Available online at www.sciencedirect.com

SCIENCE DIRECT

PERGAMON

Acta Astronautica 58 (2006) 485–498

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Economic case for the retirement of geosynchronous communication satellites via space tugs

Kalina K. Galabova*, Olivier L. de Weck*

Department of Aeronautics and Astronautics, 33-410, 77 Massachusetts Avenue, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 1 July 2004; received in revised form 31 August 2005; accepted 13 December 2005
Available online 6 March 2006

Abstract

Both the United Nations (UN) and the US Federal Communications Commission (FCC) have published a ruling that calls for geostationary earth orbit (GEO) satellites to 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 and move the satellites after all of their fuel has been exhausted. This extended lifetime can provide significant additional revenue to some satellite operators. Before committing to such a capability, however, 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 builds a framework that can be used in evaluating various on-orbit servicing opportunities and proposes that the service fee should be charged as a percentage of the additional revenue received by the satellite operators and analyzes how cost estimation uncertainties affect the value of on-orbit tugging. The presented analysis concludes that until advanced propulsion systems gain greater use, retirement via a space tug will be of value for the 10–20 most expensive GEO assets.

Keywords: Geosynchronous communication satellites; Space tug; Orbital transfer vehicle; Satellite end-of-life; Propellant gauging; Service fee

1. Introduction

Commercial telecommunications satellites generate approximately 75% of the entire geostationary earth orbit (GEO) space sector revenue. Their operational life spans between 12 and 15 years, and these limits are usually imposed by the amount of fuel available for station-keeping. 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 UN 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]. The FCC passed a similar regulation in 2004. To comply with these regulations, satellites use their residual station-keeping propellant and often sacrifice roughly six months [2] of their design lifetime, which corresponds to a significant loss of economic value.

If on-orbit tugging services were available, GEO satellites could be left in operational orbits until their propellant supplies are completely exhausted and then transferred to a disposal orbit by a tug. This alternative

* Corresponding authors.
E-mail addresses: galabova@alum.mit.edu (K.K. Galabova), deweck@mit.edu (O.L. de Weck).

0094-5765/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2005.12.014

would 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 bandwidths on the order of 36 MHz, the revenue that the satellite owner will earn from six extra months of satellite operation can be 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.

This paper presents a general methodology for evaluating the economic case of a space tug enterprise. It can be applied for a variety of tugs (e.g., bipropellant, nuclear electric, and solar electric) and on-orbit servicing missions (e.g. graveyarding, satellite rescue, and constellation deployment/reconfiguration). In Section 2, we state the assumptions of the methodology, followed by an enumeration of competing scenarios (Section 3), market forecasts (Section 4) and the fee estimation calculations (Section 5). Accurately estimating the cost of a space tug program is difficult due to the large number of uncertain parameters involved. For better estimates, sensitivity analysis needs to be performed on all participating variables (Section 6), before a cost benefit analysis (Section 7) allows conclusions about whether or not space tugging makes sense for the retirement of GEO satellites (Section 8).

2. Assumptions

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

1. The tug has universal capture capability; it can capture any potential client satellite in GEO. A visualization of the space tug concept of operations is provided in Fig. 1.
2. The tug is owned by a commercial organization and can be launched on any launch 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 tug 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 locally.
6. The tug enters its operational state 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 (with a perigee at least 300 km above the GEO belt at an altitude of 35 786 km).
10. Satellites use chemical propellant ($I_{sp} = 150/450$ 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.[1]
11. Taxes (federal, etc.) and interest are not accounted for when calculating profit.
12. Satellites are fully depreciated when the end-of-life (EOL) criterion[2] is reached.

3. Competing alternatives

Two alternatives for satellite operators are considered: retire a satellite using its own fuel or pay for tugging. Analyzing these options in greater detail, we see that there are two distinct cases, depending on whether or not there is a replacement satellite (owned by the same agency) that is ready to be launched to the same orbital slot. If a replacement is not available, the question is whether to use the satellite's residual propellant for moving to a graveyard orbit upon reaching the EOL criterion (or even before that), or whether to let a tug execute this maneuver later and to collect extra revenue while paying some fee. The first alternative results in service disruption and no additional profit, while the

[1] Utilizing electric thrusters for station-keeping is one means of complying with the graveyard policies for GEO satellites while ensuring long operational lifetime. It is one of the main competitors to spacecraft graveyarding via a tug and its effect on the on-orbit servicing market should be considered in greater detail in a future study.

[2] One method to predict the remaining amount of propellant is based on the equation of state of an ideal gas, $p \cdot V = n \cdot R \cdot T$. It utilizes transducers for measuring the pressure and temperature of the inert pressurization 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 integrated mass flow rate. A third method is based on the measured dynamics of the spacecraft after a station-keeping maneuver to determine its total mass properties. 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 is typically added.

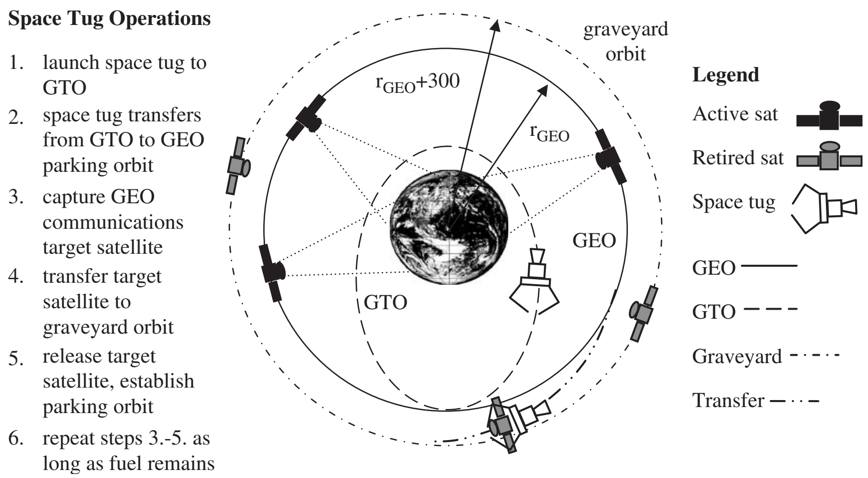

Fig. 1. Space tug concept of operations (distances not to scale).

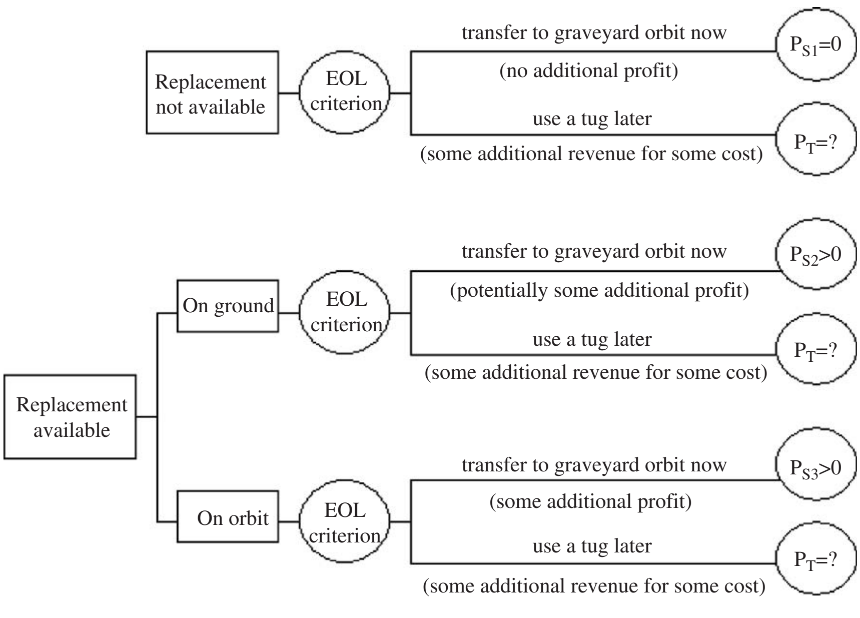

Fig. 2. Satellite end-of-life (EOL) decision tree and outcomes.

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 (e.g. at some other longitude in the GEO belt) before the EOL criterion is reached, it will be already producing revenue 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 for the examined period of six months. Fig. 2 presents these options. For a given satellite, $P_{S1} < P_{S2} < P_{S3}$, which means that the profit will be greatest if a replacement satellite is already on orbit, followed by a replacement being ready on the ground, followed by the situation where no replacement is available at all. The question is how, P_T,[3] the profit generated by the satellite operator who elects to use the tugging service compares to these three satellite profits (without tugging).

If the satellite operator decides to use the tugging service, he must enter into a binding contract with the tug operator before the spacecraft reaches the EOL 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. Before we attempt to estimate what fee should be charged for the service, we need to understand the relevant market trends in the communications satellite industry.

4. Market statistics and forecasts

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, there will be about 15 client-satellites per year in the GEO belt. This corresponds roughly to the projected steady-state replacement rate.
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 of tugging 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 and limits 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 operations, preventing the expected revenue from being reached. In short, there is 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 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 pre-paid based on preliminary estimates 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 break-even point (i.e., zero profit) for the provider.

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

1. Calculate the *total utility* of various space tug architectures differing in terms of propellant type, autonomy level, and grappling mechanism and sensors used.
2. Using NASA's Spacecraft/Vehicle Level Cost Model and accounting for cost of fuel, launch, and insurance, calculate the *total cost* of the designed tug architectures.
3. Estimate the *minimum* fee that a tug operator should charge per mission and identify the *optimal design* on the basis of a 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 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 Section 6.2). Fortunately, the majority of the GEO commercial communications satellites lie in one orbital plane (Fig. 1); 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 a graveyard orbit by

[3] See Nomenclature at end of paper.

Table 1
Tug reusability calculation results

Grappler capability	Grappler mass (kg)	Tug dry mass (kg)	Biprop fuel (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

space tugs of various mating (capture) capabilities. The calculations use the orbital and physical characteristics of satellites currently in orbit [7]. The key assumptions made in the utilized tug 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 each client satellite during the lifetime of the tug. The tug transfers itself from GTO to GEO.
4. The tug uses storable bipropellant with $I_{sp} = 325$ s.

One of the reasons why space tug programs have been canceled in the past is cost overrun. In part, it was due to unrealistic estimates regarding the design and development of key technologies unavailable at that time. In other cases, there was no well-defined business framework that would put cost and revenues in perspective and evaluate the economic case of selected existing technologies. This paper presents a generalized business model that can be applied for a variety of tug mission scenarios.

5.1. Total utility

The space tug design attributes that were considered to define space tug utility 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 a mission command is received and ending when contact with the client 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.

Table 2
Relative weights of attributes

Attribute	Weight
Mating capability	0.4
Accuracy of positioning	0.2
Adaptability	0.2
Timeliness	0.2

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 thus endanger other satellites there, and (2) damaging itself, since it is expected to be reusable and serve a number of other clients. The rest of the attributes are of lower importance. *Transfer capability* is not a critical issue because the traversed distances are only about 300 km one-way and this requires a very small change in velocity near GEO. *Timeliness* is also not critical because satellites that are already dysfunctional 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. The relative weights of the three considered attributes are shown in Table 2 and were used in the calculation of total utility.

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

The results from the trade space analysis indicated that the optimal space tug for this mission scenario should be initially parked in the GEO belt and controlled

Table 3
Space tug design variables

Design variable		Units	Allowable settings
Propulsion system	I_{sp}	s	3000 (electric) 446 (cryogenic bi) 325 (storable bi)
Level of autonomy	Type	–	Teleoperation Supervision Full autonomy
Hardware sophistication	M_{grap}	kg	300 (low) 400 (low) 500 (medium) 600 (medium) 700 (high) 800 (high)

through supervision (semi-autonomous). When the sequence of tugging missions begins, the location where the client satellite is released in the graveyard orbit becomes the new parking location. Including uncertainty factors for technology readiness of the propulsion system [7] 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 below in Section 5.3.

5.2. Total cost

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

$$C_t = C_u + C_p + C_l + C_i + C_o + D, \quad (1)$$

where C_t is the total cost, C_u the unit cost, C_p the propellant cost, C_l the launch cost, C_i the insurance cost, C_o the operational cost, and D the depreciation.

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% [8], we can calculate the unit cost, C_U, of a tug as

$$C_u = \frac{C_5(C_{fu})}{5}. \quad (2)$$

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 Robotic Arm can be used as a baseline for calculating the grappler cost for a given mass. The empirical relationships utilized by the NASA spacecraft cost are modeled as

First unit tug:

$$C_{fu} = 3.442 \cdot M_d^{0.55} + 0.3909 \cdot M_d^{0.662}, \quad (3)$$

where M_d is the dry mass of the vehicle.

Cost of a family of five identical tugs:

$$C_5 = 4.9139 \cdot M_d^{0.6055}. \quad (4)$$

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 given in $/kg.

5.2.3. Launch cost

Launch cost can be calculated by taking the average cost per kilogram for all launch vehicles capable of carrying the given space tug 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 amounts to 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% insurance for separation from the launch vehicle and 9% insurance for early phase failures occurring after separation.[4] The "on-orbit failure" insurance covers the period from the expiration of the launch and early orbit phase coverage 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 coverage can be obtained for propellant loss, power loss, etc., depending on severity and effect on payload functionality [10].

[4] Currently, the premium rate for launch and early phase insurance is between 15% and 30% of the spacecraft insured value [9].

Table 4
Cost per function

Grappler capability (dimensionless)	Grappler mass (kg)	Max # missions (#)	Space tug unit cost[a] ($M)	Launch cost ($M)	Insurance cost ($M)	Depreciation ($M)	Total cost ($M)	Total utility (dimensionless)	Cost/ utility ($M/dimensionless)
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

[a]Assuming five tugs are built.

Table 5
Minimum fee results

Grappler capability (dimension)	Grappler mass (kg)	Max # missions (#)	Total cost ($M)	Minimum fee ($M)	Total utility (dimensionless)	Affordability (dimensionless/$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

5.2.5. Operational cost

The tug operational cost was based on current annual salary listings reported by the US Federal Government's Office of Personnel Management [11] 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:

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

where D is the annual straight-line depreciation charge, C_a the original cost of the asset, V_r the residual value of the asset (the price at which it can be sold), and Y the 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

Typically, optimal architectures are determined on the basis of cost per function (utility). 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.

As seen from the table, if we had decided to compare the design architectures in terms of cost per utility, 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 space tug.

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

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

where C_t is the total cost of the tug and N_{mis} is the number of missions it is expected to perform. The results for the six design points selected above are presented in Table 5, where affordability is defined as total utility per minimum fee. This is an important result as it relates the space tug design features and utility to the price to be charged for tugging services.

The most affordable and, therefore, best design is the tug equipped with a grappler weighing 300 kg, which is assumed to be able to handle all types of satellites, although with a somewhat larger risk of damage compared to the large grappler. Fortunately, the damage level (hence, grappler capability) is not critical in this mission scenario as long as the overall integrity of the tug and client satellites are maintained 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 a corresponding minimum fee of $20.48 million per retirement maneuver executed in GEO.

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 active satellite in GEO and since it is unlikely that all transponders available on-board are utilized, we have multiplied the maximum theoretical 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 (Table 6). 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 (1992–2000).

The maximum profit that a satellite owner can obtain from the extended lifetime of the satellite, $P_{\max}$, 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, $F_{\min}$, from the revenue, R, for six months:

$$P_{\max} = \eta * R - C_o - F_{\min}, \quad (7)$$

where

$$R = \sum_{i=1}^{2} N_{\mathrm{tr},i} \cdot C_{\mathrm{tr},i} \cdot N_{\mathrm{mo}} \cdot f_i \quad (8)$$

The calculation of revenue utilizes the most current transponder indices C_{tr} (5155 $/MHz/month for Ku-band and 4921 $/MHz/month for C-band [13]), the number of transponders in the C and Ku-band, N_{tr}, the number of months, N_{mo}, as well as the bandwidth per transponder, f.

Table 6
Fraction of transponders leased [11]

Average fraction leased in 2001	0.870
Average fraction leased in 2002	0.823
Average fraction leased in 2003[a]	0.765

[a]Data were available only for the first half of the year.

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 for tugging services, 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 since 1995, but data are available to fully describe only 121 of them [12]. Out of these 121 satellites, only 62 (see Appendix B) 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 into 3 tiers. The first tier consists of all satellites yielding a profit greater than $10M in the six month period when a tugging service is purchased. The second tier comprises the satellites yielding profits between $5M and $10M in the same period. 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.

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' six-month revenues. In this case, however, only the satellites from the first tier might consider tugging to be valuable. Seven of these 12 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 eight of its satellites. The Intelsat satellites could also be given a higher 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. The sensitivity analysis is especially valuable in offering a timely prediction of the effects of budget overruns and quantifying the economic risks for the program. 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 (Fig. 2 top row).

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 in Fig. 3.

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 in the total cost column of Table 4 were correct within a \$7.5M uncertainty per tugging mission. In other words, a cost overrun of 20 times \$7.5M (\$150M), representing about 37% of total costs, could be tolerated in order for the space tug business case still to close. 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 5%, 10%, and 20% are presented in Fig. 4. The extended period of satellite operation is still six months and the cost uncertainty 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.

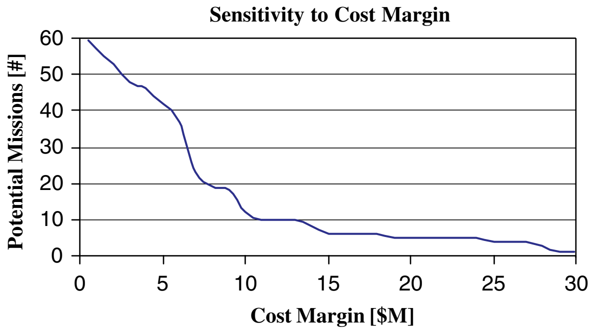

Fig. 3. Sensitivity to changes in cost margin.

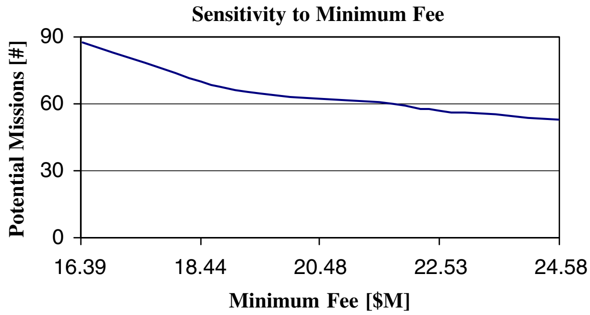

Fig. 4. Sensitivity to changes in minimum fee.

Table 7
Minimum fee sensitivity tests

Min. fee[a] (\$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
Min. fee[b] (\$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

[a] \$0M cost margin.
[b] \$10M cost margin.

The data used for the plot is presented in Table 7 along with the results corresponding to \$10M cost uncertainty margin. Clearly, sensitivity to minimum fee is

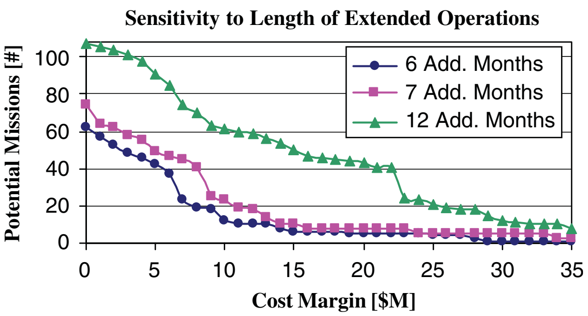

Fig. 5. Sensitivity to length of extended operations.

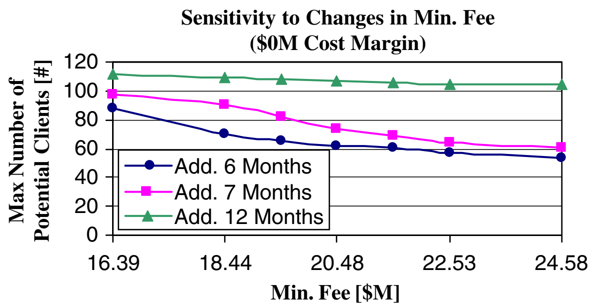

Fig. 6. Sensitivity to minimum fee for various lengths of extended operations.

greater for smaller cost margins; the $10M cost margin case is barely affected by changes in the minimum fee, primarily because only the 6–18 most profitable satellites remain as potential clients for tugging.

6.3. Sensitivity to length of extended operations

The results from assuming that satellites are allowed to operate for 6, 7, or 12 additional months are displayed in Fig. 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 10, on the average (for cost margins smaller than $10M). Doubling the baseline case period results roughly triples the number of potential 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- and 12-months lines on the plot of Fig. 5.

The sensitivity to minimum fee is shown in Fig. 6 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 extended 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 little 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. An exception to this is when the old satellite can act as a potential backup in case the new replacement satellite experiences technical difficulties or partial failures. It is well known that customers prefer to lease transponders from operators that can provide multi-string redundancy either on the satellite directly or on another satellite within the same footprint. Quantifying the value of redundancy remains for future work. 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

Table 8
Sensitivity to minimum fee for various lengths of extended operations

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

[a]Assuming $0M cost margin.
[b]Assuming $10M cost margin.

Table 9
Maximum number of potential clients for various cost margins

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 10
Maximum number of potential clients for various minimum fees

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

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. Tables 9 and 10 present the maximum number of satellites for which tugging makes economic sense for various cost margins and 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 at the earliest. When varying the minimum fee, it is seen from Table 10 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 predicts the number of potential clients 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.

The main conclusion is that satellite graveyarding via a chemically propelled space tug makes economic sense only for the 10–20 highest-value GEO communications satellites, where six months or more of useful life is wasted because of uncertainty in fuel gauging. Naturally, 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 (technology readiness) uncertainty decreases.
4. Tug is owned by a government agency.[5]
5. Satellites produce more revenue per month.
6. Tugging is reliable (i.e. failure rate and, hence, insurance rate is small).

But there are also a number of factors that might decrease the attractiveness of the space tug business case for retirement of GEO satellites at the EOL. In other words, should these trends occur, the number of cases shown in Table 11 where space tugging is profitable would decrease:

1. Increased use of electrical propulsion for station keeping of GEO satellites.
2. Improved residual chemical fuel estimates, advances in fuel gauging.
3. Development of smaller clusters or swarms of communications satellites, where the revenue per satellite ($/month) would be much smaller than current averages.

[5] If government agencies enter the arena as propulsion technology evolves and establish an economically sound case for on-orbit servicing, they would likely charge lower fees than space tug commercial operators.

Table 11
Cases justifying tugging for GEO retirement

Min. fee ($M)	Replacement	Margin ($M)	Ext. life (Mo)
16.39	No	$\leqslant 9.5$	6
16.39	R-5 Mo.	$\leqslant 6$	6
16.39	No	$\leqslant 12.5$	7
16.39	R-6 Mo.	$\leqslant 7$	7
16.39	No	$\leqslant 27$	12
16.39	R-11 Mo.	$\leqslant 12$	12
18.43	No	$\leqslant 8.5$	6
18.43	R-5 Mo.	$\leqslant 6$	6
18.43	No	$\leqslant 11.5$	7
18.43	R-6 Mo.	$\leqslant 7$	7
18.43	No	$\leqslant 26$	12
18.43	R-11 Mo.	$\leqslant 12$	12
19.46	No	$\leqslant 8$	6
19.46	R-5 Mo.	$\leqslant 6$	6
19.46	No	$\leqslant 11$	7
19.46	R-6 Mo.	$\leqslant 7$	7
19.46	No	$\leqslant 25.5$	12
19.46	R-11 Mo.	$\leqslant 12$	12
20.44	No	$\leqslant 7.5$	6
20.44	R-5 Mo.	$\leqslant 6$	6
20.44	No	$\leqslant 10.5$	7
20.44	R-6 Mo.	$\leqslant 7$	7
20.44	No	$\leqslant 25$	12
20.44	R-11 Mo.	$\leqslant 12$	12
21.51	No	$\leqslant 7$	6
21.51	R-5 Mo.	$\leqslant 6$	6
21.51	No	$\leqslant 10$	7
21.51	R-6 Mo.	$\leqslant 7$	7
21.51	No	$\leqslant 24.5$	12
21.51	R-11 Mo.	$\leqslant 12$	12
22.53	No	$\leqslant 6.5$	6
22.53	R-5 Mo.	$\leqslant 6$	6
22.53	No	$\leqslant 9.5$	7
22.53	R-6 Mo.	$\leqslant 7$	7
22.53	No	$\leqslant 24$	12
22.53	R-11 Mo.	$\leqslant 12$	12
24.58	No	$\leqslant 5.5$	6
24.58	No	$\leqslant 8.5$	7
24.58	R-6 Mo.	$\leqslant 7$	7
24.58	No	$\leqslant 23$	12
24.58	R-11 Mo.	$\leqslant 12$	12

9. Future work

We will continue to analyze both technical and commercial aspects of space tug development and deployment. Some ideas for future work are listed below:

1. Carefully consider the counter-arguments to the GEO satellite retirement business case. Some of the main threats to this business case 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 all 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 from contractual point of view because the satellite owner would have already agreed to purchase the service.
7. How would a fuel depot infrastructure in GEO affect the minimum fee?
8. Analyze other space tug business scenarios and the potential of using a multi-purpose tug.

Acknowledgments

The authors thank Dr. Gordon Roesler from DARPA (TTO) who supported and monitored the research under contract AFRL F29602-97-K-0010 and Michelle McVey from Adroit Systems Inc. for providing useful information regarding the current state of the satellite industry.

Appendix A. Nomenclature

C	client
C_5	cost of five 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)	P	provider
F_{min}	minimum fee ($M)	P_{max}	maximum profit ($M)
M_d	dry mass (kg)	P_T	profit from tugging ($M)
N_{mis}	number of missions (#)	R	revenue ($M)
N_{mo}	number of months of operation (#)	V_r	residual value of asset ($M)
N_{tr}	number of transponders (#)	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)
First 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
Second 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
Third 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

Satellite name	Longitude (deg)	BOL (yr)	EOL (yr)	6 Mo rev. ($M)	Charged fee ($M)	Revenue (%)	Profit (P&C) ($M)
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

References

[1] Committee on the Peaceful Uses of Outer Space, United Nations General Assembly, A/AC.105/663, 13 December 1996, source: ⟨http://www.oosa.unvienna.org/Reports/AC105_663E.pdf⟩.

[2] A. Ellery, An Introduction to Space Robotics, Springer–Praxis Books in Astronomy and Space Sciences, Praxis Publishers Ltd., Chichester, UK, 2000, p. 57.

[3] Johnson Space Flight Center, NASA, Spacecraft/Vehicle Level Cost Model, source: ⟨http://www.jsc.nasa.gov/bu2/SVLCM.html⟩.

[4] W. Larson, J. Wertz, Space Mission Analysis and Design, Kluwer Academic Publishers, Boston, MA, 1999, p. 804.

[5] Futron Corporation, 2001–2002 Satellite Industry Indicators Survey, source: ⟨http://www.sia.org/papers/⟩.

[6] L. Higgs, Focus Zenith: The New Concept in Space Business, Space 2002 and Robotics 2002, March 17–21, 2002.

[7] K. Galabova, G. Bounova, O. de Weck, D. Hastings, Architecting a Family of Space Tugs based on Orbital Transfer Mission Scenarios, Paper AIAA-2003-6368, AIAA Space 2003 Conference and Exhibition, Long Beach, California, 23–25 September 2003—based on Galabova K. S.M. Thesis, MIT, Cambridge, MA, 2004.

[8] W. Larson, J. Wertz, Space Mission Analysis and Design, Kluwer Academic Publishers, Boston, MA, 1999, p. 809.

[9] PanAmSat Corporation, Annual Report on Form 10-K Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934, United States Securities and Exchange Commission, Washington, DC 20549, Commission File No. 0-22531, Item 7, source: ⟨www.hoovers.com/free/co/secdoc.xhtml?ipage = 2669479&doc = 1%20⟩, release date: 15 March 2004.

[10] A. Ellery, An Introduction to Space Robotics, Springer–Praxis Books in Astronomy and Space Sciences, Praxis Publishers Ltd., Chichester, UK, 2000, pp. 595–596.

[11] Office of Personnel Management, Salaries and Wages, source: ⟨http://www.opm.gov/oca/PAYRATES/INDEX.asp⟩.

[12] Futron Corporation, Satellite Telecommunications Report, source: ⟨http://www.futron.com/spaceandtelecom/src/st.htm⟩.

[13] The London Satellite Exchange Ltd., ESAX World Satellite Transponder Index, source: ⟨www.e-sax.com⟩, date accessed: 29 April 2003.