Architecting a Family of Space Tugs based on Orbital Transfer Mission Scenarios

by

Kalina K. Galabova

B.S. in Mechanical Engineering/Aeronautical Systems (2001)
United States Military Academy

Submitted to the Department of Aeronautics and Astronautics Engineering
in Partial Fulfillment for the Degree of
Master of Science in Aeronautics and Astronautics

at the

Massachusetts Institute of Technology

February 2004

Signature of Author...
Department of Aeronautics and Astronautics

Certified by...
Olivier de Weck
Assistant Professor of Aeronautics and Astronautics
and of Engineering Systems
Thesis Supervisor

Accepted by...
Edward M. Greitzer
H.N. Slater Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Architecting a Family of Space Tugs based on Orbital Transfer Mission Scenarios

by

Kalina K. Galabova
Submitted to the Department of Aeronautics and Astronautics
on January 16, 2004 in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautics and Astronautics

Abstract

The consequences of satellite misplacement or collision with space debris reach far beyond the realm of money. The vast number of people affected by the loss of just one spacecraft indicates the vulnerability of our society to spacecraft failure. Thus, one of the biggest problems that satellite makers face today is the lack of a margin of error of any type. This thesis analyzes the business case for employing a special type of on-orbit servicer referred to as a space tug as an alternative to redundancy and replacement option. The main objective of a space tug is to prevent satellites from prematurely ending their missions.

It was found to be more realistic to design a tug (or tugs) that service groups of satellites with similar orbital and physical characteristics, rather than to design a "monster" vehicle expected to traverse the huge distances between LEO and GEO and deal with satellites of all types and sizes. Thus, the approach of this work was based on the exploration of the entire satellite population currently in orbit around Earth and on the identification of potential target groups of satellites, along with mission scenarios for servicing each of these groups. Eight mission scenarios were identified as most necessary. Two of them—GEO communications satellite retirement and satellite rescue—were presented as case studies to illustrate the modeling approach suggested by this thesis. The ultimate objective of the research was to create a family of modular, economically feasible space tugs that used a common platform and shared various components, which would allow to provide relatively inexpensive and responsive on-demand tugging services.

It was found that the optimal space tug for GEO retirement missions should be initially parked in the GEO belt and be controlled via supervision. This space tug should have a 300-kg low capability grappling mechanism and utilize storable bipropellant (Isp = 325 sec). The maximum number of satellites the tug could visit was calculated to be 20. The minimum fee for the service was estimated to be $20.48M, and the uncertainty of cost estimations should not exceed $7.5M for the nominal case. The optimal tug for satellite rescue missions was an ion electric spacecraft parked on Earth and controlled via supervision. It was not designed as reusable, and various types of grappling mechanisms or any number of fuel tanks could be attached to it, depending on mission requirements. Both architectures could use a common bus and share the same type of grappling devices.

Thesis Supervisor: Olivier de Weck
Title: Assistant Professor of Aeronautics and Astronautics and Engineering Systems

Acknowledgements

For me, working on this thesis was an opportunity to be creative and bring together the skills I have acquired in my two and a half years at MIT, but most of all to make a real professional contribution. However, I would have not been able to accomplish this without the continuous support of my advisor, Prof. Olivier de Weck, and the rest of the team working on on-orbit servicing.

This work would not be possible if not for the interest and support provided by our sponsor, Dr. Gordon Roesler, from DARPA (TTO). My gratitude also goes to Prof. Daniel Hastings and Dr. Hugh McManus for their expertise and advice throughout the completion of this thesis. Michelle McVey from Adroit Systems Inc. has also been extremely helpful in providing useful information regarding the current state of the satellite industry.

I would like to express my appreciation to my friends and teammates Roshanak Nolchiani, Carole Joppin, Gergana Bounova, and Todd Schuman, who monitored and critiqued my work at a number of presentations and group meetings. I have also immensely enjoyed being a part of the "33-409 family," and I would like to thank my officemates for making each day interesting. I feel extremely lucky to have received the opportunity to be part of the MIT Space Systems Laboratory and to be surrounded by such intelligent, motivated, and entertaining people.

Last but not least, I and am grateful for the support of Dimitar Zlatev, who read and edited every page of this thesis and cheered and encouraged me throughout.

TABLE OF CONTENTS

1 **Introduction** 17
1.1 Definitions and Acronyms 18
1.2 Motivation for Space Tug Missions 20
1.2.1 Need for an Alternative Option 20
1.2.2 Mission Scenarios 22
1.3 Value of This Research 24
1.3.1 A Different Approach 25
1.3.2 Business Case Analysis 25
1.4 Thesis Outline 26
1.5 Chapter Summary 26

2 **Literature Review** 27
2.1 On-orbit Servicing 28
2.1.1 Servicing of Manned Spacecraft/Station 28
2.1.2 Servicing of Satellites by Humans 30
2.1.3 Servicing of Satellites by Unmanned Spacecraft 32
2.1.3.1 Early Space Tug Concepts 32
2.1.3.2 Recent Proposals 37
2.1.3.3 Research at MIT 45
2.2 Summary of Previous Work Shortcomings 48
2.3 Recommendations for Improvement 51
2.4 Chapter Summary 53

3 **New Architecting Approach** 55
3.1 Description of the Proposed Approach 55
3.2 Database and Target Clusters 57
3.3 Orbital Mission Scenarios 61
3.3.1 Satellite Rescuing 61
3.3.2 Crowding and Collision Risks 62

3.3.3 Satellite Lifetime and Retirement ... 67
3.3.4 National Security and Military Advantage ... 68
3.3.5 Economic Profit from Satellites Reconfiguration ... 69
3.3.5.1 Demand Uncertainty for LEO Constellations ... 69
3.3.5.2 New Markets or Market Shift (Non-Constellation Satellites) ... 70
3.3.6 On-orbit Assembly of Massive Structures ... 71
3.3.7 Fuel Requirements for Orbit Adjustment Maneuvers ... 72
3.4 Deployment of a Family of Tugs ... 74
3.5 Chapter Summary ... 75

4 Research Methodology ... 77
4.1 Phase I: Understanding the Need ... 77
4.1.1 Problem Identification ... 78
4.1.2 Stakeholders Identification ... 80
4.1.3 Top-Level Customer Requirements ... 80
4.1.4 Conceptual Design Objective ... 81
4.2 Phase II: Modeling the System ... 82
4.2.1 Mission Attributes and Utilities ... 82
4.2.1.1 Mating Capability ... 83
4.2.1.2 Transfer Capability ... 84
4.2.1.3 Timeliness of Response ... 86
4.2.1.4 Adaptability ... 87
4.2.1.5 Total Utility Metric ... 87
4.2.2 Design Vector ... 88
4.2.2.1 Autonomy Level ... 89
4.2.2.1.1 Major Trade-offs ... 93
4.2.2.1.2 Sensing Capabilities ... 96
4.2.3.1 Grappler Sophistication ... 101
4.2.3.1 Propulsion Type ... 103
4.2.3.1 Parking Location ... 108
4.2.3 Parameters, Constraints, and Assumptions ... 110

4.2.4 Cost Estimation 110
4.2.4.1 Design and Production Cost 111
4.2.4.2 Propellant Cost 112
4.2.4.3 Launch Cost 113
4.2.4.4 Insurance Cost 114
4.2.4.5 Operational Cost 115
4.2.4.6 Depreciation 116
4.2.4.7 Cost Uncertainty Margin 117
4.3 Phase III: Evaluating the Architectures 117
4.3.1 Main Assumptions 117
4.3.2 Pareto Front and Architecture Selection 120
4.3.3 Sensitivity Analysis 121
4.4 Phase IV: Fee Estimation 122
4.4.1 Market Analysis 122
4.4.1.1 Supply and Demand 123
4.4.1.2 Competing Options 124
4.4.1.3 Satellite Industry Overview 125
4.4.2 Fee Estimation Approach 127
4.5 Phase V: Family Deployment 128
4.6 Chapter Summary 130

5 Results and Discussion 131
5.1 GEO Satellite Retirement 131
5.1.1 Motivation 132
5.1.2 Stakeholders 133
5.1.3 Assumptions 134
5.1.4 Competing Options 141
5.1.5 Market Statistics and Forecast 143
5.1.6 Fee Estimation 150
5.1.6.1 Total Utility 152
5.1.6.2 Total Cost 153

5.1.6.3 Minimum Fee and Optimal Architecture ... 154
5.1.6.4 Maximum Client's Profit ... 156
5.1.6.5 Mid-Way Fee ... 157
5.1.7 Sensitivity Analysis ... 159
5.1.7.1 Sensitivity to Cost Margin Changes ... 159
5.1.7.2 Sensitivity to Minimum Fee ... 160
5.1.7.3 Sensitivity to Length of Extended Operations ... 161
5.1.8 Cost and Benefit Analysis of the Competing Options ... 163
5.1.9 Conclusions ... 164
5.2 Stranded Satellites ... 165
5.2.1 Motivation ... 166
5.2.2 Failures Statistics and Predictions ... 167
5.2.2.1 Failure Types ... 169
5.2.2.2 Optimal Orbit ... 173
5.2.2.3 Type of Client Satellite ... 174
5.2.2.4 Type of Service Provider ... 175
5.2.3 Stakeholders ... 175
5.2.4 Assumptions ... 176
5.2.5 Competing Options ... 180
5.2.6 Fee Estimation for Satellite Rescue ... 182
5.2.6.1 Pre-Orbital Failures ... 184
5.2.6.1 Post-Orbital Failures ... 185
5.2.7 Cost and Benefit Analysis of Competing Options ... 187
5.2.7.1 Pre-Orbital Failures ... 187
5.2.7.2 Post-Orbital Failures ... 192
5.2.8 Conclusions ... 196
5.3 Deployment of a Family of Tugs ... 198
5.4 Chapter Summary ... 199

6 Summary and Conclusions ... 201
6.1 Thesis Summary ... 201

6.2 Conclusions 203
6.3 Recommendations for Future Work 205

BIBLIOGRAPHY 209

APPENDIX A: Orbital Transfer Calculations 217
APPENDIX B: GEO Satellite Data Used in Calculations 221
APPENDIX C: Commercial Communications Satellite Revenues when Mid-Way Fee for Tugging is Charged 223

LIST OF FIGURES

Figure 2.1: Manned Spacecraft 30
Figure 2.2: Mission Phases 33
Figure 2.3: Subsystems Organization 47
Figure 3.1: Design Approach 57
Figure 3.2: Distribution of LEO Satellites 59
Figure 3.3: Distribution of GEO Satellites 60
Figure 3.4: Objects in Earth Orbit 63
Figure 3.5: LEO Clutter 63
Figure 4.1: How-Why Analysis 78
Figure 4.2: Mind Map 79
Figure 4.3: Functional Decomposition 81
Figure 4.4: Main Mission Phases 85
Figure 4.5: Definition of Timeliness 86
Figure 4.6: Task Completion Time as a Function of Task Complexity 94
Figure 4.7: Information Flow Model 96
Figure 4.8: Grapplers of Different Capabilities 103
Figure 4.9: Space Tug Tradespace with Capability Indicated 121
Figure 5.1: GEO Satellites Breakdown 132
Figure 5.2: Regulated Pressurization System 137
Figure 5.3: Qualitative Representation of Temperature and Pressure Changes 138
Figure 5.4: Possible Options and Their Outcomes 142
Figure 5.5: Satellite Industry Average Profit Margins 144
Figure 5.6: Predicted Supply and Demand of Satellite Capacity 146
Figure 5.7: Recent World Commercial Satellite Revenues 147
Figure 5.8: COMSTAC Commercial GEO Satellite Forecast 149
Figure 5.9: Minimum Fee as a Function of Number of Missions 151
Figure 5.10: Sensitivity to Changes in Cost Margin 159
Figure 5.11: Sensitivity to Changes in Minimum Fee 160
Figure 5.12: Sensitivity to Length of Extended Operations 162

Figure 5.13: Sensitivity to Minimum Fee 162
Figure 5.14: Anomalies as Percent of Satellite Design Life 169
Figure 5.15: Distribution of Selected Stranded Satellites 171
Figure 5.16: Examples of Possible Satellite Initial and Destination Locations 174
Figure 5.17: Number of Satellites vs. Mission Type 175
Figure 5.18: Competing Options 181
Figure 5.19: Sensitivity to Communications Satellite Reduction of Life 189
Figure 5.20: Modularity of Tug 198

LIST OF TABLES

Table 1.1: Proposed Tug Missions 22
Table 4.1: Results from Sample Calculations 86
Table 4.2: Utility Weights 88
Table 4.3: Design Variables 89
Table 4.4: Mapping of Design Variables against Attributes 89
Table 4.5: Mapping of Sensing Capabilities against Mating Capability Criteria 98
Table 4.6: Weights of Sensing Capabilities 100
Table 4.7 Arm Manipulators for Use in Space 102
Table 4.8: Grappler Sophistication Levels 102
Table 4.9: Propulsion System Choices 104
Table 4.10: Software Design Cost 112
Table 4.11: Propellants Cost 112
Table 4.12: Launch Vehicles Data 113
Table 4.13: Average Price per Pound for Western and Non-Western Launch Vehicles 114
Table 4.14: Rough Teleoperations Cost 116
Table 4.15: Utility Weights 119
Table 4.16: Uncertainty and Risk Factors 120
Table 4.17: World Revenues in US $B 125
Table 4.18: World Commercial and Civil Government Launches 125
Table 4.19: US Commercial and Civil Government Launches 125
Table 4.20: Commercial Launches by Payload Owner Region 126
Table 4.21: Worldwide Commercial Launches by Orbit 126
Table 4.22: US Commercial Launches by Orbit 126
Table 5.1: Satellite Industry Sectors 143
Table 5.2: Number of Potential Clients per Year 149
Table 5.3: Tug Reusability 152
Table 5.4: Relative Weights of Attributes 152
Table 5.5: Performance per Cost 155
Table 5.6: Minimum Fee Results 155

Table 5.7: Fraction of Transponders Leased ... 156
Table 5.8: Minimum Fee Sensitivity Tests ... 161
Table 5.9: Sensitivity to Minimum Fee ... 163
Table 5.10: Maximum Number of Potential Clients for Various Cost Margins ... 164
Table 5.11: Maximum Number of Potential Clients ... 164
Table 5.12: Cases Justifying Tugging ... 165
Table 5.13: Launch Vehicle Failure Statistics ... 167
Table 5.14: Satellite Failure Statistics ... 168
Table 5.15: Average Number of Stranded Satellites ... 170
Table 5.16: Number of Satellites Failed On-Orbit ... 172
Table 5.17: Difficulty of Satellite Repair ... 173
Table 5.18: Baseline Case ... 177
Table 5.19: Client Satellite Parameters ... 178
Table 5.20: Mission Characteristics Weights ... 180
Table 5.21: Relative Weights of Attributes ... 183
Table 5.22: Minimum Fees for Pre-Orbital Failures Rescue Tugs ... 185
Table 5.23: Tug Costs for Post-Orbital Failures Rescues ... 186
Table 5.24: Competing Options Comparison for Stranded Communications Satellite .. 188
Table 5.25: Profits based on Value Factors ... 190
Table 5.26: Mid-Way Fees [$M] for Stranded Satellites ... 191
Table 5.27: Government Fees for Stranded Satellites ... 191
Table 5.28: Optimal Options for Cases 4, 5, 6, 12, and 15 ... 193
Table 5.29: Case 1 Profits ... 194
Table 5.30: Cases 7 and 10 Profits ... 194
Table 5.31: Cases 8 and 11 Profits ... 195
Table 5.32: Case 9 Profits ... 195
Table 5.33: Charged Fee Ranges ... 196

Chapter 1

Introduction

April 12, 1999, CAPE CANAVERAL, Fla. (AP) - A $250 million missile-warning satellite that was left stranded in a useless orbit had the Air Force scrambling Sunday in an attempt to rescue it. If the satellite cannot be salvaged, the failed mission will cost taxpayers $682 million, including the rocket cost. [AP99]

May 07, 1999, CAPE CANAVERAL, Fla. (Reuters) - Ground controllers struggled Thursday to save a $145 million communications satellite left in a perilously low orbit after a botched launch two days ago on Boeing Co.'s new Delta 3 rocket. The U.S. space industry is reeling from six failed launches in the last nine months with a total loss of around $3.5 billion.[1]

[1] http://www.chron.com/cgibin/auth/story.mpl/content/interactive/space/news/99/990507.html

These are only two of the many accounts of failed satellite missions. Not surprisingly, all of these reports underline the loss of hundreds of millions of dollars. However, owners' bankruptcy and increased nationwide taxation are not the only source of concern. The consequences of satellite misplacement or malfunction reach well beyond the realm of money. Recall the sudden computer failure of the PanAmSat Galaxy 4 that caused the satellite to start spinning in an incorrect orientation on May 19, 1998. Then, about 90 percent of the 45 million pagers in the United States failed, and some television, radio and retail store networks lost service, totaling considerable losses. Since pagers are the lifelines of many people, including doctors and emergency technicians, it was fortunate that a backup satellite was available and the crisis was resolved within a few days [Pra02]. This incident exposed, not for the first time, the dependency of our society on satellite technology and its vulnerability to individual spacecraft failure. In response to this situation, satellite makers face a difficult problem: the lack of margin of error of any type. The risk of failure can be reduced by use of redundant systems and/or back-up satellites, or by improved performance of launch vehicles. Unfortunately, this would be extremely expensive and yet would not guarantee one hundred percent risk-free missions. Currently, when a satellite fails, replacement and EVA are the only options, and they cost roughly between $20 million and $1 billion, respectively. An alternative and potentially more cost-effective option is the use of an unmanned on-orbit servicer. Provided that this idea is economically sound, its achievability could drastically change the way satellite missions are planned and conducted. The driving considerations are: 1) cost economy attained through extension of spacecraft life by correction of unexpected malfunctions, exchange of defective units, and re-supply of depleted consumables, and 2) mission flexibility by on-orbit payload changeout [Wal93].

The goal of this thesis is to analyze the business case for some of the possible missions that would employ a specific type of on-orbit servicer referred to as a space tug.

1.1 Definitions and Acronyms

The following is a list of definitions and acronyms frequently used in this thesis:

Attribute	A metric of how well the user-defined objectives are met.
BOL	Beginning of Life
Cooperative target	A satellite whose attitude control system is operational and is able to communicate with servicing tug.
Depreciation	The decline in value of a property due to aging, general wear and tear, or obsolescence.
DOF	Degree of Freedom
EOL	End of Life
EVA	Extra-vehicular activity
GEO	Geosynchronous Orbit
GIS	Geographic Information System
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
ISS	International Space Station
LEO	Low Earth Orbit
Mission scenario	A specific type of mission that can be accomplished by a space tug (see Section 1.2.2).
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
Non-cooperative target	A tumbling body, space junk.
NSSK	North-south station-keeping
On-orbit servicer	A spacecraft whose mission is to maintain or improve the original capabilities or extend the operation life of satellites. The concept usually implies the introduction of additional mass (e.g. fuel, replacement or upgrade modules).
Profit	Revenue minus expenses
Revenue	Total dollar payment for goods and services
Space debris/space junk	Any object in near-Earth space that is not a functional satellite (i.e. dead satellites, rocket bodies, mechanical parts, etc).

Space tug	A vehicle that is designed to rendezvous and "dock" with a target satellite, make an assessment of its current position, orientation and operational status, and then move it to a different orbit with subsequent release. It is a sub-class of on-orbit servicers. The interaction between a satellite and a tug is purely external.
Target	An object that needs to be moved to a different location.
TDRSS	Tracking and Data Relay Satellite System
TRL	Technology Readiness Level
Utility	A weighted measure of how valuable a certain attribute is to the customer relative to the other attributes, ranging from 0 to 1.

1.2 Motivation for Space Tug Missions

There are a number of problems in space that might be resolved by utilizing a tug. Section 1.2.1 explains the general need for a tugging vehicle. Section 1.2.2 briefly discusses the most interesting scenarios that consider tugging as an option.

1.2.1 Need for an Alternative Option

The two main applications for which a space tug might prove useful are: 1) the extension of the operational life of satellites, and 2) the prevention of satellite lifetime reduction. There are a number of problems contributing to the shortening of a satellite's life or its partial or total mission failure. The resulting loss of revenues and insurance premiums can be very high, compared to other sectors of the economy. Failures can also cause companies to lose their competitive edge due to delays in delivering service in this rapidly changing and intensely competitive business [Pra02]. It takes some time before a replacement is launched or EVA is performed, and during this time the affected satellite owner receives no revenue whatsoever. Additionally, the options of EVA and launch of a replacement might not always be available.

Other cases exist when there is nothing wrong with a satellite, but altering its location is desirable due to a market shift (in the case of communications satellites) or to surprise an enemy (in the case of military satellites). However, use of the satellite's own fuel supplies for the transfer shortens its design life. Another related problem is that fuel supplies dictate the operational lifetimes of spacecraft, and satellites are forced to "retire" even though all of their remaining subsystems might still be functional. This is especially true for communications satellites in GEO. Unfortunately, today there is no viable way to prolong the life of these very expensive and capable satellites, resulting in a wasteful loss of valuable assets every year.

The concept of a space tug is introduced as a solution to these problems and requirements. An optimized space tug infrastructure might be able to provide a faster response than the alternative two options (replacement and EVA), and, by salvaging a satellite mission at least partially, it promises satellite operators a second chance at obtaining some revenue. Therefore, there is a clear need for space tugs as an alternative and potentially more valuable option. The key question is whether the economic and operational benefits of space tugs outweigh the expense and risk of developing and using them. This thesis sets out to answer this question in the context of specific mission applications.

The main space tug applications can be grouped in three categories:

1. Orbit correction:
   a) **station-keeping:** maneuvering satellites to maintain their nominal position or track;
   b) **rescuing:** emergency capture and insertion of stranded satellites into desired orbits.
2. Collision risk mitigation:
   a) **debris removal:** removing space debris from highly populated regions;
   b) **satellite retirement**: moving dysfunctional satellites to "graveyard" altitudes or deorbiting them.
3. On-demand maneuvers:
   a) **military:** providing flexible and unpredictable relocation of US military satellites;

b) **civil:** changing the location of a satellite due to a shift in market or scientific interest.

In addition to these functions, space tugs can be used to assess the current position, orientation, and operational status of satellites.

1.2.2 Mission Scenarios

The following table lists the major problems that might be mitigated by the use of a space tug, along with their corresponding mission scenarios.

	Identified Problems	**Missions**
1	Stranded satellites	GTO/LEO-GEO satellite rescuing
2	Crowding and collisions	Orbital debris removal
3	Satellite lifetime and retirement	GEO satellite retirement
4	National security	Military satellite maneuvering
5	Demand uncertainty for constellations	(LEO) Constellation reconfiguration
6	New markets or market shift	Satellite repositioning
7	Massive space systems	On-orbit assembly/building
8	Fuel requirements	NSSK/orbit raising/decay prevention

Table 1.1: Proposed Tug Missions

A brief description of the above listed mission scenarios follows. Missions 1 and 3 are analyzed in greater detail in Chapter 5 because they are seen as potentially high value, profitable, and realistic missions that can be implemented in the near future and are of high interest to the sponsor of this research (DARPA).

Mission 1 Failures of rockets' upper stages are not a rare occasion.[2] As a result, satellites are left in useless orbits. The utilization of on-board fuel to boost the satellites up to the correct orbit is either impossible or would reduce immensely their expected

[2] The typical launch success rate is 92%.

operational life. Tugging could mitigate the problem, since saving a satellite's on-board propellant would allow it to operate for nearly as long as intended and thus produce revenues for the price of a given service fee. A tug could also be used for transferring a satellite to the ISS for repair and then moving it back to its operational orbit.

Mission 2 There are already too many objects in space and we cannot continue sending more satellites without vacating some spaces [Sim94]. This overcrowding also poses the problem of high collision probability, especially in LEO above 500 km. The mission scenario will cover not only the tugging of dead LEO satellites down to decay orbits, but will include any type of space debris (rocket stages, satellite parts, etc.) in all orbital regions.

Mission 3 Tugging allows satellites to stay longer in operational orbit and to use up their entire fuel supplies. This extended lifetime can provide millions of dollars of additional revenue.

Mission 4 National security is the reason why we need surprise maneuvers of military satellites. Currently, adversaries can time their ground activities due to the predictability of overhead passes of spy satellites. The maneuverability of these satellites is limited by the availability of on-board fuel supplies, but a tug could mate with the satellites and transfer them to the desired location. Additionally, military satellites are quite expensive, therefore another potential use for a space tug is to simply correct for orbital drift or decay and thus extend the satellite's life.

Mission 5 The traditional way of designing constellations of communications satellites is to optimize the design for a specific global capacity, based on a forecast of the expected number of users and their activity level, both of which are highly uncertain. This can lead to economic failure if the actual demand is smaller than the one predicted. It is better to deploy the constellation progressively, increasing the number of satellites as needed through reconfiguring the existing constellation on orbit [Cha03]. A tug is needed so that the satellites do not exhaust their own fuel, especially since they may have to alter their location several times.

Mission 6 Satellites might need to be relocated to cover a different part of the Earth, if the market there is bigger. A tug can capture and move them, so that their operational lives are not shortened by fuel depletion.

Mission 7 Mass and volume have always been an issue in space systems deployment, the biggest constraint being imposed by launch vehicles capabilities. On-orbit assembly of space assets, however, offers a solution to the problem. It also allows for expensive projects to be initiated without the need of having the entire budget available up-front. Additionally, it reduces the financial risks in case of launch failure or a spacecraft subsystem failure, since only the failed module would need to be replaced. It might be cost-effective to have tugs moving the assembly parts and modules, as opposed to adding propulsion tanks and guidance control systems to the separately launched parts of the assembly.

Mission 8 Satellites can trade fuel for payload or smaller launch vehicle if NSSK, orbit raising or decay prevention is done by a tug that periodically attaches itself to the satellite.

1.3 Value of This Research

Previous designs have been infeasible due to technological difficulties and cost concerns (see Chapter 2 for the analysis of previous research shortcomings). At this point of technological development, the concept of creating a single, universal vehicle to service all types of satellites in both LEO and GEO is infeasible, as will be shown in the next chapter. Conversely, the advantages offered by distributed systems can mean improvements in performance, cost, and survivability compared to traditionally suggested single-tug deployments. Additionally, previous studies have tended to look only at a portion of the possible trade space. They have been limited in both applications considered and design concepts explored. They tended to focus on either hardware or economic issues, with insufficient attention reserved for the coupling between them.

This thesis carries out a systematic exploration of the space tug trade space. Its value is two-fold. First, it offers a different approach to space tug architecting that is based on realistic and need-driven mission scenarios. Second, it quantifies the economical feasibility of space tugging.

1.3.1 A Different Approach

The approach proposed by this thesis is driven by realism, need, and utility. It is based on the investigation of several mission scenarios for which the use of a space tug might prove to be the optimal solution. What distinguishes this research from previous work is the starting point of the analysis. As mentioned above, the idea of a universal vehicle that can cover the entire space and perform many types of tugging missions is not yet viable. It is more realistic to try to build smaller and simpler tugs that operate locally in pre-defined zones. Thus, near-Earth space is divided into several orbital zones in terms of altitude and inclination, and a separate tug is assigned to each zone. The ultimate objective of the research is to create a family of economically feasible space tugs that use a common platform and share various components that would allow for the relatively inexpensive and quick response to on-demand tugging services. A detailed description of the approach is given in Section 3.1.

1.3.2 Business Case Analysis

Serviceability has never been implemented before because of questionable cost-effectiveness. Specifically, no thorough study has been published that clearly models the cost-effectiveness of such an endeavor. While the technological feasibility of the concept is increasingly less disputed, it appears that the business case for the development of a generic space tug capability has yet to be made in a convincing fashion. The main difficulty arises form the fact that the cost of a space tug is difficult to estimate because this vehicle differs from any other systems for which cost models have been created based on historical data. Additionally, economic advantages should be weighed against the unknown risk; that is, cost modeling remains to be combined with risk assessment. Errors in space business assessment can be very costly, and one of the major goals of this thesis is to analyze the potential for establishing a sound market for space tug services. The main question that will be considered is the fee to be charged so that tugging is still attractive to a sufficient number of potential customers.

1.4 Thesis Outline

The current chapter introduced the concept of on-orbit servicing and explained the motivation behind this thesis. Chapter 2 is devoted to literature review. It provides an overview of the previous and current research dealing with on-orbit servicing, particularly space tugging. It also explains the shortcomings of previous work. A new approach for space tug architecting is proposed and described in detail in Chapter 3. The specific research methodology that was followed is explained in Chapter 4. The chapter discusses the steps in system modeling and cost estimation. It explains the concepts of attributes and utility and describes how optimal architectures are selected. In conclusion, it briefly introduces the concept of family deployment with its associated difficulties. Chapter 5 presents the results from following the methodology for two mission scenarios: GEO Satellite Retirement and Satellite Rescuing. Chapter 6 summarizes all results and conclusions and closes with suggestions for future work.

1.5 Chapter Summary

The space tug concept is suggested as an alternative to satellite abandonment, replacement, or EVA repair. The objective of this thesis is to analyze the business case for the two potentially most valuable tug missions: the retirement of GEO commercial communication satellites and the rescue of stranded or malfunctioning satellites in LEO, MEO, GTO, or GEO. The main question that will be answered is in what cases the economic benefits resulting from such tug missions outweigh the expenses and risks associated with them.

Chapter 2

Literature Review

From as early as the 1960's much thought has been given to the subject of satellite on-orbit servicing and, in particular, tugging. Regardless of this fact, almost half a century has passed and tugs are still not a part of the space infrastructure. The purpose of this chapter is to review the published documentation of previous work and to identify the reasons that have made the relevant designs unsuccessful. The chapter starts by describing some of the early concepts of on-orbit servicers, with a particular emphasis on space tugging. Then, after a discussion of some recent and on-going projects, it provides a summary of the shortcomings of previous designs. The last section of this chapter suggests ideas that might help overcome existing hindrances and make satellite servicing a reality.

2.1 On-orbit Servicing

An on-orbit servicer is a spacecraft whose mission is to maintain or improve the original capabilities of satellites or to extend their operational life. The concept often implies the introduction of additional mass (e.g. fuel, replacement or upgrade modules). This section discusses several early and current projects that are representative of three categories of on-orbit servicing: servicing of a space station, servicing of satellites by humans, and servicing of satellites by unmanned spacecraft.

2.1.1 Servicing of Manned Spacecraft/Station

The concept of servicing operational spacecraft is not new. Before the mid 1980's, however, in-flight demonstration of servicing had been limited to manned spacecraft (see Figure 2.1).

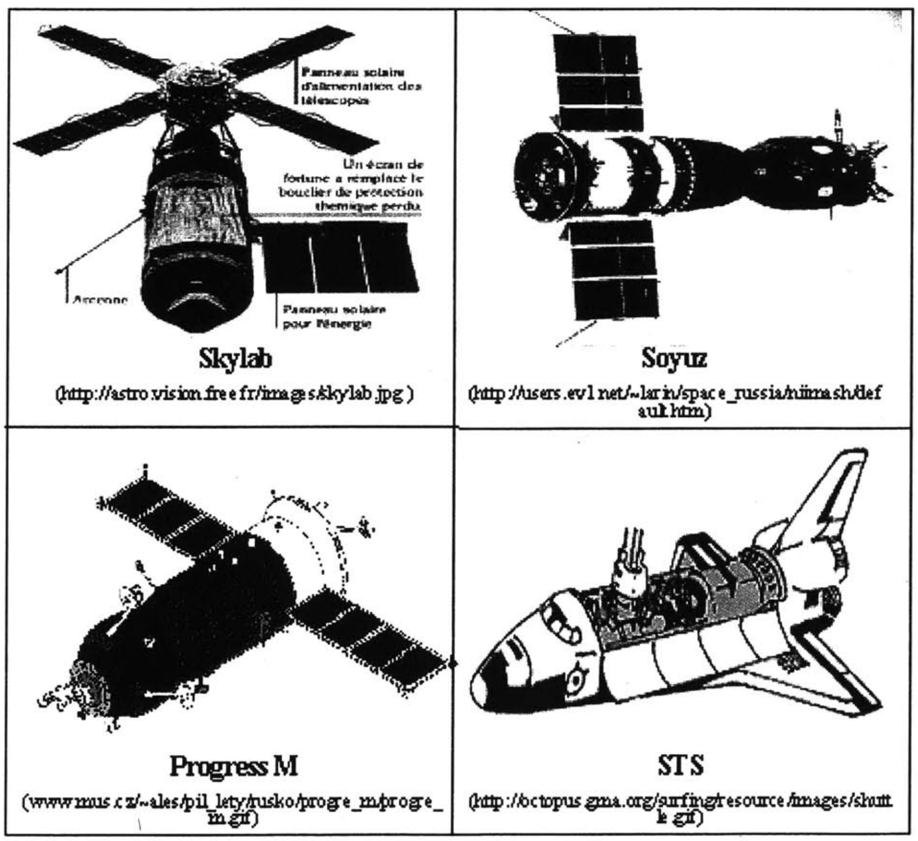


Figure 2.1: Manned Spacecraft

Skylab

Skylab was NASA's first experience with on-orbit servicing. It successfully demonstrated the feasibility of performing in-flight repair and maintenance. Between 1973 and 1974, its crew had performed various activities, including installation and deployment of a solar shield "parasol," release and deployment of a jammed solar array, installation of a rate gyro package, antenna repair, and coolant system maintenance. [Wal93]

Soyuz

The Soyuz spacecraft series was designed and built by the Soviet Union with the primary function to transport cosmonauts to and from space stations. Soyuz made its first crew delivery to the Salyut space station in 1971. Later, it was used to transport crews to Mir and the ISS, while also acting as a lifeboat in the unlikely event an emergency would require the crew to leave the station.[1]

Although Soyuz can carry about 50 kg of supplies to the station[2], its capabilities of returning cargo to Earth are very limited; it does not comply with the definition of servicer assumed for the purposes of this work. However, very early in the development of its space stations, Soviet designers realized that long-duration missions in space would demand a constant supply of consumable materials from Earth. The developer of the Salyut space station considered different configurations of a Soyuz-derived ship adapted for cargo missions. Designers studied different sizes, as well as manned and unmanned versions of the craft. The concept of the unmanned ship ultimately won out, and the government officially authorized the project in 1974. The vehicle was developed within the Salyut-6 project, and the production of the first craft was completed by November 1977. The vehicle, named Progress, blasted off toward the Salyut-6 station on January 20, 1978. A total of forty-three Progresses of the original series were launched toward the Salyut-6 and Salyut-7 space stations, all successfully completing their missions.[3]

[1] http://spaceflight.nasa.gov/station/assembly/elements/soyuz/
[2] http://users.commkey.net/Braeunig/space/specs/soyuz.htm
[3] http://liftoff.msfc.nasa.gov/rsa/mir.html

Progress M

The first Progress M spacecraft was launched toward Mir in August 1989. It was an unmanned cargo and resupply vehicle of total payload capacity up to 2,750 kg that was used to send science equipment and data to and from Mir. It could also be used to conduct experiments either while attached to the station or during free-flight. When sent back to Earth, it could be used to remove waste materials from the space station. Currently, a Progress M1 spacecraft supplied with additional propellant tanks services the ISS.[4]

Space Shuttle

The Space Shuttle was developed for a variety of purposes: station resupplying, satellite delivery and retrieval, orbital servicing, and laboratory research in space. Introduced in 1981, to date there have been one hundred and thirteen flights of the five different orbiters: Columbia, Challenger, Atlantis, Discovery, and Endeavour.

Cargo Transfer Vehicle (CTV)

In the early 1990's, NASA and the Department of Defense (DOD) conceptualized the Cargo Transfer Vehicle as an unmanned orbital stage whose primary function was to resupply the ISS via payload transfers to and from the ISS. This automated, active, unmanned space vehicle was to operate in the vicinity of and dock with an essentially passive, manned space vehicle. Comprehensive evaluation and review of the U.S. capabilities in regard to autonomous rendezvous and capture were conducted. Independent studies showed that the required autonomous capability did not exist and needed to be developed. It was decided to cancel the CTV project and to continue resupplying the U.S. part of the ISS with the Space Shuttle. [Pol98]

2.1.2 Servicing of Satellites by Humans

For more than a quarter century after the launch of the first artificial satellite, on-orbit servicing of unmanned spacecraft was not an option. It became a reality in 1984

---

[4] Ibid.

with the repair of the Solar Maximum Mission satellite. Since then, all on-orbit satellite servicing has been performed by astronauts.

NASA has done a lot of experiments that have moved on-orbit servicing from concept to reality. In the 1980's, STS 41-G carried up refueling gear and hydrazine tanks, and astronauts demonstrated that it was possible to attach hoses and valves and to pump hydrazine into the dry tanks of satellites that had exhausted their fuel supplies. Hence, the experiment proved it was possible to revive satellites reached by the Shuttle.[5]

One of the primary objectives of the STS-49 mission was to use the Endeavour's 15-meter-long Remote Manipulator System (RMS) robotic arm to capture an Intelsat satellite and replace its rocket motor so that it could reach geostationary orbit. Although successful, the capture was a challenge, since the satellite was not designed for such a procedure. The crew succeeded in capturing the satellite on the third day of EVAs, in an attempt that was at the time the longest EVA in history, 8 hours 29 minutes, surpassing the record of 7 hours 37 minutes held by the Apollo 17 astronauts.[6]

The retrieval and Earth return of Palapa B2 (1984), Westar VI (1984), and the Long Duration Exposure Facility (LDEF) and the on-orbit repair and redeployment of Leasat-3 (1985), Syncom IV-3 (1985), and the Gamma Ray Observatory (2000) are other examples of successful on-orbit servicing. In 1988, Price and Greenberg [PG88] analyzed the uses of the International Space Station infrastructure for satellite servicing and concluded that the cost of retrieval and repair of satellites on Earth was much higher compared to repair at the ISS. However, besides the fact that only satellites in a limited altitude and inclination range can be targeted, the main problem with performing on-orbit repairs is that very few satellites have been designed to facilitate such activities. The Hubble Space Telescope is one of them.

Hubble Space Telescope (HST)

The Hubble Space Telescope was launched in April 1990. Immediately after its deployment, it became obvious that its primary mirror was flawed (spherical aberration), but replacing HST with a new satellite would have been overly expensive, and therefore

[5] http://www-pao.ksc.nasa.gov/kscpao/kscstory/ch14/ch14.htm
[6]http://spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space.Flight/Shuttle/Shuttle.Missions/Flight.047.STS-49/Mission.Highlights

astronauts were assigned to performed several EVA missions in order to replace and upgrade certain parts of the telescope. These servicing events fall into five major categories: 1) direct replacement with identical or nearly identical units, 2) replacement with a significantly upgraded unit that includes new technology, 3) installation of additional hardware capable of performing new functions that enhance functionality but were not included in the original design, 4) retrofit and repair via addition of hardware or replacement of units with hardware having entirely different functions, and 5) improvised repairs of problems not anticipated prior to a servicing mission. [Lee01]

Other space systems that have been designed for at least some degree of servicing include the Multimission Modular Spacecraft, the Advanced X-Ray Astrophysics Facility, the Gamma Ray Observatory, the Space Infrared Telescope Facility, the Earth Observing System, the Zenith Star Program, and the Orbital Maneuvering System [Wal93].

2.1.3 Servicing of Satellites by Unmanned Spacecraft

The idea of servicing satellites by unmanned spacecraft has not yet become a reality. Since the early 1980's, a number of projects have been undertaken but have been canceled for a variety of reasons (these are discussed in Section 2.3). Other, more recent proposals are still under investigation. This section will focus on space tugging in particular.

2.1.3.1 Early Space Tug Concepts

A space tug is a type of on-orbit servicer whose objective is to rendezvous and "dock" with a target satellite, make an assessment of its current position, orientation and operational status, and then move the target satellite to a different orbit with subsequent release. When modeling each individual scenario, the same set of phases associated with orbital transfers are used, starting with the initiation of the tug mission and ending with the return of the tug to its parking or safe orbit. Depending on the type of the selected mission, the following steps are reiterated or arranged in different order: launch, parking orbit, orbital transfer, rendezvous, mating, towing, release, back to parking or safe orbit.

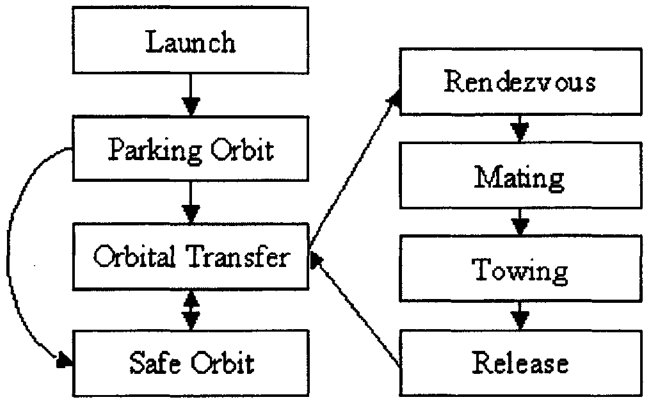


Figure 2.2: Mission Phases

The 1980's and 1990's were characterized by an immense interest towards the idea of space tugging. Many of NASA's 1980s space tug plans were based on the aerobraking concept. For example, one NASA/Marshall concept from 1985 was equipped with a huge disc-shaped aeroshell that slowed the vehicle down as it passed through the Earth's upper atmosphere. The space tug could thus return heavy payloads from geostationary or lunar orbit without using any fuel to rendezvous with the low Earth orbit space station. [Lin03]

A 1984 project suggested that large communications satellites could be delivered to Science and Applications Manned Space Platform (a man-tended free-flying laboratory for materials processing and life sciences experiments) from Earth by the Space Shuttle for final assembly and checkout. A manned Orbital Transfer Vehicle or space tug would then transport the satellites to geostationary orbit. The space tug would be permanently based at the space station in LEO. [Lin03]

Originally, in the 1990's NASA hoped to develop a space tug for manned missions to geostationary orbit and beyond. In 1984, a modular design was proposed by General Dynamics, a company that had investigated space station/space tug integration issues in the early 1980s. Spherical tanks contained liquid hydrogen and oxygen propellant for the engines; three sets would be carried for manned or heavy-lift missions while one set would suffice for delivering smaller unmanned payloads. [Lin03]

The 1986 "Pioneering the Space Frontier" policy report mentioned space tugs that would transport crew and equipment from space stations in low Earth orbit to lunar orbit. Boeing and Martin Marietta were awarded $1M study contracts in July 1984 as NASA was hoping to receive full funding to complete the $2.75B project by the 1990s. However, the project was essentially postponed indefinitely in late 1985 when the Boeing and Martin contracts expired. [Lin03]

In 1989, Gunn provided a comprehensive review of five U.S. orbital transfer vehicle programs: Payload Assist Module-Delta (PAM-D), an upgraded version designated PAM-DII, the Inertial Upper Stage (IUS), the U.S. Transfer Orbit Stage (TOS), and the Orbital Maneuvering Vehicle. The intent of these vehicles was to carry spacecraft to higher energy orbits than achievable by the Space Shuttle or various expendable launch vehicles. Capabilities ranged from providing spacecraft with only preprogrammed perigee velocity additions to man-in-the-loop remotely controlled spacecraft rendezvous, docking, retrieval, and return to a space base. The PAM-D, PAM-DII, and IUS are mature vehicles currently available for mission support. Characteristics, flight records, and costs for these vehicles are relatively well defined. The TOS was commercially developed while the OMV was government developed. [Gun89]

In 1994, Earley described the results from a study that compared various reusable space tug architectures. The following criteria were considered when selecting the best two best concepts: cost, coverage, deployment and total mission time, ability to improve spacecraft lifetime, and ability to perform optional missions. The results showed that the two best concepts were the reusable nuclear thermal propulsion (NTP) tug and the bimodal tug that combined NTP and arcjet propulsion (NTP would be used to move payloads; arcjet would be used for return of the tug to its LEO parking orbit and station keeping). Both concepts consisted of two modules: the propulsion and avionics module and the propellant and payload module. The former would stay on orbit and dock to the latter, which would be delivered by the launch vehicle. The tug would place the payload on the desired orbit and return to its parking orbit. The payback for these two concepts was projected to be between 5 and 10 years of operation. [Ear95]

A number of articles focus on more detailed aspects of space tug technologies and cost estimating. Various propulsion system options for space tugs were compared by Heald (General Dynamics Space Systems) in 1995. Emphasis was put on the cryogenic high performance propellants hydrogen and oxygen. Innovative features were discussed, including space basing with on-orbit refueling and servicing and aerobraking to minimize retropropellant requirements. Over a 30-year period, new engines such as Aerospike and the high pressure Advanced Space Engine were prototyped, but the RL10 with advanced features always proved to be most cost-effective. According to Heald, the next generation of upper stages should focus on more reliable, more expendable, and easier to process concepts. [Hea95]

Flight Telerobotic Servicer (FTS)

NASA decided to develop a $288M Flight Telerobotic Servicer in 1987, after Congress voiced concern about American competitiveness in the field of robotics. The FTS would also help astronauts assemble the Space Station, which was growing in size and complexity. The winning design was by Martin Marietta, who received a $297M contract in May 1989 to develop a vehicle by 1993. The project was cancelled in the early 1990's, when simplifications introduced in the ISS on-orbit assembly procedures invalidated the project's usefulness.[7]

Orbital Maneuvering Vehicle (OMV)

In the 1980's, the OMV was an important component in NASA's future Space Station plans. As a separately funded part of the 1984 Space Station plan, the OMV was intended as a short-range robotic space tug, operating in the vicinity of the Shuttle and Space Station.

The OMV was designed to be a free-flying, remotely controlled propulsion stage, about 15 feet in diameter and 6 feet thick, that would be carried into orbit inside the Shuttle's cargo bay. It was supposed to be a multipurpose space tug whose mission was to transport satellites from the space shuttle to other orbits, reboost satellites when their orbits decayed, retrieve and return them to the shuttle when they malfunctioned, and control their reentry into the atmosphere when their useful lives expired. Subsequent

[7] http://www.abo.fi/~mlindroo/Station/Slides

OMV enhancements would have enabled it to refuel satellites in orbit, perform in-orbit satellite repairs, and rescue out-of-control satellites. The OMV was to operate initially from the Shuttle's cargo bay but would ultimately operate from the International Space Station. [RM90]

In July 1984, NASA awarded three $1M study contracts to Vought, Martin Marietta, and TRW. The total estimated cost was $400M. TRW won the Phase B contract in June 1986. Its OMV could be equipped with enlarged propellant tanks for demanding missions or it could use a separate propulsion module that the Shuttle would return to Earth for refueling.

The OMV encountered many problems in 1989 and 1990, as the estimated total cost swelled to $1B—an increase of $600M. NASA attempted to integrate the OMV and FTS into a "Robotic Satellite Servicer." TRW and Martin Marietta were awarded $1.3M Phase B contracts in June 1990, but the cost was still prohibitive and the project did not survive the Space Station redesign in late 1990: the FTS became unnecessary after Space Station on-orbit assembly procedures were greatly simplified, while the OMV became less important after the station's free-flying space platforms were cancelled. [RM90]

Transfer Orbit Stage (TOS)

The Transfer Orbit Stage is a version of a space tug developed by Orbital Sciences Corporation. The design was compatible with the STS and Titan launch vehicles. In the late 1980's, it was in production for two NASA missions, the Mars Observer and the Advanced Communications Technology Satellite. Unfortunately, the project was cancelled after several years due to its lack of economic viability. [Meh88]

Nuclear Thermal Propulsion Engine (NTPE)

In 1993, Ortiz presented a cost analysis for a nuclear space tug. His paper is an investigation of the cost effectiveness of using a nuclear thermal propulsion engine (NTPE) to transfer payload from LEO to GEO. Costs are calculated for single and multiple uses of NTPEs and are compared to the cost of using a chemical rocket engine to perform the same task. According to the study, the reusability and high performance of the NTPE displayed the potential for significant cost reductions. [Ort93]

Active Debris Removal

As mentioned in Section 1.2, a potential mission for a space tug is the removal of space debris from highly populated orbits. Most of the related studies claim that the cost of removing large objects by a space tug or other dedicated vehicle would be prohibitive. Petro and Ashley predicted a best-case cost of more than $15M for each piece of debris removed from LEO (discounting the cost of developing the tug). Other ingenious schemes, such as the ones involving the use of tethers to deorbit large objects, were also labeled very costly. [PA89]

A number of active removal schemes for small debris have also been proposed, including "debris sweepers" (large foam balls or braking foils that impact with smaller debris) and ground- or space-based laser evaporation of debris surface material. The sweeper scheme seems technically difficult, inefficient, hazardous to functional spacecraft, and risky (it could possibly produce more small objects than it eliminated). The laser concept, although interesting, requires costly new technology, and its feasibility has not yet been proven. Other far-out and costly ideas envision the removal of space debris with an inflatable basket or using mile-wide "Nerf"[8] objects that slow the orbits of debris to send them into the atmosphere [Spa02]. Each suggested method has limitations in terms of debris size, debris orbit, and likelihood of success.

Most of these early studies concluded that, currently, technology is absent that is capable of effectively and efficiently removing small debris. They suggested that active (i.e. by a spacecraft) removal of debris would never be an economical means of reducing the debris hazard, at least for the near future. Conversely, passive removal—implying the design of future spacecraft and launch vehicles for autonomous deorbiting—might be a far more economical means of reducing the collision hazard. [CSD95]

2.1.3.2 Recent Proposals

None of the above listed concepts became a reality, mostly due to financial and technological difficulties. In the past few years, however, there has been a substantial progress in the development of propulsion systems (ion engines, electric propulsion),

---

[8] Nerfs are inexpensive plastic toy guns that shoot foam ammunitions.

spacecraft autonomy, and docking mechanisms. New ideas are surfacing that warrant a fresh look at the on-orbit servicing problem.

Orbital Transfer Vehicles (OTV)

In 1999, SpaceDev began working on the conceptual and preliminary designs of an inexpensive space vehicle that would be capable of boosting secondary payloads into longer-life orbits and that could maneuver on-orbit for such possibilities as satellite inspection, rendezvous, docking, moving, and refueling. The National Reconnaissance Office (NRO) awarded SpaceDev funds to further develop SpaceDev concepts for an Orbital Transfer Vehicle. SpaceDev's design supports long-term fuel storability, both on the ground and on-orbit. The OTV is restartable, throttleable, and relatively clean-burning. Current versions are designed to fit on relatively inexpensive commercial launch vehicles that can carry small secondary spacecraft to earth orbit. The smallest SpaceDev OTV weighs 25 kg and the largest weighs 100 kg. [Spa00]

The purpose of the OTV, as discussed by Meissinger and Collins in a 1999 paper, is to support and extend the life of satellite constellations. One OTV per constellation's orbital plane was proposed, suggesting numerous such vehicles operating simultaneously. The purpose of the OTVs was to perform emergency service of capturing and deorbiting failed satellites in order to prevent a collision with other constellation members. Along with satellite refueling and resupply, circumnavigation and close inspection of both friendly and hostile spacecraft were also part of the servicers' tasks. The research analysis focused on the trade between functional versatility and cost. The simple bus design and relatively small size of each OTV's were expected to lower the cost and speed-up the development schedule, compared to previously suggested servicer designs. The calculations assumed a dry mass of 180 kg for each OTV and an initial propellant mass of 800 kg (storable bipropellants with Isp = 300 sec were used). The cost of the entire system, not including launch, was estimated to be about $32M. The key driver for the non-recurring spacecraft development cost was the creation of autonomous rendezvous control laws for the various OTV applications. Parked within the satellite constellation, the OTV received departure sequence commands from a ground station that also provided target position data. The OTV's autonomous navigation and guidance channels controlled subsequent OTV maneuvers. A major assumption in the proposal was that the assisted orbital transfers would remain within a limited altitude range and would not involve significant plane changes. [MC99]

Orbital Servicing Vehicle (OSV)

Japan has made a big commitment to the development of automated and remotely-controlled systems for rendezvous and docking. The conceptual analysis of the unmanned Orbital Servicing Vehicle proposed by Takagi et al in the late 1990's envisioned the retrieval of about 8.5 tons of payload from 700km altitude and 28.5 deg inclination to the ISS. The OSV was reusable and serviceable on-orbit. Its design life was 10 years.

The major missions of the initial OSV were closely associated with the Space Station, They included deployment and retrieval of unmanned co-orbiting platform, change of payloads, exchange of failed equipments, resupply of consumables to platform, and supply of materials to and retrieval of products from mission payloads. The accurate performance of these missions required a remote manipulator system and a capability of automatic maneuver, including automatic rendezvous and docking. The future OSV was expected to have more autonomous ability to help during more complicated missions, such as retrieval of non-cooperative objects and on-orbit construction or refurbishment of spacecraft [TTO88]. In other words, the OSV aimed to service satellites that were designed for servicing as well as service conventional functional and failed satellites, rocket bodies, and other space debris (i.e. spacecraft that had not been designed with consideration of on-orbit servicing).

Autonomous Satellite Retrieval EXperiment (ASREX)

Also developed in Japan, the Autonomous Satellite Retrieval EXperiment (ASREX) is a free-flying manipulator with satellite capture capabilities. It is a scientifically motivated, special-purpose experimental robot for retrieving satellites. The control laws are the most critical part of the project, since movement of the manipulator causes a reactive movement of the satellite, an effect that must be compensated by position and attitude control. The final goal is to accomplish autonomous satellite capture using feedback from laser radar that is to be developed specifically for this project.[9]

Engineering Test Satellite-VII (ETS-VII)

The ETS-VII was a successful Japanese experiment performed in space in 1997[10]. It was the first autonomous rendezvous and docking between uninhabited spacecraft, where the target was well-known and cooperative.

Geosynchronous Satellite Servicer

In 2001, Turner (Space Systems/Loral) discussed the development of a geosynchronous satellite servicer that could be used for north-south station keeping (NSSK) and orbit raising (OR). Satellites are expected to be launched without apogee stage; therefore, a launch vehicle could almost double the number of satellites it could previously carry. The apogee stage would be attached to the satellite by a servicing vehicle at 10,660 km altitude. In other words, the design assumed that target satellites were designed for on-orbit servicing, which allowed them to expand their payload (e.g. increases the number of transponders) to fill the volume formerly occupied by propellant tanks. This increased revenue capability provides the economic incentive for development of on-orbit servicing. [Tur01a]

Turner described the same servicer in another 2001 paper, this time discussing the cost-effectiveness of its missions. The study envisioned that two servicing vehicles would rendezvous and dock with each client satellite once every week or month (as appropriate) and would service about a dozen spacecraft each. No intrusive servicing such as equipment exchange or repair would be performed. Instead, servicing would be limited to only orbit adjustment maneuvers through captive-carry, refueling, power transfer, and monitoring. The spacecraft being serviced would be entirely dependent upon the servicing vehicle for support in at least some of these activities. One of the main assumptions of the study was that each servicer's design and development would cost about $25M; a Soyuz could be used to launch both vehicles, at a cost of $20M. An annual take of $36M was considered reasonable. This assumption dictated the selected charge of

[9] http://www.wtec.org/loyola/ar93_94/sr.htm
[10] http://www.space.mech.tohoku.ac.jp/research/etsvii/etsvii-e.html

$3M that each client was required to pay annually. [Tur01b] No detailed justification was provided for these numbers.

Automated Transfer Vehicle (ATV)

Expected to launch in 2004, the Automated Transfer Vehicle is part of the European contribution to the ISS. The concept for this spacecraft was first proposed by the European Space Agency (ESA) in the mid-1980s as a way to transport unmanned cargo to the Space Station using an Ariane-5. The ATV is expected to be capable of boosting up the International Space Station and preventing orbital decay. It would dock at the rear of the Russian Service Module (the Russian Space Agency (RSA) had agreed to provide a rendezvous and docking system as part of an ESA/RSA agreement). Periodically boosting the ISS orbit now increasingly appears to be the ATV's most important mission, since the Russians may not be able to launch enough Progress cargo spacecraft to do the job. The final ATV version has a dry mass of 9.2 tons (including its 3,694 kg MPLM-derived Cargo Carrier) and can carry between 2.68 and 6.76 tons of propellant for ISS rendezvous and reboost. Its maximum weight at launch would be about 20.5 tons. The spacecraft would be able to carry up to 7 tons of cargo in eight International Standard Payload Racks, including 860 kg of propellant, 840 kg of water and 100 kg of atmospheric gases.

In 1998, ESA signed a $470M contract with Aerospatiale to develop the ATV. It also paid $23M to RSA and NPO Energia for integrating the ATV into the ISS Service Module, while the French space agency received $30M to develop interfaces for the ATV's customized Ariane-5 carrier rocket. Aerospatiale also signed a consortium agreement with Daimler Chrysler Aerospace, who will produce up to a dozen ATVs between 2003 and 2013. The target price is $70M per ATV plus $115M for the Ariane-5 booster.[11]

DARPA's Orbital Express

The Defense Advanced Research Projects Agency (DARPA) is one of the organizations interested in the concept of autonomous satellite servicing. The goal of its Orbital Express Space Operations Architecture program is to validate the technical

[11] http://www.estec.esa.nl/spaceflight/atv.htm

feasibility of robotic, autonomous on-orbit refueling, electronic upgrades, and reconfiguration of satellites to support a broad range of future U.S. national security and commercial space programs. The following concepts have been of particular interest:[12]

- Spacecraft-to-spacecraft interface(s) enabling preplanned electronics upgrade, refueling, reconfiguration or resupply (e.g., replenish of consumables) of one spacecraft by another;
- Autonomous Space Transporter and Robotic Orbiter (ASTRO) servicing spacecraft (envisioned to be a micro-shuttle that remains permanently on-orbit) that would autonomously conduct operations (e.g., inspection and other close-proximity operations, docking, and satellite preplanned electronics upgrade, refueling and reconfiguration), would be capable of accessing satellites at all orbital altitudes (LEO-to-GEO-to Lagrangian Points), and would be capable of performing significant plane changes (at constant altitude, via use of ascent-change plane-descent maneuvers and/or aero-assisted maneuvers);
- A new satellite design enabling a satellite to be electronically upgraded, serviced (i.e., refueled and/or have consumables replenished) and/or reconfigured (e.g., systems, subsystems or components replaced) by a servicing ASTRO spacecraft;
- New fuels (e.g., on-orbit, electrolysis-derived hydrogen and oxygen) with properties enabling satellite-to-satellite fuel transfers.

Boeing Phantom Works, along with its partners TRW and Ball Aerospace, were selected by DARPA to build ASTRO and a surrogate serviceable satellite, NEXTSat/CSC (Next Generation Satellite and Commodities SpaceCraft) and conduct an on-orbit demonstration of autonomous satellite refueling. Launch is slated for 2005, with routine, cost-effective, autonomous capability for refueling of on-orbit spacecraft planned for the post-2010 timeframe[13].

Michigan Aerospace Corporation was tasked by DARPA to develop the Autonomous Satellite Docking System—the technology for an on-orbit demonstration of autonomous rendezvous and docking of two satellites for re-supply and payload

[12] http://www.darpa.mil/tto/programs/astro.html
[13] "Automated Refueling For The Orbital Express Program," South El Monte, 08 April 2003; source: http://www.spacedaily.com/news/rocketscience-03m.html.

exchange. DARPA also has a contract with the Naval Research Laboratory (NRL) that includes a detailed design study of a single servicing vehicle, spacecraft/target simulation, and a demonstration in the laboratory's 0-g robotic simulation facility.

Demonstration of Autonomous Rendezvous Technology (DART)

NASA is another stakeholder interested in on-orbit servicing. While NASA has performed rendezvous and docking missions in the past, astronauts have always piloted the spacecraft. In 2004, DART is expected to validate the technologies required for a spacecraft to locate and rendezvous with another spacecraft without direct human guidance. Some of the objectives of the project are:

- Demonstrate autonomous rendezvous with the target satellite using only data provided to the chase vehicle at time of launch, or data acquired autonomously while on-orbit.
- Demonstrate autonomous proximity operations while in the vicinity of the target satellite.
- Demonstrate safe operations.
- Validate ground test results.
- Provide hardware capabilities for future missions by validating the Advanced Video Guidance Sensor in space.

Future applications of this technology include cargo delivery, space operations for the ISS and other on-orbit activities such as satellite retrieval and servicing missions. The DART vehicle will be launched aboard a Pegasus launch vehicle and inserted into a circular parking orbit. The vehicle will then perform a series of orbit transfers to arrive at a point near a target satellite using state-of-the-art GPS relative navigation techniques. Using the vehicle's main instrument, DART will then approach the target satellite and perform a series of proximity operations including station keeping, docking axis approaches and circumnavigation. Finally the vehicle will demonstrate a collision avoidance maneuver, after which it will depart the vicinity and transition to its final orbit. The entire sequence will be accomplished under autonomous control. The contract was awarded to Orbital Sciences Corp. [14]

---

[14] http://www.orbital.com/LaunchVehicle/AdvancedSystemsTestbeds/DART/

NASA Telerobotics Program

NASA's Telerobotics Program addresses the three specific mission and application areas: on-orbit assembly and servicing, science payload tending, and planetary surface robotics. The on-orbit assembly and servicing segment of the program focuses on the development of space robotics for the eventual application to on-orbit satellite servicing by both free-flying and platform-attached servicing robots. The target applications include tasks such as the repair of free-flying small satellites, ground-based control of robotic servicers, robotic assembly of space structures, and servicing of external space platform payloads.[15]

Docking Simulations

The Smart Systems Research Lab at NASA Ames Research Center is developing adaptive neurocontrol technologies to safely, accurately, and efficiently dock spacecraft to a target (ISS), given a wide range of difficult operating conditions. The operational scenarios include: 1) docking with a spacecraft when its thruster strengths are not well known, stuck, or leaking, 2) docking with a spacecraft whose mass properties are not well known, 3) rendezvous and capture of a non-cooperative, spinning satellite, 4) docking with a spinning target, and 5) docking with a spacecraft when some of the spacecraft's sensors have failed.[16]

Spacecraft Life Extension System (SLES)

The Orbital Recovery Corporation's Spacecraft Life Extension System would mate with a satellite, reposition it, and serve as its guidance and propulsion system, supposedly extending the satellite's operational life by at least ten years. In addition, SLES could be used to rescue spacecraft placed in wrong orbit by the launch vehicle or spacecraft that have become stranded in an incorrect orbital location during positioning maneuvers. SLES would be small enough to take advantage of low-cost rides on expendable launchers as secondary payloads, yet large enough to contain a xenon ion propulsion system that could last as long as ten years and provide sufficient impulse for the control of the SLES/satellite combination. Orbital Recovery would handle control of

[15] http://ranier.hq.nasa.gov/telerobotics_page/programdesc.html
[16] Smart Systems Research Laboratory, source: http://ssrl.arc.nasa.gov/

the tug until docking with the client satellite; docking would be a joint effort between the provider and the telecom satellite operator. Once docking and checkout have been completed, long-term control would be handed to the satellite operator, with technical support and service provided by Orbital Recovery Corporation throughout the operating lifetime.

Robotic technology from the DLR German Aerospace Center was selected for providing the SLES linkup that connects to the satellite's apogee kick motor. Aon Space provides insurance brokering and risk management services. Orbital Recovery Corporation has signed an agreement with Arianespace to send in orbit at least four SLES space tugs, beginning in 2005. Ariane's flexibility was one of the deciding factors in this choice. SLES will be carried as a secondary payload on Ariane 5 launches, with liftoff mass between 500 and 800 kg, depending on the space tug's specific mission. Although Orbital Recovery has identified more than forty potential targets[17] among spacecraft currently in orbit, whether SLES will actually fly would depend on how much it would cost to service an old satellite, as opposed to replacing this satellite with a new one.

In return for its life-extension service, Orbital Recovery Corporation would charge a fee equivalent to one year of the satellite's revenues, or about $50M [Ber02]. Because the service would be fully insured, if a failure prevents the tug from servicing the satellite, the customer would pay nothing to the provider, which minimizes the financial risk for the potential clients and thus increases the value of tugging. The service could eventually also be of great interest to satellite insurance underwriters, since they could hire Orbital Recovery rather than pay out a large claim on a stranded satellite.

2.1.3.3 Research at MIT

University researchers have addressed other problems associated with on-orbit servicing. Some of the analyses recently performed at MIT include the development of a valuation framework using real options and decision tree analysis by Elizabeth Lamassoure [Lam01] and Joseph Saleh [Sal01] and the study of the value of flexibility

[17] "Ariane 5 To Launch Space Tugs For Orbital Recovery Corp.," Paris, 3 March 2003; source: http://www.spacedaily.com/news/salvage-03a.html

offered by on-orbit servicing providing satellite refueling (Elizabeth Lamassoure), life extension (Joseph Saleh, Elizabeth Lamassoure), and tugging of GEO communication satellites (Michelle McVey) [McV02]. Undergoing work concentrates on the valuation of flexibility offered by satellite upgrading. By investigating the uncertainty in revenue and demand of subsystem upgrading, Carole Joppin attempts to answer the question: "When does it make sense to upgrade?" Another on-going study at MIT, performed by Roshanak Nilchiani, investigates the concept of a refueling space infrastructure that contains refueling depots located at various points. An orbital transportation network analysis methodology has been developed for on-orbit refueling that assesses system performance under changing requirements through time. The methodology can be easily used to identify impacts of system architecture, deployment strategy, schedule slip, market demographics, and the risk on system performance, cost, and flexibility. [HN02] Nilchiani's model assumes that fuel tanks are launched from Earth, but other ideas have been proposed that envision the deriving of fuel from asteroids[18]. Intuitively, refueling is key in making the on-orbit servicing paradigm successful because it allows the same vehicle to be used numerous times (the importance of reusability is discussed in Section 4.2.4.4.2).

Phase A of a DARPA sponsored Space Tug study was initiated at MIT in the summer of 2002. Developed at MIT from earlier work on generalized information network systems (GINA) analysis applied to space systems [Sha99], a capability referred to as Multi-Attribute Tradespace Exploration with Concurrent Engineering (MATE-CON) was used to examine over one hundred design concepts. Their performance was evaluated and the designs of interest were further analyzed using Integrated Concurrent Engineering (ICE) techniques, resulting in complete conceptual architectures. The results gave an understanding of the trade-space for such vehicles, including sensitivities to both design variables and assumed user needs. Several potentially viable designs were identified, including an electric-propulsion high delta-V vehicle dubbed the Electric Cruiser and a class of lower delta-V vehicles called *tenders*, which are the focus of this thesis. [MS03]

[18] http://www.permanent.com/p_satsrv.htm

One of the goals of this preliminary research was to create a versatile set of tools for rapid conceptual design of space tug vehicles. Designed to run in Excel, ICEMaker is a parameter exchange tool that facilitates sharing of information among members of the design team. Together with MatLab and Oculus/CO, ICEMaker was effectively used to create a software model of the entire design system comprised of linked spacecraft subsystems ("clients"), as shown in Figure 2.3. All relevant parameters were centrally stored in a "server." Publishing and subscribing to variables and parameters was done through ICEMaker, while local calculations were done in MatLab in real time via a CO link. Although this design process is automated with flags for convergence and automatic area and weight sizing, human operation at each workstation (subsystem) is still preferred in the detection of nonsensical parameters that are crucial to the ICE/CO/MatLab process.

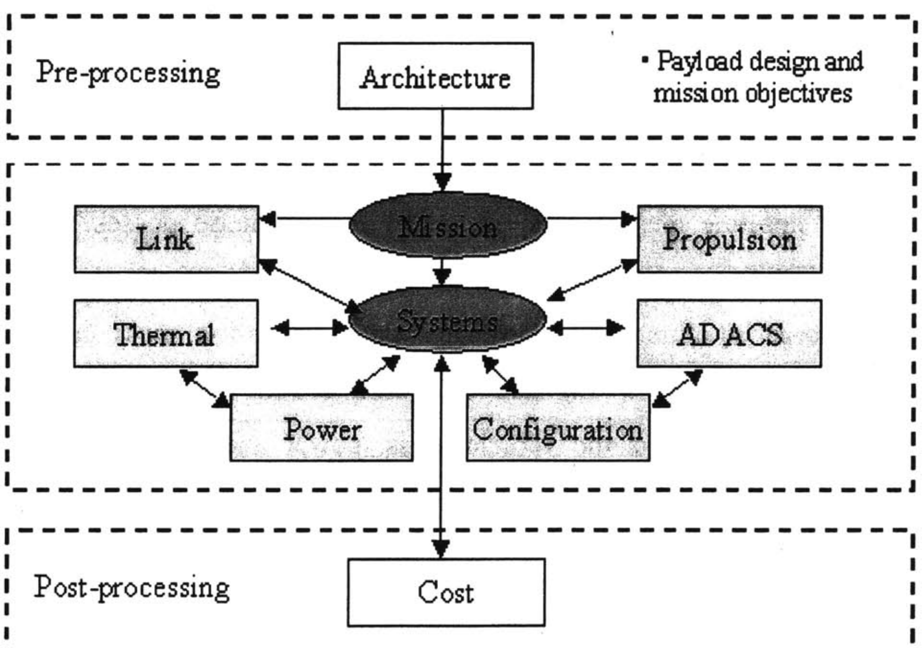


Figure 2.3: Subsystems Organization

The ICEMaker tool provides fast convergence on any mission-determined point design. The estimated convergence time, including human operation and decision-making, is about one hour. This rapid design process allows an immediate analysis of the trade space and supports a changing strategy (exploring different options) throughout the design process. The tool, however, relies on a set of key assumptions, the most important of which are listed below:

- There are two ways to model a mission: as a *few-modes* mission (8 to 24 modes), or as a *complicated* mission (up to 100 modes); straight calculations are used for the former, approximations are used for the latter.
- Calculations can be of higher or lower fidelity; high-number delta-V missions are lower fidelity (all calculations are based on worst case scenario variables).
- Only Hohmann transfers are modeled—direct or combined plane change, with optimized inclination change. Some spiral and one-tangent burn calculations are made, but not linked.
- Database is limited to US launch vehicles. Target satellites database has the potential to increase.
- Mating is *black-boxed*: outlined only by additional target mass, minute ADACS adjustments, and a grappling mechanism that was modeled as a monolithic, cylindrical solid with a radius and height of 1m.
- Every possible mission is modeled by eight generic phases. To perform a complete mission analysis, the user has to define a sequence of the above predefined mission phases, target satellite data (coordinates, desired location, mass, control system), launch vehicle, launch site, parking and safe orbit orbital elements. Based on these specifications, the tool outputs the vehicle mass, power and geometry that is driven mainly by the fuel tanks. [GBWH03]

2.2 Summary of Previous Work Shortcomings

There are a number of issues that have rendered the early servicer designs unsuccessful. They can be assigned to two main categories: realism and cost-effectiveness.

Realism

In many cases, servicer concepts never entered the design phase because they were too unrealistic for their time. Key contemporary technologies, such as advanced propulsion systems, laser evaporators, or deorbiting tethers either did not exist yet or had a low technology readiness level. Much of this technology is still not developed.

A requirement for all servicer designs, safe docking is one of the best examples of technology dependence. It implies mating with a target spacecraft without creating debris or causing damage to either vehicle. The issue becomes even more critical when the target is functional. This is an important problem to consider in almost all scenarios involving space tugs (see Section 3.3), two exceptions being the GEO satellite retirement and the debris removal cases. Many designs have circumvented the issue by assuming that the client satellite has been designed for docking, but the reality is that there are few such satellites currently in orbit. Moreover, since the current interest is focused on autonomous servicing, the problem becomes threefold: 1) how to rendezvous and dock without expecting cooperation from the target spacecraft (i.e. without exchanging status data and commands), 2) how to capture a satellite that has not been designed for docking (i.e. does not have a docking port), and 3) how to minimize human involvement.

Russia has routinely carried out completely automatic rendezvous and docking in orbit for the past 30 years, but the targets were fully known and cooperative. All U.S. dockings have been with known targets and have been performed by astronauts. The problem is that EVAs are extremely costly and can benefit only satellites located in a limited altitude and inclination range. A completely autonomous rendezvous and docking has been demonstrated in space only once—by the Japanese ETS-VII experiment, where the client spacecraft had a docking port matching the one of the tug. Orbital Recovery claims that its SLES spacecraft would be able to rendezvous and mate with a conventional satellite (i.e. one not designed to be docked with), but it assumes total target cooperation and full-time human involvement.

Two other problems have affected the viability of a number of servicer designs: the reliance on on-orbit assembly and docking and the need for refueling infrastructure. Until on-orbit assembly is established as a safe and not overly difficult practice, fully assembled robotic servicers would need to be launched from Earth. However, launch vehicle size puts a limit on the size and mass of the tug and, hence, on its fuel tanks, which in turn limits the delta-V capabilities of the tug. This is a problem because the tug must be able to visit a number of satellites at various locations (the majority of past efforts have focused on *single vehicle* designs) in order to amortize the cost of developing, launching, and operating it.

The idea of having one universal tug that can cover the entire space and perform many types of tugging missions is not a viable option at this stage of technological development. Assuming H_2/O_2 propulsion (Isp = 450 sec) for a tug with an initial mass of 4,500 kg (suitable for an Atlas V401 or Delta IVM+ launch) and a final mass of 500 kg, the rocket equation gives us:

$$\Delta V = g \cdot Isp \cdot ln(\frac{Mo}{Mf}) = 9.81 \cdot 450 \cdot ln(\frac{4500}{500}) \approx 9.7 km/s \quad (2.1)$$

A trip from GEO (v = 3.075 km/s) to LEO (v = 7.613 km/s for h = 500 km) and back to GEO with no plane change requires a delta-V of twice the difference between the velocities in LEO and GEO, which in our case amounts to 9.076 km/s. This allows the tug to do only one round trip plus some local maneuvers in GEO that require a delta-V of up to 600 m/s [GBWH03].

Evidently, multiple round-trips between GEO and LEO and large inclination plane changes (particularly in LEO) would not be possible unless advanced propulsion or on-orbit refueling is used. Unfortunately, the viability of these concepts has not been demonstrated yet, so they remain outside the realm of realism for projects that are scheduled for completion within the next few years. The only reasonable option would be to have a family of smaller and simpler tugs that operate locally and service highly populated areas.

Cost-Effectiveness

Even if a decision has been made to develop a key technology that would enable a given concept to become a reality, the uncertainty and risk associated with using this new technology would increase significantly the cost of the design, due to extensive testing and redundancy. This leads to the other main reason for design cancellation: cost-ineffectiveness.

Many of the ideas listed in this chapter describe concepts that are technologically feasible but have not been brought to realization either due to funding problems (as in the case of the OMV) or because detailed and reliable financial justification of the concept had not been performed. In fact, the cost of a tug design is very difficult to estimate with a reasonable degree of certainty. No statistical data or suitable cost models exist, and a number of uncertain factors must be considered, such as market demand, technological readiness risk, and acceptable fee range. These factors are not only hard to predict but also difficult to quantify and incorporate in the cost model that needs to be created specifically for space tug missions. Economic advantages, if any, should be weighed against the unknown risk of performing new tasks and employing new technology.

Rey and Morrison summarized the history of the Orbital Maneuvering Vehicle cancellation based on a U.S. General Accounting Office (GAO) recommendation. The main issue was whether or not NASA really had a need for a costly transfer stage. GAO found that the estimated cost of the project had greatly increased, while the OMV's capabilities had significantly decreased. Additionally, a firm requirement for the OMV to accomplish the scheduled missions did not exist. Thus, NASA was compelled to terminate the program. [RM90]

Most of the suggested servicer designs were not accompanied by an economic feasibility justification, and the value of the service was not weighed against the value of other options. Turner's paper assumed that the proposed GEO servicer had an operating cost of $1M/year and that the service would be available for $6M annually if launched on a medium-cost foreign vehicle [Tur01b]. No justification, however, was provided for these numbers. Similar to the few other economic feasibility studies performed on the subject, too many assumptions have been made and no sensitivity analysis has been performed to show how their incorrectness would affect the results of the research.

2.3 Recommendations for Improvement

Even if the previously discussed concepts were realistic and cost-efficient, they would still not be optimal because no systematic trade-space study has been performed. Reconsideration of the methodologies and assumptions applied in these projects is needed, as well as a study of a wide trade space of missions and space tug concepts, coupled with work on those technical issues determined to be key in the course of the trade studies. Such an approach could address the key issues identified in the above section in an efficient manner.

Most designs lack mission flexibility, meaning that they can service only a specific type of satellite and in a given orbital range. While designing a universal servicer that uses conventional propellant is not a feasible idea, universality of the design can be achieved through modularity and use of common or scaled components by different tugs. Additionally, there may be utility in having a number of tugs in a variety of inclinations and altitudes that would act locally most of the time, reducing the total delta-V requirements. Expendable or semi-expendable tugs (one-way missions) may be optimum in some situations. All of these complex trade offs must be evaluated by considering the total impact on both the system capabilities and its complexity and cost. [HWM02]

On the technical side of the matter, the vast majority of satellites have not been refueled, repaired, upgraded, or tugged while on orbit, and satellites that have were serviced by astronauts. Although these servicing missions eventually paid off with high revenues, they were still costly[19] and required hours of crew time. The obvious way to decrease the cost of on-orbit servicing is to use an unmanned spacecraft as a servicer. Developing robust autonomous docking control algorithms and grappling or docking mechanisms could achieve this. Human intervention would still be required due to high risk and current technology limitations, but with the advance of autonomy and grappling device technologies, the ultimate satellite servicers will need minimal or no human supervision and guidance. This would be facilitated by another expected trend—the design of serviceable satellites.

The Orbital Express ideas envision the creation of a completely new satellite infrastructure, in which satellites are designed for servicing and various servicing operations are planned in advance. Clearly, although a number of research teams are currently investigating the Orbital Express concepts, neither of the ideas can be accomplished independently. The problem here is not as much related to technological difficulty as to difficulty in altering the current infrastructure. It is difficult to convince someone to change his way of doing something if old methods have performed

[19] The cost of manned/EVA repair missions is difficult to estimate because much of the infrastructure cost gets absorbed by NASA's budget rather than charged directly to the customers.

sufficiently well in the past. Additionally, the docking mechanisms and software programs that would make satellites serviceable will add weight and complexity to the generic satellite designs. This will, in turn, increase the cost of designing, manufacturing, and launching satellites and will push back delivery times. The need for human supervision of the servicing procedures would also add to the increased cost. A convincing business case must be presented in order to make satellite operators willing to take the associated risks, and, at a minimum, the critical areas where technology should be matured further should be identified.

2.4 Chapter Summary

Although on-orbit tugging has been considered since the 1960's, space tugs are still non-existent. This is mostly due to lack of realism and cost-effectiveness of the proposed concepts. Some of the envisioned technology and support infrastructure are still not fully developed. Even if they were available, many of the projects would still fail due to high cost demands. Most of the designs were not accompanied by a trustworthy economic assessment of the proposed missions and were based on a great number of assumptions. Another key weakness was the lack of systematic trade-study comparing the costs and benefits of a large number of competing options. The goal of the approach taken by this thesis is to eliminate some/most of these shortcomings.

Chapter 3

New Architecting Approach

The selection of a design process is as important as the deriving of results. That is why this thesis attempts to employ efficient modeling of the performance and utility of space tug architectures, allowing for the exploration of many design options and mission scenarios. Complemented by sensitivity studies, the methodology could be used to determine both the key areas for more detailed technical studies and the impact of the introduction of new technologies or the failure to demonstrate the assumed capabilities.

3.1 Description of the Proposed Approach

The brief orbital dynamics analysis in Section 2.2 showed that a single vehicle using conventional propellants would not be able to perform multiple round-trips between LEO and GEO without refueling. Since reusability is key for the business case justification of tug missions (as will be shown in Section 3.2.4), it is obvious that LEO and GEO need to be considered as two separate zones of action and have a tug (or tugs) designated for each. Considering the GEO belt only, reusability is not going to be problematic because the tug would be able to reach a number of targets with a small delta-V. This, however, is not the case for LEO, largely due to plane change maneuvers. Therefore, in order to be realistic, we need to divide the LEO region further into several zones, bounded with respect to altitude and inclination.

These target orbital zones are defined by a significant concentration of satellites. Thus, what makes this research different from previous work is the starting point of the analysis. Instead of exploring the concepts of a number of different space tugs and then defining the limits of their application, this study first explores the current on-orbit satellite population and identifies the most populated regions based on a large LEO-MEO-GEO database. An underlying hypothesis of this research is that more benefit could be gained from having a *family* of smaller and simpler tugs that operate *locally*. Thus, a tug is assigned to each target zone. This approach investigates orbital regions independently and explores how the locally acting optimal tugs differ from each other. The trade study enables the evaluation of various types of space tug vehicles, recommending the most cost-effective options for each mission in terms of a number of attributes defined in Chapter 4.

The proposed approach is summarized in Figure 3.1. It does not necessarily imply the simultaneous utilization of multiple tugs (one for each target zone). The number of tugs operating at the same time would depend on the capability of individual tugs from the family and on current demand for a specific type of tugging mission. Since space tugs might be needed for a variety of applications in any part of space, the identification of most likely target groups was necessary for the formulation of realistic mission scenarios that would employ one or several tugs. The most likely scenarios are described in Section 3.3.

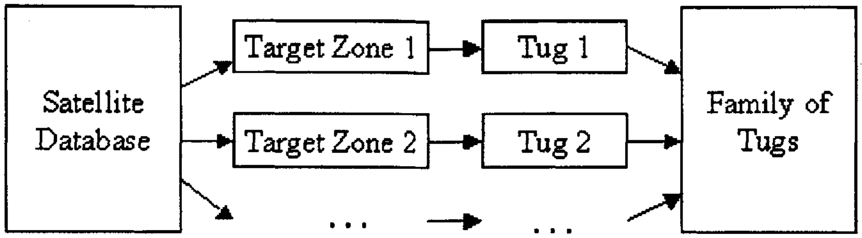


Figure 3.1: Design Approach

3.2 Database and Target Clusters

Satellite Database

The space around the Earth is populated by a great variety of satellites that differ significantly in purpose, location, size, mass, and status. However, since satellites are designed to fulfill a specific role, it may be reasonable to expect similarities both in design and in positioning of the satellites serving a specific mission, such as communications, remote sensing, astronomy, etc. The type of satellite that monitors cloud patterns for a weather station is clearly different from a satellite that sends television signals across Europe. Thus, the classical grouping of satellites according to their mission seemed to be a good starting point for the identification of target groups.

Most of the low LEO satellites are spy, meteorological, remote sensing, atmospheric, oceanographic, and cartographic. Many of these LEO satellites are positioned in polar orbits because they allow excellent coverage of the planet over time. Moreover, they need to be close to Earth to take clear pictures and sense data more accurately. The size of most of the sensors used, for example, in remote sensing or oceanographic satellites will increase inversely proportional with distance, if the same resolution is to be maintained.

Most GEO satellites perform communication services. One of the main reasons why most communication satellites are located there is that the geosynchronous orbit allows the maintaining of a communication link with the spacecraft by simply pointing the antenna in one constant direction (the sub-satellite point is fixed on the ground). This also greatly simplifies the task of tracking satellites. The other important reason for positioning communications satellites in GEO is that a larger area can be "seen" at any given time.[1]

The initial attempt, however, to define groups of spacecraft that have both similar orbital elements and physical features quickly proved ineffective—the variety of satellites was simply too wide and only a few satellites of each "classical" group were clustered together in a small altitude and inclination range. The dimensions of the satellites in each mission-defined group also turned out to be non-uniform. For example, communication satellites in the past were very different from what they are now. A common early design is that of a spin stabilized cylinder. The Hughes HS376 series are a typical example, the main body being about 3 m long (or 6 m when the communications antennae are deployed) and 2 m in diameter. This main body rotates about the long axis, typically at around 55 rpm, while the antenna and equipment shelf is despun in order to maintain contact with their ground targets. Conversely, the newer GEO satellites are three-axis stabilized and considerably larger than the earlier generation. As a result, common sense dictates that trying to design a tug that would be capable of visiting all locations or of docking with all kinds of targets would increase complexity and uncertainty and would likely not lead to an optimal architecture in terms of performance per cost (if the concept is feasible at all). Therefore, it would be more realistic to try to define groups in terms of *either* physical *or* orbital characteristics.

The attempt to identify groups of satellites having similar physical properties, including length, height, and width (or diameter and height, if cylinders), as well as stabilization, data rates and dry and wet masses also proved difficult and ineffective. Investigating the orbital properties (period, apogee, perigee, semi-major axis, inclination, and eccentricity), however, resulted in the clear definition of several populated areas.

Target Clusters

Figures 3.2 and 3.3 show the distribution of all LEO and GEO satellites from the database. All satellites launched after 1990 are marked as active (a major assumption of this research).

---

[1] MEO satellites are almost non-existent because of the high radiation environment in the Van Allen belts and because this orbit simply presents no advantage.

To define the bounds of each target cluster, constraints on altitude and inclination ranges were set. Assuming conventional storable propellants (Isp = 325 sec) for a tug with an initial mass of 7,500 kg (suitable for an Atlas V launch) and a final mass of 1,800 kg, the rocket equation gives us:

$$\Delta V = g \cdot Isp \cdot ln(\frac{Mo}{Mf}) = 9.81 \cdot 325 \cdot ln(\frac{7500}{1800}) \approx 4.55 km/s \quad (3.1)$$

If the tug is to visit twenty satellites, it can use an average of 227.5 m/s per mission, which should be roughly the sum of the delta-V used for altitude and plane change, including the delta-V for rendezvous and proximity operations:

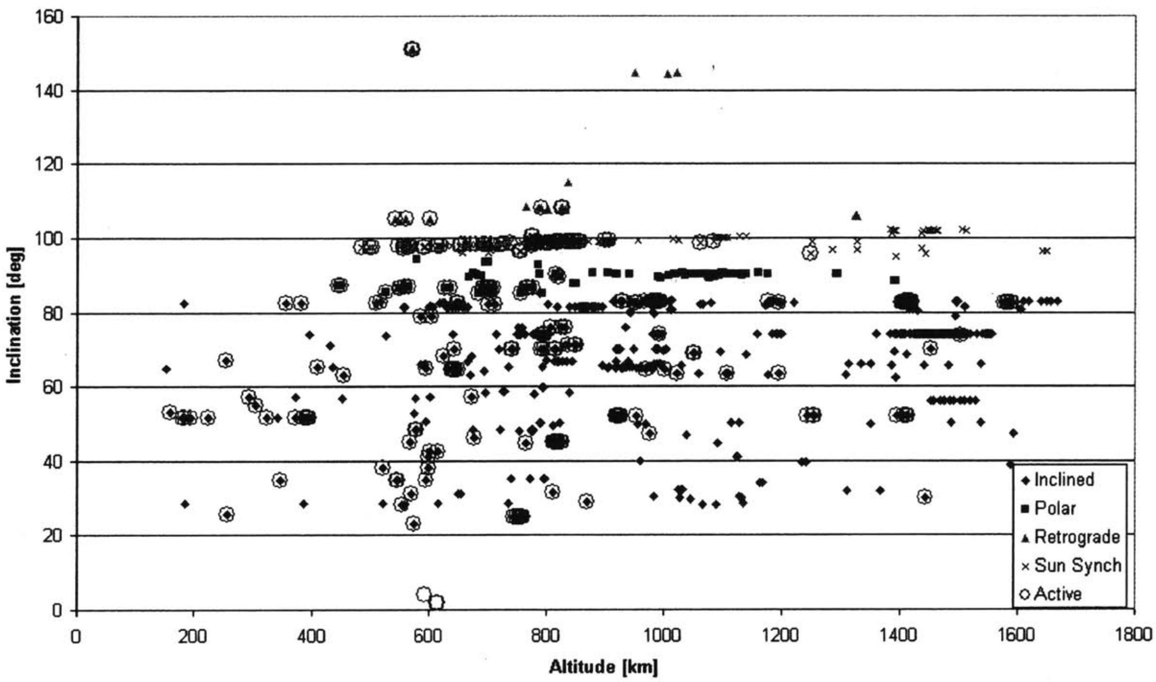


Figure 3.2: Distribution of LEO Satellites [McD02]

(Displayed are a total of 1754 LEO satellites: 1300 in inclined, 189 in polar, 23 in retrograde, and 242 in sun-synchronous orbit; 467 of these satellites are launched after 1992 and are assumed to be active.)

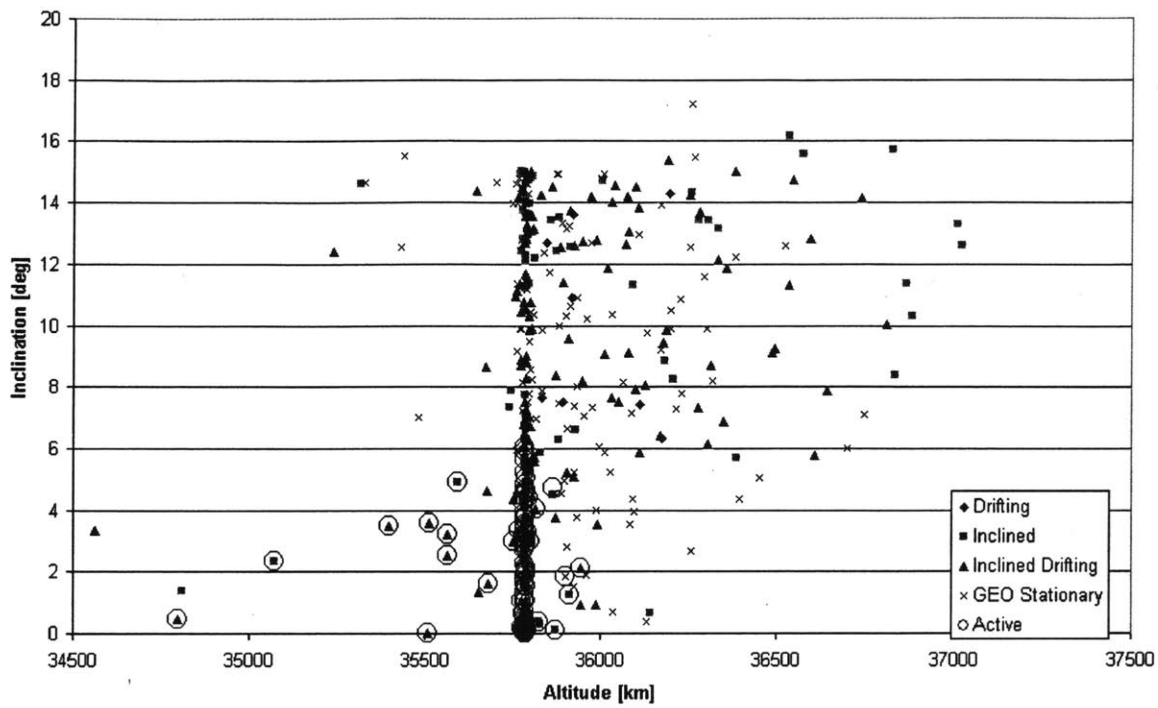


Figure 3.3: Distribution of GEO Satellites [McD02]

(Displayed are a total of 616 GEO satellites: 17 drifting, 135 in drifting, 224 in inclined drifting, and 230 in geostationary orbit; 250 of these satellites are launched after 1992 and are assumed to be active.)

$$dV\_alt = \sqrt{\mu} \cdot \left(\left| \sqrt{\frac{2}{ra} - \frac{1}{atx}} - \sqrt{\frac{1}{ra}} \right| + \left| \sqrt{\frac{2}{rb} - \frac{1}{atx}} - \sqrt{\frac{1}{rb}} \right| \right) \tag{3.2}$$

$$dV\_inc = \sqrt{Vi^2 + Vf^2 - 2 \cdot Vi \cdot Vf \cdot cos(\theta)} \tag{3.3}$$

where ra is the apogee of the orbit, rb is the perigee, atx is the semi-major axis, μ is the gravitational parameter (398600.5 km^3/s^2), θ is the change in inclination, and Vi and Vf are calculated using the following relationships:

$$Vi = \sqrt{\frac{\mu}{ra}} \qquad Vf = \sqrt{\frac{\mu}{rb}} \qquad (3.4), (3.5)$$

Using these simple astrodynamics calculations, it was calculated that ranges of 3 deg inclination and 100 km altitude for LEO and 3.5 deg inclination and 1,000 km altitude for GEO were reasonable for a tug's area of action.

3.3 Orbital Mission Scenarios

Bearing in mind the above calculated target zone limits, several main mission scenarios of interest were identified. They were briefly discussed in Section 1.2.2. A more detailed description of the involved issues is provided below.

3.3.1 Satellite Rescuing

Often, satellites are successfully launched with the first stages of the launch vehicle, but fail to reach their final operational orbit due to failures of an upper stage or their apogee or kick motor. The satellites become useless in these suboptimal locations since their sensors, instruments, and attitude control systems are designed to operate in a different orbit. Unfortunately, the utilization of on-board fuel to boost them up to the correct orbit is either impossible or would significantly reduce their expected operational life. Also, rescuing such satellites can be time critical due to battery autonomy or radiation exposure. Another problem is when a malfunction occurs while a satellite is already in its operational orbit and has possibly functioned for a while. In both cases, when EVA is not an option, replacement is the only alternative for satellite owners. However, by the time the new satellite is launched, the satellite's owners' competitiveness in the industry is diminished. Space tugs could mitigate the problem by providing emergency capture and insertion of stranded satellites into their desired orbits or by transferring malfunctioning satellites to the ISS for repair. Taking advantage of this service will save the satellite's on-board propellant and thus allow it to operate for nearly as long as it was intended. This is particularly interesting for the billion-dollar class of satellites (e.g. Milstar, DSP).

Some interesting questions for investigation are listed below; answers are provided in Section 5.2.

1. At what altitudes and inclinations do satellites get stranded most frequently?
2. What is the perceived benefit to the spacecraft operator?

3. Should the charged fee be fixed or variable (i.e. a percentage of the revenue expected to be collected by the satellite owners after delivery of the satellite to its optimal orbit or a percentage of the satellite value)?

4. What fee should the rescue tug operator charge?

5. What are the legal/economic/regulatory/insurance issues associated with this mission scenario? How can they be mitigated?

3.3.2 Crowding and Collision Risks

Operational spacecraft are faced by two types of collision risks. First, functional GEO spacecraft located within the same longitude window could collide with each other. Second, a piece of debris may collide with an operational station-kept spacecraft. Chances of the second type of collision occurring are significantly greater than the first.

Many of the objects released into space in the lowest orbits have fallen back to Earth; LEO orbits are "self-cleaning" below 500 km. The upper atmosphere gradually slows down objects and they burn up within a few months or years as they re-enter the atmosphere. However, if an object is above the last traces of Earth's atmosphere, it will stay in orbit for thousands or even millions of years. The statistics from June 2000 show that 8,927 tracked man-made objects were currently in orbit around the Earth, amounting to approximately 2 million kg. Of them, 2,671 were satellites (both functional and not), 90 were space probes, and 6096 were mere chunks of debris, of which approximately 3,000 were burned-out booster rockets.[2] Figure 3.4 shows how the number of objects in orbit has increased over the last 40 years.

[2] http://www.space.com/spacewatch/space_junk.html

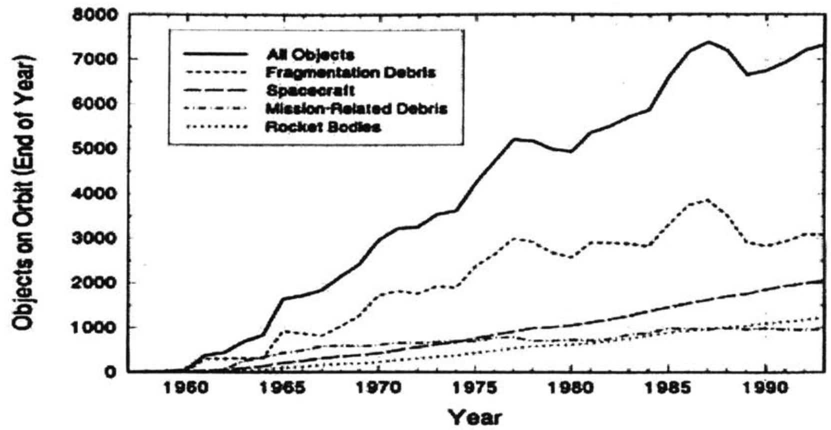


Figure 3.4: Objects in Earth Orbit [CSD95]

Clustered around regions where space activity has been the greatest, most space debris is located at less than 2,000-km altitude, at around 20,000 km (semisynchronous orbit), and at 36,000 km. In and near the GEO region, the limited number of these objects, their wide spatial distribution, and the lower average relative velocities combine to produce a substantially lower probability of collision in GEO as compared to LEO. Special collision possibilities exist in GEO because of the close proximity of operational spacecraft at selected longitudes, but these collision hazards can be reduced or eliminated by spacecraft control procedures. Thus, our major focus should be on mitigating the crowding and collision problems in LEO. Figure 3.5 depicts the clustering of objects in LEO.

Figure 3.5: LEO Clutter [CSD95]

Orbital debris generally moves at very high speeds relative to operational satellites. In GEO, the relative velocity at impact is only about 0.5 km/s, but in LEO it is on the order of 10 km/s [New02]. The U.S. Space Command in Colorado Springs is capable of tracking 10-cm and larger objects in LEO, and it warns NASA every time a close approach is likely to happen. If the Shuttle is in orbit, NASA directs the crew to make a very small thruster firing to avoid collision. Similar maneuvers are occasionally performed by the orbiting telescopes and the ISS.

The space station is wrapped in the bulletproof material Kevlar for protection from particles smaller than 1 cm. Debris larger than 1 cm but smaller than 10 cm in length is very dangerous because it is too small to be spotted by a radar and too large to be stopped by Kevlar. The strongest impact, however, can come from the largest objects: leftover satellites and rocket boosters [Spa02]. In December 2001, the Space Shuttle pushed the ISS away from a discarded 8-year-old Russian rocket booster that was passing close and could have caused a collision. This was the fourth maneuver for that year.[3] Unfortunately, not all spacecraft can maneuver to avoid debris. For instance, a tethered rocket was lost in 1994 when the collision with a small space debris particle severed the tether. Another example of damage is the three-quarter-inch hole in Hubble's high-gain antenna caused by a small object [Spa02].

The probability of collision (PC) in orbit is a function of the spatial density (SPD) of objects in a given region, the average relative velocity (VR) between the objects in this region, the collision cross section (XC) of the scenario being considered, and the time (T) spent in the given region by the object at risk. The following relationship can be used:

$$PC = 1 - e^{(-VR \cdot SPD \cdot XC \cdot T)} \tag{3.6}$$

It is derived from the kinetic theory of gases by assuming that the motion of objects is random. For a moderate-sized satellite (XC = $10 m^2$) in an 800 km circular orbit, the PC is about 1/100,000 per year. The PC equation may be approximated by the product of the four terms as long as the collision probability value is very small (less than 1/10,000):

[3] Space News, "Space Is Big, But Not Big Enough", Paris (ESA), 30 September, 2002; source: http://www.spacedaily.com/news/debris-02a.html.

$$PC \approx VR \cdot SPD \cdot XC \cdot T \quad (3.7)$$

Clearly, as the catalogued population, lifetime, and satellite size increase, the PC will also increase. [Exp93]

The best way to lower the threat of collisions is to remove satellites from orbit at the end of their operational lifetimes. This can be done passively through debris prevention (i.e. not allowing satellites to become/produce debris) or actively through debris removal (i.e. deorbiting dysfunctional objects using a designated vehicle or technology, such as a tug, a tether, a laser beam, etc.).

Debris prevention necessitates retention of equipment normally tossed into orbit (such as covers and separation devices) with hinges and tethers, expulsion of residual propellants and pressurants (to prevent explosions that frequently result in numerous small particles), and propulsive reorbit maneuvers (which eliminates the largest sources of debris). Modifying the designs of spacecraft and launch vehicles to implement these debris mitigation measures adds to system development cost. Requiring the upper stages of launch vehicles to re-enter the atmosphere directly or to have a short orbital lifetime may influence launch trajectory and performance. Likewise, any weight added to the launch vehicle or to the spacecraft to meet the debris mitigation objectives lowers the useful payload capacity, since additional propellant or electrical power resources will be needed.[4] Not changing the design but simply using residual satellite propellant would reduce the active mission lifetime. Regardless of these inconveniences, in 1995 NASA issued a guideline stating that satellites and upper stages within 1,250 miles of the Earth should remain in orbit for no longer than twenty-five years after the end of their functional lives. But the guideline applies to only government-owned spacecraft and can be waived if other considerations prevail. NASA and the Defense Department continue to leave upper stages in orbit because existing designs do not lend themselves to deorbiting. Additionally, more than half of the annual launches are of commercial satellites, and commercial companies are not under any obligation to limit orbital debris propagation. Clearly, they have interest in keeping their satellites operational for as long as possible,

[4] http://www.oosa.unvienna.org/isis/pub/sdtechrep1/sect03c2.html

but reserving fuel for deorbiting would decrease the spacecraft's operational time by several months.[5] This problem begs the need for active debris removal.

Retrieval of old satellites and large pieces of space debris with the Space Shuttle is possible but often unfeasible. The successful recoveries of Westar VI and Palapa B2 were mostly due to the fact that control of the satellites was still possible. Both satellites were maneuvered into Shuttle accessible orbits and despun via ground control. Such operations would not be possible for inactive satellites. Thus, a designated vehicle must be used for the task of removing debris from orbit. Unfortunately, all technologically achievable concepts that have been considered in the past have proven economically not feasible. For instance, in 1996 the National Research Council Committee concluded that even if appropriate technology were developed, it would probably be much more expensive than reserving residual fuel to bring a spacecraft down at the end of its functional life.[6] However, due to a number of technological advances, we believe that it is time for a fresh look at the problem.

A trade study should be performed that compares the added weight due to shielding and the lost fuel due to evasive maneuvers against the cost of debris removal. One of the main problems of the economic analysis of space debris removal is that space is a common good and stakeholders causing and suffering from space debris are not necessarily the same (and they are difficult to identify). This is analogous to the dilemma of the environmental impact of global warming on Earth.

Some specific questions that must be addressed are:

1. What are the critical orbits that yield a substantial density of non-decaying or slowly-decaying space debris and are additionally populated by high-value manned or unmanned spacecraft?
2. What is the typical weight penalty added by shielding against space debris?
3. What is the typical delta-V penalty for evasive maneuvers?
4. What is a reasonable object size for targeting?
5. What relative delta-V regime should be considered?

[5] http://www.theatlantic.com/issues/98jul/junk.htm
[6] http://www.theatlantic.com/issues/98jul/junk.htm

6. Are there any instances where, based on reasonable assumptions, the costs of a space debris removal capability would be smaller than the penalties occurred by the current practice of shielding, evasive maneuvers or acceptance of higher impact probability? [Wec03]

3.3.3 Satellite Lifetime and Retirement

If satellites are not removed from the GEO belt after the end of their operational time, orbital mechanics tells us that they will slowly drift toward two stable longitudes at 105E and 75W [New02]. These two locations will eventually become overcrowded and collisions will occur, spreading fragments in the entire GEO area. That is why it has been proposed that satellites be equipped with sufficient onboard propulsion for end-of-life boost to graveyard orbits. As a result, the current practice of "satellite retirement" utilizes on-board residual propellant to raise the spacecraft orbit by about 300 km. This procedure has become a major life-limiting factor for GEO satellites because usually all other systems are functional. An alternative option would be to let a space tug mate with the satellite and perform the transfer. 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.

Some of the questions that need to be answered are:

1. How much does a tug design, fabrication and operation cost?

2. What is the perceived benefit to the spacecraft operator? (This includes the questions: What is the revenue generated per year of spacecraft operation? What is the perceived additional lifetime that the spacecraft will gain by being allowed to operate to exhaustion?)

3. How should the contract be written: as a fixed fee or a percentage of the additional revenue generated between end-of-life criterion and actual exhaustion?

4. What fee should the tug operator charge?

5. What are the legal/economic/regulatory/insurance issues associated with this mission scenario? How can they be mitigated? [Wec03]

Answers to these questions are provided and discussed in Section 5.1.

3.3.4 National Security and Military Advantage

US military satellites are used for meteorological, missile warning and tracking, surveillance and reconnaissance, intelligence, navigation, and communications purposes. Civilians can sometimes also benefit from US military satellites, although at a worse resolution. In general, however, the mission of military satellites is to protect national assets and to obtain information about world situations pertinent to the security of the nation [New02]. In Operation Iraqi Freedom, for example, about 70% of the weapons were precision-guided, many of them utilizing GPS systems. Reconnaissance satellites could pick up and record radio and radar transmissions while passing over Iraq. Communications and intelligence satellites were utilized to plan and execute attack. Weather satellites enabled soldiers to both prepare for and take advantage of the weather.[7]

The Satellite Industry Association claims that approximately $60B will be invested over the next few decades to modernize military space capabilities.[8] One possible innovation might be the inclusion of a space tug in the military space infrastructure to move satellites to different locations, thus saving satellites' fuel supplies and surprising potential enemies by positioning the spacecraft at unpredictable orbits. It might be even desirable to closely monitor or move space assets from other nations out of their operational orbits for tactical reasons. Such transfers could be permanent or only temporary depending on the mission scenario. Additionally, military satellites are quite expensive, so another potential use for a space tug is to simply correct for orbital drift or decay and thus extend the satellite's life.

Some of the questions that need to be considered are:

1. How much is reasonable for the government to spend on a single tug mission?
2. How can budget adjustment (mostly budget cut) affect the project?
3. What are the potential implications from achieving such unprecedented tactical advantages? How might other countries react to this potential "threat"?
4. What are the achievable altitude and inclination envelopes of a single mission?

---

[7] Satellite Industry Association, "Satellites Connecting the World," source: http://www.sia.org/papers/
[8] Ibid.

5. Will the tug be reusable or only serve one spacecraft?

3.3.5 Economic Profit from Satellites Reconfiguration

Sometimes, it is desirable to change the location of a spacecraft due to changes in market demand or other uncertain factors. The two relevant mission scenarios are the reconfiguration of LEO constellations and the repositioning of single (i.e. non-constellation) satellites.

3.3.5.1 Demand Uncertainty for LEO Constellations

In April 2000, bankrupt Iridium (a $5 billion system) announced that it would abandon all of its 88 satellites and let them burn in the atmosphere. The Motorola-backed company had spent billions of dollars to build a worldwide satellite telephone network that would allow its subscribers to make phone calls from any point on the planet. Unfortunately, while the system worked fine, company salesmen discovered that there was little demand for the expensive and bulky phones because cheaper land-based systems had infiltrated the majority of markets. [You00]

In October 2000, GlobalStar Telecommunications Ltd. reported losses that had grown five times since the previous year, forcing financial backer Loral Space Communications Ltd. to terminate its support. The Orbcomm constellation also proved unprofitable. Orbcomm Inc. laid off a hundred employees in July 2000 and filed for bankruptcy two months later, putting the future of its 35-satellite constellation in question. [You00]

These three examples show a major flaw in the traditional approach of architecting constellations of communications satellites. Evidently, optimizing the design for a specific global capacity based on a forecast of the expected number of users and their activity level (both of which are highly uncertain) can lead to economic failure if the actual demand is smaller than the one predicted. Therefore, it is better to deploy the constellation progressively, increasing the number of satellites as needed through reconfiguring the existing constellation on orbit. Chaize's research [Cha03] shows how to find the best reconfigurable constellations within a trade space. The approach provides system designers and managers with real options that enable them to match reconfiguration paths with the actual evolution of demand. Specific case studies have demonstrated significant economic benefits of the proposed approach when applied to LEO constellations of communications satellites, where lifecycle cost and capacity are traded against each other, given a fixed channel performance requirement. Additionally, a potential collision within a constellation will lead to the creation of a debris cloud that may result in damage to other constellation members or disruption of their daily routine. Therefore, it may be worthwhile to perform a collision avoidance maneuver. A tug can be valuable in preventing satellites from exhausting their own fuel, especially since they may have to alter their location several times.

It would be interesting to investigate the following issues:

1. How much has market demand uncertainty influenced the profitability of a constellation? (This should include a historical survey and a parameter sensitivity analysis.)

2. What are the potential benefits for the constellation owner from using tugging services?

3. What should the tug operator charge?

4. How can the risk of damaging the satellites be estimated and reduced?

5. What is more cost-effective: adding extra fuel for potential (but uncertain) satellite reconfiguration or hiring space tugs?

3.3.5.2 New Markets or Market Shift (Non-Constellation Satellites)

Communication satellites might require relocation in order to cover a different part of the Earth, in response to a bigger market, more profitable opportunities, or short-term demand peaks (e.g. wars, Olympic games, etc.). A tug can capture and move these satellites, so that their operational lives are not shortened by fuel depletion. The idea can also be applied to scientific spacecraft, if collection of data from various locations is desired. This would increase the science returns and would make the launching of other satellites to operate in the locations of interest unnecessary.

The greatest value of repositioning of satellites via space tugs can be observed when other forms of on-orbit servicing are also used. For example, great scientific benefits can be obtained if a scientific satellite already in space is supplied with a recently developed instrument that would enable it to perform better observations, malfunctioning equipment is repaired, more fuel and power are supplied, etc. Then, very few new satellites would be launched, since the operational lifetime of older satellites can be theoretically extended indefinitely. This would not only save the money to be otherwise used for the design, manufacturing, and launching of new satellites, but it would also prevent additional crowding and increase of collision probabilities.

To check the economic viability of this scenario, several issues must investigated:

1. What are the assumptions (e.g. serviceable satellites, reliable on-orbit servicers, etc.) that make this mission scenario interesting?

2. How much profit can be obtained for a number of different cases associated with satellite repositioning (with/without provision of other types of servicing)?

3. Who are the potential customers?

4. What are the risks associated with tugging functional spacecraft? How can they be quantified and compared against the benefits from the service?

5. What is the range of tug capabilities? How far would the tug be able to go (in terms of altitude and plane changes)? What sizes/masses of satellites can it mate with and carry?

6. How much should the tug operator charge?

7. Would it make more sense to have several tugs? Where should they be parked?

3.3.6 On-orbit Assembly of Massive Structures

Mass has always been an issue in space systems deployment, the biggest constraint being imposed by launch vehicle capabilities. A large, heavy spacecraft requires a large, expensive launch vehicle. On-orbit assembling of space assets, however, offers a solution to the problem. It also allows for expensive projects to be initiated without the need of having the entire budget available up-front. Additionally, it reduces the financial risks in case of launch failure or a spacecraft subsystem failure, since only the failed module would need to be replaced. The reason why on-orbit assembly has been limited in practice is due to several problems: 1) the problem of maneuvering the construction modules, 2) the need for astronaut assistance, and 3) the TRL and risks of autonomous navigation and docking in space. The Shuttle and its robotic arm could be used to assemble the modules, but this limits the construction to low Earth orbit locations and might be too costly (mainly due to required hours of astronaut training). Additionally, using astronauts brings up the issue of safety. Thus, using autonomous transfer vehicles (i.e. tugs) to move the assembly parts and modules might be a better idea. Its major advantage is the ability to assemble structures in various altitudes. All associated difficulties, however, need to be addressed when discussing the economic feasibility of the concept. The most important questions for consideration are:

1. What projects might benefit from on-orbit assembly of modules and structures?
2. Who should provide the service: a country's government, commercial firm, or multinational organization? How would either of these choices affect the charged fee?
3. What technological advancements are needed (mostly in the field of autonomy and docking)?
4. Would reusability of the tug be possible? How can it be achieved (refueling from on-orbit depots/ISS)?
5. What might be the potential implications on launch costs?
6. Who are the potential customers?
7. What are the risks associated with this type of space tug service?

3.3.7 Fuel Requirements for Orbit Adjustment Maneuvers

The propulsion and station-keeping subsystems are typically composed of thrusters and a source of fuel and oxydizer, or liquefied gas, whose limited volume usually determines the duration of a satellite mission. Although the other subsystems may continue to function long after the station-keeping fuel has run out, the satellite mission will most likely be terminated due to the subsequent orbit degradation and loss of satellite control. Fuel, however, is a limiting factor not only for spacecraft operational lifetimes but also for their payload size and mass. Satellites can trade fuel for payload or a smaller launch vehicle if north-south station keeping (NSSK), orbit raising (OR) or decay prevention (DP) is performed by space tugs that attach themselves to the satellites permanently or temporarily.

Reducing the cost of a satellite can be achieved if less mass is launched, which could be the case if satellites are redesigned to account for expected servicing, which implies making their fuel tanks much smaller. At this stage, however, it might be necessary to analyze the case for satellites whose design is not optimized for servicing. It might be difficult to convince satellite owners that satellite redesign would pay off, given that the old methods have worked satisfactorily and there is a significant risk associated with trying new ideas. Another important issue that requires consideration is that the use of a tug for orbit OR, NSSSK, and/or DP makes the client spacecraft completely dependent on the tugging vehicle, since the client spacecraft would have very little contingency fuel on board. Therefore, it is better to analyze tugging when provided as a service without the spacecraft being designed for it. Later, this assumption can be changed.

The potential for economic savings as a result of utilizing a tug or some other technology for satellite orbit adjustment maneuvers has been explored by a number of studies. In late 2002, plans were publicly announced to make the first known attempt to "push" a spacecraft in Earth orbit using energy beamed up from the ground. These plans envision launching the so-called Cosmos Sail mission on a Russian launch vehicle. Once the spacecraft is in orbit (about 800 km) and its sail is deployed, a microwave beam emitted from the Jet Propulsion Lab's Goldstone 70-meter antennae in California's Mojave Desert will be used to give the spacecraft an extra push. While the push received from the Goldstone microwave beam will be tiny compared to the effect of solar radiation on the sail, the spacecraft's mission is to test the feasibility of beam-boosted sails.[9] In early 2003, Orbital Recovery Corp. made it known that it has developed a business plan for a tug that docks with a GEO satellite and remains coupled with it in order to prolong

[9] "Satellite To Be 'Boosted' By Microwave Beam Proposed," Huntsville, AL, 1 November 2002; Source: http://www.spacedaily.com/news/rocketscience-02zk.html.

its lifetime when stationkeeping propellant nears exhaustion. In return for its orbit adjustment service, Orbital Recovery would charge a fee equivalent to one year of the satellite's revenues, or about $50 million [Ber02].

It would be interesting if an independent research were performed that has the same goals and envisions the same docking methods as Orbital Recovery. The analysis should answer the following questions:

1. Who are the potential customers?
2. What benefits do they get from renting a tug?
3. Is satellite designed with servicing in mind necessary for the business justification of the space tug concept in the context of this mission scenario?
4. What other assumptions may need to be made in order to make the idea economically feasible?
5. What are the alternative options (e.g. on-orbit refueling, launching satellite directly to GEO) and what is their value for the potential customers?
6. What fee should be charged for the service?
7. Is it better to perform NSSK and/or OR on one satellite only or to periodically move to different satellites (NSSK is normally done once every 41 days)?
8. What are the risks associated with capturing a functional satellite (especially if it is done periodically, which is the case when one tug services several satellites simultaneously)?

3.4 Deployment of a Family of Tugs

Since all of the above mission cases are very likely to be attempted in the future, there might be a possibility that a few or all of them are initiated at approximately the same time. Then, it would be highly desirable if a universal tug design existed that could be used in all mission scenarios. However, because the missions are so different (in terms of target status and specifications, range capability requirements, etc.), such a design might not be feasible. Instead, it might be a better idea to design a family of modular tugs using a common platform and sharing various components, while differing mostly in the scale of their bus, propulsion, and mating modules. Simplicity, reusability, universality, and cost and risk reduction are the features that should best characterize the tugs in the family. Simplicity is achieved by having relatively small tugs using off-the-shelf hardware parts. Reusability is facilitated by the fact that the tugs are confined to a specific target zone. Regarding universality, it is desirable that the designs be as similar as possible, so that they can quickly respond to changes in requirements or serve in other types of missions. All of these features lead to cost and risk reductions, which is the goal of every design.

Although the concept of a family of tugs will be addressed again in Section 4.5, it can be fully explored only after all mission cases have been analyzed and optimal tugs have been identified for each mission case.

3.5 Chapter Summary

A new architecting approach has been utilized for the modeling of the performance and utility of space tugs. It starts with exploring the current on-orbit satellite population and identifies target orbital zones, characterized by satellite clustering. A number of different missions can be associated with these orbital zones, and a separate tug is designed for each of them. The resulting family of smaller and simpler tugs allows for greater flexibility, lower risks, and potentially lower service costs.

Chapter 4

Research Methodology

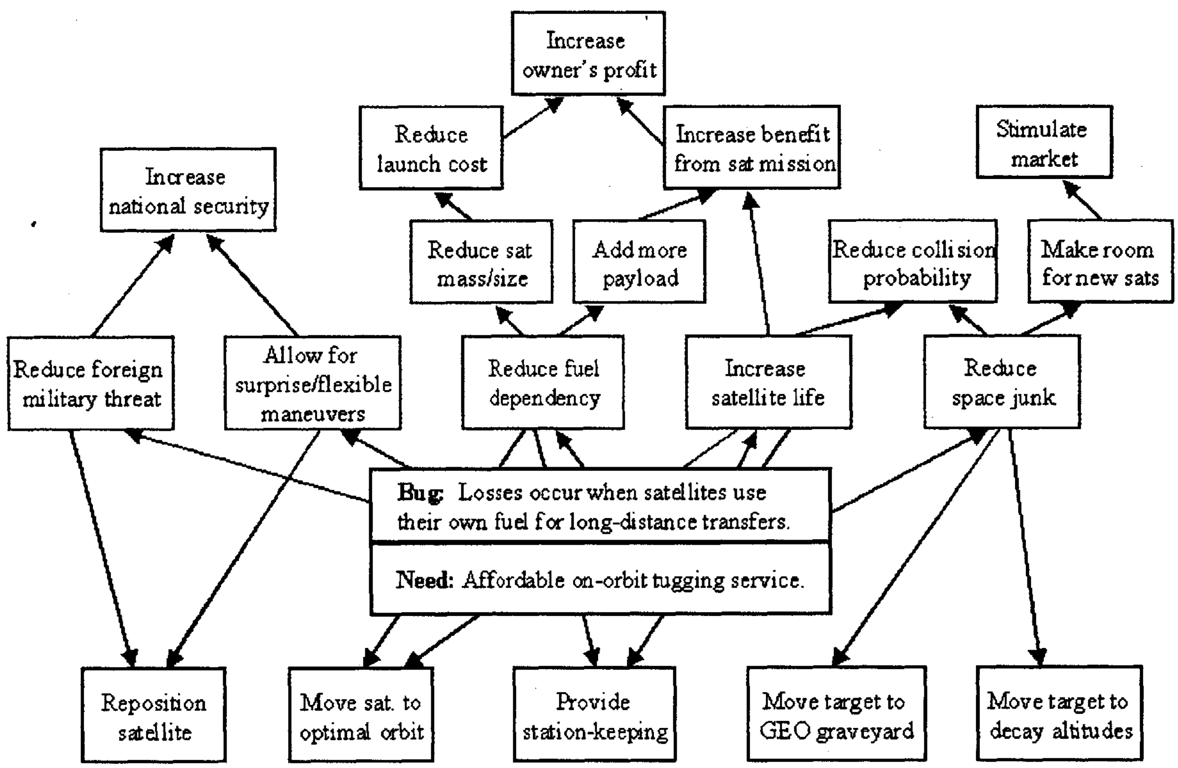
4.1 Phase I: Understanding the Need

Design projects should be always initiated in response to some need. In actuality, about 80 percent of all new product designs are market-driven, and the assessment of the market, i.e. the establishment of what exactly the customer wants, is imperative [Ull97]. Indeed, the most commonly used criterion for project success is whether the product performs the desired functions in the exact manner that is requested by the customers. Therefore, prior to starting the design, it is very important to clearly understand the customers' needs and requirements.

The need for a space tug was discussed in detail in Chapter 1 of this thesis, where a number of problems regarding the utilization of space assets were identified. Although these problems shared a common possible solution (namely, a space tug), they were associated with different stakeholders, who would most likely impose different requirements. Thus, it is logical to expect unique designs for each scenario.

4.1.1 Problem Identification

A technique called How-Why analysis is sometimes used to help identify and better understand the root problem that needs to be solved, as well as to formulate a problem statement. The first step is to write a "bug" (something undesirable that needs to be eliminated) and the corresponding need. While working up, the question being answered is "Why?"; while working down, the question being answered is "How?" These two questions can be asked at any block (response) to fully explore that entry. "Why?" can be asked until circular arguments begin, and "How?" can be asked until the entries begin to constrain the solution. Figure 4.1 presents the How-Why diagram for the problem under analysis in this thesis.



Problem statement: Examine under what conditions tugging becomes affordable to most potential customers.

Figure 4.1: How-Why Analysis

Mind-mapping is another procedure often used before the initialization of the design process. It helps understand the scope and depth of a problem, as well as its inputs, outputs, interrelations, and desirable functions. Additionally, it involves writing down a central idea and brainstorming associated concepts. The goal of mind-mapping is to facilitate the identification of all aspects of the problem that should be considered during the design process; the construction of visual and meaningful relationships between ideas assists the designer's recall and understanding. A Mind Map of the space tug problem is presented in Figure 4.2. The brainstormed ideas address the problem statement identified by the How-Why analysis and show important interconnections. For example, it was suggested that the fee for tugging is dependent mostly on the combination of the cost of tugging and the revenues that potential customers receive from the operation of satellites.

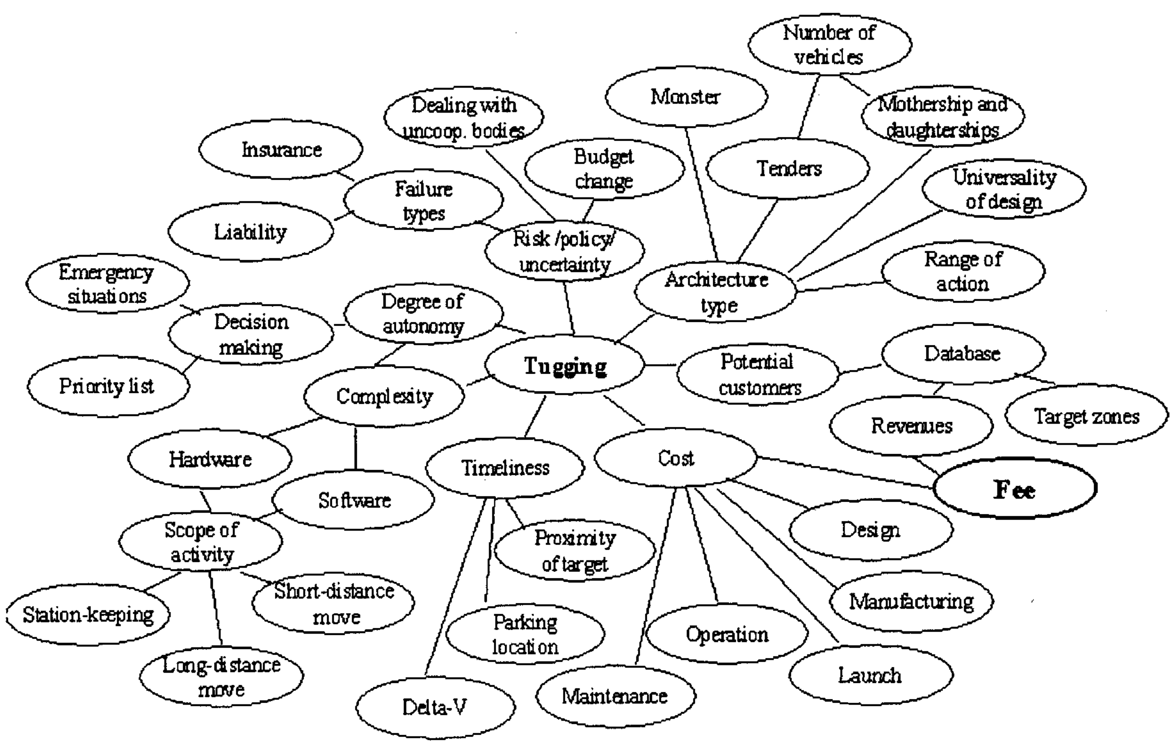


Figure 4.2: Mind Map

4.1.2 Stakeholders Identification

Stakeholders are all parties that have a share or some interest in an enterprise. They can be divided into three groups: clients (or customers), providers, and third parties. Apropos space tugging, clients include satellite operators, the scientific community, or the military.[1] Clients impose system requirements by defining what the product must ultimately be able to do. The providers are, clearly, the organizations (government or commercial) that provide the tugging service. Their goal is to satisfy customer requirements as best as possible, while simultaneously fulfilling their own interests. The last group of stakeholders—third parties—can include everyone indirectly involved in the mission of a space tug, e.g. designers, manufacturers, launch providers, insurance companies. Satellite manufacturers, for example, determine what satellite capabilities can be provided at what price. Issues such as co-operative satellite design (i.e. designing satellites to be serviceable) impact the manufacturers directly.

As mentioned earlier, the different mission scenarios will have different stakeholders. Their identification is an important step in the early phase of the design process, because it affects the utility measures and the optimal architecture selection, as will be described later in this chapter.

4.1.3 Top-Level Customer Requirements

Regardless of the type of project, customer desires drive the development of the product. There are two major types of customer requirements: physical and functional. The physical requirements describe the desired physical properties of the product, such as size and shape. In our case, customers are most likely to leave these as a designer's choice and only define the functions they would like that the tug be able to perform. Figure 4.3 displays the functional requirements chart for a general space tug mission. It starts with the identification of the overall function of the tug, i.e. the moving of targets, and decomposes it into sub-functions until form constraints are reached. The sub-

[1] Common people are involved as stakeholders but not as direct clients. Their category can be further divided into subscribers (people with televisions or cell phones, interested in weather forecast, etc.) or taxpayers, depending on whether the focus is on government or commercial satellite missions.

functions focus the designer's thoughts on *what* the product must do, but they do not specify *how*. The designer must group the functional requirements in a way that makes them independent of one another, since two or more dependent requirements introduce unnecessary complexity without providing additional benefits. When requirements are dependent on one another, in some cases they can be combined into one [Suh90].

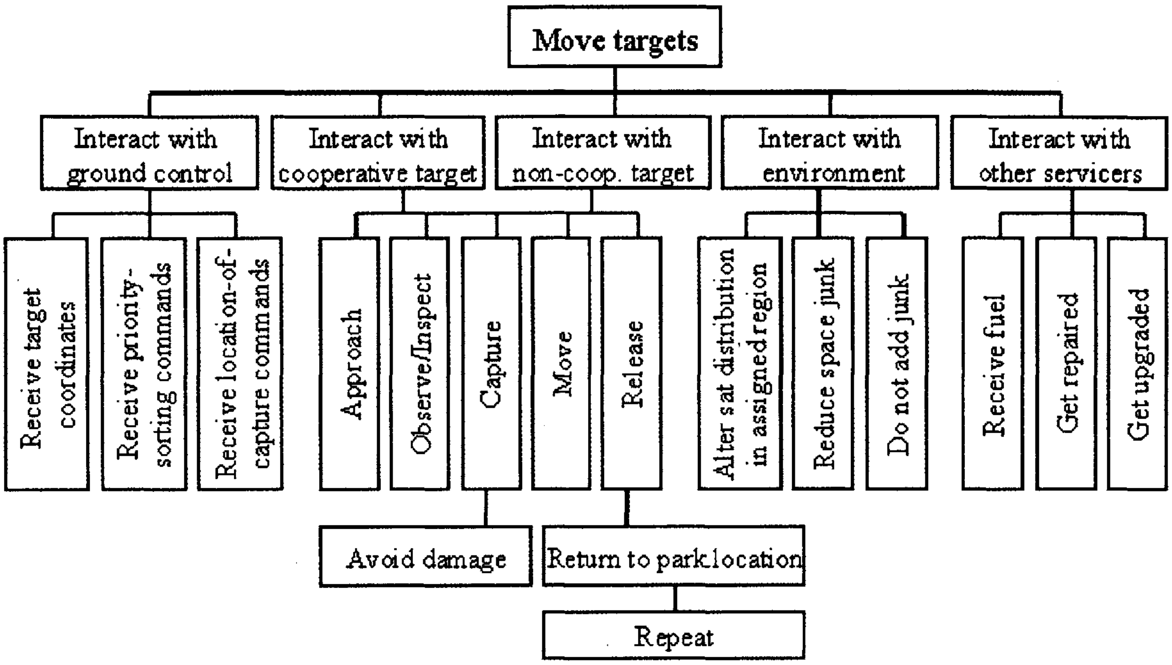


Figure 4.3: Functional Decomposition

Functional decomposition is one of the most critical steps in a design. It sets the stage for identifying ideas in Phase II that could fulfill each of the identified functions.

4.1.4 Conceptual Design Objective

The objective of this research is to analyze the business case of various mission scenarios. However, before accounting for all factors that make tugging of value, a simple but trustworthy model for creating tug architectures must exist. The next section describes the modeling approach.

4.2 Phase II: Modeling the System

A design capability referred to as Multi-Attribute Tradespace Exploration (MATE) was used to model a great number of space tug architectures and identify the best options. In MATE, user needs are defined in terms of system attributes that are assigned single-attribute utilities and then combined in a single utility function. To create the space tug design tradespace, a design vector composed of independent variables having a significant impact on the attributes was selected. A change in each of these variables produced a different architecture in the tradespace. Thus, a very large number (hundreds to hundreds of thousands) of design concepts having different costs and performance can be created. The results, collectively referred to as the tradespace, can then be explored. This process consists of the search for not only optimal solutions, but also for the understanding of design sensitivities, key trade-offs, critical uncertainties, and vulnerabilities to changes in the market or national policy [MS03].

4.2.1 Mission Attributes and Utilities

Attributes define the desired system performance. They are quantifiable variables capable of measuring how well a user-defined objective is met. A problem that might complicate the analysis is that different types of customers would define the mission goals differently or assign different weights on the same attributes. In a government-funded project, for example, scientists would want to maximize the scientific returns from a mission with little regard to its cost. The taxpayers, conversely, would prefer the least expensive system that does not necessarily meet more than the minimum set of requirements.

The most important attributes of a space tug mission are: mating capability, transfer capability, timeliness, and adaptability.

4.2.1.1 Mating Capability

Mating capability is a measure of the degree of damage inflicted on the satellite and the tug during the mating phase of a tugging mission. It is especially important in the cases when the target satellite is still functional and when the tug is reusable. Therefore, before and during mating, a comprehensive series of status checks must be carried out. Mating capability also determines the range of masses, inertia, and geometry the tug can handle.

The mating performance of a tug depends on the type of target (cooperative or non-cooperative) and the hardware and software capabilities [Fir86] of the tug in terms of:

1. *Sensing*:

a. Object location: Determining the exact location of an object.

b. Effort sensing: Measuring the response of the target to stimuli from the space tug.

2. *Manipulation*:[2]

a. Task-level control: Specifying and executing given procedures to accomplish a task, including computations, decisions, communications, as well as specifying sensor action and manipulator motion. It also includes the adjustment of the preprogrammed motions to match the actual positions of objects based on information provided by sensors.

b. Gripper control: Controlling gripper action to maintain a firm hold of the target and exerting a controlled force and torque on the satellite.

3. *Mobility*:

a. Long-range navigation: Traversing distances that are quite large relative to the size of the arm. Important during the rendezvous phase.

b. Short-range navigation: Traversing distances that are comparable to the arm's size. It is important to avoid collisions between manipulator and satellite parts. Important during the mating phase.

---

[2] To reduce the chance of damage, prompt manipulator action is required, since the zero velocity condition is very brief (on the order of a few minutes).

4.2.1.2 Transfer Capability

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. The propellant mass can be presented as the difference between the wet mass (m_w) and the dry mass (m_d) of the tug:

$$m_p = m_w - m_d \tag{4.1}$$

Assuming Hohmann transfer orbits, the delta-V required for each maneuver is calculated for given target position and tug parking location. The propellant burnt during each maneuver (m_{p_used}) is calculated with the formula:

$$m_{p\_used} = m_{w\_prior} \cdot \left(1 - e^{\frac{-dV}{Isp \cdot g}} \right) \tag{4.2}$$

where m_{w_prior} is the wet mass of the tug before the maneuver, dV is the delta-V required for the maneuver, Isp is the specific impulse of the propellant used, and g is the gravitational constant. An initial assumption has been made for the wet mass at launch, but it is altered through a loop of iterations until convergence is reached.

The dry mass (m_d) of the tug can be calculated by selecting a grappler mass (m_g) from a range of possibilities (see Section 4.2.2.2) and assuming that it is 65% of the total dry mass. For satellites, the payload mass is normally about 25-30% of the spacecraft dry mass, but it usually comprises much lighter equipment than a mechanical arm. A grappling mechanism would weigh significantly more than the components comprising the rest of the spacecraft subsystems (power, structure, thermal, propulsion, etc.). That is why such a high number, 65%, was selected.

$$m_d = \left(\frac{100}{65} \right) \cdot m_g \tag{4.3}$$

For maneuvers involving the transfer of a tug mated with a satellite, the mass of the target needs to be added to the dry mass of the tug.

Mission Phases

Figure 4.4 is an alternative representation of the phases depicted in Figure 2.2. It presents a schematic of the main mission phases, starting with transfer to the satellite orbit, after task has been assigned to the tug. The figure assumes that the target is in the GEO belt and needs to be transferred to graveyard orbit (300 km above GEO). This is the set-up for the GEO satellite retirement scenario that is discussed in Section 5.1.

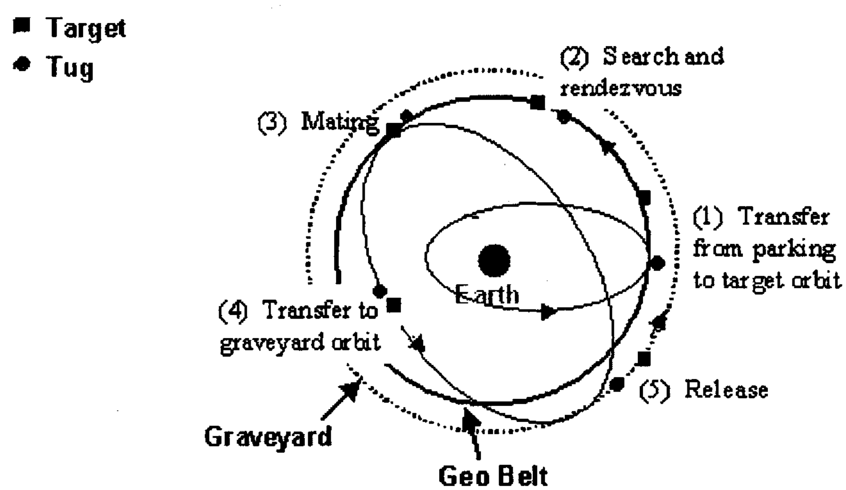


Figure 4.4: Main Mission Phases

The portion of the Matlab code that was used in calculating the mass of the available and the utilized propellant is provided in Appendix A. A sample analysis with numerical values is given below.

Inputs:

- *Tug*: 500 kg grappler, storable bipropellant (N2H4/N2O4; Isp = 325 sec), parked in GEO belt
- *Target*: Intelsat 804, 1601 kg, move it from 0.02 deg inclination and 35785.5 km altitude to graveyard orbit (300 km above the GEO belt, same inclination; tug remains parked there after target release).

Outputs:

tug dry mass = 769.2308 kg

total propellant needed by the tug = 596.1662 kg (including mass of oxidizer)

Mission Phase	Thrust [N]	delta-V [m/s]	Fuel [kg]
Park	227.47	1543	524
Transfer to target	0.22	2.92	0.77
Rendezvous	0.14	1.82	0.48
Mating	1.52	20 (assumed)	5.26
Towing	0.82	10.88	8.30
Release	1.50	20 (assumed)	15.19
Total	*231.67*	*1598.62*	*553.99*

Table 4.1: Results from Sample Calculations

Note that because of the initial proximity of the tug and the target and the small distance that needs to be traveled to reach the desired destination, most propellant (and delta-V) is spent to reach parking orbit (GEO belt) after injection in GTO by the launch vehicle.

4.2.1.3 Timeliness of Response

As shown in Figure 4.5, 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). In other words, timeliness tells us how quickly a satellite can be moved to the new location.

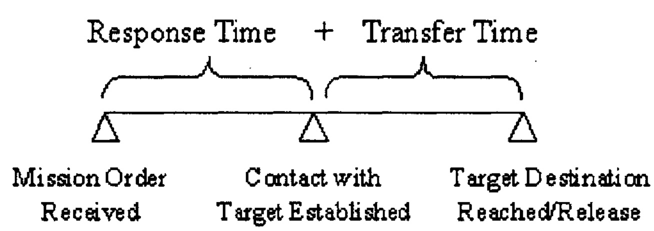


Figure 4.5: Definition of Timeliness

Timeliness is of great importance when a satellite is stranded at a suboptimal orbit (especially in the radiation belts), when a military surprise maneuver is to be performed, or when imminent collision with a piece of space debris must be averted. Timeliness is driven primarily by the type of propellant used for long-distance transfer and the parking location of the tug. The sensing capabilities used for long- and short-distance navigation and the grappler capabilities for the mating phase of a mission also affect the response time, but not that drastically, therefore their influence will be neglected.

A recent paper [BMW04] describes an experiment designed to test the efficiency of three possible two-dimensional search strategies—random, semi-autonomous, and autonomous—in the context of autonomous rendezvous in space. It was found that the semi-autonomous algorithm was the most energy-efficient but also the most time-consuming approach. The conclusion was that an autonomous algorithm is most suitable for space applications. The results also suggested that, depending on preliminary knowledge of the search space and mission requirements, a hybrid approach might be more efficient.

4.2.1.4 Adaptability

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. The range of capabilities can be measured apropos the type of targets that can be tugged (functional versus dead, small versus large, and light versus heavy) and the distance between the target and the pre-defined zone of action of the tug. In this thesis, adaptability is mainly used to analyze whether a given tug can perform a different type of mission from the one for which it was optimized.

4.2.1.5 Total Utility Metric

Utilities are used as numerical values of attribute "goodness," reflecting how valuable, relative to other attributes, a certain attribute is to the customer. They range from zero to one, zero being the minimum acceptable performance level. A total utility function (U_{tot}) captures the weighted sum of all attributes as follows:

$$U_{tot} = V_{mc} \cdot W_{mc} + V_{tc} \cdot W_{tc} + V_t \cdot W_t + V_a \cdot W_a \tag{4.4}$$

where V_{mc}, V_{tc}, V_t, and V_a are the estimated utility values of mating capability, transfer capability, timeliness, and adaptability, respectively, and W_{mc}, W_{tc}, W_t, and W_a are their assumed weights. Mapping this total utility function against the estimated cost of tugging is used for evaluating the various architectures in the design tradespace.

The following weights were assumed for the two case studies explored in this thesis. The rationale for the selection of these weights is provided in Chapter 5.

Mission Scenario	W_{mc}	W_{tc}	W_t	W_a
GEO Sat. Retirement	0.4	0.2	0.2	0.2
Satellite Rescuing	0.3	0.3	0.3	0.1

Table 4.2: Utility Weights

The next section describes the design variables used in populating the space tug tradespace. It also explains how these variables are used in estimating the values of the four attributes of interest.

4.2.2 Design Vector

The design vector comprises a set of independent variables that have a significant impact on attributes and can be controlled by the engineer/designer. Creating all possible combinations of variables is a means to consider multitudes of architectures. Apparently, a large design vector would be impractical to explore; that is why only the most critical variables need to be identified and included. This work has selected the following design variables: autonomy level, sensing capabilities, grappler sophistication, propulsion type, and parking location. Their allowable settings are summarized in Table 4.3. To facilitate computation, no more than six different values were assigned to each variable.

Design Variable		Units	Allowable Settings
Parking Location	h	km	0 - 36000
	i	deg	0 - 180
Propulsion System	Isp	sec	3120 (electric)
			1500 (nuclear)
			446 (cryogenic bi)
			325 (storable bi)
Level of Autonomy	type	-	telepresence
			supervision
			full automation
Grappler Sophistication	M_{grap}	kg	300 (low)
			400 (low)
			500 (medium)
			600 (medium)
			700 (high)
			800 (high)

Table 4.3: Design Variables

Table 4.4 shows what design variables affects each attribute; "+," "-," and "o" indicate increase, decrease, or neutral effect, respectively, on the utility attribute of interest due to an increase in each design variable.

Attributes \ Design Variables	Autonomy Level	Grappler Sophistication	Propulsion Type	Parking Location
Mating Capability	+/–	+	o	–
Transfer Capability	+/–	–	+	o
Timeliness	+	o	–	+
Adaptability	+/–	+	+/–	+/–

Table 4.4: Mapping of Design Variables against Attributes

4.2.2.1 Autonomy Level

Robots have found wide use on Earth. They prevent exposure of humans to danger, save labor costs, and bring quality to a product or service through repeatable precision. The same motivation exists in regard to space, where automation can potentially contribute by:

- eliminating risks for humans;

- reducing the workload for operators on the ground (i.e. less management, maintenance, and teleoperator work-hours);
- limiting the required communication between ground stations and spacecraft, which becomes an issue when communication paths have excessive delays, are too intermittent, or are unavailable for supervisory control, e.g. in polar orbit;
- sustaining reliable performance in terms of fault tolerance and self-maintenance [HL88].

The nature of work of a space tug requires it to be unmanned. Even if it is parked and serviced by the International Space Station, the (possibly necessary) action of passing through radiation belts or the weight an inhabitable craft implies is prohibitive. An MIT undergraduate study [SSE94] had focused on the design of a manned space tug, but the result was a "monstrous" vehicle that no realistic project budget would allow. Automation is clearly the only potentially affordable option, but the key issue is the degree of autonomy to be employed.

Autonomy refers to the tug's ability to operate and make decisions without human assistance. This thesis investigates three levels of human involvement:

1. *Telepresence*: Synonymous to remote control, it refers to direct and continuous human control, with no automatic control loops. The idea behind telepresence is that humans would be able to "see" remote places through sensors and telecommunication, while remaining in a safe environment. Unfortunately, teleoperation in space has severe limitations. Commanding a remote device in every degree of freedom is extremely inefficient if communication time is small (this applies to the case of a distant spacecraft).

The telepresence case is strictly subjected to the interpretation by the ground computers; once the human operator gives a command, the tug systems will execute it without questioning. Besides this high operational risk, timeliness is another important issue, especially in emergency situations. The problem in this case is due to potential signal delays; a teleoperated tug cannot react unless guided by the operator. Even when signal delays are not an issue, it has been discovered that a human takes much more time to perform a task through teleoperation than he would directly in situ [HL88].

2. *Supervision*: Supervisory control is a mixture of manual and automatic control modes. It implies monitoring the mission from the ground or the ISS and directing the critical activities of the space tug systems, supplying key decisions and solutions to problematic situations.

The supervisory autonomy level allows for decisions to be made automatically, without having to wait for the ground operator. This is a great advantage because, in urgent situations, speed of response could be critical. Additionally, risks are smaller for this autonomy level because computer decisions can always be overridden by commands from the human controller.

3. *Full Automation*: This option allows for a full automatic control by the on-board computers as a response to data from sensors. The minimum level of human intervention, which corresponds to maximum autonomy, would be to provide approximate target position data and give a command for initiation of the departure sequence from the standby position in which the tug would normally be in between missions. The tug should be able to obtain target specifications through observation and system ID, and all mission phases should be fully controlled by the tug's on-board software, navigation, and controls systems.

A fully automatic spacecraft must possess a decision-making capability. For example, it needs to be able to select which target to go to when several satellites need tugging at the same time. Once it arrives at a target, it needs to be able to identify the satellite's state (functional, dysfunctional, cooperating, non-cooperating), locate the best spot for grappling, and achieve control over the satellite. Some of the associated requirements are:

1. Ability to sense, identify, and correct malfunctions either instantly or very quickly.

2. Increased computing power. Improved computers with erasable memory storage are required for signal and symbolic processing. They should be capable of executing billions of operations per second.

- Spatial/geometric reasoning (navigation in space is very different from navigation on Earth).
- Sophisticated visual and tactile sensors.

- A database of detailed targets' structural and functional descriptions. This would be of great help when interpreting sensor data. In view of storage memory availability, it would be optimal if only the major satellite types (differentiated in terms of bus manufacturer) are pre-stored on board. This set can be utilized as a backup during emergency situations when communication with ground is not possible. Otherwise, specific satellite information could be downloaded on demand.
- Algorithms that achieve automatic interpretation of complex objects under variable conditions [Fir86].
- Fault analysis and recovery programs capable of identifying problems and suggesting corrective actions.

Unfortunately, the risks of using full automation are high because the necessary technology/software sophistication has not yet been developed and tested. Thus, the technological readiness and costs associated with full autonomy are the two most critical factors that might adversely influence the design decisions. However, we should keep in mind that although the complexity of fully autonomous systems makes them more expensive than other options, damaging a satellite could be even more costly.

The Remote Agent Example. Creating highly autonomous spacecraft is one of the main priorities of NASA's New Millennium Program. With its software experiment, called the Remote Agent, *Deep Space 1* became the first self-aware, self-controlled, and self-operated robotic machine used for space exploration. The Remote Agent was capable of planning and executing many activities with only general direction given from the ground. Its software included a "planner" that generated a set of time-based and event-based activities. Because of its immediate access to a much more current and complete information regarding the spacecraft's operational state, compared to what was available to ground controllers, it could make better use of onboard resources such as computer memory and power.[3]

[3] http://nmp.jpl.nasa.gov/ds1/tech/autoraFAQ.html

4.2.2.1.1 Major Trade-offs

Placing *autonomy level* in the design vector will not only enrich the variety of space tug architectures but will also help analyze the trade-offs between various levels of human involvement and suggest an optimal autonomy level for tugging services. A number of issues need to be considered when trading off between spacecraft autonomy and ground operations. Some of the major ones are development time for onboard software versus ground software, uplink/downlink bandwidth, resource management, life cycle costs, safety, timeliness, risk of damage, availability, and complexity. The most prominent pros and cons are briefly discussed below.

Human error

On-board software is being used increasingly to reduce the potential for human error for a variety of calculations. To assess the relative risk of human error versus a flight software bug, however, many factors must be taken into account, e.g. the maturity of the software development process, the flight software team experience, the mission operations team experience, and the complexity of the planned operations.

Communication and Timeliness

The space tug systems must respond to stimuli (both internal and external) not only appropriately but also in time. The farther a spacecraft is from the ground, the more difficult round-trip communications with the ground station become. The frequency of ground contacts decreases, and that poses a serious problem: What is the effect of a communications hardware malfunction (e.g. antenna damage)? Or what if a decision needs to be made while out of contact with ground? Damage on the satellite or the tug might be done before teleoperators learn about the problem and correct it. This drives the need of preprogramming sufficient autonomy in the tug's software systems, so that the success of its missions is not jeopardized. The ability to plan spacecraft activities onboard allows the spacecraft to respond to major instrument failures or other anomalies in a timely manner. This is critical both for the survival of the spacecraft and for the success of its mission. Onboard fault diagnosis and recovery software should be able to detect, identify, and remedy spacecraft faults, both minor and critical, in a matter of minutes.

Heer and Lum [HL88] provide a good explanation of the dependency of task completion time on task complexity. Not considering communications delays and other external factors, they see the relationship as presented in Figure 4.6.

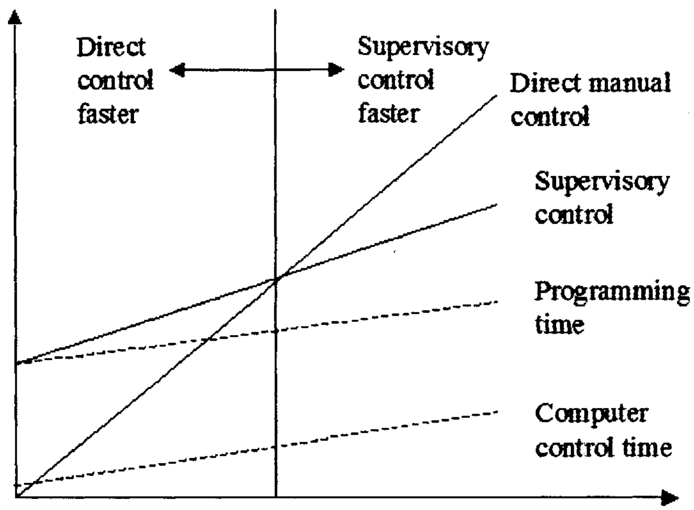


Figure 4.6: Task Completion Time as a Function of Task Complexity

As shown, programming a computer to perform even the simplest task consumes time. As the task increases in complexity, the programming time also increases (see "programming time" line). The time it takes an already programmed computer to execute a task may be very short for simple tasks, but it increases with task complexity (see "computer control time"). For a supervisory control, the ordinates for these dotted lines must be added. The resulting line ("supervisory control"), when compared with the direct manual execution, is greater for simple tasks, but less for a relatively complex task, due to computer efficiency. The exact location of the crossover point depends on the telerobot capability, the human programming and manipulation skills, and the task complexity.

Resource management

Personnel resources are seldom unlimited. Unless the space tug is fully autonomous, it must be supervised 24 hours a day. One of the determinants of a successful mission is the availability of qualified personnel, which is expensive. Aside from cost savings brought about by reducing the size of operations staffs, other resources may also enter the equation. For example, computers are another area that can force a trade-off. Only limited types of processors are available for flight use, and their number on-board may be limited as well. At some point, the computer resources on-board may not be able to handle all the desired tasks, and some tasks may have to be performed on the ground. Another resource-related issue is that automated systems may add to power, thermal, mass, and maintenance requirements. Additionally, impact on sensors and data-bus bandwidth is not known; increased autonomy might raise the associated needs substantially [HL88].

Cost

The cost of developing and testing flight software is considerable, when appropriate quality assurance procedures are followed. The cost of developing ground software or procedures may be less, but the recurring cost of ground execution over the mission lifetime may exceed the flight software development costs. In addition, trade-offs may be made to minimize organizational costs over multiple missions. Thus, the use of multiple tugs makes increased autonomy more desirable.

Complexity

Increasing the complexity of the on-board software increases not only the development time and cost but also the chances that there exists a bug that may jeopardize the mission. At the current stage of technological progress, operational uncertainty is too high even for the most advanced technologies, and complex robotic tasks are unlikely to be performed with a satisfactorily low risk level in the highly unstructured and dynamically varying space environment. Autonomous systems require adaptability, which is difficult to build in since it is practically impossible to predict and design for all possible situations.

Schedule

Development schedule can also be an important trade-off factor. Spacecraft development is driven by a launch schedule. Functions that can be done either on the spacecraft or on the ground and are not needed until late in the mission should not be allowed to delay spacecraft development.

The NEAR Example. The fixed and extremely short development time of only 27 months and the 16-day launch window made schedule the overriding consideration in the NEAR spacecraft design decisions. It is important to note, however, that part of the on-board autonomy on NEAR was implemented as a series of rules and commanded macro responses that were re-programmable from the ground. While this added some complexity to the on-board software, it allowed the flexibility of moving some functions from the ground to the spacecraft at a later time. [LS96]

4.2.2.1.2 Sensing Capabilities

Specific sensor suites and software complexity are assigned to each autonomy level. The combination of software and sensor capabilities is defined in this thesis as "sensing capability." The sensing process consists of converting the relevant object properties into a signal and then transforming this signal into information needed by the on-board computer or the ground operator to plan the motions of the robotic arm via thruster commands. As shown in Figure 4.7, visual, distance, and force sensors produce signals that are converted to an array of numbers that is then analyzed to obtain an understanding of the environment. [Fir86]

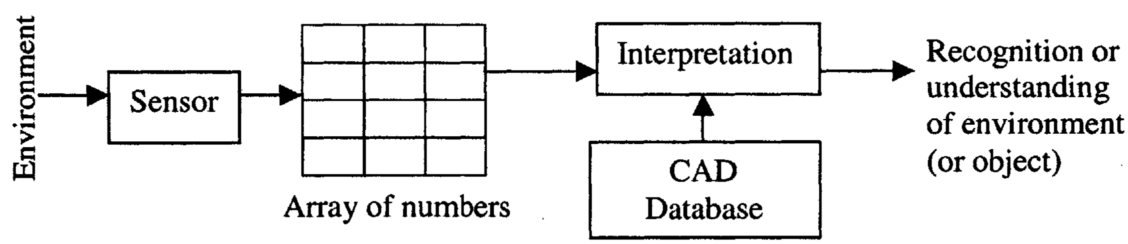


Figure 4.7: Information Flow Model [Fir86]

Types of Sensors

1. *Position determination radar.* It is used during the rendezvous phase of a mission.
2. *Proximity sensors.* These are sensing devices that detect when an object comes within a specified distance (on the order of a few centimeters) of the tug's grappler. Some of them operate by shining a light on the target and measuring the intensity of the reflected light. Ambient light can interfere with a simple optical

beam. As a result, most sensors now use a modulated pulse with a frequency up to the low KHz range. This allows better detection at longer distances with lower power.[4] Other proximity sensors use laser for range determination.

3. *Tactile sensors.* They measure and report the contact force/torque. One way to do this is via measurement of the pressure distribution over the surface of the gripper. For that, an array of tactile simulators has to be placed on the arm's fingertips [Fir86].
4. *Visual sensors (cameras).* Their role is to display a picture of the work area. If there are several cameras, they should be pointed at different angles to provide peripheral vision [Fir86]. They are most useful when significant human control is exercised.

Software Complexity

The information provided by the sensor types listed above is processed by computers on-board or on the ground. The following is a list of the major requirements for software capabilities [Fir86]:

1. *Signal processing.* The processing of data from radars, imaging devices, and other sensors is problematic when the data rate is high. Special-purpose computers might be needed to handle the complex algorithms.
2. *Visual understanding.* By visual understanding we mean the ability of the on-board computer to develop scene interpretation from image data. Free-flying objects may appear in any orientation, creating a difficult recognition problem. Shadows, reflections, and occluded parts are some of the image degradations that make visual sensing difficult to interpret, particularly during eclipsed parts of the orbit. Variations in the shape of non-rigid components and equipment due to major structural damage will also make shapes difficult to recognize. Three-dimensional imagery might alleviate these problems.
3. *Tactile identification.* Tactile identification is an analysis of the responses to force or torque actuators or the end effectors of the tug's grappling mechanism.

---

[4] http://claymore.engineer.gvsu.edu/eod/mechtron/mechtron-101.html#pgfId-867972

4. *Pattern recognition.* This involves matching observed patterns against patterns in a database, template, or model.
5. *Situation assessment.* Situation assessment necessitates the ability to deduce from sensor observations and previous knowledge the important facts about the space tug's surroundings. Ideally, the software systems would be able to deal with incomplete or contradictory information.
6. *Planning and scheduling.* This implies the ability to develop a time sequence of things to be done and/or procedures to be followed.
7. *Implementation.* The execution of a control strategy to achieve a goal is defined here as implementation.
8. *Emergency response.* Reaction to emergency situations must be provided quickly, so that service is maintained and damage is avoided. The main focus is on the ability to respond in a timely manner. The success of the response is of secondary importance because of its high uncertainty.

Table 4.5 maps the above capabilities against the mating capabilities defined in Section 4.2.1.1.

Perception	Object location	Signal processing Visual understanding Pattern recognition
	Effort sensing	Visual understanding Tactile identification Signal processing
Manipulation	Task-level control	Situation assessment Planning and scheduling Implementation Emergency response
	Gripper control	Implementation
Mobility	Short-range navigation	Situation assessment Planning and scheduling Implementation
	Long-range navigation	Situation assessment Planning and scheduling Implementation

Table 4.5: Mapping of Sensing Capabilities against Mating Capability Criteria

The utility of sensing capability was calculated through assigning a risk factor ranging from 0 to 1 (1 signifying minimal risk) to each capability. With respect to autonomy level, the sensing capabilities are assumed to be associated with the following risks:

Telepresence

SP low, medium, high

VU low (done on ground)

TI low, medium, high (dependent on the sensors used)

PR low (done on ground)

SA low (done on ground)

PS low (done on ground)

I low, medium, high (mostly hardware dependent)

ER medium, high (Emergency implied quick actions; communication delays increase the risks if response cannot be immediately provided by ground operators.)

Supervision

SP low, medium, high

VU low, medium (verified on ground)

TI low, medium, high (dependent on the sensors used)

PR low, medium (verified on ground)

SA low, medium (verified on ground)

PS low, medium (verified on ground)

I low, medium, high (strongly dependent on hardware)

ER low (Even if communication with ground is not possible at the given moment, the on-board computer is capable of responding to the emergency. Even if its response lead to failure, the probability for this is smaller compared to the full automation case because there is still the chance of human intervention.)

Full Automation

SP low, medium, high

VU medium, high (Visual data can be very ambiguous; in this case, there is no possibility of a teleoperator to check its validity.)

TI	low, medium (Expensive software is expected to be used.)

PR	medium, high

SA	medium, high

PS	medium, high

I	low, medium, high (It is strongly dependent on the hardware that is used.)

ER	low, medium (The response may be timely but the outcome may not be successful. Planning a response for a situation that has not been predicted during the design of the software is perhaps the most uncertain task.)

The following weights were assigned to each sensing capability for the two case studies analyzed in this thesis:

Mission Scenario:	GEO Ret.	Rescue
PERCEPTION	**0.3**	**0.2**
Object Location	*0.3*	*0.3*
Signal Processing (speed)	0.1	0.1
Visual Understanding	0.3	0.3
Pattern Recognition	0.6	0.6
Effort Sensing	*0.7*	*0.7*
Signal Processing	0.1	0.1
Visual Understanding	0.4	0.4
Tactile Identification	0.5	0.5
MANIPULATION	**0.5**	**0.4**
Task-Level Control	*0.7*	*0.7*
Situation Assessment	0.25	0.25
Planning & Scheduling	0.25	0.25
Implementation	0.25	0.25
Emergency Response	0.25	0.25
Gripper Control	*0.3*	*0.3*
Implementation	1	1
MOBILITY	**0.2**	**0.4**
Short-Range Navigation	*0.8*	*0.5*
Situation Assessment	0.3	0.3
Planning & Scheduling	0.3	0.3
Implementation	0.4	0.4
Long-Range Navigation	*0.2*	*0.5*
Situation Assessment	0.3	0.3
Planning & Scheduling	0.3	0.3
Implementation	0.4	0.4

Table 4.6: Weights of Sensing Capabilities

Perception is a more challenging task in LEO/GTO than in GEO due to faster dynamics, more perturbations, faster changing lighting conditions, etc. This, however, does not mean that *Perception* should be given a higher weight in the rescue scenario compared to the GEO satellite retirement scenario. The reason is that these are relative weights that are selected in comparison to the other capabilities (i.e. manipulation and mobility) for each mission type. Thus, although perception during rescue missions is more difficult and, hence, more critical than during a GEO retirement mission, it is less important than the capabilities to reach, capture, control, and transfer the target to the optimal location.

4.2.2.2 Grappler Sophistication

A robotic manipulator is a chain of rigid links attached via a series of joints. Manipulator technology is well-developed for many tasks on Earth that can be performed by relatively short arms (less than 2 m long) that move at a relatively slow speed (less than 1 m/s) [Fir86]. A space tug, however, would need a longer arm that would move slowly and carefully while approaching the satellite, but then must be able to provide prompt manipulation, since the zero relative velocity conditions can last only a few minutes. Additionally, on Earth gravity limits the range of orientation in which a part may be encountered, therefore five-jointed arms can be used quite successfully; in the zero-g space environment, each joint provides a single degree of freedom (DOF), so the arm needs at least six joints to place its gripper in an arbitrary position and orientation. Most manipulators proposed for use in space have seven joints. The extra joint provides an additional degree of freedom that may be used to operate the arm more dexterously, for example by reaching around an obstacle or into confined spaces. Although it is desirable for the tug's grappler to be capable of fine manipulation, such "redundant" arms (i.e. those with more than six joints) are more difficult to control. An arm with fewer than six joints is also difficult to control, but for the opposite reason: it does not have complete freedom of motion. For any given hand position, there will be some direction in which it cannot move [Fir86]. Thus, we propose that the space tug arm have 6 DOF, i.e. the tradespace will not contain tugs with various numbers of segments and types of joint. Table 4.7 contains the specifications of four manipulator arms designed for use in space.

Manipulator System	Mass [kg]	Mass Handling [kg]	DOF* [#]	Length* [m]
Canadarm (Shuttle arm)[5]	410.5	29,484	6	15
Canadarm 2 (Space station arm)[6]	1,800	116,000	7	17.6
ERA (European Robotic Arm)[7]	630	8,000	5	11.3
JEM (Japanese Experiment Module) arm [Hen94]	370	7,000	7	9.7

* pertaining to the arm, not the end effector

Table 4.7: Arm Manipulators for Use in Space

This thesis considers the grappling mechanism to be independent of the selected level of autonomy. The architecture model presents the arm sophistication in discrete levels as low, medium, and high in terms of its mass (see Table 4.8). A heavier grappler does not simply mean that a heavier satellite can be captured and moved but is also indicative of increased sensing capabilities and dexterity due to added arm segments, sensors, cameras, and other auxiliary equipment.

Grappler Sophistication	Grappler Mass [kg]	Capability Value
Low	300	0
Low	400	0.2
Medium	500	0.4
Medium	600	0.6
High	700	0.8
High	800	1

Table 4.8 Grappler Sophistication Levels

In Table 4.8, the low capability grappler weighing 300 kg is assigned a value of zero. This does not mean that it has no capabilities (it would not have been included in the tradespace if this was the case). A value of zero indicates the lowest *relative* value that can be assigned to a grappler; it corresponds to the lowest (but still valuable) grappling capability.

[5] http://spaceflight.nasa.gov/station/assembly/elements/mss/subsystems.html
[6] Ibid.
[7] http://www.esa.int/export/esaHS/ESAQEIOVMOC_iss_0.html

If a more detailed analysis is desired, various grapplers can be considered that differ in terms of number of arms, number of segments and joints of each arm (or, collectively, number of DOF), and number of end effectors (zero—then the arm is a "tentacle", one—it has a "hook," two—it has "claws," more than two—"fingers"). For reference, a mass of 300 kg is typical for small industrial robots [SSE94]. Figure 4.8 shows a basic comparison between a low and high capability grappling arms.

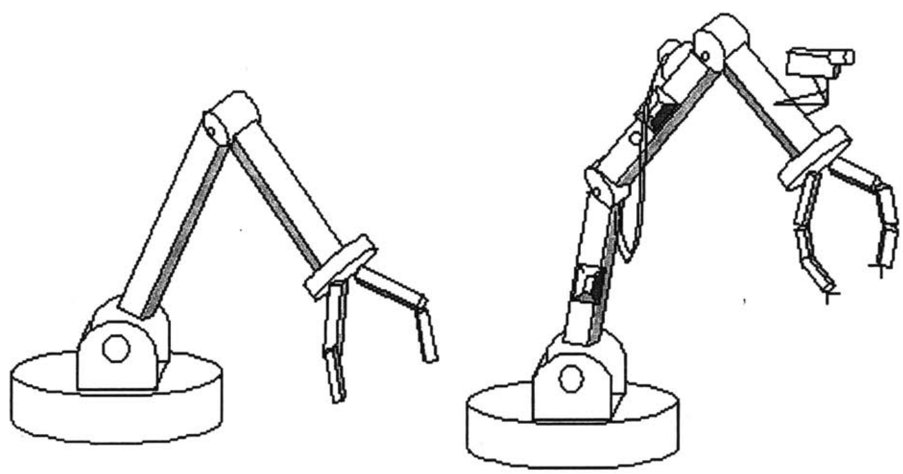


Figure 4.8: Grapplers of Different Capabilities

Please note that there are other, non-contact, ways of tugging a satellite. For example, new revolutionary concepts such as electromagnetic formation flying (EMFF), where vehicles fly formation based on actively generated and controlled electromagnetic fields are surfacing. However, the concepts are currently too speculative to be incorporated into a systematic space tug design.

4.2.2.3 Propulsion Type

Definition of terms

Fuel is a substance that burns when combined with oxygen, producing gas for propulsion. It stores chemical energy, which is transformed to kinetic energy.

Oxidizer is an agent that releases oxygen for combination with a fuel.

Mixture ratio is the ratio between the mass of oxidizer burned and the mass of fuel burned (liquid bipropellant motors only).

Propellant is the chemical mixture burned to produce thrust in rockets.

Thrust is the amount of force applied, based on the expulsion of gases.

Specific impulse (Isp) is the total impulse that the motor generates per unit of propellant weight. It indicates how many kilograms of thrust are obtained by the consumption of one kilogram of propellant in one second. The higher the specific impulse, the less propellant the motor uses to generate a certain total impulse, hence the higher the propellant efficiency.

There are a number of propulsion system options that can be considered, but some of them has been excluded from this analysis because they are either not well-developed (like water electrolysis, pulsed inductive, etc.) or are clearly inferior to the rest for the purposes of a space tug (like cold gas, solid propellant, or monopropellant). To alleviate the calculations load, only two types of chemical propulsion systems, one nuclear, and one electric have been analyzed as options. They are listed in Table 4.9, along with their specific impulses and assumed "speed" multiplication fractions.[8]

Propulsion System	**I_{sp} [sec]**	**Speed Factor**
Storable bipropellant	325	0.4
Cryogenic	446	0.4
Nuclear	1500	1
Electric	3120	0

Table 4.9: Propulsion System Choices

Chemical propulsion is said to be energy-limited because chemical reactants have a finite amount of energy per unit mass, which ultimately limits their achievable exhaust velocity or specific impulse (I_{sp}). However, the rate at which energy is supplied to the propellant is independent of the mass of propellant, therefore very high powers and thrust levels can be achieved. The problem is that even though a chemical system can have a high thrust-to-weight ratio, its propellant is quickly expended at a low Isp.

[8] Chemical propulsion systems can achieve exhaust velocities of about 4 km/s, nuclear—10 km/s, and electric-ion—0.1 km/s. Source: http://www.islandone.org/APC

Both types of chemical propulsion systems investigated in this thesis utilize liquid bipropellants. In a liquid propellant rocket, the fuel and oxidizer are stored in separate tanks and are fed through a system of pipes, valves, and turbopumps to a combustion chamber where they are combined and burned to produce thrust. A good liquid propellant is one with a high specific impulse (or a high speed of exhaust gas ejection). This implies a high combustion temperature and exhaust gases with small molecular weights. However, there is another important factor, which must be taken into consideration: the density of the propellant. The use of low-density propellants means that larger storage tanks will be required, which increases the mass of the spacecraft. Storage temperature is also important. A propellant with a low storage temperature, i.e. a cryogenic, will require thermal insulation, further increasing the mass of the craft.

Liquid bipropellants are classified as "storable" or "cryogenic" based on whether they remain liquid throughout the normal terrestrial temperature range or only at very low temperatures. In general, the advantages of liquid propellants include the highest energy per unit of fuel mass, variable thrust, and a restart capability. In addition to that, raw materials, such as oxygen and hydrogen, are in abundant supply and are relatively easy to manufacture. Disadvantages of liquid propellant rockets include requirements for complex storage containers, complex plumbing, precise fuel and oxidizer injection metering, high speed/high capacity pumps, and difficulty in storing cryogenically fueled vehicles.

Cryogenic Propulsion

The word "cryogenic" is a derivative of the Greek *kyros*, meaning "ice cold." Thus, a cryogenic propellant is one that uses very cold liquefied gases, such as liquid hydrogen (LH2) or liquid oxygen (LOX), as the fuel and the oxidizer. Storing and handling these fluids is difficult because LH2 is extremely volatile and flammable, and LOX is a very powerful chemical oxidizer [Smi01]. This is why they are less desirable for use in vehicles that must be kept launch-ready for months in advance. Handling cryogenics in orbit is also going to be a complex operation that necessitates constant awareness of the orientation of fuel tanks, acceleration vectors, and location of tank vents.[9] Additionally, LH2 has a very low density (0.59 pounds per gallon) and therefore requires a storage volume many times greater than other fuels (which, in turn, necessitates a larger launch vehicle). Moreover, liquid hydrogen must also be kept substantially colder than liquid oxygen. LOX and LH2 tanks have to be thermally isolated from each other, otherwise LOX will tend to freeze while LH2 will tend to boil[10] [Goe02]. Despite these drawbacks, the high efficiency of liquefied gases such as liquid hydrogen[11] and liquid oxygen makes these problems worth coping with when reaction time and storability are less important.

Nuclear Propulsion

The strength of nuclear propulsion is that it is more efficient than chemically propelled spacecraft. Nuclear thermal engines employ a very compact mass of nuclear fuel (typically H_2) to release tremendous amounts of energy that is used to heat lightweight hydrogen gas and release it through a nozzle to get thrust. The nuclear reaction heats the hydrogen to produce much higher velocities than the velocities attained via chemical combustion, and high Isp can be achieved with low thrust. Thus, for a given amount of propellant, the space tug can either carry a lot more payload (i.e. heavier grappler and sensors) or, for the same amount of payload, it can travel faster to the desired destination. Another option is for the space tug to carry the same payload and travel at the same speed as a chemically propelled tug, but that it weigh a lot less[12] and use a smaller launch vehicle. Please note, however, that there is a fixed lower bound limit of the nuclear propulsion system mass, when scaling it down.

During the 1950s and 1960s, NASA spent over $10B to build the nuclear rocket program. The program was eventually cancelled because of fear that a launch accident would contaminate major portions of Florida and beyond. Since the 1960s, there have been eight space nuclear power accidents by the U.S. and the former Soviet Union, several of which released plutonium into the Earth's atmosphere. After a 30-year shutdown of plans for the nuclear rocket, the Bush administration has resuscitated the

[9] http://www.asi.org/adb/04/03/09/storing-cryogenics-0g.html
[10] LOX remains in a liquid state at temperatures of –183° C, while LH2 remains liquid at – 253° C.
[11] Liquid hydrogen delivers a specific impulse about 40% higher than other rocket fuels [Bra96].
[12] A nuclear thermal rocket engine uses approximately 50% less propellant mass than the theoretically best chemical engine [KT99].

technology by giving NASA nearly $1B over the next five years to expand its nuclear propulsion research and development program. [Gag03]

Electric Propulsion

Unlike chemical propulsion systems, electric ones are typically not energy limited, and an arbitrarily large amount of energy can be delivered from the external solar or nuclear power source to a given mass of propellant so that the exhaust velocity or Isp can be an order-of-magnitude larger than that of chemical systems. Electric propulsion systems, however, are power-limited because the rate at which energy from the external source is supplied to the propellant is proportional to the mass of the power system. Typical values for the whole power system (power supply, converters, thrusters) of an electrically driven vehicle are about 30 kg/kW for contemporary systems and a predicted 10 kg/kW for advanced systems. This has the result of limiting the thrust of the electric propulsion system for a given spacecraft mass. Nevertheless, even though electric propulsion vehicles are low thrust-to-weight ratio, they can build a large total impulse and operate for hours to years. Since the Isp (~3000 sec) is higher than that of conventional chemical systems, a given payload can be delivered to its operational orbit using a fraction of the propellant that would be used for chemically propelled systems. [LFB97]

Artemis Example. On 12 July 2001, Ariane 5's supper stage malfunctioned and left ESA's telecommunications satellite Artemis (which stands for Advanced Relay and Technology Mission) in a lower-than-intended elliptical orbit with an apogee of only 17,487 km, far short of the 35,853 km required for the targeted geostationary transfer orbit. Using almost all of its chemical propellant, Artemis managed to escape this orbit (where it had to contend with the destructive Van Allen radiation belts) and reached a circular orbit at an altitude of 31,000 km only a few days after launch. Since then (February 2002), rescue efforts have continued using the satellite's four ion engines, originally designed only to control the satellite's inclination and correct its orbit drift. At an average speed of 15 km a day, Artemis rose in spirals towards geostationary orbit, which it finally reached in February 2003. [SD03]

4.2.2.4 Parking Location

A parking orbit is a temporary orbit that provides safe and convenient location for the tug as it waits to be assigned a mission. Three parking options are considered: 1) on the ground, 2) in the populated zone of intended operation, or 3) in LEO, not in a designated orbital zone of action.

Ground

One advantage of parking a tug on the ground is that no fuel will be spent for station keeping. Also, the risk of damage by micrometeorite or space debris is eliminated. Ground parking is the best option for scenarios in which the potential target location is unknown (the Satellite Rescuing scenario is one example). It minimizes the required plane changes and the distance to the target that needs to be traveled, provided the selected launch vehicle possesses sufficient lift capabilities. Another significant advantage of this parking location is that it supports *adaptability*: the optimal grappling mechanism can be selected and attached to the tug prior to launch. It should be noted, however, that while tug operational costs are minimized, maintenance costs are maximized, since the tug might wait on the ground for a long time. The other main disadvantages are that a launch vehicle needs to be available and a launch window must exist. The time a tug should be launched depends on the launch site's latitude and longitude and the tug's desired inclination and right ascension of the ascending node. For a launch window to exist, the launch site must pass through the orbital plane. This requirement restricts the inclination (i) that can be achieved from a given launch latitude (L) [WL99]:

- No launch window exists if $L > i$ or $180° - i$.
- One launch window exists if $L = i$ or $180° - i$.
- Two launch windows exist if $L < i$ or $180° - i$.

The choice of optimal launch vehicle is another key issue. The most influential factors are launch vehicle cost, location density of potential targets, and launch site longitude and latitude. The objective is to find the least expensive vehicle that has the capability to reach an orbital region that is densely populated by potential targets.

In summary, parking a tug on the ground favors *mating capability* and *adaptability*, but may not be the optimal choice in terms of *timeliness*. *Transfer capability* is not significantly influenced by this option. In scenarios where a tug is intended for use in several missions, ground should only be the initial parking location.

Target zone

Target orbital zones for each scenario can be identified as described in Chapter 3. If a tug is parked in such a zone, it might be required to make a plane change, but it will be very small, due to the size restrictions of the orbital zone (see Section 3.2). Similarly, the distances that would need to be traversed will also not be an issue, although a set of Hohmann transfers might be needed to synchronize the true anomalies of the tug and the target.

Depending on whether maintenance cost is expected to exceed operational costs that occur while the tug awaits mission assignment, there are two options for launching the tug in this parking orbit: 1) tug is launched in the zone after its services are requested, or 2) the tug is inserted into the zone in advance (to save money that would otherwise be spent for maintenance on ground).

Parking a tug in the orbital zone of its intended operation favors *timeliness* and *transfer capabilities* (this corresponds to the plus signs in the respective column of Table 4.3). The tug's grappling mechanism should be optimized for capturing the satellites in the targeted orbital zone, so *mating capability* should be sufficiently high for the majority of potential targets. *Adaptability*, however, is expected to be difficult, especially if the new scenario is too different from the initially intended one (i.e. requiring the use of a very different grappler or the travel to a distant location).

LEO

Parking a tug in Earth orbit but outside an identified target zone of operation can be selected if the tug has universal capabilities and is intended to perform a variety of missions that require trips from LEO to GEO or within LEO. In this case, it is best to select the parking location to be in a LEO orbit that is high enough to reduce the effect of atmospheric drag yet low enough to be accessible by an inexpensive launch vehicle. A great advantage would be if the parking location were accessible to astronauts for repair or refueling of the tug. If this is not possible, both plane change and distance to target may present a serious problem, therefore advanced propulsion would be a necessity.

4.2.3 Parameters, Constraints, and Assumptions

Parameters

Unlike design variables, parameters are variables that the designer cannot control and which affect all architectures in the same way. The parameters in this research are assumed to be the expected revenues from properly functioning satellites, the market demand and its associated uncertainty, and the potential customers.

Constraints

There are two kinds of design constraints: *input constraints*, which are constraints in design specifications, and *system constraints*, which are constraints imposed by the system in which the design solution must function. The input constraints are usually expressed as bounds on size, weight, material, and cost[13], whereas the system constraints normally concern software and hardware capacity and interfacial bounds such as geometric shape [Suh90]. In the case of a space tug, obvious design constraints are the maximum dimensions and mass of the tug, which are dictated by the payload bay fairing size and lift capabilities of available launch vehicles, unless the tug is fabricated in modules that to be assembled in space. In addition to that, the customer can impose constraints on the maximum response and transfer time, the damage done on the tugged satellite, the minimum mass the tug will be able to capture and move, the overall cost, the minimum hardware and software capabilities, etc.

4.2.4 Cost Estimation

Before attempting to answer the question of how expensive tugging services should be, the total cost of a tug mission must be estimated. The total cost is a sum of the following components:

[13] In our model cost is an output.

$$C_t = C_u + C_p + C_l + C_i + C_o + D \qquad (4.5)$$

where C_u is the tug unit cost (it includes the non-recurring tug development costs), C_p is the propellant cost, C_l is the launch cost, C_i is the insurance cost, C_o is the cost of tug operation, and D is the depreciation of the tug. All cost estimations are done with numbers converted to FY03.

4.2.4.1 Design and Production Cost

The NASA Spacecraft/Vehicle Level Cost Model provides a rough cost estimate of development and production of a spacecraft based on its dry mass (M_d). Since this 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. Its total cost is $180M[14] and it weighs 630 kg. Hence, its cost per kilogram is $285,714.29. This number is multiplied by the assumed grappler mass to obtain an estimate of its total cost. To account for the difference in sensing capabilities utilized by different tug architectures, we add the following sensor capability costs: $5,000 of any low capability sensing, $10,000 for medium, and $50,000 for high. These numbers were assumed based on a large database compiled by the Robotics Institute of Carnegie Mellon University.[15] Lastly, referencing the current annual salary listings reported by the Federal Government's Office of Personnel Management,[16] the labor cost paid for the creation of the software needed to operate the arm is calculated using the following numbers[17]:

[14] http://home.comcast.net/~issguide/1994news.html
[15] http://www.frc.ri.cmu.edu/robotics-faq/10.html#10.1
[16] http://www.opm.gov/oca/PAYRATES/INDEX.asp
[17] A normal software design team consists of six programmers and one manager

Autonomy Level	Telepresence	Supervision	Full Automation
Coding [yr]	1	3	5
Software Engineers [#]	6	6	10
SE Annual Salary [$]	71,250	101,000	150,000
Software Team Managers [#]	1	1	1
STM Annual Salary [$]	78,500	110,000	150,000

Table 4.10: Software Design Cost, FY03
(SE = Software Engineer, STM = Software Team Manager)

4.2.4.2 Propellant Cost

The propellant cost is estimated by multiplying the mass of the necessary fuel and oxidizer by their specific costs measured in $/kg and adding up the results. Table 4.11 gives the cost per kilogram for various propellants and oxidizers paid by NASA in the 1980's (inflation was adjusted to FY2003 in the cost model):

Name			Density [g/cm3]	Cost [$/kg]
Fuel	RP-1	rocket prolellant-1[18]	0.81	0.20
	LH2	liquid hydrogen	0.07	3.60
	N2H4	monopropellant hydrazine	1.01	17.00
	MMH	monomethyl hydrazine	0.88	17.00
	UDMH	unsymmetrical dimethyl hydrazine	0.79	24.00
	NH3	amonia	0.60	0.08
Oxidizer	LOX	liquid oxygen	1.14	0.08
	N2O4	nitrogen tetroxide	1.45	6.00
	LF2	liquid fluorine	1.51	6.00
	H2O2	hydrogen peroxide	1.44	2.00
	ClO3F	perchloryl fluoride	1.43	30.00[19]

Table 4.11: Propellants Cost [EA03]

[18] RP-1 is a special grade of kerosene-like hydrocarbon.
[19] This was the price for small commercial quantities. Only $3.30 was charged if 5 million kg were bought per year.

4.2.4.3 Launch Cost

Launch cost can be calculated by taking the average cost per kilogram for all launch vehicles capable of carrying a tug to its desired destination. Table 4.12 lists the capacity and price of the launch vehicles considered in this research.

Class	Vehicle Name	Country	Inclination [deg]	LEO Alt. [km]	LEO Cap. [kg]	LEO Cost [$/kg]	GTO Cap. [kg]	GTO Cost [$/kg]
Small	Athena 2	USA	28.5	185	2,065	11,622	590	40,678
	Cosmos	Russia	62.7	400	1,500	8,667	0	-
	Molniya	Russia	62.7	N/A	1,800	N/A	1600	
	Pegasus XL	USA	28.5	185	443	30,474	0	-
	Rockot	Russia	62.7	300	1,850	7,297	0	-
	Shtil	Russia	77-88	200	430	465	0	-
	START	Russia	51.8	200	632	11,687	0	-
	Taurus	USA	28.5	185	1,380	13,768	448	42,411
	Titan 2	USA	34.6	N/A	1,900	8,023	0	-
Medium / Intermediate	Ariane 44L	Europe	5.2	200	10,200	11,029	4,790	23,486
	Atlas 2AS	USA	28.5	185	8,618	11,314	3,719	26,217
	Atlas 3	USA	28.5	185	10,764	8,477	4,500	
	Delta 2	USA	28.5	185	5,144	10,692	1,800	30,556
	Delta 4	USA	28.5	185	11,475	6,250	6,565	19,180
	Dnepr	Russia	46.1	200	4,400	3,409	0	-
	Long March 2C	China	37.8	200	3,200	7,031	1,000	22,500
	Long March 2E	China	37.8	200	9,200	5,435	3,370	14,837
	PSLV	India	N/A	N/A	3,700	N/A	800	N/A
	Soyuz	Russia	51.8	200	7,000	5,357	1,350	27,778
Heavy	Ariane 5G	Europe	5.2	550	18,000	9,167	6,800	24,265
	Atlas 5	USA	28.5	185	12,500	6,008	7,640	14,991
	Long March 3B	China	28.5	200	13,600	4,412	5,200	11,538
	Proton K	Russia	51.6	200	19,760	4,302	4,630	18,359
	Proton M	Russia	51.6	200	21,000	4,048	6,190	13,732
	Space Shuttle	USA	28.5	204	28,803	10,416	5,900	50,847
	Titan 4	USA	28.5	N/A	20,822	9,900	8,276	24,908?
	Zenith 2	Ukraine	51.4	200	13,740	3,093	0	-
	Zenith 3SL	Multinat.	0	200	15,876	5,354	5,250	16,190

Table 4.12: Launch Vehicles Data [Fut02b]

As seen from Table 4.12, non-Western (i.e. Chinese, Russian, and Ukrainian) launch vehicles cost less than their Western counterparts (American and European) due to lower labor and infrastructure costs. Table 4.13 compares the average prices per kilogram for both.

Vehicle Class	LEO		GEO	
	Western	Non-Western	Western	Non-Western
Small	41,045	15,591	91,573	N/A
Medium/Intermediate	24,273	11,697	58,969	47,840
Heavy	21,579	9,458	82,779	33,861

Table 4.13: Average Price per Kilogram for Western and Non-Western Launch Vehicles [Fut02b]

If the provider of the tugging services is a commercial organization, it will be able to purchase any of the above listed vehicles except the Shuttle and Titan, which are not available for commercial use. If the tug owner is a government agency, it might be required to launch its tug on a domestic vehicle, as is the case for the United States.

When selecting a launch vehicle, the choice of launching the tug as a primary or a secondary payload must be considered. Although secondary and ride share options cost less, they have several constraints. They offer no control over launch time or orbit selection; there might be long periods of waiting on Earth until the primary payload is ready; the cost is not necessarily inexpensive.

4.2.4.4 Insurance Cost

This section discusses the insurance of the space tug (not the client satellites). A tug failure can occur during an orbital transfer or while capturing a satellite. We can assume that an insurance claim would be valid in all cases when the tug fails to transfer the satellite to its desired destination, regardless of the actual distance the satellite has been moved. What does affect the insurance rate (and hence the claimed returns) is the failure's impact on the tug's revenue-generating ability. In other words, the value of the claim depends on how long the tug had been operational at the time the failure occurred.

A brief description of the various insurances from pre-launch to end-of-life of the tug follows.

The first type of insurance that can be purchased by the tug operator is "transit and pre-launch" insurance. It covers any significant damage or delay from launch (of the order of 2-3 months). The premium rates are about 0.5% of the spacecraft cost. A second type—the "launch and early phase" insurance—covers failures that occur between lift-off and commissioning (the placement of spacecraft in operational orbit and subsystem confirmation). The most typical failures covered by this insurance are launch failure, failure of kick motors, and deployment failure. According to some sources, the premium rate is usually between 16% and 21% of the spacecraft cost (split between 9-13% for launch and 8-11% after separation) [El100]. Other sources state that the cost of launch insurance is actually associated with the reliability of the selected launch vehicle. For example, using a vehicle with an 85% reliability results in a launch insurance rate of 30%, whereas launching a vehicle that has a reliability of 99% reduces the insurance rate to 15% [GG88]. 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 onward. The early orbit phase covers and provides for the replacement and re-launch of the tug, its loss of revenue, and fulfillment of contractual obligations. The total and partial loss coverage is normally between 1.75% and 4% of the satellite 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 [El100].

4.2.4.5 Operational Cost

The tug's operational cost is estimated based on the following assumed annual salaries of a ground crew employed to operate or supervise the tug missions:

Autonomy Level	Telepresence	Supervision	Full Automation
Tug Operational Life [yr]	10*	10*	10*
Teleoperators [#]	5	3	0
TO Annual Salary [$]	70,000	50,000	0
Teleoperations Managers [#]	1	1	0
TOM Annual Salary [$]	98,500	78,500	0

*10 years is assumed to be the design life of a reusable tug. The tug modeled in the satellite rescuing scenario is not reusable, and we assume it will operate for no longer than a month.

Table 4.14: Rough Teleoperations Cost
(TO = Teleoperator, TOM = Teleoperations Manager)

4.2.4.6 Depreciation

As the tug is used over a period of time, its value will fall. 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.[20] The most popular techniques for estimating depreciation are the straight-line method and declining balance method. The straight-line method 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:

$$D = \frac{C_a - Vr}{Y} \tag{4.6}$$

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). In contrast, the declining balance method assumes that the asset depreciates more in the earlier years. To achieve this pattern of depreciation, a fixed annual depreciation percentage is applied to the written-down value of the asset. Thus, depreciation is calculated as a percentage of the reducing balance. It should be noted that, whichever method of depreciation is selected, the total depreciation to be charged over the useful life of a fixed asset would be the same. The straight-line method may often be

[20] http://www.investorwords.com

chosen simply because it is easy to understand and calculate. Only the allocation of the total depreciation charge between accounting periods is affected by the choice of method.[21]

4.2.4.7 Cost Uncertainty Margin

Due to the difficulties in estimating the cost of tugging missions (see Section 2.2), the maximum fee that would make tugging economically interesting must be evaluated as a function of cost uncertainty. Since the assumption of an uncertainty margin is itself difficult to justify, a set of numbers will be used instead to show the sensitivity in regard to miscalculated costs.

4.3 Phase III: Evaluating the Architectures

Following the MATE process, the costs of hundreds of different tug architectures are evaluated against the users' utilities to understand which systems best satisfy customer needs. The result is collectively referred to as the design tradespace. The architectures characterized by a minimum cost per function (i.e. total cost divided by total utility) represent the optimal designs. This cost per function (CPF) metric is the criterion used for selecting the best tug architectures.

4.3.1 Main Assumptions

The following is a summary of the major assumptions applied to the space tug model:

1. The tug has universal capture capability; it can capture any spacecraft.

This part of the space tug research does not discuss the technical issues associated with rendezvous and capture of a target satellite, but assumes it is technically feasible.

2. The grappling mechanism is 65% of the total dry mass of the tug.

[21] http://www.tutor2u.net/business/accounts/assets_fixedassets_depreciation.asp

3. If commercially owned, the tug can be launched on any launch vehicle, US or foreign, that is normally associated with commercial payloads.

US and Western launch vehicles are in general more expensive then their Eastern counterparts. Thus, if the tug were owned by a Western company, restricting the options, for example, to only American launches would raise the minimum fee requested for tugging, making the service less attractive to potential customers.

4. The NASA Spacecraft/Vehicle Level Cost Model[22] is used for cost estimation.

Derived from the NASA/Air Force Cost Model (NAFCOM) database, this on-line model provides a quick, although rough, order-of-magnitude estimation of the development and production cost of an Earth-orbiting unmanned spacecraft. Learning curves are applied if more than one tug is built.

5. Following Larson and Wetz's [LW99] guidelines, a TRL uncertainty of 40% is added to the cost estimations of developing and building a fully autonomous tug, 10% to a tug with a supervisory autonomy level, and 0% for a teleoperated tug.

6. A delta-V of 20 m/s is required for capture or release of client satellites (i.e. for proximity operations).

7. If reusable, a tug has a design life of 10 years.

This assumption is used when accounting for the annual depreciation rate of the tug vehicle.

8. The clients will accept the service if it is expected to provide any additional profit that is greater than zero.

9. Taxes (federal, etc.) and interest are not accounted for when calculating profit.

10. Table 4.25 lists the weights that were assumed when calculating the total utility function. The design variables used for the estimation of each attribute are also listed together with their assumed relative importance.

[22] http://www.jsc.nasa.gov/bu2/SVLCM.html

Mating Capability	***0.4***
Grappler Sophistication	0.5
Autonomy Level	0.5
Transfer Capability	***0.2***
Propulsion Type	0.9
Autonomy Level	0.1
Timeliness	***0.2***
Propulsion Type	0.8
Parking Location	0.2
Adaptability	***0.2***
Autonomy Level	0.1
Grappler Sophistication	0.3
Propulsion Type	0.4
Parking Location	0.2

Table 4.15: Utility Weights

Uncertainty and Risk

There is *uncertainty* in a mission if one or several future mission parameters cannot be predicted exactly. If the uncertainty can have negative outcome, it is called *risk*. For example, there is a risk that the functionality of a moved asset can be degraded due to a damage inflicted by the tug during the capture, transfer, or release phases. Accounting for the risk in a mission is very important because people might agree to have space tugs approach, grapple, and transfer their satellites only when the risks of failure have been quantified. Of course, the risk tolerance of various stakeholders can differ. Nevertheless, creating even a rough but logical uncertainty model increases the credibility of the space tug design model. The challenge arises from the fact that it is impossible to predict what exactly is going to happen, when it is going to happen, and to what degree it will affect the tug's service. Table 4.16 lists the uncertainty factors that were assumed and included in the utility calculations of this thesis. A risk of 1 corresponds to minimum risk. Risk is assumed driven primarily by complexity; the greater the complexity of a mechanism, the greater the potential risk of failure. Mission criticality is also considered in the uncertainty analysis. Capabilities like signal processing for telepresence, planning and scheduling for full automation, and situation assessment and implementation for all types of autonomy are mission critical. Their utility has been decreased by an additional factor of 0.8 because they would doom the mission should they fail. The rest of the capabilities will also affect the mission but to a much lesser extent.

TRL Uncertainty Factor	
Telepresence	1
Supervision	0.9
Full Automation	0.6
Sensor Failure Risk Factor	
Low Complexity	1
Medium Complexity	0.9
High Complexity	0.8
Mission Critical Capability Failure Factor	
Critical Capability	0.8
Non-critical Capability	1
Grappler Failure Risk Factor	
300 kg	1
400 kg	0.9
500 kg	0.8
600 kg	0.7
700 kg	0.6
800 kg	0.5

Table 4. 16: Uncertainty and Risk Factors

4.3.2 Pareto Front and Architecture Selection

Many practical problems are characterized by more than one objective, and these objectives are often competing. Unlike single-objective optimization, which results in a single, easily identified solution, multiobjective optimization leads to a number of optimal design trade-offs, forming the Pareto optimal set. These architectures are non-dominated, i.e. there are no other solutions that would decrease some criterion without causing a simultaneous increase in at least one other criterion. The plot of the objective functions whose non-dominated vectors are in the Pareto optimal set is called the Pareto front. On the cost versus utility plot (Figure 4.9), these desirable designs are down (low cost) and to the right (high performance).

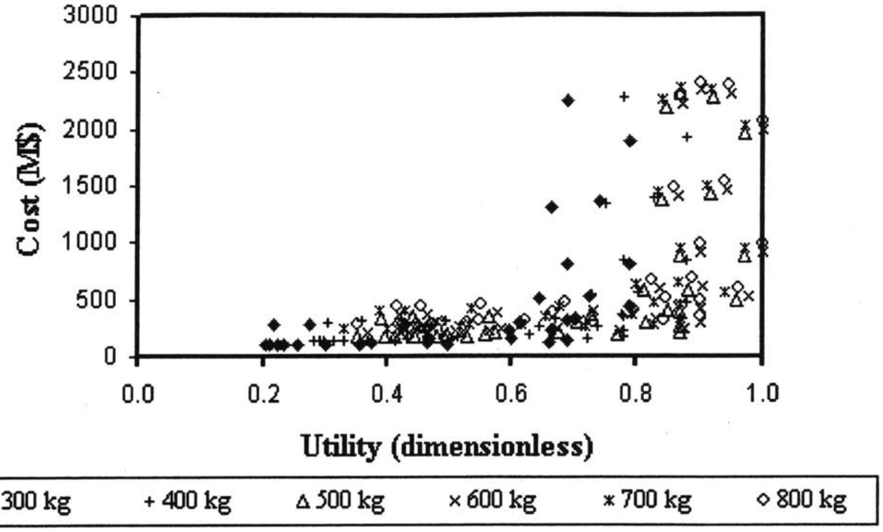


Figure 4.9: Space Tug Tradespace with Capability Indicated[23] [MS03]

The single architecture that will be selected as optimal for a given space tug mission scenario will be chosen from the Pareto set and will be associated with the smallest minimum fee that can be charged for tugging.

4.3.3 Sensitivity Analysis

Both mission and design uncertainty need to be addressed when modeling a space tug and its operations. Uncertainty exists in terms of change in demand, customers, tug capabilities, correctness of supplied target data (coordinates and description), sensor capabilities, validity of cost margin and other assumptions, and so on. Sensitivity analysis is performed for the selected space tug designs to ensure robustness to problem assumptions and fixed parameters. Here, we perform sensitivity analysis by varying a single parameter at a time and holding the rest constant. It should be noted that although this simplifies the work, it ignores the non-linear couplings that might exist between the system parameters.

[23] The following weights were assumed for this plot: 0.6 for transfer capability, 0.3 for mating capability, 0.1 for timeliness, and 0 for adaptability.

4.4 Phase IV: Fee Estimation

This section suggests a generic approach for calculating the fee that should be charged for tugging. However, before we attempt to estimate the optimal fee for a given mission scenario, we need to understand the market trends in the satellite industry.

4.4.1 Market Analysis

This work does not attempt to quantify the uncertainties in prices and demand, and it does not intend to produce its own predictions. Instead, the analysis is based on the statistical and forecasted trends provided by some of the leading aerospace consulting companies, adopting the most conservative numbers, since, historically, predictions have proven to be over-optimistic.

The *State of the Space Industry*, for example, provides a top-level overview and forecast of the trends that influence current and future growth of the space industry. Among the trends cited in its 2002 annual report are:

- The military's growing reliance on space;
- The *end* of the late 1990's boom market for commercial satellites and launchers;
- Consolidation and privatization of satellite operators;
- Anticipated changes and strategy shift in NASA as it undergoes new leadership;
- U.S. export licensing;
- The emerging of new business opportunities such as real-time monitoring of flight data from aircraft and the use of imagery and GIS (Geographic Information System) for disaster management, planning, and recovery. [Sac02]

The Price Mechanism

The price mechanism is the product of a market economy in which consumers and producers exercise freedom of choice within the market: buying or not buying, selling or not selling. It describes the system by which prices adjust themselves to the pressure of supply and demand and operate to keep supply and demand in balance. The price of a product or service reflects change in the requirements of consumers (i.e. demand) or change in the obstacles to supplying them (i.e. supply), putting simultaneous pressure on the whole body of producers and consumers to modify their plans and their behavior in the direction that is appropriate given the new degree of scarcity or abundance [CS82].

4.4.1.1 Supply and Demand

The *Law of Demand* states that when the price of a good or service increases, all other things being equal, people tend to buy less of it; conversely, when prices decline, all other things being equal, people tend to buy more. There are two main reasons for this trend. First, an increase in the price of an item means that it has become more expensive relative to its competing products. The availability of these "substitutes" (i.e. the competing goods) drives, to a great extent, the amount consumers are willing to substitute by buying these less expensive alternatives. If the product does not have good substitutes that are also cheaper, consumers are expected to be less sensitive to the price increase. A second reason why people tend to buy less when price increases is that the purchasing power of their money is reduced. This means that the consumers' dollars do not buy as much quantity of the product or service as before. The phenomenon depends largely on the budget portion devoted to the product under consideration. If consumers spend a large share of their budget on a given product and its price significantly increases, many people will choose to purchase less of that product [Pet77]. For example, if the price of satellite insurance doubles, many satellite owners might decide to buy only partial insurance (full spectrum of satellite insurances is listed in Section 4.2.4.4). On the other hand, if the price of a particular sensor increases, the general spending trends will probably not be affected since not many consumers spend a large share of their budget on that particular sensor.

Unless mistaken or forced, no consumer will buy something unless the consumer expects to benefit from this purchase. The demand for tugging services varies based on economic conditions (state of aerospace economy in general and cost of tugging), success rate of tug missions, and other factors. *Price elasticity of demand* is defined as the percent change in quantity demanded resulting from a 1% change in price. The actual price elasticity of demand for a good or service is determined by two factors [Pet77]:

1. The share of the item in the overall budget of consumers.

If an item has many good substitutes, it will have a relatively large elasticity coefficient. This means that if its price increases, people will be able to switch to lower-priced substitutes. As a result, the percentage change in quantity for a 1% change in price would be relatively large.

2. The quality and number of substitutes available.

4.4.1.2 Competing Options

In general, the options with which an on-orbit servicer must compete are: sending astronauts to capture a satellite and repair it or bring it back to Earth (EVA); moving a satellite using its own propulsion, which may be followed by the launching of a new (replacement) satellite; leaving the satellite where it is (abandoning), which also may be followed by the launching of a new satellite to perform the mission the old one was not capable of performing. For mission scenario in GEO, extravehicular activity is not applicable because it is confined to low inclination LEO ($i = 28.5^{o}$ and $e \approx 0$) or ISS (51.6^{o}) orbits. Besides availability, other disadvantages of this option are its timeliness and cost. There is usually a long lead time between satellite failure and the contingency repair operation due to the need of extensive preparations and launch schedule contracts. The first Hubble Space Telescope repair mission, for example, occurred 3.5 years after the launch of the telescope. Additionally, servicing performed by the Shuttle is so expensive that only very high-value assets (such as Hubble) are targeted. The costs of a Space Shuttle mission are between $245M and $1B, being strongly dependent on astronaut training and other variable factors. For instance, astronauts trained for 400 hours in the neutral buoyancy tanks at Marshal Space Flight Center and Johnson Space Center in preparation for the first HST repair. The mission total cost was about $700M. [El102]. Although humans have proven useful in space repairs, EVAs do expose astronauts to a number of potential hazards. Furthermore, using astronauts as repairmen is not an effective utilization of resources.

4.4.1.3 Satellite Industry Overview

The satellite industry is rapidly evolving from being dominated by government and military activities to experiencing dramatic growth in commercial arenas. Table 4.17 shows the statistical and projected revenues for space transportation, satellite communications, global positioning system (GPS), and remote sensing. As seen, satellite communications represent the largest and fastest growing segment of the space industry.

	1996	1997	1998	1999	2000	2001*	2002*
Sat. Communications	35.33	45.46	56.10	60.52	67.57	77.74	88.69
Space Transport	4.89	5.65	5.49	5.65	5.39	7.04	6.60
GPS	4.44	5.43	6.73	8.15	9.62	11.02	12.40
Remote Sensing	0.10	0.12	0.14	0.15	0.17	0.20	0.23
Total	*44.76*	*56.66*	*68.46*	*74.48*	*82.75*	*96.00*	*107.92*

*predicted

Table 4.17: World Revenues in US $B [Fut01]

Table 4.18 lists the number of world commercial and civil government (i.e. non-military) launches between 1996 and 2002.

	1996	1997	1998	1999	2000	2001*	2002*
Commercial	24	36	36	36	27	39	47
Civil Government	23	19	21	22	28	33	21
Total	*47*	*55*	*57*	*58*	*55*	*72*	*68*

*predicted

Table 4.18: World Commercial and Civil Government Launches [Fut01]

The corresponding trends for the United States only are shown in Table 4.19.

	1996	1997	1998	1999	2000	2001*	2002*
Commercial	9	16	17	13	4	16	18
Civil Government	9	5	10	9	9	9	7
Total	*18*	*21*	*27*	*22*	*13*	*25*	*25*

*predicted

Table 4.19: US Commercial and Civil Government Launches [Fut01]

Table 4.20 lists the number of worldwide commercial launches in terms of payload owner region. It indicates that most potential customers for tugging services are likely located in the United States, Russia, or Europe.

	1996	1997	1998	1999	2000
N&S America (non US)	2	0	2	1	1
Asia/Oceania	6	7	2	6	3
Africa/Middle East	2	0	0	2	2
Europe	4	5	8	4	7
United States	10	24	24	23	14
Total	*24*	*36*	*36*	*36*	*27*

Table 4.20: Commercial Launches by Payload Owner Region [Fut01]

Most commercial launches go to GEO. Launch providers began offering commercial launches to low Earth orbits in 1997. The surge in the non-GEO launches between 1997 and 1999 is due to the deployment of Iridium and Globalstar.

	1996	1997	1998	1999	2000
GEO Launches	22	23	19	18	20
Non-GEO Launches	2	13	17	18	7
Total	*24*	*36*	*36*	*36*	*27*

Table 4.21: Worldwide Commercial Launches by Orbit [Fut01]

While the worldwide number of GEO launches remained steady at an average of 21 launches per year, the United States experienced a decline in 1999 and 2000 due to delays in the Delta 3 program.

	1996	1997	1998	1999	2000
GEO Launches	7	7	7	4	3
Non-GEO Launches	2	9	10	9	1
Total	*9*	*16*	*17*	*13*	*4*

Table 4.22: US Commercial Launches by Orbit [Fut01]

Along with the addition of commercial launches to LEO, the launch vehicles from the former Soviet Union and China increased worldwide commercial capacity and competition. Another trend affecting the space transportation market is the fact that satellites are becoming larger and heavier, especially commercial communications satellites, since more power and transponders are being added. In response to that, most launch service providers now offer upgraded vehicles to accommodate larger and heavier spacecraft.

4.4.2 Fee Estimation Approach

The fee charged for tugging must be affordable to potential customers, but it must also justify the resources spent by tug owners/operators. In other words, employing a tug should never result in negative total profits (i.e. combined profits of all missions performed by the tug) both for the client and for the provider of the service. Before we propose a way for estimating what the charged fee should be, it is important to determine whether it is better to charge a fixed fee or a percentage of the additional revenue generated by the satellite owner. The problem with selecting a fixed price is that it will be overly affordable for some operators and prohibitively 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 every satellite operator, there still exists a risk that something would go wrong with the satellite during the extended period of work, preventing the expected revenue from being realized. In short, there is a vast uncertainty as to whether the investment will pay off; therefore it is 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 satellite operators. ***We recommend that the tug operator charge a certain percentage of the revenue resulting from the life extension of the client satellite.*** As commonly done in most businesses, the fee should be prepaid based on preliminary estimations and then adjusted upon satellite retirement, using actual revenue figures. If a failure affecting the revenue flow occurred after the contract has been signed, the client would be required to pay only a set minimum fee that corresponds to zero profit for the provider.

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

1. Calculate the utility of various architectures differing in terms of propulsion type, autonomy level, grappling mechanism, and parking location.

2. Using NASA's Spacecraft/Vehicle Level Cost Model and accounting for the cost of fuel, launch, operations, 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 affordability per cost.

4. Calculate the maximum profit expected by the satellite operators.

5. If the tug is owned by a commercial organization, find the "mid-way" fee that would give the tug operator and the satellite operators the same profit. If the tug is owned by a governmental organization, a nominal fee should be paid that would be affordable to the great majority of clients.

6. Perform a sensitivity analysis to identify the major factors affecting the calculations.

4.5 Phase V: Family Deployment

As discussed in Chapter 3, the idea of creating a universal space tug is not yet feasible, due to technological and financial complications. Instead, designing a family of modular tugs would provide the necessary flexibility for covering all possible mission scenarios. This concept can significantly reduce the risk associated with budget, schedule, and operational failure.

Programs are often being cancelled because they have exceeded their assigned schedule and budget constraints. Sometimes, this is not a result of faulty design process but is due to unrealistic schedule and cost estimates in the first place. In other cases, the constraints are being strictly followed but an external event, such as the occurrence of a Congress budget cut (if a government project) before completion of the design. In either case, the result is the same—the project is aborted, and the spent time and resources are entirely wasted. This has happened to all space tug programs in the past and is the major reason why there are still no tugs in space.

In order to not fall into pit holes encountered in the past, precautions must be taken to minimize the debilitating effect of adverse events on budget and schedule. The staged deployment of a family of tugs would minimize these risks. Even if budget constraints do not allow the deployment of the entire family in its optimal configuration, parts of it (entire tugs or only modules) could still be launched and used.

Evolvability of complex systems such as a space tug is difficult to design for. Derived from the viewpoint of expandability and upgradability, the idea of *modularity* for the space tug family can reduce the number of potential problems. While a special attachment may be added in the future to allow for more diverse and demanding applications, the emphasis on a much simpler bus design is a key aspect of the tug's smaller size, significantly lower cost, and faster development schedule.

The reliability of the first tug must be extremely high because a failure might indefinitely postpone future space tug launches. Both the development and the deployment of the family of tugs must be well sequenced. Careful provisions must be made in both hardware and computer software to accommodate future features so that additional capability can be built. This can save expensive restructuring of the software and hardware when additional capability is needed. The key is to embed the incremental development in every subsystem of the space tug. For example, if a tug uses electric or nuclear power, we would want its reactor to be scalable. On-board software must also evolve as mission goals change or expand. The tug's sensing capabilities must evolve smoothly towards greater autonomy and complexity. The progression should be in the following order:

1. Total human control should be exercised at the start until more is learned about the environment in which the tug operates and a good understanding of the encountered situations and problems is achieved.

2. Partial control should be given to the on-board software under the close supervision of a teleoperator to see how well autonomy algorithms work.

3. Semi-autonomous control should gradually be increased in order for it to be tested. If necessary, the ground operator could override decisions.

4. When all observed defects have been fixed, supervision can become increasingly more relaxed.

5. Greater autonomy can be employed if the previous step has shown it is safe to do so.

6. Full automation (i.e. no human control) could be implemented only after required software capabilities and technologies have been built.

4.6 Chapter Summary

The customer needs and requirements were identified first. Then the space tug tradespace was modeled using the MATE design capability, based on depicting the system performance in terms of mission attributes and total utility. The four attributes investigated in this work are: mating capability, transfer capability, timeliness, and adaptability. The design variables used in creating various space tug architectures are: autonomy level, grappler sophistication, propulsion system type, and parking location. The resulting architectures were compared in terms of cost per function metric dividing the total cost of each design by its estimated utility. Lastly, the deployment of a family of modular tugs was discussed as a way to reduce budget, schedule, and operational failure risks.

Chapter 5

Results and Discussion

This chapter uses the design methodology explained in Chapter 4 to analyze two of the eight proposed mission scenarios (see Table 1.1): the GEO satellite retirement and the GTO/LEO-GEO satellite rescuing. These were selected because they promise to yield the most value in the context of commercial space operations.

5.1 GEO Satellite Retirement

The purpose of this section is to analyze the business case of providing tugging services to commercial communication satellites in GEO at the time of their retirement. The potential market has been investigated, along with the benefits offered from competing tugging options. The final results and recommendations have been based on the performed sensitivity analysis to changes in key assumptions.

5.1.1 Motivation

Communication satellites in GEO are large and expensive but, provided that the market demand for their services does not drop significantly, they are also extremely profitable. Thus, not surprisingly, the satellite industry is steadily evolving from being dominated by government and military activities to becoming a predominantly commercial arena. Currently, commercial telecommunications represent approximately 75% of the entire GEO sector, as shown in Figure 5.1.

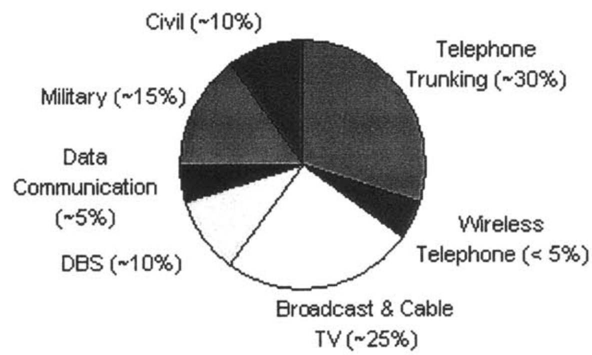


Figure 5.1: GEO Satellites Breakdown [Fut98]

Nowadays, GEO communications satellites typically have a design life of 12 to 15 years. Usually, it is the amount of fuel available for stationkeeping that determines their lifespan. All on-board systems might be properly working and capable of continuing to function 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 [CPUOS96]." To comply with this regulation, satellites use their residual propellant for the transfer and often sacrifice at least six months [Ell00] of their design lifetime, which corresponds to a significant loss of economic value. However, if 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 operator due to the extended use of on-board transponders. Assuming a typical commercial communication satellite that has 24 Ku-band and 24 C-band transponders with bandwidths of 36 MHz and using the most current transponder indices (5,155 $/MHz/Month for Ku-band and 4,921 $/MHz/Month for C-band) [LSE03], the revenue that the satellite owner will earn from six extra months of satellite operation is more than $50M. Clearly, the exact amount would depend on the actual number of active transponders of each type and the length of period they are used, as well as on market demand fluctuations. As long as the cost of the tug mission is less than the expected additional profit, however, a demand for tugging services in GEO can be justified and expected.

5.1.2 Stakeholders

The stakeholders considered in this scenario are the tug operator (the service provider), certain satellite operators (the potential clients), and the insurance companies.

Tug Operators

Before offering the service, the tug owner must ascertain that he can: 1) execute the mission form a technical standpoint, 2) "sell" it (i.e. there will be customers), and 3) make a reasonable profit. If either of these conditions were not met, the tug operator would have no incentive to supply the service.

Commercial Satellite Operators

These are the direct customers. If they decide that satellite retirement through tugging makes a large contribution to their revenues in comparison to what the service costs, tugging has a chance of finding and maintaining a market.

Insurance Companies

Commercial space related investments are rarely made without the purchase of insurance to cover hardware losses or provide indemnification against third party claims. At least seven forms of space insurance are available: pre-launch, launch, on-orbit satellite life, transponder life, service interruption, special event, and third-party liability.

After the client has selected a broker, the broker approaches several potential underwriters for a rate quotation. Next, the client decides which quotation to accept (usually the lowest) and the broker presents the decision to the underwriters, each of whom then decides whether to participate. The insurance rates change based on the technology readiness level and prior experience with a given type of satellite [Gol85]. If the cost of insuring the tug is unbearable, the tug operator would not offer the service.

5.1.3 Assumptions

In addition to the assumptions listed in Section 4.3.1, the following assumptions were used throughout the analysis of the GEO satellite retirement case:

1. Only GEO commercial communications satellites (both US and foreign) are considered as potential targets for tugging.

2. The tug is owned by a commercial organization.

This assumption has an effect on the fee charged for tugging and the type and number of clients to whom tugging is offered. If a government agency were to provide the service, it would prefer to focus on government-owned assets. Even if it is available to commercial satellites, it is likely that it will only be offered to domestic ones. Thus, although a government owner is expected to offer less expensive services (because it is a usual practice for the government to absorb the majority of infrastructure costs), there is a trade-off between this more affordable service and the significantly decreased size of the client pool. For retirement services, specifically, a greater demand is expected from the commercial sector (US and international), and that is why we suggest that the tug should be owned by a commercial organization (see Figure 5.1). It is more appropriate to assume a government owner for other types of tug missions, such as the tactical maneuvering of military satellites.

3. Being commercially owned, the tug can be launched on any launch vehicle, US or foreign, that is normally associated with commercial payloads.

4. No other company/institution is offering tugging services.

5. The tug enters its operational stage in 2007.

6. The clients make an arrangement with the tug operator near the end of life of the satellite.

Although it is desirable to have a backlog of tug clients in order to make a long-range mission plan, we recommend that unless the client is bound by a contract to pay some fee regardless of whether tugging service is performed, the service should not be reserved too long in advance because this would prevent other potential clients from signing up (since a tug can visit only a finite number of satellites, the service might be declared unavailable to the clients who sign up too late). Since there is no guarantee that all satellite subsystems will be properly working by the time the propellant end-of-life criterion[1] is reached, meaning that tugging might turn out not to be affordable due to the low revenues that were accumulated, signing up should be done near the satellite's end of life.

7. Satellites sacrifice at least six months of their operational lifetime if they use their own propellant to move to graveyard orbit.

Longer periods of extended operation will also be considered, but six months is assumed to be the business justification's worst case when calculating the extended life revenues.

8. Satellites use chemical propellant.

Tugging would be of no value for satellites that use, for example, electric propulsion, since propellant would not be the life-limiting factor in this case. Satellite operations will cease either due to power depletion or because of a sub-system failure. In either case, there will be sufficient on-board fuel to retire the satellite to graveyard orbit (provided the propulsion system has not failed). Thus, tugging makes sense only for missions using conventional propellant, whose exhaustion leads to the end of satellite operational life.

9. The revenue of the client decreases due to satellite depreciation, but it happens at the same rate the price charged for the satellite service increases (i.e. they balance out and the revenues for the satellite operators remain approximately the same).

As a consequence of this assumption, client profit calculations do not account for depreciation of the satellites.

---

[1] See the Fuel Gauging Practices note at the end of the section.

Fuel Gauging Practices

There are three principal methods to predict the remaining amount of propellant for orbital maintenance and stationkeeping. The first is called the "gas law" method, which is based on the equation of state of an ideal gas. The pressure and temperature of the inert gas in the propellant tanks is measured by transducers and the volume of the gas is computed knowing precisely the pressure and temperature at launch. Assuming incompressibility of the propellant, the volume of the remaining propellant can be deduced and the mass determined from the known density as a function of temperature. Corrections must be applied for the expansion of the tanks and the propellant vapor pressure. The second method is called the "bookkeeping" method. In this method the thruster time for each maneuver is carefully measured and recorded. The propellant consumed is then calculated from the mass flow rate expressed in terms of the pressure using an empirical model. The third method is much more sophisticated and is based on the measured dynamics of the spacecraft after a stationkeeping maneuver to determine its total mass properties system ID. In general, these three independent methods provide redundant information that can be applied to check one another. Unfortunately, there is still uncertainty as to the precise quantity of remaining fuel, so a safety margin adds to the penalty.[2]

The solution of a sample gauging system design problem is presented below.[3] It uses the gas law method to find the necessary number and location of sensors for the monopropellant tank of a GEO communications satellite, assuming a 0.5 m in diameter spherical MMH propellant tank pressurized by a nitrogen reservoir at 150 psi and depressurized to 100 psi. It is assumed that initially the propellant tank contains 90% MMH and 10% N_2 gas. As fuel is burned at a given mass flow rate $\dot{m}_p$ in time interval Δt, MMH propellant leaves the tank. The volume difference ΔV is now filled by the pressurant gas and the pressure $P_p(t)$ drops. When it reaches below 100 psi, the regulator valve opens and admits more N_2 gas to increase the pressure to 150 psi again. As this increases the temperature, it needs to be waited until thermal equilibrium is reached. From the ideal gas law we can then determine the volume fraction of propellant

[2] http://www.aticourses.com/rocket_tutorial.htm

remaining, if we know the temperature, pressure, and molar mass of the gas in the tank. The molar mass is determined by measuring P_p and T_g in the pressurization tank.

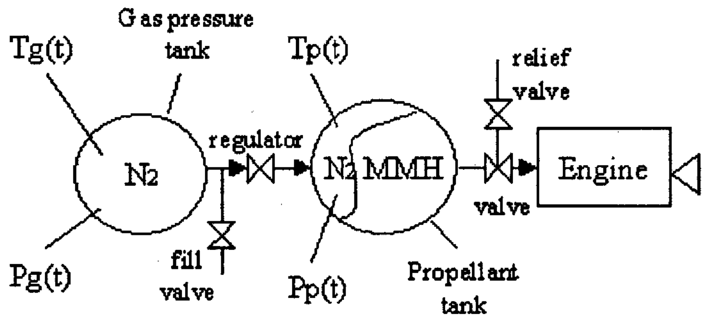


Figure 5.2: Regulated Pressurization System

During one cycle, the blow-down ratio is:

$$R \equiv \frac{V_{gf}}{V_{gi}} \cong \left(\frac{V_{gi} + V_p}{V_{gi}} \right) = \frac{V_T}{V_{gi}} \tag{5.1}$$

where V_T = total tank volume, V_p = total propellant volume, and $V_{gi/f}$ = initial/final gas volume. Equation 5.1 neglects the propellant volume at the end of the cycle and the density changes with temperature. Due to conservation of energy, approximation of the pressurant mass requires:

$$m_{gi} = \frac{P_p \cdot V_p}{R \cdot T_i} \cdot \left(\frac{k}{1 - \left(\frac{P_g}{P_i} \right)} \right) \tag{5.2}$$

where m_{gi} = initial pressurant mass, P_i = initial gas pressure (assumed 3000 psi = 20,684.272 KPa), T_i = initial gas temperature (assumed 300 K), k = specific heat ratio (1.40 for nitrogen), R = gas constant (296.8 J/(kg·K)), and P_p and V_p are instantaneous values.

As a first order approximation, we assume that the following is true:

1) N_2, the pressurization gas, can be described with the ideal gas law

[3] Courtesy of Prof. Olivier de Weck, Department of Aeronautics and Astronautics and Engineering Systems

$$p \cdot V = \bar{R} \cdot T \tag{5.3}$$

where $\bar{R} = 8.314 \cdot 10^3$ J/K.

2) Incompressibility of the MMH propellant.
3) There are no leaks in the system, so that the initial gas mass is always preserved.
4) Both tanks are thermally insulated.

We need to find the mass of the propellant as a function of time, $m_p(t)$. We know that

$$V_g(t) = V_T - V_p(t) \tag{5.4}$$

which measures the gas volume directly, but we can also infer from P_g and T_g for υ kilomols of N_2 in the propellant tank that:

$$V_g(t) = \frac{\nu \cdot R \cdot T_g}{P_g} \tag{5.5}$$

Equation 5.5 is valid for thermal equilibrium, i.e. the temperature outside the tank should also be known.

The depressurization consists of applying a step input to the propellant tank from 100 psi to 150 psi. Because of the incompressibility assumption, V_p, V_g, and V_T do not change. Thus, the temperature inside the tank will change.

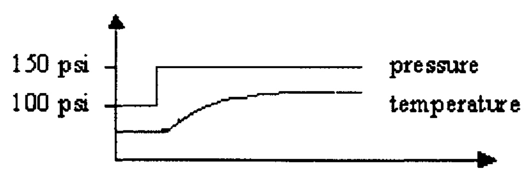


Figure 5.3: Qualitative Representation of Temperature and Pressure Changes

With the assumptions made, if measurements are taken at thermal equilibrium, we do not need to consider the dynamics of the process.

The following is a list of the steps guiding the gauging process:

1) *Initial filling of the system*: The initial filling of the propellant and gas tanks is assumed to be happening at T_i = 300 K. The total volume of the propellant tank is constant:

Division at MIT.

$$V_T = \frac{4}{3} \cdot \pi \cdot r^3 = \frac{4}{3} \cdot \pi \cdot (0.25)^3 = 65.45 \cdot liters \tag{5.6}$$

Substituting in Equation 5.2, we obtain the initial mass of the gas, m_{gi} = 0.118 kg. Since there was initially 90% MMH in the propellant tank, we multiply VT by 0.9 and then by the density of MMH, which is about 0.86 kg/m^3, to obtain the initial mass of the propellant, which comes up to be about 50.6 kg. Next, substituting V_T (0.0654 m^3), the assumed initial temperature T_i (300 K) and the given pressure of 150 psi (1034.214 KPa) in Equation 5.5, we calculate that $\upsilon_0 = 2.7 \cdot 10^{-2}$ kmol if all fuel is used up. Since 1 mol N_2 weighs 28 g, this corresponds to 0.756 kg of N_2 in the propellant tank. Furthermore, knowing that N_2 was 10% and MMH was 90% of the mixture, we find that $\upsilon_g = 2.7 \cdot 10^{-3}$ kmol and $\upsilon_p = 2.44 \cdot 10^{-2}$ kmol.

2) *Fuel Burn*: A fuel burn for a duration Δt and mass flow rate $\dot{m}_p$ reduces the volume $V_p(t)$ and mass, which the propellant occupies in the propellant tank. Let Δt range be between 1 and 20 sec and $\dot{m}_p$ be 0.01 kg/sec (a typical value). Using that the density of MMH (0.86 kg/m^3), we can compute the new gas and propellant volumes:

$$V_{g1}(t) = V_{g0}(t) + \frac{\dot{m}_p}{\rho_p} \cdot \Delta t \tag{5.7}$$

3) *Monitor Pressure*: As fuel enters the combustion chamber, the volume occupied by the gas, $V_g = V_T - V_{p1}(t)$, increases. Assuming an adiabatic process, this will lead to a reduction in the gas pressure.

$$p_{gi}(t) = \frac{v_0 \cdot \overline{R} \cdot T_0}{V_{gi}(t)} \tag{5.8}$$

where v_0 is the molar mass of N_2 with regulator valve closed, T_i is the adiabatic temperature of the tank, and $V_{gi}(t)$ is the instantaneous volume of the gas in the tank.

4) *Depressurization*: When $P_{gi}(t) \leq 100$ psi, the regulator valve is opened and the tank is depressurized. Since $V_{pi}(t)$ is constant, the temperature will increase.

$$T_i(t) = \frac{V_{p1(t)} \cdot p_1(t)}{v_1 \cdot \overline{R}} \tag{5.9}$$

where v_1 is the new gas molar mass in the propellant tank and $p_1(t)$ is 150 psi.

5) *Computation of Propellant Mass*: By monitoring the pressure and temperature in the pressurant tank, we can infer how much gas remains in the tank. The rest of the gas must now be in the propellant tank. Therefore, we can backtrack to calculate the propellant mass m_p after depressurization.

The N_2 molar mass content is:

$$v_g = \frac{p_g(t) \cdot V_g}{\overline{R} \cdot T_g(t)} \tag{5.10}$$

where $p_g(t)$ and $T_g(t)$ are instantaneous pressure in temperature measured by transducers in the gas tank. The molar mass $v_i(t)$ of the nitrogen present in the propellant tank is:

$$v_i = v_0 - v_g \tag{5.11}$$

The volume $V_g(t)$ which the N_2 gas occupies in the propellant tank is:

$$V_{gp} = \frac{v_i \cdot \overline{R} \cdot T_p(t)}{p_p(t)} \tag{5.12}$$

where $T_p(t)$ and $p_p(t)$ are instantaneous temperature and pressure in the propellant tank measured by transducers ($p_p(t)$ should be equal to 150 psi after depressurization). Finally, the mass of the remaining propellant is:

$$m_p = \rho_p \cdot \left(V_T - V_{gp}(t)\right) \tag{5.13}$$

The conclusion of the analysis is that in its simplest version, the PVT-gauging system requires four sensors: one temperature and one pressure transducer in each of the two tanks. The purpose of including this example, however, was to show how the uncertainties in the pressure and temperature measurements in both the fuel and the pressurization tanks and the uncertainties due to all other assumptions propagate through to become fuel quantity uncertainties. The uncertainty in the estimation of the amount of fuel left is one of the most critical factors in the business case and justification of tugging.

5.1.4 Competing Options

In general, the options that compete with tugging are: sending astronauts to capture a satellite and repair it or bring it back to Earth (EVA), moving a satellite using its own propulsion, which might be followed by launching a new satellite (replacement), or leaving the satellite where it is (abandoning), which also might be followed by launching a new satellite to perform the mission the old one was not capable of performing. For this mission scenario, extravehicular activity is not applicable because it is confined to low inclination LEO orbits only (below 60 deg). Gaining additional revenue through abandoning a satellite in the GEO belt after all of its on-board fuel is exhausted is also not an option because of the UN treaty mentioned above. Thus, only two choices remain for the satellite operator to select from: retire the satellite using its own propellant or pay for a tugging service. 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 slot.

If a replacement is not available, the question 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 perform the transfer 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 5.4 presents these options[4]. For a given satellite, $P_{S1} < P_{S2} < P_{S3}$. The question is how P_T compares to these three satellite profits.

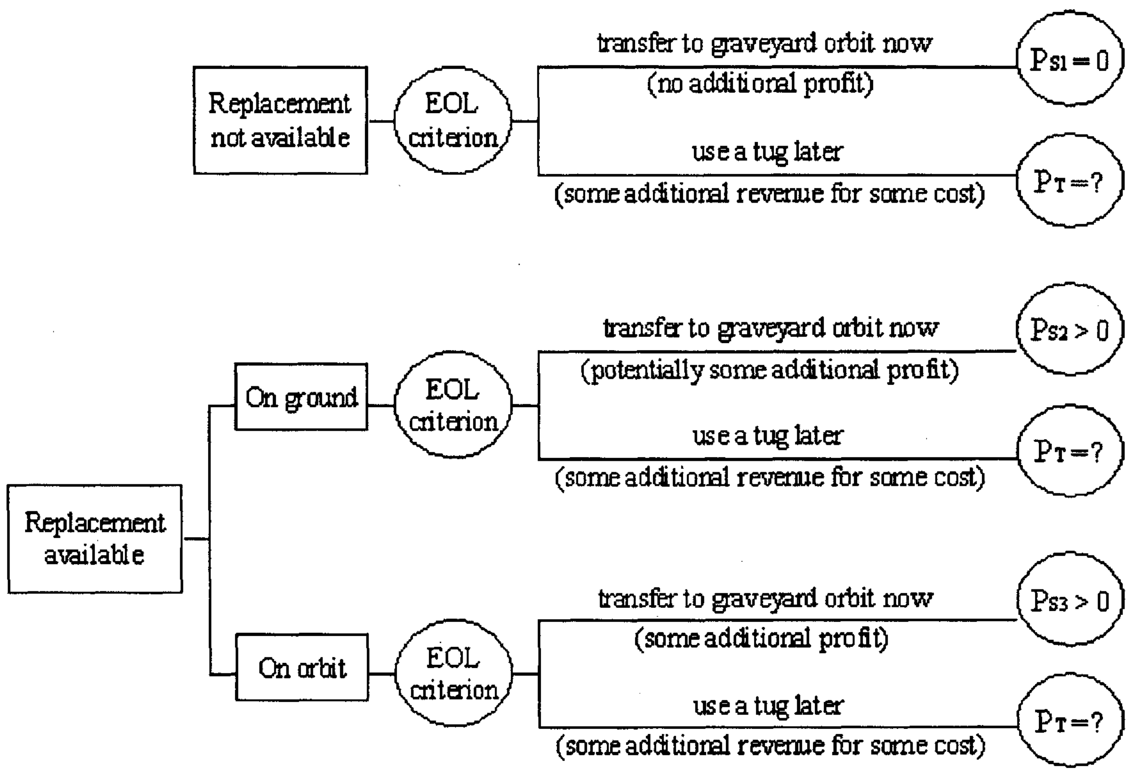


Figure 5.4: Possible Options and Their Outcomes

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. The discussion follows the one from the previous

[4] The satellite owner is the stakeholder who chooses between these options. The insurance company affects the process by adjusting the insurance rates, and the tug operator decides whether to provide the service and what fee to charge for it.

chapter but is now focused specifically on GEO communications satellites as potential GEO tug clients.

5.1.5 Market Statistics and Forecast

Communication satellites were first mentioned in 1962 in *The U.S. Industrial Outlook* under "International Communication." The satellite industry was assigned a separate category in 1978, when, for the first time, *The Outlook* reported satellite industry revenues, estimating them at about $154M [Liv00]. Twenty-five years later, the revenues have increased more than 560 times, reaching $86.8B in 2002 [Atr03]. To encourage demand and improve profitability, satellite operators often lease or sell access to their satellite transponders to service providers such as telecommunications and data relay firms. With the development of these new commercialization procedures, the distinction between firms supplying, carrying or leasing capabilities has become increasingly hazy [Dub85].

To give the reader some basic idea of what the four main sectors of the satellite industry include, Table 5.1 lists the services provided by each sector. In this work, only the satellite services sector will be taken into consideration, since it is directly influenced by the option of tugging services.

Satellite Services
▪ Transponder leasing
▪ Retail/Subscription services
    o Direct-to-home
    o Wireless telephone
    o Data services
    o Direct radio
    o Remote sensing
	Ground Equipment Manufacturing[5]
	▪ Mobile terminals
	▪ Gateways
	▪ Control stations
	▪ VSATs & USATs
	▪ DBS dishes
	▪ Handheld phones

Launch Industry ▪ Launch services ▪ Vehicle manufacturing ▪ Component and subsystem manufacturing	Satellite Manufacturing ▪ Satellite manufacturing ▪ Component and subsystem manufacturing

Table 5.1: Satellite Industry Sectors

[5] The ground equipment manufacturing sector consists of the manufacturing of satellite uplink and downlink terminals, including VSATs (very small aperture terminals), consumer mobile satellite data and telephone units, and direct-to-home television receivers and dishes.

There are two general categories for satellite communication services: Mobile Satellite Services (MSS) and Fixed Satellite Services (FSS). Mobile satellite services serve mobile users at all latitudes without the use of ground stations for signal relay. They are not pertinent to this analysis, however, since their satellites are in either low or medium earth orbit. Fixed satellite services refer to communications that are broadcast to users who are fixed in a particular location. Typically, FSS provide large quantities of video, imagery, and voice data. Such high capacity transactions are usually referred to as "wideband" or "broadband" transmissions.[6] Figure 5.5 shows the profitability of satellite manufacturing, fixed satellite services (FSS)[7], and ground equipment manufacturing, representing the last couple of years. On average, FSS providers were able to attain net income margins (net income divided by revenues) of 33%. The ground equipment sector is a distant second (6%), followed closely by satellite manufacturing (5%).[8]

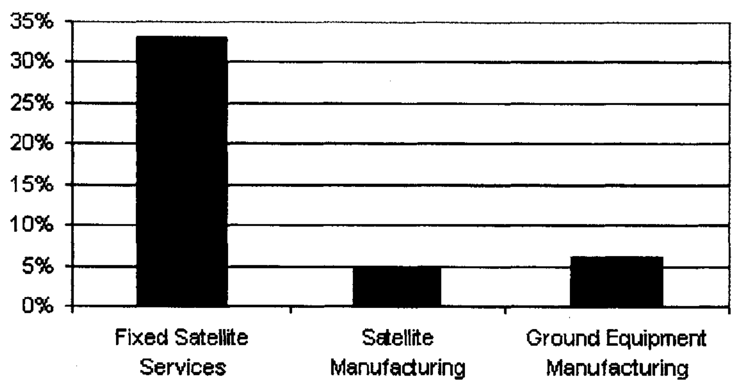


Figure 5.5: Satellite Industry Average Profit Margins

One reason why the FSS sector is so profitable is the high barriers to entry for FSS operators resultant from the scarcity of GEO orbit slots and spectrum, tight regularity control and relatively closed national markets. The limited number of providers has created an oligopoly, which guarantees the high profits associated with such a condition. Another reason might be the ability to leverage new technology in this sector. Ironically, these same factors limit the number of GEO satellites ordered every year. This

6 http://www.gwu.edu/~spi/spacemil9.html

7 A radiocommunications service between ground stations at specified fixed positions when one or more satellites are used.

has led to a continuous shrinking of the satellite manufacturing market, reducing its profitability. Lastly, the ground equipment manufacturing sector is increasingly competitive but characteristically claims low margins.[9]

Demand

Since the satellite operators are the customers for tugging services, to be able to predict the demand for tugging missions, we first need to predict the demand for satellite services. Statistics show that until recently, the satellite communications market was growing because satellites could not only rival but also surpass their air or ground alternatives in bandwidth and coverage. Compared to coaxial cables or wireless links, communication satellite transmission offered a flexible, competitive answer to long-distance communications problems between two points, from one point to several points, and linkages between moving points (ships, aircraft). A satellite can also provide high quality transmission for an area with low population density and few telephone lines (e.g. many developing countries) and make the handling of large information flows possible within short periods of time [Dub85]. Nowadays, however, the existing market of space consumers has reached a point of near saturation, where the supply of goods and services currently outweighs the demand [Hig02]. Figure 5.6 shows the trend for future satellite capacity[10] supply and demand, forecasted in a 2003 report by Futron Corporation, the space industry's leader in research, analysis, and forecast of satellite communications markets and programs. The figure is based on available data for satellites currently in orbit, future satellite projects that have been publicly announced, and likely replacement satellites.

---

[8] Futron Corporation, "Just How Profitable Is the Satellite Business?" source: http://www.futron.com/pdf/profitabilityanalysistopbimedia.pdf.
[9] Ibid.
[10] Transponders come in different capacities; a standard measuring unit is a 36-MHz transponder equivalent.

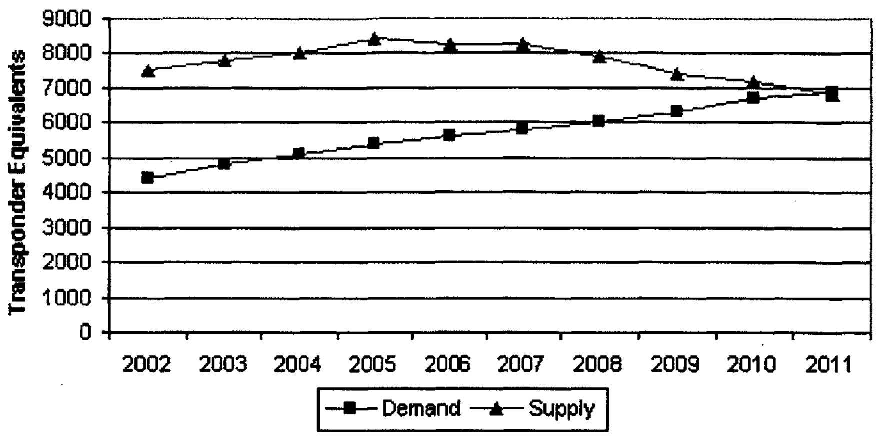


Figure 5.6: Predicted Supply and Demand of Satellite Capacity [Fut03]

As Futron explains, while only 376 transponder equivalents were launched in 2001, an unprecedented supply of 980 transponder equivalents was introduced in 2002, which increased the global supply of satellite bandwidth by 15%. Most of this capacity was ordered in the late 1990's, when the Internet and telecommunications experienced a boom. In the last few years, however, there was a significant drop in the cost of terrestrial bandwidth. The prices for fiber optic cable capacity, for example, have decreased by an order of magnitude and some commercial operators have withdrawn from the satellite market [Fut03]. Even traditionally solid customers have reduced their demands for satellite-provided services. As a result, the current supply is almost double the demand. Thus, although the demand curve has a positive slope, the commercial telecommunications satellite market has recently been experiencing diminishing revenue trends. ***Based on this, we will assume that the transponder capacity of a particular replacement satellite is no greater than the capacity of the satellite that is being replaced.*** Even if more transponders are launch, we expect that the fraction that is actually leased remains at best the same.

Revenues

Until the past couple of years, telecommunications satellites had economic value far exceeding the cost of their development. Figure 5.7 is based on statistical data for the world commercial satellites revenue from 1996 to 2002 provided by Futron. The characteristic trend of over-prediction is observable from the predicted revenue for 2002 (compare the last two bars in the figure).

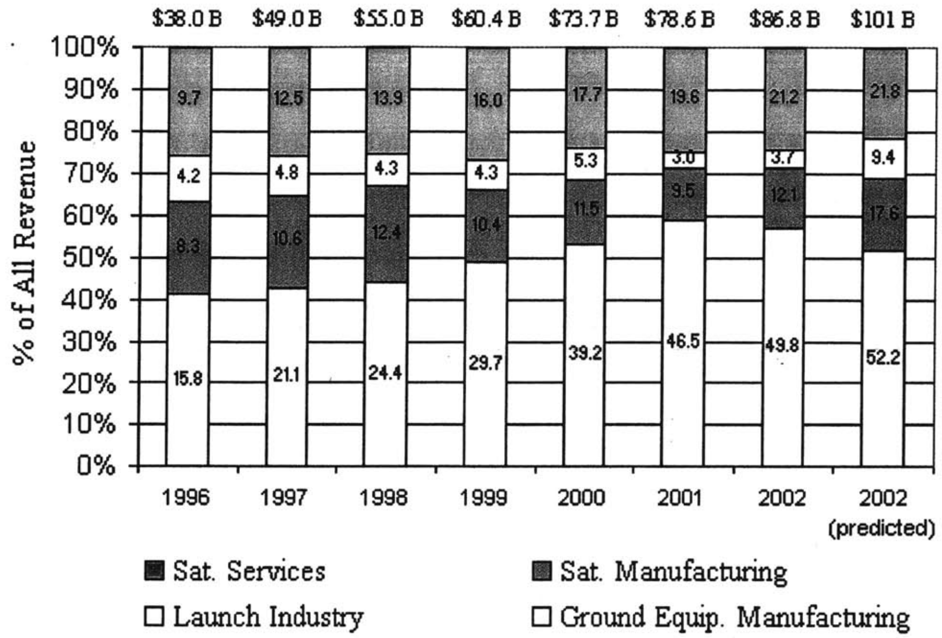


Figure 5.7: Recent World Commercial Satellite Revenues[11]

Achieving profitability in the satellite services arena does not come from a simple formula. The following factors play a major role in forming the decisions faced by the satellite operators:[12]

- The global downturn in the overall telecommunications industry;
- The trend toward major mergers and industry consolidation that is driven by globalization and current market problems;
- Shifting demand for different types of digital services and greater emphasis on mobility;
- New markets arising from digital convergence and new IP-based services;
- New or changing satellite and ground terminal technology;
- Regulatory shifts and the opening of new national and international markets to competition;

[11] Futron Corporation, "2001-2002 Satellite Industry Indicators Survey," source: http://www.sia.org/papers/.
[12] Futron Corporation, "Satellite Industry Statistics 2002," source: http://www.sia.org/industry_overview/.

- Industry changes due to merging satellite and terrestrial networks, the oversupply of fiber-optic capacity, and the move to achieve greater global economies of scale.

In 2002, every satellite industry sector experienced growth. The total industry revenue grew moderately by about 10%. Government spending and strong consumer demand for satellite video services were responsible for much of this growth. Although industry revenues have been positive, other indicators, such as prices, profit margins, stock prices, and new orders, have experienced negative trends and reflect significant financial stress in the satellite industry. Driven by consumer-oriented video services, the satellite services sector slowed its growth to a 7% increase (traditional transponder leasing revenues remained flat). The ground equipment sector has been consistently growing, although by only 8% in 2002. The infrastructure sectors (satellite and launch) continued to be hampered by overcapacity. While global launch industry revenues grew by 23% in 2002, US revenues declined by 9% because of the smaller number of US launches and lower launch prices. Although non-US launch prices also declined on average, the higher number of launches offset their decrease. While the US satellite manufacturing revenues grew by 16% in 2002, the world revenues increased by 27%. This increase reflected the large number of contracts awarded in 2000 and 2001. The significant decline in orders for 2002 is expected to affect the revenues for the next couple of years.[13] This change, however, is not expected to result in a decrease of overall profit; at the very least, the revenue level will remain constant. Therefore, we can assume that as long as the demand for satellite services does not decrease significantly, we can expect a potential market for tugging.

To estimate the maximum number of potential clients for tugging services each year, we first look at the prediction of established market analysts. Figure 5.8 displays the total number of commercial GEO satellites launched per year, as recorded and predicted by the Commercial Space Transportation Advisory Committee (COMSTAC). Based on this forecast, for the next ten years we can expect about 23 new satellites on average per year. This would be the maximum number of potential clients, assuming that tugging is

[13] Ibid.

already established as practice by the time they reach the end of their design lives (normally, 10-15 years).

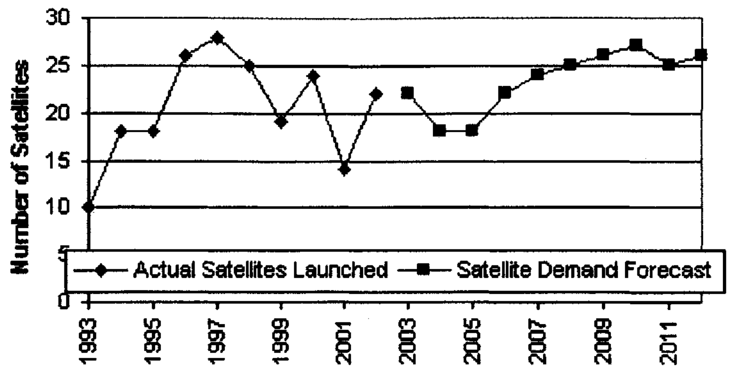


Figure 5.8: COMSTAC Commercial GEO Satellite Forecast

If the first tug is introduced for example in 2007, during its first year of operation it will target satellites launched between 1992 and 1997. According to the figure above, this corresponds to an average of 22 per year. Our database, however, shows that many of these satellites are already out of service. Clearly, to make a valid business case, it is imperative to have an accurate and frequently updated database of satellites still orbiting the Earth. Fortunately, copious information about the number and functionality of commercial communication satellites is available in the public domain. Table 5.2 lists the number of satellites per expected end of life year (in the GEO belt alone), launched between 1992 and 2002 that, to our knowledge, are still in Earth orbit. The number of customers to actually purchase the tugging service would depend on the revenue they expect to accrue and the fee set by the tug operator.

Expected EOL	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
# Sat.	11	15	14	13	10	16	20	14	15	17	5*	7*

* Note that launches in the next couple of years will increase these numbers.

Table 5.2: Number of Potential Clients per Year

The main conclusions derived from the above analysis are summarized below:

1. As long as the demand for satellite services does not dramatically decrease, there can be a potential market for tugging services.

2. On average, about 15 client-satellites per year can be expected.

3. The transponder capacity of the near-future communications satellites will not exceed the capacity of the satellite being replaced.

The specific questions that remain to be answered are:

1. What is the perceived benefit to the spacecraft operator from tugging?

2. Should the fee for tugging be fixed or variable? How much should be charged?

3. What are the legal/regulatory/insurance issues involved? How can they be mitigated?

An attempt to give a quantitative answer to these questions will be given through analyzing and comparing the relative costs and benefits of the competing options of transfer to graveyard orbit (see Figure 5.4).

5.1.6 Fee Estimation

The fee estimation approach outlined in Section 4.4.2 was followed. However, before we proceed with the analysis, we will take a general look at the feasibility of retiring GEO commercial communications satellites via a space tug. Intuitively, it is very important that the tug be reusable. A tug devoted to only one mission is unlikely to be profitable because the minimum fee that should be charged will be too high. The fee is greatly decreased if total cost of providing the service is spread over several missions. Figure 5.9 shows how it changes with the increase of the number of satellites that can be serviced by a tug with a low capability grappling mechanism (300 kg robotic arm).

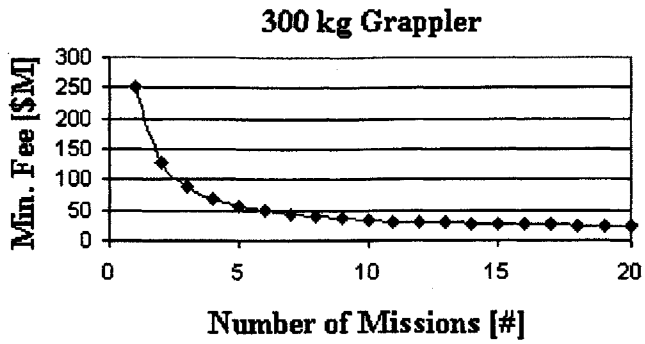


Figure 5.9: Minimum Fee as a Function of Number of Missions

As seen from the figure, reusability is clearly critical for reducing the minimum fee that should be charged, especially since even a difference of a couple of million dollars can affect the number of satellite operators who will be interested in the service (this will be further discussed in the Section 5.1.7.2). The good news is that 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 delta-V of the order of tens of meters per second per mission. Table 5.3 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 (Appendix B shows the satellite data used in the calculations). 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 delta-V of 20 m/s is required for capturing or releasing any client satellite during the lifetime of the tug (see sample calculations in Section 4.2.1.2).
4. The tug uses a storable bipropellant with Isp = 325 sec.

Grappler Capability	Grappler Mass	Dry Mass	Biprop Fuel (Stor)	Max # Missions
[-]	[kg]	[kg]	[kg]	[#]
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 5.3: Tug Reusability[14]

5.1.6.1 Total Utility

The design attributes that were considered are mating capability, transfer capability, adaptability, and timeliness. The relative weights of the three considered attributes are shown in Table 5.4 and were used in the calculation of total utility (see Section 4.2.1.5).

Attribute	Weight
Mating Capability	0.4
Transfer Capability	0.2
Adaptability	0.2
Timeliness	0.2

Table 5.4: Relative Weights of Attributes

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 results from the tradespace analysis indicated that the optimal space tug for this mission scenario should be initially parked in the GEO belt[15] and controlled through supervision. The analysis 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 (Isp = 325 sec) superior in terms of performance achieved per given cost. The optimal mass and sophistication of the tug's grappling mechanism is selected in Section 5.1.6.3.

5.1.6.2 Total Cost

As stated in Section 4.2.4, the total cost, C_t, of a space tug is a sum of the following costs:

$$C_t = C_u + C_p + C_l + C_i + C_o + D \tag{5.14}$$

where C_u is the tug unit cost, C_p is the propellant cost, C_l is the launch cost, C_i is the insurance cost, C_o is the cost of tug operation, and D is the depreciation of the tug.

Unit Cost

Assuming that there will be a market for the consecutive operation of at least five space tugs of the same family (i.e. about 100 tugging missions total; Table 5.2 showed that about 134 potential clients can be expected from 2007 to 2015) and the learning curve is 95% [LW99], we can calculate the unit cost (C_u) of a tug by dividing the combined cost of five tugs (C_5) by the number of tugs ($N_{tugs} = 5$):

$$C_u = \frac{C_5}{N_{tugs}} \tag{5.15}$$

---

[14] No on-orbit fuel depots assumed.

[15] When the sequence of tugging missions begins, the location where the client satellite is released in graveyard orbit becomes the new parking location.

The relationship for C_5 utilized by the NASA Spacecraft/Vehicle Level Cost Model were reverse-calculated to be approximately:

$$C_5 = 4.9139 \cdot M_d^{0.6055} \quad (5.16)$$

As explained in Section 4.2.4.1, we 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.

Propellant Cost

The propellant cost was estimated by multiplying the mass of the necessary propellant by its cost (see Table 4.10).

Launch Cost

The launch cost was estimated 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 (see Table 4.11).

Insurance Cost

The insurance rates cited in Section 4.2.4.4 were used, and an insurance claim was assumed to be valid in all cases when the tug fails to transfer the satellite to at least 300 km above the GEO belt.

Depreciation

Depreciation was estimated using equation 4.6.

5.1.6.3 Minimum Fee and Optimal Architecture

Normally, optimal architectures are determined on the basis of cost per function. Table 5.5 summarizes the results for the best representatives of each grappler category that were listed in Table 5.3 if the same metric was chosen. As seen from the table, if we had decided to compare the design architectures in terms of cost versus performance, we would have identified the tug with the 600-kg grappler as the best option (i.e. it has the lowest cost per function). 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.

Grappler Capability	Grappler Mass [kg]	Max # Missions [#]	Unit Cost [$M]	Launch Cost [$M]	Insurance Cost [$M]	Annual Deprec. [$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

Table 5.5: Performance per Cost

The minimum fee (F_{min}) that should be charged per mission is:

$$F_{\min} = \frac{C_t}{N_{mis}} \tag{5.17}$$

where C_t is the total cost and N_{mis} is the maximum number of missions the tug is able to perform. Note that this approach does not use any net present value (NPV) discounting. The results for the six design points selected above are presented in Table 5.6.

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

Table 5.6: 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. Thus, as a baseline for the subsequent analysis, we will assume a minimum fee of $20.48M.

5.1.6.4 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 leased 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 (1992-2000).

Month-Year	Available Transp.	Total Number	Fraction Leased	Month-Year	Available Transp.	Total Number	Fraction Leased
Jan-01	3	34	0.912	Apr-02	82.8	422.2	0.804
Feb-01	3	34	0.912	May-02	82.8	446.2	0.814
Mar-01	7	64	0.891	Jun-02	124.8	629.2	0.802
Apr-01	7	64	0.891	Jul-02	129.8	641.2	0.798
May-01	15	112.5	0.867	Aug-02	142.8	727.2	0.804
Jun-01	28	232.5	0.880	Sep-02	162.8	849.2	0.808
Jul-01	28	232.5	0.880	Oct-02	162.8	849.2	0.808
Aug-01	47	326.5	0.856	Nov-02	170.8	897.2	0.810
Sep-01	59	359.5	0.836	Dec-02	190.8	980.2	0.805
Oct-01	59	359.5	0.836	Jan-03	0	0	-
Nov-01	59	375.5	0.843	Feb-03	15	94	0.840
Dec-01	59	375.5	0.843	Mar-03	15	94	0.840
Jan-02	7.4	38.4	0.807	Apr-03	60	194	0.691
Feb-02	22.4	163.7	0.863	May-03	66	224	0.705
Mar-02	48.8	325.2	0.850	Jun-03	77.8	309.9	0.749
Average Fraction Leased (2001):							**0.870**
Average Fraction Leased (2002):							**0.823**
Average Fraction Leased (2003*):							**0.765**

* First half of the year

Table 5.7: Fraction of Transponders Leased[16]

[16] Futron Corporation, Satellite Telecommunications Report (2001, 2002, 2003), source: http://www.futron.com/spaceandtelecom/src/st.htm.

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:

$$P_{max} = \eta * R - C_o - F_{min} \quad (5.18)$$

where

$$R = \sum_{i=1}^{2} N_{tr} \cdot C_{tr} \cdot N_{mo} \cdot f \quad (5.19)$$

N_{tr} is number of transponders, C_{tr} is the specific revenue from a transponder [$M/MHz/Month], N_{mo} is number of months of operation, and f is transponder bandwidth [MHz]

5.1.6.5 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. As explained in [Coo97], if value is a fundamental property of a product, then it cannot be equal to the price, which can be arbitrary. The buyer receives a net value equal to the value V gained through the use of the product minus the price P paid to the seller. The seller receives a net value equal to the price minus the cost C needed to manufacture the product. If the buyer and the seller bargain with equal strength, the mutually agreed balanced selling price would be $P = P_B$, and they receive equal amount of free value, i.e.

$$P_B - C = V - P_B \quad (5.20)$$

From this pricing strategy it follows that for a simple market transaction, the balance price lies halfway between cost and value:

$$P_B = \frac{V + C}{2} \tag{5.21}$$

This is what we have called "mid-way" fee (see Section 4.4.2).

Our database includes 162 GEO satellites launched in or after 1992, but data is available to fully describe only 121 of them. Out of these 121 satellites, only 62 result in a 6-month 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 the 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 C (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.[17]

5.1.7 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 for the sensitivity analysis, only the case when there are no available satellite replacements is considered.

5.1.7.1 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 5.10. This is again explained by the fact that tugging is only attractive to a small group of high-revenue satellites (see Appendix C).

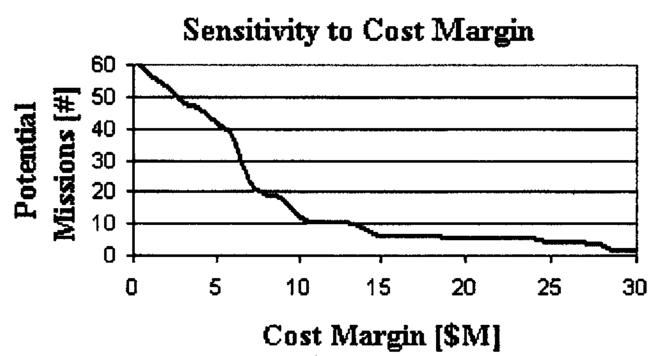


Figure 5.10: Sensitivity to Changes in Cost Margin

[17] As seen in Appendix C, Intelsat 707 presents a special case. The reason why its potential revenue is so high is the utilization of a significant number of large bandwidth transponders: 10 C (36MHz), 2 C (41MHz), 16 C (72MHz), 6 Ku (72 MHz), and 8 Ku (112MHz). Since the resulting potential revenue is much greater than the rest of the satellites, it might require separate negotiations when establishing the tugging fee.

To justify the selected minimum fee, the tug needs to visit 20 satellites during its 10-year-long design life.[18] 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.

5.1.7.2 Sensitivity to Minimum Fee

The results from increasing and decreasing the baseline minimum fee by five, ten, and twenty percent are presented in Figure 5.11. 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 decreased 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.

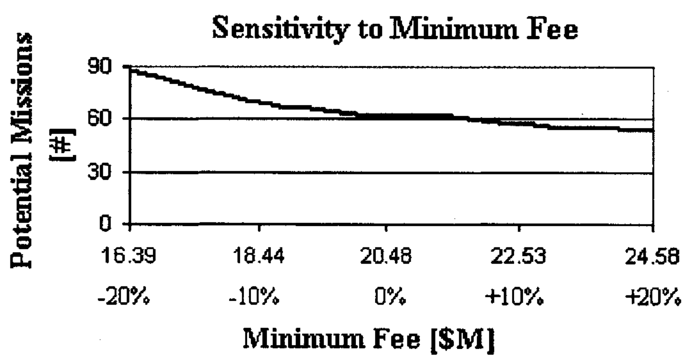


Figure 5.11: Sensitivity to Changes in Minimum Fee

The data used for the plot is presented in Table 5.8 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, again because tugging is only attractive to the relatively small group of tier 1 satellites.

[18] The other four tugs from the production family can be manufactured and released later. The argument presented here investigates the worst-case scenario, so we do expect them to share the same pool of potential customers, but this is not a requirement.

Min. Fee [$M]	# Sats [no repl.]
16.39	88
18.43	70
19.46	65
20.48	62
21.51	61
22.53	57
24.58	53

*$0M cost margin

Min. Fee [$M]	# Sats [no repl.]
16.39	19
18.43	18
19.46	15
20.48	12
21.51	10
22.53	10
24.58	10

*$10M cost margin

Table 5.8: Minimum Fee Sensitivity Tests

5.1.7.3 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 on Figure 5.10 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 (i.e. to service 20 satellites), 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 (see Fuel Gauging Practices note in Section 5.1.3). 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 5.12.

There is a possibility that a satellite operator might try to falsify the results from the EOL criterion estimations in order to negotiate a lower fee for tugging. That is why the initially agreed-upon fee should only be considered as a preliminary estimation and it should be adjusted accordingly upon complete depletion of the satellite fuel.

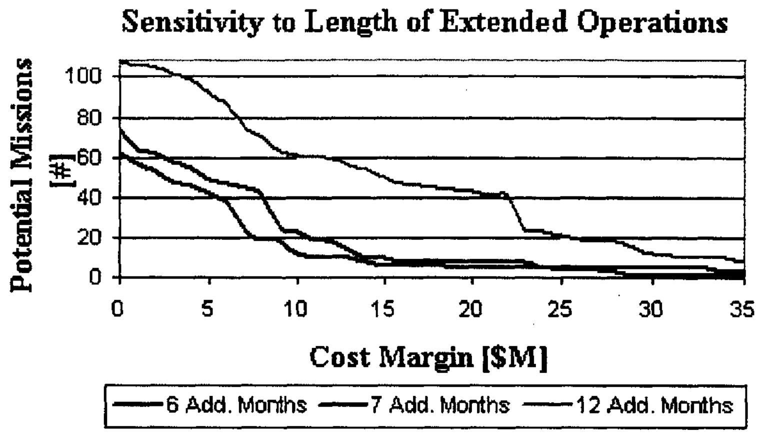


Figure 5.12: Sensitivity to Length of Extended Operations

The sensitivity to minimum fee is presented in Figure 5.13 and Table 5.9 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.

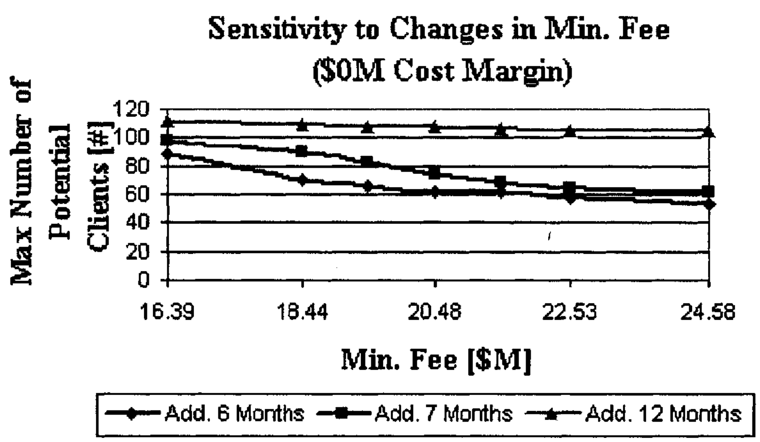


Figure 5.13: Sensitivity to Minimum Fee

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 5.9: Sensitivity to Minimum Fee

5.1.8 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, unless we consider the value of having the old satellite remain operational as a backup.[19] 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 5.10 and Table 5.11 present the maximum number of satellites for which tugging makes economic sense for various cost margins and minimum fees.

[19] Most satellite service providers launch and check out a replacement satellite *before* removing the old one form service. This is somewhat of a problem for the argument of this thesis. However, there might be some value in delaying the replacement and having the old one operational as a backup until the replacement is commissioned (the old satellite should then be tugged).

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 5.10: 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 5.11: Maximum Number of Potential Clients

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.

5.1.9 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 5.12:

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

Table 5.12: Cases Justifying Tugging
(GEO Satellite Retirement Case)

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 (see Assumption #2 in Section 5.1.3).
5. Satellites produce more revenue.
6. Tugging is reliable (i.e. failure rate and, hence, insurance rate is small).

5.2 Stranded Satellites

This section investigates the business case and justification of another one of the eight identified mission scenarios, namely the providing tugging services to 1) satellites stranded in LEO or GTO due to rocket upper stage or apogee kick motor failure or 2) malfunctioning satellites that can be repaired on Earth or at the ISS.

5.2.1 Motivation

On November 26, 2002, *Space Daily* reported that a large commercial venture was called into question when Astra 1K, aiming to transmit television programs and Internet into homes across Europe, failed to reach its ultimate orbit of 36,000 km. Due to Proton's misfiring upper stage booster, it was left hovering just 200 km from Earth. At stake were not only the expenses for building and launching the satellite but also the millions of dollars of expected revenue. Experts claimed that it was theoretically possible to use the satellite's own propellant to boost it into the desired orbit, but that would "immensely reduce the satellite's expected lifespan."[20] On December 10, a decision was made to purposely re-orbit Astra 1K into the Earth's atmosphere and then into the Pacific Ocean. The project cost SES Astra, a major telecommunications provider based in Luxembourg, about 280 million dollars.

There have been some spectacular recoveries from deployment or on-orbit failures, but these are the exception rather than the rule. For example, *Hipparcos* was launched into the wrong orbit due to a fault in its apogee kick motor. Extensive changes were made to its mission, with the objective to achieve the maximum possible scientific return in these conditions, and, overall, the operation was considered a great success [Ell02]. However, most of the other similar cases have led to sub-optimal operation and degraded performance. Such mishaps are not rare and often create financial fiascos for the investors. For example, soon after two *GeoStar* satellites had failed (one had experienced a launch failure and the other an in-place satellite failure), GeoStar Satellite Systems declared bankruptcy, even though both satellites were insured [Pra02]. With the increasing use of satellites, such failures are not only expected to become more common, but are also expected to affect more people—both investors and consumers. When EVA is not possible, replacement is the only option for satellite owners. By the time the new satellite is launched, however, their competitiveness in the industry may be diminished. The traditional way to alleviate the problem of reliability is to impart a high degree of redundancy. Unfortunately, this imposes launch mass penalties while reducing payload mass, normally leading to increased costs and reduced performance. There comes a point when diminishing returns from increased redundancy favor an alternative approach to spacecraft reliability—on-orbit tugging. Taking advantage of this service would save the stranded satellite's on-board propellant and thus allow it to operate for nearly as long as it was intended. The salvaged profit, however, must be reduced by the amount of the fee charged for tugging. The rest of Section 5.2 will explore the reasonable ranges for this mission scenario's service fee.

5.2.2 Failures Statistics and Predictions

A great number of satellites were destroyed or prevented from reaching their final destination due to launch failure. Table 5.13 lists the number of launch failures since the beginning of the space era. Although a tug can do nothing to prevent launch failures from occurring, we include these statistics because they are a major factor that must be considered by any satellite operator when estimating the potential risks of his ventures.

Year	US		World (total)		Year	US		World (total)	
	Success	Failure	Success	Failure	1981	18	1	121	4
1957	0	1	2	1	1982	18	0	120	10
1958	5	18	6	22	1983	22	0	126	3
1959	11	8	14	9	1984	21	1	127	3
1960	16	13	21	19	1985	17	1	120	6
1961	22	19	28	22	1986	6	3	103	9
1962	48	11	68	13	1987	8	1	110	5
1963	37	9	54	16	1988	11	1	115	7
1964	56	8	86	14	1989	18	0	101	1
1965	61	9	110	15	1990	26	1	114	7
1966	72	5	116	18	1991	17	2	86	5
1967	58	3	129	12	1992	28	1	94	3
1968	43	5	117	14	1993	23	2	78	5
1969	38	3	107	20	1994	26	1	89	4
1970	28	2	113	12	1995	26	4	72	8
1971	31	4	119	15	1996	32	1	69	8
1972	31	2	106	7	1997	37	1	84	5
1973	23	2	109	8	1998	34	2	76	6
1974	23	2	105	8	1999	27	4	70	8
1975	27	4	124	8	2000	28	0	85	4
1976	24	2	125	6	2001	22	2	59	5
1977	23	3	123	7	2002	17	0	65	4
1978	32	1	123	5	2003	20+	0	40+	1
1979	16	0	106	5	**Total**	**1239**	**166**	**4237**	**404**
1980	12	3	102	7	**Average**	**24**	**3**	**74**	**9**

Table 5.13: Launch Vehicle Failure Statistics[21]

[20] http://www.spacedaily.com/news/launchers-02q.html
[21] http://www.aero.org/publications/crosslink/winter2001/03.html and www.futron.com

Between 1962 and 1983, roughly 2,500 spacecraft failures of any type were recorded [Ell00]. The number for the last 20 years has been reduced by a factor of 10, approximately. Table 5.14 displays the statistics for total and partial satellite failure. Amateur radio satellites, manned vehicles, satellites exploded due to lower stage launch vehicle failure, spacecraft beyond Earth orbit, and test masses were excluded from the count. The main reason for the surge in failures in the late 1990's is the recent tendency to design and manufacture satellites faster to gain market advantages, which, unfortunately, leads to cutting corners in evaluating and testing the designs and, hence, to an increase number of satellite malfunctions. Another part of the explanation could be that reporting has increased and failure information is more readily available.

Year	Low Orbit	BOL Mech. Failure	BOL Comp. Failure	Other Failures	All Failures
1981	1	0	0	1	2
1982	1	1	1	3	6
1983	1	0	1	1	3
1984	5	0	1	2	8
1985	2	0	1	4	7
1986	1	0	0	2	3
1987	4	1	0	0	5
1988	5	0	1	2	8
1989	2	0	0	3	5
1990	2	1	0	7	10
1991	2	0	1	4	7
1992	1	0	0	3	4
1993	2	1	0	5	8
1994	2	0	0	4	6
1995	2	1	1	8	12
1996	4	3	1	14	22
1997	4	2	2	21	29
1998	7	3	3	40	53
1999	3	1	2	19	25
2000	1	1	0	17	19
2001*	9	?	?	?	24
2002*	1	?	?	?	22
2003*	0	?	?	?	17
Total	**62**	**15**	**15**	**160**	**305**

*http://www.sat-index.com

Table 5.14: Satellite Failure Statistics [SA01]

Failures occurring in the first 30 days of a satellite mission were considered beginning of life (BOL) failures. "Mechanism failures" are assumed to be failures occurring at separation and solar array or antenna deployment. "Component failures" include failures of transponders, control processors, or payload instruments. The "Other failures" column includes any other type of BOL failures plus failures occurring later in the satellite lifetime. In actuality, most satellite anomalies occur within the first couple of years of operation, as shown in Figure 5.14. This means that a great number of satellites fail to produce even a small portion of the revenue or the scientific data expected from them. The problems that cause satellite failures may be easy to fix in space or they may require fixing on Earth. Some of the problems may involve just moving the satellite to its operational orbit (see Section 5.2.5).

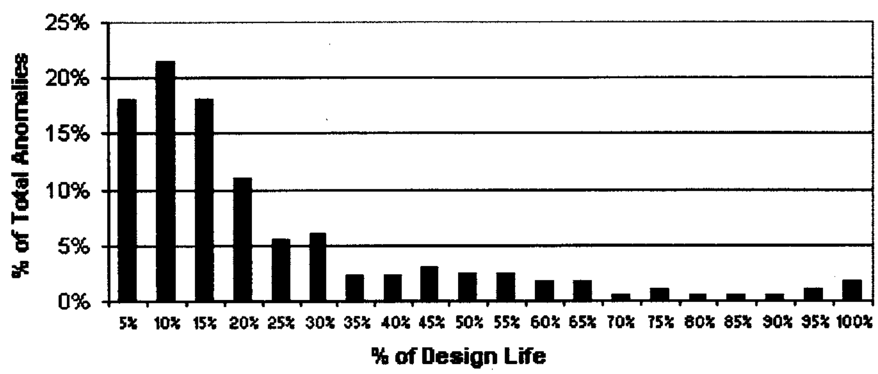


Figure 5.14: Anomalies as Percent of Satellite Design Life

(1985 – 2001 Statistics) [Fut02a]

The business case analysis presented by this work is based on the following factors: failure type, optimal orbit, type of client satellite (by function and country), and type of tug service provider (national or international, commercial, civil government, or military).

5.2.2.1 Failure Types

We are interested in two main types of satellite failures, which we have dubbed "pre-orbital" and "post-orbital."

Pre-orbital Failures

Excluding total launch vehicle failures that result in the total destruction of a satellite, pre-orbital failures are those that are caused by launch vehicle upper stage failure or by satellite apogee kick motor malfunction. They both lead to satellite being stranded in a suboptimal orbit. One difference is that an upper stage failure usually leaves a satellite much farther away from the desired destination. Another difference is in the insurance claim. As mentioned in Section 4.2.4.4, the premium rate for a launch upper stage failure and the rate due to apogee kick motor failure are assumed to be 10% and 9% of the satellite cost, respectively. The "Low orbit" column of Table 5.14 lists the number of stranded satellites since 1981. Table 5.15 summarizes the total and average (per year) number of occurrences of stranded satellites for the given periods of time.

Period	Total	Average
22 Years (1981-2002)	62	2.8
10 Years (1993-2002)	35	3.5
5 Years (1998-2002)	21	4.2

Table 5.15: Average Number of Stranded Satellites

Although the trend of increasing average occurrences of such malfunctions is unfortunate for satellite operators and insurance agencies, it suggests an increased opportunity for the provider of tugging services.

Twenty-three stranded satellites with known orbital elements were analyzed to check if any location peaks/trends would appear. Figure 5.15 shows the distribution of the satellites in terms of inclination and semi-major axis ranges. The peak is in LEO, around 28 degrees inclination, which is Cape Canaveral's launch latitude.

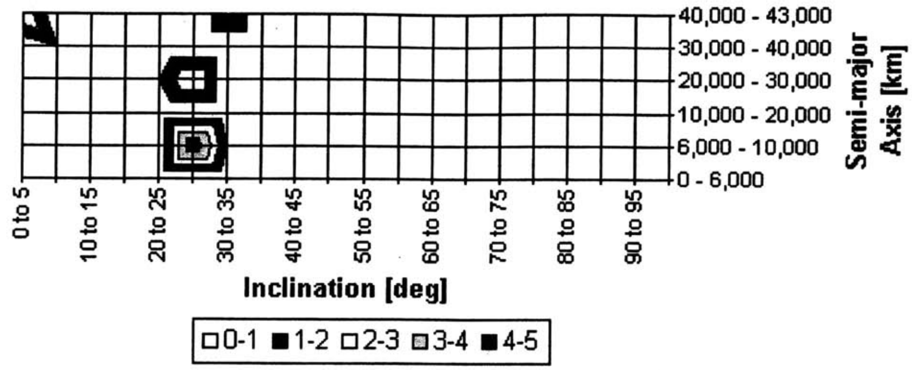


Figure 5.15: Distribution of Selected Stranded Satellites

Post-Orbital Failures

Satellites fail sometimes after successful launch and deployment into correct orbit, e.g. solar panels do not deploy or a part comes loose and needs to be reconnected. For example, although Iridium experienced no launch failures in its fifteen launches, seven satellites failed, one of which expended all its fuel accidentally and three of which experienced attitude control problems [Ell00]. In mid-1997, NASDA lost a satellite called "Midori," for which it had spent a total of $759M, having loaded it with $229M worth of NASA instruments. The mission was supposed to measure ozone levels and to be the key to an international research project on global climate changes. It reached the correct orbit but its solar panel failed to deploy, dooming the entire mission [Pra02]. Another example of post-orbital failure was the Anik-E2, which had already begun operation in GEO when its momentum-wheel control system went out of control, causing the satellite to spin around endlessly. The misfortune of the Anik-series satellite operator continued when Anik-E1's replacement experienced a simple electrical disconnection in one of its solar panels and was forced to operate on half power and to broadcast fewer channels [Pra02]. A tugging service could alleviate such problems if the space tug could move the failed satellites to the ISS to be either repaired by astronauts or sent back to Earth for refurbishment[22]. The number of post-orbital failures from 1981 to 2000 is displayed in Table 5.16. As seen from the table, 4 to 6 BOL and 7 to 12 midlife failures per year can be expected.

[22] The Space Shuttle is currently the only option with substantial down mass.

Year	BOL Failure	Midlife Failure	All Failures	Year	BOL Failure	Midlife Failure	All Failures
1981	1	0	2	1991	2	1	7
1982	3	1	6	1992	0	2	4
1983	1	0	3	1993	2	2	8
1984	1	2	8	1994	0	3	6
1985	1	2	7	1995	2	6	12
1986	0	1	3	1996	7	5	22
1987	1	0	5	1997	6	15	29
1988	1	2	8	1998	10	25	53
1989	0	1	5	1999	7	8	25
1990	5	1	10	2000	2	8	19
20 Years (1981-2000)			**Total**		52	85	242
			Average		2.6	4.25	12.1
10 Years (1991-2000)			**Total**		38	75	185
			Average		3.8	7.5	18.5
5 Years (1996-2000)			**Total**		32	61	148
			Average		6.4	12.2	29.6

Table 5.16: Number of Satellites Failed On-Orbit [SA01]

In Section 4.2.4.4, it was assumed that the associated on-orbit failure insurance was only 4% of the satellite cost. The insurance claim return, combined with the expected returns (revenues or scientific data) the satellite could produce if it were repaired, determine whether the satellite operator would prefer abandoning and possibly later replacing the satellite or having it repaired by astronauts or on Earth.

Table 5.17 divides the possible on-orbit failures in regard of ease to fix. Low difficulty problems could be fixed on-orbit by astronauts, whereas high difficulty problems must be fixed on Earth. Investigating the economics of satellite retrieval performed by astronauts, Price and Greenberg [PG88] estimated that, given a LEO retrieval-repair-relaunch scenario, $9M is required for repair on the ISS and $95M for repair on Earth. For GEO retrieval-repair-relaunch scenarios, $85M is required for repair on the ISS and $149M for repair on Earth. Even if these numbers are not completely accurate, at least they show the huge discrepancies between refurbishment in space versus on Earth. In Section 5.2.7, a cost-benefit analysis will be performed in order to determine whether repair should be pursued (based on the difficulty of the task) or whether the satellite should be abandoned.

Year	Low Difficulty	High Difficulty	Year	Low Difficulty	High Difficulty
1981	0	1	1991	0	5
1982	1	3	1992	0	2
1983	0	2	1993	1	4
1984	0	3	1994	0	3
1985	0	4	1995	1	7
1986	0	2	1996	3	13
1987	1	0	1997	2	21
1988	0	3	1998	3	34
1989	0	3	1999	1	17
1990	1	2	2000	1	17
20 Years (1981-2000)		**Total**		15	146
		Average per year		0.75	7.3
10 Years (1991-2000)		**Total**		12	123
		Average per year		1.2	12.3
5 Years (1996-2000)		**Total**		10	102
		Average per year		2	20.4

Table 5.17: Difficulty of Satellite Repair [SA01]

5.2.2.2 Optimal Orbit

The propellant mass and the total cost of a space tug will be significantly different if it were designed to move a satellite from GTO to GEO, versus from LEO to GEO (and vice versa) or from LEO to somewhere else in LEO. Additionally, statistics have shown that LEO satellites fail at an approximately 40-50% higher rate than those in GEO [El100]. However, GEO satellites are generally more expensive, so we expect a potential interest in the tugging of both LEO and GEO satellites. Figure 5.16 is a simple representation of possible target initial locations (represented by a single satellite symbol) and desired destination locations (represented by a tug-satellite system) for the satellite rescue scenario.

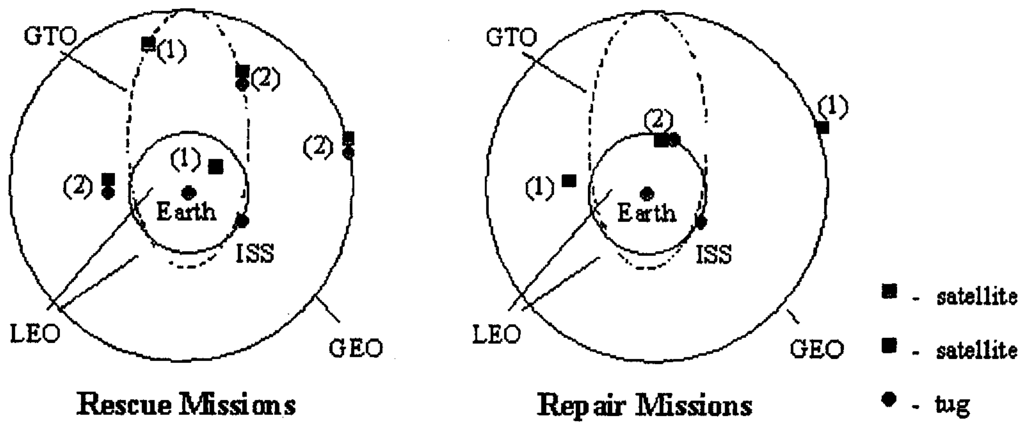


Figure 5.16: Examples of Possible Satellite Initial and Destination Locations

5.2.2.3 Type of Client Satellite

Regulations might exist that make a service more expensive for international clients. A more detailed analysis should investigate the possible implications of such a policy. This work assumes that no bias exists on country-of-origin bases when tugging is offered or a fee is charged.

With respect to client satellite function, an important factor to the analysis is the profit or scientific return that is expected from the particular satellite mission. This would be used to estimate the fee that would make tugging attractive to both the clients and the service provider.

Figure 5.17 shows the number of satellites launched between 1990 and 2001 (launch failures excluded) corresponding to the following mission types: communications (*Comm.*), Military (*Mil.*), Earth science (*E. Sci.*), technology (*Tech.*), space science (*S. Sci.*), and deep space (*Deep S.*). Although there are separate mission scenarios that deal with military satellites and LEO constellations, the satellite rescue scenario is the one that investigates their transfer to optimal orbits or to repair locations. Figure 5.17 shows the relative difference in number of satellites used for various missions in all orbits. The deep space satellites and satellites termed "other" are excluded from the study.

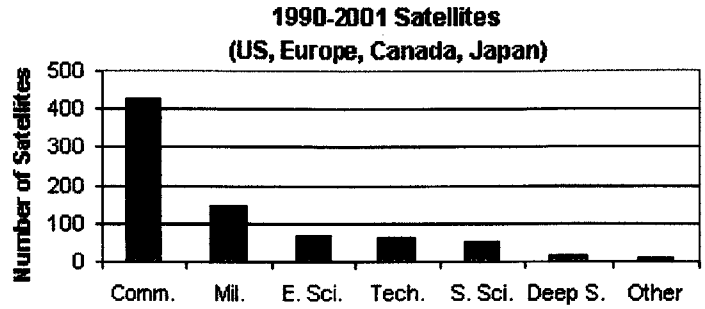


Figure 5.17: Number of Satellites vs. Mission Type [RS03]

5.2.2.4 Type of Service Provider

The results of the business case analysis might differ significantly based on the type of tug service provider: government versus commercial organization, or domestic versus international/multinational. To simplify the analysis while still capturing the main differences, we investigate the following two cases of a tug service provider: a commercial organization (U.S. or foreign) or the U.S. government.

5.2.3 Stakeholders

As in the GEO satellite retirement case, the main stakeholders in this mission scenario are the tug service provider, certain satellite operators (both commercial and government), satellite insurance companies, and third parties (most notably the launch providers). This time, however, the effect that tugging might have on the insurance business is expected to be more profound.

Satellite insurance rates depend on the total cost of the spacecraft and on the level of malfunction or anomaly in its operation. In recent years, the rates have dramatically increased, mostly due to an increase in the number of insurance claims. One factor is the increased number of satellites launched every year. Another factor is the reality that technical complexity of satellites has increased significantly over the last decade, but that reliability has decreased, mostly because of shortened manufacturing schedules. The decrease in satellite production cycle enables satellite operators to enter the market quicker, providing their customers with additional capability in shorter time. However, this puts pressure on the manufacturers, who are forced to perform less rigorous tests and evaluation of satellites before delivery. With proven technology, this rarely leads to a problem. With newer technologies, however, shortened production cycles increase the probability of failure. As a result, since 1988, major on-orbit anomalies have risen by 146%, and space insurance rates have risen by 129%. These raised rates threaten the economic viability of certain satellite ventures. Therefore, if tugging does help decrease satellite insurance rates, it will also encourage more participants in the space business. [Fut02a]

Owing to a US policy that dates back to the 1930's, the US government does not carry commercial insurance to guard against losses. It manages risk by analyzing launcher and spacecraft reliability and by paying special attention to safety.[23] The only parties that insure their assets in this scenario would be entirely commercial satellite operators and the tug owner, provided he represents a commercial firm.

5.2.4 Assumptions

Most of the assumptions used in this case study are derived from the statistics discussed above:

1. Client satellites are either stranded in LEO enroute to LEO/GEO or are stranded in GTO enroute to GEO.

2. On average, 3 stranded satellites, 5 BOL and 10 midlife failures can be expected per year in all orbits.

Since communications satellites are about two and a half times the combined number of science and technology satellites, and are about three times the number of military satellites, we expect most of the clients to be communications satellite operators. Using the numbers assumed above, as well as specific cases from the last five years, we select the following failure occurrences as a baseline case:

[23] http://www.space.com/news/insurance_991001.html

Type of Satellite	Stranded			BOL Failure			Midlife Failure		
	#	Location	Nationality	#	Location	Nationality	#	Location	Nationality
Comm.	1	GTO-GEO*	Foreign	3	1LEO, 2GEO	2US, 1For.	7	2LEO,5GEO	5US, 2For.
Sci.&Tech.	1	LEO-LEO⁺	US	1	LEO	US	2	LEO	1US, 1For.
Military	1	LEO-GTO⁺	US	1	LEO	US	1	LEO	US

*Apogee/kick motor failure
⁺Launch vehicle upper stage failure

Table 5.18: Baseline Case (per year)

The table reflects the fact that LEO spacecraft are generally research, military, or civil government. LEO commercial satellites are almost exclusively part of constellations.

3. For the baseline case of rescuing stranded satellites (i.e. the pre-orbital failure case), calculations done by our model use the following parameters, representing the most common occurrences (the majority of the numbers represent actual cases of stranded satellites):

- For LEO-to-LEO transfer, we assume that the client satellite has a mass of 800 kg (average for most LEO satellites) and is being moved from an altitude and inclination of 300 km and 80° to 800 km and 85°, respectively.
- For LEO-to-GTO transfer, we assume that the client satellite has a mass of 2000 kg (average for a GEO communications satellite) and is being moved from an apogee of 17,528 km, a perigee of 592 km, and an inclination of 2.9° to an apogee of 35,953 km, a perigee of 858 km, and an inclination of 2°.
- For GTO-to-GEO transfer, we assume that the client satellite has a mass of 2,000 kg and is being moved from to an apogee of 35,953 km, a perigee of 858 km, and an inclination of 0° to a circular 35,953 km orbit of 0° inclination.

4. For the post-orbital failures case, we assume the following parameters:

Case	Location	Failure Type	Nationality	Altitude [km]	Inclination [deg]	Mass [kg]
			Communications			
1*	LEO	BOL	US	770	86.5	725
2	LEO	Midlife	US	692.5	86.5	556
3**	LEO	Midlife	US	1,414	52	425
4	GEO	BOL	US	35,953	5	3,000
5	GEO	BOL	Foreign	35,953	0	3,000
6	GEO	Midlife	US	35,953	0	3,000
7	GEO	Midlife	US	35,953	0	2,000
8	GEO	Midlife	US	35,953	0	1,500
9	GEO	Midlife	US	35,953	7	1,000
10	GEO	Midlife	Foreign	35,953	0	2,000
11	GEO	Midlife	Foreign	35,953	0	1,500
			Science & Technology			
12	LEO	BOL	US	800	98	800
13	LEO	Midlife	US	1,400	45	800
14	LEO	Midlife	Foreign	800	85	600
			Military			
15	LEO	BOL	US	20,080	53	2,000
16	LEO	Midlife	US	1,100	63.4	1,500

*Iridium, **Globalstar

Table 5.19: Client Satellite Parameters

Note that, in general, satellites are heavier when BOL anomalies occur, due to the fact that they have more fuel at that time.

5. If using a stranded satellite's own propellant is a viable option to boost the satellite to its optimal orbit, we assume that the satellite's mission lifetime is shortened by two-thirds for LEO-to-LEO or LEO-to-GEO transfers and by one-fourth for GTO-to-GEO transfers.

6. The design lives of military and communications satellites are both assumed to be 12 years; the design life of a science satellite is assumed to be 7 years.

7. An average satellite depreciates at a rate of $21M per year [UT89].[24]

8. All commercial client satellites are insured. As mentioned before, the U.S. government does not purchase insurances.

9. For simplicity, policy issues have been ignored.

Although we have decided to neglect possible regulatory issues that deal with offering commercial tugging service to a foreign customer (the case when the service provider is a U.S. or foreign commercial company), we expect that if the tug service is provided by a government organization, it will most likely serve only national assets. Therefore, our analysis in this case (when the provider is the U.S. government) considers only U.S.-owned satellites.

10. A single company offers the tugging service (i.e. no competition exists between tug providers).

11. The revenue coming from commercial communications satellites is measured based on the number of transponders and the transponders' frequency carried by a standard communications satellite, i.e. 24 C-band and 24 Ku-band transponders at 36 MHz (see Section 5.1).

12. Since it is too difficult to try to estimate a dollar value of the returns from a scientific or military satellite mission, we model these satellites as if they were used for communications (with the same number and type of transponders specified above), but we modify the resulting revenues by multiplying them with a "value factor." The value of these non-communications missions is measured based on:

- *Volume*: How much data was expected from the mission?
- *Uniqueness*: Are there any other satellites/ground equipment that measures the same phenomenon?
- *Importance*: How critical is it to obtain the data?

Table 5.20 presents the value factors that were assumed for the business case analysis. Since the significance (or criticality) of a mission is more important than both its uniqueness and the data that is produced, it is assigned the highest weight. We assume that there is little chance that a satellite owner would decide to salvage a mission that is not critical or not unique, unless the fee for the service is much lower than the cost of sending a new satellite (if replacement were planned), which is why these characteristics are given a weight of 0. In regard to data volume, however, even if a relatively small amount of data were expected from a certain satellite, this data might still be critical or unique, so we do not eliminate the possibility that the satellite owner would decide to pay for the rescue or repair of the satellite; thus, the corresponding weight is 0.1 and not 0.

---

[24] We use this assumption instead of the linear depreciation scheme from Equation 4.6 because we do not have the necessary data for the costs of the individual satellites under investigation.

Factor	Weight	Characteristic	Weight
Criticality	0.5	Critical	1
		Of average criticality	0.5
		Not critical	0
Uniqueness[25]	0.3	Unique	1
		Semi-unique	0.5
		Not unique	0
Data Volume	0.2	Large volume	1
		Average volume	0.5
		Small volume	0.1

Table 5.20: Value Factors

13. The rescue space tug is not reusable. Designing it for a single mission is not only more affordable and realistic[26], but it also bears less risk.

14. There will be a market for at least 10 rescue tugs.

5.2.5 Competing Options

In this case study, a rescue tug can be used for the following two cases:

1. To boost a satellite to its optimal orbit.
2. To bring a satellite to the ISS for repair.

The first case is related to pre-orbital failures, and the second case is related to post-orbital anomalies during the functioning of a satellite. Figure 5.18 shows the possible routes of action.

[25] A unique mission is one that has not been performed before and is not being performed currently by another satellite. A semi-unique mission has either been done before or is going to be performed by one or a few other satellites now or in the near future. A mission is not unique if it performs a routine function.

[26] Manufacturing learning curves are still possible for one-way tugs, but not amortizing the unit cost of a single tug over several missions

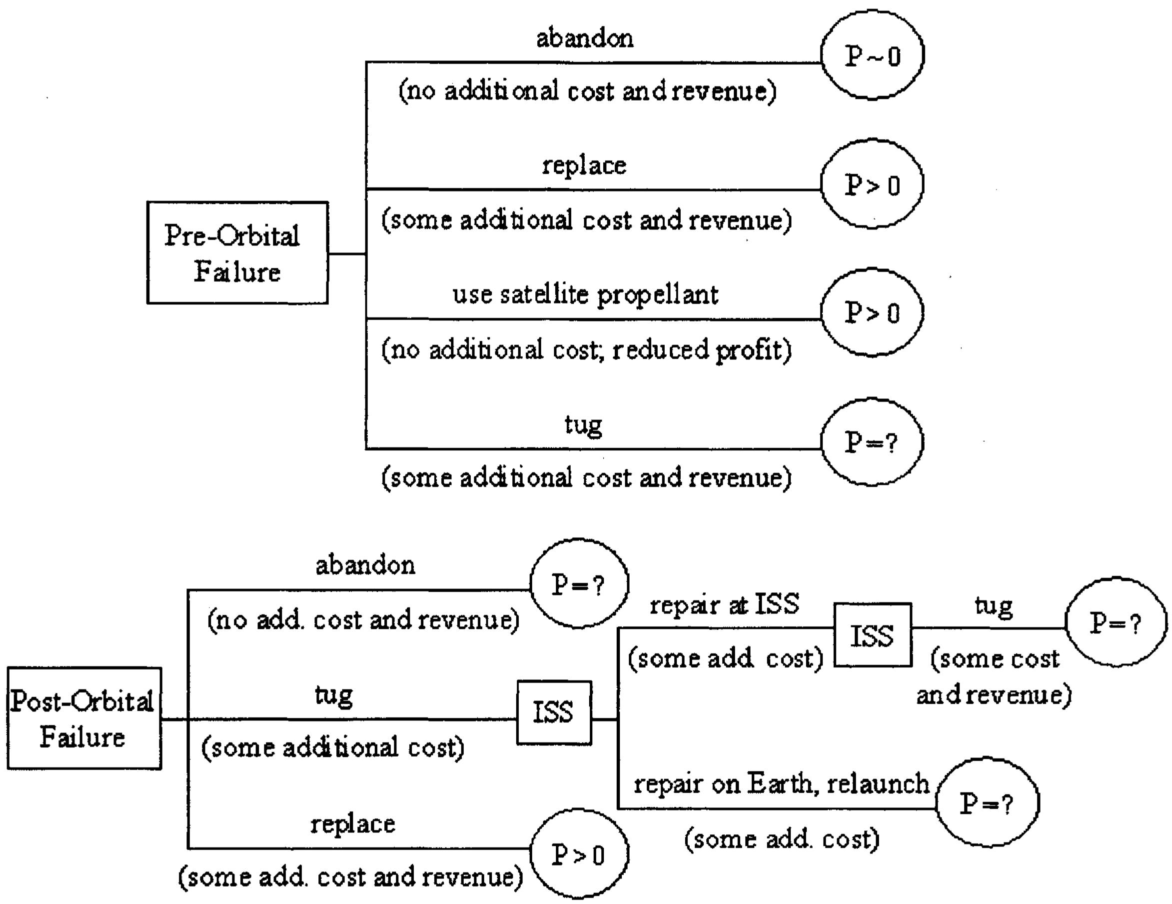


Figure 5.18: Competing Options

As shown, EVA is not a viable alternative to tugging in this mission scenario. EVA cannot be performed unless a tug delivers the malfunctioning satellite to the ISS or to the Shuttle. On the other hand, tugging such a satellite is pointless if this were not followed by EVA repair, in the cases when the problem is of relatively low complexity. Thus, EVA does not compete with tugging, but with repair on Earth. Effectively, the decision to choose tugging competes only with the choices of satellite abandonment, satellite replacement, or using the satellite's own propellant to reach the desired orbital location (if this is possible[27]). Abandonment or replacement would be preferred if it were not possible to move or fix the satellite in space or if the service were too expensive.

[27] For this option to exist, the total delta-V to reach the intended orbit must be smaller than the cumulative delta-V budgeted for lifetime stationkeeping.

Using the satellite's propellant supplies for transfer to the optimal orbit would be acceptable and affordable if relatively small distances were to be covered.

5.2.6 Fee Estimation for Satellite Rescue

Approach

The general approach described in Section 4.4.2 was followed when the client was a communications satellite owner. For the remaining cases, the approach was modified after the first two steps. Steps 3 was eliminated because, assuming no reusability, the total cost of the tug was also the minimum fee that needs to be charged. Step 4 was modified by modeling the military and science missions as if they were performed by communications satellites and then multiplying the resulting revenues by the value factors listed in Table 5.20. Subtraction of the minimum fee (i.e. the total cost) for tugging from the estimated revenues produced the maximum profit for the client. It was assumed that the decision whether to choose tugging versus the other competing options was based solely on the results from comparison of the respective profits.

In the cases when tugging is considered the best option, we expect that the client would be willing to pay less than the second-best alternative cost. To estimate what profit the provider of the service could make, while nonetheless keeping tugging attractive to the potential clients, we subtract the profit from the second-best option from the profit generated by using a commercially owned tug if the minimum fee was charged. We divide this result by two, and then add it to the minimum fee for tugging. For example, if it is estimated that the cost to replace a satellite is $350M with an expected revenue of $500M and a profit of $100M (assuming operational cost is 10% of the revenue, 500 – 350 – 50 = 100), and the cost for tugging (i.e. the minimum fee) is $200M with an expected revenue of $400M and, therefore, a profit of $160M, the fee calculation would be: (160-100)/2 + 200 = 230. A fee of $230M results in $30M profit for the provider and a profit of $30M more than the second-best option for the satellite operator (which was $100M). Thus, this is the mid-way fee that should be charged by a commercial service provider. (Please note that the approach is different than the mid-way fee calculations in the GEO satellite retirement case!) The insurance claim that a commercial satellite operator would request is not included in this calculation in order to serve as a cost uncertainty margin. If the tug is owned by the government, a fixed nominal surcharge would be charged for the service in addition to the minimum fee, resulting in a total charge that is much less than the mid-fee charged by a commercial tug service provider.

Total Utility

Table 5.21 shows the relative weights of the tug attributes. Because the satellite rescue scenario involves functional satellites, damage must be carefully avoided and, therefore, *mating capability* is very important. *Transfer capability* is important because a satellite cannot perform its mission unless delivered to the required destination. *Timeliness* becomes critical if 1) a satellite is stranded in the radiation belts zone, the satellite's orbit is decaying too fast, or 3) a satellite cannot be powered up again after battery depletion. Additionally, timeliness is important because satellite owners would prefer to begin generating profit as soon as possible. Nevertheless, relative to the mating and transfer capabilities of the tug, the importance of timeliness is moderate. Since tugs in this scenario are assumed to be non-reusable[28] (because the orbital transfer would exhaust most/all of their fuel, and because there might not be another satellite stranded in close vicinity), *adaptability* is of even lower priority. Adaptability is still somewhat important, though, because the grappling mechanism attached to the tug might not be optimal for some missions. Grappler universality is designed to negate this issue, but since 100% universality is unrealistic, we still assign some importance to adaptability. Note that adaptability would mostly be influenced by the parking location of the tug, since parking on the ground would allow the attachment of the optimal grappler for a given mission.

Attribute	Weight
Mating Capability	0.3
Transfer Capability	0.3
Adaptability	0.1
Timeliness	0.3

Table 5.21: Relative Weights of Attributes

[28] The tug would either be re-orbited or permanently attached to the satellite, so that it can provide stationkeeping for it until the tug's fuel supplies are fully exhausted.

The rescue missions due to pre-orbital and post-orbital failures are considered separately because corresponding optimal tug architectures, potential customers, and alternative options differ for both cases.

5.2.6.1 Pre-Orbital Failures

Optimal Architectures

In the event of a pre-orbital failure, the results from the tradespace analysis indicated that the optimal space tug for this mission scenario should be parked on the ground and controlled via supervision[29]. It should use storable bipropellant (N2O4/N2H4) for GTO-to-GEO transfers and ion electric propulsion (Xe) for LEO-to-LEO and LEO-to-GTO transfers.[30] Since the grappler can be selected after a contract has been signed between the tug service provider and the satellite operator, there is no need to specify a given mass and capability for the grappler, but it should be noted that the lower the mass, the lower the cost per function and the minimum fee. The decision as to which grappler mass and capability to choose would be based on the fee the client is willing to pay and the risk he is willing to take by using a grappler of a certain capability.

Total Cost

The total cost of the tug mission was estimated as described in Section 4.2.4, except that the depreciation of the tug was excluded. The market predictions have shown us that at least a dozen cases per year could require tug rescue missions, so a tug is not expected to be stored on Earth for more than a couple of months.

The unit cost of a tug was calculated based on the assumption that at least 10 tugs would be built, with a 95% building process learning curve. The formula utilized by the NASA Spacecraft/Vehicle Level Cost Model for estimating the total cost of 10 tugs, C_{10}, was reverse-calculated to be approximately:

---

[29] Without using a TDRSS data link, the capture maneuver of the tug needs to be time coordinated with limited ground contact windows (about 17 minutes contact time per revolution of 106 minutes period [Rey99]). This amount of time is probably insufficient for successful docking through teleoperation.
[30] Our Matlab model used only Hohmann transfers. This has affected the results for the transfer capability of the tug and, hence, the optimal propulsion system.

$$C_{10} = 6.4147 \cdot M_d^{0.6225} \quad (5.8)$$

where M_d is in kilograms and C_{10} is in \$M (\$FY03). The rest of the costs were calculated as described in Section 4.2.4. The results are shown in Table 5.22 where the minimum fee is equal to the total cost of the tug and its rescue mission, including the tug's launch cost.

Location-Destination [-]	Grappler Mass [kg]	Dry Mass [kg]	Prop. Mass [kg]	Minimum Fee [$M]	Total Utility [-]
LEO-LEO	300	704.55	531.17	174.16	0.33
	400	818.18	564.95	219.56	0.37
	500	931.82	598.74	261.99	0.39
	600	1045.50	632.53	304.19	0.41
	700	1159.10	666.32	346.16	0.43
	800	1272.70	700.11	387.96	0.43
LEO-GTO	300	704.54	274.80	174.50	0.33
	400	818.18	288.57	217.05	0.37
	500	931.82	302.33	259.31	0.39
	600	1045.50	316.10	301.32	0.41
	700	1159.10	329.87	343.11	0.43
	800	1272.70	343.64	384.73	0.43
GTO-GEO	300	619.32	647.39	191.26	0.42
	400	732.95	691.95	237.52	0.45
	500	846.59	736.50	282.68	0.48
	600	960.23	781.05	327.56	0.50
	700	1076.90	826.81	371.01	0.51
	800	1230.80	887.12	418.28	0.52

Table 5.22: Minimum Fees for Pre-Orbital Failures Rescue Tugs

5.2.6.2 Post-Orbital Failures

All post-orbital failure cases use an ion electric tug (fuel: xenon) for the transfer to the ISS and possibly back to the satellite's operational orbit. Considering only the three grappler masses specified above, the main results from modeling each mission case are presented in Table 5.23 (ISS repair case; cost of repair not included). The costs corresponding to a government owner are slightly higher due to the fact that only U.S. launch vehicles could be used, which, as noted above, are more expensive than their foreign counterparts. Cost per function was estimated by dividing the total tug cost by the total utility of the tug.

Case	Grappler Mass [kg]	Dry Mass [kg]	Prop. Mass [kg]	Total Utility [-]	Com. Tug Cost [$M]	Cost per Function [$M]	Gov. Tug Cost [$M]	Cost per Function [$M]
1	300	816.12	1446.30	0.33	186.05	565.36	192.94	586.31
LEO	500	1132.50	1802.60	0.39	274.93	699.42	289.11	735.51
	700	1448.80	2158.90	0.43	362.87	853.64	385.84	907.69
2	300	774.33	1279.20	0.33	328.34	997.76	220.56	670.24
LEO	500	1091.00	1636.70	0.39	200.19	509.29	273.65	696.18
	700	1311.80	1610.80	0.43	281.73	662.77	357.48	840.98
3	300	573.88	477.33	0.33	166.64	506.38	170.81	519.06
LEO	500	841.84	640.08	0.39	255.43	649.82	262.01	666.56
	700	1111.40	809.14	0.43	339.49	798.66	350.98	825.69
4	300	823.03	1474.00	0.33	227.21	690.44	199.32	605.69
GEO	500	1077.60	1583.00	0.39	317.15	806.83	286.84	729.73
	700	1332.10	1692.00	0.43	407.78	959.30	374.11	880.10
5,6	300	850.55	1584.00	0.33	226.85	689.34	247.01	750.61
GEO	500	1107.40	1702.40	0.39	321.92	818.97	341.53	868.87
	700	1453.80	2178.80	0.43	426.78	1004.00	452.14	1063.65
7,10	300	738.28	1134.90	0.33	212.82	646.72	225.03	683.83
GEO	500	995.15	1253.30	0.39	303.88	773.08	319.58	813.01
	700	1252.00	1371.70	0.43	395.18	929.66	414.71	975.60
8,11	300	682.15	910.40	0.33	203.19	617.45	213.57	649.00
GEO	500	939.02	1028.80	0.39	296.26	753.70	309.09	786.33
	700	1197.20	1152.30	0.43	386.51	909.27	402.91	947.85
9	300	608.88	617.35	0.33	191.00	580.40	198.47	603.12
GEO	500	862.49	722.67	0.39	283.47	721.16	293.81	747.45
	700	1119.30	840.80	0.43	374.12	880.13	387.81	912.31
12	300	931.01	1905.90	0.33	202.08	614.08	207.25	629.79
LEO	500	1267.30	2341.90	0.39	295.00	750.49	302.02	768.35
	700	1603.60	2777.90	0.43	386.48	909.20	395.01	929.26
13	300	572.08	470.12	0.33	168.15	510.96	170.61	518.45
LEO	500	832.62	603.21	0.39	256.57	652.72	259.19	659.38
	700	1094.70	742.24	0.43	343.58	808.27	346.93	816.15
14	300	774.01	1277.80	0.33	187.64	570.21	191.38	581.57
LEO	500	1623.70	1087.80	0.39	300.36	764.13	305.30	776.70
	700	1311.80	1610.70	0.43	362.25	852.20	367.94	865.58
15	300	733.33	1115.10	0.33	183.81	558.56	187.18	568.80
LEO	500	991.30	1237.90	0.39	270.97	689.35	275.03	699.68
	700	1249.30	1360.70	0.43	356.94	839.70	362.02	851.65
16	300	765.44	1243.60	0.33	186.84	567.77	190.50	578.89
LEO	500	1047.10	1461.30	0.39	275.92	701.95	280.49	713.58
	700	1328.80	1678.90	0.43	363.69	855.59	369.54	869.35

Table 5.23: Tug Costs for Post-Orbital Failures Rescues
(ISS repair case)[31]

[31] Included are only the costs of tugging a satellite from its initial orbit to the ISS, but not the repair costs.

5.2.7 Cost and Benefit Analysis of Competing Options

This section describes how the cost and revenues from the competing options were estimated and compared.

5.2.7.1 Pre-Orbital Failures

Cost

Using the NASA Spacecraft/Vehicle Level Cost Model, an approximate design and production cost was assigned to each of the satellite masses assumed in the baseline model. For the commercial provider/client case, the launch cost was calculated by taking the average cost per kilogram for all launch vehicles capable of carrying a tug/satellite to its desired destination. When considering a government agency as a provider or a client, only U.S. launch vehicles were included.

The cost of abandoning a stranded satellite was equal to the design, manufacturing, and launching of the satellite minus the insurance claim. The cost of replacing the satellite was double the cost of designing, manufacturing, and launching it.[32] Although commercial communications satellites were assumed to purchase insurance, the cost of the purchased insurance was not added to the cost of replacement because it approximately balanced out with the launch failure insurance claim. The cost of using the satellite's own propellant to move it to the correct orbit (if possible) was assumed to be equal to the cost of abandonment. The cost of tugging that was used in the cost and benefit analysis was the minimum fee calculated in the previous section. For each mission, three cases were considered, for which a tug with a different grappler was used—300 kg, 500 kg, or 700 kg. In addition to that, two types of tug cost were included—one for a commercial tug provider and one for a government provider. A tug with a high capability grappler was expected to rescue a stranded satellite without any damage, so in this case we assumed that the entire operational lifetime of the satellite was

[32] Since the satellite has already been designed, the second satellite, i.e. the replacement, might cost 60%-90% of the cost of the first satellite. This does not account for inflation and assumes that no redesign needs to be made. Since redesign might need to be implemented (it the failure was in a satellite subsystem, not in the launch vehicle), there is uncertainty as to whether the total cost of the new satellite would be greater or

preserved. For lower capability grapplers, a certain number of years was subtracted from the expected lifetime of the client satellite to account for the higher probability of damage during tugging.

Revenue

There is no revenue from abandoning a stranded satellite. Replacing it would result in revenue that would be calculated in the same way we would calculate revenue for a communications satellite, subtracting the assumed depreciation. The same relationship was assumed in the estimation of the revenue in the case when the satellite's own propellant was used, but only for one-third of the satellite design life since in this case it was assumed that two-thirds of the design life was sacrificed. When calculating the revenue from tugging, there is a high uncertainty regarding the number of years by which the satellite's operational life is reduced as a result of damage inflicted by the tug. For this reason, we tested for various numbers of years lost and deduced the sensitivity in revenue to these variables.

Profit

For all competing options, profit was calculated as the difference between revenue and cost. The results for a stranded communications satellite (2000 kg, GTO-to-GEO transfers) are shown in Table 5.24.

	Grappler [kg]	Abandon [$M]	Replace [$M]	Own prop. [$M]	Com. Tug [$M]	Gov. Tug [$M]
Cost	300	299.59	656.17	299.59	191.26	194.33061
	500	299.59	656.17	299.59	282.68	287.19179
	700	299.59	656.17	299.59	371.01	375.79866
Revenue	300	0.00	1001.62	688.21	897.15	897.15
	500	0.00	1001.62	688.21	949.38	949.38
	700	0.00	1001.62	688.21	1001.62	1001.62
Profit	300	-299.59	345.44	388.62	705.89	702.82
	500	-299.59	345.44	388.62	666.70	662.19
	700	-299.59	345.44	388.62	630.61	625.82

Table 5.24: Competing Options Comparison for Stranded Communications Satellite

lower than the cost of the original satellite (and by how much), and therefore we compromise by assuming

As seen in Table 5.24, the abandonment of this large and expensive satellite resulted in a negative profit. Replacing it or using its own propellant for the transfer to GEO would cost too much, so it was determined that tugging should be the option chosen by the satellite operator. Even if we altered the assumptions of the sacrifice in operational life due to using the satellite's on-board propellant—from one-fourth to one-tenth—the resulting profit of $576.67M would still be lower than the profit associated with tugging. However, the results in Table 5.24 assumed that the tug reduced the operational life of the satellite by one year if its grappler was of low capability (300 kg) and by one-half year if its complexity was medium (500 kg). No reduction was assumed if a high capability grappler (700 kg) was used. ***These numbers turn out to be crucial in the business case analysis of a rescue tug.***[33] The profits from tugging resulting from varying them, applied to the communications satellite case, are presented in Figure 5.19. It is shown that tugging is of value (i.e. results in higher profits than the alternative options) only if a low mating capability tug reduced satellite lifetime by no more than five years, a medium mating capability tug reduced it by no more than four and a half years, and a high mating capability tug reduced it by no more than four years. The profits from tugging become negative if satellite operational life were reduced by eight, seven and a half, and seven years, respectively.

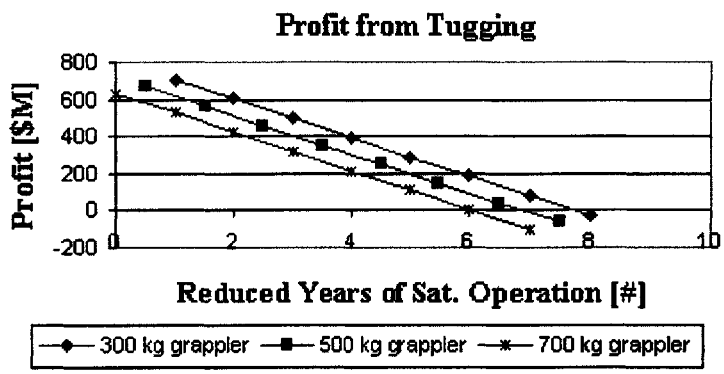


Figure 5.19: Sensitivity to Communications Satellite Reduction of Life due to Tugging

that the two satellites are of equal cost.

[33] This drives the need for developing high reliability rendezvous and grappling technologies, which was not critical in the GEO satellite retirement scenario.

When science or military satellites are stranded in suboptimal orbits, baseline revenues from each option are multiplied by the value factor that characterizes the specific mission. Table 5.25 presents the profits for various value factors, assuming that the life of a science satellite were shortened by two-thirds and by half a year if, respectively, on-board propellant was used and a tug of medium grappler capability was used.

Value Factor	Abandon [$M]	Replace [$M]	Own prop. [$M]	Com. Tug [$M]	Gov. Tug [$M]
1.00	-159.22	127.10	-167.46	165.05	160.71
0.90	-159.22	53.98	-191.84	97.14	92.80
0.85	-159.22	17.41	-204.03	63.19	58.85
0.82	-159.22	-4.53	-211.34	42.82	38.48
0.75	-159.22	-55.72	-228.40	-4.71	-9.05
0.70	-159.22	-92.28	-240.59	-38.66	-43.01
0.67	-159.22	-114.22	-247.90	-59.04	-63.38
0.65	-159.22	-128.84	-252.78	-72.62	-76.96

Table 5.25: Profits based on Value Factors
(science satellite)

For the assumed parameters, tugging was found to be preferable in all failure cases. Due to the lack of insurance, many cases led to greater losses than revenues. Therefore, we expect an interest in tugging mostly for scientific satellites whose data returns are: 1) critical, unique, and of large volume (1.00); 2) critical, unique, and of average volume (0.90); 3) critical, semi-unique, and of large volume (0.85); 4) critical, unique, and of small volume (0.82).

Testing the sensitivity toward assumed satellite life reduction due to tugging for a mission with a value factor of 1, it was observed that a tug with a medium, i.e. 500 kg grappler capability, was of value only if satellite life reduction did not exceed a year. For a 300 kg grappler, the limit was found to be two years, and for a 700 kg grappler it was found to be half a year. These limits became slowly extended for missions of lower values. Repeating the analysis for a military satellite, the corresponding results were found to be five and a half years (300 kg) and four and a half years (500 kg and 700kg). These numbers were higher due to the longer design life of a military satellite as compared to a science spacecraft. Another difference was that the military would not be interested in salvaging only missions that were: 1) non-critical and non-unique; 2) of average criticality and non-unique; 3) non-critical, semi-unique, and producing average or small data volume.

Charged Fee

As suggested in Section 5.2.6, in order to calculate the fee that should be charged by a commercial service provider, we first subtracted the profit from the second-best option from the profit from using a tug, divided by two, and added the resulting number to the minimum fee for tugging. Using the baseline assumptions, we obtained the following mid-way fees:

Grappler [kg]	Science Sat. Fee	Prov. & Cl. Profit	Military Sat. Fee	Prov. & Cl. Profit	Comm. Sat. Fee	Prov. & Cl. Profit
300	210.93	36.77	416.85	242.35	352.96	161.71
500	280.97	18.97	485.89	226.58	426.23	139.04
700	349.17	3.01	557.03	213.92	496.79	120.99

Table 5.26: Mid-Way Fees [$M] for Stranded Satellites

If the government owned the tug, a fixed nominal surcharge such that tugging remains affordable for the majority of the potential clients should be added to the minimum fee. The government-imposed fees for a surcharge of $1M are listed in Table 5.27. As seen, the difference in charged fees between commercial and government provider was greatest when applied to military satellites and least when applied to communications satellites.

Grappler [kg]	Science Satellite	Military Satellite	Comm. Satellite
300	176.26	176.08	195.33
500	267.34	261.41	288.19
700	352.34	348.34	376.80

Table 5.27: Government Fees for Stranded Satellites

For all mission types, the fee charged by a government provider was lower than the mid-way fee charged by a commercial organization if the fixed surcharge was not greater than $14M. For surcharges of $15M or more plus the estimated minimum fee, communications satellite operators would pay less if the tug service provider were a commercial organization; a surcharge of approximately $140M is needed to make government-owned tugs less attractive for science rescue missions, and about $230M for the rescue of military satellites. This discrepancy is due to the fact that, due to high costs and low revenues, the second-best alternative in the latter two cases (military and science satellites) is much less profitable than tugging.

It is important to note that all of the above calculations assumed that there would be at least 10 customers in order to justify the assumed learning curve. Based on the statistics and trends shown in Table 5.14, we had assumed in Section 5.2.4 that there would be three stranded satellites on average per year. Since the value of the tugging option will be compared to the value of the alternative options, the tug service provider needs to make sure that the charged fee is such that it is affordable (and preferable!) to at least two of the three potential clients a year.

5.2.7.2 Post-Orbital Failures

Analysis of post-orbital failures followed the same procedure as in the pre-orbital failure analysis, with the single difference that the option of using the satellite's own propellant was excluded because it was infeasible and the option of repairing the satellite on Earth was added. Refurbishment on Earth required a tug to transfer the malfunctioning satellite to the ISS, from which location it would be picked up by the Shuttle and brought down to Earth. The return trip of the satellite to its operational orbit did not require tug service because a launch vehicle would be purchased for the transfer to the desired location. Statistically, the cost of the repair-on-Earth option was cited as much higher in comparison to the cost of repair in space (see Section 5.2.2.3). However, astronauts can perform only low-complexity repairs (currently and in the near future), hence this option is needed for malfunctioning valuable space assets that would be too expensive to replace and could not be fixed in space. Due to the complexity of the required repair task, we assumed that the cost of the repair service performed on Earth would be 150% what an EVA repair would cost, although EVAs are themselves known to be very expensive.

Ellery [Ell00] has quoted ~$70,000/man-hour as the cost of an EVA. Special training and possibly bringing new parts for replacement or upgrade must also be considered. The Solar Maximum EVA repair lasted 7h and cost $55M.[34] Intelsat VI was repaired for $150M [GG88]. The first Hubble repair mission lasted a total of 35h (currently the longest EVA) and cost about $700M [El100], but this represents a singular case that is not expected to be repeated. Based on these statistics, we can divide the malfunctions that are fixable in space into three categories, with respect to task complexity. The simplest repairs would cost $50M, the ones of average complexity would cost $100M, and the most complex repairs would cost $150M. We added these costs to the tug total costs calculated earlier. The result was the minimum fee charged for repairs on the ISS or in its vicinity.

Profit

The comparison between the profits from all competing options gave different results based on the assumed complexity of the repair task. Table 5.28 lists the post-orbital failure cases (see Table 5.19) that identified the same option as optimal for any task complexity.

Case	Optimal Option	Main Reason
4	Tugging	Replacement cost was too high.
5	Tugging	Replacement cost was too high.
6	Tugging	Replacement cost was too high.
12	Replacement	Replacement produced more revenue.
14	Replacement	Replacement cost was lower.
15	Tugging	Replacement cost was too high.

Table 5.28: Optimal Options for Cases 4, 5, 6, 12, and 15

The results for the most interesting of the other cases are listed in the tables below, given grappler masses of 300kg, 500 kg, and 700kg. The option of abandonment was omitted because it always resulted in negative profits.

[34] http://www.otterbein.edu/Home/fac/UWTRTT/web/spaceflt.html

Task Complexity	Grappler Mass [kg]	Replacement Profit	Com.Tug ISS Profit	Gov.Tug ISS Profit	Com.Tug Earth Profit	Gov.Tug Earth Profit
Low	300	671.85	**765.57**	758.67	751.06	746.16
	500	671.85	**676.69**	662.50	666.52	657.16
	700	**671.85**	588.75	565.78	580.03	564.54
Average	300	671.85	**715.57**	708.67	676.06	671.16
	500	**671.85**	626.69	612.50	591.52	582.16
	700	**671.85**	538.75	515.78	505.03	489.54
High	300	**671.85**	665.57	658.67	601.06	596.16
	500	**671.85**	576.69	562.50	516.52	507.16
	700	**671.85**	488.75	465.78	430.03	414.54

Table 5.29: Case 1 Profits [$M]

In Case 1, low complexity repair tasks placed preference on tugging for 1) repairs on Earth or the ISS using a tug with a 300 kg grappler, or 2) repairs on the ISS, using a tug with 500 kg grappler. Average complexity tasks would lead to tugging only if the tug had a low complexity grappler (due to the low service cost) and the repair was performed on the ISS. High complexity repairs were considered too expensive for this case, so replacement would be launched instead. Please bear in mind that the cost of reboosting the satellite from the ISS back to its operational orbit is included in the calculations; however, it is assumed that after repair on Earth, a satellite will be sent to the intended location (operational or a transfer orbit) via a launch vehicle and a tug will not participate in the transfer.

Task Compl.	Replace	Com.Tug ISS	Gov.Tug ISS	Com.Tug Earth	Gov.Tug Earth
Low	401.47	**738.79**	726.58	722.34	711.97
	401.47	**647.73**	632.04	634.30	621.19
	401.47	**556.43**	536.91	545.91	529.78
Average	401.47	**688.79**	676.58	647.34	636.97
	401.47	**597.73**	582.04	559.30	546.19
	401.47	**506.43**	486.91	470.91	454.78
High	401.47	**638.79**	626.58	572.34	561.97
	401.47	**547.73**	532.04	484.30	471.19
	401.47	**456.43**	436.91	395.91	379.78

Table 5.30: Cases 7 and 10 Profits[35] [$M]

[35] Case 7: US GEO satellite, midlife failure; Case 10: Foreign GEO satellite, midlife failure. Both are at 0 deg inclination and weigh 2,000 kg.

For Case 7 and Case 10, tugging and repair would be preferred for all tasks except for high complexity repairs on Earth when the tug has a 700-kg grappler.

Task Compl.	Replace	Com.Tug ISS	Gov.Tug ISS	Com.Tug Earth	Gov.Tug Earth
Low	401.47	**738.79**	726.58	722.34	711.97
	401.47	**647.73**	632.04	634.30	621.19
	401.47	**556.43**	536.91	545.91	529.78
Average	495.66	**698.42**	688.04	650.03	640.38
	495.66	**605.35**	592.52	560.58	549.06
	495.66	**515.11**	498.70	473.66	459.33
High	495.66	**648.42**	638.04	575.03	565.38
	495.66	**555.35**	542.52	485.58	474.06
	495.66	465.11	448.70	398.66	384.33

Table 5.31: Cases 8 and 11 Profits[36] [$M]

Case 8 and Case 11 favored tugging and repair on Earth or the ISS for low and average complexity tasks, except when an average repair was performed on Earth and a high grappler capability tug was used for the transfer mission. For high complexity tasks, tugging was preferred when: 1) 300 kg grappler was used (due to the low cost of the tug), and 2) 500 kg grappler was used to transfer a satellite for repair on the ISS.

Task Compl.	Replace	Com.Tug ISS	Gov.Tug ISS	Com.Tug Earth	Gov.Tug Earth
Low	603.34	**760.62**	753.14	729.06	721.18
	603.34	**668.14**	657.81	640.32	630.08
	603.34	577.49	563.81	553.43	540.51
Average	603.34	**710.62**	703.14	654.06	646.18
	603.34	**618.14**	607.81	565.32	555.08
	603.34	527.49	513.81	478.43	465.51
High	603.34	**660.62**	653.14	579.06	571.18
	603.34	568.14	557.81	490.32	480.08
	603.34	477.49	463.81	403.43	390.51

Table 5.32: Case 9 Profits[37] [$M]

In Case 9, tugging was selected for 1) any complexity repair on the ISS that employed a tug with a 300 kg grappler, 2) low or average complexity repairs on the ISS for which the rescue tug had a 500 kg grappler, 3) low or average repairs on Earth when

[36] Case 8: US GEO satellite, midlife failure; Case 11: Foreign GEO satellite, midlife failure. Both are at 0 deg inclination and weigh 1,500 kg.
[37] Case 9: US GEO satellite, midlife failure, drifted to 7 deg inclination, weighing 1,000 kg.

the tug had a 300 kg, and 4) low complexity repairs on Earth when the tug had a 500 kg grappler.

Charged Fee

The same approach was used for calculating the actual charged fee as in the pre-orbital failure cases. The ranges of fees presented in Table 5.33 are for a government fee surcharge of $1M and depend mainly on the complexity of the repair, the grappler capability, and the assumed damage done to the satellite during tugging. ***Science and LEO communications missions are not included because they favor the option of replacement.***

Sat. Type	Com. ISS	Gov. ISS	Com. Earth	Gov. Earth
GEO Comm.	320-670	265-605	335-690	280-640
Military	320-530	240-515	330-585	260-580

Table 5.33: Charged Fee Ranges

It is important to bear in mind that at least 10 tugs need to be employed in order to justify the learning curve assumption. Based on the statistics and trends shown in Table 5.14, an assumption was made in Section 5.2.4 that 5 BOL and 10 midlife failures can be expected per year. This provides a sufficient number of potential clients, as long as the charged fee is kept low enough to allow at least about 1/3 of the potential clients.

5.2.8 Conclusions

Space tugs can potentially save tremendous amounts of money by mitigating the ramifications of failed satellites and the extremely high insurance premiums for expensive spacecraft, as well as give companies assurance that failures will not cause them to lose their competitive edge due to delays [Par02]. Given the statistically predicted regular occurrences of satellite failures, it seems probable that a supervised tug could provide a valuable service, especially if the cost of tugging decreased and the reliability of the service increased with time.

For a stranded communications satellite that needed to go from GTO to GEO (i.e. execute apogee burn and phasing), tugging is of value (i.e. results in higher profits than the alternative options) only if a low mating capability tug reduced the satellite lifetime by no more than five years, a medium mating capability tug reduced it by no more than four and a half years, and a high mating capability tug reduced it by no more than four years. For stranded science satellites, the corresponding numbers are two, one, and half a year; for military satellites, the numbers are five and a half, four and a half, and four and a half, respectively.

When the tug service is offered by a commercial company, the fee that is charged for rescuing stranded satellites was estimated to be between $210M and $350M for a science satellite, between $350M and $500M for an average communications satellite, and between $415M and $560M for a typical military satellite. The fees depended not only on the selected grappler sophistication, but also on the assumed number of sacrificed satellite years caused by a possible damage due to tugging. When the tug service is provided by a government organization, a nominal surcharge of a few million dollars was charged in addition to the minimum fee for tugging. It is clear that these fees will warrant rescue tugging only for high value satellites above the $200M class. The fees are roughly one order of magnitude higher than for the GEO satellite retirement case, mainly because of the more demanding orbital maneuvers and because the costs are not amortized over several satellites.

When rescuing malfunctioning satellites that are already in their optimal orbit, tugging was always the optimal option for all military and most GEO communications baseline satellites. Scientific missions were associated with higher revenues and lower costs for launching a replacement as compared to tugging and repair. Most LEO communications satellites that were investigated also favored the replacement option due to the lower cost of launching a replacement.

Both the pre-orbital and the post-orbital failure analyses showed that although the minimum fee associated with a government tug service provider was slightly higher than the minimum fee corresponding to a commercially offered service, the fee actually charged in the former case was much lower. Theoretically, this means that more potential customers would be interested in purchasing the tug service. However, there exist a number of policy issues that could actually reduce the size of the potential market, limiting it to U.S. satellites only.

5.3 Deployment of a Family of Tugs

Based on the two case scenarios, a family of tugs could be developed by using a common platform and by sharing components. Modularity is a key component of the tug family concept. It is introduced to the tug design via three modules: bus, propulsion, and mating mechanism.

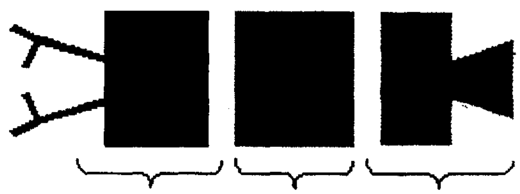


Figure 5.20: Modularity of Tug

Although the optimal tug for the GEO satellite retirement scenario is a storable bipropellant spacecraft and the best tug for most rescue missions is an electric spacecraft, they can still use a common bus. Various types of grapplers can be attached to this bus and be used for either of the mission scenarios. However, at the initial stages of offering tugging services, it does not make economic sense to have six types of grapplers and a large number of propulsion tanks of different sizes. We suggest that until tugging is established as a common practice, only three types of grappling mechanisms should be produced and kept in storage: 300 kg, 500 kg, and 700kg, corresponding to low, medium, and high capability, respectively. We also recommend fabricating only two types of propulsion tanks: a 45 kg tank for electric propulsion and 100 kg tank for storable fuel.[38] The propellant requirements will vary for each mission, so a different number of these tanks will be attached to the bus of each tug.

We want to once again emphasize the importance of modularity. A more detailed investigation of space modularity is beyond the scope of this thesis but it is strongly recommended to be carried in the future. The value of modularity is mainly in making designs more risk-tolerant and flexible. Tugs need to be able to deal with a variety of targets at various locations, and different configurations of its modules can help it perform sufficiently well for a lower cost. Also, tugs need to be designed in such a way that only slight modifications are needed if the current paradigm changes and satellites start being designed for servicing, which we hope will happen soon.

5.4 Chapter Summary

This chapter used the design methodology described in the previous chapter to analyze two mission scenarios: the retirement of GEO commercial communications satellites and the rescue of stranded and malfunctioning satellites. The GEO satellite retirement business case showed that providing tugging services makes economic sense in several cases (see Table 5.12) and is strongly dependent on the uncertainty of cost estimations and the length of the period of extended satellite operation. As long as the cost uncertainty margin did not exceed about $10M, it was shown that a sufficient number of commercial communications satellite operators could claim that providing the tug service would be valuable and economically justified. The satellite rescue scenario analysis was based on a somewhat different approach, which led to the major conclusion that tugging might be of high value to military and GEO commercial communications missions, but would most likely be too expensive for the operators of scientific of LEO communications missions.

[38] It is generally assumed that tanks weigh about 10% of the mass of the propellant.

Chapter 6

Summary and Conclusions

6.1 Thesis Summary

The space tug concept has been investigated since the 1960's, but all projects have proven infeasible due to technological or budgetary difficulties. Most of these previous studies have been limited in both considered applications and explored design concepts. This thesis carries out a systematic exploration of the space tug trade space. It offers a different approach to space tug architecting that is based on realistic and need-driven mission scenarios and it quantifies the economical feasibility of space tugging. Eight mission scenarios were identified as most promising:

Satellite Rescuing

Each year, a number of satellites are left in useless orbits, and the utilization of on-board fuel to boost them up to the correct orbit is either impossible or would significantly reduce the satellites' expected operational lives. Space tugs could mitigate the problem by providing emergency capture and insertion into the desired orbits of the stranded satellites. It could also transfer malfunctioning satellites to the ISS for refurbishment.

Orbital Debris Removal

A space tug can mitigate the overcrowding and collisions problem by tugging dead LEO satellites down to decay orbits or boosting dysfunctional GEO satellites to graveyard orbits.

GEO Satellite Retirement

A tug would allow satellites to operate until their fuel supplies are exhausted. The number of communications satellites in GEO, coupled with their significant cost, provides the tug operator with a substantial market opportunity.

Military Satellite Maneuvering

The maneuverability of military satellites essential for tactical surprise maneuvers is limited by the availability of on-board fuel supplies, but a tug could mate with these satellites and transfer them to the desired location.

(LEO) Constellation Reconfiguration

Designing constellations of communications satellites based on a forecast of the expected number of users and their activity level can lead to economic failure if the actual demand is smaller than the predicted one. It is better to deploy the constellation progressively, using a tug whenever reconfiguration is required, so that the satellites do not exhaust their own propellant.

Satellite Repositioning

A tug can be used to capture and move satellites that need to be relocated to cover a different part of the Earth, in response to a market shift.

On-Orbit Assembly/Building

On-orbit assembling of space assets allows for large structures to be built without the requirement of launching all components at the same time. It might be cost-effective to have tugs moving the assembly parts and modules, as opposed to adding propulsion tanks and guidance systems to the separately launched parts of the assembly or confining the constructed structure to LEO, where it can be assembled by astronauts.

NSSK/Orbit Raising/Decay Prevention

Satellites can trade fuel for payload or smaller launch vehicle if NSSK, orbit raising, or decay prevention is done by a tug that periodically attaches itself to the satellite.

The approach used by this thesis to analyze the business case for these mission scenarios is driven by realism, need, and utility. It divides the near-Earth space into target orbital zones, determined by type of mission and satellite population density, and assigns a separate tug to each zone. Economic advantages were weighed against the unknown risks. The main question to which an answer was sought was the fee amount that should be charged so that tugging became attractive to a sufficient number of potential customers. The ultimate objective of the research was to create a family of economically feasible space tugs using a common platform and sharing various components that would allow for the relatively inexpensive and quick response to on-demand tugging services.

6.2 Conclusions

Two of the eight proposed mission scenarios were investigated: the GEO satellite retirement and the satellite rescuing cases. The results from the tradespace analysis indicated that the optimal space tug for the former should be initially parked in the GEO belt and controlled through supervision. It should have a 300-kg low capability grappling mechanism and utilize storable bipropellant (Isp = 325 sec). The maximum number of satellites the tug could visit was determined to be 20, and the minimum fee for the service was estimated to be $20.48M. The business case analysis of the GEO satellite retirement scenario showed that if a "mid-way" fee is charged as a percent of the revenue collected by the clients, then providing tugging services makes economic sense in several cases (see Table 5.12), for most of which no replacement satellite was available for at least four months after the old satellite had reached the EOL criterion. It was shown that variations of the minimum fee did not significantly affect the demand for tugging services, while the uncertainty of cost estimations could drastically alter results. As long as the cost uncertainty margin did not exceed about $10M, it was shown that a sufficient number of commercial communications satellite operators could claim that providing the tug service would be valuable and economically justified.

Except for the GTO-GEO rescue of stranded communications satellites, for which case storable bipropellant can be used, the optimal tug for satellite rescue missions is an electric spacecraft (ion) that is supervised from the ground and is also parked there. It is not reusable and any type of a grappling mechanism or any number of fuel tanks can be attached to it, depending on the mission requirements. Based on statistical indicators, servicing opportunities are expected to occur on a regular basis, and it was shown that mostly military and GEO commercial satellites will consider the tug service of value. The fees that are charged are much higher than the fees charged for the retirement of a GEO communications satellite because higher delta-V's need to be achieved and the revenues resulting from salvaging a satellite mission are much higher than those resulting from a six-month long extended operation at the end of life of a satellite. The satellite rescue case study also analyses the possibility of having a government tug service provider. In this case, instead of calculating a mid-fee, a small surcharge on the order of a few million dollars is charged in addition to the total cost for tugging (or tugging plus repair). A major conclusion from the analysis was that science and LEO communications missions are generally in favor of the satellite replacement option, while military and GEO communications missions are more likely to value tugging higher than the other competing options.

From both analyses, it is obvious that the lower the fee for tugging, the greater the number of potential clients and the permissible cost uncertainty. Several ways to decrease the fee and thus increase the value of tugging are:

1. Tug visits more satellites.
2. More tugs are produced.

3. Tug is owned by a government agency.
5. Satellites produce more revenue or valuable data.
6. Tugging proves to be a sufficiently reliable service.

Potential "threats" to the GEO satellite retirement and the satellite rescue scenarios must also be considered. Some of the developments that might reduce the viability of the two cases of tugging are:

1. Electrical propulsion systems on all/most LEO and GEO satellites.
2. Trends towards constellations and swarms of smaller satellites.
3. Shorter mission lifetimes.
4. Higher reliability and lower cost of launch vehicles and satellites.

6.3 Recommendations for Future Work

Although the tug mission model suggested by this work can provide valuable insights apropos the justification of space tug utilization, there is a lot to be refined or added. In general, further attention needs to be given to the following areas:

1. Improvement of model fidelity

Better models of space tug orbital transfers and control need to be built, and Satellite Toolkit could be then used to validate specific scenarios of interest. A *reliability* model is also needed to describe how the performance of the tug might degrade over time. Autonomy level, software complexity, possible hardware failures, and any effects the environment might have on the performance of the tug should be taken into consideration. There should be a module that actually attempts to *design* a grappling mechanism. The autonomy of the tug can also be described and modeled in greater detail; the suggested three autonomy levels can be broken down further.

Another major improvement concerns the assumed Hohmann transfers. In reality, the change in velocity required for a given maneuver is highly dependent on the timeliness requirements and the relative location of the spacecrafts. For example, if a tug is to travel to a functional satellite, time requirements will dictate the form of the maneuver. The delta-V needed for changing orbital planes can be overly expensive if direct plane change maneuvers are used. If time allows, the orbit of the tug should be adjusted slightly to effect an altitude change in apogee, perigee, or both, which would allow nodal regression to precess the servicer orbit relative to the target orbit [Rey01].

2. *Validation of business cases*

In order to check whether the assumptions made in the case studies were reasonable, interviews with potential stakeholders must be conducted.

3. *Legal and regulatory issues*

Legal and regulatory constraints can limit the number and type of potential clients (with respect to nationality, government affiliation—civil or military, etc.), launch vehicles that can be used (international or US only), propellant (nuclear propellant might not be allowed), parking location (satellite slots might not be given up easily to be occupied by tugs), etc. Additionally, policy changes can significantly affect the operation of a space tug, so the possible effects need to be investigated.

4. *Flexibility and risk analysis*

The change in any assumption or requirement needs to be predicted and analyzed. All risks should be identified and ways for their mitigation should be considered.

5. *Extended mission coverage*

The business case of the other six space tug mission scenarios suggested in this thesis needs to be analyzed. The potential of using a multi-purpose tug (i.e. a tug suitable for multiple business cases) must be explored in further detail.

6. *Tug retirement*

More attention should be devoted to the problem of retiring the tug. The GEO satellite retirement case assumes it remains in graveyard after delivering its client satellite there. For the other mission scenarios, does it burn in the Earth atmosphere or is it left as a space junk?

A number of recommendations can be given with regard to the two case studies presented in this work

GEO Satellite Retirement

1. The counterarguments to the GEO satellite retirement business case need to be carefully considered. Some of the main concerns are:

a) improvements in fuel gauging technology, which will reduce the wasted life due to measurement uncertainty;

b) switching to all electric propulsion, meaning that fuel will no longer be the life-limiting factor of the new generation of satellites;

c) c) clusters and swarms of small communications satellites, which will reduce the revenue per satellite.

2. The impact of competition presented by other commercial companies' tugs has to be investigated.

3. Sensitivity analysis needs to be performed on all variables included in the estimations for tug cost (e.g. insurance rate, depreciation, launch vehicle selection, etc.), and on any other variables or assumptions.

4. A tug failure scenario must be fully explored. It must be calculated whether the insurance return is sufficient to support the continuation of the tugging business.

5. The effect of satellite failure during the extended period of work must be analyzed. This is of interest 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, nothing more than this minimum fee should be charged.

6. The effects of a fuel depot infrastructure on the fee for tugging must be analyzed.

Satellite Rescuing

1. Policies and their effects must be considered, especially in the case when the tug service is provided by a government organization.

2. The science and military satellite revenues should be estimated more accurately.

3. Interviews should be conducted with owners of military and/or science satellites to determine what they would base their decision on when considering the option of tugging.

4. Sensitivity analysis to cost estimation uncertainty must be performed.
5. The possibility of reusing a rescue tug can be investigated.
6. The issue of provider competition needs to be analyzed.

Additional questions that need to be covered include the following:

1. Tug family incremental development

Detailed development and deployment guidelines need to be suggested.

2. Tug maintenance

The space tug will likely need a lot of fuel. Will it get it from a space station or on-orbit refueling depot? Who is going to repair the tug when it gets damaged or parts of its grappling mechanism get loose? The proposed model does not include servicing the tug; investigating the possibilities might lead to drastically different results.

3. Optimal number of tugs

At a given time in space, how many tugs should there be? Where will tugs be parked?

4. Mothership and daughterships

A more futuristic use of a space tug would be if it serves as a carrier or mother vehicle for small servicing satellites (for refueling, upgrading, etc.) or for missions outside the Earth gravity well.

5. New generation satellites

Satellite operators should be interviewed to see if they would be willing to design (and under what conditions) their satellites for docking. Satellite operators have shown tendency toward conservatism when it comes to introducing new technologies.

6. New satellite infrastructure

If on-orbit servicing establishes itself as a safe and valuable practice, how will it affect the design of new satellites? What would be the cost savings from relaxing the redundancy requirements and lowering the insurance rates?

7. New technologies

How would key technologies such as advanced propulsion systems, improved proximity sensors, more capable grappling devices, and increased spacecraft autonomy affect the space tug concept?

BIBLIOGRAPHY

[AP99] The Associated Press. Air Force Works to Rescue Stranded Satellite. *Florida Today*, 12 April 1999, Source: http://www.floridatoday.com/space/explore/stories/1999/041299g.htm

[Atr03] Atrexx. Global Capacity & Facility Exchange. Satellite Industry Statistics Release. 11 April 2003.

[Ber02] B. Berger. Firm Awaits To Offer Alternative To Replacing Satellites. *SPACE.com*. 03 September 2002.

[Bra96] A. E. Braeunig. Rocket and Space Technology. *SciLinks*, 1996, Source: http://users.commkey.net/Braeunig/space/index.htm.

[BMW04] G. Bounova at al. Search Algorithms for Space Tug Rendezvous: Simulation and Experiment. IEEE Paper 1281, IEEE Aerospace Conference, Big Sky, MT, March 6-13, 2004.

[Cha03] M. Chaize. Enhancing the Economics of Satellite Constellations via Staged Deployment and Orbital Reconfiguration. Master's thesis, MIT, Department of Aeronautics and Astronautics, May 2003.

[Coo97] H. Cook. Product Management: Value, Quality, Cost, Price, Profit, and Organization. New York, NY: Chapman & Hall, 1997.

[CPUOS96] Committee on the Peaceful Uses of Outer Space, United Nations General Assembly. A/AC.105/663. 13 December 1996.

[CS82] A. Cairncross and P. Sinclair. Introduction to Economics. Boston, MA: Butterworths, 1982.

[CSD95] Committee on Space Debris, National Research Council. Orbital Debris: A Technical Assessment. Washington, D.C.: National Academy Press, 1995.

[Dub85] P. Dubarle. The Space Industry: Trade Related Issues. Washington, D.C.: OECD Publications and Information Center, 1985.

[EA03] Encyclopedia Astronautica. Rocket Propellants. Last updated: December 2, 2003, Source: http://www.astronautix.com/props/.

[Ear95] S. M. Earley. Reusable Space Tug Concepts. Symposium on Space Nuclear Power and Propulsion, 12th Conference on Alternative Power from Space, Proceedings. Pt. 2 (A96-12172 01-20), Woodbury, NY, AIP

Press (AIP Conference Proceedings, No. 324), 1995, p. 641-649, Albuquerque, NM, Jan. 8-12, 1995.

[Ell00] A. Ellery. An Introduction to Space Robotics. Springer-Praxis Books in Astronomy & Space Sciences, Praxis Publishers Ltd, Chichester, UK, 2000.

[Ell02] A. Ellery at al. A Proposed Public-Private Partnership for the Funding of Robotic In-Orbit Servicers. Albuquerque, NM, 5th International Conference and Exposition/Demonstration on Robotics for Challenging Situations and Environment, 2002.

[ESA93] European Space Agency Press Release. N° 40-1993: OLYMPUS: End of mission. August 26, 1993, Source: http://www.esa.int/export/esaCP/Pr_40_1993_p_EN.html

[Exp93] Ad Hoc Expert Group of the IAA Committee on Safety, Rescue and Quality. Orbital Debris. *ACTA Astronautica*, v. 31, October 1993, Oxford; New York: Pergamon Press, 1993.

[Fir86] O. Firschein at al. Artificial Intelligence for Space Station Automation. Crew Safety, Productivity, Autonomy, Augmented Capability. Park Ridge, NJ: Noyes Publications, 1986.

[Fut98] Futron Corporation. Space Transportation and the Global Space Commerce Market. AIAA Defense and Civil Space Programs Conference, October 28, 1998.

[Fut01] Futron Corporation. Trends in Space Commerce. June 2002, Source: www.futron.com.

[Fut02a] Futron Corporation. Satellite Insurance Rates On the Rise—Market Correction or Overreaction? July 10, 2002, Source: www.futron.com.

[Fut02b] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002, Source: www.futron.com.

[Fut03] Futron Corporation. U.S. Government Market Opportunity for Commercial Satellite Operators: For Today or Here to Stay? April 29, 2003, Source: www.futron.com.

[Gag03] B. Gagnon. Nuclear Power In Space And The Impact On Earth's Ecosystem. *SpaceDaily*, January 27, 2003.

[GBWH03] K. Galabova, G. Bounova, G., O. de Weck, and D. Hastings. Architecting a Family of Space Tugs Based on Orbital transfer Mission Scenarios. AIAA Space 2003 Conference, Long Beach, CA, Paper 2003-6368, 2003.

[GG88] C. Gaelick and S. Greenberg. Transportation System Choices: ROI Implications. AIAA paper 88-0840, AIAA 12th International Communication Satellite Systems Conference, Arlington, VA, March 13-17, 1988.

[Goe02] G. Goebel. Spaceflight Propulsion. *In The Public Domain*, Version 1.0, March 1, 2002, Source: http://www.vectorsite.net/tarokt.html.

[Gol85] N. Goldman. Space Commerce: Free Enterprise on the High Frontier. Cambridge, MA: Ballinger Pub. Co., 1985.

[Gun89] C. R. Gunn. United States Orbital Transfer Vehicle Programs. IAF, International Astronautical Congress, 40th, 8 p., Malaga, Spain, October 7-13, 1989.

[Hen94] M. Hendricks. At the Slithering Frontier of Robotics. *Johns Hopkins Magazine*, April 1994.

[HL88] E. Heer and H. Lum. Machine Intelligence and Autonomy for Aerospace Systems. *Progress in Astronautics and Aeronautics*, v.115, American Institute of Aeronautics and Astronautics, Inc. Washington, D.C. 1988.

[HN02] D. Hastings, R. Nilchiani. Developing an Orbital Transportation Network Analysis Methodology for On-Orbit Refueling of Satellites. AIAA CoreTech 2002 Conference, Colorado Springs, CO, Nov. 19-21, 2002.

[HWM02] D. Hastings, O. de Weck, H. McManus. System Architecting for Space Tugs. Research Proposal for DARPA, 2002.

[Hea95] D. A. Heald. A Survey of Upper Stage Propulsion Options. AIAA Paper 95-2568, AIAA, ASME, SAE, and ASEE, Joint Propulsion Conference and Exhibit, 31st, San Diego, CA, July 10-12, 1995.

[Hig02] L. Higgs. FocusZenith: The New Concept in Space Business. Space 2002 and Robotics 2002, March 17-21, 2002.

[Kre02] J. Kreisel. OOS ≠ Only One Solution: The Big Picture. 1st Bilateral DLR-CSA Workshop on On-Orbit Servicing of Space Infrastructure Elements via Automation & Robotics Technologies, DLR, Cologne Area, Germany, November 25-26, 2002.

[KT99] D. Kozdron and J. Tieman. Propulsion: Nuclear vs. Chemical. *Sophomore Engineering Clinic I*, November 24, 1999.

[Lam01] E. Lamassoure. A Framework to Account for Flexibility in Modeling the Value of On-Orbit Servicing for Space Systems. S.M Thesis in Aeronautics and Astronautics at the Massachusetts Institute of Technology, June 2001.

[LW99] W. Larson and J. Wertz. Space Mission Analysis and Design. Boston, MA: Kluwer Academic Publishers, 1999.

[Lee01] S. Leete. Design for On-Orbit Spacecraft Servicing. Core Technologies for Space Systems Conference, 2001.

[LFB97] S. D. Leifer, R. H. Frisbee, and J. R. Brophy. The NASA Advanced Propulsion ConceptsProgram at the Jet Propulsion Laboratory. *33rd Joint Propulsion Conference*, AIAA Paper 97-2792, Seattle, WA, July 6-9, 1997.

[LS96] S. C. Lee and A. G. Santo. Tradeoffs in Functional Allocation between Spacecraft Autonomy and Ground Operations: The NEAR (Near Earth Asteroid Rendezvous) Experience. AIAA Paper SSC96-VI-6, 10th Annual AIAA/USU Small Satellites Conference, Logan, UT, September 16-19, 1996.

[Lin03] M. Lindroos. Space Tug. *Encyclopaedia Astronautica,* 2003, Source: http://www.astronautix.com/craft/spacetug.htm.

[Liv00] D. Livingston. The Obstacles to Financing New Space Industries. Space 2000 Conference, Reston, VA, 2000.

[LSE03] The London Satellite Exchange Ltd. ESAX World Satellite Transponder Index. Source: www.e-sax.com, date accessed: 29 April 2003.

[Mat03] B. Mathiesen. Statistical Error Analysis. University of Michigan Introductory Physics Labs, Source: http://instructor.physics.lsa.umich.edu/ip-labs/tutorials/errors/rand.html, Last updated: September 2003.

[MS03] H. McManus and T. Schuman. Understanding the Orbital Transfer Vehicle Trade Space. AIAA Space 2003 Conference, Long Beach, CA, Paper 2003-6370, 2003.

[McD02] J. McDowell. Jonathan's Space Report. December 2002 update, Source: http://planet4589.org/space/log/satcat.txt.

[McV02] M. McVey. Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market. S.M Thesis in Aeronautics and Astronautics at the Massachusetts Institute of Technology, June 2002.

[Meh88] J. H. Mehoves. The Transfer Orbit Stage Program – A commercial space transportation development. IAF PAPER 88-177, IAF, International Astronautical Congress, 10 p., 39th, Bangalore, India, Oct. 8- 15, 1988.

[MC99] H. Mesissinger and J. Collins. Mission Design and System Requirements for a Multiple-Function Orbital Transfer Vehicle. AAIA Paper 99-4439, AIAA Space Technology Conference, Alburquerque, New Mexico, 28-30 Sept. 1999.

[New02] D. Newman. Interactive Aerospace Engineering and Design. Dubuque, Iowa: McGraw-Hill, 2002.

[NPA91] NASA Public Affairs. The Kennedy Space Center Story. Kennedy Space Center, FL: 1991, Source: http://www-pao.ksc.nasa.gov/kscpao/kscstory/ch14/ch14.htm

[OR02] Orbital Recovery. Practical Aspects of On-Orbit Servicing in the Commercial Marketplace. 1st Bilateral DLR-CSA Workshop on On-Orbit Servicing of Space Infrastructure Elements via Automation & Robotics Technologies, DLR, Cologne Area, Germany, November 25-26, 2002.

[Ort93] L. Ortiz. A cost analysis for a nuclear space tug. *Advances in the Astronautical Sciences*. Vol. 82 , p. 1361-1374, 1993.

[PA89] A. Petro and H Ashley. Cost Estimates for Removal of Orbital Debris. *Orbital Debris from Upper-Stage Breakup*, Progress in Astronautics and Aeronautics, Vol. 121, AIAA, Washington, D.C., 1989.

[PG88] K. Price and J. Greenberg. The Economics of Satellite Retrieval. AIAA Paper 88-0843.

[Pet77] W. Peterson. Introduction to Economics. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1977.

[Pol98] M. Polites. NASA Automated Rendezvous and Capture Review, Executive Summary. NASA/TP—1998–208528, Marshall Space Flight Center, Alabama, July 1998.

[PG88] K. Price and J. Greenberg. The Economics of Satellite Retrieval. AIAA Paper 88-0843, 1988.

[Pra02] M. Prado. Emergency Satellite Rescue or Repair Services. *Permanent*, 2002, Source: http://www.permanent.com/p-satsrv.htm.

[Rey99] C. Reynerson. Spacecraft Modular Architecture Design for On-Orbit Servicing. AIAA Paper 99-4473, AAIA Space Technology Conference & Exposition, Albuquerque, NM, Sept. 28-30, 1999.

[Rey01] C. Reynerson. Spacecraft Servicing—First Order Model for Feasibility and Cost Effectiveness. 2001 Core Technology for Space Systems Conference, Colorado Springs, CO, November 28-30, 2001.

[RM90] C. Rey C. and J. Morrison. Space Transportation: NASA has no firm need for increasingly costly orbital maneuvering vehicle. General Accounting Office, Washington, DC. National Security and International Affairs Div. Report Number GAO/NSIAD-90-192; B-239570.

[RS03] B. Robertson and E. Stoneking. Satellite GN&C Anomaly Trends. *Advances in the Astronautical Sciences*, Vol. 113, AAS 03-071, 2003.

[SA01] B. Sullivan and D. Akin. A Survey of Serviceable Spacecraft Failures. AIAA Paper 2001-4540.

[Sac02] S. Sacknoff. Space Industry Revenues Dip to $82.8 Billion. M&A Transactions Surpass $29 Nillion in Value as 61 Companies Change Hands. *Spacebusiness.com*, February 24, 2002.

[Sal01] J. Saleh. Weaving Time Into System Architecture: New Perspective on Flexibility, Spacecraft Design Lifetime, and On-Orbit Servicing. PhD Thesis in Aeronautics and Astronautics at the Massachusetts Institute of Technology, December 2001.

[SD03] SpaceDaily. Artemis On Orbit At Last. Paris, Feb 06, 2003, Source: http://www.spacedaily.com/news/artemis-03b.html.

[Sha99] G. Shaw. The Generalized Information Network Analysis Methodology for Distributed Satellite Systems. PhD Thesis in Aeronautics and Astronautics at the Massachusetts Institute of Technology, 1999.

[Sim94] J. Simpson, ed. Preservation of Near-Earth Space for Future Generations. New York, NY: Cambridge University Press, 1994.

[Smi01] D. Smitherman et al. Space Resource Requirements for Future In-Space Propellant Production Depots. Space Resources Utilization Roundtable III, Colorado School of Mines, Golden Colorado, CO, October 24–26, 2001.

[Spa00] SpaceDev News Release. SpaceDev Funded for Orbital Transfer Vehicle Motor Firings. Posted: April 9, 2000, Source: http://spaceflightnow.com/news/n0004/09spacedevotv/.

[Spa02] H. Sparks. No Littering' Plea Extended to Space Junkyard. *Space News*, 17 May 2002.

[SSE94] 16.83 Space Systems Engineering. Project Freebird: An Orbital Transfer Vehicle. Department of Aeronautics and Astronautics, MIT, Spring 1994.

[Suh90] N. P. Suh. The Principles Of Design. New York: Oxford University Press, 1990.

[TTO88] T. Takagi, N. Tsuya, and H. Obara. Orbital Servicing Vehicle. *Proceedings of the Sixteenth International Symposium on Space Technology and Science*, Volume II, 1988.

[Tur01a] A. Turner. Development of Geosynchronous Satellite Servicing. 2001 Core Technology for Space Systems Conference, 2001.

[Tur01b] A. Turner. Cost-effective spacecraft dependent upon frequent non-intrusive servicing. AIAA Space 2001 - Conference and Exposition, Albuquerque, NM, Aug. 28-30, 2001 AIAA Paper 2001-4554.

[Ull97] D. G. Ullman. The Mechanical Design Process. New York, NY: McGraw-Hill, 1997.

[UT89] Undergraduate Team. An Earth Orbiting Satellite Service and Repair Facility. Final Design Report. The University of Texas at Austin Department of Aerospace Engineering and Engineering Mechanics, December 15, 1989.

[Wal93] D. Waltz. On-Orbit Servicing of Space Systems. Malabar, FL: Krieger Publishing Company, 1993.

[Web84] J. Q. Weber. Advanced Liquid Propellant Systems for Chemical Propulsion. *Progress in Astronautics and Aeronautics*, Vol. 89, 1984.

[Wec03] O. de Weck. System Architecting for Space Tugs Research Project – Phase B. April 2003.

[You00] D. G. Young. An Astronomical Failure. Washington, D.C., October 31, 2000, Source: http://204.180.200.9/~jryoung/dgyoung/space.html.

Appendix A: Orbital Transfer Calculations

```
% Assumptions:
m_per_sec_dVmat = 20;
m_per_sec_dVrel = 20;
m_per_sec_dV_ADACS = 100;                          % total delta V (rotational ADACS)

if VAR1.prop_type == 18                                      % electric propulsion
  kg_other = 70;                                % assumed weight of the power system
else
  kg_other = 50;                 % subsystems total mass (excluding prop and structures)
end

kg_wet_mass(1) = 100;                                      % assumed for iteration
kg_dry_mass(1) = (100/65)*VAR1.kg_arm;

% From launch injection to parking orbit:
km_park_apogee = max(VAR1.park_a,LV1.launch_alt) + CONST.km_earth_radius;
km_park_perigee = min(VAR1.park_a,LV1.launch_alt) + CONST.km_earth_radius;
km_park_a = (km_park_perigee + km_park_perigee)/2;
km_per_sec_park_Va = sqrt(CONST.mu/km_park_apogee);
km_per_sec_park_Vb = sqrt(CONST.mu/km_park_perigee);
km_per_sec_park_Vtxa = sqrt(CONST.mu*(2/km_park_apogee - 1/km_park_a));
km_per_sec_park_Vtxb = sqrt(CONST.mu*(2/km_park_perigee - 1/km_park_a));
km_per_sec_dVpark_planar = abs(2*km_per_sec_park_Va*sin(0.5*(LV1.launch_i-
                           VAR1.park_i)*pi/180));
km_per_sec_dVpark_hoh = abs(km_per_sec_park_Va-
                         km_per_sec_park_Vtxa)+abs(km_per_sec_park_Vb-km_per_sec_park_Vtxb);
m_per_sec_dVpark = 1000*(km_per_sec_dVpark_hoh + km_per_sec_dVpark_planar);

for i = 1:nn
  if i == 1
    kg_dry_mass(i)= kg_dry_mass(1);
    kg_wet_mass(i) = kg_wet_mass(1);
  else
    kg_dry_mass(i)= kg_dry_mass(i-1);
    kg_wet_mass(i) = kg_wet_mass(i-1);
  end

  for j = 1:100
    kg_prop_park(i) = kg_wet_mass(i)*(1 - exp(-m_per_sec_dVpark/(ENG.max_Isp*CONST.g0)));

    if i == 1
      kg_tot_prop_burnt(i) = kg_prop_park(i);
    else
      kg_tot_prop_burnt(i) = kg_prop_park(i)+ kg_tot_prop_needed(i-1) - kg_prop_park(i-1);
    end

    % Transfer to 50m away from target:
    trans_to_tar_i = VAR1.tar_i(i);
    if i == 1
      km_trans_to_tar_apogee(i) = max(VAR1.park_a,VAR1.tar_a(i) - CONST.m_rend_dist) +
                                  CONST.km_earth_radius;
      km_trans_to_tar_perigee(i) = min(VAR1.park_a,VAR1.tar_a(i) - CONST.m_rend_dist) +
```

```
                               CONST.km_earth_radius;
else
  km_trans_to_tar_apogee(i) = max(VAR1.dest_a(i-1),VAR1.tar_a(i) - CONST.m_rend_dist) +
                              CONST.km_earth_radius;
  km_trans_to_tar_perigee(i) = min(VAR1.dest_a(i-1),VAR1.tar_a(i) - CONST.m_rend_dist) +
                               CONST.km_earth_radius;
end

km_trans_to_tar_a(i) = (km_trans_to_tar_apogee(i) + km_trans_to_tar_perigee(i))/2;
km_per_sec_trans_to_tar_Va(i) = sqrt(CONST.mu./km_trans_to_tar_apogee(i));
km_per_sec_trans_to_tar_Vb(i) = sqrt(CONST.mu./km_trans_to_tar_perigee(i));
km_per_sec_trans_to_tar_Vtxa(i) = sqrt(CONST.mu.*(2./km_trans_to_tar_apogee(i) –
                                  1./km_trans_to_tar_a(i)));
km_per_sec_trans_to_tar_Vtxb(i) = sqrt(CONST.mu.*(2./km_trans_to_tar_perigee(i) –
                                  1./km_trans_to_tar_a(i)));
km_per_sec_dVtrans_to_tar_hoh(i) = abs(km_per_sec_trans_to_tar_Va(i) -
                                   km_per_sec_trans_to_tar_Vtxa(i)) +
                                   .abs(km_per_sec_trans_to_tar_Vb(i) -
                                   km_per_sec_trans_to_tar_Vtxb(i));
if i == 1
  km_per_sec_dVtrans_to_tar_planar(i) = abs(2*km_per_sec_trans_to_tar_Va(i)*
                                        sin(0.5.*(VAR1.park_i-VAR1.tar_i(i))*pi/180));
else
  km_per_sec_dVtrans_to_tar_planar(i) = abs(2*km_per_sec_trans_to_tar_Va(i)*
                                        sin(0.5.*(VAR1.dest_i(i-1)-VAR1.tar_i(i))*pi/180));
end

m_per_sec_dVtrans_to_tar(i) = 1000.*(km_per_sec_dVtrans_to_tar_hoh(i) +
                              km_per_sec_dVtrans_to_tar_planar(i));
kg_wet_before_trans_to_tar(i) = kg_wet_mass(i) - kg_tot_prop_burnt(i);
kg_prop_trans_to_tar(i) = kg_wet_before_trans_to_tar(i)*(1 - exp(-
                          m_per_sec_dVtrans_to_tar(i)/(ENG.max_Isp*CONST.g0)));
kg_wet_after_trans_to_tar(i) = kg_wet_before_trans_to_tar(i) - kg_prop_trans_to_tar(i);
kg_tot_prop_burnt(i) = kg_tot_prop_burnt(i) + kg_prop_trans_to_tar(i);

% Rendezvous (starts from 500m away from target):
km_rend_apogee = VAR1.tar_a(i) - CONST.m_rend_dist + CONST.km_earth_radius;
km_rend_perigee = VAR1.tar_a(i) + CONST.km_earth_radius;
km_rend_a = (km_rend_apogee + km_rend_perigee)/2;
km_per_sec_rend_Va = sqrt(CONST.mu./km_rend_apogee);
km_per_sec_rend_Vb = sqrt(CONST.mu./km_rend_perigee);
km_per_sec_rend_Vtxa = sqrt(CONST.mu.*(2./km_rend_apogee - 1./km_rend_a));
km_per_sec_rend_Vtxb = sqrt(CONST.mu.*(2./km_rend_perigee - 1./km_rend_a));
km_per_sec_dVrend_planar = abs(2.*km_per_sec_rend_Va.*sin(0.5.*(trans_to_tar_i-
                           VAR1.tar_i(i)).*pi/180));
km_per_sec_dVrend_hoh = abs(km_per_sec_rend_Va-
                        km_per_sec_rend_Vtxa)+abs(km_per_sec_rend_Vb-km_per_sec_rend_Vtxb);
m_per_sec_dVrend(i) = 1000*(km_per_sec_dVrend_hoh + km_per_sec_dVrend_planar);
kg_wet_before_rend(i) = kg_wet_after_trans_to_tar(i);
kg_prop_rend(i) = kg_wet_before_rend(i)*(1 - exp(-
                  m_per_sec_dVrend(i)/(ENG.max_Isp.*CONST.g0)));
kg_wet_after_rend(i) = kg_wet_before_rend(i) - kg_prop_rend(i);
kg_tot_prop_burnt(i) = kg_tot_prop_burnt(i) + kg_prop_rend(i);

% Mating:
m_per_sec_dVmat(i) = 20;                     % delta V - target control, ideally ADACS
```

```
        kg_wet_before_mat(i) = kg_wet_after_rend(i);
        kg_prop_mat(i) = kg_wet_before_mat(i)*(1 - exp(-
                        m_per_sec_dVmat(i)/(ENG.max_Isp*CONST.g0)));
        kg_wet_after_mat(i) = kg_wet_before_mat(i) - kg_prop_mat(i);
        kg_tot_prop_burnt(i) = kg_tot_prop_burnt(i) + kg_prop_mat(i);

        % Towing:
        tow_i = VAR1.dest_i(i);
        km_tow_apogee = max(VAR1.tar_a(i),VAR1.dest_a(i)) + CONST.km_earth_radius;
        km_tow_perigee = min(VAR1.tar_a(i),VAR1.dest_a(i)) + CONST.km_earth_radius;
        km_tow_a = (km_tow_apogee + km_tow_perigee)/2;
        km_per_sec_tow_Va = sqrt(CONST.mu./km_tow_apogee);
        km_per_sec_tow_Vb = sqrt(CONST.mu./km_tow_perigee);
        km_per_sec_tow_Vtxa = sqrt(CONST.mu.*(2./km_tow_apogee - 1./km_tow_a));
        km_per_sec_tow_Vtxb = sqrt(CONST.mu.*(2./km_tow_perigee - 1./km_tow_a));
        km_per_sec_dVtow_planar = abs(2*km_per_sec_tow_Va*sin(0.5*(VAR1.dest_i(i)-
                                VAR1.tar_i(i))*pi/180));
        km_per_sec_dVtow_hoh = abs(km_per_sec_tow_Va-
                            km_per_sec_tow_Vtxa)+abs(km_per_sec_tow_Vb-km_per_sec_tow_Vtxb);
        m_per_sec_dVtow(i) = 1000*(km_per_sec_dVtow_hoh + km_per_sec_dVtow_planar);
        kg_wet_before_tow(i) = kg_wet_after_mat(i) + VAR1.kg_tar(i);
        kg_prop_tow(i) = kg_wet_before_tow(i)*(1 - exp(-
                        m_per_sec_dVtow(i)/(ENG.max_Isp.*CONST.g0)));
        kg_wet_after_tow(i) = kg_wet_before_tow(i) - kg_prop_tow(i);
        kg_tot_prop_burnt(i) = kg_tot_prop_burnt(i) + kg_prop_tow(i);

        % Release:
        m_per_sec_dVrel(i) = 20;                                  % Assumed--ADACS dV
        kg_wet_before_rel(i) = kg_wet_after_tow(i);
        kg_prop_rel(i) = kg_wet_before_rel(i)*(1 - exp(-m_per_sec_dVrel(i)/(ENG.max_Isp*CONST.g0)));
        kg_wet_after_rel(i) = kg_wet_before_rel(i) - kg_prop_rel(i) - VAR1.kg_tar(i);
        kg_tot_prop_burnt(i) = kg_tot_prop_burnt(i) + kg_prop_rel(i);

        kg_tot_fuel_and_oxi_mass_trans(i) = kg_tot_prop_burnt(i);
        kg_tot_fuel_and_oxi_mass_ADACS(i) = kg_wet_mass(i)*(1-exp(-
                                    m_per_sec_dV_ADACS/(ENG.max_Isp*CONST.g0)));
        kg_tot_mass_burnt(i) = kg_tot_fuel_and_oxi_mass_trans(i) +
                            kg_tot_fuel_and_oxi_mass_ADACS(i);
        kg_oxi_mass(i) = kg_tot_mass_burnt(i)*(ENG.mix_ratio/(ENG.mix_ratio + 1));  % mass of oxidizer
                                                                                    needed
        kg_fuel_mass(i) = kg_tot_mass_burnt(i)/(1 + ENG.mix_ratio);            % mass of fuel needed
        kg_tot_prop_needed(i) = kg_oxi_mass(i) + kg_fuel_mass(i);

        for k = 1:3
          kg_wet_mass(i) = kg_tot_prop_needed(i) + kg_dry_mass(i);
          kg_stru = 0.12*kg_wet_mass(i);          % assume structures are 12% of wet mass at launch
          kg_tanks = 0.1*kg_tot_prop_needed(i);

          if kg_tanks + kg_stru + VAR1.kg_arm + kg_other > kg_dry_mass(i)
            kg_dry_mass(i) = kg_tanks + kg_stru + VAR1.kg_arm + kg_other;
          end
        end
      end

    tot_dV(i) = m_per_sec_dVpark + m_per_sec_dVtrans_to_tar(i) + m_per_sec_dVrend(i) +...
      m_per_sec_dVmat(i) + m_per_sec_dVtow(i) + m_per_sec_dVrel(i);
```

Appendix B: GEO Satellite Data Used in Calculations

```
% Intelsat 804
VAR1.tar_a(1) = 35785.5;
VAR1.tar_i(1) = 0.02;
VAR1.kg_tar(1) = 1601;

% Intelsat 803
VAR1.tar_a(2) = 35786;
VAR1.tar_i(2) = 0.07;
VAR1.kg_tar(2) = 1601;

% Intelsat 801
VAR1.tar_a(3) = 35787.5;
VAR1.tar_i(3) = 0.13;
VAR1.kg_tar(3) = 1601;

% Intelsat 802
VAR1.tar_a(4) = 35785.5;
VAR1.tar_i(4) = 0.05;
VAR1.kg_tar(4) = 1601;

% Agila 2
VAR1.tar_a(5) = 35787;
VAR1.tar_i(5) = 0.06;
VAR1.kg_tar(5) = 600;

% Telstar 5
VAR1.tar_a(6) = 35786;
VAR1.tar_i(6) = 0.05;
VAR1.kg_tar(6) = 3239;

% Hot Bird 3
VAR1.tar_a(7) = 35786;
VAR1.tar_i(7) = 0.12;
VAR1.kg_tar(7) = 1281;

% PAS 4
VAR1.tar_a(8) = 35786;
VAR1.tar_i(8) = 0.06;
VAR1.kg_tar(8) = 2000;

% Intelsat 902
VAR1.tar_a(9) = 35778;
VAR1.tar_i(9) = 0.17;
VAR1.kg_tar(9) = 1500;

% Intelsat 901
VAR1.tar_a(10) = 35786.5;
VAR1.tar_i(10) = 0.06;
VAR1.kg_tar(10) = 1590;

% Telstar 7
VAR1.tar_a(11) = 35786;
VAR1.tar_i(11) = 0.02;
VAR1.kg_tar(11) = 3239;

% Telstar 6
VAR1.tar_a(12) = 35786.5;
VAR1.tar_i(12) = 0.01;
VAR1.kg_tar(12) = 3239;

% Americom 1
VAR1.tar_a(13) = 35786;
VAR1.tar_i(13) = 0;
VAR1.kg_tar(13) = 1500;

% Intelsat 905
VAR1.tar_a(14) = 35786;
VAR1.tar_i(14) = 0.3;
VAR1.kg_tar(14) = 1590;

% Intelsat 904
VAR1.tar_a(15) = 35786;
VAR1.tar_i(15) = 0;
VAR1.kg_tar(15) = 1590;

% Intelsat 906
VAR1.tar_a(16) = 35786;
VAR1.tar_i(16) = 0;
VAR1.kg_tar(16) = 1590;

% Apstar 2R
VAR1.tar_a(17) = 35785.5;
VAR1.tar_i(17) = 0;
VAR1.kg_tar(17) = 1415;

% Eutelsat W1
VAR1.tar_a(18) = 35786.5;
VAR1.tar_i(18) = 0;
VAR1.kg_tar(18) = 1430;
```

% Americom 3
VAR1.tar_a(19) = 35786;
VAR1.tar_i(19) = 0;
VAR1.kg_tar(19) = 1300;

% Americom 2
VAR1.tar_a(20) = 35786;
VAR1.tar_i(20) = 0;
VAR1.kg_tar(20) = 1300;

% Intelsat 907
VAR1.tar_a(21) = 35787;
VAR1.tar_i(21) = 0.01;
VAR1.kg_tar(21) = 1473;

% PAS 8
VAR1.tar_a(22) = 35787;
VAR1.tar_i(22) = 0.04;
VAR1.kg_tar(22) = 1500;

% Satmex 5
VAR1.tar_a(23) = 35786;
VAR1.tar_i(23) = 0.01;
VAR1.kg_tar(23) = 1500;

% Zhongwei 1
VAR1.tar_a(24) = 35787;
VAR1.tar_i(24) = 0.01;
VAR1.kg_tar(24) = 1418;

% PAS 7
VAR1.tar_a(25) = 35787;
VAR1.tar_i(25) = 0.07;
VAR1.kg_tar(25) = 1500;

% JCSAT-8
VAR1.tar_a(26) = 35788;
VAR1.tar_i(26) = 0.05;
VAR1.kg_tar(26) = 1200;

% NSS-7
VAR1.tar_a(27) = 35787;
VAR1.tar_i(27) = 0.01;
VAR1.kg_tar(27) = 1500;

% Galaxy 11
VAR1.tar_a(28) = 35788;
VAR1.tar_i(28) = 0.05;
VAR1.kg_tar(28) = 2775;

% Telstar 12
VAR1.tar_a(29) = 35786;
VAR1.tar_i(29) = 0.06;
VAR1.kg_tar(29) = 3673;

% GE 4
VAR1.tar_a(30) = 35786;
VAR1.tar_i(30) = 0.02;
VAR1.kg_tar(30) = 1751;

Legend:

VAR1.tar_a = satellite altitude [km]
VAR1.tar_i = satellite inclination [deg]
VAR1.kg_tar = satellite mass [kg]

Appendix C: Commercial Communications Satellites 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

*The table status is of September 2003. Included are only GEO commercial communications satellites resulting in positive profits after 6 months of extended operation.

Legend:

C = Client
P = Provider
EOL = End Of Life
BOL = Beginning Of Life