REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30-06-2009

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Cost Effectiveness of On-Orbit Servicing

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
48470255

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZST
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Edwards AFB CA 93524-7160

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RZ-ED-TP-2009-270

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-RZ-ED-TP-2009-270

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (PA #09320).

13. SUPPLEMENTARY NOTES
For presentation at the 2009 AAS/AIAA Astrodynamics Specialist Conference.

14. ABSTRACT

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Mr. Roy Hilton
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	SAR	14	N/A

AAS 09-XXX

COST EFFECTIVENESS OF ON-ORBIT SERVICING

Tiffany Rexius*

This study was performed to model on-orbit servicing (OOS) of a pre-existing Low Earth Orbit and geostationary constellation. A conceptual model of each spacecraft was developed to determine mass and power allocation required based on the mission of the spacecraft. An OOS mass was added to the spacecraft which represented the mass of the components necessary to allow the spacecraft to be docked with. The servicing missions modeled were refueling, replacement of parts, and relocation. The driving factor of cost was sensitivity to OOS mass. For most constellations, OOS was not cost effective unless the OOS mass was very low.

INTRODUCTION

On-orbit servicing (OOS) refers to the manned or unmanned in-space servicing of spacecraft. This can include the repair/replacement of components, relocation of spacecraft, or fluid transfer. OOS has drawn increased interest due to the benefits associated with servicing rather than replacing spacecraft. This analysis was performed to determine if on-orbit servicing could cost effectively correct the occurrence of a component failure, early fuel depletion, wrong orbit insertion, or beginning of life (BOL) failure. On-orbit servicing would only be economically feasible if the cost of a constellation with servicing was less than the constellation would cost with replacing the malfunctioning satellite. The project approach taken was to define specific constellations to be serviced that would reflect different capabilities for the OOS spacecraft. A Low Earth Orbit (LEO) and a Geostationary (GEO) constellation based on existing constellations were chosen. The LEO constellation chosen was designed after the Discoverer II radar constellation design and the GEO constellation was based on the Wideband Global SATCOM (WGS) communication constellation.

The primary reason for defining a specific mission for the constellations was to more accurately base a cost estimate on the payload and to size the relevant subsystems. The pointing constraints and power budget modeled were appropriate for the mission class of each constellation. All servicing was assumed to be completely autonomous. A conceptual model of each spacecraft in the constellation was developed to determine the mass and power allocation required. An OOS mass was added to the spacecraft to represent servicing modifications for docking mechanisms, increased modularity of subsystems for component replacement, and other components that would be CONOPS specific.

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A reliability model was developed from an observed failure rate based on historical data which categorized previous satellite failures by year of occurrence with respect to the spacecraft's percent completion of life. Cost analysis was performed to determine which type of on-orbit serving would be most cost effective. The cost of each constellation was calculated for several different servicing concepts; this was compared to a baseline cost estimate assuming that the constellation was not serviced and any failures resulted in a shorter lifetime/limited coverage of the constellation. Servicing was either scheduled on a regular basis or serviced only when there was a failure, dependent upon the type of on-orbit servicing performed.

SATELLITE DESIGN

A "basic satellite" was designed with detailed sizing of the attitude determination and control[1] (ADC), power[1], and propulsion[2,3] subsystems. The ADC subsystem was sized based on the moment of inertia of the spacecraft which was calculated with the size and mass of the solar array. Disturbances were calculated such as gravity-gradient, solar radiation, magnetic field and aerodynamic forces. These values along with any pointing requirements defined by the mission were used to estimate the size and number of momentum wheels required by the spacecraft for control. The number and type of sensors were also estimated and their power requirements were used to help define the necessary power required.

Power required by each subsystem and the payload were used to determine a BOL power requirement. The degradation of the power supply was calculated based on the altitude and period of the constellation as well as the anticipated depth of discharge. The batteries were sized with a factor of safety and it was assumed that the same power requirements would be needed by all the subsystems during eclipse.

$$Ld = \left(1 - \frac{degradation}{year}\right)^{satellite\ life} \tag{1}$$

$$P_{EOL} = P_{BOL} L_d \tag{2}$$

$$A_{solar\ array} = \frac{P_{sa}}{P_{EOL}} \tag{3}$$

Equation 1 and Equation 2 were used to determine the amount of degradation on the solar array throughout the lifetime of the satellite. This was used to calculate the necessary size of the solar array given in Equation 3. A multi-junction solar array was modeled for all spacecraft with a power output of 301 W/m^2. The batteries chosen were NiH2 with a specific power of 35 W/kg.

The driving factors for the size of the propulsion system were the change in velocity (delta v) budget sized for station-keeping and orbit maintenance[5], and the type of propellant used. The propulsion system was sized either for the bipropellant N2O4/MMH with a specific impulse of 300 sec, or a monopropellant system of hydrazine with a specific impulse of 220 sec. An in-depth sizing of the propulsion system was performed, the tanks and valves were sized based on the volume of propellant necessary to fulfill the ADC subsystem as well as an end of life (EOL) requirement[3,4]. The thickness and mass of the tanks was calculated based on the maximum and allowable pressure. Additional allotments for propellant mass were calculated based on average trapped and uncertainty values for propellant mass[3].

The rest of the subsystems were sized using percent averages based on satellites with similar size and mission[1]. The thermal subsystem was assumed to be 4% of the dry mass of the satellite, the structures and mechanisms subsystem was assumed to be 22% of dry mass, and the thermal/command and data handling subsystems was set at 10% of the dry mass of the satellite.

An OOS mass value was added to represent the additional mass that would be added to the spacecraft for docking mechanisms, increased modularity of subsystems for component replacement, and mechanisms for fluid transfer, etc. The OOS mass value was varied for different cases, but sizing of specific components included in the OOS mass was not conducted.

OOS Spacecraft

The same design process was used to size the servicing spacecraft, also called the OOS spacecraft. The OOS spacecraft was designed depending on the CONOPS that are described in the CONOPS section below. The payload was dependent on the type of servicing mission performed. For refueling the OOS spacecraft would carry a set payload of propellant or a payload of components. An OOS mass value was also added based on percent dry mass but was different than the OOS mass value chosen for the satellite serviced. The ADC, Power, and propulsion subsystems were all sized in detail using the same process and assumptions mentioned previously. An OOS spacecraft that visited more than 1 satellite would have additional propellant based on the total required delta V to service the additional satellites. The propulsion system chosen for the OOS spacecraft was the bipropellant N_2O_4/MMH. The majority of the OOS spacecraft were designed with a lifetime of less than 15 years.

Constellations

The LEO constellation was based loosely on the Discoverer II constellation concept at an altitude of 770 km consisting of 3 planes of 8 satellites. The GEO constellation was modeled after WGS consisting of 1 plane of 6 satellites. The lifetime of all the satellites in the constellations were designed to be 15 years. An overview of the LEO radar constellation and the GEO communication constellation are shown below in Table 1.

Table 1. LEO & GEO Satellite Design.

Category	LEO	GEO
Altitude	770 km	35786 km
Payload Mass	2500 kg	2500 kg
Total Power	2810 W	2805 W
Total Mass	6400 kg	5900 kg
Satellite Cost	$330M	$647M

These single satellite cost estimates were very similar to known values for the Discoverer II and the WGS constellation.

COST MODELING

The cost estimating relationships used were based on historical data and are estimated as being within ±25% of the actual final cost. The subsystem cost was primarily based on mass in FY2000 dollars and then adjusted to FY2005 dollars[1]. The power subsystem cost was driven not only by weight but also by the BOL power requirement. The cost of the separate payloads was calculated depending on the mission of the spacecraft which was either a communication or radar payload. Cost estimates for the integration, assembly and test, the labor and material cost, contractor costs for systems engineering, program management, planning, etc. were added into the total constellation cost. The launch cost was based on FY2005 launch vehicle cost estimates.

The cost of the OOS spacecraft was added to the total constellation cost. For the refueling only case, the cost of a single satellite servicer was to be added for each satellite in the constellation. For a two satellite servicer half of the OOS spacecraft were added to the total constellation cost, and so on.

CONOPS

A variety of servicing scenarios were compiled and then narrowed down to reflect the necessary capability. Five separate servicing categories were analyzed. The cases and their descriptions are listed below in Table 2:

Table 2. Servicing Categories.

Case 0	Business as usual
Case 1	Refueling only
Case 2	Attach Permanently
Case 3	Attach, drop off, and leave
Case 4	Replace/swap

Case 0: Business as Usual

Case 0 was used as the baseline constellation to compare the total cost of the constellations with servicing against. The lifetime of the satellites for the LEO and GEO constellation were assumed to be 15 years and no OOS spacecraft were sized for this case. If there was a failure in Case 0 then the malfunctioning satellite would have to be replaced with the same satellite, and that additional cost would be added to get the total constellation cost.

Case 1: Refueling Only

In Case 1 the propulsion system of the satellites in the constellation was downsized because the spacecraft would be refueled. The propulsion subsystem of the satellites in the constellations was downsized by 33% and it was assumed that each satellite would be refueled once. The OOS spacecraft had an additional mass of 10% of the dry mass of the satellite added to the spacecraft for the ability to service. This was called the OOS mass fraction and for this case would include docking mechanisms and devices for fluid transfer.

Two separate modes of operation were analyzed for the OOS spacecraft. The first was that the OOS servicer would fuel several satellites sequentially, transferring to a transition orbit in between satellites serviced. The payload of the OOS spacecraft was equal to the propellant that it was going to replace. An OOS spacecraft that was going to refuel 3 satellites would have 3 times the payload of a single satellite servicing OOS spacecraft. This servicer was designed to refuel from 1 to 6 satellites. The second mode of operation was that after refueling a satellite the OOS spacecraft would return to a “depot” that was in a parking orbit 100 km away. The OOS spacecraft would stop at the depot to pick up the next payload then transfer from there to the next satellite to be refueled and so on. The depot was not designed, nor was cost analysis performed. This case was briefly investigated for a GEO communication constellation but did not appear to be cost effective such that this case was only analyzed for the LEO radar constellation.

Case 2: Attach Permanently

For Case 2 the OOS spacecraft would attach to the malfunctioning satellite and remain permanently attached. The satellite may only have one servicing. This case assumed that the satellite had a large malfunction, such as early fuel depletion without the ability to be refueled or an attitude determination and control subsystem malfunction. If either of these occurred the life of the satellite would essentially be over since the satellite would no longer be able to accomplish its mission. The servicing spacecraft would permanently dock with the satellite and provide the necessary control such that the satellite would not have to be replaced.

The OOS mass added to this case for both the satellites in the constellation and the OOS spacecraft was larger than in Case 1. The components in the satellites would have to be modular such that any could be taken over by the OOS spacecraft. The OOS spacecraft was also designed to be larger for the ability to remain attached permanently and, if required, assume control of certain malfunctioning subsystems of the satellite. The satellites in the constellation had an OOS mass of 10% the OOS spacecraft had an OOS mass of 20%.

Case 3: Attach, Drop Off, and Leave

For Case 3 an OOS spacecraft would attach to a malfunctioning satellite and replace a component, or add an upgrade that would increase the lifetime or capability of the spacecraft and then leave. No prescheduled visits were assumed. The lifetime of the satellites in the constellation was assumed to be 15 years and this case was analyzed for both the LEO radar and GEO communication constellations.

A 15% OOS mass was added to the spacecraft due to increased modularity and docking compatibility. A 20% OOS mass was assumed for the OOS spacecraft, the same as in Case 2. The servicer was designed for a lifetime of 5 years, and in between servicing the spacecraft would dock at a depot. As mentioned before the depot was not designed and no cost estimate was added to the overall cost of the constellation. The OOS spacecraft was sized to service anywhere between 1 to 5 satellites. Cost analysis was performed with and without the OOS spacecraft stopping by a depot.

Case 4: Replace/Swap

In Case 4 the OOS spacecraft would dock with the malfunctioning satellite and would remove a component and replace it as opposed to Case 3 where the component was added, but nothing was removed. This case was modeled for both the LEO radar and the GEO communication constellations. A 15 year lifetime of the satellites in the constellation was assumed. A 20% OOS mass was added to the satellite due to the increased modularity required. Also a 20% OOS mass fraction was chosen. The servicer was designed for a lifetime of 5 years.

OOS MASS

The servicing missions modeled are listed in Table 3 along with the initial OOS mass estimates for the type of mission and the OOS mass added to the OOS spacecraft.

Table 3. OOS Mass Percentage.

Case	OOS CONOPS	OOS Mass (Satellite)	OOS Mass (Servicer)
0	Business as usual	None	None
1	Refueling only	8%	10%
2	Attach Permanently	20%	20%
3	Attach, drop off, and leave	15%	20%
4	Replace/swap	15%	20%

The OOS mass values vary depending on the amount of modifications to the spacecraft that would be necessary for the type of servicing specified. Some of the OOS mass values listed in Table 3 were varied to reflect the total constellation cost sensitivity to OOS mass.

RELIABILITY MODEL

The reliability model used was based on historical data, which predicted complete loss of mission failures with respect to the percentage of design life. The total number of anomalies verses the percent of design life may be seen below in Figure 1:

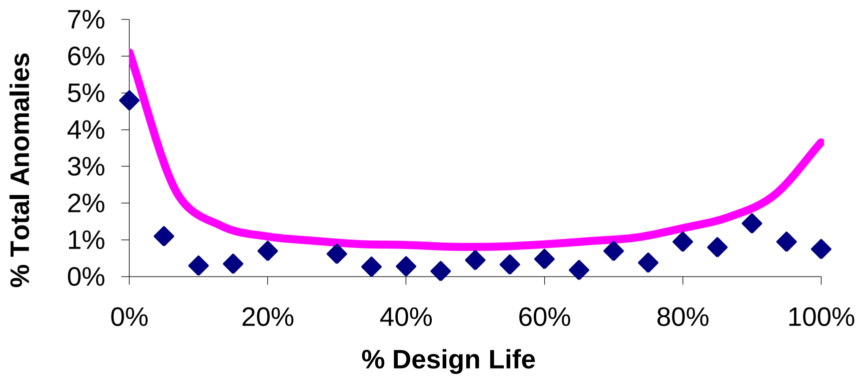

Figure 1. Reliability Model.

The blue dots represent historical data[4,6] of total spacecraft failures and the pink line represents the model prediction of all failures. The pink "all failures" line is slightly higher to represent minor failures which may occur that would not cause an end of life (EOL) for a spacecraft, but would hamper the satellites ability to complete its intended mission. The "all failures" line was designed after an observed failure rate, also known as a bathtub curve which is used in reliability engineering. The higher percentage failure rate at the BOL of the spacecraft is also called infant mortality and is based on there being a larger percentage of failures in the BOL of the spacecraft. The relatively constant middle portion of the trend is based on average failures of a spacecraft. The increase in failures towards the EOL of the spacecraft is due to general wear out. There is around a 16% probability that a spacecraft in the constellation will have a life ending failure.

The failure rate described above and seen in Figure 1 was used to determine the average number of visits. For each on-orbit servicing case a percentage of failures were assumed to be un-serviceable. This fraction was varied depending on the type of serving assumed. If a constellation was designed for only refueling, then any other non-fuel related problems would result in a non-fixable problem.

Table 4. Fraction of Failures Unserviceable.

Case	Fraction Unserviceable	Average # of Visits	% Completion of Life
Case 0	100%	0	91%
Case 1	100%	1.00	91%
Case 2	20%	0.17	97%
Case 3	40%	0.18	94%
Case 4	30%	0.17	95%

The fraction of unserviceable satellites for the Case 0 and Case 1 had a value of 100% because they were not designed to be serviced in the event of a component failure. In the refueling only case there was a prescheduled refueling time. The OOS servicer does not however have the ability to fix a satellite that experienced a component failure. The percent completion of life could not be greater than 100% with the way it was calculated. Case 0 and Case 1 have the same percent completion because they would not be able to be serviced in the event of a component failure.

The fraction unserviceable was chosen to be slightly higher for Case 4 because it was assumed that not all components would be able to be swapped out. For Case 2 there would be very few spacecraft that would be unserviceable because the OOS spacecraft would be designed to attach permanently and take control of some of the malfunctioning components of the spacecraft.

Failure Prediction

A Monte Carlo simulation was performed to predict the failure rate, year of failure, and the percent completion of life as seen in Table 4. An array of random numbers was generated ranging between 0 and 1. The predicted failure rate was used from Figure 1, based on the bathtub curve model. If the random number generated was less than the predicted failure based on the percent completion of the lifetime of the satellite, then it was assumed that a failure occurred in that year. This relationship is shown in Equation 4 and Equation 5.

$$Random\ Number < \ Failure\ Rate_{\%\ Lifetime} = No\ Failure \tag{4}$$

$$Random\ Number > \ Failure\ Rate_{\%\ Lifetime} = Failure \tag{5}$$

If it was predicted that a failure would occur that year, the unserviceable fraction was used to determine if the failure could be fixed or not. These random variables were calculated and averaged over 1000 runs to determine the average lifespan of the spacecraft, as seen in Table 4, as well as the average number of visits. For Case 2, a spacecraft would only be able to be serviced once due to the OOS spacecraft attaching permanently.

In Case 0 and Case 1, if there was a life ending failure experienced by a satellite the cost of a replacement satellite was added to the total constellation cost. If the satellite could be serviced in Case 2, 3 and 4, then the cost of the servicing spacecraft was added to the constellation cost. If there were multiple failures in a constellation then a multiple satellite servicer would decrease the total cost of the constellation as opposed to having single OOS spacecraft every time there was a failure.

RESULTS

Each case was compared with the baseline constellation cost and if applicable the cost of a baseline constellation with replacement satellites if there was a failure. The dashed lines labeled, "Baseline Const. w/ 1 Failure" and "Baseline Const. w/ 2 Failures" are for the baseline constellation cost if there was a failure. This does not take into account the probability of their actually being a failure. The baseline constellation cost is represented by dashed lines on all the plots. The cost of a constellation with servicing is represented by a solid line, and a constellation that includes an OOS spacecraft visiting a depot is represented by a dotted line.

Case 1 Results

The refueling only case was modeled only in LEO. Two separate timeframes were chosen initially to model the cost effectiveness of refueling. The first assumed that the satellite's propulsion system was downsized by 1/3 and visited twice in its lifetime. The second assumed that the propulsion system was downsized by half and was visited once. The first option was not cost effective it was better to have the satellite refueled only once during its lifetime.

An OOS spacecraft was designed to replace around half of the fuel carried by the satellite. The second option was modeled further assuming the propulsion system was downsized by around 50% less than the baseline propellant required. The propellant carried by the OOS spacecraft for servicing was considered its payload. The more satellites serviced, the larger the size of the OOS spacecraft due to the increased payload and the increased delta v, but the fewer OOS spacecraft necessary to refuel the entire constellation.

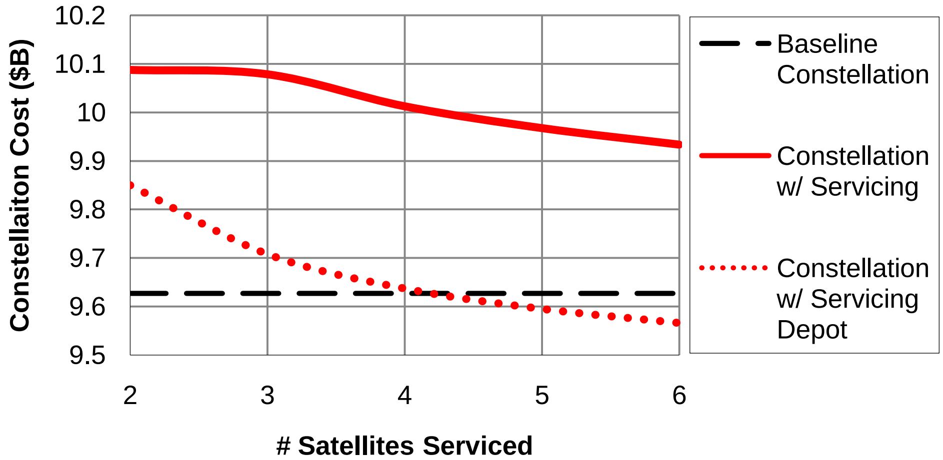

Figure 2. Case 1 Results.

There was a crossover at around 4 satellites serviced for the depot-visiting OOS spacecraft. The cost of the depot was not accounted for such that the depot-visiting OOS spacecraft cost plotted was lower than it would have been otherwise. The cost of the constellation with an OOS spacecraft that could refuel every satellite in the plane of 8 spacecraft would be similar in total cost to the baseline constellation. Due to this the creation of a refueling OOS spacecraft is not necessarily cost-effective.

Case 2 Results

The attach permanently case was modeled in LEO and GEO. The malfunctioning satellite could only be serviced once. The depot-visiting option was not practical for this case. The constellation with servicing cost was calculated as if there was one OOS spacecraft launched per plane of the constellation. The probability that more than one satellite per plane would have a life altering failure was very minimal.

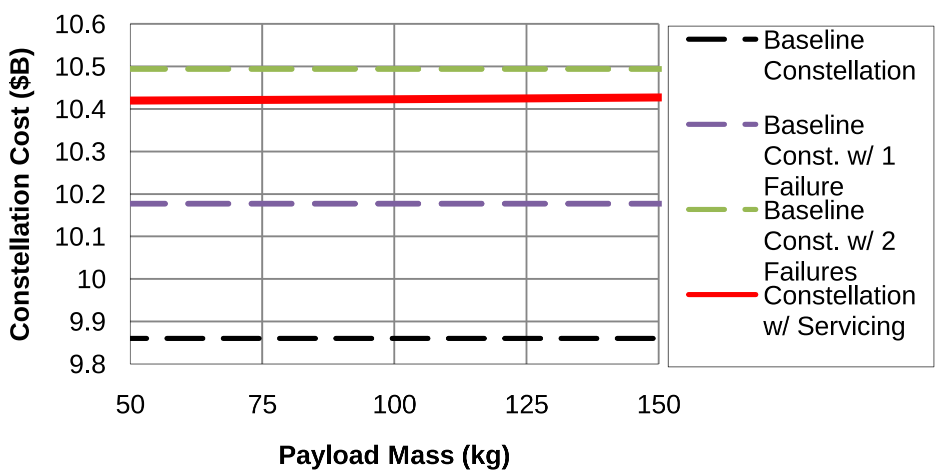

Figure 3. Case 2 LEO Results.

The payload was varied to determine its effect on overall cost, as the replacement of some components would weigh less than others. As can be seen in Figure 3 the total cost the satellite constellation with servicing costs more than the baseline constellation with no failures. The baseline constellation would have to experience at least 2 complete satellite failures that would require replacement for this method to be cost effective. Varying the payload mass slightly increases the OOS cost, but hardly enough to notice.

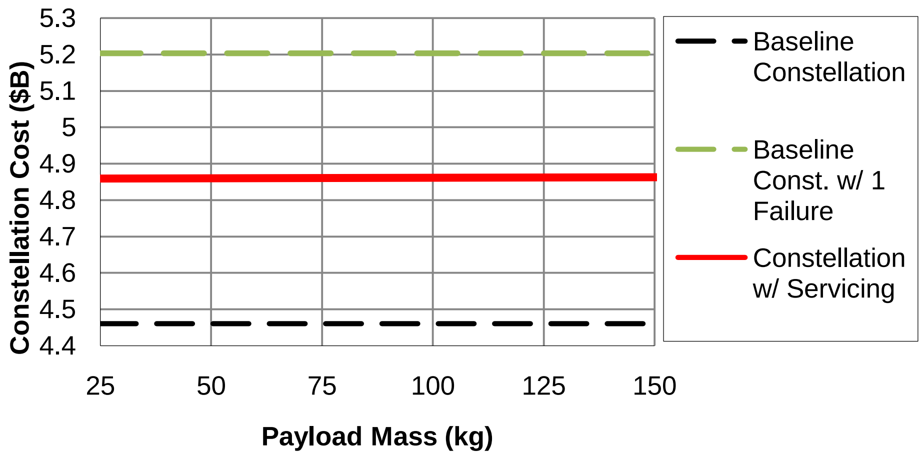

Figure 4. Case 2 GEO Results.

The trend for Case 2 in GEO is very similar to the case in LEO. If the GEO constellation of 6 satellites experienced one complete failure that would have to be replaced, then the cost of the modifying the satellites to have to ability to be serviced would be cost effective. The probability that one in six satellites in the constellation would experience a complete failure is relatively small. From Table 4, the average lifespan of satellites in the baseline constellation is around 91%.

Case 3 Results

The attach, drop off, and leave case was analyzed in a similar manner. The constellation had a 15% satellite OOS mass for the added capability.

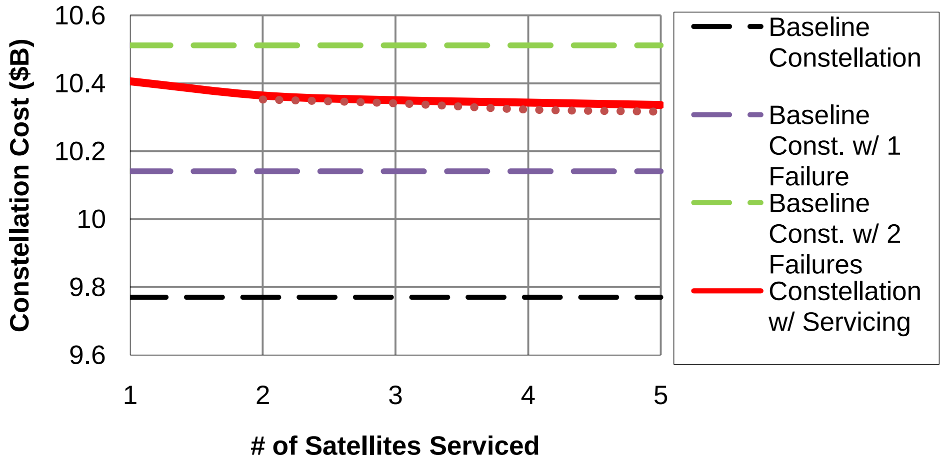

Figure 5. Case 3 LEO Results.

Servicing the constellation would be cost effective if the baseline constellation experienced 2 complete failures as seen in Figure 7. Increasing the number of satellites serviced decreases the cost of the constellation with servicing, but 2 satellites in the baseline constellation would have to be replaced before servicing would be cost effective. The depot option did not decrease overall cost much from the non-deport servicing option.

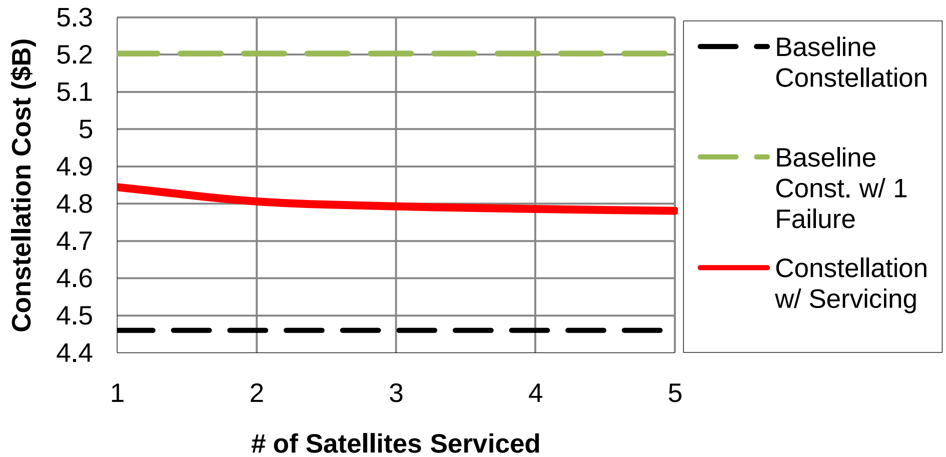

Figure 6. Case 3 GEO Results.

Servicing more than one satellite decreases the overall constellation cost, but not enough to cost less than the baseline constellation. The depot was only analyzed for the LEO constellation. If one satellite in the GEO constellation failed and had to be replaced the servicing would be cost effective. But from the failure analysis there is a 16% chance of that occurring.

Case 4 Results

The replace/swap case assumed an OOS mass fraction of 20%. This was higher due to the increased modularity of the subsystems.

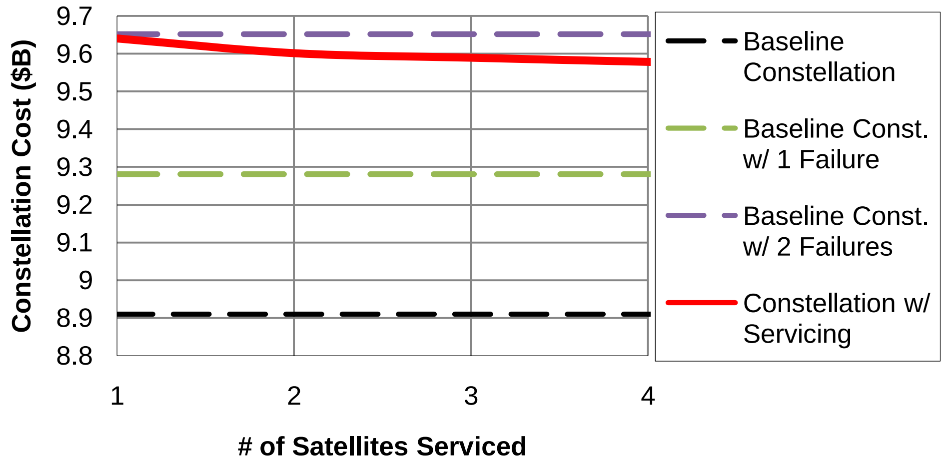

Figure 7. Case 4 LEO Results.

Similarly to the figures above, the servicing option appears cost effective only if there are at least 2 complete satellite failures in the LEO constellation. Visiting additional satellites caused a decrease in overall cost but the decrease began to level out. From the failure prediction model, the odds of a single satellite having a complete failure are around 16%.

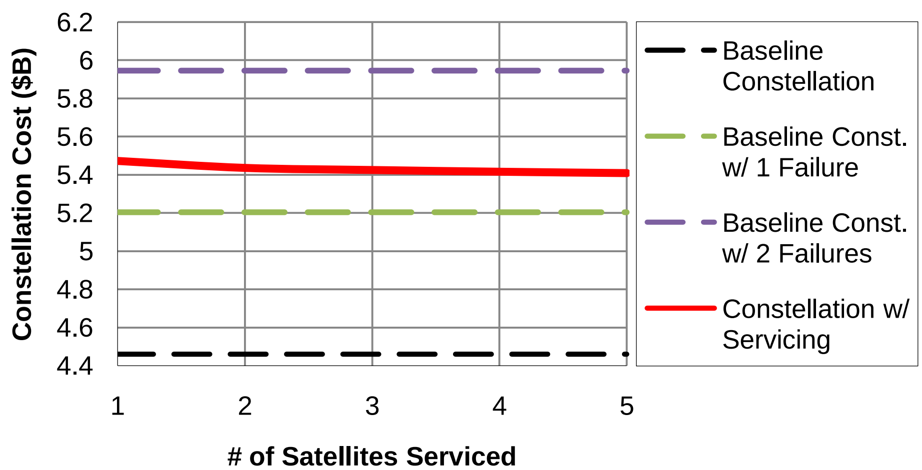

Figure 8. Case 4 GEO Results.

The total constellation cost with servicing slowly decreases with the number of satellites serviced, but still costs more than the baseline case. The GEO constellation would have to have two or more complete satellite failures for the servicing option to be cost effective.

CONCLUSION

For on-orbit servicing to be cost effective there need to be around two complete satellite failures per constellation. This varies slightly depending on the type of OOS mission profile being performed. Downsizing the propulsion system on satellites for scheduled refueling does not appear to decrease the overall cost of the constellation.

Varying the mass of the payload carried for component replacement missions had a very minimal effect on total constellation cost. From the Monte Carlo analysis the probability of a satellite failing sometime during its lifetime is around 16%, such that most servicing missions in LEO do not appear cost effective. Due to the higher launch cost to lift a payload to GEO the servicing option appears slightly more cost effective for the GEO constellation. One satellite failure in a GEO constellation would be more cost effective to fix rather than replace with the OOS mass fractions used.

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