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System Value Model of a Launch Vehicle

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Abstract

System Value provides a mathematical representation of stakeholder's preferences for the system. System value represents the utility that the system provides to the stakeholders. For a launch vehicle, important values are revenue generated through successful payloads, mission reliability, and the ability to accommodate payloads without modification to the payload instruments or spacecraft bus. This paper considers the value provided by a heavy lift launch vehicle to the satellite industry and to human exploration. An estimate is developed for a generic launch vehicle value in terms of impact to the Gross Domestic Product. Thermo-economics are applied in the calculation of system value. Mission reliability considers both successful delivery and on time delivery (i.e., operational availability). Payload accommodation considers mainly the diameter of the payload fairing for various types of missions.

Keywords: Gross Domestic Product, Launch Vehicle, Mission Reliability, Operational Availability, Payload Accommodation, Satellite, System Value, Thermo-Economics

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1. Launch Vehicle Value

The value provided by a launch vehicle provides critical information enabling the system design to be compared to the expectations of the stakeholders. The value model allows project managers and engineers to see the benefits of different types of missions that utilize the launch vehicle, the value of various attributes of the launch vehicle capabilities, and the overall value of the benefits provided by the launch vehicle. This can help resolve conflicting preferences between different stakeholders or between stakeholders and the development organizations expectations.

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Nomenclature

MTBF= Mean Time between Failures
MAT= Maintenance Access Time
MTTR= Mean Time to repair
$\dot{C}_T = total\ annual\ cost\ of\ the\ launch\ vehicle$
$c_{ei} = unit\ cost\ of\ external\ exergy\ inputs$
$\dot{\in}_\iota = annual\ exergy\ input\ from\ external\ sources$
$\dot{Z}_n$ = Annual zonal cost of capital expenditure and other associated costs
V= Value of the launch vehicle
$V_1 = Value\ of\ the\ launch\ vehicle\ thermodynamic\ efficiency$
$V_2 = Value\ of\ mission\ reliability$
$V_3 = Value\ of\ fairing\ geometry$
$V_L = Mission\ value\ lost$
$L_R = launch\ rate$

The launch vehicle attributes can be determined by analyzing the concept of operations document. A system attribute is a quality of the system that directly impacts the value of the system. For a launch vehicle, these are the attributes that effect the benefits of the supported missions. The attributes of a launch vehicle are cost, mission reliability, maintainability, launch availability, launch rate, launch vehicle thermodynamic efficiency, and fairing geometry. The attribute of cost is total cost of the system (manufacture, design, and launch) and it is the attribute that links all of the others together (see fig. 1). Mission reliability is the percentage number which takes into account the successful launch of the launch vehicle, the successful achievement of the ascent target, and the successful achievement of the payload mission. The launch rate is the number of launches per year. The launch rate is driven by planetary windows, and commercial business needs.

Launch availability can be calculated using a Discrete Event Simulation (DES). The system simulation takes into account the various factors affecting the launch vehicles ability to launch as planned. These factors include weather, range safety, launch vehicle subsystem failures and repair, maintenance operations, and the ability to have the vehicle at the launch pad based on manufacturing and assembly schedules.

The relationships between the attributes, whether they are independent or dependent of each other, and how important each attribute is to the overall system is illustrated in Fig. 1. This model indicates mission reliability is dependent on launch availability.

2. Thermo-Economics

Thermo-economics is based on calculating the cost of the system based on the system thermodynamics. Thermo-economics integrates the laws of thermodynamics with economic theory. Thermo-economics states that the total annual cost of inputs, and the total annual capital expenditures of a system can be added together to calculate a system's cost per year. The cost relationship for a launch vehicle is defined by Equations (1) – (8). These equations are based on the manufacturing base producing multiple discrete units, not a continuous flow of products (like gasses or liquids) and not a single unit (such as a building).[i]

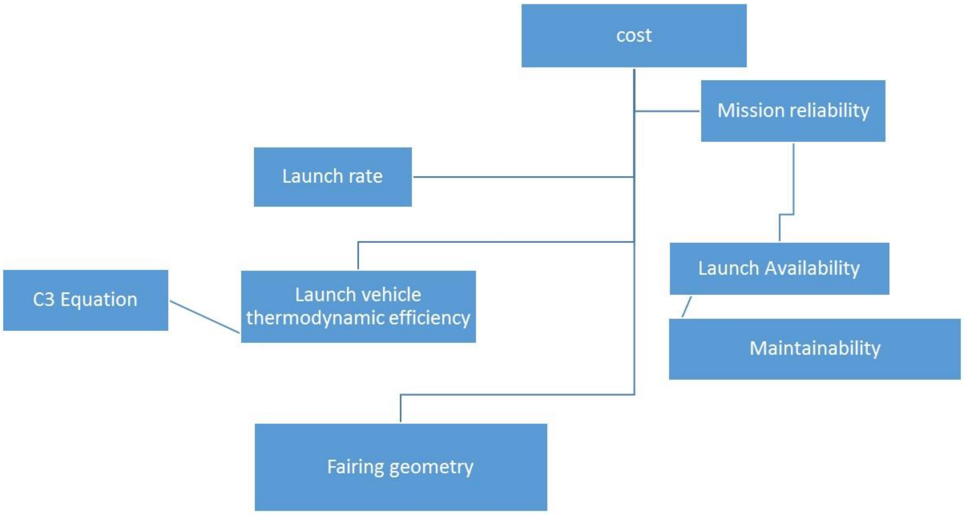


Fig. 1. Launch Vehicle Attributes Related to System Value

$$\dot{C}_T = \sum_i c_{ei} \, \dot{\in}_\iota + \sum_n \dot{Z}_n \tag{1}$$

The components (c_{ei} and $\dot{\in}_\iota$) of the objective function are defined as,

$$c_{ei} = \frac{\$}{J}, \tag{2}$$

$$\dot{\in}_\iota = \frac{J}{yr}. \tag{3}$$

For a rocket, the cost and exergy terms relate to the propellant cost and energy provided during combustion,

$$c_{ei} = \frac{\frac{\$}{kg}}{J/kg} \rightarrow \left(\frac{propellant\ cost}{exergy}\right) = \$/J \tag{4}$$

$$\dot{\in}_\iota = \frac{kg}{yr}\left(\frac{J}{kg}\right) \rightarrow \left(\frac{mass}{year}\right) * HHV = \frac{J}{yr}. \tag{5}$$

Z_n is based on both the unit cost and the manufacturing base cost each year.

$$\dot{Z}_n = \frac{\$}{yr} \rightarrow \frac{unit\ cost + manufactoring\ base\ cost}{yr} \tag{6}$$

where

$$\frac{unit\ cost}{yr} = L_R * unit\ cost. \tag{7}$$

Therefore

$$\dot{Z}_n = L_R * unit\ cost + \frac{manufactoring\ base\ cost}{yr}. \tag{8}$$

3. Mission Reliability

Reliability, Availability, and Maintainability (RAM)[ii] are also important factors in the value of the launch vehicle to the stake holders. Operational availability, A_0, is defined as:

$$A_O = \text{MTBF/(MTBF+M).} \tag{9}$$

$$A_O = \frac{Uptime}{Downtime}. \tag{10}$$

A_0 is used when considering the effects of both the design and the support system on availability. The equations used for launch reliability, flight reliability and maintainability are the classical definitions:

$$R_{flight} = \frac{\#\ successes}{\#\ missions} \tag{11}$$

And

$$R_{launch} = \frac{\text{\#successful launches}}{\#\ Launch\ Attempts}. \tag{12}$$

The maintainability for a launch vehicle is defined as

$$\text{M = MTTR+MAT.} \tag{13}$$

The overall mission Reliability can thus be defined for a launch vehicle as,

$$R_{mission}\ (R_m) = R_{launch} * A_O * R_{flight}. \tag{14}$$

4. Revenue Value

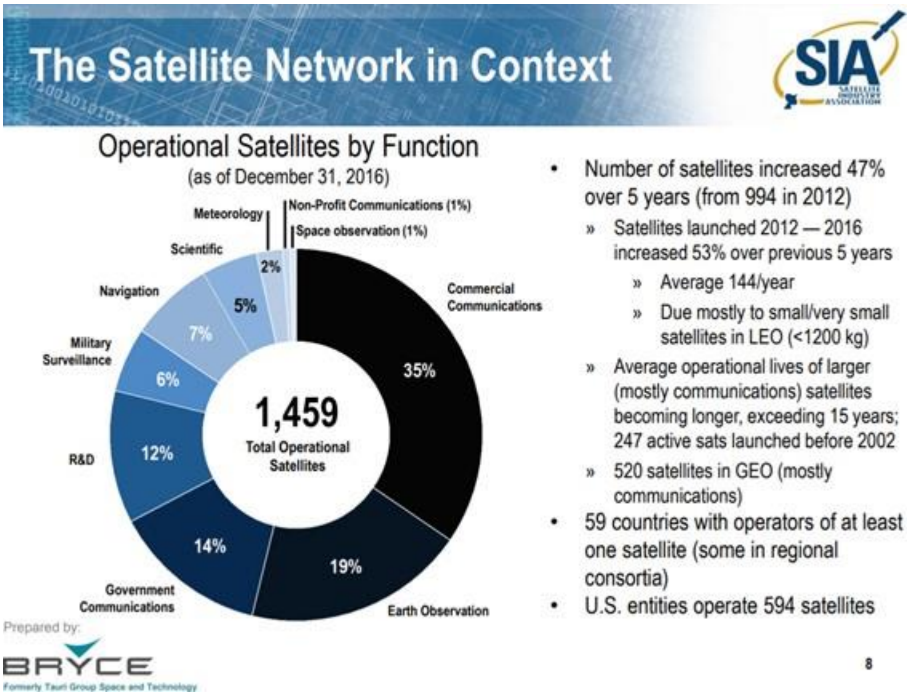
Launch vehicle missions can be crewed or cargo missions. Launching satellites into Earth orbit is a standard launch vehicle cargo mission. The launch vehicle benefits for a satellite can be determined based on values provided by the Satellite Industry Association (SIA) and published in their annual report for the preceding year[iii]. The values in the report do not account for inflation rates and so must be adjusted for inflation.

$$Revenue = P(1+i)^n. \tag{15}$$

Considering a launch vehicle example, there are 3 preferences considered for a launch vehicle (there may be others beyond those considered in this example). These are revenue, mission reliability, and payload capacity. A heavy lift launch vehicle is considered here with a flight rate of 2/year.

The first preference considered is the revenue that can be obtained from use of the launch vehicle to perform certain missions. Cargo missions are a large portion of the current launch vehicle market, placing satellites in orbit for various purposes. Satellite revenue for 2016 was P=\$127.7 billion. With the average annual inflation rate serving as the interest rate, i =2.22% , the actual revenue is \$130.5 billion in 2017 \$ (n = 1). Using the percentages shown in Fig. 2, the values in Table 1 were calculated by multiplying the total revenue of \$130.5 by the percentage of the selected functions. The earth observation percentage of 19% was used to determine the monetary value for optical sensing. Interplanetary mission value was assumed to be 5% of the scientific function. The benefit of the astronomical telescope was based on the value of space observation (1%). The value of the payloads for the satellite and launch vehicle missions represent the benefits of the missions minus the cost of the missions.

Fig. 2. 2017 Satellite Industry Report Satellite Mission Type Distribution



The Satellite Network in Context

Operational Satellites by Function

(as of December 31, 2016)

- Number of satellites increased 47% over 5 years (from 994 in 2012)
  - » Satellites launched 2012 — 2016 increased 53% over previous 5 years
    - » Average 144/year
    - » Due mostly to small/very small satellites in LEO (<1200 kg)
  - » Average operational lives of larger (mostly communications) satellites becoming longer, exceeding 15 years; 247 active sats launched before 2002
  - » 520 satellites in GEO (mostly communications)
- 59 countries with operators of at least one satellite (some in regional consortia)
- U.S. entities operate 594 satellites

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Table 1. Value of Satellite Benefits

Table 2 shows the benefits for different types of missions. The scientific benefit was calculated taking the sum of the monetary value from optical sensing, interplanetary missions, and astronomical telescopes in Table 1. The benefit of commercial services is the same as commercial communications shown in Fig. 1. The resource mining benefit is the profit from one tungsten mine (a mineral that has high potential in planetary and asteroid mining). The benefit of human exploration was calculated by taking percentage estimates from the U.S. gross domestic product (GDP) as broken down in Table 3. The premise, is that human exploration provides value in several different ways that feed growth in the national GDP. Table 3 shows the calculation of the benefit of human exploration. The total benefit for human exploration is the sum of the four components.

Table 2. Launch Vehicle Benefits for Various Mission Types

Launch Vehicle Benefits	$ Value
Scientific	$326,337,350,000.00
Commercial Services	$456,872,290,000.00
Resource Mining	$6,161,582.33
Human Exploration	$5,877,600,000,000.00

Table 3. Human Exploration Benefits to the United States Economy

Human Exploration:		(measured by using % of US GDP)		$ Value:
National Renown:		0.06	=	$ 1,116,000,000,000.00
Extended Science		0.1	=	$ 1,860,000,000,000.00
Technological Gains:		0.056	=	$ 1,041,600,000,000.00
Medical Advances:		0.1	=	$ 1,860,000,000,000.00

The following assumptions were used in the construction of the benefit of human exploration.

- The time reference for the human exploration benefit is 100 years, the given numbers are only estimates.
- National renown was chosen as 6% and was assumed to be the impact of the moon landing on the United States' political influence.
- Extended science and medical advancement are 10% assumed to be the possibility of a scientific breakthrough happening in the span of 100 years.
- The percentage for technological gains was chosen since as 2016 the internet's impact of the U.S. GDP is 5.62%

In order to calculate V_1 the value of C_t must be determined from Equations (1) – (8). The value of C_t is found from the launch vehicle stages propellant cost/mass (i.e., $/lbm or $/Kg) (e.g., liquid hydrogen, kerosene (RP-1), liquid oxygen, PBAN or HTPB). The Defense Logistics Agency has a standard price listing for various propellants.[iv]

The values of c_{ei} and $\in_i$ of each fuel type (liquid hydrogen, liquid oxygen, RP-1, and SRM propellant[v]) are found from Equations (4) and (5) using the appropriate values from Table 4. Z_n is calculated from Equation (8). Using the manufacturing base cost for a typical heavy launch vehicle and a flight rate of 2/year yields Z_n = 2.21 $B/yr. C_t is calculated from Equation (1) yielding a value of C_t as $2.26 $B/yr.

Table 4. $/kg values for Launch Vehicle Propellants

Propellant Cost, $/Kg	
Liquid Hydrogen	$4.63
Liquid Oxygen	$0.18
RP-1	$6.30
SRB Propellant	$37.48
Propellant Heating Value (HHV), J/Kg:	
H2, O2	141,800,000.00
RP-1	43,600,000.00
SRB Propellant	4,583,457.43

With the system cost, C_t, known the value of the launch vehicle, V_1, can be calculated by subtracting the launch vehicle benefit (shown individually in Table 2) from the launch vehicle cost, C_t. The benefits in Table 2 are used to provide 4 separate values for the launch vehicle as shown in Table 5. These calculations assume a flight rate of 2 per year with one flight being used in each category (i.e., Scientific, Commercial, Mining, Human Exploration) every two years. Note that the value of resource mining is negative indicating that one launch every two years to support a single mine is not valuable at the assumed benefit generated by the mine. Instead, it would take 366 tungsten mines in order to provide neutral value for one launch every two years. This indicates the mining of minerals on other solar system bodies would need to be on a planetary scale and not individually sustainable at current launch costs.

Table 5. Launch Vehicle Value

Launch Vehicle Value	=	Benefit -Ct
Value to Scientific Uses	=	$ 63,008,431,752.36
Value to Commerical Services	=	$ 20,584,576,252.36
Value to Resource Mining	=	$ (2,252,876,665.31)
Value to Human Exploration	=	$ 2,936,540,961,752.35
Total Value	=	$ 3,017,881,093,091.75

5. Mission Reliability Value

The second preference considered is the reliability of the launch vehicle to successfully complete the mission on the stakeholder's schedule. The value for mission reliability is calculated using Equation (14) using the values shown in Table 6.

Table 6. Launch Vehicle Mission Reliability

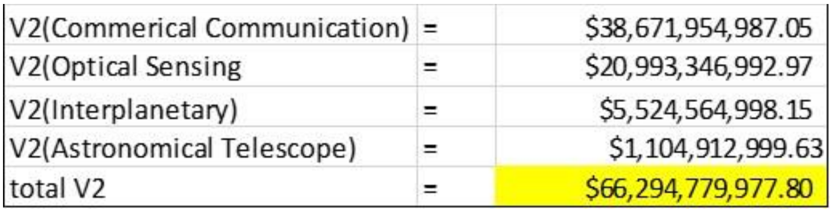
Parameter	Quantity
Launch Probability (R_{launch})	90%
Flight Reliability (R_{flight})	99%
Availability (A_0)	95%
Mission Reliability (R_m)	84.65%

Now that R_m is known, the value of the mission reliability, V_2, for each of the mission types in Table 2 can be calculated as,

$$V_2 = (R_m)(Value\ of\ Satellite\ Benefit) \tag{16}$$

Table 7 gives the value of mission reliability for each type of satellite mission and the total value for a mission reliability of 84.65% (on time and successfully deployed).

Table 7. Value of Mission Reliability for Satellite Mission Types



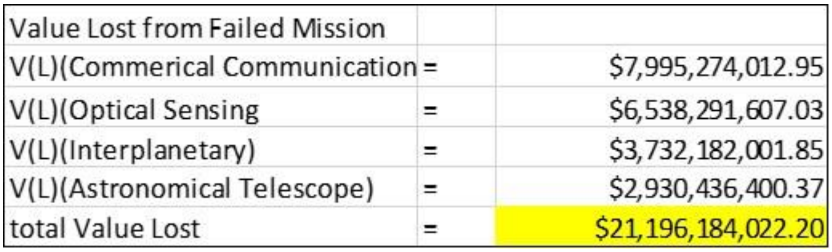
V2(Commerical Communication)	=	$38,671,954,987.05
V2(Optical Sensing	=	$20,993,346,992.97
V2(Interplanetary)	=	$5,524,564,998.15
V2(Astronomical Telescope)	=	$1,104,912,999.63
total V2	=	$66,294,779,977.80

Related to the value of successfully completing the mission as requested by the stakeholder, is the cost of the loss of the mission. The value of the loss is calculated as,

$$V_L = (1 - R_m)(Value\ of\ Satellite\ Benefit) + \text{Unit Cost} + \text{Satellite Cost.} \tag{17}$$

Table 8 shows the value lost for a mission not successfully completed. Not that this is not only the cost of the launch vehicle and satellite, but also the revenue and other aspects lost due to mission failure.

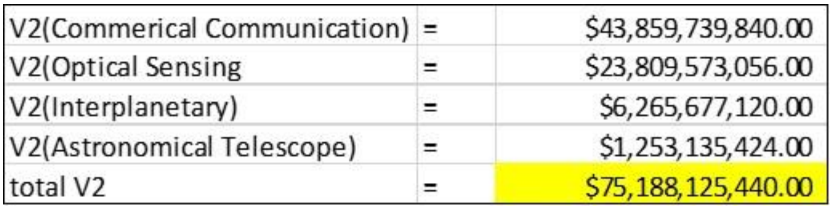
Table 8. Lost Value of Unsuccessful Satellite Missions



Value Lost from Failed Mission		
V(L)(Commerical Communication	=	$7,995,274,012.95
V(L)(Optical Sensing	=	$6,538,291,607.03
V(L)(Interplanetary)	=	$3,732,182,001.85
V(L)(Astronomical Telescope)	=	$2,930,436,400.37
total Value Lost	=	$21,196,184,022.20

The system value model can also help understand the difference that system reliability makes on the benefit provided by the system. For example, if mission reliability where increased from 84.65% to 96% the system value increases based on a higher benefit return. Table 9 shows the increase is system value when the mission reliability (on schedule and successfully) is increased to 96%. The value of the launch vehicle increases by $8,893,345,462. Thus an 11.35% increase in reliability yields almost $9B in increased value. This is an increase of $783,209,640.00 for every 1% reliability increase.

Table 9. Value of 96% Mission Reliability



V2(Commerical Communication)	=	$43,859,739,840.00
V2(Optical Sensing	=	$23,809,573,056.00
V2(Interplanetary)	=	$6,265,677,120.00
V2(Astronomical Telescope)	=	$1,253,135,424.00
total V2	=	$75,188,125,440.00

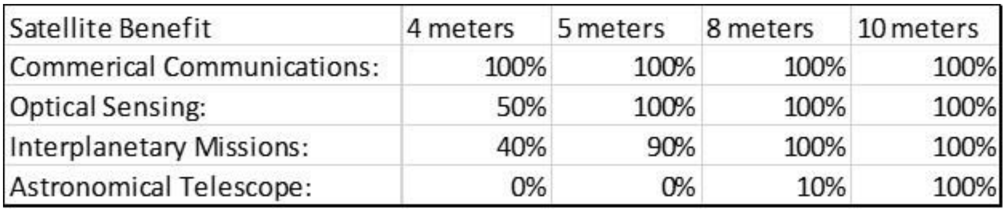
6. Payload Accommodation Value

The third preference considered is the value, V3, to accommodate larger diameter payloads. This is calculated looking at changes in fairing diameter. The change in the diameter enables a larger class of payloads to be accommodated such that the increased value in the larger payload is related to the diameter as shown in the relationship,

$$V_3 = \Delta diameter * \left(\frac{\Delta value\ of\ payload}{meter}\right). \tag{18}$$

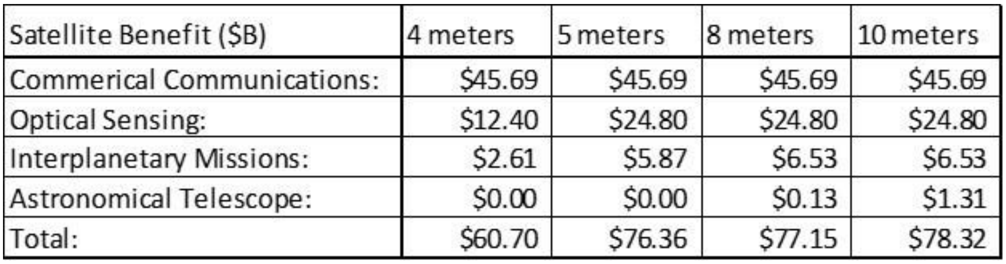
To evaluate the differences, value was calculated for 4 meter, 5 meter, 8 meter, and 10-meter payload fairing diameters. The 4-meter fairing is of value primarily to commercial communications. 40% of interplanetary satellites and 50% of optical sensing satellites are also assumed to be accommodated by this fairing diameter. The 5-meter fairing increases the value to the optical sensing satellites, providing room for larger monolithic mirror diameters. 90% of interplanetary mission are assumed to be accommodated by this larger fairing. Interplanetary missions gain benefit from an 8-meter fairing supporting the larger satellite dimensions when deploying landers or rovers. This fairing also allows for larger satellite busses to accommodate more instruments (and thus more measurements). 10% of the interplanetary satellites are assumed to benefit from this diameter. The 10-meter fairing is of most value to astronomical telescopes where large diameter monolithic mirrors are needed to reduce development costs and increase imaging capabilities for distance astronomical phenomena including identification of terrestrial planets around other stars. The value changes assume the larger fairings still provide the same value for the smaller satellites. Table 10 shows the percentage of satellite missions supported by the different fairing diameters. Table 11 shows the value of each fairing diameters to the various satellite mission types.

Table 10. Percentage of Satellite Market Supported by Different Fairing Sizes



Satellite Benefit	4 meters	5 meters	8 meters	10 meters
Commerical Communications:	100%	100%	100%	100%
Optical Sensing:	50%	100%	100%	100%
Interplanetary Missions:	40%	90%	100%	100%
Astronomical Telescope:	0%	0%	10%	100%

Table 11. Value to Satellite Market of Different Fairing Sizes



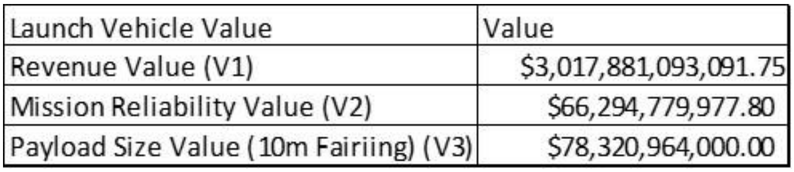
Satellite Benefit ($B)	4 meters	5 meters	8 meters	10 meters
Commerical Communications:	$45.69	$45.69	$45.69	$45.69
Optical Sensing:	$12.40	$24.80	$24.80	$24.80
Interplanetary Missions:	$2.61	$5.87	$6.53	$6.53
Astronomical Telescope:	$0.00	$0.00	$0.13	$1.31
Total:	$60.70	$76.36	$77.15	$78.32

Looking at the delta total values in Table 11, it is noted that the biggest value increase for the satellite market is from the 4-meter to the 5-meter fairing at a value of $15,664,192,800.00. The increase from 5-meters to 8-meters yielded a smaller increase of $783,209,649.00 (or $261,069,880/meter). The 10-meter fairing yielded an increase of $1,174,814,460 (or $587,407,230/meter). Thus, the 5-meter fairing has the most increase in value over the other fairing dimension. The 8-meter fairing has only a modest increase over the 5-meter fairing. The 10-meter fairing provides more value in total and in overall increase to the heavy lift launch vehicle has compared to the 8-meter fairing.

7. Summary

Table 12 gives the 3 preference values calculated for the heavy lift launch vehicle with a 10-meter fairing. Future research will consider weighting and the proper way to combine the value generated by each of the 3 preferences considered into a total value for the system. The weighting takes into account the importance of a specific system characteristics to the stakeholder. Properly combining the values must take into account the relationship of the system characteristics that are common across multiple value preferences (i.e., common to two or more of the values V_1, V_2, and V_3). This prevents unintentional inflating of the total system value when combining the preferences.

Table 12. Preference Values for a Heavy Lift Launch Vehicle with 10-meter Fairing



Launch Vehicle Value	Value
Revenue Value (V1)	$3,017,881,093,091.75
Mission Reliability Value (V2)	$66,294,779,977.80
Payload Size Value (10m Fairiing) (V3)	$78,320,964,000.00

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