ECONOMIC JUSTIFICATION FOR RETIREMENT OF GEOSYNCHRONOUS COMMUNICATION SATELLITES VIA SPACE TUGS

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Abstract—A United Nations policy mandates that geostationary earth orbit (GEO) satellites should be placed in a disposal orbit at the end of their operational lives. Current procedures utilize spacecraft residual propellant and represent a major life-limiting factor for GEO satellites. An alternative approach would be to allow a space tug to capture the satellites and perform the transfer after all of the fuel has been exhausted. This extended lifetime can provide significant additional revenue to the satellite operators. Before committing to such a capability, the lifecycle costs of a space tug infrastructure must be carefully weighed against the opportunity costs of the current retirement practice. This paper investigates the questions of tug costs, perceived benefits, and service fee. It proposes that the service fee should be charged as a percentage of the additional revenue received by the satellite operators and analyses how cost estimation uncertainties affect the value of on-orbit tugging. It appears that there is a potential, albeit limited, opportunity for space tugging of the 10-20 most valuable GEO assets. Future trends that are likely to impact the case for space tugging are the increased use of electrical propulsion systems, improved residual fuel estimation techniques as well as the development of clusters and swarms of smaller communications satellites.

1. MOTIVATION

Commercial telecommunications represent approximately 75% of the entire GEO sector. They are large and expensive, but they are also extremely profitable. Their operational life spans between 12 and 15 years, and these limits are usually imposed by the amount of fuel available for stationkeeping. All on-board systems might be capable of functioning properly for a long time, but without fuel the satellite cannot maintain its operational orbit—it drifts and becomes useless. To mitigate the problem of accumulating space debris, a United Nations policy requires that "at the end of operational life, geostationary spacecraft should be placed in a disposal orbit that has a perigee at least 300 km above the geostationary orbit."[1] To comply with this regulation, satellites use their residual propellant for the transfer and often sacrifice at least six months[2] of their design lifetime, which corresponds to a significant loss of economic value.

If on-orbit tugging services are available, GEO satellites can be left in operational orbit until their propellant supplies are completely exhausted and then transferred to a disposal orbit by a tug. This alternative will bring additional revenue to the satellite operators due to the extended use of on-board transponders. For a typical commercial communication satellite that has 24 Ku-band and 24 C-band transponders with

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bandwidths of 36 MHz, the revenue that the satellite owner will earn from six extra months of satellite operation is more than \$50M. Thus, as long as the fee for the tugging mission is less than the expected additional profit, a demand for tugging services in GEO can be expected.

2. ASSUMPTIONS

The following assumptions were used throughout the analysis of the GEO satellite retirement case:

1. The tug has universal capture capability; it can capture any potential client in GEO.
2. The tug is owned by a commercial organization and can be launched on any vehicle, US or foreign, that is large enough and can inject the space tug into GTO.
3. The NASA Spacecraft/Vehicle Level Cost Model[3] is used for cost estimation.
4. Three levels of autonomy are investigated: teleoperation, supervision, and full autonomy. Their technology readiness level (TRL) uncertainties are assumed to be 0%, 10% and 40%, respectively.[4]
5. A ΔV of 20 m/s is required for capturing or releasing the client satellites.
6. The tug enters its operational stage in 2007 and has a design life of 10 years.
7. Only GEO commercial communications satellites (both US and foreign) are considered as potential targets for tugging.
8. The clients will accept the service if it is expected to provide additional profit greater than zero.
9. Satellites sacrifice at least six months of their operational lifetime if they use their own propellant to move to a graveyard orbit (at least 300 km above the GEO belt).
10. Satellites use chemical propellant (Isp = 150÷450 s). Tugging would be of no value for satellites that use, for example, electric propulsion, since propellant would most probably not be the life-limiting factor then.
11. Taxes (federal, etc.) and interest are not accounted for when calculating profit.
12. Satellites are fully depreciated when end-of-life (EOL) criterion[‡] is reached.

3. COMPETING OPTIONS

There are two choices for the satellite operator to select from: retire the satellite using its own fuel or pay a tug service to do the transfer. Analyzing these options in greater detail, we see that there are two distinct cases, depending on whether or not there

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[‡] One method to predict the remaining amount of propellant is based on the equation of state of an ideal gas, $p \cdot V = n \cdot R \cdot T$, and utilizes transducers for measuring the pressure and temperature of the inert gas in the propellant tanks. A second method relies on the careful measurement and recording of the thruster time for every maneuver, and the consumed propellant is then calculated from the mass flow rate expressed in terms of the pressure. A third method is based on the measured dynamics of the spacecraft after a stationkeeping maneuver to determine its total mass properties system ID. (http://www.aticourses.com/rocket_tutorial.htm) Even if these three independent methods are applied together to check one another, there is still uncertainty as to the precise quantity of remaining fuel, so a safety margin adds to the penalty.

is a replacement satellite (owned by the same agency) that is ready to be launched to the same slot. If a replacement is not available, the questions is whether to use the satellite's residual propellant for moving to graveyard orbit upon reaching the end-of-life criterion (or even before that), or whether to let a tug do that and collect extra revenue while paying some fee. The first option results in service disruption and no additional profit, while the second one can bring positive, negative, or zero profit to the satellite operator, depending on the fee charged and the revenue produced by the satellite during the extended period of operation. Tugging is assumed to be of value to the satellite operator if it produces any amount of profit that is greater than zero.

There are two cases to be considered when a replacement is available. If it is ready and waiting on Earth, its launch will eventually lead to a positive profit for the satellite operator (provided no failures occur or the satellite is insured) but the amount will depend on how many months after the retirement of the old satellite the launch takes place. If the replacement is already in orbit (at some other longitude in the GEO belt) before the EOL criterion is reached, it will be already producing profit for the satellite owners. Tugging, on the other hand, may bring either greater, smaller, or equal profit—the numbers will differ for each particular satellite. Tugging would be of value to the satellite operator only if it provides a profit greater than the profit coming from the replacement satellite. Figure 1 presents these options. For a given satellite, $P_{S1} < P_{S2} < P_{S3}$. The question is how P_T compares to these three satellite profits.

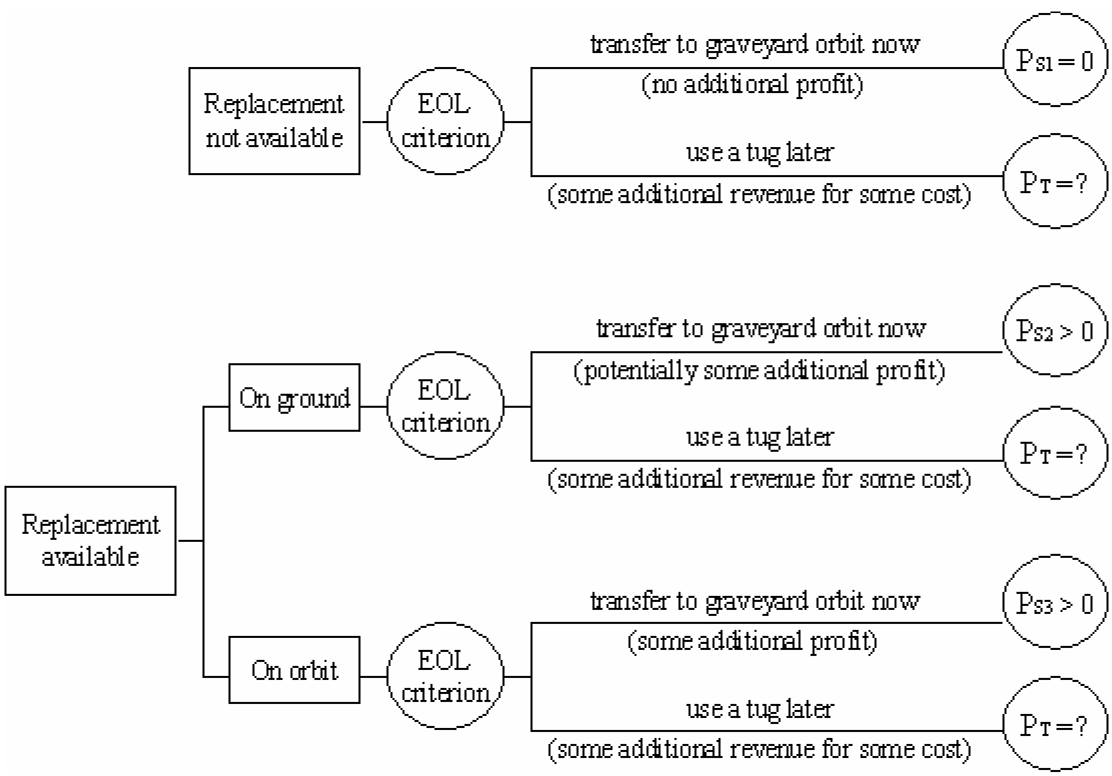

Figure 1: Possible Options and Their Outcomes

If the satellite operator decides to use tugging services, he must enter into a binding contract with the tug operator before the spacecraft reaches the end-of-life criterion. In order for the tugging service to be profitable for its provider, the charged fee must cover the cost of the mission and part of the cost for design, manufacturing, and launching of the tug. In other words, the extra revenue resulting from extending the operational life of a satellite will not come to the satellite operator for free. Before we attempt to estimate what fee should be charged for the service, we need to understand the market trends in the satellite industry.

4. MARKET STATISTICS AND FORECAST

To be able to predict the demand for space tugging, we first need to predict the demand for satellite services. Using statistical and forecasted trends provided by some of the leading aerospace consulting companies and adopting the most conservative numbers, three main conclusions were derived from the analysis of the current state of the satellite industry:

1. As long as the demand for satellite services does not dramatically decrease, there can be a potential market for tugging services.[5]
2. On average, about 15 client-satellites per year can be expected.
3. The transponder capacity of near-future communications satellites will not exceed the capacity of the satellites being replaced.[6]

5. FEE ESTIMATION APPROACH

Before the price of the service is estimated, it is important to decide whether the fee will be fixed or variable. The problem with selecting a fixed price is that it will be overly affordable for some operators and too expensive for others. This restricts the tugging service to clients with relatively high revenues, thus limiting the number of potential clients. Even if the fee is set to be lower than the expected revenue of all satellite operators, there still exists a risk that something will go wrong with the satellite during the extended period of work, preventing the expected revenue from being reached. In short, there is a vast uncertainty as to whether the investment will pay off, and it is therefore doubtful that many of the potential clients will be interested in the service. Conversely, a variable tugging fee does not hold a similar investment risk for the satellite operators if it is estimated as a percentage of what has actually been gained by them as additional revenues resulting from the life extension of their satellites. Therefore, we recommend that the tug operator charge a variable fee. As commonly done in most businesses, the fee should be prepaid based on preliminary estimations and then adjusted upon satellite retirement, using the actual revenue figures. If a failure affecting the revenue flow occurs after the contract has been signed, the client is required to pay only a set minimum fee, which corresponds to a zero profit for the provider.

To estimate what the charged percentage should be, the following steps need to be completed:

1. Calculate the <u>utility</u> of various space tug architectures differing in terms of propellant type, autonomy level, and grappling mechanism and sensors used.

2. Using NASA' Spacecraft/Vehicle Level Cost Model and accounting for cost of fuel, launch, and insurance, calculate the total cost of the designed architectures.
3. Estimate the minimum fee that a tug operator should charge per mission and identify the optimal design on the basis of cost per function.
4. Calculate the maximum profit expected by the satellite operators.
5. Find the "mid-way" fee that would give the tug operator and the satellite operators the same profit.
6. Perform a sensitivity analysis for major factors affecting the calculations.

Reusability is a critical for reducing the minimum fee that should be charged, especially since even a difference of a couple of million dollars affects the number of satellite operators who will be interested in the service (this will be further discussed in the Section 6.2). Fortunately, the majority of the GEO commercial communications satellites lie in one orbital plane; therefore, over its design lifetime, a tug can reach multiple satellites with a ΔV of the order of tens of meters per second. Table 1 shows the maximum number of satellites that can be transferred to graveyard orbit by tugs of various mating capabilities. The calculations use the orbital and physical characteristics of satellites currently in orbit. The key assumptions made in the utilized spacecraft model are that:

1. The grappling mechanism is 65% of the dry mass of the tug.
2. The structure represents 12% of the mass of the tug at launch.
3. A total ΔV of 20 m/s is required for capturing or releasing all client satellites during the lifetime of the tug.
4. The tug uses a storable bipropellant with Isp = 325 sec.

Grappler Capability	Grappler Mass [kg]	Dry Mass [kg]	Biprop Fuel (Cryo) [kg]	Max # Missions [#]
Low	300	1820.60	5805.20	20
Low	400	1912.00	5716.20	18
Medium	500	1954.70	5432.60	16
Medium	600	1958.10	4991.30	14
High	700	2077.80	5015.80	13
High	800	2184.90	4989.50	12

Table 1: Tug Reusability

5.1. Total Utility

The design attributes that were considered are mating capability, accuracy of positioning, adaptability, and timeliness:

1. *Mating capability* is a measure of the capability of the tug to capture a satellite without causing damage. It is influenced by the sophistication of the grappling mechanism, the software capabilities possessed by the tug, and its level of autonomy.
2. *Transfer capability* is a measure of the tug's range of action. In this work, it is quantified in terms of the maximum amount of propellant a tug can carry.
3. *Adaptability* is a measure of how well the system responds to changes in requirements or initial assumptions in terms of ease of response and range of capabilities.

The ease of response is driven by the tug's level of autonomy. Adaptability also depends on the selected propulsion type and parking location of the tug.

4. *Timeliness* is defined as the sum of response time (starting when mission order is received and ending when contact with the satellite is established) and transfer time (from contact establishment to satellite release at the desired destination). The grappler sophistication and autonomy level affect the mating phase of the mission, the parking location influences the response time, and the selected propellant type affects both the response and the transfer times.

Mating capability is the most important attribute in the GEO satellite retirement scenario because, although the tugged satellites are dysfunctional, the tug should avoid 1) creating debris in the GEO belt and endanger the satellites there, and 2) damaging itself, since it is expected to be reusable and serve a number of missions. The rest of the attributes are of lower importance. *Transfer capability* is not a critical issue because the traversed distances are only about 300km one-way and this requires a very small change in velocity. *Timeliness* is also not critical because the satellites are already dysfunctional, so they can wait until the tug becomes available, unless it is desirable to vacate the orbital slot quickly, so that a replacement starts operating as soon as possible. Lastly, *adaptability* is not required, since the reusability of the tug is expected to create sufficient profit, but it would be valuable if a satellite gets stranded in GTO and is unable to reach GEO. The relative weights of the three considered attributes are shown in Table 2 and were used in the calculation of total utility.

Attribute	Weight
Mating Capability	0.4
Accuracy of Positioning	0.2
Adaptability	0.2
Timeliness	0.2

Table 2: Relative Weights of Attributes

The design variables that were considered in this scenario are listed in Table 3.

<table>
<tr><th colspan="2">Design Variable</th><th>Units</th><th>Allowable Settings</th></tr>
<tr><td rowspan="3">Propulsion System</td><td rowspan="3">Isp</td><td rowspan="3">sec</td><td>3000 (electric)</td></tr>
<tr><td>446 (cryogenic bi)</td></tr>
<tr><td>325 (storable bi)</td></tr>
<tr><td rowspan="3">Level of Autonomy</td><td rowspan="3">type</td><td rowspan="3">-</td><td>Teleoperation</td></tr>
<tr><td>Supervision</td></tr>
<tr><td>Full Autonomy</td></tr>
<tr><td rowspan="6">Hardware Sophistication</td><td rowspan="6">M_{grap}</td><td rowspan="6">kg</td><td>300 (low)</td></tr>
<tr><td>400 (low)</td></tr>
<tr><td>500 (medium)</td></tr>
<tr><td>600 (medium)</td></tr>
<tr><td>700 (high)</td></tr>
<tr><td>800 (high)</td></tr>
</table>

Table 3: Design Variables

The results from the tradespace analysis indicated that the optimal space tug for this mission scenario should be initially parked in the GEO belt and controlled through supervision. When the sequence of tugging missions begins, the location where the client satellite is released in graveyard orbit becomes the new parking location. The analysis also suggested that if we did not account for risk and uncertainty, nuclear propulsion would be the optimal choice for this mission scenario. Including the uncertainty factors listed in Section 4.3.1, however, made the storable bipropellant option superior in terms of performance achieved per given cost. The optimal mass and sophistication of the tug's grappling mechanism is selected in Section 5.3.

5.2. Total Cost

The total cost of a space tug is a sum of the following costs:

$$C_t = C_u + C_p + C_l + C_i + C_o + D \tag{1}$$

(see Appendix A: Nomenclature)

5.2.1 Unit Cost

The NASA Spacecraft/Vehicle Level Cost Model calculates the approximate cost of development and production of a spacecraft based on its dry mass. Assuming that there will be a market for the consecutive operation of at least five space tugs of the same family and the learning curve is 95%[7], we can calculate the unit cost, C_U, of a tug.

$$C_u = \frac{C_5}{C_{fu}} \tag{2}$$

Since the NASA cost model assumes some average payload cost, we have chosen to calculate the cost of the grappler separately and then add it to the cost calculated by the model for the remaining dry mass of the tug to obtain the first unit cost. The estimation of the cost associated with mating is based on assumptions for the grappler cost, the sensor capability scaling, and the annual salaries of the software engineering team employed to create the necessary software. The ISS European Robotic Arm can be used as a baseline for calculating the grappler cost for a given mass. The relationships utilized by the NASA spacecraft cost model are approximately:

$$C_{fu} = 3.442 \cdot M_d^{0.55} + 0.3909 \cdot M_d^{0.662} \tag{3}$$

$$C_5 = 4.9139 \cdot M_d^{0.6055} \tag{4}$$

5.2.2 Propellant Cost

The propellant cost is estimated by assuming a type of fuel for each propellant option and multiplying the mass of the necessary propellant by its specific cost measured in \$/kg.

5.2.3 Launch Cost

Launch cost can be calculated by taking the average cost per kilogram for all launch vehicles capable to carry the given wet mass to GTO, excluding the ones known not to carry commercial payloads.

5.2.4 Insurance Cost

The first type of insurance that can be purchased by the tug operator is "transit and pre-launch" insurance, which costs about 0.5% of the tug value. A second type—the "launch and early phase" insurance—covers failures occurring between lift-off and commissioning (the placement of the satellite in operational orbit and subsystem confirmation). We have assumed 10% launch insurance and 9% insurance for early phase failures occurring after separation. The "on-orbit failure" insurance covers the period from the expiration of the launch and early orbit phase cover and provides for the replacement and re-launch of the tug, its loss of revenue, and fulfillment of contractual obligations. The combined total and partial loss coverage is normally between 1.75% and 4% of the spacecraft cost. To be conservative, we assume a 4% rate. Other types of insurance payments can be given for propellant loss, power loss, etc., according to their severity and effect on the payload functioning.[8]

5.2.5 Operational cost

The tug operational cost was based on current annual salary listings reported by the Federal Government's Office of Personnel Management[9] for the ground crew employed to operate or supervise the tug missions.

5.2.6 Depreciation

The value of the tug will decrease as it is used over a period of time. This phenomenon is known as depreciation. In its simplest terms, it can be defined as the decline in the value of a property due to aging, general wear and tear, or obsolescence. The straight-line method for estimation of depreciation assumes that the asset depreciates by an equal percentage of its original value for each year it has been used. The depreciation charge for the asset can be calculated using the following formula:

$$D = \frac{C_a - Vr}{Y} \tag{5}$$

where D = Annual straight-line depreciation charge, C_a = Cost of the asset, V_r = Residual value of the asset (the price at which it can be sold), and Y = Useful economic life of the asset (in years). It should be noted that whatever method of depreciation is selected, the total depreciation to be charged over the useful life of a fixed asset would be the same.

5.3. Minimum Fee and Optimal Architecture

Normally, optimal architectures are determined on the basis of cost per function. Table 4 summarizes the results for the best representatives of each grappler category that were listed in Table 1 if the same metric was chosen.

Grappler Capability [-]	Grappler Mass [kg]	Max # Missions [#]	Unit Cost* [$M]	Launch Cost [$M]	Insurance Cost [$M]	Depreciation [$M]	Total Cost [$M]	Total Utility [-]	Cost/Utility [$M/-]
Low	300	20	261.02	146.50	45.19	34.80	409.66	0.37	1105.46
Low	400	18	292.41	146.55	56.24	35.09	449.79	0.41	1087.03
Medium	500	16	321.78	141.92	62.92	34.32	477.90	0.45	1068.22
Medium	600	14	349.45	133.51	69.16	32.61	499.22	0.47	1059.06
High	700	13	382.04	136.28	76.66	33.11	539.64	0.49	1110.88
High	800	12	414.08	137.83	84.03	33.13	577.74	0.49	1177.66

*assuming 5 tugs are built

Table 4: Cost per Function

As seen from the table, if we had decided to compare the design architectures in terms of cost per function, we would have identified the tug with the 600-kg grappler as the best option. However, calculating the minimum fee corresponding to each of these architectures shows that the optimal performance architecture is of less value for the service provider and clients than a worse performing but more affordable architecture.

The minimum fee that should be charged per mission is calculated as follows:

$$F_{\min} = \frac{C_t}{N_{mis}} \tag{6}$$

The results for the six design points selected above are presented in Table 5, where affordability is defined as total utility per minimum fee.

Grappler Capability [-]	Grappler Mass [kg]	Max # Missions [#]	Total Cost [$M]	Minimum Fee [$M]	Total Utility [-]	Affordability [-/$M]
Low	300	20	409.66	**20.48**	0.37	0.0181
Low	400	18	449.79	24.99	0.41	0.0166
Medium	500	16	477.90	29.87	0.45	0.0150
Medium	600	14	499.22	35.66	0.47	0.0132
High	700	13	539.64	41.51	0.49	0.0117
High	800	12	577.74	48.14	0.49	0.0102

Table 5: Minimum Fee Results

The most affordable and, therefore, best architecture is the tug equipped with a grappler weighing 300kg, which is assumed to be able to handle all types of satellites, although with a large risk of damage. Fortunately, damage level (hence, grappler capability) is not critical in this mission scenario and, therefore, using a low-capability robotic arm is acceptable. The identified optimal tug uses storable bipropellant and has a supervisory level of autonomy. As a baseline for the subsequent analysis, we will assume its corresponding minimum fee of $20.48M.

5.4. Maximum Client's Profit

As discussed in the market analysis section, transponder leasing revenues are expected to remain steady in the next few years and are unlikely to experience significant growth. Since our database consists of number and type of transponders for each satellite and since it is unlikely that all transponders available on-board are utilized, we have multiplied the maximum six-month revenue (which assumes that all transponders are leased) by a fraction η, representing the fraction of leased transponders. For the satellites launched between 2001 and 2003, we have taken the average fraction value for the respective year. For the lack of statistical information (and to be conservative), we have assumed a slightly lower number, 0.7, for the years prior to that (1992 to 2000).

Average fraction leased in 2001	0.870
Average fraction leased in 2002	0.823
Average fraction leased in 2003*	0.765

*Data was available only for the first half of the year.

Table 6: Fraction of Transponders Leased[10]

The maximum profit that a satellite owner can obtain from the extended lifetime of the satellite is obtained by subtracting the operational cost, C_O, (normally assumed in the satellite industry to be 10% of the collected revenue) and the minimum fee for tugging from the revenue, R, for 6 months:

$$P_{max} = \eta * R - C_o - F_{min} \tag{7}$$

where

$$R = \sum_{i=1}^{2} N_{tr} \cdot C_{tr} \cdot N_{mo} \cdot f \tag{8}$$

The calculation of revenue utilizes the most current transponder indices (5,155 \$/MHz/Month for Ku-band and 4,921 \$/MHz/Month for C-band[11]).

5.5. Mid-Way Fee

The calculated minimum fee implies no profit for the tugging service provider and maximum profit for the client. However, since the goal is to achieve a stable market, we need to increase the fee to a point when it will be of value to both customer and provider. Our database includes 162 GEO satellites launched in or after 2007, but data is available to fully describe only 121 of them. Out of these 121 satellites, only 62 result in a positive profit if tugging services are purchased when the minimum fee is set to $20.48M. For these cases, the provider can achieve the same profit as his customers if the fee is between about 55% and 90% (different for each individual satellite) of the revenue accrued from the extended period of operation. Based on the resulting profit (which is same for the provider and the client), we can divide the 62 satellites in three tiers. The first tier consists of all satellites bringing a greater than \$10M profit when a tugging service is purchased. The second tier comprises the satellites resulting in profits between \$5M and \$10M. The third tier contains the rest of the satellites (i.e. with a profit from \$0M to \$5M). With a minimum tugging fee of \$20.48M, 12 satellites fall into the first tier, 30 into the second, and 20 into the third. The results from calculating the mid-way fee are displayed in Appendix A (only the cases resulting in positive profit are included).

Because of uncertainties in cost estimates, we need to assume some margin when performing numerical evaluations. If we select, for example, a \$10M cost uncertainty margin per satellite tugging operation and exclude the cases for which the client's and provider's profit results is less than \$10M, the average percentage corresponding to the mid-way fee is reduced to about 55% - 70% of the clients' 6-month revenues. In this case, however, only the satellites from the first tier might consider tugging valuable. Seven of these twelve potential clients are Intelsat satellites. The International Telecommunications Satellite Organization is the world's largest commercial satellite communications services provider. A special agreement might be signed between it and the tugging service provider, obliging the provider to charge a lower fee, while the client is bound to purchase the service for at least 8 of its satellites. The Intelsat satellites can also be given a priority, in case another customer wants to have his satellite tugged to graveyard orbit at the same time.

6. SENSITIVITY ANALYSIS

There are many factors that affect the calculated number of potential clients. In this section, we determine the elasticity of demand for tugging services with respect to variations in cost uncertainty margin, minimum fee, and length of extended period of satellite operation. To simplify the representation of the results from the sensitivity analysis, only the case when there is no available satellite replacement is considered.

6.1. Sensitivity to Cost Margin Changes

Keeping the minimum fee set to \$20.48M and analyzing the results for a six-month long operational extension, we observe that the number of potential clients can vary significantly when the cost uncertainty margin is less than \$10M. For higher margins, the sensitivity of the results is very small, as shown on Figure 2.

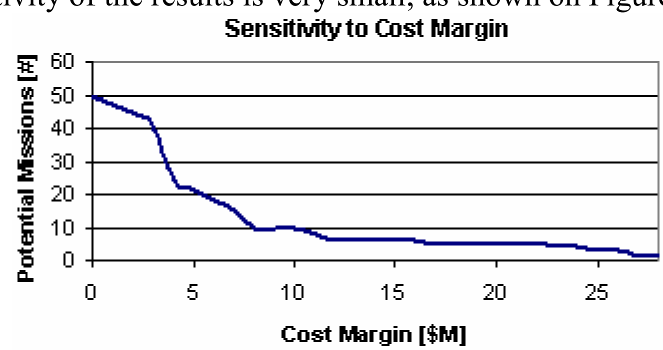

Figure 2: Sensitivity to Changes in Cost Margin

To justify the selected minimum fee, the tug needs to visit 20 satellites during its 10-year-long design life. This would be possible only if the cost estimations presented above were correct within a $7.5M uncertainty per tugging mission. This estimation can serve as a target for mission uncertainty reduction.

6.2. Sensitivity to Minimum Fee

The results from increasing and decreasing the baseline minimum fee by five, ten, and twenty percent are presented in Figure 3. The extended period of satellite operation is still six months and the cost margin is considered zero. As seen from the plot, the maximum number of potential clients is affected significantly only when the fee is changed by more than 10% (i.e. the fee is lower than $18.44M). For all other changes, the sensitivity to variation of the minimum fee is relatively small.

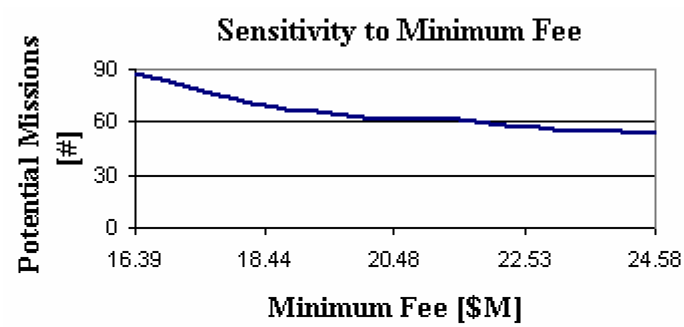

Figure 3: Sensitivity to Changes in Minimum Fee

The data used for the plot is presented in Table 7 along with the results corresponding to $10M margin. Clearly, sensitivity to minimum fee is greater for smaller cost margins; the $10M cost margin case is barely affected by changes in the minimum fee.

Min. Fee [$M]	# Sats [no repl.]
17.81	75
20.35	62
22.90	57
25.44	50
27.99	47
30.53	41
33.08	25

*$0M cost margin

Min. Fee [$M]	# Sats [no repl.]
17.81	18
20.35	12
22.90	10
25.44	10
27.99	8
30.53	6
33.08	6

*$10M cost margin

Table 7: Minimum Fee Sensitivity Tests

6.3. Sensitivity to Length of Extended Operations

The results from assuming that satellites are allowed to operate for six, seven, or twelve additional months are displayed in Figure 5 for different cost margins. As shown by the plot, an additional extension to the baseline case (six months) even of only one month increases the potential number of clients by about ten, on the average (for cost margins smaller than $10M). Doubling the baseline case period results roughly triples the number of client satellites. To justify the selected minimum fee, the cost uncertainty for the 7-month long extension must be less than $11M, and less than $25M for the 12-month long extension. Please note that some satellites will indeed sacrifice only six months of their design life when retiring by using their own residual propellant, while others might sacrifice even more than a year. Therefore, the actual number of satellites that might take advantage of the tugging service will most probably lie between the 6-months and 12-months lines on the plot of Figure 4.

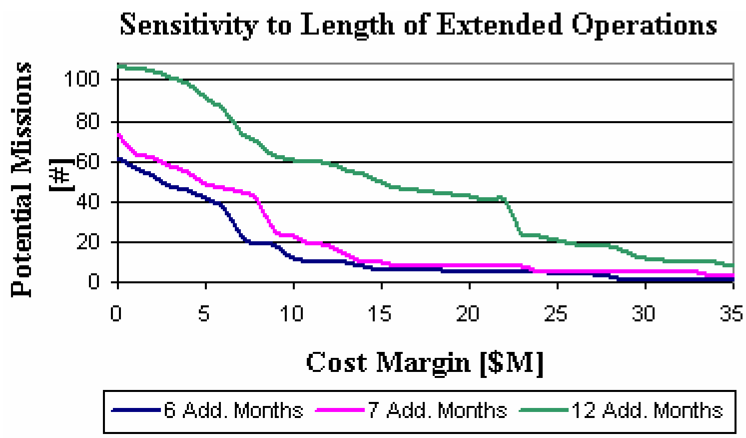

Figure 4: Sensitivity to Length of Extended Operations

The sensitivity to minimum fee is shown in Figure 5 and Table 8 for the three cases discussed above. The results show that elasticity of demand decreases with the increase of satellite revenue due to longer periods of operation.

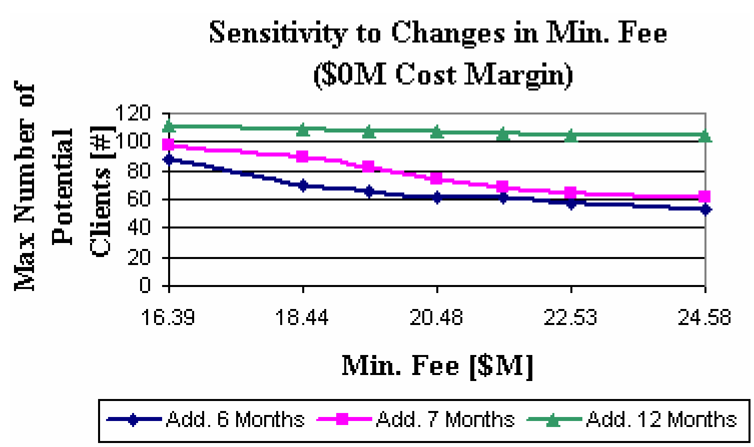

Figure 5: Sensitivity to Minimum Fee for Various Lengths of Additional Operation

Min. Fee [$M]	# Satellites Add. 6 Mo.	Add 7 Mo.	Add. 12 Mo.
16.39	88	98	112
18.43	70	90	109
19.46	65	82	108
20.48	62	74	107
21.51	61	69	106
22.53	57	64	105
24.58	53	61	104

*Assuming $0M cost margin

Min. Fee [$M]	# Satellites Add. 6 Mo.	Add 7 Mo.	Add. 12 Mo.
16.39	19	41	70
18.43	18	25	63
19.46	15	24	63
20.48	12	23	61
21.51	10	20	61
22.53	10	19	60
24.58	10	18	59

*Assuming $10M cost margin

Table 8: Sensitivity to Minimum Fee for Various Lengths of Additional Operation

7. COST AND BENEFIT ANALYSIS OF THE COMPETING OPTIONS

The results from the last section assumed that no replacement was available. In the case, when a replacement is already launched, tugging is of no value because the profit that will be gained from allowing the old satellite to exhaust its entire fuel supply is negligible in comparison to the profit coming from the newly launched satellite. In the third case, when the replacement is ready but a launch vehicle is not readily available, we calculate the revenues and profits when launch occurs after one, two, and up to five months after the EOL criterion is reached (for the baseline case of six months). Since the satellite market analysis had led us to the assumption that the replacement satellite is not likely to exceed the transponder capability of the old satellite, each replacement used in the comparison is assumed to be an exact replica of its predecessor. We compare the client profits from the replacement with the profits when tugging is selected (i.e. when the old satellite is left in operation for six more months). If the former are greater, the option of replacement is preferred before tugging. Table 9 and Table 10 present the maximum number of satellites for which tugging makes economic sense for various cost margins and minimum fees.

Margin	No Repl.	R - 1 Mo	R - 2 Mo	R - 3 Mo	R - 4 Mo	R - 5 Mo
$0M	62	0	0	0	5	41
$5M	42	0	0	0	5	41
$10M	12	0	0	0	5	41
$15M	6	0	0	0	5	41
$20M	5	0	0	0	5	41
$25M	4	0	0	0	5	41
$30M	1	0	0	0	5	41

Table 9: Maximum Number of Potential Clients for Various Cost Margins

Min. Fee	No Repl.	R - 1 Mo	R - 2 Mo	R - 3 Mo	R - 4 Mo	R - 5 Mo
16.39	88	0	0	0	8	53
18.43	70	0	0	0	6	47
19.46	65	0	0	0	5	43
20.48	62	0	0	0	5	41
21.51	61	0	0	0	5	41
22.53	57	0	0	0	5	24
24.58	53	0	0	0	4	19

Table 10: Maximum Number of Potential Clients for Various Minimum Fees

The cost margin results tell us that, assuming six months of extended satellite operation, tugging is of value for: 1) the cases of no replacement having a cost uncertainty margin smaller than $7.5M and 2) when replacement can be launched five months after the old satellites has reached its EOL criterion. When varying the minimum fee, it is seen from Table 5.11 that tugging does not make economic sense when a replacement is launched within the first four months after the retirement of the old satellite (by using its own propellant). As long as the minimum fee is less than $24.5M and there is no cost uncertainty (this is the case represented in the table), tugging would be of potential interest if a replacement cannot be launched within the first four months.

8. CONCLUSIONS

The business case analysis of the GEO Satellite Retirement scenario shows that if a "mid-way" fee is charged as a percent of the revenue collected by the clients from allowing satellites to exhaust their entire supplies of propellant before retiring, providing tugging services makes economic sense in the cases listed in Table 11:

Min. Fee [$M]	Replace-ment	Margin [$M]	Ext. Life [Mo.]
16.39	No	≤ 9.5	6
16.39	R-5 Mo.	≤ 6	6
16.39	No	≤ 12.5	7
16.39	R-6 Mo.	≤ 7	7
16.39	No	≤ 27	12
16.39	R-11 Mo.	≤ 12	12
18.43	No	≤ 8.5	6
18.43	R-5 Mo.	≤ 6	6
18.43	No	≤ 11.5	7
18.43	R-6 Mo.	≤ 7	7
18.43	No	≤ 26	12
18.43	R-11 Mo.	≤ 12	12
19.46	No	≤ 8	6
19.46	R-5 Mo.	≤ 6	6
19.46	No	≤ 11	7
19.46	R-6 Mo.	≤ 7	7
19.46	No	≤ 25.5	12
19.46	R-11 Mo.	≤ 12	12

Min. Fee [$M]	Replace-ment	Margin [$M]	Ext. Life [Mo.]
20.44	R-6 Mo.	≤ 7	7
20.44	No	≤ 25	12
20.44	R-11 Mo.	≤ 12	12
21.51	No	≤ 7	6
21.51	R-5 Mo.	≤ 6	6
21.51	No	≤ 10	7
21.51	R-6 Mo.	≤ 7	7
21.51	No	≤ 24.5	12
21.51	R-11 Mo.	≤ 12	12
22.53	No	≤ 6.5	6
22.53	R-5 Mo.	≤ 6	6
22.53	No	≤ 9.5	7
22.53	R-6 Mo.	≤ 7	7
22.53	No	≤ 24	12
22.53	R-11 Mo.	≤ 12	12
24.58	No	≤ 5.5	6
24.58	No	≤ 8.5	7
24.58	R-6 Mo.	≤ 7	7

20.44	No	≤ 7.5	6	24.58	No	≤ 23	12
20.44	R-5 Mo.	≤ 6	6	24.58	R-11 Mo.	≤ 12	12
20.44	No	≤ 10.5	7				

Table 11: Cases Justifying Tugging

The main conclusion is that the lower the minimum fee for tugging, the greater the number of potential clients and the allowable cost uncertainty. Several ways to decrease the minimum fee and thus increase the value of tugging are listed below:

1. Tug visits more satellites.
2. More tugs are produced.
3. TRL uncertainty decreases.
4. Tug is owned by a government agency.
5. Satellites produce more revenue.
6. Tugging is reliable (i.e. failure rate and, hence, insurance rate is small).

9. FUTURE WORK

Some ideas for future work are listed below:

1. Carefully consider the counterarguments to the GEO satellite retirement business case. Some of the main threats are: 1) improvements in fuel gauging technology, which will reduce the wasted life due to measurement uncertainty; 2) switching to all electric propulsion, meaning that fuel will no longer be the life-limiting factor of the new generation of satellites; 3) clusters and swarms of small communications satellites, which will reduce the revenue per satellite.
2. Investigate the impact of competition presented by other commercial companies' tugs.
3. Research in greater detail the legal/regulatory issues involved and suggest methods for mitigation.
4. Perform a sensitivity analysis on al variables included in the estimations for tug cost (e.g. insurance rate, depreciation, launch vehicle selection, etc.)
5. Explore fully a tug failure scenario and calculate whether the return from insurance is sufficient to support the continuation of the tugging business.
6. Analyze the effect of satellite failure during the extended period of work. This is interesting because the satellite owner would have already agreed to purchase the service. The minimum fee for tugging must be paid regardless of whether sufficient revenue has been accrued by the satellite owner. Therefore, the contract should have a provision stating that in cases of satellite failure when the produced revenue is not sufficient to cover even the minimum fee, this minimum fee should still be charged, but no more than that.
7. How would a fuel depot infrastructure affect the fee?
8. Analyze other space tug business scenarios and the potential of using a multi-purpose tug.

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Appendix A: Nomenclature

C	=	Client
C_5	=	Cost of 5 tugs, [$M]
C_a	=	Cost of asset, [$M]
C_{fu}	=	First unit cost, [$M]
C_i	=	Insurance cost, [$M]
C_l	=	Launch cost, [$M]
C_o	=	Operational cost, [$M]
C_p	=	Propellant cost, [$M]
C_t	=	Total cost, [$M]
C_{tr}	=	Cost of a transponder, [$M/MHz/Month]
C_u	=	Unit cost, [$M]
D	=	Depreciation, [$M]
f	=	Transponder bandwidth, [MHz]
F_{min}	=	Minimum fee, [$M]
M_d	=	Dry mass, [kg]
N_{mis}	=	Number of missions, [#]
N_{mo}	=	Number of months of operation, [#]
N_{tr}	=	Number of transponders, [#]
P	=	Provider

P_{max}	=	Maximum profit, [$M]
R	=	Revenue, [$M]
V_r	=	Residual value of asset, [$M]
Y	=	Useful economic life of asset, [yr]

Appendix B: Satellite Revenues when Mid-Way Fee for Tugging is Charged

	Satellite Name	Longitude [deg]	BOL [yr]	EOL [yr]	6 Mo Rev. [$M]	Charged Fee [$M]	% Revenue	Profit (P&C) [$M]
1st Tier	Intelsat 707	0.87W	1996	2007	951.22	440.77	46.34	415.33
	Intelsat 904	60.00E	2002	2012	86.64	51.71	59.68	26.27
	Intelsat 905	24.5W	2002	2012	86.64	51.71	59.68	26.27
	Intelsat 906	64.00E	2002	2012	83.15	50.14	60.30	24.69
	Intelsat 907	27.50W	2003	2013	77.30	47.51	61.46	22.07
	NSS-7	22.00W	2002	2014	64.48	41.74	64.73	16.30
	Anik F1	107.25W	2000	2015	54.85	37.40	68.20	11.96
	PAS 1R	44.96W	2000	2015	54.85	37.40	68.20	11.96
	Intelsat 901	18.06W	2001	2011	52.33	36.27	69.31	10.83
	Intelsat 902	63.34E	2001	2011	52.33	36.27	69.31	10.83
2nd Tier	Galaxy 11	90.94W	1999	2014	45.92	33.38	72.71	7.94
	PAS 10	68.50E	2001	2016	45.46	33.18	72.98	7.74
	Telstar 12	14.97W	1999	2014	44.43	32.71	73.63	7.27
	Atlantic Bird 3	5.00W	2002	2017	44.32	32.67	73.70	7.22
	Eutelsat W5	70.50E	2002	2014	43.99	32.52	73.92	7.07
	Asiasat 4	122.00E	2003	2018	43.22	32.17	74.43	6.73
	Galaxy 3C	95.00W	2002	2017	42.99	32.07	74.59	6.62
	GE 4	101.07W	1999	2014	42.80	31.98	74.72	6.54
	Agila 2	146.06E	1997	2009	41.03	31.18	76.01	5.74
	Asiasat 3S	105.55E	1999	2014	39.54	30.51	77.17	5.07
	JCSAT-8	154.00E	2002	2013	39.40	30.45	77.29	5.01
3rd Tier	Apstar 2R	76.50E	1997	2012	39.03	30.28	77.60	4.84
	NSS 6	95.00E	2002	2016	38.97	30.26	77.64	4.82
	PAS 4	72.03E	1995	2010	37.82	29.74	78.63	4.30
	Eutelsat W1	9.98E	2000	2012	36.89	29.32	79.48	3.88
	Americom 1	103.01W	1996	2011	36.56	29.18	79.79	3.73
	Americom 2	84.87W	1997	2012	36.56	29.18	79.79	3.73
	Americom 3	87.07W	1997	2012	36.56	29.18	79.79	3.73
	Galaxy 10R	122.98W	2000	2015	36.56	29.18	79.79	3.73
	Galaxy IVR	98.97W	2000	2015	36.56	29.18	79.79	3.73
	GE 6	71.98W	2000	2015	36.56	29.18	79.79	3.73
	PAS 8	166.03E	1998	2013	36.56	29.18	79.79	3.73
	Satmex 5	116.79W	1998	2013	36.56	29.18	79.79	3.73
	Telstar 5	97.00W	1997	2009	36.56	29.18	79.79	3.73

	Telstar 6	92.99W	1999	2011	36.56	29.18	79.79	3.73
	Telstar 7	128.95W	1999	2011	36.56	29.18	79.79	3.73
	Zhongwei 1	87.52E	1998	2013	36.56	29.18	79.79	3.73
	Intelsat 801	31.46W	1997	2007	36.07	28.95	80.27	3.51
	Intelsat 802	174.02E	1997	2007	36.07	28.95	80.27	3.51
	Intelsat 803	21.39W	1997	2007	36.07	28.95	80.27	3.51
	Intelsat 804	64.20E	1997	2007	36.07	28.95	80.27	3.51
	Eurobird	28.52E	2001	2013	33.92	27.99	82.51	2.54
	PAS 7	68.56E	1998	2013	33.80	27.93	82.64	2.49
	Hot Bird 3	13.09E	1997	2009	33.35	27.73	83.14	2.29
	Atlantic Bird 1	12.50W	2002	2017	32.99	27.57	83.56	2.12
	Telstar 402R	88.99W	1995	2007	31.89	27.07	84.90	1.63
	Asiasat 2	100.55E	1995	2008	31.36	26.83	85.57	1.39
	LMI 1	75.00E	1999	2014	30.19	26.31	87.14	0.86
	Atlantic Bird 2	8.07W	2001	2013	29.07	25.80	88.76	0.36
	HGS-3	50.03E	1996	2008	28.56	25.57	89.55	0.13