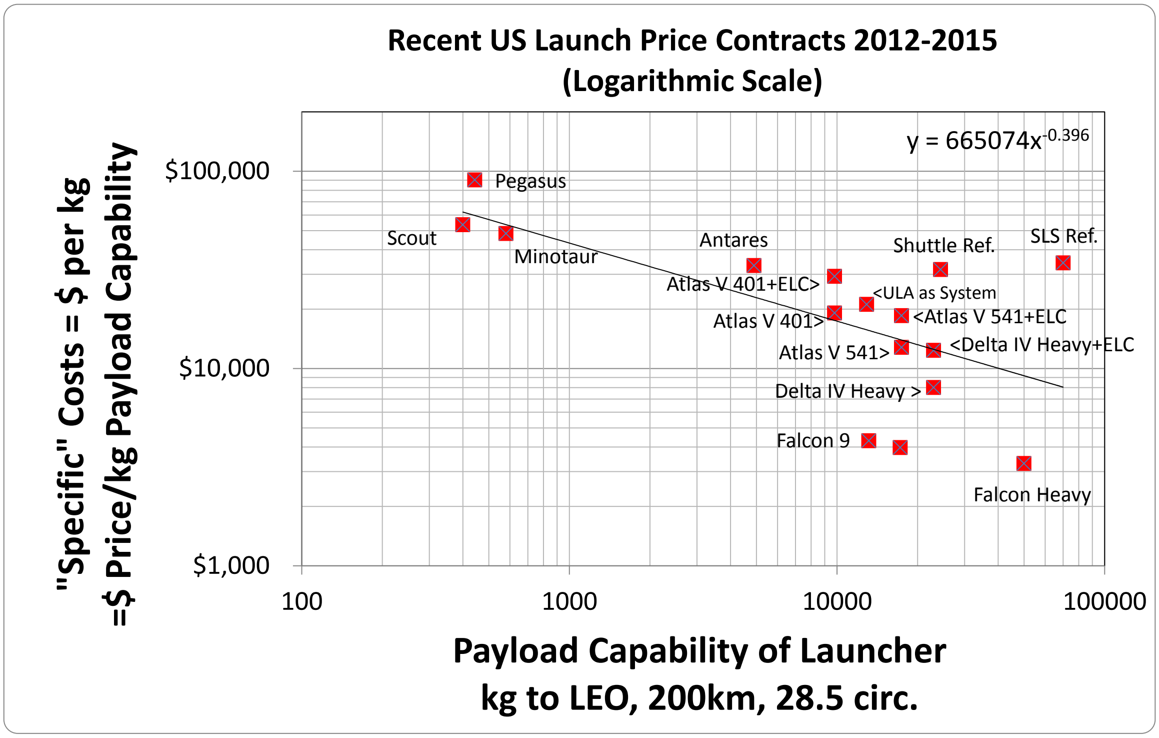


Figure 2: US Launchers and recent launch price contracts (2012-2015), using a logarithmic scale and applying a power curve fit.

2. Causality-not quite: The measure "cost per pound", though popular, should be considered mostly an accounting identity. The measure graphed does not tell which way causality runs, if causality exists, or why. The temptation to take two variables plotted on a graph, after seeing these form some line or curve, is to conclude that X causes Y (or vice versa, as the axis could just as well have been flipped). Behind all the points in such a graph is a story, with more understanding required as to what is causal, which points may form a "family" of similar points, and why there may not be points elsewhere.

3. Price vs. costs: For the particular views in Figure 1 and Figure 2, only recent launch prices are being used. These are a "price" to a customer, related (in likely different ways and degrees) to that "cost" for a launch provider that comes from recurring costs. Non-recurring, up-front, capital or one-time costs are not typically in such prices or similar analysis (but given uncertainty around data and business models, it should not be discarded that these costs may find their way in to what appear to be "recurring" measures and "prices"). On this note, the United Launch Alliance launchers are shown both with and without the Evolved Expendable Launch Vehicle (EELV) Launch Capabilities (ELC) contract, an approximate $1B a year amount paid[6] to ULA by their main customer, the US Air Force. This is returned to ahead when moving to the topic of measures of productivity (such as a number of launches over a year, over which costs of this sort could be amortized for measurement purposes).

[6] Mike Gruss, "U.S. Air Force Claims Big Savings on EELV Block Buy," *SpaceNews*, January 31, 2014, http://www.spacenews.com/article/military-space/39348us-air-force-claims-big-savings-on-eelv-block-buy (last visited May 27, 2014).

4. Apples or Oranges: An attempt to show costs per kilogram and include systems for which the question may go begging, such as the Space Shuttle, must be cautious about comparing apples to oranges. The requirement to deliver people and cargo cannot (easily) be compared to a requirement to deliver only some cargo. To help in this regard, the Space Shuttle value as shown in Figure 1 and Figure 2 has had crew discounted from total recurring costs (all costs since 1981 to the end of the program) at a "Soyuz" going rate of $70M a crew member. Alternative ways of getting to a valid comparison are likely possible, but in all cases, such normalizing should be required of any attempt as using costs per kilogram. In the spirit of "buyers beware", when costs per kilogram are presented in discussions about affordability, audience questions about the normalizing done should follow.

Cons of a cost per kilogram metric include:

1. Causality-not quite: Causality may be assumed, erroneously, from seeing affordability in a cost per kg point of view (regardless of the prior caveats). A decision maker may be lead to believe that a smaller launcher is one that will reduce costs versus a larger launcher, merely by virtue of the scale undertaken. This would not be wholly correct. The decision maker (considering a launcher development and/or business) would need to understand the similarities (or not) of their plans to the launcher points that already exist. These similarities and differences go far beyond just design and scale (including how business will be done, processes, practices, etc.) More importantly, the opportunity to delve further into what causes costs would be lost by jumping to what could be an erroneous assumption ("all other things being equal").

2. Productivity not included: A specific companies launcher, of a specific scale, capable of lofting a specific payload to a specific location, for a specific price (the price being a cost as seen by the paying / payload customer) does not necessarily imply anything on its own about the launcher systems capability to produce X number of flights, at a repeatable rate. The readiness to produce many more than X number of flights as well, if customers were to ask, also needs to be considered apart from the price of a single launch. A customer may value such productivity, beyond just the purchase or procurement of one launch, or even repeat business, even to the extent of many launches over time. Constellations of satellites, on-orbit infrastructure, and customers or business cases that require a high tempo, must consider more than just a price, or a price per kilogram. This is further addressed ahead.

3. By the yard-not quite: Transportation to space is not yet a commodity, a mature business sector, such that the metric of costs per kilogram is useful in a "buy by the yard" sense. A reader presented with cost per kilogram charts should realize the jump between points is discrete, not continuous. The payload that exceeds the capability of launcher A must either lose weight or jump to the next launcher scale, even if not using all the capacity of that next scale of launcher. This brings about the concepts of "minimum price of entry" and "barriers to entry", discussed further ahead.

Pros of a cost per kilogram metric include:

1. An indicator of competitiveness: The measure of affordability as costs per kilogram is analogous to airlines "costs per available seat mile[7]" (CASM). Since CASM is in the pennies, this may be referred to as "pennies per available seat mile". This value is watched as particularly telling of the competitiveness of an airline. Similarly, for US space launch, the metric of costs per kilogram may prove to be a good indicator of competitiveness among companies as the industry matures.

[7] The Glossary of the Airline Data Project, http://web.mit.edu/airlinedata/www/Res_Glossary.html (last visited May 27, 2014)

Beyond costs per kilogram for a launcher, or the prices a single customer seeking a specific launch may find for a US launcher, there is the matter of up-front costs, the non-recurring costs to develop new systems, launchers, or in general all the capital spent to create a capability. It is not unusual to find a cost per kilogram, or a cost per launch that makes no distinction between non-recurring up-front costs (research, development, infrastructure, etc.) and recurring costs during use. Total lifetime program costs[8] used for costs per launch are arguably a useful measure if the objective is to assess the ability of a system to be developed again or copied by another party.

If the thought is that one day many launchers (reusable, expendable, etc.) might compete in a market much as airliners compete in an airline market, then the up-front development cost is of especial interest. The up-front cost is a barrier to entry which has to be overcome while considering benefits in the future having uncertainty. High upfront costs may also serve to reduce the ability to learn by doing, or even reach operational status (cancelation) either for individual enterprises or the industry in general. A new concept promising low costs per launch or per kg may have technical risks; one that is high cost up-front has programmatic risks. If the thought is the up-front cost is a yearly cost, no different than later yearly costs in operational years, and that having the capability is the main goal (with less or no regard to encouraging others to copy or follow) then including up-front costs in a per launch or per kg view may be perceived to be of less use.

II. Productivity, Flight Rate and Yearly Capability

If the desire is to consider productivity, a flight rate capability or responsiveness for a system alongside costs, new perspectives beyond costs per kilogram are required. What is achieved in the bigger picture by a space launch industry? What capabilities have been demonstrated measured by the payload tonnage leaving Earth per year?

One way to visualize three variables at a time, cost, capability, and productivity (throughput), would be to use a bubble chart as shown in Figure 3. A 3rd variable, yearly payload capability can be measured for major industry players. This would be the sum off all the payload capability that was launched on a family or system as a whole (all United Launch Alliance / ULA rockets, all Space Shuttle launches, etc.) over a year.

[8] Jeremy Hsu, "Total Cost of NASA's Space Shuttle Program: Nearly $200 Billion," *Space.com*, April 11, 2011, http://www.space.com/11358-nasa-space-shuttle-program-cost-30-years.html (last visited May 28, 2014)
"The average cost per launch was about $1.2 billion (in 2010 dollars) during the shuttle's operational years from 1982 to 2010. But it rises to $1.5 billion per flight when factoring in lifetime program costs, according to the new analysis, which covered the 131 shuttle missions flown between 1982 and 2010."

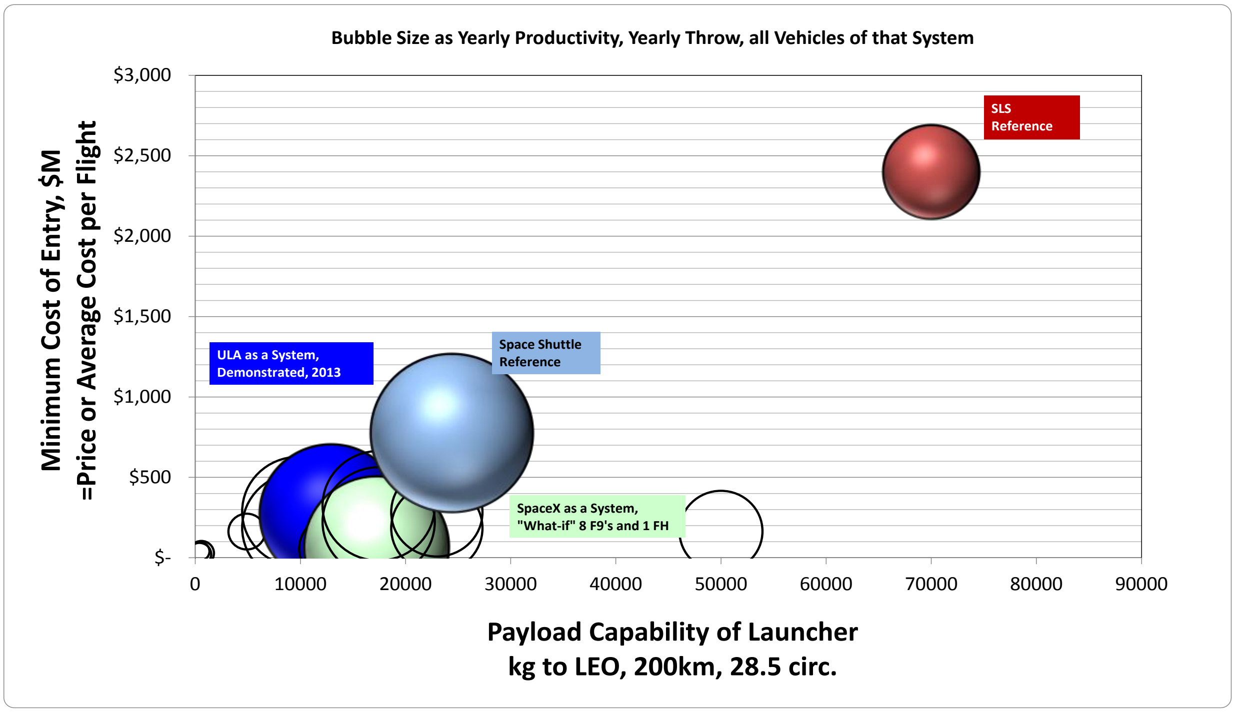


Figure 3: Using a bubble chart to show three variables; average payload capability of a system of launchers, the average cost of entry (or price to a customer), and the total tonnage capability deployed over a recent calendar year, as bubble size.

Caveats apply to such a view:

1. Capability vs. Actual Utilization: The total “capability” of a single launcher may not be fully used by the payload customer for assorted reasons. As a result, the actual delivered payload masses to orbit over time will always be less than the sum of the capabilities advertised for any configuration. A payload may be just too large for a smaller vehicle. Other factors such as price or reliability may have influenced a vehicle choice. A payloads size may also have been driven by factors other than the eventual vehicle (if known). Launchers only come in steps of capability, within a certain range of sizes, and so on.

2. Uncertainties: There are abundant uncertainties in a tonnage measure for US launcher productivity. The SLS has not yet flown, for example. The Shuttle point is a very different point (crew, cargo, payloads, labs, etc.) than the “payloads” in expendable systems. It has been included as reference, treated again as before. SpaceX has only begun regular launches. Though SpaceX has taken about the same amount of time between their 1st and 9th launch of Falcon 9, as Lockheed did with Atlas between their 1st and 9th launch (1,414 vs. 1,660 days resp.) more data over the next couple of years should allow more definitive comparisons.

On the observation about comparing apples, a crewed launcher such as the Space Shuttle, to oranges, un-crewed vehicles, such as Delta IV, Antares, etc., a useful productivity measure for crew has been observed in summaries of the Space Shuttle’s accomplishments. The data in Figure 1 shows a measure of value to a human spaceflight customer, a person day in space, while comparing only among launchers that carried crew. Mixing crewed and un-crewed launchers, as in Figure 3, because the comparison begs to be tried, should keep such caveats in mind.

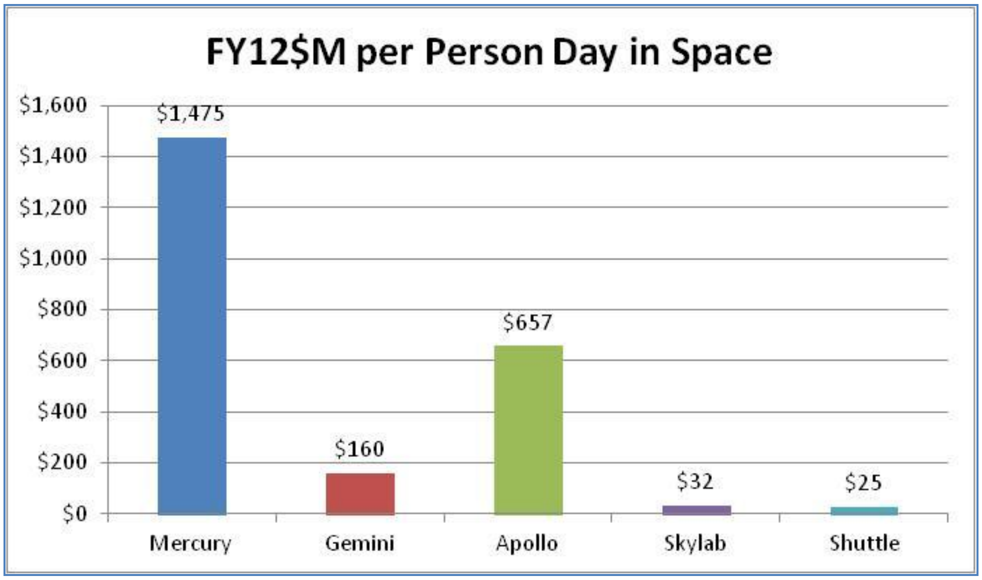


Figure 4: Courtesy Andy Prince, "Human Spaceflight Value Study, Was the Shuttle a Good Deal?" NASA Cost Symposium, 2012.

III. Competitiveness

"Commercial" launches have drawn a great degree of attention after the end of the Cold War. There are assorted definitions of a "commercial" launch. In FAA parlance, a commercial launch is "internationally competed or FAA-licensed[9]" (with the "or" definition leading to denoting an Antares and Cygnus and a Falcon 9 and Dragon ISS supply run as commercial). In NASAs use of the term "commercial" the idea of competition plus some other relationship (here contract type, rather than a license) also surfaces, but across a spectrum. An item can be more or less commercial to NASA along the spectrum shown in Figure 5. The confusion that occurs often where "commercial" is misunderstood to be merely any participant from the private sector is clarified here by thinking of the spectrum of activities which have more or less of these two ingredients. In this way any two activities can be compared more easily as one being more or less commercial that the other, by thinking relative to each other's having more or less of the ingredients from the definition.

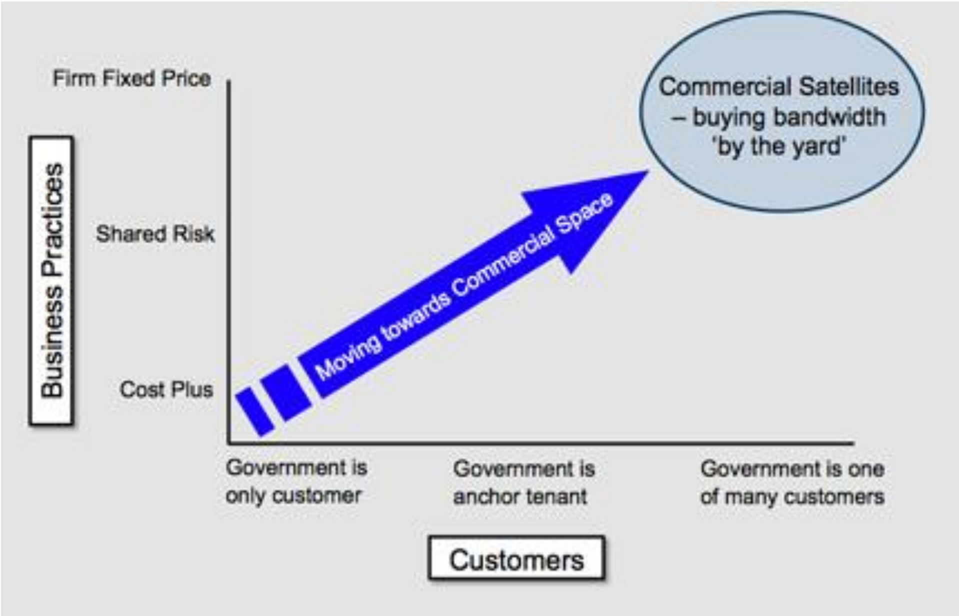


Figure 5: What is "commercial[10]" space to NASA?

This market for launches that may be competed internationally (or at the least fairly competed nationally within a competitive field), or purchased at arms-length, for government or non-government customers, as a fixed price service, as one would expect in a maturing market, is still small. The total here has hovered around 20 launches a year for some time. One recent shift is an emerging US commercial competitiveness as shown in 2013 in Figure 6. This uptick in recent US competitiveness is promising. More importantly, it remains to be seen if the market will actually grow, meaning some change in costs, or other factors unknown, that goes beyond just a particular customer substituting rocket X for rocket Y. While every win by a launcher's country of origin will be cheered on by that country, global market growth is a different matter.

[9] FAA, "Commercial Space Transportation 2013 Year in Review," http://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/year_review/ (last visited May 28, 2014)

[10] NASA, http://www.nasa.gov/offices/oct/partnership/comm_space/ (last visited May 21, 2014)

Comparisons of US and foreign launchers have always been difficult, with most attempts devolving into comparisons of prices, contracts, etc. Prices are affected by exchange rates, costs of labor, and many other non-technical factors. When the US took the initial step in the mid-80's to allow US satellites aboard European launchers, this was considered necessary, and healthy competition[11]. Later, the introduction of competition from non-market economies (Russia, China, Ukraine) would bring difficulties that persist to this day.

If commercial launch market growth is to occur, and US launch systems and industry are to play a leadership role, prices (and metrics, either as per kg, or per launch, or for multiple customers on one launch, etc.) are usually expected to have to drop further. While a cost or price or a relationship to causes may be necessary to understand an industry better (as with this paper), a satellite customer can be expected to have little interest in weather a price is driven by exchange rates, a regions labor rates, improved design or technology, or an efficient business organization. With this in mind, one further way to measure how "commercial" an activity is becoming could be through understanding the ingredients that will drive prices down enough, to a point where market growth goes up.

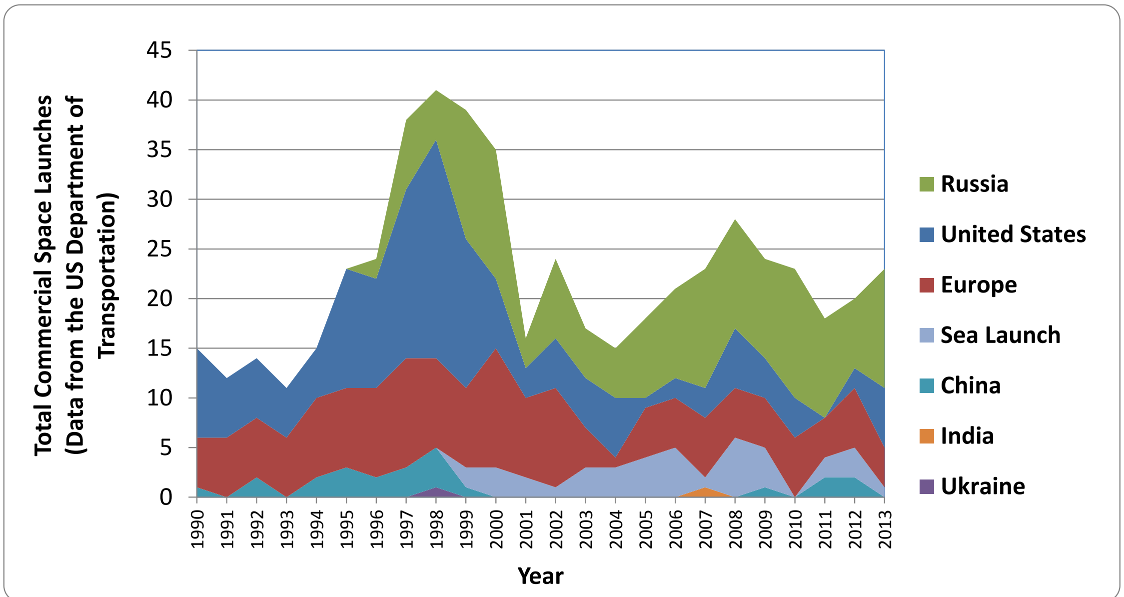


Figure 6: Worldwide Commercial Space Launches[12].

[11] Victor Zaborsky, "Economics vs. Non-Proliferation, US Launch Quota Policy Toward Russia, Ukraine and China," *The Nonproliferation Review*, Fall-Winter 2000, http://cns.miis.edu/npr/pdfs/73zabor.pdf (last visited May 29, 2014)

[12] Graph created from raw data at the Department of Transportation for launches through 2012, http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_39.html (last visited May 29, 2014), plus 2013 data from the Federal Aviation Administration, "Commercial Space Transportation 2013 Year in Review," http://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/year_review/ (last visited May 29, 2014)

Table 1 shows what some of the key ingredients may be for more commercial activity in the launch business, here from the point of view of a government (or NASA) as a customer, partner or co-investor.

Table 1: Basic ingredients for a space exploration element (launch, spacecraft, habitat, etc.) being more commercial[13]. The more these ingredients are captured, the more commercial the element is.

Ingredient	Rationale
Product development and use, amortizing costs	The business case depends on having non-government customers. The product for the government is developed with non-government customers in mind. The product or service is also provided to non-government customers.
Contracts	The government uses firm fixed price type of contracts.
Efficiency	Provider applies mostly commercial best practices. These practices or “how” are outputs. Capability, performance, safety, and cost goals are inputs.
Incentives	Multiple suppliers (industry) and multiple buyers (government and non-government) rationalize incentives, leading to success even when many requirements (performance, safety, cost) appear at odds. No monopoly (single provider) or monopsony (single buyer).

It is natural to think some tipping point, some cost per kg, might cause a dramatic increase in the commercial launch market of larger satellites, or that smaller but very capable satellites would feed this trend, or that the technology to build satellites more cheaply would stimulate market growth. With Russian Protons at about 4,445$/kg[14] or Falcon 9’s at $4,297/kg[15], the customer view of costs may be “around $4,000/kg on some rocket”. Endless debate about the magic number on costs/kg or other factors (flight rate, packaging, services, bundling, etc.) that will cause launch services market growth has been documented[16]. Of promise, but still to be proven over the long run, and over flights per year, as well as generating demand in its size range, the first contracted Falcon Heavy launch would yield a cost/kg of only $3,300/kg[17]. The later comes tantalizingly close to the mythical “$1000 dollars per pound” often considered encouraging of market growth.

[13] Whitehouse Fact Sheet on National Space Policy, http://www.whitehouse.gov/the-press-office/fact-sheet-national-space-policy (last visited June 2, 2014). The formal, actual definition of what is “commercial” is expressed in the current space policy: “The term “commercial,” for the purposes of this policy, refers to space goods, services, or activities provided by private sector enterprises that bear a reasonable portion of the investment risk and responsibility for the activity, operate in accordance with typical market-based incentives for controlling cost and optimizing return on investment, and have the legal capacity to offer these goods or services to existing or potential nongovernmental customers.”

[14] Federal Aviation Administration, “Commercial Space Transportation, 2010 Year in Review,” https://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/year_review/ (last visited May 29, 2010).

Taking the $100M launch cost of the Proton M, capable of placing a 22,000kg payload into low Earth orbit, yields the value of $4,545/kg.

[15] SpaceX, http://www.spacex.com/falcon9, (last visited May 29, 2014).

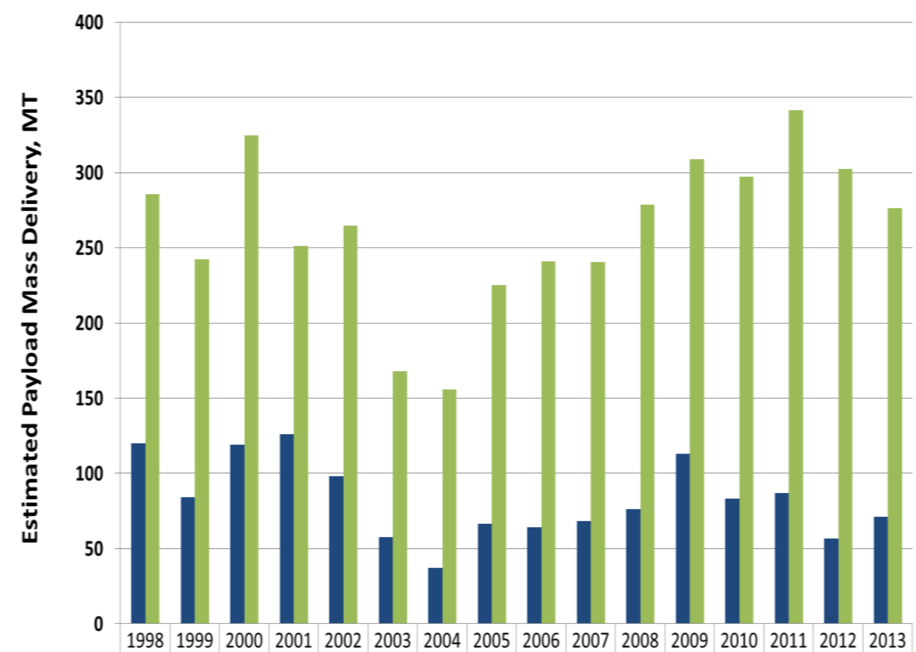
Taking the price of $56.5M for the launch of 13,150kg to low Earth orbit, yields a value of $4,297/kg.

[16] Commercial Space Transportation Study of 1994, http://www.hq.nasa.gov/webaccess/CommSpaceTrans/ (last visited May 29, 2014). This was among the first and most comprehensive studies into launch market elasticity, the ability of low prices to cause market growth. “We have not been able to prove the commercial space market elastic enough to enable the revenues per flight to be greater than the combined payback and operations costs per flight for a completely commercially developed system.”

[17] Stephen Clark, “SpaceX books first two launches with U.S. military,” *Spaceflight.com*, December 6, 2012, http://spaceflightnow.com/news/n1212/06spacexdod/ (last visited May 29, 2014).

Taking the $165M price assuming a payload capability of 50,000kg yields the $3,300/kg.

Inevitably, after seeing individual launcher measures such as cost/kg, or capability of these over a year, or comparing just numbers of certain launches among global players, the question arises about actual tonnage delivered. Payload masses are always less, sometimes very much so, than launch vehicle capability to any orbit. Such a view considering vehicle payload utilization is shown in Figure 7.



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
U.S. Space Payload Mass Deliverd (MT/Yr)	120	84	119	126	98	58	37	66	64	68	76	113	83	87	57	71
World Space Payload Mass Delivered (MT/Yr)	285	242	325	251	264	168	156	225	241	241	278	309	297	341	302	276

Figure 7: A view combining the launch record with estimated actual payload masses[18].

Naturally such a view reflects how prices per launch or per unit of mass must be higher than advertised when considering, by way of analogy, how full a truck actually was on any run.

IV. Direct vs. Indirect Costs

Measures of space launch affordability, productivity, competitiveness, utilization or related measures inevitably enter into cause and effect. A start to understanding the relationship for launch vehicles among many factors, technical and non-technical, is to ask "where" costs arise. Knowing what comprises costs should help answer what causes costs. These concepts (comprising, where costs are, and causing, why these costs arise) are distinct.

It is known that the farther an aerospace industry process is from the final product, the more those processes make up most of the costs of that product. For example, in the aerospace industry from the early 1970's to the early 1990's:

> "Overhead costs were neither visible nor understood, so common practice was to use poorly documented (sometimes proprietary) factors to "burden" the labor estimates. The practice has persisted, even though direct manufacturing labor has nearly disappeared as a cost driver, and overhead has grown to represent more than half the cost of defense systems, and may rise to represent two-thirds of these costs.[19]"

[18] The data here has been compiled from two main sources: (1) FAA Commercial Space Transportation, Year in Review reports, http://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/year_review/ (last visited June 2, 2014) and (2) Payload launch masses estimated from SpaceLaunchReport.com, www.spacelaunchreport.com (last visited June 2, 2014).

[19] James McCullough, Stephen Balut, "Trends in a Sample of Defense Aircraft Contractors Costs," 1991, http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA225663 (last visited June 2, 2014)

There is abundant evidence in the launch business that “where” costs are, or what comprises costs as a category, would usually be far away from visible activity at the product deliverable. These indirect, or overhead[20] costs in industry, and their growth, have been noted for decades. The temptation to cut back on what is visible, or direct, such as focusing on materials[21], can be shown to be only the smallest part of understanding affordability. As recently as 2011 it was noted that “about three-quarters of the 84 recommendations in the EELV [Evolved Expendable Launch Vehicle] program should-cost review are associated with overhead and indirect costs[22]”.

While a treatment of what comprises costs in detail, versus what causes or drives costs, are two distinct concepts beyond the scope of this paper, models have been proposed that integrate the “where” of direct vs. indirect costs, the direct outcome of productivity and flight rate, and the “why” driving these[23]. In general the question of what causes costs is hampered by a lack of good data as already noted, but at the proper level of detail a notion of weak and strong linkages at least begins to properly distinguish “where” from “why”. Distinguishing the “why” of cost drivers (causes of costs) from merely “where” (what comprises cost) is a necessary first step to understanding launch vehicle affordability and productivity.

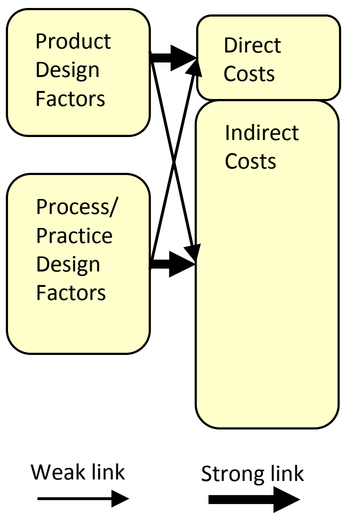


Figure 8: Technical product design factors (“what”; such as a number of parts, or different fluids, or the type of fluid, and reliability, etc.) distinguished from non-technical process factors (“how”; such as development practices, the flow of information, manufacturing steps, etc.)

[20] Jeffrey G. Miller, Thomas E. Vollmann, “The Hidden Factory,” September 1985, http://hbr.org/1985/09/the-hidden-factory/ar/1 (last visited June 2, 2104)

[21] Paul D. Collopy, Richard Curran, “The Challenge of Modeling Cost,” *1st International Conference on Innovation and Integration in Aerospace Sciences*, http://vddi.org/cost-solution.pdf (last visited June 2, 2014).
“Consider that, in 1996, according to The Boeing Company website, the list price of the Boeing 777-200 was $110 million. The empty weight of the aircraft was 314,300 lbs. (US Bureau of Mines Mineral Yearbook) The price per pound was therefore about $350. Titanium is one of the more expensive materials used in the aircraft. The cost of raw titanium (sponge) varies widely, but a typical value is $5 per pound (US Bureau of Mines Mineral Yearbook). Thus, if the whole aircraft were made of titanium, raw material cost would be less than 1.5% of price, easily less than 2% of manufacturing cost.”

[22] Amy Butler, “USAF Eyes Overhead In Sweeping EELV Cost Reviews,” *Aviation Week*, May 6, 2011, http://aviationweek.com/awin/usaf-eyes-overhead-sweeping-eelv-cost-reviews (last visited June 2, 2014)

[23] Edgar Zapata, “New Approaches in Reusable Booster System Life Cycle Cost Modeling", Joint Army Navy NASA Air Force (JANNAF) conference, May 2013, http://science.ksc.nasa.gov/shuttle/nexgen/Nexgen_Downloads/JANNAF_2013_Zapata_Presentation_w_footer.pdf (last visited June 2, 2014)

V. What is Needed?

To summarize, there are popular affordability metrics and figures-of-merit (such as cost-per-pound) that can be calculated and construed in many different ways, depending on the economic viewpoint of the observer. What information is still needed to discriminate *cost-per-pound of launch vehicle payload capability* from, say *cost-per-pound of payload actually delivered* in an investment period? In other words, if information that relates costs to productivity remains unavailable to technologists, for instance, what specifically, then, is needed? Both cost and productivity information must be related in two critical areas for aerospace and propulsion systems technologists to provide substantive improvements. In particular:

A. Recurring Production and Supply Chain Cost-per-Pound Contribution; specifically,
- Annual Production and Supply Chain Costs as a function of Unit Production Rate

B. Recurring Operations (both flight and ground) Cost-per-Pound Contribution
- Annual Operations Costs as a function of delivery (flight) rate

Where contemporary technologists can help the most is in understanding how to act on problem areas other than where the flight mass concentrates. The systems designer and technology communities should demand greater knowledge of where recurring production infrastructure can be improved, as well as what can improve production responsiveness, and by how much.[24]

Similarly, the community needs to know where specific operations and support functions can be reduced by design of the flight system and through greater attention to investments in this area than are normally given during the marketing and initial design of a launch vehicle, for instance.[25,26,27,28,29]

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[24] Zapata, E., McCleskey, C., Martin, J., Lepsch, R., Hernani, T., Life Cycle Analysis of Dedicated Non-Launch Technologies, 2014 Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), 23 – 26 June at the Von Braun Center in Huntsville, AL

[25] Wong, G. S., Zeis, J. M., Farhangi, S., Operationally Efficient Propulsion Systems Study Data Book, Vol. IV—OEPSS Design Concepts, RI/RD90-149-4, NASA Kennedy Space Center April 24, 1990.

[26] Robinson, J. W., et al, Advanced Space Transportation Concepts and Propulsion Technologies for a New Delivery Paradigm, AIAA 2013-3803, 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 15-17 July 2013, San Jose, California.

[27] Joyner II, C., Levack, D., Rhodes, R., and Robinson, J., "Propulsion System Choices and Their Implications", AIAA-2010-6504. 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Nashville, Tennessee, July 25-28, 2010.

[28] Garcia, J, *et al*, ―A Systems Approach to Developing an Affordable Space Ground Transportation Architecture using a Commonality Approach,‖ 48th Joint Propulsion Conference; Atlanta, Georgia, August 1, 2012.

[29] McCleskey, C. M., Rhodes, R. E., Chen, T. T., and Robinson, J. W., ―High-Payoff Space Transportation Design Approach with a Technology Integration Strategy,‖ Technical paper AIAA 2011-5571, presented at 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Diego, California, 31 July - 03 August 2011.

VI. Closing

In closing, understanding affordability and flight rate measures from different viewpoints, objectively, is critical to the US launcher industry if these measures are to see improvement. NASA plans in spaceflight and space exploration, even as pioneering[30], must add-up within foreseeable budgets that depend on such improvements. Barring significant budget increases, the affordability and productivity of US launchers is a critical variable in any planning that wants to go further, faster, for longer.

By way of a basic model, if transportation draws some percent of all the NASA budget resources available today, any desire to go further, for longer, has only a handful of variables to trade. These variables are affordability, flight rate, and time. Lowering flight rate, or extending a schedule (particularly in development) can only go so far. Timelines may only go so far before results are so far away as to risk stakeholder support in the near term. Flight rates can only go so low before these too reach a zero lower bound (or some point at which no further advantage in yearly cost is gained by lowering flight rate). This leaves launcher affordability to contend with. Notionally this is shown in Figure 9 to include eventually in-space transportation elements (upper stages, spacecraft, etc.)

Some objective measures and an understanding of cost relationships have been presented. Government and industry stakeholders are encouraged to further the work here, with improvements in the assortment of measures and analysis provided.

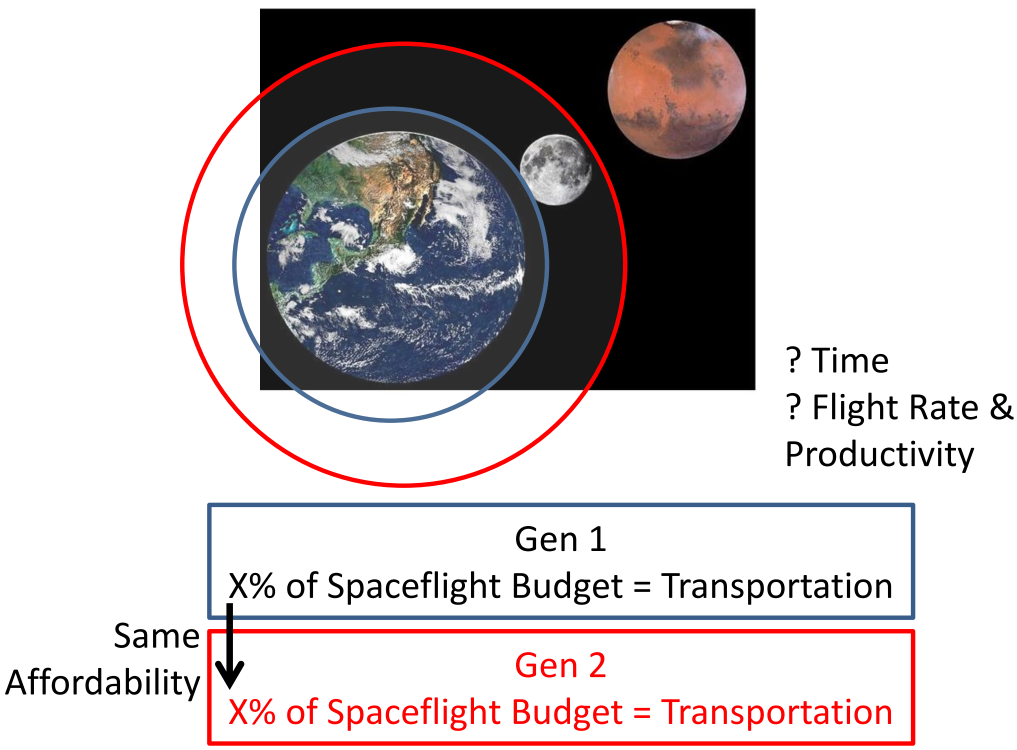

Figure 9: If some fixed resource is dedicated to launch, and a business or government enterprise also wants to go further, for longer, then launcher/transportation affordability must significantly improve.

[30] NASA, "Pioneering Space: NASA's Next Steps on the Path to Mars," May 29, 2014, http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf (last visited June 2, 2014)