Problem: Space Shuttle Problem: No More Space Shuttles

On July 21, 2011, the 135th and final US Space Shuttle landed in Florida after its 13-day mission into orbit, complete with a docking at the International Space Station (ISS). NASA will now have to rely on other nations or commercial endeavors to travel into space until a replacement vehicle is developed and constructed. Develop a comprehensive ten-year plan complete with costs, payloads, and flight schedules to maintain the ISS.

Some interesting facts possibly worthy of your consideration:

- The ISS is at full capacity with 6 astronauts, but can surge during shuttle docks to as high as 13.
- The ISS is scheduled to remain in service until at least the year 2020.
- Historically, transport to the ISS using US Shuttles has cost between $5000-10,000 per pound. Shuttle missions have lasted approximately 10-14 days in orbit. Missions on board the ISS typically last around six months.
- Recently, progress has been made within private industry to launch unmanned rockets into space.
- Russia is willing to launch US astronauts into space at a cost of about $60 million each.

High School Mathematical Contest in Modeling

Problem A: No More Space Shuttles

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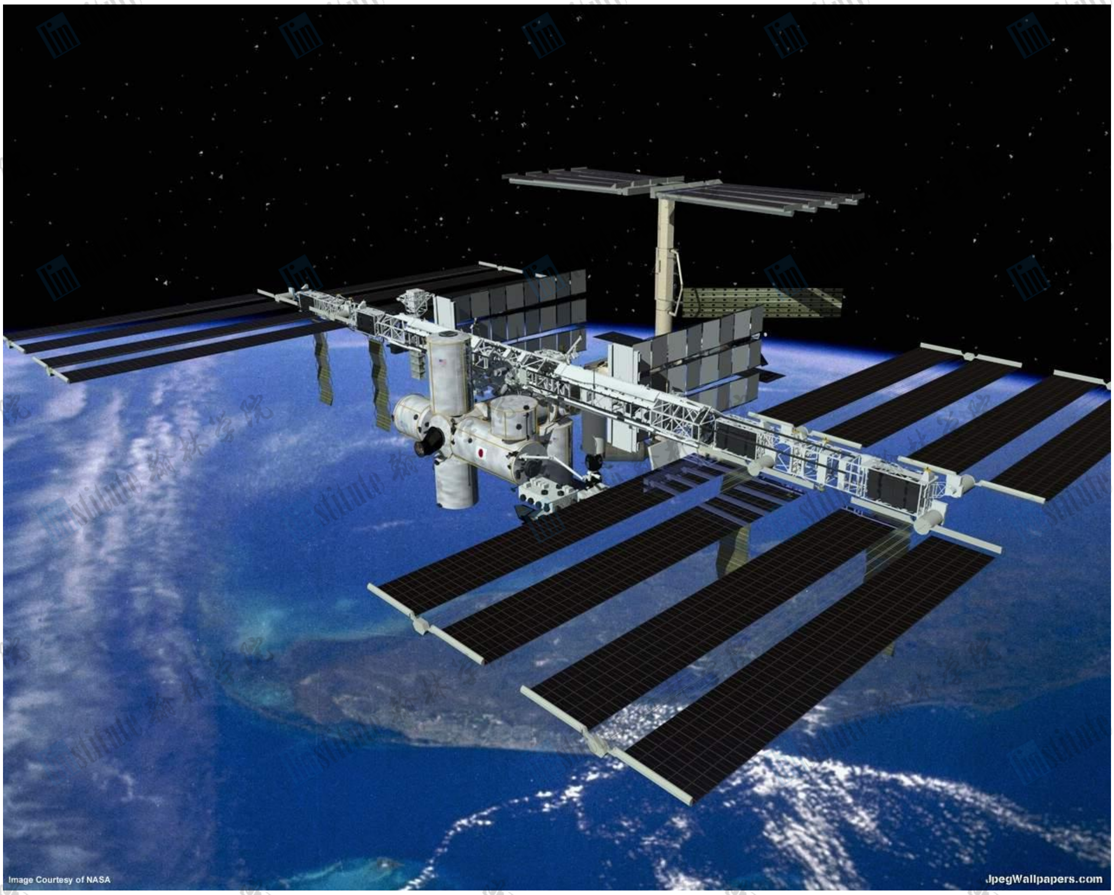

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Problem Summary

The International Space Station (ISS) is a satellite in low Earth orbit, where scientists since 1998 have been investigating the long-term effects of a zero gravity environment on humans. On July 21, 2011, the final US Space Shuttle landed in Florida. Historically, these space shuttles have been used to maintain the ISS, by bringing up additional modules and by having astronauts conduct routine spacewalks and repairs. Without the space shuttles, we need to find a way to continue maintaining the ISS. We will consider the funds appropriated by the US government and the various methods of taking astronauts up into space in order to develop a comprehensive plan to maintain the ISS until 2021.

Assumptions:

- Cost is the deciding factor in selecting the best option
- Reliability and payload conditions are not an issue in selecting private contractors; it is assumed that both are adequate before the brand is considered.
- National origins, political considerations and existing relationships with the various governments are not considerations in deciding choices.
- Launch prices of rockets remain consistent
- Cost of personnel is negligible
- 2.2 lbs = 1 kg. This conversion was used throughout our model to convert between units.
- Research cost is done separately, thus we don't have to consider it
- No non-incremental technological breakthroughs
- Trends are the same as current
- We have the authority to override NASA's existing plans
- Cost of each launch was included in the fiscal year that it docked in
- Dextre is included in the launch mass of Canadarm 2, therefore we do not have to find a separate mass of Dextre
- The payload of the docking spacecraft is proportional to the payload of the rocket; therefore we can compare rocket payload/price ratios in order to find the best choice, but still use the specifications of the docking spacecraft to more accurate calculate the final costs.
- Manned Dragon Spacecraft can also carry the same tonnage as unmanned Dragon spacecraft flights.

Glossary:

- Fiscal Year (FY): A set period for counting annual financial statements. For US government purposes, a fiscal year begins on October 1st of the previous calender year and ends on September 30th of the corresponding calender year. For example, FY 2012 goes from October 1st 2011 to September 30th 2012
- ISS: International Space Station
- Module: A large component that is attached to the main frame of the ISS
- NASA: National Aeronautics and Space Administration
- Payload: The amount in mass of cargo that a given rocket or spacecraft is delivering to its destination
- Spacecraft/Landing Craft (terms used interchangeably for our purposes): A smaller vessel launched by a separate rocket which in turn is capable of docking at the ISS and carrying the needed supplies

Background Research:

As a group, we initially started out by just trying to understand what the International Space Station (ISS) is, how it functions and all the "basics" that we needed to understand before attacking this problem. We compiled a list of guiding questions and answered them to acquaint ourselves with the problem we were faced with.

Q:	What is the ISS? What is its purpose?
A:	The ISS is a satellite in low Earth orbit, which normally houses six astronauts in a zero gravity environment. It was established to help scientists determine the long-term effects of a zero gravity environment on the human body—so the astronauts are the main test subjects. The ISS is almost completely done with construction, with only one module left to deliver up to space, due to be done in 2012. The ISS was established in 1998, and is expected to remain in operation until 2020, and possibly even until 2018.

Q:	What countries are involved with the ISS? Are they funding us (looking from NASA's perspective)?
A:	There are several countries involved with the ISS. Countries that are contracted with the ISS include Japan, Russia, Denmark, Sweden, Norway, France, Germany, Italy, Netherlands, Belgium, Switzerland, Spain, Canada and the US. Brazil used to be apart of this, but is no longer affiliated with the ISS. These countries will not provide any additional funding for us.

Q:	What is a "normal" mission?
A:	Soyuz missions are the Russian missions dealing with rotating astronauts, usually three at a time every six months. These missions are primarily concerned with the maintenance of the ISS. Space shuttle missions are typically eight to fourteen days long, and are more concerned with spacewalks, specific repairs and the addition of modules for the space station. Space shuttle missions are run by the US only. Astronauts that are brought up to the ISS are always from one of the contracted countries, but they are usually American or Russian.

Q:	How often does a space station need maintenance? What kind of maintenance does a space station need?
A:	Whenever astronauts are delivered up to the ISS, they conduct their routine maintenance duties. So there are routine check-ups every three months, when new astronauts are brought up to the ISS. However, aside from these general repairs, there are two irregular circumstances when urgent maintenance is required—software error and hardware malfunction. When there is software error, the ground control will fix it. When there is hardware malfunction, spacewalks are conducted. But either way, these costs are negligible in comparison to the overall scheme of things.

Q:	What is the "timeline" of the ISS? What is NASA's current ISS plan?
A:	The ISS was built in 1998, and NASA intends to keep the ISS in operation until at least 2020, possibly even 2028. They intend to use the ISS as a base for Mars expeditions in the future. The ISS is built by sending up additional modules built on Earth. These modules are typically assembled by various countries, but launched in the US. When the shuttles were decommissioned (due to safety reasons), all but one of the modules had already been attached to the ISS. This last module is produced and will be launched by Russia in 2012. This will complete the ISS.

Q:	What is the ISS plan for the future?
A:	Because the space shuttles were decommissioned, NASA has looked to commission private companies to supply them with spacecrafts to send up cargo and astronauts. NASA has commissioned two companies, Orbital Sciences and SpaceX, to send up payloads and astronauts for NASA in the period 2011-2015. There is no set plan after 2015. In response to a leaked email, Michael Griffin, OMB Officer, responded in a press conference, "We will take no action to preclude continued operation of the ISS past 2016." In a statement released July 2011 by the Russian Space Agency, Russia and its partners plan to plunge the ISS into the ocean after 2020. Their rationale behind such a radical move is because they don't want "space junk".

From these questions, we decided to look at this model from a three-pronged perspective. The first explored model will deal with NASA's existing plan for the ISS. The second explored model will deal with a business model, namely privatization of transport to ISS and optimization of its cost. The third explored model will deal with alternative approaches such as space elevators and space planes. We will assess the efficiency of these models, and come up with a summative 10-year plan, inclusive of costs, payloads and flight schedules.

Part 1: Baseline Projections

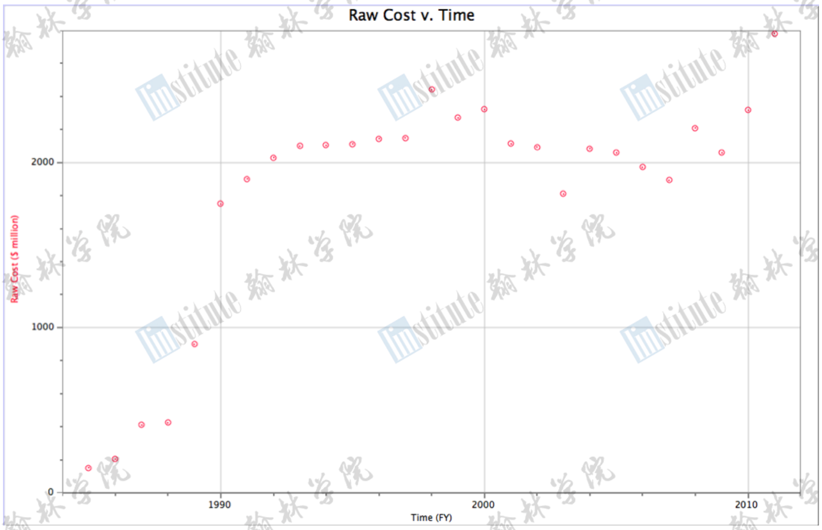
Part 1A: Transforming Raw to Adjusted Data

We decided that the first logical step to take would be to see how the US is appropriating their funds for the ISS. After researching, we obtained the data in regard to the fiscal years of US. We decided that the best way to represent this data was simply to graph it and observe a trend. The following tables and figures represent these numbers.

Table 1.1: Raw US ISS Funding Data ($ million)

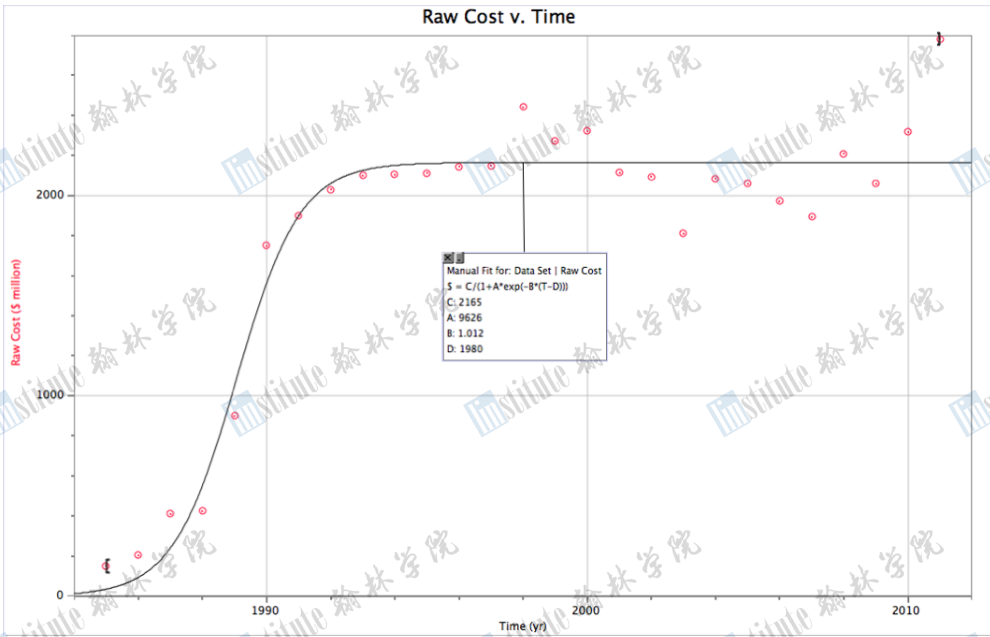
Fiscal Year	Request	Appropriated
1985	150	150
1986	230	205
1987	410	410
1988	767	425
1989	967	900
1990	2050	1750
1991	2430	1900
1992	2029	2029
1993	2250	2199
1994	2106	2106
1995	2113	2113
1996	2115	2144
1997	2149	2149
1998	2121	2441
1999	2270	2270
2000	2483	2323
2001	2115	2115
2002	2114	2093
2003	1839	1810
2004	2285	2085
2005	2412	2058
2006	1995	1972
2007	1894	1894
2008	1894	2209
2009	2060	2060
2010	2317	2317
2011	2780	2780

Figure 1.1: Raw Space Station Funding v. Year



After looking at this scatter plot of data, we decided that the best fit would probably be a logistic equation. This is because while other functions such as cubic functions or other polynomials will be able to more accurately interpolate, a logistic functions fits the logically expected overall trend; in which as the craft nears completion, the maintenance costs will stabilize. This equation was determined to be $y = \dfrac{2165}{1 + 9626\ e^{-1.012\,(x-1980\,)}}$ through a regression. This model is graphed in Figure 1.2, seen below.

Figure 1.2: Raw ISS Funding v. Fiscal Year (Logistics Curve)



Because this is a logistic regression, there is no correlation "R-squared" value available, and so we must rely on residuals and percentage error to determine accuracy of this model.

Figure 1.3: Residual Graph of Raw Data

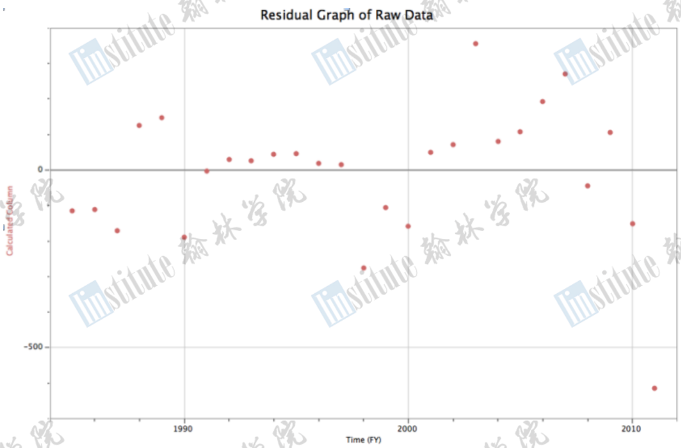
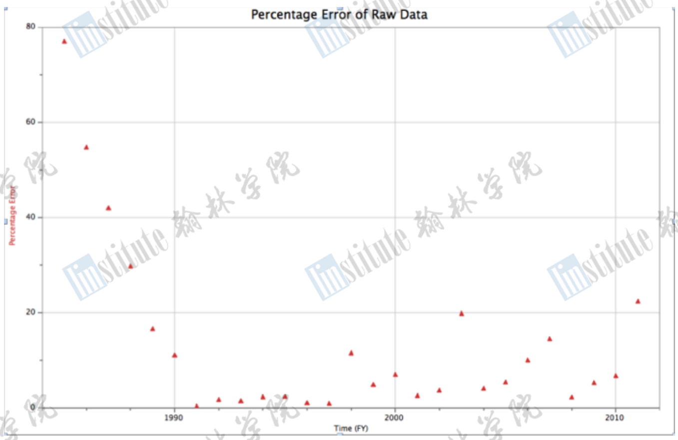


Figure 1.4: Percentage Error of Raw Data



We obtained residuals by subtracting the actual value from the predicted value, and plotting that against time. For percentage error, we took the absolute value of the residual, divided by the actual value, and multiplied by 100. By analyzing these two graphs, we can see that because the residuals are randomly scattered, that this is quite a good fit. The reason there is a high percentage error is because of how a logistic model is formulated. A typical logistic model has to go through the point (0, 0). However, because we shifted the graph 1980 units to the right, the graph goes through (1980, 0). Therefore, in making that "curve" for the first few points, it is likely that the equation underestimated funding costs for the initial years of this project.

The next step we took was to make adjustments to the data. We understood that we could not just extrapolate off of the logistics model because the funds up to this point include costs of launching modules, which the US no longer needs to do, since the Russians are launching the last module in 2012 without US funds.

We researched all the modules that were sent up from US grounds, and determined the total mass of these modules per fiscal year (See Appendix 1A). Using the assumption given in the prompt that historically, transport to the ISS using US shuttles costs about 1 lb = $5000 to $10,000, we subtracted the module costs from the fiscal year fund. Upon further research, we found the cost of development of these modules, and subtracted that value from the fiscal year fund as well. The following tables and figures show these calculations.

Table 1.2: Modules Assembly and Development Data

Fiscal Year	Appropriated ($mil)	Cost of Module Development ($mil)	Mass of Modules (pounds)
1985	150	–	–
1986	205	–	–
1987	410	–	–
1988	425	–	–
1989	900	–	–
1990	1750	–	–
1991	1900	–	–
1992	2029	–	–
1993	2199	–	–
1994	2106	–	–
1995	2113	–	–
1996	2144	–	–
1997	2149	1766.3	0
1998	2441	1386.1	0
1999	2270	1055.5	25546
2000	2323	703.6	0
2001	2115	824.8	116012.6
2002	2093	437.1	33924
2003	1810	310.2	61864
2004	2085	153.5	0
2005	2058	78.1	5887.2
2006	1995	1972	34980
2007	1894	1894	66695
2008	1894	2209	105947.6
2009	2060	2060	44000
2010	2317	2317	61626.4
2011	2780	2780	43346.6

The mathematical procedure to calculate the adjustment prices is as followed:

1) Appropriated Fund – Cost of Module Development – 5000Mass = Low Price
2) Appropriated Fund – Cost of Module Development – 10000Mass = High Price

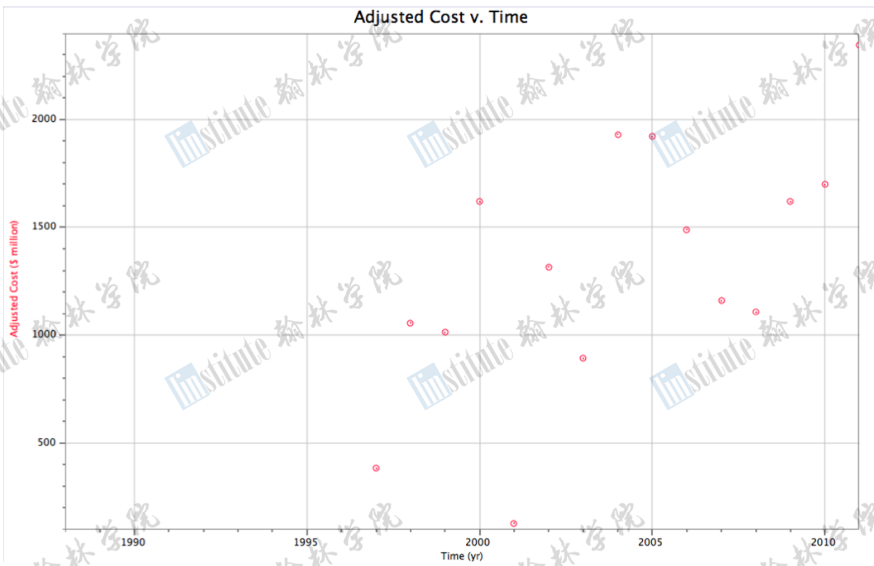
Table 1.3: Adjusted Prices

Fiscal Year	Adjusted price (1lb=$5000)	Adjusted price (1lb=$10000)
1997	382.7	382.7
1998	1054.9	1054.9
1999	1011.5	1139.5
2000	1619.4	1619.4
2001	127.6	708.9
2002	1315.9	1485.9
2003	891.8	1195.8
2004	1931.5	1931.5
2005	1920.9	1950.4
2006	1489.4	1664.7
2007	1158.4	1492.6
2008	1106.3	1637.1
2009	1619	1839.5
2010	1699.4	2008.2
2011	2345.6	2562.8

*Note: we discounted all years previous to 1997 because costs did not exist at that time.

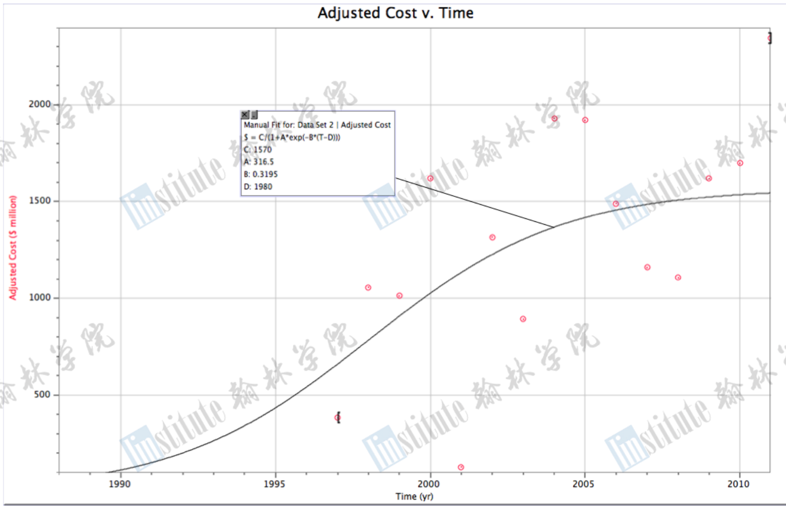
We decided to select the measure that 1 lb = $10,000 because upon further research, this value is a closer estimate the actual value. The scatter plot of the data is graphed below in Figure 1.5.

Figure 1.5: Adjusted ISS Fund v. Time



We applied the logistic curve to this graph as well because of two reasons. First, on a "naked eye" account, a logistic curve seems to fit the best. Second, because thinking logically, there is no money invested in the beginning, and then there is a period of exponential expansion before the funding levels out again. The logistic regression equation is $y = \dfrac{1570}{1 + 316.5e^{-0.3195(x-1980)}}$.

Figure 1.6: Adjusted ISS Fund v. Time (Logistic Curve)



Once again, because this is a logistic regression, there is no correlation "R-squared" value available. Therefore, we must rely on residuals and percentage error to determine accuracy of this model.

Figure 1.7: Residual Graph of Adjusted Data

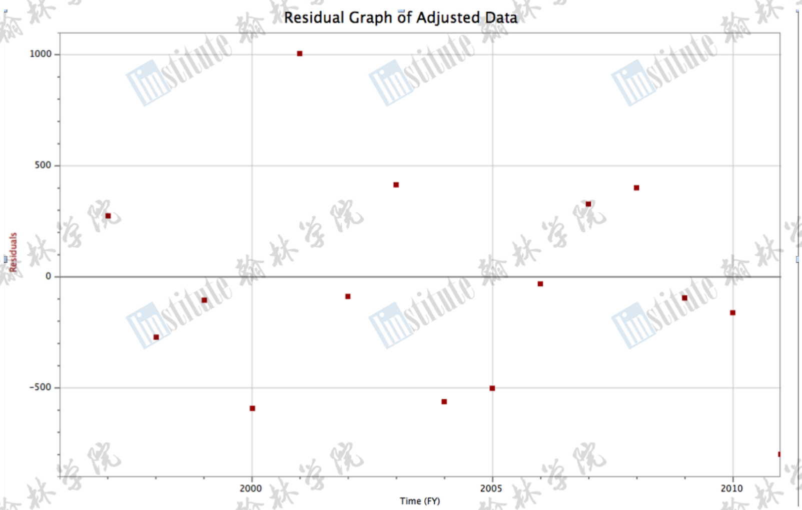
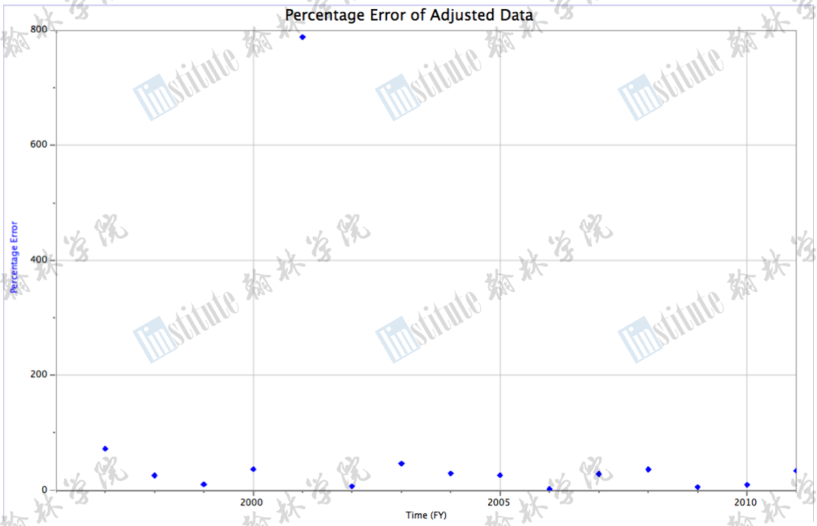


Figure 1.8: Percentage Error of Adjusted Data



We followed the same procedure as above to derive the residual and percentage error. Again, the residuals are randomly scattered, indicating a good fit. And in terms of percentage error, there is a very obvious outlier during the fiscal year of 2001. The reason this outlier occurs in 2001 is because a lot of modules were sent into space during that year (in comparison to other years), totaling up to 116012.6 pounds. This means that a lot of the funding from the government in 2001 went into constructing/launching modules in comparison to other years. This point should therefore not be considered in observing the overall trend of percentage error. Aside from that point, all the other years seem to have quite low percentage errors, indicating that the logistic curve is once again, quite a good fit for the data we calculated.

The reason we attempted this adjustment was to attempt modeling the amount of money NASA spent on maintenance of the ISS. We believed this value could be obtained by deducting values of things that would be unnecessary once the space station was completed (i.e. construction, operations development, functionality upgrades). However, that amount varied widely from year to year, suggesting that rather than having a fixed amount for maintenance, NASA has a fixed budget for the entire ISS. They appropriate money as they see fit. Therefore, this model did not accurately estimate long-term costs of maintenance fees, which was what we were attempting to model.

Part 1B: Supply by Tonnage

Therefore, we took a second approach to achieve this goal. Keeping in mind that our end goal is to evaluate the cost of this project, we came up with a simple equation to find maintenance cost. We assumed that the total mass of all payloads (T) is equal to the mass of assembly parts (A) plus the mass of maintenance parts (M). We simplified this to the equation with variables, and came up with T = A + M. If our goal is to find M, we need to find T and A.

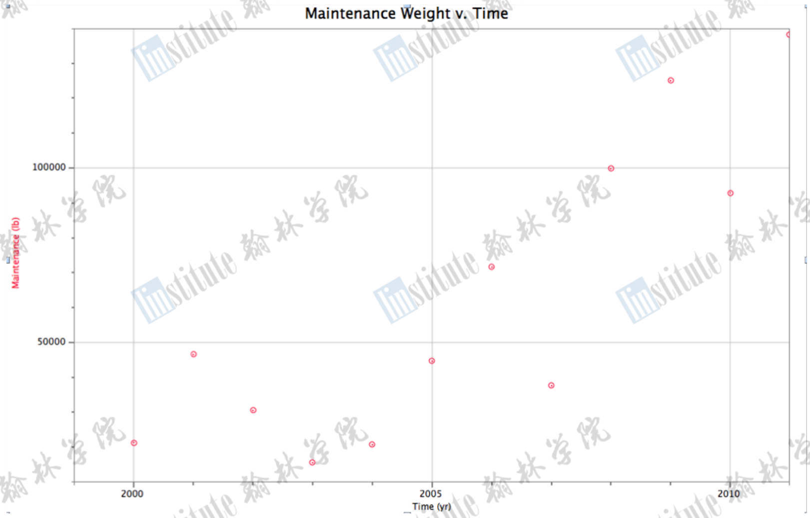
We wanted to model this data as accurately as possible. Starting from the year 2000, we tracked down every single spacecraft that has been flown up to the ISS (Appendix 2), summing up the masses of each aircraft carrier in each corresponding year. The total payload value in pounds (T) is seen in column two of Table 1.4. Now that we have the values of T, we just have to subtract the values of A in order to find the values of M. But we already found the values of A in Part 1A of this project (Appendix 1A)—except this time instead of sorting the values by Fiscal Year, we are sorting them by "normal" years. Summing up those values into column three of Table 1.4, we can now just do a simple subtraction of T – A=M. The result (M) is found in column four of Table 1.4. Now that we have the repairs/maintenance cost, we can estimate how much money we need for the future, since there will no longer be any modules being added to the ISS. The last column, cumulative ISS mass, was calculated by summing all modules in that given year. The initial cumulative mass is the mass of Zarya, launched in 1999.

Table 1.4: Change in Mass over Years

Year	Total Payload (lb)	Total Mass of Modules (lb)	Repairs or Maintenance (lb)	Cumulative ISS Mass (lb)
2000	117300	95986	21314	164043
2001	110570	63928	46642	193101
2002	126360	95788	30572	236641
2003	15600	0	15600	236441
2004	20800	0	20800	236441
2005	20800	5887	44638	242328
2006	110659	38980	71679	281308
2007	131810	94129	37681	375437
2008	172210	72380	99830	447817
2009	177110	52074	125036	499891
2010	130980	38108	92872	537999
2011	152997	14808	138189	552807

After collecting all that data, naturally we tried to find a model that would suit the data. The scatter plot of the data, a comparison between time and repair/maintenance mass is seen in Figure 1.9.

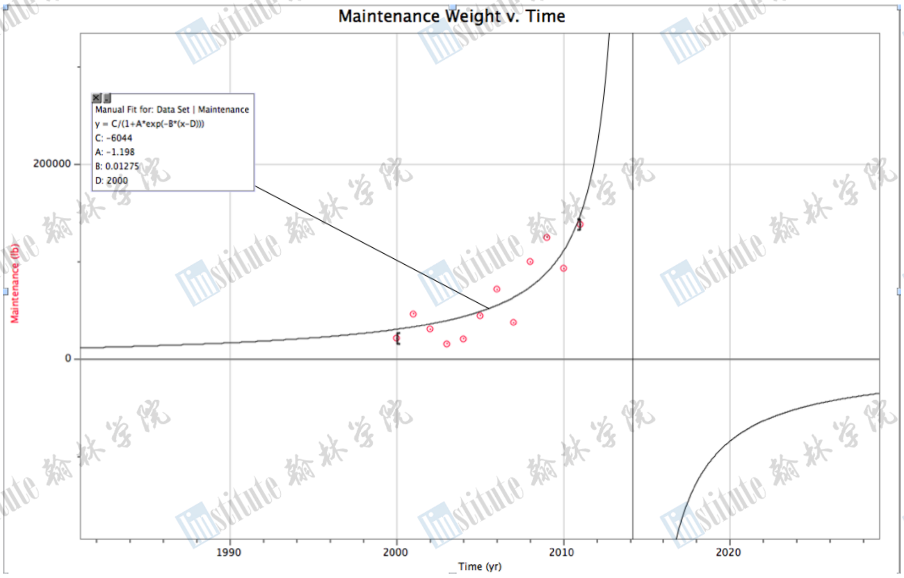
Figure 1.9: Maintenance Mass v. Time



The first thing we realize as we look at this scatter plot is that the maintenance mass is steadily increasing over time. We attempted several regressions to the model, and found that none of them were particularly good. The best correlation value we had was the exponential model. But since we are attempting to extrapolate data from this model, the exponential model is clearly not a viable option. We also considered a linear model, but discovered that this is also not a practical model because it is fairly safe assumption that maintenance cost will remain fairly steady each year, since no more modules are being added to the ISS. Therefore, we can logically assume that the best fit will be with a logistic curve.

When we put the AutoFit for the logistic curve, the equation did not model our data in the way we wanted at all (Figure 1.10). The equation that LoggerPro gave us was $y = \frac{-6044}{1 - 1.198\, e^{-0.01275\,(x - 2000)}}$. This left us with an awkward vertical asymptote in the year 2011, and an even more awkward negative horizontal asymptote, implying we have negative supply requirements. This is obviously incorrect.

Figure 1.10: Maintenance Mass v. Time (AutoFit Logistic Curve)



This left us with only one option—to manually adjust the variables of the logistic curve, creating our own equation which we felt fit the data much better (Figure 1.11). Because we know that the ISS will complete construction by 2012, maintenance costs should theoretically level out to some degree after that year. With this thought in mind, the equation we found was $y = \frac{1.507}{1 + 14.04\, e^{-0.3737\,(x - 2000)}}$.

Figure 1.11: Maintenance Mass v. Time (Manual Logistic Curve)

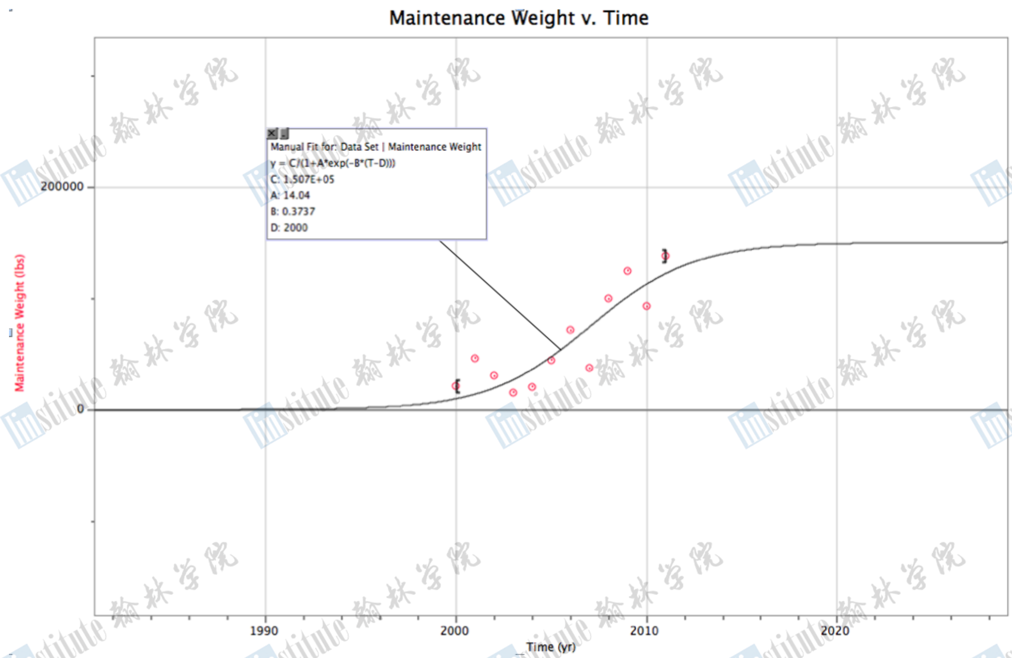


Figure 1.12: Residual Graph of Manual Logistic Fit

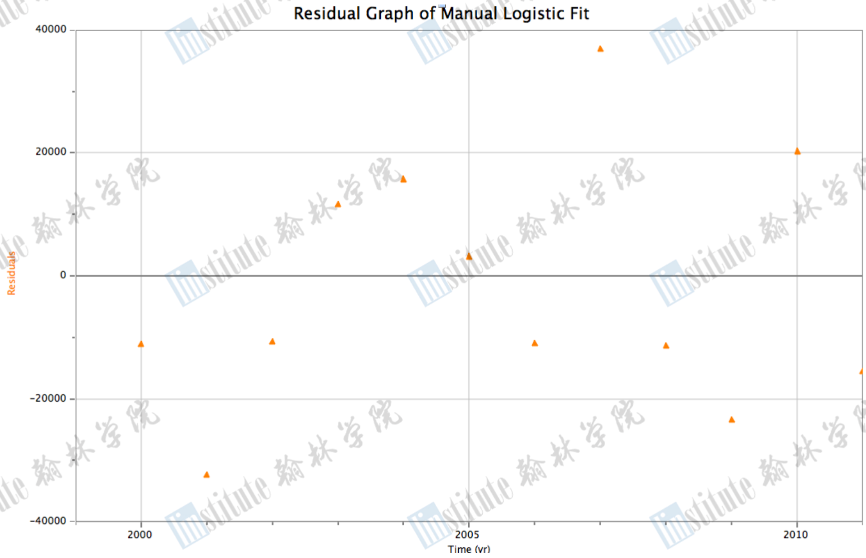


Figure 1.13: Percent Error of Manual Logistic Fit

We obtained residuals and percent error in the same method as Part 1A. By analyzing these two graphs, we can see that because the residuals are randomly scattered, that this is quite a good fit. The reason there is a high percentage error is because of how a logistic model is formulated. A typical logistic model has to go through the point (0, 0). However, because we shifted the graph 2000 units to the right, the graph goes through (2000, 0). Therefore, in making that "curve" for the first few points, it is likely that the equation underestimated a lot of the mass, thus making the percent error for the first couple of points extremely high.

Now that we established that this model is a good fit for the data, we can extrapolate the data for the following ten years. The numbers from this extrapolation are seen in the following table:

Table 1.5: Extrapolated Mass

Year	Maintenance Mass (lb)
2012	122500.01
2013	130090.70
2014	135885.28
2015	140182.35
2016	143300.91
2017	145528.90
2018	147102.85
2019	148205.94
2020	148974.72
2021	149508.44
Total Mass	1299202.98

Taking the integral of the payload function over the next ten years, we find that the total mass according to our model is approximately 1299200 lbs.

$$\int_{2012}^{2021} \frac{150700}{1+14.04e^{-0.3737(t-2000)}}\,dt \approx 1299200$$

Part 1C: Supply by Proportion

While we were calculating the supply by tonnage over time, we realized that it might be more accurate to model the supply with respect to the percent completed, rather than just using time passed. The most important factor we are considering is how to effectively maintain the components of the ISS. In Part 1B, we simply analyzed the data to form a function of time that modeled the data and tried to extrapolate. However, we believe that alternatively, we can try to find maintenance cost as a function of how much of the ISS has been completed. If we model it this way, then we would get a constant value for the maintenance fee after the last module is been added to the ISS in 2012.

Table 1.6: Maintenance Weight v. Proportion Completion

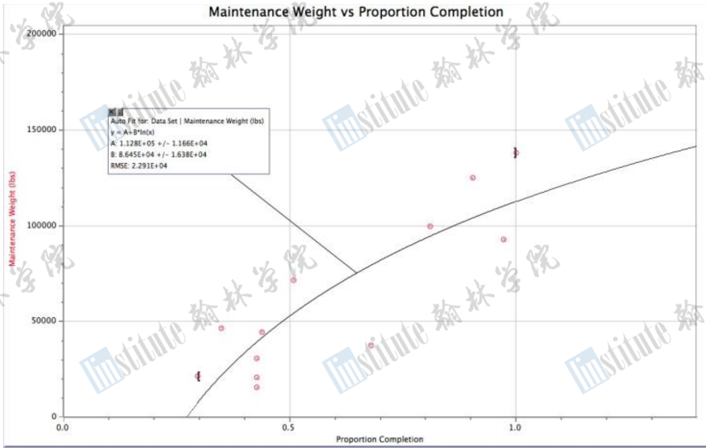
Proportion completion	Maintenance Weight (lb)
0.29675	21314
0.34931	46642
0.42771	30572
0.42771	15600
0.42771	20800
0.43836	44638
0.50887	71679
0.67915	37681
0.81008	99830
0.90428	125036
0.97321	92872
1.00000	148189

We then graphed this data onto a scatter plot, seen in Figure 1.14.

Figure 1.14: Maintenance Weight v. Proportion Completion Scatter Plot

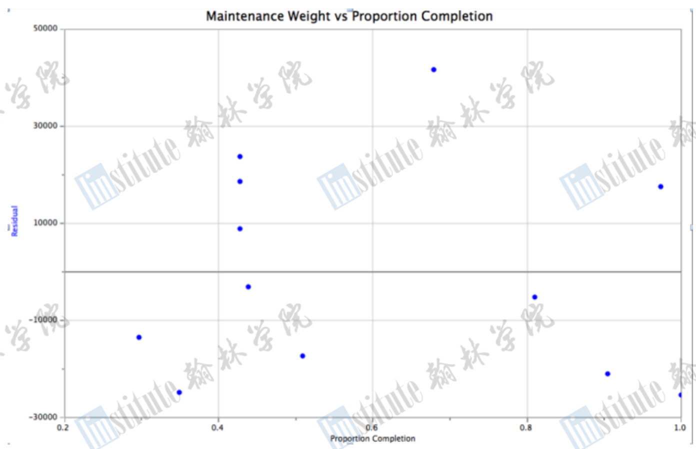
We observe through the scatter plot that the general shape shows an increasing trend. We also logically assume that after the ISS is complete, that the maintenance cost should be consistent. Because we know that there is a built in limit over time, the maintenance weight is just going to stabilize at whatever the value is at proportion completion "1". We fit a natural logarithm because the weight appeared to increase at a decreasing weight. The equation derived using regression is $y = 112800 + 86450 \ln x$.

Figure 1.15: Maintenance Weight v. Proportion Completion (Natural Logarithm)



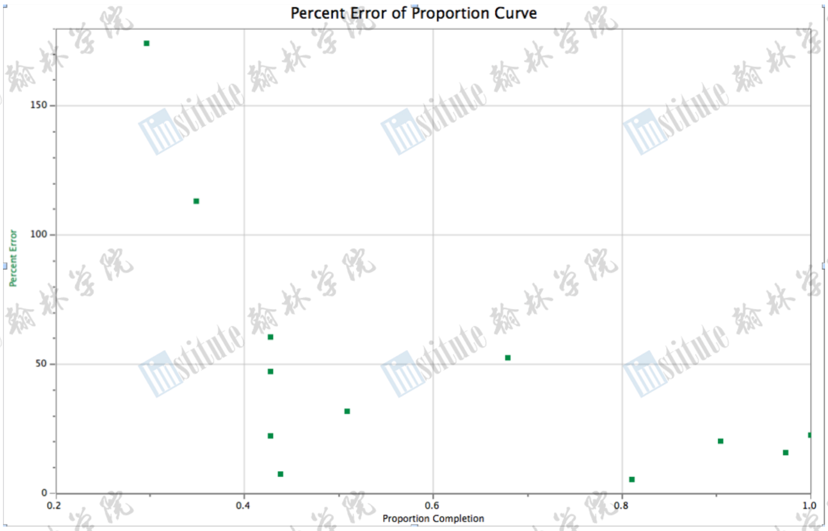
In order to determine the accuracy of this model, we looked at the correlation coefficient, residual plots and percent error. The correlation coefficient of this model is 0.7359, which is quite accurate in terms of modeling "real life" situations. The residual plot (seen in Figure 1.16) is randomly scattered, also indicating a good fit.

Figure 1.16: Residual Graph of Maintenance Weight v. Proportion Completion



We also used percent error to determine accuracy, as seen in Figure 1.17 below. The reason that the first couple of points have such a high percent error is partly because the point-values are really small. Percent error is the difference between the predicted and the actual over the actual. Therefore, when the actual value is extremely small, as seen in the first few cases, the same sort of residual values will produce very high percent errors. But otherwise, the percent errors seem quite low, also indicating a pretty good fit.

Figure 1.17: Percent Error of Maintenance Weight v. Proportion Completion



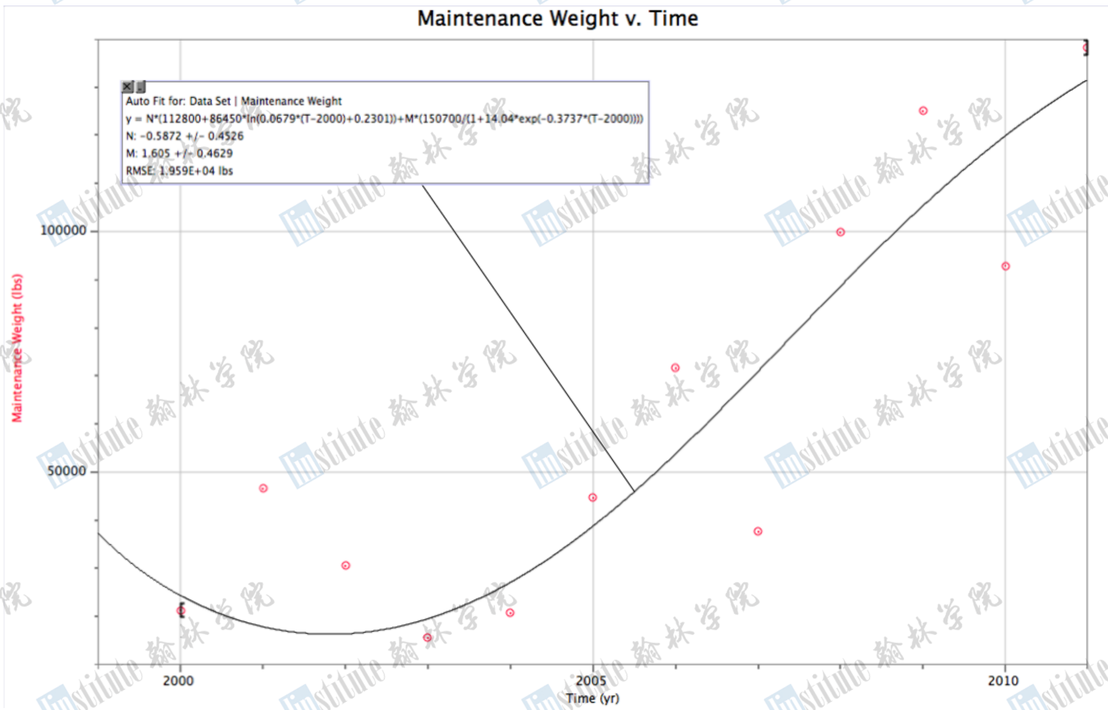
We used this regression because we wanted to determine an estimate of what the weight is going to be at 100% completion without having to base it on a single point (which is what Table 1.6 provides). Using this natural logarithmic model, we conclude that when the ISS is completely finished, maintenance weight should be approximately 112800 pounds. This is found by substituting x=1 for the equation $y = 112800 + 86450 \ln x$.

Part 1D: Supply by Combination (Tonnage and Proportion)

Now that we have established two different methods of obtaining maintenance costs, we decided that we could try and find a weighted average between the two models. We incorporated both models by writing them as a single multiple regression function; one was multiplied by a constant "M" while the other was multiplied by a constant "1–M". The two values were then added together to create our function.

In an attempt to find this optimal value "M", we did a least square regression of both models. However, when we did this, we got a value of "M" which was greater than 1. This means that one of the functions had a negative weighting. This also means that the long-term estimation was greater than either one of our existing models. Although this function fit the data fairly well, it does not make much sense. This function is modeled in Figure 1.18.

Figure 1.18: Combined Maintenance Weight v. Time



Part 1E: State-funded Model

We decided to use the calculated data from Part 1B (Supply by Tonnage) because the data was the most logically justifiable out of the three supply models. Also, the data from Part 1B fit the expected long-term trends the most realistically.

This first model we created uses the assumption that after US space shuttles were decommissioned, Russia is going to continue flying up maintenance parts required to keep the ISS running. In Part 1A, we already concluded that the cost per pound is $10,000. We apply this assumption to this extrapolated mass calculated in Table 1.4, and came up with the costs for the following ten years.

Table 1.7: Extrapolated cost of State-funded Model

Year	Maintenance Fees ($mill)
2012	1225
2013	1301
2014	1359
2015	1402
2016	1433
2017	1455
2018	1471
2019	1482
2020	1489
2021	1495
Total Cost	12992

Furthermore, using the same flight schedules, we found that the current system for crew changes is that three out of the crew of six are switched out by Soyuz shuttle every three months, for a total of twelve crew changes per year. While it would undoubtedly be cheaper to require fewer astronauts to work longer shifts, overexposure in zero gravity conditions will have unpredictable effects on the astronaut's physical health. It is best to leave the personnel schedule as is until further data is collected, and even then to make only incremental changes.

We know that twelve astronauts are launched per year and the Russian government is willing to pay $51 million for every US astronauts. Therefore, the total annual cost of personnel changes will be $612 million per year, for a total of $6.12 billion over the 2012-2021. Adding the costs for cargo transportation, this totals $19.112 billion over that interval of time.

Strengths and weaknesses

The main weakness in this model is that it is prohibitively expensive. Since cost is our main consideration, this almost immediately rules out this model. However, we still use it as a baseline comparison because out of all of the viable options we have considered, this is the one that is most similar to the historical approach.

In turn, a strength of this model is that it encourages international relations between Russia and the USA. This approach is essentially financing the Russian space program, which in turn runs the resupply of the day-to-day maintenance needs of the ISS. As such, this would require large amounts of international cooperation, and will facilitate future cooperation. In addition, the Russian Soyuz has proven to be incredibly reliable, since this is the space rocket that the ISS has been using since its launching. Moreover, the Soyuz had also been used by the Soviet and then Russian space program since 1966. And it had also previously supplied the Mir space station for its entire operative history, which is over ten years. This would ensure our astronaut's safety, and would also almost guarantee that any given supply mission would succeed. Out of the forty-six launches that have delivered supplies to the ISS, only one of them failed to launch.

Figure 1.19: A Soyuz rocket

*Note: This picture is in the public domain because NASA originally published it, and NASA policy states that NASA material is not protected by copyright unless otherwise noted.

Part 1F: Procurement costs

Aside from finding the maintenance cost (flying the missions), there is also the cost of actually obtaining the supplies necessary to maintain the ISS, as well as costs such as administration, training etc. We chose to estimate this cost by taking the projection of the overall costs based on the logistic curve of the overall budget and subtracted the projected maintenance cost to find the projection for the remaining expenses of the NASA portion of ISS costs.

Table 1.8: Procurement Costs

Year	Projected Budget Fee ($mill)	Projected Maintenance Fees ($mill)	Projected Procurement Cost ($mill)
2012	2165	1225	328
2013	2165	1301	252
2014	2165	1359	194
2015	2165	1402	151
2016	2165	1433	120
2017	2165	1455	98
2018	2165	1471	82
2019	2165	1482	71
2020	2165	1489	63
2021	2165	1495	58
Total Cost	21650	12992	1418

*Note: Projected Procurement Cost is calculated by subtracting Maintenance Fees and personnel change fees, which are constant at $612 million per year, from Budget Fees

Part 2: Privatization Model

Part 2A: Finding the Right Brand

Since this entire problem is focusing on the retiring of the space shuttles, we needed to find a suitable alternative to continue maintenance of the ISS. The projection of Part 1B is based on the assumption that after the space shuttles retire, the Russian Soyuz rockets would carry up the crew and cargo instead in their Progress spacecraft, for a cost of approximately $10,000/pound. However, we believe that it is possible to use charter flights to bring up the crew and cargo for a much cheaper price, thereby lowering the total cost significantly. NASA thought the same way, when faced with this same predicament.

When NASA looked into commercializing these crew and cargo flights, they ran a program called the Commercial Orbital Transportation Services (COTS) in an attempt to coordinate private companies interested in supplying spacecraft. Instead of using government-operated vehicles, the proposed spacecraft is supposed to be fully owned and financed by the private companies commissioned by NASA. The private companies are not bound to the US government—they are also allowed to serve commercial customers.

In the attempt to find the most suitable private company, NASA conducted a competition that tested in four categories:

1) External unpressured cargo delivery and disposal
2) Internal pressurized cargo delivery and disposal
3) Internal pressurized cargo delivery, return and recovery
4) Crew Transportation

There were two rounds to NASA's selections. In their first round in 2006, NASA selected six semi-finalists, finally announcing that SpaceX and RpK had won Phase I of the COTS program. Space X's spacecraft was the Falcon series and RpK was the K-1 rocket. However, because RpK did not raise sufficient funds by the deadline set by NASA, NASA terminated this agreement.

NASA needed a second company to assist their commercialization of flights, and so they held another round of competitions. Several other brands jumped onto this opportunity in November 2007. Although NASA did not promise financial support, they agreed to share information to assist the development process of these rockets. Orbital Sciences Corporation won the second round with their Cygnus spacecraft, including the Taurus launchers.

With this COTS test in mind, we also compiled a list of potential rockets, as seen in Table 2.1. We looked at all the companies that NASA considered and took the "best of the best" out of those space rockets. In an attempt to decide which vehicle best suited our needs, we decided that the deciding factor would be cost per pound. In order to find this ratio, we needed to know the different payloads and launch prices of each vehicle, which we compiled into column two and three of Table 2.1.

Table 2.1: Potential Competitors

Launch Vehicle	Payloads (lbs)	Launch Price ($mill)	Cost per Pound ($)
Falcon 9	23050	59.5	2436
Falcon Heavy	117000	125	1068
Taurus II	12650	N/A	N/A
Delta IV (Heavy)	49940	170	3404
K-1	4400	17	3864
Atlas V 551	4411	192	4353
Athena II	4520	26	5752

*Note: Taurus II did not release their data for the launch price.

Based off of our compiled list, we see the Falcon series made by SpaceX is clearly the best choice out of the data we have. We assume that because NASA chose Orbital Sciences Corporation (maker of Taurus II), that that rocket is also a leading choice in terms of cost efficiency. However, the spokesperson of Orbital Sciences Corporation, Pieczynski, refused to publically announce the launch price of his rocket, stating only that it would be "quite a bit south" of $100 million. As we do not have enough data, we will not consider this rocket, and will use the Falcon series instead.

Part 2B: Finding Landing Craft Efficiency

SpaceX, the company that created the Falcon series, is currently designing the Falcon Heavy. However, their earlier Falcon 9 design is already the most cost efficient choice available, based on Table 2.1. The Falcon Heavy is not due to be released until 2013, and they have not designed a landing craft for it yet either. Therefore, we will assume the use of the Falcon 9 for all intensive purposes. The Falcon 9's Dragon landing craft carries 13,228 pounds, which is included in the launch price. That gives a final cost efficiency of $4498/pounds.

If we use the baseline model that we created in Part 1B, we can apply this new cost per pound ratio to the extrapolated mass we found in Table 1.5. Using the same projected supply requirements by tonnage but the new cost efficiency ratio we can calculate a new projection for cargo transportation costs for the Falcon 9 rocket instead of the Soyuz.

Table 2.2: Extrapolated Costs of Privatization

Year	Maintenance Fees ($mill)
2012	551
2013	585
2014	611
2015	631
2016	645
2017	655
2018	662
2019	667
2020	670
2021	673
Total Cost	5891

Similarly, if we calculate the costs of crew transportation using the SpaceX Dragon instead of the Russian Progress, the maximum crew change per flight remains 3, which facilitates continued use of the same schedule, however launch costs are reduced to $59.5 million, giving an average cost of just $19.8 million per seat. However, since the manned version of the SpaceX Dragon will only be completed in the beginning of 2014, we will continue to use Soyuz flights until then.

Using this revised cost for the 12 crew-changes per year, this requires $612 million per year for the years 2012-2013, and $238 million per year for all crew changes from 2014-onwards, or $3.128 billion for the entire period. Adding this to the costs of cargo transportation gives $9.019 billion dollars from 2012-2021, saving $10.093 billion over the interval, or cutting costs by 52.8%. These amount to quite dramatic savings.

Strengths and Weaknesses

One of the main weaknesses of this approach is that only seeks to improve the efficiency of cargo transportation, and makes no changes to the tonnage of cargo, the scheduling of launches or other factors which could have potentially enormous inefficiencies hidden in the setup. However, this is almost inevitable, as there is simply not enough data to go on in order to optimization of specific needs of the astronauts, the science program and the station itself. The most detailed data we have been able to find is only the tonnage of supplies going to the space station, and even then we have had to separate out component mass to find the tonnage of routine everyday supplies that are consumed by the station. We have not been able to find the specific supplies that comprise these shipments, and so are unable to tell whether superfluous, wasteful, or overly expensive supplies are being sent and thus have been unable to streamline this process.

Another weakness, also one related to data, is that we have been unable to find whether the manned variant of our favored Dragon landing craft can carry cargo as well; in the absence of data we have assumed that it carries only negligible amounts of the astronaut's personal goods like the Progress does, however for all we know our 13,228 pound figure is for manned models, and unmanned models can carry even more, leading to tremendous amounts of wasted capacity.

The most obvious strength in this model is that it is significantly cheaper than the baseline model in using Soyuz rockets. This represents huge savings in money, which is what we are main consideration when deciding what model to use.

A more "hidden" strength of this approach would be that private charter models are flexible because it is not difficult to switch between different charter companies. NASA seems to have noticed this, because of the two companies they chose (SpaceX and Orbital Sciences Corporation), SpaceX was by far the most cost efficient of the choices, while Orbital Sciences has a long history of launching satellites for commercial or military purposes, which means it's reliable.

Part 3: Experimental Solutions

Part 3A: Space Elevators

A space elevator is literally an elevator that is able to take a payload up to space. We looked into the space elevator, because we saw it as a very low-cost possibility. In our initial stages of research, we saw that upon completion of the space elevator, price of taking payload up to space could be as low as $100/pound, or perhaps even lower.

A typical space elevator would require several parts:

1) A base anchoring the space elevator to earth
2) A single length of extremely strong material, able to support its own weight over an extremely long distance
3) A counterweight at the top of the space elevator
4) A "climber" that is able to bring the payload up the length of the wire, essentially the "elevator"

When people say "space elevator", they are usually referring to a structure that reaches the Geo-stationary Earth Orbit, which would include a 40,000km long cord. However, in terms of modern technology, this is not physically possible. The closest we have gotten to a space elevator of this type is a 400g payload being carried up a 1km cable in 3 minutes and 48 seconds. This is clearly nowhere near the payload or speed we need to maintain the ISS.

The only materials strong enough to create such a cord (the second requirement) that humans have discovered are carbon nanotubes. The strongest nanotubes in existence, while not strong enough to build a 40,000km long cable, is strong enough to build a 1,000km long cable. This is more than enough for us to build a space elevator to reach the ISS.

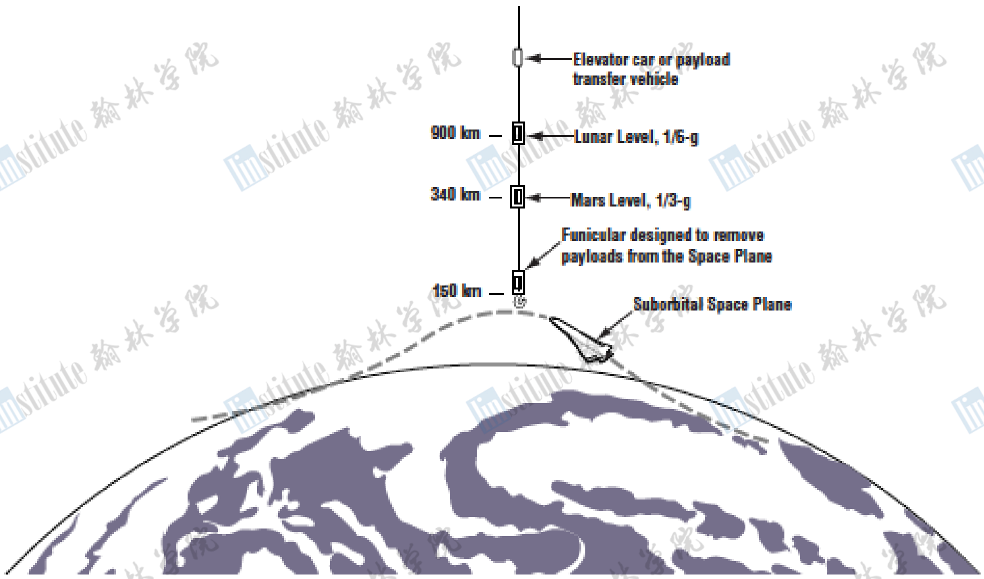
The ISS is located in low Earth orbit, slightly less than 400km above Earth's mean sea level. Because of counteracting forces, if we want to bring something a certain payload up the space elevator to a certain distance "x", the length of the cable required is going to be at least "2x", as there must be a counterweight at the top of the cable. This means that a cord is physically feasible to construct with the technology available to us today.

We then seek to endeavor whether or not building a space elevator will result in a more efficient plan than using space rockets to maintain the ISS. We found material cost statistics of creating such a space elevator (from Earth to the ISS). If this cost is less than all plans we previously modeled, we will then explore how much we can reduce our expenditure by.

In order to find total cost of this specific space elevator, we realized that we needed to find the cost of several components to create a space elevator:

1) Carbon nanotubes (to create the cord)
2) Base (on Earth)
3) Climber ("elevator")
4) Cost of assembly

Figure 3.1: Space Elevator Diagram



*Note: This picture is in the public domain because NASA originally published it, and NASA policy states that NASA material is not protected by copyright unless otherwise noted.

We realized that the cost of the base and the climber was constant, so that could be done later. The primary concern in building such a space elevator dealt with the construction of the carbon nanotube cord.

In order to find the cost of such a cord, we needed to find variables certain commonly understood equations, and collect data for the corresponding variables, as seen in Table 3.1.

$$Volume = \pi * Radius^2 * Height$$

$$Density = \frac{Mass}{Volume}$$

$$TotalCost = \frac{Cost}{Mass} * Mass$$

<u>Table 3.1</u>: Data for Calculation for Cost of Space Elevator

Cost of industrial nanotubes per gram	$100
Radius of carbon nanotubes required	0.3175 cm
Density of carbon nanotubes	1.33g/cm^3
Length of space elevator	1000 km

We then plugged in the variables and came up with the total cost of the carbon nanotube cord:

$$V = pr^2h = p(0.3175cm)^2(1000km) * \frac{100000cm}{1km} = 3.167 * 10^7 cm^3$$

$$m = V * r = 3.167 * 10^7 cm^3 * \frac{1.33g}{1cm^3} = 4.21 * 10^7 g$$

$$P = 4.21 * 10^7 g * \frac{\$100}{1g} = 4.21 * 10^9$$

We see here that total cost of creating just the carbon nanotube cord will cost $4.21 billion. We decided to stop investigating this option because it is already more expensive than our Privatization model, seen in Part 2 of this paper.

In addition, construction time is not instant. Various figures have shown that such a project would a minimum of ten years to complete. In order to recuperate losses incurred by this project, the construction time needs to be one to two years. Thus, we conclude that while such an elevator is feasible and may be a great alternative the long run, it is not a possibility for a ten-year plan.

Part 3B: Spaceplanes

Spaceplanes are vehicles that can fly in both orbital height (low Earth orbit) and suborbital heights. They are modeled closely after airplanes that we are all familiar with. This means that they have to be able to land, thus being reusable. Upon initial research, we realized that this would be a low-cost alternative if it were feasible. Thus, we decided to look into its feasibility.

The space shuttle is the most commonly cited example of a spaceplane. Space shuttles took off vertically and land horizontally back on Earth, and were reused. Now that space shuttles are obsolete, private companies have begun to invest into spaceplanes that have the ability to enter orbit.

There are two major privately designed spaceplanes to date, one is manned and one is unmanned. The manned spaceplane is called SpaceShipOne, which attained maximum height of 112.4 km. However, if we are to send this to the ISS, which is 400km in space, this spaceplane cannot reach the ISS. The unmanned spaceplane is called Boeing X-37, which has actually been able to enter low Earth orbit. Although this spaceplane has the ability to reach the ISS, because spaceplane is very small, weighing only 11,000 pounds with virtually no space to carry payload, this is also not a reasonable option to carry cargo up to the ISS.

Therefore, we reasonably assumed that spaceplanes are also not viable options.

Part 4: The 10-Year Plan

Part 4A: Cost

After all the approaches we attempted in this paper, we found that the most efficient cost-saving method was to switch away from the Russian-run Soyuz cargo and personnel change flights, and to instead charter flights from private companies. Looking at potential service providers in both the personnel changes and cargo deliveries, we found that SpaceX's Dragon spacecraft, delivered by the Falcon 9, was the most cost effective option in both categories.

The following table (Table 4.1) compares the respective maintenance costs of Russian run Soyuz space rockets and private run Falcon 9 space rockets, as well as the savings from switching.

Table 4.1: Comparison between Soyuz and Falcon 9 Maintenance Fees

Year	Soyuz Maintenance Fees ($mill)	Falcon 9 Maintenance Fees ($mill)	Savings ($mill)
2012	1225	551	674
2013	1301	585	716
2014	1359	611	748
2015	1402	631	771
2016	1433	645	788
2017	1455	655	800
2018	1471	662	809
2019	1482	667	815
2020	1489	670	819
2021	1495	673	822
Total Cost	12992	5891	7101
Total (With Personnel Costs)	19112	9019	10093

*Note: The first two years for the Falcon 9 maintenance fees are still using Soyuz to carry personnel because the Falcon 9 manned spacecraft is still unavailable.

Since the projected procurement cost is all of the costs besides maintenance costs, and we couldn't find enough data on its composition to optimize it, we just used the same projections from the baseline model, and added it to the privatized model to find the final total NASA budget per year of the ISS. We had to consider that SpaceX manned flights were not available until 2014, so we used Soyuz flights until then, which still gave us pretty substantial savings.

Table 4.2: Total ISS Expenses

Year	Unmanned Maintenance Fees ($mill)	Manned Maintenance Fees ($mill)	Projected Procurement Cost ($mill)	Projected Total Cost ($mill)
2012	551	612	328	1491
2013	585	612	252	1449
2014	611	238	194	1043
2015	631	238	151	1020
2016	645	238	120	1003
2017	655	238	98	991
2018	662	238	82	982
2019	667	238	71	976
2020	670	238	63	971
2021	673	238	58	969
Total Cost	5891	3128	1418	10437

Overall, the total projected costs over the ten-year period from 2012 to 2021 have been reduced from $21.65 billion to $10.437 billion. This represents total savings of $11.213 billion, which is 51.8% of the total budget. By implementing the privatization model, we managed to save considerable amounts of money.

Part 4B: Payload

Using our previously calculated values for the annual tonnage of necessary supplies, we found that the annual supply requirements. Dividing these values by the SpaceX Dragon's tonnage capacity and then rounding to the nearest whole number, we get that the annual number of required missions, as follows:

Table 4.3: Total Payload and Annual Flight Breakdown

Year	Maintenance Weight (lb)	Number of flights
2012	122500	9
2013	130091	10
2014	135885	10
2015	140182	11
2016	143301	11
2017	145529	11
2018	147103	11
2019	148206	11
2020	148975	11
2021	149508	11
Total	1299203	106

Part 4C: Flight Schedule

In order to develop a comprehensive flight schedule, we needed to analyze the amount of payload needed per year and optimal conditions for launching. The most important factor dealing with optimal launching conditions is that the ISS has to be directly above the launching facility, which is located at Cape Canaveral, FL. This launch facility is called Cape Canaveral Air-force Station, which has the coordinates of 28° 29' N and 80° 34' W. We selected this launch facility because it is the ISS's main launching facility.

The space shuttle must be launched within five minutes of the time when the ISS is directly above (in the same plane with) the Cape Canaveral Air-force Station to ensure rendezvous with the ISS. In order to determine how often this incidence occurs, we need to consider the rotation of the Earth and the rotation speed of Earth. The rotation speed of the earth is going to have the ratio of 1 circumference per day. The ISS rotates relative to Earth, since it is in orbit with Earth. By dividing the circumference of the Earth (40,000km) by the rotational speed of Earth (1665 km/hr), we find that the ISS is going to pass over the same points of Earth's surface about every 24.02 hours. ($\frac{40,000\ km}{1665\ km/hr} = 24.02\ hr$)

We also found that one of the main considerations that NASA took when it was considering flight schedules was that it needed to make sure that sun beta angles (angle of the sun relative to the plane of incidence) must be less than 60°, otherwise the space craft will be unable to land due to visibility reasons. However, we were not able to find any sources that provided any information with regard in how to actually calculate these values, and therefore we did not consider this variable.

Other variables for launching dates include weather, lighting, time of day and orbit inclination. Because these factors, especially weather, are inherently unpredictable, the schedule needs to be flexible (as in real life).

We also need to consider temperature of the launching site. In 2003, the temperature of the launch site was below 4˚C, which is the normal minimum for spaceship launches. This was one of the contributing factors to Columbia's subsequent disintegration, and the death of the onboard crewmembers. As such, care must be taken to make sure that the temperature at the launch site is safely above 4˚C. If the temperature is below 4˚C, the launch must be rescheduled.

Next, we looked at the launch windows of NASA's past plans for STS-133 and STS-135, which are space shuttles sent from Cape Canaveral Air Force Station to the ISS in 2011. The data given to us tells us when the window was open, in plane and closed. This window changes every day by a slight amount. We want to find the difference of in plane time for every day in February and July of these two space shuttles. We chose STS-133 and STS-135 launched in February and July respectively to get a good idea of the general trend because these months are the most extreme months in a year.

Table 4.4: Change in In-Plane Time for STS-133

STS-133	STS-135
-25:43	-22:34
-22:33	-22:32
-25:42	-25:42
-22:32	-22:32
-25:42	-25:43
-22:32	-22:33
-25:41	-22:32
-22:33	-25:43
-25:41	-22:33
	-22:31
	-25:44
	-22:33
	-25:41
	-22:34
	-22:32

*Note: See Appendix 4 and 5 for Launch Windows used

Since there were gaps in the data for STS-135, we looked more closely at STS-133. We noticed that the in-plane time would shift back about 25 minutes and 42 seconds and 22 minutes and 33 seconds on alternating days. We used this to determine our launch times. See Appendix 6.

Table 4.5: Flight Schedule

Spacecraft	Man or Unmanned	Launch Date	Launch Time
Soyuz	3P	01/01/2012	11:37:26
Falcon 9	Unmanned	02/10/2012	19:32:06
Falcon 9	Unmanned	03/21/2012	03:50:54
Falcon 9	Unmanned	04/30/2012	11:21:26
Soyuz	3P	06/09/2012	19:16:06
Falcon 9	Unmanned	07/19/2012	03:10:46
Falcon 9	Unmanned	08/28/2012	11:05:26
Falcon 9	Unmanned	10/07/2012	19:00:06
Soyuz	3P	11/16/2012	02:54:46
Soyuz	3P	01/01/2013	08:42:44
Falcon 9	Unmanned	02/06/2013	18:13:56
Falcon 9	Unmanned	03/14/2013	03:45:08
Falcon 9	Unmanned	04/19/2013	13:16:20
Soyuz	3P	05/25/2013	22:47:42
Falcon 9	Unmanned	06/30/2013	08:18:44
Falcon 9	Unmanned	08/05/2013	17:49:56
Falcon 9	Unmanned	09/10/2013	03:20:08
Soyuz	3P	10/16/2013	12:52:20
Falcon 9	Unmanned	11/21/2013	22:23:32
Falcon 9	3P	01/01/2014	05:48:02
Falcon 9	Unmanned	02/06/2014	15:19:14
Falcon 9	Unmanned	03/14/2014	00:15:26
Falcon 9	Unmanned	04/19/2014	10:21:38
Falcon 9	3P	05/25/2014	19:52:20
Falcon 9	Unmanned	06/30/2014	05:24:02
Falcon 9	Unmanned	08/05/2014	14:55:14
Falcon 9	Unmanned	09/10/2014	00:26:26
Falcon 9	3P	10/16/2014	09:57:38
Falcon 9	Unmanned	11/21/2014	19:28:50
Falcon 9	3P	01/01/2015	02:53:20
Falcon 9	Unmanned	02/03/2015	13:36:56
Falcon 9	Unmanned	03/08/2015	00:20:32
Falcon 9	Unmanned	04/10/2015	11:04:08
Falcon 9	3P	05/13/2015	21:47:44
Falcon 9	Unmanned	06/15/2015	08:31:20
Falcon 9	Unmanned	07/18/2015	19:14:56
Falcon 9	Unmanned	08/20/2015	05:58:32
Falcon 9	3P	09/28/2015	16:42:08
Falcon 9	Unmanned	10/25/2015	03:25:44
Falcon 9	Unmanned	11/27/2015	14:09:20
Falcon 9	3P	01/01/2016	23:58:38
Falcon 9	Unmanned	02/03/2016	10:42:14
Falcon 9	Unmanned	03/08/2016	21:01:42
Falcon 9	Unmanned	04/10/2016	07:45:18
Falcon 9	3P	05/13/2016	18:28:54
Falcon 9	Unmanned	06/15/2016	05:12:30
Falcon 9	Unmanned	07/18/2016	15:56:06
Falcon 9	Unmanned	08/20/2016	02:39:42
Falcon 9	3P	09/28/2016	10:58:30
Falcon 9	Unmanned	10/25/2016	00:06:54
Falcon 9	Unmanned	11/27/2016	10:50:30
Falcon 9	3P	01/01/2017	21:03:56
Falcon 9	Unmanned	02/03/2017	07:47:32

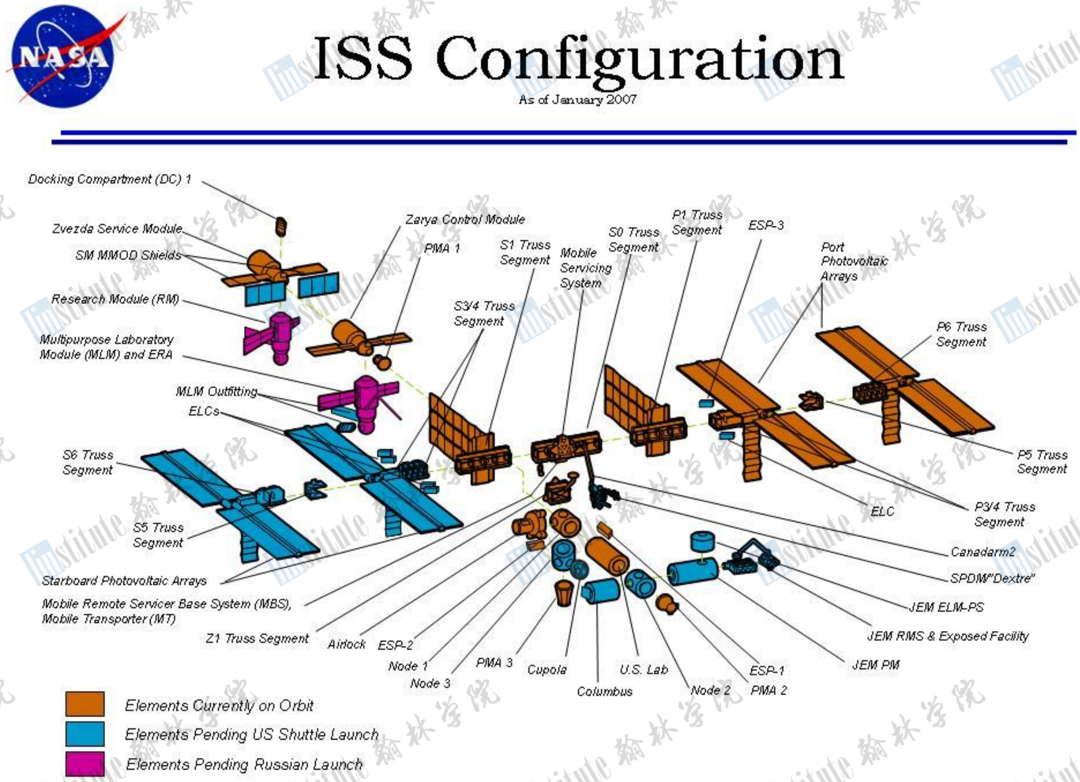
Falcon 9	Unmanned	03/08/2017	18:31:08
Falcon 9	Unmanned	04/10/2017	05:14:44
Falcon 9	3P	05/13/2017	15:58:20
Falcon 9	Unmanned	06/15/2017	02:41:56
Falcon 9	Unmanned	07/18/2017	13:25:32
Falcon 9	Unmanned	08/20/2017	00:09:08
Falcon 9	3P	09/28/2017	08:27:56
Falcon 9	Unmanned	10/25/2017	21:36:20
Falcon 9	Unmanned	11/27/2017	08:19:56
Falcon 9	3P	01/01/2018	18:09:14
Falcon 9	Unmanned	02/03/2018	04:52:50
Falcon 9	Unmanned	03/08/2018	15:36:26
Falcon 9	Unmanned	04/10/2018	02:20:02
Falcon 9	3P	05/13/2018	13:03:38
Falcon 9	Unmanned	06/15/2018	23:47:14
Falcon 9	Unmanned	07/18/2018	10:30:50
Falcon 9	Unmanned	08/20/2018	21:14:26
Falcon 9	3P	09/28/2018	05:33:14
Falcon 9	Unmanned	10/25/2018	18:41:38
Falcon 9	Unmanned	11/27/2018	05:25:14
Falcon 9	3P	01/01/2019	15:14:32
Falcon 9	Unmanned	02/03/2019	01:58:08
Falcon 9	Unmanned	03/08/2019	12:41:44
Falcon 9	Unmanned	04/10/2019	23:25:20
Falcon 9	3P	05/13/2019	10:08:56
Falcon 9	Unmanned	06/15/2019	20:52:32
Falcon 9	Unmanned	07/18/2019	07:36:08
Falcon 9	Unmanned	08/20/2019	18:19:44
Falcon 9	3P	09/28/2019	02:38:32
Falcon 9	Unmanned	10/25/2019	15:46:56
Falcon 9	Unmanned	11/27/2019	02:30:32
Falcon 9	3P	01/01/2020	12:19:50
Falcon 9	Unmanned	02/03/2020	23:03:26
Falcon 9	Unmanned	03/08/2020	09:22:54
Falcon 9	Unmanned	04/10/2020	20:06:30
Falcon 9	3P	05/13/2020	06:50:06
Falcon 9	Unmanned	06/15/2020	17:53:42
Falcon 9	Unmanned	07/18/2020	04:17:18
Falcon 9	Unmanned	08/20/2020	15:00:54
Falcon 9	3P	09/28/2020	23:19:42
Falcon 9	Unmanned	10/25/2020	12:28:06
Falcon 9	Unmanned	11/27/2020	23:11:42
Falcon 9	3P	01/01/2021	09:25:08
Falcon 9	Unmanned	02/03/2021	20:08:44
Falcon 9	Unmanned	03/08/2021	06:52:20
Falcon 9	Unmanned	04/10/2021	17:35:56
Falcon 9	3P	05/13/2021	04:19:32
Falcon 9	Unmanned	06/15/2021	15:03:08
Falcon 9	Unmanned	07/18/2021	01:46:44
Falcon 9	Unmanned	08/20/2021	12:30:20
Falcon 9	3P	09/28/2021	20:49:08
Falcon 9	Unmanned	10/25/2021	09:57:32
Falcon 9	Unmanned	11/27/2021	20:41:08

Appendix 1A: List of Modules Added to ISS

Date Launched	Corresponding Fiscal Year	Spacecraft	Mass (kg)
1998/11/20	1999	Zarya	19323
1998/12/04	1999	Unity PMA-1 & PMA-2	11612
2000/10/11	2001	Z1 Truss PMA-3	8755
2000/11/30	2001	P6 Truss Solar Arrays	15824
2001/02/07	2001	Destiny	14515
2001/03/08	2001	ESP-1	7851
2001/04/19	2001	Canadarm2	4899
2001/07/12	2001	Quest	6064
2001/09/14	2001	Pirs	3580
2002/04/08	2002	S0 Truss	13970
2002/06/05	2002	Mobile Base System	1450
2002/10/07	2003	S1 Truss	14120
2002/11/23	2003	P1 Truss	14000
2005/07/26	2005	ESP-2	2676
2006/09/09	2006	P3/P4 Truss Solar Arrays	15900
2006/12/09	2007	P5 Truss	1818
2007/06/08	2007	S5 Truss ESP-3	12598
2007/10/23	2008	Harmony P6 Truss (Relocation)	14288
2008/02/07	2008	Columbus	12800
2008/03/11	2008	Dextre ELM-PS	4200
2008/05/31	2008	JEM-PM	15900
2008/05/31	2008	JEM-RMS	970
2009/03/15	2009	S6 Truss Solar Arrays	15900
2009/07/15	2009	JEM-EF	4100
2009/11/10	2010	Poisk	3670
2009/11/16	2010	ExPRESS Logistics Carrier 1&2	8890
2010/02/08	2010	Cupola	1800
2010/02/08	2010	Tranquility	12247
2010/05/14	2010	Rassvet	5075
2011/02/24	2011	Leonardo	4082
2011/02/24	2011	ExPRESS Logistics Carrier 4	4445
2011/05/16	2011	AMS-02	6731
2011/05/16	2011	ExPRESS Logistics Carrier 3	4445

*Note: We only took the data from the spacecrafts that left from the US because we are subtracting the launching data from the fiscal year funds. Thus, we do not need to consider all the Russian spacecrafts
**Note: Dextre mass is already accounted for in the Canadarm 2 launch

Appendix 1B: ISS Basic Configuration Visual (As of January 2007)



Source: http://www.nasa.gov/images/content/166624main_iss_config_012007.jpg

Appendix 2: List of Payloads of All Non-Soyuz ISS Missions

Launch Year	Spacecraft/Mission (Unmanned or Manned)	Payload (lbs)
2000	Zvezda ISS-1R (U)	42000
2000	ISS-1P (U)	5200
2000	ISS-2P (U)	5200
2000	STS-101 (M)	3970
2000	STS-106 (M)	22530
2000	STS-92 (M)	2970
2000	STS-97 (M)	17430
2001	ISS-3P (U)	5200
2001	ISS-4P (U)	5200
2001	ISS-5P (U)	5200
2001	Pirs ISS-4R (U)	7900
2001	STS-98 (M)	32000
2001	STS-102 (M)	12700
2001	STS-100 (M)	10800
2001	STS-104 (M)	18170
2001	STS-105 (M)	20000
2001	STS-108 (M)	9000
2002	ISS-7P (U)	5200
2002	ISS-8P (U)	5200
2002	ISS-9P (U)	5200
2002	STS-110 (M)	28950
2002	STS-111 (M)	26580
2002	STS-112 (M)	27720
2002	STS-113 (M)	27510
2003	ISS-10P (U)	5200
2003	ISS-11P (U)	5200
2003	ISS-12P (U)	5200
2004	ISS-13P (U)	5200
2004	ISS-14P (U)	5200
2004	ISS-15P (U)	5200
2004	ISS-16P (U)	5200
2005	ISS-17P (U)	5200
2005	ISS-18P (U)	5200
2005	ISS-19P (U)	5200
2005	ISS-20P (U)	5200
2005	STS-114 (M)	29725
2006	ISS-21P (U)	5200
2006	ISS-22P (U)	5200
2006	ISS-23P (U)	5200
2006	STS-121 (M)	34885
2006	STS-115 (M)	32174
2006	STS-116 (M)	28000
2007	ISS-24P (U)	5200
2007	ISS-25P (U)	5200
2007	ISS-26P (U)	5200
2007	ISS-27P (U)	5200
2007	STS-117 (M)	42070
2007	STS-118 (M)	30940
2007	STS-120 (M)	38000
2008	ISS-28P (U)	5200
2008	ISS-ATV1 (U)	5060

2008	ISS-29P (U)	5200
2008	ISS-30P (U)	5200
2008	ISS-31P (U)	5200
2008	STS-122 (M)	38160
2008	STS-123 (M)	37290
2008	STS-124 (M)	32600
2008	STS-126 (M)	38300
2009	ISS-32P (U)	5200
2009	ISS-33P (U)	5200
2009	ISS-34P (U)	5200
2009	ISS-HTV1 (U)	9900
2009	ISS-35P (U)	5200
2009	Poisk ISS-5R (U)	6200
2009	STS-119 (M)	37380
2009	STS-127 (M)	30080
2009	STS-128 (M)	37420
2009	STS-129 (M)	35330
2010	ISS-36P (U)	5200
2010	ISS-37P (U)	5200
2010	ISS-38P (U)	5200
2010	ISS-39P (U)	5200
2010	ISS-40P (U)	5200
2010	STS-130 (M)	39010
2010	STS-131 (M)	33800
2010	STS-132 (M)	32170
2011	ISS-HTV2 (U)	11685
2011	ISS-41P (U)	5200
2011	ISS-ATV2 (U)	15620
2011	ISS-42P (U)	5200
2011	ISS-43P (U)	5200
2011	ISS-44P (U)	5200
2011	ISS-45P (U)	5200
2011	STS-133 (M)	36514
2011	STS-134 (M)	34760
2011	STS-135 (M)	28418

*Note: Soyuz missions are excluded because it only has a payload of 220 pounds, making its payload comparatively negligible

** Note: After the Columbia crash in 2003, the US space shuttle program was put on hold for two years, canceling all its manned flights.

Appendix 3: Flight Times of Soyuz Missions

Spacecraft	Launch Time	Docking Time	Flight Time (Launch-Docking) (min)
ISS-1P	6/8/2000 18:26:00	8/8/2000 20:12:00	2986
ISS-2P	11/16/2000 1:32:00	11/18/2000 3:47:00	3039
ISS-3P	2/26/2001 8:09:00	2/28/2001 9:50:00	2981
ISS-4P	5/20/2001 22:32:00	5/23/2001 0:24:00	2992
ISS-5P	8/21/2001 9:24:00	8/23/2001 9:51:00	2907
ISS-4R	9/14/2001 22:35:00	9/17/2001 1:05:00	3030
ISS-6P	11/26/2001 18:24:00	11/28/2001 19:43:00	2959
ISS-7P	3/21/2002 20:13:00	3/24/2002 20:57:00	4364
ISS-8P	6/26/2002 5:36:00	6/29/2002 6:23:00	4367
ISS-9P	9/25/2002 16:58:00	9/29/2002 17:00:00	5762
SS-10P	2/2/2003 12:59:00	2/4/2003 14:49:00	2990
ISS-11P	6/8/2003 10:34:00	6/11/2003 11:15:00	4361
ISS-12P	8/29/2003 1:48:00	8/31/2003 3:40:00	2992
ISS-13P	1/29/2004 11:58:00	1/31/2004 13:13:00	2955
ISS-14P	5/25/2004 12:34:00	5/27/2004 13:54:00	2960
ISS-15P	8/11/2004 5:03:00	8/14/2004 5:03:00	2880
ISS-16P	12/23/2004 22:19:00	12/25/2004 23:58:00	2979
ISS-17P	2/28/2005 19:09:00	3/2/2005 19:10:00	2881
ISS-18P	6/16/2005 23:09:00	6/19/2005 0:45:00	2976
ISS-19P	9/10/2005 9:08:00	9/10/2005 10:42:00	2974
ISS-20P	12/21/2005 18:38:00	12/23/2005 19:46:00	2948
ISS-21P	4/24/2006 16:03:00	4/26/2006 16:12:00	2889
ISS-22P	6/24/2006 15:08:00	6/26/2006 16:24:00	2956
ISS-23P	10/23/2006 13:41:00	10/26/2006 14:28:00	4367
ISS-24P	1/18/2007 2:12:00	1/20/2007 3:58:00	2987
ISS-25P	5/12/2007 3:25:00	5/15/2007 5:10:00	4425
ISS-26P	8/2/2007 17:34:00	8/5/2007 18:40:00	4386
ISS-27P	12/23/2007 7:12:00	12/26/2007 8:14:00	4382
ISS-28P	2/5/2008 13:02:00	2/7/2008 14:30:00	2968
ISS-29P	5/14/2008 20:22:00	5/16/2008 21:39:00	2957
ISS-30P	9/10/2008 19:50:00	9/17/2008 18:43:00	10013
ISS-31P	11/26/2008 12:38:00	11/30/2008 12:28:00	5750
ISS-32P	2/10/2009 5:49:46	2/13/2009 7:18:00	4408
ISS-33P	5/7/2009 18:37:09	5/12/2009 19:24:23	7247
ISS-34P	7/24/2009 10:56:53	7/29/2009 11:12:00	7215
ISS-35P	10/15/2009 1:14:37	10/18/2009 1:40:00	4345
ISS-5R	11/10/2009 14:22:04	11/12/2009 15:44:00	2962
ISS-36P	2/3/2010 3:45:31	2/5/2010 4:26:00	2920
ISS-37P	4/28/2010 17:15:09	5/1/2010 18:32:00	4397
ISS-38P	6/30/2010 15:35:05	7/4/2010 16:17:00	5802
ISS-39P	9/10/2010 10:22:58	9/12/2010 11:57:00	2974
ISS-40P	10/27/2010 15:11:50	10/30/2011 16:36:00	4404
ISS-41P	1/28/2011 1:31:39	1/30/2011 2:39:00	2947
ISS-42P	4/27/2011 13:05:22	4/29/2011 14:28:00	2963
ISS-43P	6/21/2011 14:38:15	6/23/2011 16:37:00	2999
ISS-45P	10/30/2011 10:11:13	11/2/2011 11:41:00	4410

Appendix 4A: STS-133 Launch Windows

DATE.......WINDOW OPEN...IN PLANE......WINDOW CLOSE..DOCKING
02/24/11...04:45:27 PM...04:50:27 PM...04:55:27 PM...Flight Day 3
02/25/11...04:19:44 PM...04:24:44 PM...04:29:45 PM...FD 3
02/26/11...03:57:11 PM...04:02:11 PM...04:07:11 PM...FD 3
02/27/11...03:31:29 PM...03:36:29 PM...03:41:29 PM...FD 3
....03:44:38 PM...FD 4
02/28/11...03:08:57 PM...03:13:57 PM...03:18:57 PM...FD 3
03/01/11...02:46:46 PM...02:48:15 PM...02:53:15 PM...FD 3
....02:56:24 PM...FD 4
03/02/11...02:20:43 PM...02:25:43 PM...02:30:43 PM...FD 3
03/03/11...02:03:24 PM...02:00:02 PM...02:05:02 PM...FD 3**
....02:08:11 PM...FD 4
03/04/11...01:32:29 PM...01:37:29 PM...01:42:29 PM...FD 3
03/05/11...01:09:56 PM...01:14:56 PM...01:19:56 PM...FD
03/06/11...12:44:15 PM...12:49:15 PM...12:54:15 PM...FD 3

** In-plane launch time precedes the planar open due to phasing

Appendix 4B: STS-135 Launch Windows

DATE.......WINDOW OPEN...IN PLANE......WINDOW CLOSE..DOCKING/NOTES AM...FD 4 -- NO LAUNCH BETWEEN 07/11-15 DUE TO DELTA 4 LAUNCH CONFLICT --- Mon 07/11...10:10:58 AM...10:15:58 AM...10:20:58 AM...FD 3 ....10:24:16 AM...FD 4 Tue 07/12...09:46:34 AM...09:50:16 AM...09:55:16 AM...FD 3 ....09:56:18 AM...FD 3 ....09:58:27 AM...FD 4 Wed 07/13...09:22:42 AM...09:27:42 AM...09:32:42 AM...FD 3 ....09:35:57 AM...FD 4 Thu 07/14...09:00:10 AM...09:05:10 AM...09:10:10 AM...FD 3 Fri 07/15...08:34:28 AM...08:39:28 AM...08:44:28 AM...FD 3 ....08:47:39 AM...FD 4 -- SHUTTLE LAUNCH WINDOW RE-OPENS AFTER DELTA 4 LAUNCH -- Sat 07/16...08:11:54 AM...08:16:54 AM...08:21:54 AM...FD 3 ....08:25:10 AM...FD 4 Sun 07/17...07:49:22 AM...07:54:22 AM...07:59:22 AM...FD 3 Mon 07/18...07:23:39 AM...07:28:39 AM...07:33:39 AM...FD 3 ....07:36:52 AM...FD 4 Tue 07/19...07:01:06 AM...07:06:06 AM...07:11:06 AM...FD 3 ....07:14:22 AM...FD 4 Wed 07/20...06:38:34 AM...06:43:34 AM...06:48:34 AM...FD 3 Thu 07/21...06:12:51 AM...06:17:51 AM...06:22:51 AM...FD 3 ....06:26:04 AM...FD 4 Fri 07/22...05:50:18 AM...05:55:18 AM...06:00:18 AM...FD 3 ....06:03:36 AM...FD 4 Sat 07/23...05:27:47 AM...05:32:47 AM...05:37:47 AM...FD 3 Sun 07/24...05:02:03 AM...05:07:03 AM...05:12:03 AM...FD 3 ....05:15:17 AM...FD 4 Mon 07/25...04:39:30 AM...04:44:30 AM...04:49:30 AM...FD 3 ....04:52:49 AM...FD 4 Tue 07/26...04:18:19 AM...04:18:49 AM...04:23:49 AM...FD 3 ** ....04:26:59 AM...FD 3 Wed 07/27...03:51:15 AM...03:56:15 AM...04:01:15 AM...FD 3 ....04:04:30 AM...FD 4 Thu 07/28...03:28:43 AM...03:33:43 AM...03:38:43 AM...FD 3 ....03:41:08 AM...FD 4 * Two window panes, both for flight day 3 dockings; in-plane time precedes window open ** Two window panes, both for flight day 3 dockings

<u>Appendix 5:</u> TI-84 Program used to Determine Launch Times

```
: 0 → H
: 0 → M
: Prompt Y, N
: (365.25)(Y-1)+N → A
: 734214.5 → B
: A – B → C
: 1448C → D
: Lbl 1
: If D ≤ 86400
: Then
: Goto 2
: Else
: D – 86400 → D
: Goto 1
: Lbl 2
: IF D ≤ 50400
: Then
: 50400 – D → D
: Goto 3
: Else
: 136800–D→D
: Goto 3
: Lbl 3
: If D > 3599
: Then
: D-3600 → D
: H+1 → H
: Goto 3
: Else
: Goto 4
: Lbl 4
: If D > 59
: Then
: D-60 → D
: M+1 → M
: Goto 4
: Else
: Goto 5
: Lbl 5
: Disp H, M, D
```

Appendix 6: Bibliography

AFP. "Space Station to Be Sunk After 2020." *Discovery News*. Discovery Communications, LLC, 27 July 2011. Web. 12 Nov. 2011. <http://news.discovery.com/space/space-station-end-ocean-110727.html>.

"Athena - Specifications." *Space and Tech*. Andrews Space & Technology, 2001. Web. 12 Nov. 2011. <http://www.spaceandtech.com/spacedata/elvs/athena_specs.shtml>.

"Atlas 5 Rocket." *Dark Government*. Dark Government, 2011. Web. 12 Nov. 2011. <http://www.darkgovernment.com/news/atlas-5-rocket/>.

"Atlas V - Specifications." *Space and Tech*. Andrews Space & Technology, 2001. Web. 12 Nov. 2011. <http://www.spaceandtech.com/spacedata/elvs/atlas5_specs.shtml>.

Behrens, Carl E. "The International Space Station and the Space Shuttle." *Congressional Research Service*. Congress, 18 Mar. 2009. Web. 13 Nov. 2011. <http://www.fas.org/sgp/crs/space/RL33568.pdf>.

Bizony, Piers. *Island in the Sky: Building the International Space Station*. London: Aurum, 1996. Print.

Bond, Peter. *The Continuing Story of the International Space Station*. London: Springer, 2002. Print.

"Combined White Knight/SpaceShipOne Flight Tests." *Scaled Composites*. Scaled Composites, LLC., 2011. Web. 13 Nov. 2011. <http://www.scaled.com/projects/tierone/combined_white_knight_spaceshipone_flight_tests>.

De Selding, Peter B. "NASA Funds Keep August Debut of Orbitals Taurus 2 on Track." *Space News*. Imaginova Corp., 17 Feb. 2011. Web. 12 Nov. 2011. <http://www.spacenews.com/launch/110217-nasa-funds-taurus2-track.html>.

Duggins, Pat. *Final Countdown: NASA and the End of the Space Shuttle Program*. Gainesville, FL: University of Florida, 2007. Print.

Edwards, Bradley C., and Eric A. Westling. *The Space Elevator*. Houston, TX: BC Edwards, 2003. Print.

"Falcon 9 Overview." *Space Exploration Technologies*. Space Exploration Technologies Corp., 2011. Web. 12 Nov. 2011. <http://www.spacex.com/falcon9.php>.

"Falcon Heavy Overview." *Space Exploration Technologies*. Space Exploration Technologies Corp., 2011. Web. 12 Nov. 2011. <http://www.spacex.com/falcon_heavy.php>.

"Fiscal Year 2012 Budget Estimates." *NASA*. US Government Office of Management and Budget, 2011. Web. 13 Nov. 2011. <http://www.nasa.gov/pdf/516674main_NASAFY12_Budget_Estimates-Overview-508.pdf>.

Harland, David M., and John E. Catchpole. *Creating the International Space Station*. New York: Praxis, 2002. Print.

Hartmut, Frommert. "International Space Station Flight Schedule." *Spider*. SEDS, 8 Nov. 2011. Web. 13 Nov. 2011. <http://spider.seds.org/shuttle/iss-sche.html>.

"International Space Station." *NASA*. US Government Office of Management and Budget, 2003. Web. 13 Nov. 2011. <http://www.nasa.gov/pdf/1977main_iss.pdf>.

"The International Space Station." *NASA*. US Government Office of Management and Budget, 2005. Web. 13 Nov. 2011. <http://www.nasa.gov/pdf/55411main_28%20ISS.pdf>.

Mosher, Dave. "Space Elevator." *The Spaceward Foundation*. The Spaceward Foundation, 2008. Web. 13 Nov. 2011. <http://www.spaceward.org/elevator>.

Mould, David. "Statement of NASA Administrator Michael Griffin on Aug. 18 Email." *NASA*. NASA, 7 Sept. 2008. Web. 12 Nov. 2011. <http://www.nasa.gov/home/hqnews/2008/sep/HQ_08220_griffin_statement_email.html>.

"National Aeronautics and Space Administration." *NASA*. US Government Office of Management and Budget, 2011. Web. 13 Nov. 2011. <http://www.nasa.gov/pdf/516675main_NASAFY12_Budget_Estimates-508.pdf>.

"Physical Properties of Carbon Nanotubes." *MSU Physics and Astronomy Department*. Michigan State University. Web. 13 Nov. 2011. <http://www.pa.msu.edu/cmp/csc/ntproperties/equilibriumstructure.html>.

"Previous Years' Budgets." *NASA*. US Government Office of Management and Budget, 2011. Web. 13 Nov. 2011. <http://www.nasa.gov/audience/formedia/features/MP_Budget_Previous.html>.

"Reference Guide to the InternatIonal Space Station." *NASA*. NASA, Nov. 2010. Web. 13 Nov. 2011. <http://www.nasa.gov/pdf/508318main_ISS_ref_guide_nov2010.pdf>.

Smitherman, Jr., D.V. "Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium." *Marshall Space Flight Center*. NASA, Aug. 2000. Web. 13 Nov. 2011.

"SpaceX Plans World's Largest Commercial Rocket." *Flight International*. Reed Business Information Ltd, 11 Apr. 2011. Web. 12 Nov. 2011. <http://www.flightglobal.com/news/articles/spacex-plans-worlds-largest-commercial-rocket-355419/>.

"Taurus - Specifications." *Space Exploration Technologies*. Space Exploration Technologies Corp., 2011. Web. 12 Nov. 2011. <http://www.spaceandtech.com/spacedata/elvs/taurus_specs.shtml>.

"U.S. Destiny Laboratory." *NASA*. NASA, 2011. Web. 12 Nov. 2011. <http://www.nasa.gov/mission_pages/station/structure/elements/destiny.html>.

Wade, Mark. "ISS Zarya." *Encyclopedia Astronautica*. Encyclopedia Astronautica, 2011. Web. 12 Nov. 2011. <http://www.astronautix.com/craft/isszarya.htm>.

Wade, Mark. "Kistler K-1." *Encyclopedia Astronautica*. Encyclopedia Astronautica. Web. 12 Nov. 2011. <http://www.astronautix.com/lvs/kislerk1.htm>.

"X-37 Orbital Test Vehicle." *The Official Website of the United States Air Force*. United States Air Force, 03 Mar. 2011. Web. 13 Nov. 2011. <http://www.af.mil/information/factsheets/factsheet.asp?fsID=16639>.

"Zvezda Service Module." *NASA*. NASA, 2011. Web. 12 Nov. 2011. <http://www.nasa.gov/mission_pages/station/structure/elements/sm.html>.