DOCTOR:

Developing On-Orbit Servicing Concepts, Technology Options, and Roadmap

Final Report

International Space University

Summer Session Program 2007

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Abstract

Space has become a vital medium for a wide range of applications and endeavors. However, space operations have yet to become routine. Spacecraft failures have a large impact on the spacecraft manufacturing and operations industries. These impacts include increased development costs and time-lines, lost revenues, and the potential to contribute to the problem of space debris. On-Orbit Servicing of spacecraft promises to be a key element in developing a future space infrastructure. On the path to realizing this future, multiple factors must be considered.

Team DOCTOR starts with a definition and introduction of On-Orbit Servicing, including a review of past servicing missions and a description of servicing mission categories. These are divided into Inspection, Maneuvering and Manipulation missions. The Team's detailed analysis of the key challenges and opportunities in this field of space applications incorporates different aspects of the problem. Areas under consideration include policy, economic, technical, and interdisciplinary impacts on On-Orbit Servicing. This led the Team to a gap and feasibility analysis, resulting in a roadmap vision for On-Orbit Servicing as an integral part of space activities. This vision is presented with considerations for the Near-, Mid-, and Far-Term, including its applicability and potential to enable and enhance existing agency roadmaps. The Team developed a Feasibility Matrix to serve as a flexible tool to assess mission feasibility from multiple perspectives. As a follow-on to this analysis, the Team proposed a system architecture for a challenging Mid-Term mission, for which the robotic Orbital Replacement Unit Exchange mission was chosen. This architecture includes a trade study, system design, and a market analysis. We conclude with the Team's vision of On-Orbit Servicing as a vital component of a future space infrastructure, as well as recommendations for continued development to ensure the realization of this vision.

Faculty Preface

The On-Orbit Servicing (OOS) project at the ISU summer session 2007 in Beijing China was undertaken by 27 students (Team DOCTOR) supported by a Co-chair (Alex ELLERY), a Shepherd (Ozgur GURTUNA), and a Teaching Assistant (Xavier GIRALT). The study was undertaken by the students with very little direction from the co-chair (Alex ELLERY), so Team DOCTOR represents a fresh look at OOS from a variety of perspectives and skill-levels, including university graduate students, university professors, recent space professionals, experienced space professionals, military and civilians from a wide variety of engineering and non-engineering disciplines as well as from a wide variety of nations. The approach taken was a sound one beginning with a classification of different types of OOS tasks which were graded within a feasibility matrix in terms of technical, policy, commercial and interdisciplinary dimensions. From the feasibility matrix, near-term, mid-term and far-term groupings were identified, from which a mid-term OOS task was selected for detailed study based on feasibility, utility and desirability – the Orbital Replacement Unit (ORU) Exchange task *as an operational service*. The technical architecture involved extensive trade analysis to simultaneously satisfy technical, commercial and legal constraints, representing a complex iteration of mutual interactions. The result was a consideration of a plausible scenario of a commercially-viable mid-term solution involving robotic ORU exchange in the GEO ring including consideration of logistic re-supply of ORUs to GEO orbit and their disposal. This last factor is we believe unique in attempting to provide a solution to the difficult issue of debris mitigation inherent in space logistics. The technical proposal is outlined in thorough detail including associated issues with modularity and standardization of spacecraft and the implementation of robotics technology. Following the detailed mid-term OOS analysis, the project is completed with a vision of future space exploration, emphasizing the lessons from ISS applied to human, lunar, and planetary exploration. In this vision, OOS and related technologies are viewed as essential rather than desirable components of space exploration. The problem of logistics, re-supply, servicing and maintenance beyond Earth orbit become the driving forces behind plausibility and cost of supporting long-duration human missions. OOS is thus seen as a major component of space infrastructure.

Alex ELLERY Co-Chair	Ozgur GURTUNA Shepherd	Xavier GIRALT Teaching Associate and Shepherd

Student Preface

"You can't make money doing this"
"We looked at this 30 years ago, it won't work"
"This doesn't interest us"
"No, no, no…it's completely impossible!"

Yes, the doubters are always out there, even in the space field. Beyond the time constraints, the communication barriers, the personality differences, and the mixed messages in creating an innovative, detailed report in 100 pages within 3 weeks, we were always hitting one of our biggest barriers: pessimism. *They* say On-Orbit Servicing is not novel, that it is not a money-maker, that it would be easier to just send a new satellite into orbit.

We disagree.

True, there are many hurdles to overcome, but we are in the midst of a transition; where it is no longer viable or *responsibl*e for satellite companies to simply discard a malfunctioning satellite, and where there must be an option or effort to use emerging technologies to salvage, revive, extend the life, or de-orbit such expensive spacecraft.

This is just the start. The potential applications and new markets derived from On-Orbit Servicing are limited by your imagination. How we use it now will enable our efforts to allow humanity to leave Low-Earth Orbit, making it an integral part of any future exploration program.

Therefore, to the doubters we say: On-Orbit Servicing is feasible and we will make it so. Our team consists of 27 space experts from 13 different countries. We have engineers, investment bankers, policy makers, university professors, and robotics experts. ISU SSP07 has allowed us to work in an intercultural, international, and interdisciplinary environment, and has enabled us to create life-long friends and express the vision we share as we all worked together.

It has been a joy to be immersed in the Chinese culture for a summer, and we feel that we have experienced a part of history as China's civil space program is blossoming. We sincerely thank Xavier Giralt for keeping us on track and motivated, Ozgur Gurtuna for his brilliant suggestions, Alex Ellery's "tell it like it is" approach, James Chartres' clapping, and Gary Martin's unwavering support.

- *Team DOCTOR*

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List of Acronyms

A

ACS	Attitude Control System
AEB	Agência Espacial Brasileira (Brazilian Space Agency)
AFB	Air Force Base
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
AKM	Apogee Kick Motor
ARPANET	Advanced Research Project Agency Network
ASAT	Anti-satellite
ASTRO	Autonomous Space Transport Robotic Operation
ATV	Automated Transfer Vehicle

B

BER	Bit Error Rate
BOL	Beginning of Life

C

CASC	China Aerospace Science and Technology Corporation
CCW	Counter Clockwise
CEV	Crew Exploration Vehicle
CME	Coronal Mass Ejection
CMG	Control Moment Gyroscope
CNSA	China National Space Administration
COTS	Commercial Orbital Transportation Services
CSA	Canadian Space Agency
CW	Clockwise
CX-OLEV	ConeXpress-Orbital Life Extension Vehicle

D

DARPA	Defense Advanced Research Projects Agency
DART	Demonstration of Autonomous Rendezvous Technology
DC	Direct Current
DLR	Deutsches Zentrum Für Luft und Rahmfahrt (German Aerospace Center)
DMSO	Defense Modeling and Simulation Office
DND	Department of National Defence
DOCTOR	Developing On-Orbit Servicing Concepts, Technology Options, and Roadmap
DoD	Department of Defense
DOF	Degrees of Freedom

E

EC	European Commission
ECSS	European Cooperation on Space Standardization
EGNOS	European Geostationary Navigation Overlay Signal
ELV	Expendable Launch Vehicle
EM	Environmental Monitoring
EOL	End of Life
ESA	European Space Agency
ETS	Engineering Test Satellite
ERA	European Robotic Arm
EVA	Extravehicular Activity

F

FY	Fiscal Year

G

GEO	Geostationary Earth Orbit
GES	Global Exploration Strategy
GLONASS	Global Orbiting Navigation Satellite System
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit

H

HEO	Highly Elliptical Orbit
HST	Hubble Space Telescope
HTV	H-II Transfer Vehicle

I

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
IRR	Internal Rate of Return
ISO	International Standards Organization
ISR	Intelligence, Surveillance and Reconnaissance
ISRO	Indian Space Research Organization
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ISS OSA	Integrated Sensor System Open System Architecture
ISU	International Space University
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union

J

JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
JEMRMS	JEM Remote Manipulator System
JSC	Johnson Space Centre
JSF	Joint Strike Fighter
JWST	James Webb Space Telescope
L	
LEE	Latching End Effectors
LEO	Low Earth Orbit
L2	Lagrange Point 2
LIDAR	Light Detection and Ranging
LV	Launch Vehicle
M	
MBS	Mobile Base System
MDA	MacDonald, Dettwiler and Associates Ltd.
MEO	Medium Earth Orbit
MFD	Manipulator Flight Demonstration
Mini-AERCam	Miniature Autonomous Extravehicular Robotic Camera
MMH	Mono Methyl Hydrazine
MOL	Middle of Life
MSL	Mars Science Laboratory
MSS	Mobile Servicing System
N	
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
NRL	Naval Research Laboratory
NEO	Near Earth Object
NEOSSat	Near Earth Object Surveillance Satellite
NORAD	North American Aerospace Defense Command
NPV	Net Present Value
O	
ODORU	On-Demand ORU
OE	Orbital Express
OOS	On-Orbit Servicing
ORC	Orbital Recovery Corporation
ORU	Orbital Replacement Unit
ORUPP	ORU Piggyback Payload
OSSL	Orbital Satellite Services, Ltd.
OSTJF	Open System Joint Task Force
OTCM	ORU Tool Changeout Mechanism
P	
PDGF	Power Data Grapple Fixture
PPP	Public-Private-Partnership
PRC	People's Republic of China
R	
ROTEX	Robotic Technology Experiment
RpK	Rocketplane Kistler
S	
SAE	Society of Automotive Engineers
SBIRS	Space-Based Infrared System
SBL	Space-Based Laser
SELENE	SELenological and ENgineering Explorer
SFA	Small Fine Arm
SLES	Spacecraft Life Extension System
SM	Servicing Mission
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SSI	Space Security Index
SSL	Space Systems Laboratory
SSN	Space Surveillance Network
SSP	Summer Session Program
SSRMS	Space Station Remote Manipulator System
STM	Space Traffic Management
STS	Space Transportation System
SUMO	Spacecraft for the Universal Modification of Orbits
T	
TP	Team Project
TRL	Technology Readiness Level
U	
UN	United Nations
USAF	United States Air Force
USD	United States Dollar
USSTRATCOM	United States Strategic Command
W	
WTO	World Trade Organization
X	
XEUS	X-ray Evolving Universe Spectrometer

Chapter 1
Introduction

Spacecraft servicing can enable valuable assets to be repaired and maintained in space like other mobile system on Earth. Servicing technologies will become increasingly important as space activities grow and new spacecraft are placed in orbit. The development of a servicing infrastructure will facilitate future exploration, security, and commercialization of space.

1.1 Defining On-Orbit Servicing

Space has become a vital medium for a wide range of applications and activities. The reliance on space-based assets will most likely continue, if not accelerate, as our capabilities to develop, launch, and operate spacecraft mature. It is the stated goal of several space agencies to establish a self sufficient space-based infrastructure that includes planetary transportation and human habitats as well as robust commercial activity. An important element of a self sufficient infrastructure is the ability to perform On-Orbiting Servicing (OOS).

A comprehensive definition of OOS is not readily available in the literature. A United States patent by Kosmas (2006, p.1) describes OOS as "a service vehicle for performing an in-space operation on a selected target spacecraft." Bourjolly et al. (2005, p. 1) define OOS as "the robotic capability of maintaining and repairing satellites." Dittmann and Sommer (2002, p. 6) state that "a trivial definition does not exist". Given the disparity of denotation our Team proposes the following definition:

> **On-Orbit Servicing is a service offered for scientific, security, or commercial reasons that entail an in-space operation on a selected client spacecraft to fulfill one (or more) of the following goals: inspect, move, refuel, repair, recover from launch failure, or add more capability to the system.**

Our Team has designated "Servicer" as the spacecraft that provides a service, and "Client" as the spacecraft that receives a service. Finally, it is possible for a Servicer satellite to be self-servicing, i.e. to act as its own Client.

1.2 Mission Statement

The overall objective of our Team Project (TP) is to develop a rationale and methodology for implementing OOS of space assets. Team DOCTOR's Mission Statement reflects our intent to fulfill this objective:

> **To use an interdisciplinary approach to explore the concept of on-orbit servicing, identify the key existing and future technological, economic, and policy drivers, and propose a structured approach to its progressive incorporation into the activities of the space industry.**

1.3 Motivation for OOS

On-Orbit Servicing is uniquely situated to provide potential solutions to many of the current and approaching technical, economic, policy, and societal challenges to routine and affordable space operations. Humanity is still in the early stages of the space age and has kept space exploration and utilization in an immature state. On-Orbit Servicing has the potential to provide the first step towards a self-sufficient space infrastructure.

In order to limit on-orbit failures, spacecraft manufacturers design extensive redundancies and fault tolerance into spacecraft systems. This increases the development costs and timelines. However, satellites regularly fail, leaving them partially operational but uncontrolled in orbit. Moreover, these failures have to be addressed in future designs, thus potentially increasing development costs. Effective OOS technology will enable satellite manufacturers to reduce constraints on fault tolerance, decreasing costs and increasing the technical performance of future satellites. On-Orbit Servicing also addresses increasing international concern over space debris and orbital crowding. Servicing missions that remove damaged satellites from useable orbits aid in debris mitigation. In general, OOS can provide near-term and tangible benefits to satellite manufacturers, operators, and space-faring nations, including cost reduction, mission enhancement, and mission enablement.

On-Orbit Servicing will also provide the first step towards the creation of a robust space infrastructure. Advanced robotic servicers can also be used for In-Situ Resource Utilization (ISRU) or in space construction. Future generations of OOS vehicles may assist in the construction, supply, and maintenance of space habitats and planetary surface manufacturing facilities, thus paving the way for human development of space. How we develop and use OOS technology today will impact the future direction of humanity's expansion into the solar system.

1.4 Purpose and Scope

On Earth, mobile systems like ships, aircraft, cars, and submarines have supporting infrastructure that enables periodic refueling, repair, maintenance, and upgrading. Spacecraft on the other hand, move in an inhospitable environment which is expensive to access. Consequently, servicing infrastructure has not naturally developed. Most spacecraft are built with redundant, reliable components but at great expense. Moreover, current spacecraft are discarded after reaching end-of life (EOL). We believe that OOS will enable spacecraft to be repaired and maintained like any other mobile system.

Our work aims to examine previous research in OOS, to assess market feasibility and needs, to establish considerations and criteria for an OOS design, and to outline a roadmap for the future development of a servicing infrastructure. This report uses an interdisciplinary, intercultural, and international approach to develop our OOS vision. Throughout this process, our team has worked toward a preferred destination: a robust and widespread space infrastructure in which OOS plays a vital role.

The scope of this paper encompasses robotic and human OOS mission scenarios from the present to 50 years in the future; for civil, commercial, and military applications in all orbits; analyzed from policy, economic, and technical perspectives.

1.5 Methodology

We conducted an extensive literature review to provide the Team a solid foundation with which to begin this project. This research also supports the initial feasibility analysis of potential OOS missions. Next, we identified gaps in the space community's ability to develop a viable OOS system that hinders continued advancement in this field. This is done by performing a gap analysis. We highlighted one of the enabling technologies identified in the gap analysis: Orbital Replacement Unit (ORU) Exchange, for a detailed architecture study. Finally, we presented our proposed roadmap over three phases:

- Near-Term Activities, looking at activities in the next 10 years
- Mid-Term Activities, looking at an event horizon of 10-30 years in the future
- Long-Term Activities, looking at an event horizon of 30-50 years in the future

Each of these phases will discuss a sequence of OOS missions, linked to their key enablers and drivers.

1.6 Supporting Material

1.6.1 Feasibility Matrix

The feasibility matrix is a customary tool in the aerospace industry, frequently used to assess the merits of potential technology solutions. By assigning quantitative values and weighting to a given set of criteria, we are better able to understand which technology options are more feasible or desirable. The Team performed a feasibility analysis on a set of 14 missions in five orbits, weighted against the following criteria categories: policy, economics, technology, and interdisciplinary. The results of our analysis can be found in Annex A.

1.6.2 Report Structure

Chapter 1 introduces the reader to Team DOCTOR and the concept of OOS. This chapter includes a definition of OOS, our mission statement, project scope, research methodology, and introduces supporting tools used in our analysis.

Chapter 2 provides additional background information on flown OOS missions. The chapter discusses the hazards of the space environment, common satellite failures and how OOS missions can mitigate these failures. We also include examples of previous missions and emerging efforts to privatize OOS. Finally we discuss the definitions of the various OOS missions considered in our analysis.

Chapter 3 discusses some of the challenges to achieving our vision for OOS. Policy, economic, and technical challenges are highlighted, including technology transfer, dual use, economic motivation, customer trust, and technology maturity. These challenges are considered throughout the rest of the report.

Chapter 4 describes potential solutions to some of the challenges discussed in Chapter 3. The Team highlights process solutions, such as technology diffusion through military agencies; technology solutions, such as spacecraft interface standardization; and regulatory solutions, such as space traffic management regulations. This chapter also includes a cost benefit analysis from the perspectives of satellite manufactures and operators.

Chapters 5, 6, and 8 presents our team's Near-, Mid-, and Far-Term visions for OOS. Potential customers, the OOS missions that will be able to serve these customers and additional space activities enabled by these missions are discussed for each of these time periods.

Chapter 7 provides a detailed description of a potential mission architecture present in the Mid-Term vision. This chapter discusses various architecture trades and provide a detailed description of our selected mission design: ORU Exchange. In addition to describing the technical details of the mission, we provide a market analysis for this baseline architecture.

Chapter 9 includes a final overview of our report along with conclusions and recommendations.

Chapter 2

Background of OOS

2.1 What Makes a Spacecraft Fail?

2.1.1 The Space Environment

The Sun's energy creates a hazardous environment around near-Earth space. Electrically conductive plasma can charge satellites, potentially resulting in a violent and possibly damaging discharge. The number of spacecraft failures due to plasma charging is directly linked to the solar cycle (Baker 2000). The solar cycle is characterized by a periodic variation in the frequency and intensity of solar activity, e.g. coronal mass ejections (CME) and solar flares. The solar cycle has an 11 year period caused by polar rotations of the Sun's magnetic field and is correlated with number and latitude of sunspots. The time during peak solar activity is referred to as solar maximum.

Charged particles from a CME or solar flare can hit the Earth, resulting in a geomagnetic storm. During these storms, solar plasma becomes trapped in the Earth's magnetosphere, thus increasing both the density and the energy of the charged particles in near-Earth space. Some of the particles are trapped in the Van Allen Belts and can take several days to decay. In addition, a solar flare can produce increased X-ray radiation, which evaporates electrons from conducting material on the spacecraft and creates a voltage difference (Figure 1-1). This radiation also decreases the lifetime of many materials.

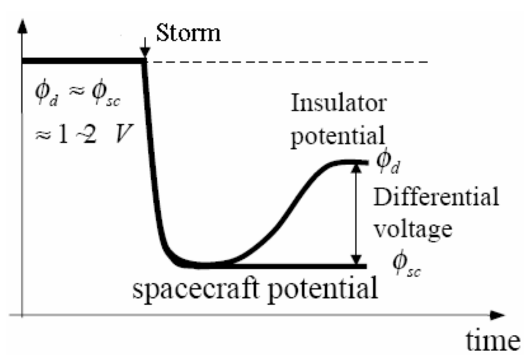


Figure 1-1: Impact of solar particles on spacecraft

2.1.2 Common Failures

As Ellery et al. (2007, p. 5) note, "most spacecraft failures occur due to environmental conditions, human intervention, excess load beyond design tolerance, systematic design faults or random failures." These failures can occur at the beginning of a satellite's lifetime, during the operation of the satellite, or near the end of the satellite's lifetime. Examples include launch failures resulting in an undesired Geostationary Transfer Orbit (GTO) parking orbit, electronic faults caused by charging or radiation, or worn equipment and expired fuel. OOS missions can respond to satellite failures by assessing damage, repairing components, or replacing worn and used systems.

2.2 Historical OOS Missions

2.2.1 Human Servicing Missions

Human OOS using Extravehicular Activity (EVA) has been conducted for more than two decades. These EVAs have been primarily restricted to valuable assets like the Hubble Space Telescope (HST) or the International Space Station (ISS), because of the expense associated with highly complex robotics (Hastings et al. 2001).

1984: Solar Maximum Repair Mission (STS-41C): Astronauts operating from the Space Shuttle, and using the Shuttle Remote Manipulator System (SRMS), repaired the Solar Maximum spacecraft, which suffered two on-orbit failures. The spacecraft re-entered the Earth's atmosphere in 1989 (Hamilton 2007).

1990-present: HST: After a BOL failure, the HST has been subsequently repaired and serviced through a series of shuttle and SRMS-based spacewalks. There are plans for one more servicing mission in 2008 to enable the HST to continue operating into the next decade. The HST was originally designed in the 1970s and launched in 1990, and OOS servicing has progressively upgraded the observatory's capabilities. The HST is the one of the scientific missions that is specifically designed for routine servicing by spacewalking astronauts. It has a serviceable, modular design that allows astronauts to replace worn out equipment and upgrade instruments.

1998: ISS: The Space Station was designed to be resupplied by various human vehicles, including the Space Shuttle, Soyuz, and even future Orion spacecraft. ISS servicing missions combine human and robotic servicing techniques. ISS robotics include the Space Station Remote Manipulation System (SSRMS, or "Canadarm2"), the Mobile Base System (MBS) and the Special Purpose Dexterous Manipulator (SPDM or "Dextre"). These integrated robotic systems play a key role in space station assembly and maintenance; moving equipment and supplies around the station; supporting astronauts working in space; and servicing instruments or other payloads attached to the space station. Additionally, the Japanese Experiment Module Remote Sensing Manipulator (JEMRMS) will be used for manipulation of external experiments on the Exposed Facility attached to Japan's Kibo module.

2.2.2 Robotic Servicing Missions

1993: Robotic Technology Experiment (ROTEX) studied by Hirzinger et al. (1993), was a DLR experiment conducted on the Space Shuttle Spacelab D2-Mission. This German experiment was designed to assess several operational modes, such as telemanipulation from both on-board the shuttle and from the ground.

1997: The National Space Development Agency of Japan's (NASDA) Manipulator Flight Demonstration (MFD) (Nagatomo et al. 1997 cited in Nagatomo 1998; Nagatomo et al. 1998) was a robotic arm experiment conducted on-board Space Shuttle mission STS-85. The main objectives of this flight demonstration were to evaluate the human-machine interface of the robotic arm, to demonstrate the attachment and detachment of an ORU, and to open and close a hinged door.

1997: The Engineering Test Satellite 7 (ETS-VII), developed and launched by the Japanese Space Agency, was the world's first telerobotic satellite aimed at developing the required technologies for autonomous rendezvous and docking (Yoshida 2003).

2005: Demonstration of Autonomous Rendezvous Technology (DART) was a technology demonstration mission that successfully acquired its target, but failed during final rendezvous.

2007: Orbital Express (OE) was a project of the Defense Advanced Research Projects Agency (DARPA), an agency of the U.S. Department of Defense (DoD) (Dornheim 2006). It successfully demonstrated autonomous spacecraft refueling and servicing techniques.

Other projects have been proposed by governmental organizations to service commercial or scientific satellites:

- ConeXpress Orbital Life Extension System (CX-OLEV)
- Proposed HST servicing mission using a variation of the SPDM and OE technology
- Ranger, a spaceflight-qualified dexterous robotic servicing system based largely on the requirements for robotic servicing of the HST (Space Systems Laboratory (SSL) 2005).
- European Robotic Arm (ERA)

2.2.3 Emerging Private Enterprises

Orbital Satellite Services, Ltd (OSSL), formerly known as Orbital Recovery Corporation (ORC), adopted the basic design of the cancelled CX-OLEV and is now offering life extension services for commercial telecommunication satellites in Geostationary Earth Orbit (GEO). OSSL has just recently contracted with Eutelsat to provide OOS to GEO satellites and has developed strategic partnerships with Arianespace, AON Space, The German Aerospace Center (DLR, Deutsches Zentrum Für Luft und Rahmfahrt), Dutch Space, Swedish Space Corporation, Sener, and Kayser-Threde (Xue 2007, pers. comm. 2 August).

GEO Ring Services is another start-up company which offers propellant supply and inspection services for spacecrafts in GEO, as stated in the Apofasi newspaper (2005) website.

2.3 Mission Categories

2.3.1 OOS Technical Overview

As an initial methodology to select potential OOS missions for further exploration, Team DOCTOR designed a taxonomy system to categorize the various OOS mission types. The first level classifies potential missions based on their functional elements. Specifically, the Team separated OOS missions into three categories according to their interaction with the Client satellite:

- Missions that remotely *inspect* the client satellite
- Missions that actively *manipulate* systems, or components on the Client satellite
- Missions that *maneuver* the Client satellite through momentum transfers, or stabilization

The second level of the taxonomy describes the desired goal of the OOS mission, while the final level accounts for mission differences due to operational orbits. The specific missions are described below.

2.3.2 Inspection Missions

There are a large number of failure modes that could lead to a partial decrease of performance or the total loss of a spacecraft. Logistics problems, as well as limitations in cost, mass, power, and telecommunication bandwidth limit the amount of data provided by the satellite for failure analysis from ground control. The Inspection Mission category makes it possible to conduct OOS activities that can provide additional information to analyze and diagnose the cause of a satellite failure.

This OOS mission type is defined by the absence of physical interaction between the Servicer and the Client spacecraft. Many different technologies are available to perform the on-orbit remote sensing of a Client satellite. Some examples include:

- Infrared (IR) sensors to verify the functionality of the solar panel
- X-ray sensing of spacecraft
- Visual inspection by means of a camera to verify impact of debris and or meteorites
- Sensing to verify the status of a mechanism in terms of kinematics and/or functionality

The Team considered two types of operation:

- Fly-by: inspecting the Client satellite for a limited time from a distance, without phasing into the Client's orbit.
- Proximity Operation: phasing into the Client's orbit using active orbital correction to "fly" around the Client satellite and take multiple images from varying angles and distances.

2.3.3 Manipulation Missions

Team DOCTOR defines the Manipulation Mission category as any OOS mission in which the Servicer spacecraft physically changes or manipulates the Client spacecraft or its components. All types of refueling and repairing missions fall under this broad category. Other manipulation missions require robotic servicers with rendezvous and docking capabilities that provide life extension or failure recovery services to the Client satellite. Fuel or electronics ORUs provide a solution to many of the Manipulation Mission challenges.

Another life extension option is to dock the Servicer spacecraft to the Client and replace lost propulsion and guidance, navigation, and control (GNC) capabilities. This option avoids the need for dexterous robotics and the challenge of transferring fuel by essentially taking over these functions for the ailing Client.

The Team has evaluated several dedicated refueling concepts that could be included in a robotic servicing infrastructure. For example, a one-time refueling servicer could transfer fuel to a Client spacecraft, as was demonstrated by OE mission (reference Section 2.2.2). Eventually, a large fuel depot could be placed in orbit with enough fuel to extend the life of several satellites. Large fuel depots along with robust robotic servicing will enable the development of future space infrastructure including on-orbit construction.

The Team considered nine types of manipulation missions:

- Human Servicing: Astronaut servicing such as the HST servicing missions.
- ORU Exchange: Robotic Servicer physically removes an ORU and replaces it with a new ORU.
- Propulsion GNC/Life Extension Module: Servicer docks to the Client and provides these functions for the rest of the satellite's life.
- Refueler: A single servicer transfers fuel to a single client, and the mission is over. The Servicer may remain docked, but it does not service any other satellites.

- Refueler and Depot: The depot is a large fuel tank, and the refueler travels to and from the depot and multiple clients in order to transfer fuel.
- Stand-Alone Fuel Depot: The depot does not have any secondary refueler spacecraft, so either it is self propelled or the satellites travel to it.
- Fuel Depot with ORU Spares and Tools: Similar to a single-purpose Fuel Depot, but this spacecraft also contains spare ORUs and tools as well as fuel.
- Robotic Construction: Autonomous or teleoperated robotic spacecraft used to build structures in space or on planetary surfaces.
- Human Construction: Astronauts building structures in space, including stations and surface facilities.

2.3.4 Maneuvering Missions

The Team defines the Maneuver Mission category as any kind of OOS that is dedicated to changing the Client spacecraft's position and velocity in space. This may be done on a single occasion or repeatedly over a specified period of time. A conceptually simple way of enabling the Servicer to take control of the Client's orbit is by rigid attachment of the Servicer vehicle to the Client spacecraft. The Client's propulsion system is switched off (if it has not already failed) and the Servicer's own actuators are used to maneuver the Servicer together with the Client into any desired orbit. Future innovations may provide other technologies that enable orbital transfer without rigid docking. However, any mission that includes refueling, repair, or exchange of the Client's propulsion system will not be considered a maneuvering mission: these mission types are included as part of Manipulation (reference Section 2.3.3).

The Team considered three types of maneuvering missions:

- De-Orbiter (One-time Use): The Servicer docks to client and de-orbits itself with the client. This mission does not necessarily require atmospheric re-entry. De-orbiting can include removal to a graveyard orbit.
- Re-Orbiter (Multiple Use)/Space Tug: The Servicer changes the orbit of a satellite, undocks, and is then available for another Client. This mission can be performed multiple times by a single Servicer.
- Human Capture and Return: Astronauts retrieve a satellite on EVA, and return it to Earth.

One possible application for the above missions is the compensation for launch vehicle failure. If a launch vehicle fails to deliver a spacecraft into its designated parking orbit, the spacecraft may have to perform a larger than planned maneuver to reach its operational orbit. Fuel reserved for stationkeeping will be used for this purpose, shortening the spacecraft's lifetime. If the gap between the current and desired orbit is too great, all onboard fuel reserves may not be sufficient to compensate. In this case, the mission is lost. An OOS maneuvering mission could move the client from the incorrect to the correct orbit, thereby saving the satellite.

A second application targets Clients at EOL. Spacecraft that are no longer operational are supposed to be moved to designated graveyard orbits or de-orbited to Earth, thereby limiting the amount of space debris. However, if a spacecraft has run out of fuel or failed altogether, it cannot perform this final maneuver. In this case, an OOS Servicer can "clean up" the orbit by removing the failed satellite. Another reason for employing a Servicer to de-orbit a spacecraft is to extend the spacecraft's lifetime. Usually, a certain amount of fuel is available for the final burn that de-orbits a satellite. If this fuel can be used for nominal operations with the Servicer providing the final boost, the satellite can continue generating profit beyond its original lifetime.

Chapter 3
Challenges

This section describes various challenges and considerations that impact the feasibility of OOS. It is important to develop a clear understanding of all the issues in order to propose effective solutions going forward.

3.1 Economic Challenges

One of the most challenging issues facing OOS is economics. Schedule, development and technological costs are prohibitive for most OOS missions. Currently, satellite operators use other techniques to investigate satellite failure of end of life, such as onboard diagnostics and ground simulations. These techniques are preferred because they are less expensive. Even if an inspection mission is conducted, there is no chance to recover the satellite. Thus, the price for these missions corresponds only to information gathering, not to a restoration of service. Military customers may be interested in this type of information, but often commercial customers may not be. Indeed, most managers in a commercial environment are less interested in the "details of what went wrong", and more interested in "what can we do about it".

For the economic evaluation of missions, many interdisciplinary aspects shall be taken into account. The complexity for economic evaluation of OOS increases when considering other factors, such as the societal value of space debris reduction, and the points of view of different actors in the space industry. Insurance companies may be interested in OOS for its possibilities to reduce payouts in case of failure, and satellite operators may be interested in OOS for its ability to increase the operational lifetime of their assets. On the other hand, satellite manufacturers may see a decrease in their business if satellites last longer. Indeed, planned obsolescence is an important driver in the business world. If the satellite manufacturing industry views the concept of "design for servicing" as harmful to their industry, they will resist it. Another consideration is that satellite operators may prefer to take advantage of new technology improvements, rather than make old technology last longer (Saleh et al. 2005). This consideration could be mitigated by making payloads, such as transponders and scientific payloads, among the replaceable units. In this way, servicing is not just providing lifetime extension, but also providing important capability upgrades.

3.2 Engineering Risks

Another major challenge with OOS is the technical risk associated with missions. Many OOS missions are more risky than regular satellite missions, due to the additional complexity associated with rendezvous, docking and servicing interactions between the Servicer and Client. Adding to the risk is the fact that many of the technologies and operational concepts associated with OOS are still in a research and development phase. Additional technology development, testing, and commissioning are required to reduce real and perceived risks and make OOS more feasible.

3.3 Technology Transfer and Export Controls

In a knowledge economy, ideas, innovations, and technologies drive growth and have direct economic value (Jaffe et al. 2002). Consequently, nations have established laws and policies to maintain property rights for ideas and protect sensitive technologies. OOS missions require some interaction between the Servicer and the Client supported by a mutual exchange of information. Additional information can be acquired inadvertently through the process of OOS. These interactions could lead to two different difficulties: the exchange of information could conflict with national policies and the necessity to exchange information during Servicer and Client acquisition could represent an obstacle for certain servicing customers. Clients may not want to reveal technical information on their design and/or failures occurring on their spacecraft to the servicing company.

Space technology can be an essential element of economic, strategic, and military security. Consequently, it is unsurprising that space technologies have the potential for dual civilian and military application. The term "dual-use" refers to this bi-modal nature. For OOS missions, dual-use applications can exist whenever a Servicer has a military client, or if a Servicer inspects, moves, or manipulates a Client without permission. Almost all the technologies developed for OOS can also be used in a military application. Some countries may wish to maximize their investment in space and promote dual-use technologies in order to ensure national security while enabling scientific or economic growth. However, dual-use space technologies make it possible to hide military intentions behind the label of "peaceful purposes." International arms control treaties attempt to limit the proliferation of dual-use space technologies and the feasibility of OOS missions with obvious dual-use components could be negatively impacted by these treaties.

In addition, the U.S. International Traffic in Arms Regulations (ITAR) restrictions limit the proliferation of technologies that can have military applications. These can also compromise the feasibility of OOS missions making use of ITAR-controlled technologies.

3.4 Liability, Insurance, and Licensing

The Liability Convention, recommended by the United Nations (1972), establishes absolute liability to a launching state for damage caused on the ground or air, and limited liability based on fault for damage caused to third parties in space. Due to the complex maneuvers and the close proximity between Client and Servicer spacecraft, OOS activities can have several special policy issues regarding insurance and liability. Of particular interest is on-orbit insurance covering damage to the Client, Servicer, or third party satellites due to a collision. The actual impact of national insurance and liability policies will depend on the types of spacecraft involved (e.g. commercial, military, or governmental) and the types of missions. Moreover, international missions that include a Servicer and Client from different countries could be very complex from a licensing perspective. The absence of legal regulations for many OOS applications increases the difficulties of manipulation and maneuvering missions from the legal point of view. In particular OOS missions will suffer from:

- Lack of regulations on high-resolution sensing on spacecraft belonging to different companies or countries than the servicing satellites for inspection missions.
- Lack of regulations about liability and responsibility of docked satellites for manipulation and maneuvering missions.
- Lack of common practices on insurance for manipulating satellites.
- Lack of common practices on insurance and regulations on human missions.

3.5 Space Debris

Brisbe and Pessoa-Lopes (2001, p. 1) state that "Space debris is increasingly becoming an important factor when considering the exploration, utilization, and environmental protection of outer space." Besides natural objects threatening collision, man-made objects like upper stages, fragments from satellite collisions or break ups, and even items as small as paint flakes pose a significant hazard to spacecraft. Also, decommissioned satellites quickly become uncontrolled vehicles that pose a significant hazard for spacecraft operating in similar orbits. In addition to posing a threat to operational satellites, continued debris creation could clog useful orbits creating congestion problems for Space Traffic Management (STM). The National Aeronautics and Space Administration (NASA) and other space agencies have guidelines to limit the creation of debris during nominal operations and EOL de-orbiting into the atmosphere or boosting to graveyard orbits as stated in NASA's Office of Safety and Mission Assurance (1995). Due to the particularly limited resource in GEO, regulations are emerging that require adequate fuel to remain in order to boost unused satellites into a higher graveyard orbit (FAA 2002). There may be opportunities for the use of OOS to assist in either boosting or de-orbiting these vehicles after their fuel, and usefulness, has been expended. Servicing failed satellites or increasing the satellite lifetime can also mitigate the impact of space debris.

OOS missions also increase the risk of generating debris. This creates additional debris challenges if failed components are not effectively disposed of, or if there is an anomaly during rendezvous and docking. OOS missions are inherently risky with rendezvous and manipulation of other spacecraft, increasing the potential for collision and, in turn, creating more debris.

3.6 Space Traffic Management

Under normal circumstances, operational satellites stay within their intended orbit. Servicing satellites are different. They approach their Client's spacecraft and enter into its orbital space. These approaches need to be carefully managed for the safety of both participating spacecraft and all other spacecraft which may be nearby. Guidelines need to be developed on this approach. Complex proximity operations need to be tracked and controlled.

As space becomes more populated, it may become increasingly difficult to launch an OOS mission, to reach the Client, or to work in space. Future STM regulations may further restrict OOS spacecraft to operate in a certain manner in certain orbits.

3.7 Technology Readiness Level

Technology Readiness Level (TRL) is a measure used by many of the world's space agencies and companies to assess the relative maturity of a given technology (materials, components, etc.). Typically, when a given technology is first conceptualized, it is not suitable for immediate application and its TRL is low. Indeed, new technologies need to be extensively tested and refined, which increases technical maturity and the TRL. Once a technology is sufficiently proven it can be used in an operational space mission.

Since many of the technologies necessary for OOS are still under development, the TRL for OOS in general is quite low. This means that operational OOS is still considered a high-risk activity. Additional technology development, testing and commissioning is required to increase TRL and make OOS more feasible.

3.8 Standardization

Currently, there are several satellite manufacturers in the international market, providing a large variety of satellite applications. As a result, there are a large variety of satellite designs. Most satellites are not designed for servicing but are optimized for various functions. Satellites are usually designed for a predetermined lifetime. Most satellites finish their useful lifetime when they run out of fuel and are no longer able to perform maneuvers or attitude control. Since these satellites are not designed for servicing, the useful life of the satellite is over, even though all other equipment may still be functional. Most of the OOS missions need some kind of interaction with its Client spacecraft. This implies that the satellite design should permit this interaction. Some servicing concepts, like the lifetime extension concepts SMART-OLEV and ConeXpress, are able to take advantage of the fact that the apogee kick motors have a common design. As such, Servicers can dock to the apogee kick motor and perform station-keeping for the Client. The disadvantage with this approach is that a single Servicer can only service one Client. From an economic and technical prospective, it is preferable for a Servicer to be able to service multiple Clients but this requires that the Clients are designed for servicing and have a certain level of standardization. This brings about business concerns about the economics of standardization.

Different communities, like civil or commercial space, will respond differently to various standardization policies. There is the question of who sets the standards, who owns the rights, how does the standard change and evolve. These questions all need to be addressed in a workable solution. Regardless of the standards selected and who manages the standardization (private industry or government), it is clear that servicing standards need to be defined in order to make most concepts of OOS feasible, especially from an economic perspective. Finally, another issue that should be taken into account regarding standardization is that widespread standardization may limit technology development and system performance. Customization is currently used widely to optimize performance versus mass and power cost.

3.9 Customer Trust

The final challenge discussed in this section relates to customer trust. Although there have been many technology demonstrations of OOS capability, the overall concept is not nearly as proven in an operational and commercial context. It is still perceived as a very high-risk endeavor. Several successful missions need to occur in order for a larger portion of the satellite industry to make OOS an important part of their operational context. Given the importance of space activities, few actors are willing to take the risk of being the first to accept the servicing for an operational satellite. To close this gap, we need to demonstrate that the risk associated with OOS is low, by showing that OOS can be done on operational spacecraft.

3.10 Summary

A detailed gap analysis for each OOS concept and the various challenges is provided in the Feasibility Analysis section (see Annex A), by aid of a feasibility matrix. The matrix can be used to identify the key factors that impact the feasibility of certain OOS concepts. Upon reviewing the various factors, the Team determined that some factors impact all OOS concepts and need particular attention. Those primary factors are:

- Standardization in spacecraft design
- Economic preference for life extension over replacement (Economic Motivation)
- Confidence among satellite operators in OOS technical feasibility (Customer Trust)

Solutions to address these primary factors are proposed in the next section.

Chapter 4

Bridging the Gap - Solutions

As mentioned in the previous section, there are important barriers preventing the widespread use of OOS. If these barriers cannot be overcome, OOS will advance no further than technology demonstrations and near-term scenarios. Standardization is a particularly important gap to analyze. If satellite operators and manufacturers can be convinced to design for servicing, many interesting OOS missions can be enabled, which in turn can enable a more efficient and integrated space infrastructure for future exploration.

One approach to standardization could be that governments impose standardization upon the industry, with the idea that extending satellite lifetime would control space traffic. But this is easier said than done, because OOS technology has not yet been proven in an operational sense and is still considered a high risk activity. It may be irresponsible for governments to impose OOS under present conditions, considering that satellites are such an important part of daily life. In any case, given the risks associated with the first operational OOS missions, insurance premiums would likely be higher for the first satellites to perform OOS. Once OOS technology is proven to be reliable and capable of extending satellite lifetime, then one can expect insurance premiums to decrease.

What is required to initiate the OOS industry is for OOS to move from being a 'technology in demonstration' (which is its current status) to being a 'technology in operation.' In this section, we propose solutions to the major impediments to OOS. Several pathways are considered:

- Industry-driven standardization
- Technology diffusion through military
- Standardization through Public-Private Partnership
- ISS standards based on ISS robotics spin-off
- Commercial Space Standards Board
- STM regulations

The first four of these pathways are specific project proposals which can create market-driven standardization. The last two discuss policy approaches which can favor standardization. Each is an alternate future scenario, with the end result that commercial satellite manufacturers agree to change their architecture designs to incorporate the concept of "design for servicing."

4.1 Industry-Driven Standardization

Two models are considered for industry-driven standardization to enable satellite manufacturers to design for servicing. The first discusses the case where a large satellite operator decides to enter the OOS business. The second case analyzes the business case for a satellite manufacturer to create an OOS business.

4.1.1 Large Satellite Operator Initiative

One approach for voluntary standardization is for a large and successful communications satellite operator to initiate OOS using its own assets. This can be done through strategic partnership with a smaller satellite manufacturer and perhaps another company specializing in robotics. In this way, the large company would continue to make money from its core communications business, but also invest in the future of OOS. This investment would be interesting for the satellite operator, because if the OOS is operationally successful, it becomes a pivotal innovation, allowing their satellites to last significantly longer than those of their competitors. This provides a dramatic increase in profit margin.

This partnership would be interesting for the smaller partner as well because it allows the company to differentiate itself from others in the field, and offer a unique product. Once competing operators realize that servicing technology works and provides a competitive advantage, the small manufacturing company could quickly become an industry leader providing a new technology for satellite operators. Another advantage of a large company is to offer servicing to its competitors. Robotic OOS then becomes an additional service that the large company can provide as a spin-off business, generating additional revenues beyond the initial service revenues.

To maintain and grow the servicing side of the business, the company should consider open and accessible robotic compatibility standards. This should entice other companies to adopt robotic compatibility standards, rather than develop their own. This has proven to be a very effective business strategy to establish standards. For example, in the early 1980s, JVC promoted its VHS format using an open licensing program, and beat out Sony's Betamax format, which many considered technically superior, to become the standard format for consumer analog video cassette recorders, without any government intervention (Grindley 1995). Another strategy that could be considered is to offer pre-positioned spares on-orbit, which could be used for the company's own satellites or for its clients. This may be costly, but may provide additional incentive for other companies to develop serviceable satellites.

The problem with this model is that the large organization incurs major development costs and initial risks. Thus far, no satellite company has been willing to take on these risks. Unless launch costs decrease substantially, satellite operations will remain very expensive as will service to the end-users of satellite technology. Once the OOS paradigm is proven on-orbit in an operational system, the large organization that decides to invest in this capability would gain network benefits derived from being the first user, and first provider of services, in a brand new market. They can also define the robotic compatibility standards, and the manner in which they are used and evolve. This provides an advantage that can be used to gain an operational advantage (Besen and Farell 1994; Besen 1999).

4.1.2 Entrepreneurial On-Orbit Servicing Initiative

Historically, satellite manufacturing has been less profitable than service-based satellite businesses. A successful entrepreneurial OOS company that is able to extend the lives of commercial satellites would begin to erode satellite manufacturing sales. Manufacturers who are affected by dwindling sales are likely to purchase successful servicing companies or begin to offer OOS services. In the short term, these manufacturers may suffer a short-term decline in profitability as it incurs non-recurring costs, but over time product flexibility will give the manufacturer an advantageous position. Furthermore, any manufacturer that offers servicing would begin to standardize elements of its own satellite designs to gain maximum benefit from its associated servicing business.

The deployment of standards would not only be realistic and feasible, but also profitable for any company that has the necessary talents and financial resources to develop it. Service-based businesses are often more profitable than margin-over-cost manufacturing, and the first movers toward standardization will make above-average profits. For the purposes of this analysis, we have assumed that a successful servicing business would have a profit margin of around 25%, as opposed to 10% for manufacturing. However, we must emphasize the following cost/benefit analysis is based on several assumptions, and that in reality no standards for servicing have been developed for GEO communication satellites to date.

The cost/benefit model we developed uses parametric costing based on NASA cost heuristics (NASA Johnson Space Center (JSC) 2007). Although there exist other more defined models, this one enables us to see basics outputs of parametric costing. Input variables are as follows:

- Servicer costs (non-recurring, production, launch, launch insurance)
- ORU Costs (non-recurring, production, launch costs, launch insurance)
- Liability insurance costs
- Operation costs

We assume the average cost of a non-standardized satellite is around $150 million USD, and a standardized satellite costs about $175 million USD. With a 10% profit margin, this equates to $15 million USD and $17.5 million USD profit per satellite, respectively. Assuming five manufacturers each control 20% of the market of around 20 GEO satellites per year (Union of Concerned Scientists 2007), this means that one manufacturing company will produce four satellites a year leading to $60 million USD of profit. This is the economic landscape prior to "design for servicing."

We further assume an initial demand of four servicing missions per year, once the standardized satellites begin to need servicing. If we assume a $75 million USD fee for each service mission, a profit margin of 25% leads to $75 million USD in profit over four missions. Looking at a time span of 15 years, one possible scenario is that a manufacturer sells four satellites a year over the entire period (non-servicing scenario). Another scenario is that the manufacturer sells four satellites each year for a period of 10 years, in the last five years only performs servicing for $75 million USD per year, assuming the servicing missions allow for five years of life extension. Calculations show that with a profit margin of 25% for servicing missions and 10% for manufacturing, net profit over the 15 years would be $975 million USD and $900 million USD, respectively. Additionally, one needs to assume that after a time span of 10 years, the market share of the companies offering standardization will rise. Performing the same calculations with an increased market share of 25% after the tenth year equates to selling five more satellites, creating additional profits of another $75 million USD. Thus in total, the company would make $150 million USD more over a time span of 15 years, making additional $10 million USD a year of profits. As other manufacturers respond and start their own standardization initiatives, market shares should stabilize, but all manufacturers that offer service businesses should be more profitable. Table 4-1 illustrates the total cost and revenues of the architecture we present in Chapter 7.

The non-recurring costs have been split up according to NASA JSC advanced cost models (NASA JSC 2007) over a time span of five years. Important factors like liability, launch, and ORU insurance have been factored in, as well as operational costs of the system after launch. Reduced costs in the ORU production are based on an assumed learning curve of 95%. Given these assumptions, our model indicates the break even point in year 10.

It is important to note that even a satellite manufacturer, who will most likely sell a reduced number of units after the introduction of such a capable system, should enjoy increased profitability over time, due the higher-margin servicing missions compared to manufacturing margins. The problem is that a large initial investment is required, and in our example above, the business takes about ten years to break even. Even the most forward-looking business executives might not look this far into the future. However, if a company has patience and follows through, this might be acceptable. If not, other models may be required to initiate the OOS business.

Table 4-1: Cost Model for OOS Delivered by a Satellite Manufacturer

$ million	Develop				Build	Launch!	Launch 4 ORUs each year after				
Year	0	1	2	3	4	5	6	7	8	9	10
Non-recurring servicer	-62	-111	-91	-46	-10						
Non-recurring ORU	-10	-19	-15	-8	-2						
Servicer production					-86						
Servicer launch						-102					
Servicer launch insurance						-24					
ORU production					-37	-33	-32	-31	-30	-29	-29
ORU launch						-19	-19	-19	-19	-19	-19
ORU launch insurance						-8	-8	-8	-8	-8	-8
Liability insurance						-10	-10	-10	-10	-10	-10
Operations						-10	-10	-10	-10	-10	-10
Total cost	-73	-130	-106	-54	-134	-207	-79	-78	-77	-77	-76
Total cost cum	-73	-203	-308	-362	-496	-703	-782	-860	-937	-1.014	-1.090
Discounted @ 10%	-73	-191	-278	-319	-410	-522	-566	-606	-642	-675	-704
Total revenues					0	75	298	298	298	298	298
Total revenues cum					0	75	373	671	970	1.268	1.567
Discounted @ 10%	0	0	0	0	0	46	215	368	507	634	749

4.2 Technology Diffusion Through Military

A major problem with a purely commercial OOS endeavor is the large start-up cost and risk, both technical and economic. Other possible solutions mentioned here consider opportunities and methods for governments to take on the initial costs and risks, and then proceed to commercialize the technology. In a talk to International Space University (ISU) students during the summer of 2007, NASA Assistant Associate Administrator Mark Uhran mentioned that throughout history, governments' responsibility has always been exploration, and private sector's responsibility has always been development. A similar sentiment is expressed in the Global Exploration Strategy (GES), jointly released by four major space agencies (GES 2007). Since OOS is presently in an exploratory state, it needs public money. Once ready for development, private sector could take over. The first case we propose is for a government organization to take the initiative to support OOS through the U.S. military.

As evidenced by the development and testing of OE and ongoing research and development in OOS (Madison 2000), the U.S. military is interested in OOS of its space assets and will continue in the development and operational deployment of these capabilities (David 2004). In general, virtually all military satellite technology would fall under strict export restrictions (U.S. Directorate of Defense Trade Controls 2007). As such, the robotics compatibility standards would likely not be made public, at least not during initial development phases.

Many military standards have been transferred and used in commercial world. The most prominent example would be the Internet, which was created by the same organization that funded OE: DARPA. The Advanced Research Projects Agency Network (ARPANET), as the Internet was originally known, was first brought online in 1969. Its purpose was to provide access to powerful research computers from facilities scattered around the U.S. The technology was later spun off into the commercial sector, allowing its rapid growth and expansion through increased commercial investment, and continuing to meet the needs of its government clients (Leiner et al. 2003). Another more recent example is the High Level Architecture, developed by the U.S. Defense Modeling and Simulation Office (DMSO) to ensure simulation interoperability between all DoD simulations but later commercialized as an Institute of Electrical and Electronics Engineers (IEEE) open standard (DMSO 2007). In the space arena, the Global Positioning System (GPS) is another example of publicly available military technology. Although the U.S. military operates the spacecraft in the GPS system, the signals and standards are openly available for commercial applications. Another area that the military is looking to commercialize is their launch operations (Borky 2000). The advantage of commercialization is that the technology continues to be developed by the private company, and the military needs continue to be served without further military investment. This allows military funds to be redeployed in other areas. A service developed and maintained by the private sector does not need to be developed and maintained in parallel by the military sector. Furthermore, commercialization agreements could be put in place whereby the military could be a "preferred client," receiving free or low-cost use of the service, in consideration of its upfront investment in the research and development.

Applying these analogies to OOS, we can make a case that establishing a robotic Servicer, initially developed to service military satellites, could also be commercialized and put into use on commercial satellites, when it is not actively servicing military satellites. This would free the military from committing further resources to OOS operations. As part of the commercial agreement, the company taking ownership of the Servicer could be required to service military satellites at an agreed-upon low cost.

The problem with this solution may be in the military's willingness to make their robotic compatibility standards publicly available. This information could reveal military satellite design, which is counter to the ITAR philosophy of restricting military spacecraft design information. If a potential servicing client needs to receive ITAR clearance to receive the standards, it may reduce the client base, and the servicing company may be restricted from servicing satellites from other nations. That said, robotic compatibility standards are available for the ISS (NASA/CSA 1997), and this information is not ITAR-controlled in that environment.

If the robotic compatibility standards are openly published and if the technical success of OOS for lifetime extension is proven by successful deployment in an operational military context, then the satellite industry would be able to benefit from military investments. This would allow satellites to operate longer, without having to pay the up-front development costs of the Servicer and without incurring the risks associated with the first servicing missions. This should provide motivation for satellite operators to adopt the standards and consider designing for servicing.

4.3 Standardization through Public-Private Partnership

Another proposal to encourage the satellite industry to "design for servicing" could be through a public-private partnership (PPP). This model is also a market-based approach to standardization, but involves collaboration between one or more government space agencies and private industry.

In this model, the space agency would incur most of the development costs and initial risks, and offer a two-phased mission, combining science objectives with OOS technology demonstration objectives. In the first phase, the agency would commission a Servicer satellite per the following specifications: designed for servicing, equipped with robotic arms, equipped with a serviceable scientific payload (i.e. which can be removed and replaced). The ideal scientific payload for this satellite would be one that requires data over a long period of time (10-20 years) and that has an important social impact. One candidate could be an earthquake precursor determination satellite. The earthquake precursor satellite system is an ideal piggyback payload because it has an important social component yet it may have trouble getting funding on its own, due to its experimental nature. This project is also a good candidate as a joint project between two or more space agencies, since some countries have particular interest in robotics, while other countries have particular interest in earthquakes. For example, this could be a good project for a joint collaboration between the space agencies of Canada and Japan, Japan and China, or Canada and China. Japan, with particular interest in earthquakes and robotics, would be an ideal actor in this project.

During the first phase, the first demonstration of the robotic Servicer could be to remove and replace its own payloads. Once the servicing technology demonstration mission is completed, the satellite could continue providing science data for its science mission. Having two important objectives will help generate momentum for the project. However, care must be taken to ensure that the science objectives and technology demonstration objectives are complementary.

The second phase of the mission takes place some time later, after the initial self-servicing has been demonstrated, and the scientific payload has gathered some data. In the second phase, another serviceable scientific satellite, without robotic arms, is launched, compatible with the original Servicer. Instead, in addition to scientific payloads, it also carries additional standard ORUs, such as fuel tanks and batteries. The scientific payload itself should also be an ORU. To complete the technology demonstration, the robotic Servicer would then maneuver to the new satellite and perform standard servicing operations. Examples could be to exchange scientific payloads or the Servicer could replace its own fuel tank with a new one. At the conclusion of these activities, both satellites would return to their science functions. There would also be a number of extra ORUs on-orbit, which could be logistics for the satellite pair or could be additional scientific equipment. These ORUs could be used as incentives to encourage future companies to adopt standard interfaces, in order to take advantage of the ORUs that have already been launched.

Depending on the science objectives and requirements of the mission, additional satellites could be launched with the same specifications to form a constellation. If there is a large number of satellites, all of whom that are designed to be Clients for the Servicer, this improves the credibility of the OOS concept.

The mission described above could be run exclusively by an agency or partnership of agencies. Alternately, it could be a PPP, in which the government agencies pay for the development and launch of the satellites, Servicer, and scientific equipment and a private company is selected to operate the Servicer and science payload (undertaking those costs). An example of this kind of PPP would be the partnership between the Canadian Space Agency (CSA) and MacDonald Dettwiler and Associates (MDA) on the Radarsat-2 program, where CSA paid for the satellite but MDA is responsible for operations (CSA 2006a). The benefit to the government is that scientific objectives are being advanced simultaneously with OOS technology maturation, which will be instrumental in limiting space traffic and widening the satellite market. The benefit for the company would be that they do not incur all the risks (or costs) associated with the initial servicing missions but are able to provide services to the government and begin to create the satellite servicing market. The incentive for other satellite operators to demand satellites that are designed for servicing is that once the servicing concept has been validated, there could be ORUs already available on-orbit which could mitigate against a shortened lifetime for a future satellite.

An additional benefit of this particular scenario is that it could create goodwill for OOS among the general public. OOS could be perceived as a socially responsible way to perform business in space. Furthermore, companies that associate themselves with the mission (by developing standardized satellites) could be perceived as more ethical. The importance of the public perception of a space project is important in keeping the project relevant and funded.

Finally, it is important to emphasize that any government space agency with an interest to develop space infrastructure around the Moon or Mars should consider OOS as an enabling technology. In addition to supporting the construction of Moon-orbiting or Mars-orbiting infrastructure, OOS can also mitigate risks associated with exploration missions, providing options for corrective or preventive maintenance on spacecraft in areas where humans presently cannot reach. This is particularly important for Mars missions where the global success rate historically has been under 50% (Knight 2006). Indeed, the GES Framework for Coordination, published jointly by fourteen space agencies in May 2007, makes frequent reference to the necessity of robotic pathfinders as predecessors to human exploration (GES 2007). In addition, comprehensive NASA studies on Mars exploration have indicated that hardware destined for Mars should allow problems to be "fixed in place if possible" (Hoffman and Kaplan 1997) as a risk mitigation strategy. Clearly, OOS creates this possibility. The experience gained by OOS robotics in exploration missions will be essential in order to understand and plan how to deal with adversity in extreme environments, for both robotic and human space missions.

4.4 ISS Robotics Spin-off Initiative

Another proposal to launch OOS is to continue using the ISS robotics, specifically Canadarm2 and Dextre, after the ISS program has been completed. This approach leverages existing ISS infrastructure and experience, reducing development costs and risks. This initiative is possible because the symmetrical Canadarm2 has the capability to "walk off" from one base point to another (CSA 2006b). Part of Canadarm2's operational concept is to be able to capture and berth free-flyers, the first example being the Japanese H-II Transfer Vehicle (HTV), which provides logistics to the ISS and whose operations are planned to begin in 2009 (JAXA 2007a). An option to keep the robotics alive after ISS and spur OOS is to have a joint project between Japanese Aerospace Exploration Agency (JAXA) and CSA and their industrial partners. A redesigned HTV, equipped with the appropriate power, data and video interfaces, could become a new base point for the Canadarm2. The Canadarm2 can then walk off onto the HTV and pick up Dextre. The redesigned HTV can then detach from ISS as a roaming servicing platform for LEO satellites.

Primary benefits of this innovative approach to OOS come from the fact that all the robotics have already been built and tested, and the robotic compatibility standards are easily available (NASA/CSA 1997). Many companies are familiar with the ISS robotic compatibility standards and could develop compatible serviceable satellites if there were requirements to do so. That said, Dextre is capable of servicing 'non-standard' interfaces as well. If new or different interface styles are required, new robotic tools could be developed and attached to the redesigned HTV.

For this mission to have success in opening up the OOS market, it should include candidate operational satellites to be serviced, which have at least some level of serviceability (as HST does). Since commercial customers may be hesitant to undertake this task in the near term, the operational satellite probably needs to be funded by a space agency, as part of this project. The candidate satellite could be an existing science satellite, such as HST or James Webb Space Telescope (JWST) or a new science satellite, such as the earthquake precursor system outlined in the previous example. As indicated in all other proposals, demonstrating and proving OOS on operational satellites seems to be the best way to tear down the barriers currently preventing OOS from moving beyond the technology demonstration phase and into operational capability.

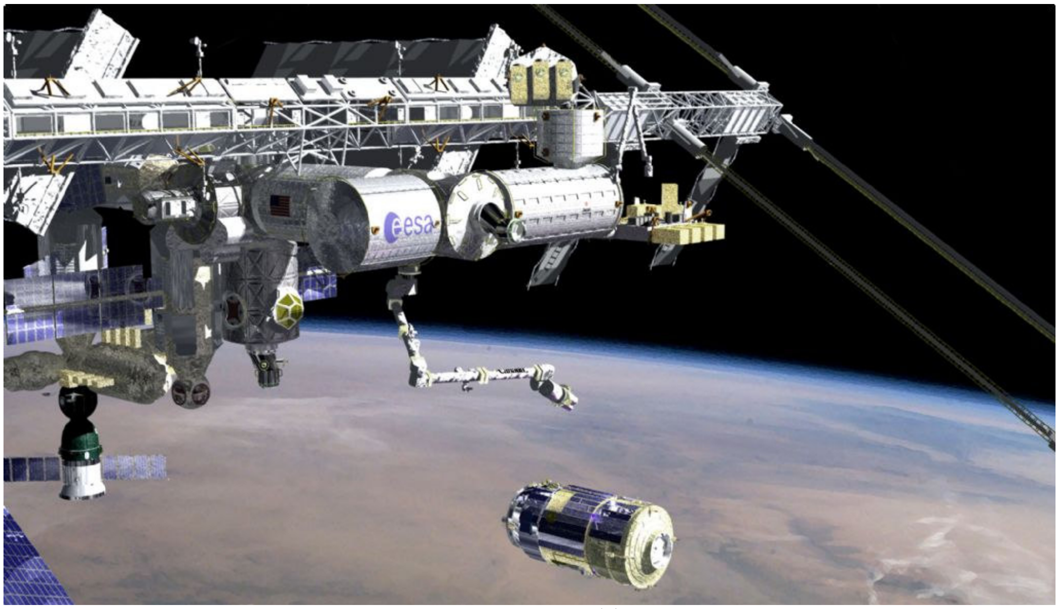


Figure 4-1: Canadarm2 capture of HTV (JAXA 2007b)

4.5 Commercial Space Standards Board

There are two possible drivers of standards: government and private industry. In the case of spacecraft design, private companies have and may continue to initiate standardization for components by voluntary means. Standardization often results through informal interactions between organizations which address technical and economic constraints. Alternatively, national and international policies can set formal standards.

To coordinate standardization, one step could be for the principal industry manufacturers, space agencies and large customers to arrange a series of meetings in which standardization protocols can be discussed and agreed upon. This kind of approach has been taken by the members of the European Space Agency through the European Cooperation of Space Standardization (ECSS 2007). This forum currently coordinates standardization in space project management, space product assurance and space engineering, and is an excellent example of international cooperation on space-related standardization. The activities of the ECSS could be expanded to include standards to support OOS. Other international forums that may be appropriate for discussions and agreements on OOS, or serve as models, could include bodies such as the International Standards Organization (ISO), the International Electrotechnical Commission (IEC) and the International Telecommunications Union (ITU).

For the Joint Strike Fighter collaboration, the United States Secretary of Defense established the Open System Joint Task Force (OSTJF) to guide collaboration between its contractors and assist in the development of standards (OSTJF 2007). We propose that a similar approach be developed for future spacecraft servicing missions, by means of a *Commercial Space Standards Board*.

This *Commercial Space Standards Board* could:

- Identify spacecraft interfaces that should be standardized
- Create standards for servicing operations
- Present standards to recognized standardization bodies to be adopted and ensure consistency with international standards organizations like ECSS, IEEE, Society of Automotive Engineers (SAE), and ISO

Governments should encourage the adoption of these standards by being the first to adopt them for their satellite activities.

Standards need to be developed in a systematic way, considering the impact on economic feasibility. The following standards represent the minimum to enable servicing missions in the future. They are meant for medium and larger satellites due to the increased difficulty in servicing smaller satellites.

- Physical interfaces for docking
- Robot/Tool Grapple interfaces
- Bolting interfaces: sizing, exposure, volume
- Data connections
- Power connections
- Video connections (if required)
- Fluid connections (if fuel tanks will be among orbit replaceable units)
- Communication interfaces between Client and Servicer
- Client survivability properties (during power loss due to servicing)
- Rendezvous and docking standards
- Minimum servicer standards (ability to provide power, force)
- Attitude Control System (ACS) module
- Fuel Tanks
- Transponder Interfaces
- Electronics Boxes
- Payload Interfaces
- Satellite Buses

For robotic grapple interfaces and bolting interfaces, standards from the ISS Dextre robotics may be re-used or modified to support OOS. (NASA/CSA 1997)

4.6 Space Traffic Management Regulations

Future regulations for STM could improve the feasibility of OOS. During the ISU SSP2007, a team project dedicated to STM proposed a number of solutions to control the growth of space traffic. Their proposals include recommendations for collision avoidance capability and an EOL disposal plan on spacecraft, as mitigation against the possibility of space debris. They also recommend the definition and regulation of sun-synchronous orbital zones, similar to the zoning of GEO by the ITU. Since not all satellites may be able to perform advanced stationkeeping, a solution for those satellite operators could be to subscribe to an OOS maneuvering service. Currently, EOL considerations are regulated in the GEO orbit by the ITU, but there are no such regulations in place for other orbits. If these recommendations were to be accepted, new national and international regulations would be in place that would create conditions to encourage satellite operators and manufacturers to "design for servicing", a key enabler for widespread OOS mission. Alternately, if a spacecraft operator chooses not to be serviceable, the same policies could require that the spacecraft should be able to, as a minimum, de-orbit into the atmosphere of Earth, or transfer into a graveyard orbit, and this may require another form of OOS.

Although there are some challenges for OOS that may come from new STM regulations as mentioned in the previous section (i.e., proximity operations), we believe that implementation of space traffic regulations will favor the OOS industry, because the existing paradigm of "leave it there when it's done" would no longer be acceptable.

4.7 Summary

Many pathways have been presented to enable the first commercial steps into OOS. Only one of these missions has to be successful in order to create standardization in spacecraft manufacturing, opening the door for OOS. A common requirement for most of these cases is that public money is needed to fund and conduct the initial phases, which are high-cost and high-risk. As has been often mentioned, commercial interest in OOS will rise only after the technology and its benefits are proven in an operational context. Governments are particularly well-positioned to perform this exploratory phase, given the many national commitments to space exploration and development. If OOS can be seen as an enabler for existing visions for the exploration of the Moon, Mars and beyond, then it should not be too hard to find funding for OOS programs, within the context of exploration. Once the initial barriers are crossed, the benefits of OOS should present themselves to the Earth-orbiting commercial satellite industry, and OOS can be expanded and utilized by all the actors in the space community.

Chapter 5
Near-Term Vision

Our roadmap has three distinct time periods; Near-term (0-10 years), Mid-Term (10-30 years), and Far-term (30+ years). The Near-term vision focuses on OOS applications and enabled space missions that are currently being planned and are feasible with state-of-the-art technology. The following section provides a brief description of Team DOCTOR's Near-Term vision.

The Team selected six OOS missions to include in our Near-Term vision. These missions are De-Orbiter, Proximity, Fly-by, Propulsion GNC Life Extension, Human Servicing, and Human Construction (see Figure 5-1). Each of these services can potentially start at approximately the same time and their missions can be conducted in parallel to other OOS missions. These services can use existing technologies. Rendezvous, proximity operations, and docking have been demonstrated by a wide variety of crewed and supervised robotic vehicles. Autonomous robotic docking was successfully demonstrated by ETS-VII in 1997. Fly-by, Proximity, Propulsion GNC and De-Orbiter are applied to communication satellites in GEO, GPS in Medium Earth Orbit (MEO), Lunar or Mars orbit satellites and remote sensing/science/weather satellites. Free flying robotic inspection capability was achieved on STS-87 with the flight of Miniature Automomous EVA Robotic Camera (Mini-AERCam). For the HST, the SRMS was used to directly grasp a grapple fixture and place HST into a servicing fixture. Human Servicing and Human Construction is similar to HST servicing missions.

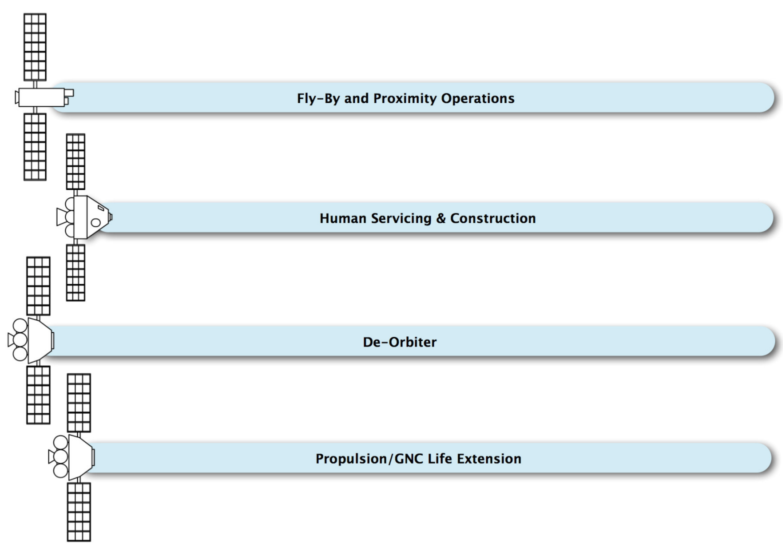


Figure 5-1: Near-Term Roadmap

5.1 Potential Customers

By 2004 there were over 286 commercial satellites in GEO orbit. It is expected that 50 of these satellites will need to be replaced by 2009 (Wingo 2004). In addition, there is a classified number of military communication satellites. There are also numerous military satellites from several nations in all orbits that may contract with private servicing companies to increase the lifetime of those assets. In case of an initial failure of the satellite, other clients can include satellite manufacturers and insurance companies for repair and/or exterior examination. There is also an increasing number of remote sensing, science and weather satellites in various orbits around the Earth, Moon and Mars. Deep space probes as well as space stations in LEO owned by government space agencies such as NASA, CSA, the European Space Agency (ESA), JAXA and Roskosmos can also be serviced. In the near term there will be three Global Navigation Satellite System (GNSS) commercial/military systems in MEO of which the U.S. GPS and the Russian Global Orbiting Navigation Satellite System (GLONASS) use a constellation of 24 satellites each, whereas the European Galileo system will use 30 satellites. At present, NASA has communication, navigation and weather-monitoring capabilities on its science spacecraft orbiting Mars, as well as ESA's Mars Express mission. In 2009, China National Space Administation's (CNSA) micro-satellite will piggyback atop the Russian Phobos Grunt mission in aim of orbiting around Mars while the primary Grunt payload will continue to Phobos (Huanxin 2007). There will be two space telescopes at the second Lagrange point (L2): ESA has scheduled to launch its Herschel Space Observatory in 2008 while NASA's JWST plans to launch in 2013. Various agencies have lunar orbiting satellites such as ESA's SMART-1 launched in 2004, CNSA's Chang'e satellite planned to be launched in 2007, JAXA's SELenological and ENgineering Explorer (SELENE) lunar-orbiting satellite targeted to be launched in 2007, and NASA's Lunar Reconnaissance Orbiter and the Indian Space Research Organization's (ISRO) Chandrayaan-1 in 2008. Bigelow Aerospace, a private U.S. company, aims to have its first orbital habitation module in orbit by 2012.

5.2 Key Considerations and Enablers

5.2.1 Technological Aspects

The current state of space technology, technology development programs, and the application of technology directly influence the Near-Term future of OOS. Some of the most important issues are highlighted below.

Utilizing the ISS: With industry reluctant to engage in OOS activities in the Near-Term, it is apparent that the ISS represents a crucial test bed for OOS. Thus a catalyst for OOS would be a distinct ISS OOS research program, whereby the various space agencies would develop, either individually or in a coordinated fashion, a program of OOS tests utilizing the various robotic arms of the ISS. Such demonstrations would go beyond the standard/required robotic maintenance operations on the ISS. Furthermore, in order to safely demonstrate OOS of satellites at an appropriate distance from the ISS, it might be beneficial to develop a platform to which the various ISS robotic arms could transfer and temporarily move away from the ISS. Another possible demonstration mission, for inspection rather than manipulation, might be to use the mini-AERCam to rendezvous with a satellite other than the ISS. Finally, related to OOS conducted by humans, the ISS may serve as a possible platform to test non-ISS related human servicing and construction activities. For this, a platform such as the Crew Exploration Vehicle (CEV) or modified Automated Transfer Vehicle (ATV) may be necessary to enable astronaut mobility away from the ISS.

Spin-in technologies and "Grand-Challenge" Competitions: In the U.S., DARPA has initiated an innovative and highly successful Grand Challenge prize contest to design, build and operate fully autonomous ground vehicles. This type of activity could also be replicated for OOS robotic technology demonstration missions.

5.2.2 Economic and Financial Aspects

In the Near-Term, the formation of an OOS industry is not economically feasible. Current OOS activities are restricted to technology demonstrations and ISS operation. Commercial development has thus far been hampered by an understandably reluctant GEO telecommunications industry. OOS in the GEO market can be seen as threatening to the existing GEO space industry, where satellite life extension may lessen the demand for satellite manufacturing and launch orders. Additionally, the development cost of the complete OOS infrastructure and OOS standardization makes the OOS option cost prohibitive. On the other hand, there may be a commercial interest in OOS from the GEO satellite insurance industry as an alternative to on-orbit satellite failure payouts. Satellite operators such as Inmarsat are also interested in OOS to extend the lifetime of its aging satellite fleet if the OOS technology becomes mature and cost effective.

5.2.3 Policy and Social Aspects

Updates will have to be made to the current body of international space law defining rules and responsibilities for the various actors involved in OOS. Furthermore, the issues of liability and insurance will have to be addressed for scenarios in which OOS missions fail and/or cause greater spacecraft impairment. Over the Near-Term, we cannot expect great changes to be made in international laws and regulations. The issues highlighted in the feasibility study will be overcome by means of specific agreements and system policies. In particular, aspects that ought to be taken into account include those described below.

ITAR: Many technologies available in the near term are bound by ITAR rules. This strongly reduces the possibility of exchanging information and increases the difficulties associated with OOS missions, thus basically reducing the available market for OOS beyond the U.S. military. Moreover, the potential dual-use of OOS technology may create sensitivities between the U.S. and foreign governments. Thus strict regulatory regimes (e.g. involving information exchange) and easier technology diffusion will be necessary to promote OOS in commercial and non-U.S. market sectors.

Legal Aspects: The absence of legal regulations on docking and provisions for the division of responsibilities between parties (e.g. the owners of two docked satellites), adds to the difficulties of manipulation and maneuvering missions. Since governments will ultimately be responsible for the actions of their respective companies, detailed regulations will be required (e.g. for docking phases). Insurance for damage caused by the servicing satellite to the client satellite and vice versa, together with the issue of third party damage, will be an added cost for OOS in this time frame, due to the generally unproven nature of the technology. Specific contractual clauses on the relative liability between client and service module during the docked phase will be necessary in order to manage, limit and/or avoid legal conflicts.

STM and Debris: Servicing failed satellites or increasing satellite lifetimes reduces space debris. This may act as powerful leverage within the international space community for the development of specific policies that enable OOS. On the other hand, on-orbit manipulation, especially in the case of human construction missions, may lead to the creation of additional space debris. Hence specific technologies and quality procedures will be required to mitigate the creation of space debris.

5.3 Missions and Activities Enabled

Current activities in Earth orbit are already enabled and therefore not dependent upon advances in OOS. Near-Term OOS capabilities, while potentially important, are not on the critical path to future space activities.

5.4 Summary

There are some promising applications of OOS that can enhance Near-Term space missions (see Figure 5-2). However, with few exceptions current operating and planned space missions do not require OOS for successful performance. Future technology demonstrations and spacecraft standardization will be necessary for OOS to develop into an integral component of the space infrastructure.

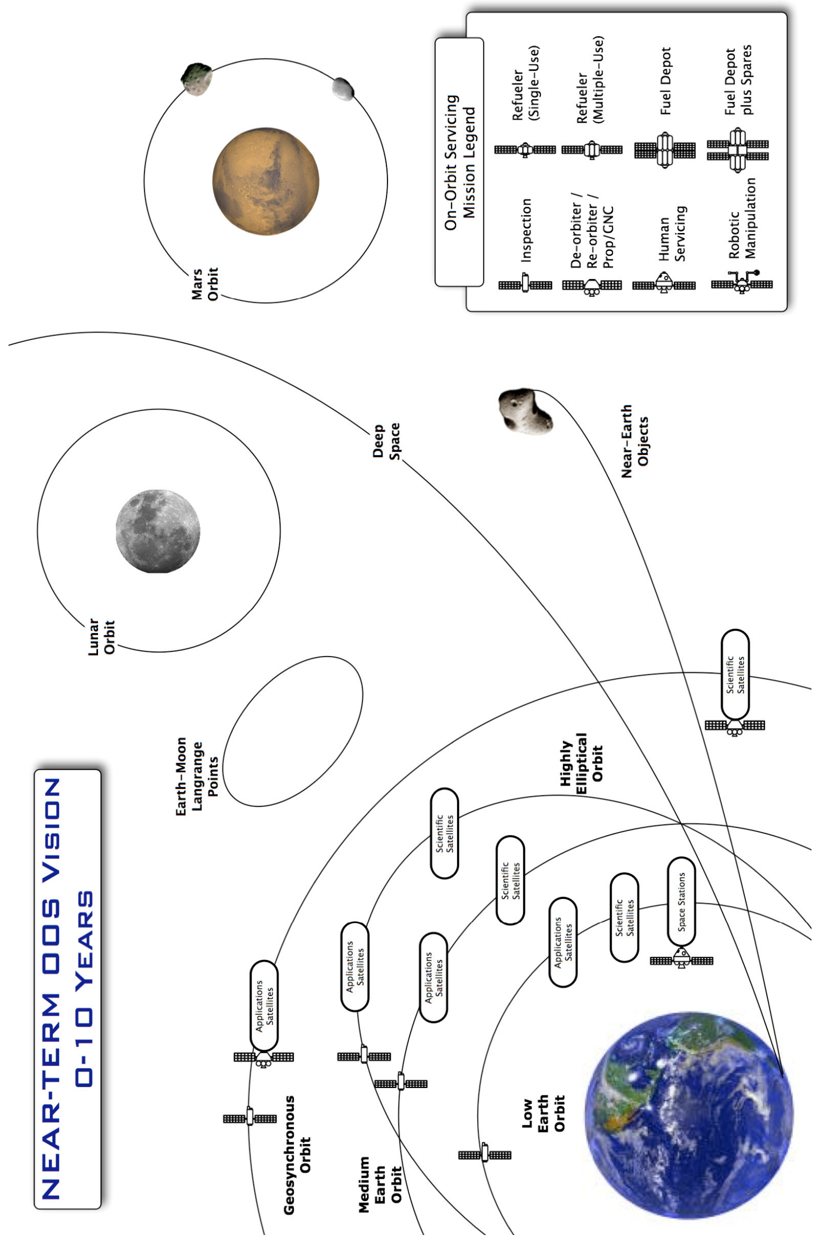


Figure 5-2: Near-Term OOS Vision

Chapter 6
Mid-Term Vision

In the Team's vision, the next 10-30 years promise to be an active time for OOS. Technological advantages, combined with economic and political drivers will create an environment highly conducive to the OOS industry. The following chapter will examine areas for growth as well as identify potential barriers to implementation.

The Team envisions that six OOS missions will be feasible in our Mid-Term vision. These missions are ORU Exchange, Space Tug, Refueler, Depot, and Robotic Construction as new OOS missions coming on-line during the Mid-Term (see Figure 6-1). In this period, we expect services such as ORU and Space Tug to mature, as they have technologies associated with the subsequent development of Refueling, Depot, and Robotic Construction activities.

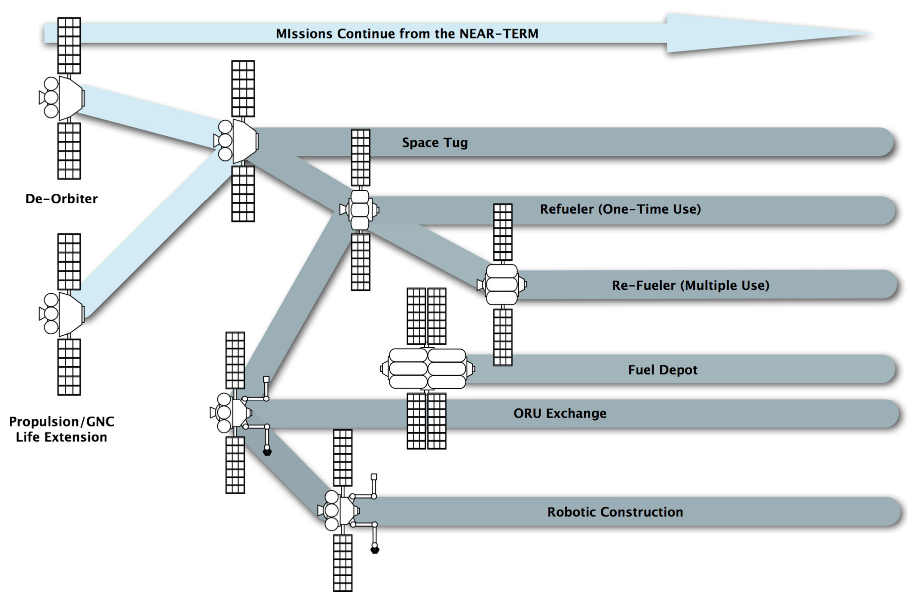


Figure 6-1: Mid-Term Roadmap

6.1 Potential Customers

In the Mid-Term, the Team envisions the same customers as for Near-Term, but with a few anticipated new ones. NASA is also considering a human mission to a NEO before 2020 (David 2006a). As exploration missions to Mars increase, there will be more communication satellites orbiting Mars in order to relay the data to Earth. Other activities of potential OOS customers include orbital hotels and habitats, more communication satellites in GEO and a civil exploration space station in L1. The Space Tug service for target spacecraft relocation is under development at the Naval Research Laboratory (NRL). ORU, Space Tug, Refueler and Depot are applied to communication satellites in GEO, GPS, among other potential customers. Robotic Construction can be applied to orbital hotels and stations.

6.2 Key Considerations and Enablers

6.2.1 Technological Aspects

In the Mid-Term, technologies that are currently at the research and development stage within university and government labs may become feasible for enabling enhanced OOS. Studies of such technologies have been compiled by ESA's Advanced Concepts team, some of which are outlined in Table 6-1. Novel servicing modalities, such as the fractionated servicing architecture developed at the University of Florida (Tatsch 2006), in which the servicing platform is broken into a number of modules that combine to do the work of one large "monolithic" platform, may also enable enhanced OOS in the Mid-Term. Other OOS platforms closer to practical application (most have ground based mock-ups/demonstrators), include DLR's Spacecraft Life Extension Mission (SLES), ESA's ConeXpress-Orbital Life Extension Vehicle (CX-OLEV), the University of Maryland's Ranger and Carnegie Mellon University's Assembly Skyworker.

Table 6-1: Technologies that may enable OOS in the Mid-Term

Technology	Likely Benefits
Informatics and Microelectronics	Increased processing power
Nanotechnology	Decreased platform mass
Artificial Intelligence	Increased autonomy
Biomimetics	Improved robotic capabilities
Advanced Propulsion / Micro-propulsion	Improved manoeuvrability and docking

Robotic Enablers: For OOS, the most critical challenges relate to enhancing mobility and manipulation, together with overcoming time-delays. A number of upcoming missions will play a crucial role in demonstrating the ability to surmount such technological challenges, and thus will build confidence in the capabilities of OOS. Specific examples of such platforms are outlined in Table 6-2, some of which are distinct OOS demonstrators (e.g. the Spacecraft for the Unmanned Modification of Orbits (SUMO) military satellite) and many of which are robotic platforms designed to augment the ISS (Wilcox 2006).

Table 6-2: Robotic OOS platforms available in the Near-Term

ISS Robotic and Inspection Platforms – Ready for launch	OOS Platforms – Under development
SPDM/Dextre – CSA	Eurobot – ESA
ERA – ESA	Robonaut – NASA
Main arm and Small Fine Arm (SFA) – JAXA	SUMO – DARPA

Spin-in technologies and "Grand-Challenge" Competitions: Another enabler of Mid-Term OOS will be the harnessing of spin-in technologies. Suitable spin-in technologies may include prosthetic arm technology, of which the most advanced version of which is currently being developed by DARPA. Additional telerobotic surgical technology being developed by DARPA is the advanced TraumaPod.

Standardization: One major enabler of OOS in the Mid-Term is standardization. As discussed in Chapters 3 and 4, standardization introduces a measure of commonality across both physical and electronic interfaces would greatly ease the difficulty inherent in on-orbit servicing of spacecraft from multiple manufacturers and operators. To advance such standardization, a rational first step would be for the principal industry manufacturers, space agencies and large customers (e.g. military, satellite operators, government agencies) to arrange a series of meetings in which standardization protocols can be discussed and agreed upon. Considering the international nature of OOS, bodies such as ISO, IEC and the ITU may be the most appropriate forums for such discussions and agreements.

6.2.2 Economic and Financial Aspects

Due to the research and development efforts from civil and military governmental agencies such as the ETS-VII, ISS, OE and HTV, confidence in OOS technologies is likely to mature in the Mid-Term. Additionally, there will be an average of 20 GEO satellites launched per year through the end of the Mid-Term in 2017. At this point an OOS business such as Orbital Satellite Services may become more accepted by the GEO satellite community. A business model for an ORU Exchange system in GEO is presented in Section 7.4. Although the GEO market may likely provide a steady stream of revenue for OOS, industrial growth for servicing in this market will likely remain low due to the limited number of slots that are allocated in GEO. Additionally, insurance companies can reduce their losses through utilization of OOS by recovering failed satellites that would otherwise result in full claim payment (Butler 2007, pers. comm. 20 July; Jackson 2007, pers. comm. 20 July).

Aside from the GEO communication satellite industry, in the Mid-Term, OOS providers may also focus on the various civil exploration programs. OOS contracts may be awarded by civil space agencies within each country under commercial development funding. The NASA Commercial Orbital Transportation Services (COTS) is a good example of a potential development program for OOS missions such as lunar logistics supply, robotic large structure construction, and human vehicle rescues. Another sustainable market may be various military programs in which national security objectives outweigh cost.

By the Mid-Term, space habitats such as the inflatable modules planned by Bigelow Aerospace, may already be into their second generation. OOS systems can serve as the enabling technology for successful LEO habitats, and the success of these ventures may lead to reduction in launch cost due to increased number of flights to Earth orbit. This industry may well become self-perpetuating and enable the rapid expansion of OOS as an integral component. In this industry sector, OOS should focus on supply, repair, rescue, orbit maintenance, vehicle protection, debris mitigation and insurance substitution. To develop OOS technology for civil and military use, governmental incentives such as tax brakes may be offered to OOS manufactures, clients and operators.

6.2.3 Policy and Social Aspects

All the obstacles highlighted in the Near-Term will most likely remain relevant in the Mid-Term. Nevertheless, the evolution of the social, political and technological parameters will lead to significant changes in the political and legal environment with regard to OOS. The aspects that will change the evaluation of barriers to OOS in the Mid-Term period are the following:

Space Debris: It is expected that this problem will increase over the next several decades. Consequently, with the heightened attention of international space actors, the development of policies dealing with this problem is needed. The combination of OOS as one possible solution to mitigate space debris, together with the flight-proven capabilities of OOS demonstrated in the Near-Term, could lead to accelerated formulation of international policy and legal solutions.

ITAR: Two aspects of this issue may decrease difficulties for realizing a robust OOS market in the Mid-Term. First, non-U.S. companies will likely increase the development of ITAR-free technologies, which implies the availability of OOS solutions independent of U.S. providers. Second, the reduction in market size for U.S. companies due to ITAR regulations will lead to a push for a progressive easing of ITAR restrictions. As a consequence, a reduction in ITAR related problems is foreseeable.

The time frame for the development of international regulations, which will most likely start in the Near-Term, will continue into the Mid-Term. The capabilities of OOS demonstrated in-flight, together with the laws developed for rendezvous and docking and on-orbit manipulation will facilitate rules governing relative liability, third-party liability and the insurance costs for damage to client modules and third parties.

6.3 Missions and Activities Enabled

Over the Mid-Term, developments in OOS will likely contribute to an overall framework of technologies that should help enable longer-term space activities. These activities are not necessarily dependent on advanced OOS capabilities in order to be realized. Indeed, OOS will serve merely to potentially assist these activities. OOS development will most likely outpace the introduction of other required advances that are more central to these endeavours.

Near-Earth Object (NEO) Missions: Future missions will likely place reconnaissance probes around NEOs in order to more accurately track their trajectory through the solar system and understand their composition and/or potential threat to Earth. Advances in OOS technology will allow service satellites to orbit closely to these objects (Wells 2003). Moreover, technologies developed for OOS could be applied to a risk mitigation strategy for NEOs. For example, an advanced Servicer could conceivably rendezvous and attach a propulsion system to gradually alter the trajectory of a potentially threatening NEO (NASA NEO 2007).

L1 Station/Observatory: Mendell and Hoffman (1991, p. 1) state that "a crewed space station at the libration point between the Earth and the Moon provides an environment that is more suitable for almost every research objective, from microgravity to planetary exploration." However, a station based at such a great distance from Earth will be largely dependent upon cargo, servicing and repair vehicles. Ideally, these Servicers would operate autonomously, thus reducing the risk to the human inhabitants and freeing them up to perform scientific duties. Moreover, a reliable L1 station could be used as a stepping-stone for more ambitious deep-space projects, such as a Mars expedition. The L1 point is also an ideal location for observatories, particularly if the ability to autonomously service them is available.

Mars Satellite Constellations: There have been several proposed Mars satellite constellations, with varying purposes in mind. ESA's proposed constellation focuses mainly on the use of radio occultation to better understand the Martian atmosphere and more accurately predict entry requirements for landing on the planet. A Mars-orbiting constellation will also be useful to provide a navigation system, similar to GPS, for human and robotic missions (Maliq 2004). NASA has considered a "Marsnet" for communications between multiple points on Mars, and across deep space (JPL 1999). Maintaining a robust system around Mars will require autonomous operation of Servicers. OOS processes developed for Earth-orbiting satellites can be applied in Mars orbit. However, the Servicer will need to be highly autonomous and will be limited in its ability to replace faulty parts. An orbiting depot may eventually be a feasible element of a Mars OOS system, though this will almost certainly only develop in the very long-term future.

6.3.1 Summary

In the next 10 to 30 years policies, economic practices, and technical standards will have sufficient time to mature, enabling OOS applications. In addition the number of potential customers will continue to grow as more space actors launch spacecraft that can benefit from a robust OOS infrastructure (see Figure 6-2). Due in part to standardization, some near-Earth and deep space missions will be enabled by OOS technologies. If the Team's vision is realized as outlined in this Report, the next 10 to 30 years promise to be a very active period for OOS and space development.

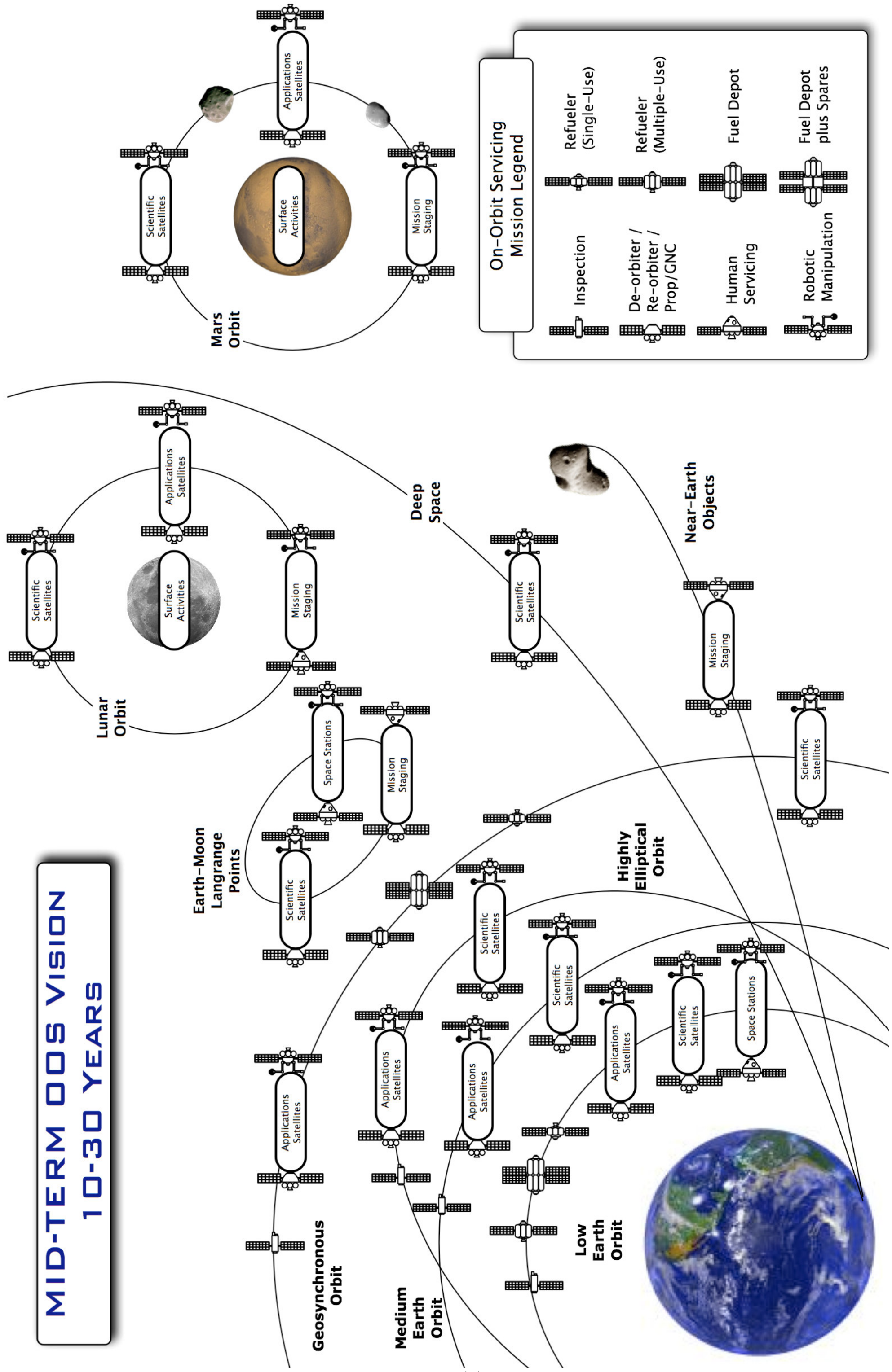


Figure 6-2: Mid-Term Vision

Chapter 7

Mid-Term System Architecture

The system trades and the resulting architecture for an ORU Exchange mission in GEO are presented in this section. This specific mission was chosen for the case study for several reasons. First, from a technical standpoint, the mission is feasible in the near-term, thus it is possible to develop a systems level design using some reasonable assumptions about the evolution of current technology levels. Second, the potential economic benefits of a mission capable of repairing high value satellites are extremely exciting, however in the near term these missions are infeasible due to the lack of standardization. The development of this architecture and the associated business plan demonstrate the economic gains to be achieved if standardization is adopted. Last, the mission is a critical stepping stone within the roadmap to an on-orbit infrastructure. The mission requires additional dexterous robotics compared with the simpler inspection and maneuvering type missions, but is not overly complicated or completely Far-Term such as the Fuel Depot missions. The ORU Exchange mission bridges the gap between the feasible Near-Term and the presently infeasible but very promising Far-Term missions.

Several potential ORU Exchange Servicer concepts were conceived, and the final design evaluated and refined. The chosen design, named On-Demand ORU (ODORU), is technically feasible given a typical evolution of some critical areas, primarily ion propulsion and autonomous rendezvous and docking. Finally a business model shows the economic potential for satellite operators if such a service existed, as well as the impressive economic feasibility of ODORU. This architecture clearly demonstrates the value of ORU Exchange both on its own and as an important enabler for a future OOS infrastructure.

7.1 Mission Requirements

The requirements of the mission were derived from technical, economic and policy considerations. The potential market for an ORU Exchange service was estimated based on typical satellite failures as outlined in Chapter 2. Provided the Servicer can remove and replace such critical and failure prone components as solar panels, ACS components, transponders, batteries and other systems, an economically feasible business plan can be developed. This business model dictated that the Servicer must be capable of performing four services (of the type mentioned above) each year, that it must have a lifetime of at least five years, and that it must be able to respond to a call for service within six months. In addition to the services mentioned above, the Servicer must also have the capability to deliver fuel ORUs, as most satellites in GEO use all their stationkeeping fuel before any other components fail.

Requirements for the disposal of the Servicer at its EOL were derived from current and evolving policies concerning space debris. In the Near- to Mid- Terms, satellites in GEO will likely be required to remove themselves to a graveyard orbit, thus this generated a requirement that the Servicer must not produce any debris in GEO (eg. spent ORUs) and it must remove itself to graveyard at the end of its lifetime.

7.2 Architecture Trade Study

This section discusses the numerous trades performed, how the trades were done, and the reasons for choosing the final ODORU design.

7.2.1 Architecture Concepts

Several overall mission ideas were developed to satisfy the requirements for an ORU Exchange mission. The following set of architectures were chosen as candidates for thorough investigation, and subsequently developed at a systems level to enable trades on parameters such as mass, schedule, cost and risk. Within each of these concepts, several design parameters were traded: quantity and mass of ORUs, ion vs. chemical propulsion, and launch scenarios for LEO, GEO via GTO, or direct to GEO. Ultimately, the design that best satisfied all of the requirements is described in Section 7.3.

Single Servicing Vehicle with Multiple ORUs (i.e. "All-Up"): The All-Up concept requires a single Servicer to be launched with the entire set of ORUs it would replace during its lifetime. This mission does not allow for re-supply from ground, thus the Servicer's life is over when all of the ORUs have been used. Figure 7-1 shows this concept.

Servicing Vehicle and Resupply Vehicle (i.e. "Resupply"): The Resupply concept requires the development of a second Servicer which would bring a replacement suite of ORUs to the original Servicer when required. Some of these ORUs could be used by the original Servicer for self-servicing (e.g. refueling to provide further life extension). Figure 7-1 shows this concept.

Servicing Vehicle and Single ORU Replacements via Piggyback Launches (i.e. "On-Demand ORU"): The ODORU concept involves launching single ORUs as secondary payloads to resupply the original Servicer's suite of ORUs. Each ORU would require some inert mass such as an Apogee Kick Motor (AKM) to circularize at GEO, but it must remain small and simple to fit in a piggyback launch opportunity. When required, an ORU for the Servicer can be launched to extend the Servicer's lifetime. Figure 7-2 shows this concept.

Servicing Vehicle and Single ORU Replacements via Host Satellites (i.e. "Social Security"): The Social Security concept involves launching single ORUs attached to future satellites, to resupply the servicing vehicle's suite of ORUs. This concept is slightly different from that of ODORU as it requires satellite companies to allocate space on a new satellite for an ORU, which will be delivered to a different, failed Client, with the expectation that in future years the service will be reciprocated. This architecture relies on satellite operators making an investment in the satellite's future, by enabling servicing of another satellite. Figure 7-2 shows this concept.

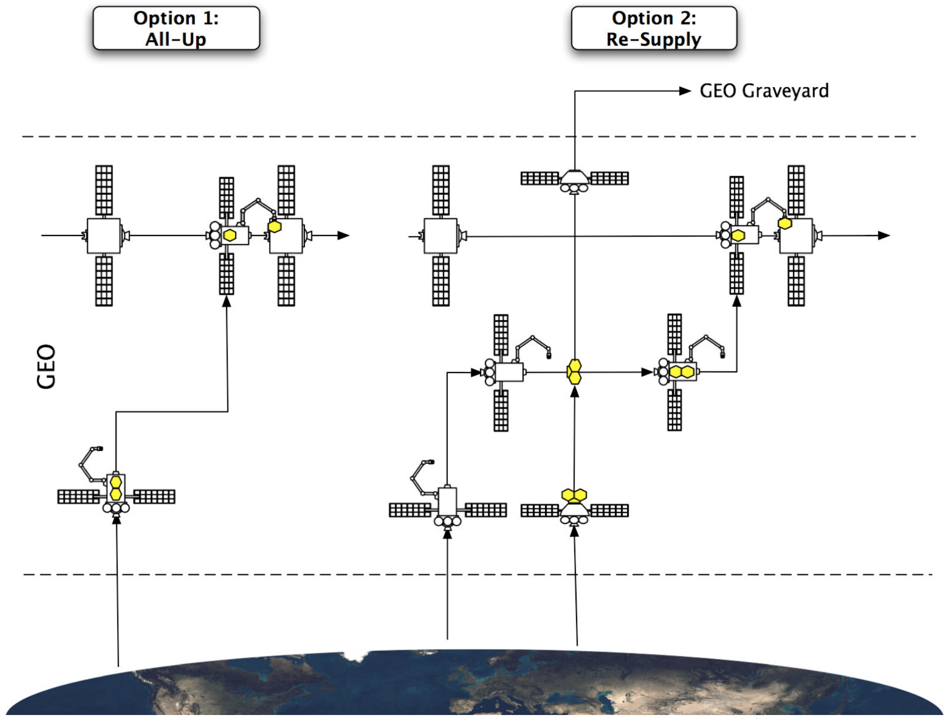


Figure 7-1: Representation Mission Concepts One and Two

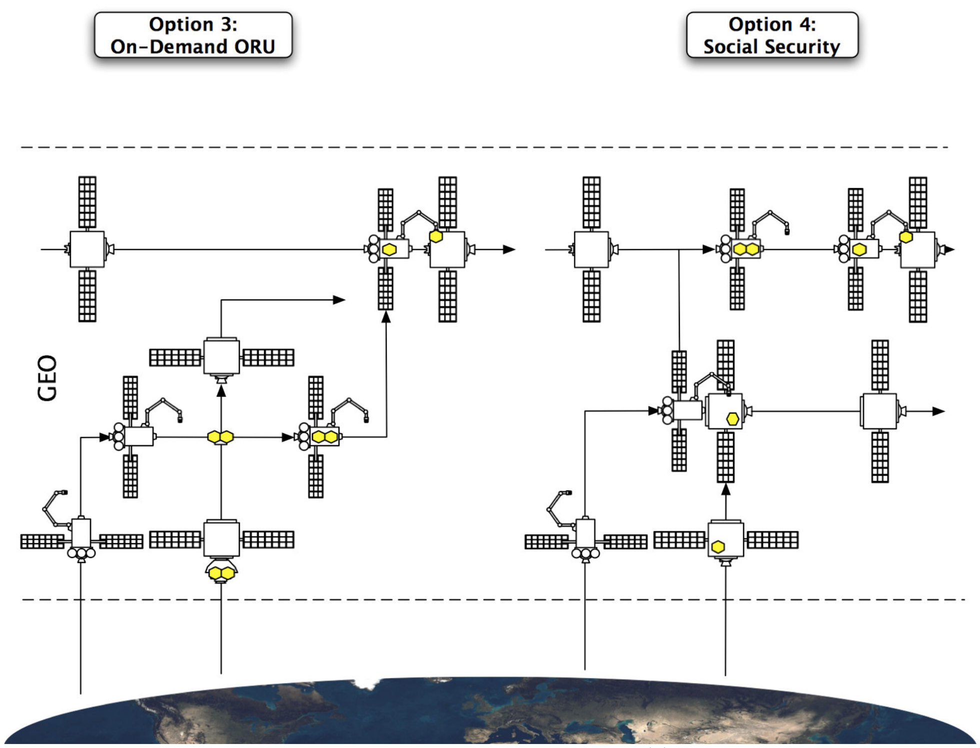


Figure 7-2: Representation Mission Concepts Three and Four

7.2.2 Description of System Trades

Estimates of payload mass and inert mass fraction were generated for each concept based on the mission needs, and used in combination with the mission delta-v budget as inputs to the rocket equation:

$$r = \frac{m_f}{m_i} = EXP\left(-\Delta v \big/ g \cdot I_{sp} \right)$$

Equation 1: Tsiolkovsky's rocket equation.

r is the ratio between the final mass, m_f , and the initial mass, m_i. I_{sp} is the specific impulse, g is 9.8 m/s^2, and Δv is the change in velocity.

Initial spacecraft mass and propellant mass estimates were generated for comparison. Additionally, overall cost estimates for each mission were generated based on parametric cost algorithms, and estimations based on costing tools including the Advanced Missions Cost Model available from NASA (NASA JSC 2007).

Launch costs were calculated based on extension of historical cost per kilogram estimates (Larson 1999). Production costs of subsequent ORUs were reduced assuming a 95% learning curve. Development and operations schedules were created, all costs were discounted at 10% per annum, and the Net Present Value (NPV) calculated for each to compare between missions.

In addition to the mass and cost estimates, economic and policy considerations were included in the analysis, summarized in Table 7-1:

Table 7-1: Summary of Systems Trades

Mission Architecture	Advantages	Disadvantages
All Up	• One launch, one vehicle	• Must determine ORU suite a priori • High economic risk • Limited number of ORUs
Resupply	• Can provide large numbers of ORUs • Few rendezvous needed • Can self-service	• Must determine ORU suite a priori • High launch cost for re-supply • Must develop two spacecraft • Highest development costs
On-Demand ORU	• Can provide ORUs on demand • Low launch cost for re-supply • Can self-service	• Requires rendezvous with uncooperative ORU • ORU will be launched to wherever host launch vehicle dictates
Social Security	• Can provide ORUs on demand • Can self-service • Technically simple • Low mass to orbit	• Requires policy adjustments from satellite operators • High economic risk

7.2.3 Trade Study Results

The system trades show that missions such as the All-Up and Resupply concepts are economically very risky. Spacecraft failures cannot be predicted, thus it is risky to predict a priori which ORUs a Servicer may eventually require. If the suite of ORUs is large enough to account for any type of spacecraft failure, the analysis showed the cost becomes prohibitive, especially the initial investment cost to develop such a large vehicle, with unknown revenue streams in the distant future. Thus the suite must be small and based on probabilistic estimations of expected failures, which introduces significant risk. There will not be any revenue for the servicing company, if no satellites fail, or if the Servicer fails to have the desired ORU complement on board. This is a risk that investors are not willing to take. It should also be noted that the resupply mission proved to be the highest cost option, due to the development costs to develop two large spacecraft.

The ODORU and Social Security options were both appealing on a mass, cost and schedule basis. By launching one ORU at a time, at a relatively low cost, specific spacecraft failures can be targeted and serviced specifically. It was still assumed that the Servicer would have a small suite of ORUs onboard to reduce the response time between services, e.g. the Servicer may have a fuel tank, a battery, a transponder, and a solar panel. If a client requires a battery, the Servicer can immediately service that satellite while a replacement battery ORU is prepared for the next piggyback launch opportunity. Thus the Servicer does not have to wait for that ORU but can service the Client right away. This represents a shift of the demand from the client to the Servicer.

The Social Security option was technically the most feasible option, as the host satellite provides the 1500m/s of delta-v to circularize the orbit at GEO from GTO. Additionally it is simpler for the Servicer to locate and dock to the host satellite than to a spin-stabilized, but uncooperative ORU. However, it is clear that even in the Mid-Term, satellite operators will not be willing to sacrifice payload mass on a new satellite for an ORU for another satellite. This is due to the unknown nature of satellite failures. There is no economic motivation to sacrifice revenue now, for potential savings in the future.

Ultimately the ODORU architecture was chosen as it satisfies all the requirements for the lowest cost, without requiring large changes to satellite operator policies or economics. It combines the best aspects of the considered missions, without sacrificing response time, increasing economic risk, or requiring excessive initial investment. The technical challenges of stabilizing the ORU in GEO, locating it with the Servicer, and removing spent ORUs were investigated thoroughly prior to choosing this architecture. Feasible options are possible, and will be discussed in the detailed design, Section 7.3.

7.2.4 Additional Considerations

Other design trades were done concurrently with the systems analysis for each concept. Each will be discussed within the framework of the ODORU architecture only.

The Servicer must make many maneuvers to service many spacecraft, and therefore has a large delta-v budget. The propulsion systems considered to perform these maneuvers were ion and chemical. Ion engines are more efficient than chemical engines (higher I_{sp}), thus significantly reducing the amount of fuel needed and therefore the overall mass of the spacecraft. However, the tradeoff is that ion engines have very low thrust, and thus maneuvering takes much longer than it does with chemical. Furthermore ion engines require much greater power, thus larger batteries and solar arrays.

The analysis confirmed that significant mass and cost savings could be realized by using ion engines, thus a timeline analysis was performed to determine if the three month response time requirement could also be satisfied. Assuming a reasonable evolution of ion engines over the next two decades, it was shown that all the requirements could be met (see Section 7.3.1).

In addition, three launch possibilities were traded: 1) The Servicer could be launched directly to GEO on a Proton launch vehicle; 2) Launch to GTO and transfer to GEO with ion engine; and 3) Launch to LEO and transfer to GEO.

The first option was not chosen because the Proton is the only launch vehicle to provide this type of launch, thus it is not advisable to base the mission architecture on this design. It is unlikely that a follow-on launch vehicle will be developed, as most GEO satellites are presently launched to GTO and use an AKM to circularize at GEO. This is the second option, which requires approximately 1500 m/s of delta-v when done by an AKM, and about 2000 m/s when performed by an ion engine. This is a simple option as there are many launch vehicles throughout the world providing this service.

The third option requires approximately 5900 m/s of delta-v to transfer from LEO to GEO with an ion engine (considerably more than the 3900 m/s required to perform a Hohmann transfer with a chemical engine), but launch costs to LEO are approximately 25% those of launch costs to GTO. The analysis was performed to compare the two options and it was found that launching to LEO produced a cost savings of about 5%. However, the time to transfer to GEO was found to take about 6 months, given the extremely low thrust-to-weight ratio. When two years of lost revenue was included into the economic analysis, it was evident that launching to GTO was the best option.

7.3 System Design for On-Demand Orbital Replacement Unit

The ODORU system is a comprehensive mission architecture capable of servicing many types of spacecraft failures in a responsive timeframe. The following is an overall outline of the system architecture, followed by the mission timeline, and finally some of the important subsystems are described in detail.

7.3.1 Concept

The ODORU concept involves the design and operations of a complex servicing spacecraft known as the ODORU Servicer, and simple, ORU piggyback-launched payloads. The ODORU Servicer is delivered into GTO via a dedicated launch. It then uses solar electric propulsion to spiral outward and acquire GEO within four months. It contains a suite of four ORUs determined a priori to address the most common satellite failures. The Servicer and Client rendezvous and dock, after which the Servicer removes the failed component and replaces it with the new ORU. Concurrently, a replacement ORU is prepared and launched as a secondary payload on a subsequent launch. The Servicer emplaces the removed ORU on a dedicated and separate disposal spacecraft, and then moves to rendezvous with the newly launched ORU, and the cycle begins again.

The architecture is simple and elegant, as it keeps the costs low while making the response time very quick. It also enables specific failures to be targeted as components can be launched on demand. Finally, the ODORU maintains low economic risk, as it does not rely on specific spacecraft failures. If there are not any failures for example, the Servicer can replace fuel ORUs and continue to generate revenue.

7.3.2 Servicer Design

The ODORU Servicer is a spacecraft capable of maneuvering in GEO with an ion engine. It is also capable of autonomous rendezvous and docking with a Client spacecraft as well as the piggyback ORUs. It employs dexterous robotics capabilities to remove and replace ORUs of various types. The Servicer mass budget is as follows as seen in Table 7-2:

- Robotic Arms: 2 x 125 kg = 250 kg
- Number of ORUs onboard: 4
- Mass of each ORU: 65kg

• Servicer Launch Mass: 2550 kg
• Servicer Dry Mass: 2130 kg
• Ion Engines: 4 x 100 kg = 400 kg

Table 7-2: Mass Distribution of the Servicer

Robotic Arm	ORUs	Bus system	Ion engine	Ion engine Propellant
10% (250kg)	10% (260kg)	48% (1220kg)	16% (400kg)	16% (420kg)

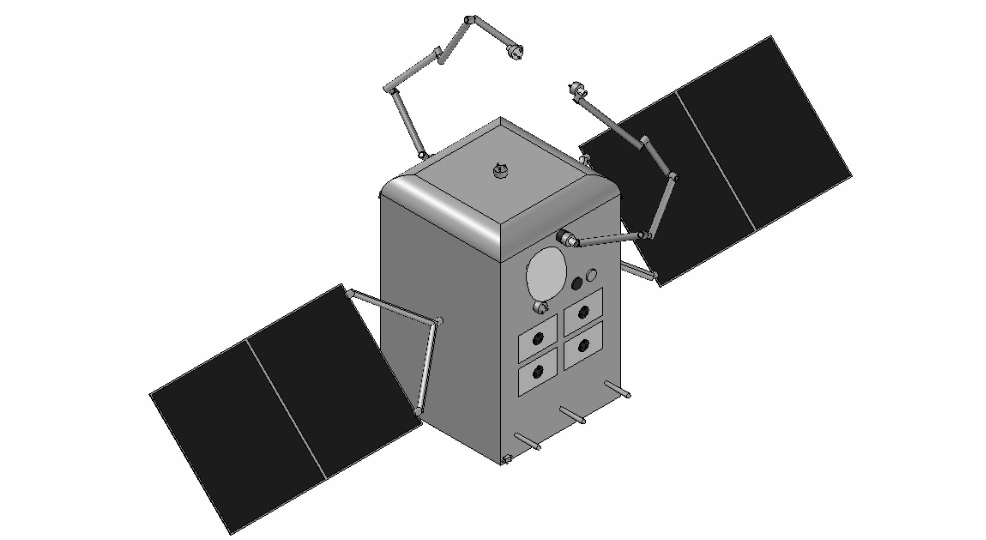


Figure 7-3: ODORU Servicer Design

7.3.3 ORU Piggyback Platform System Design

The ORU Piggyback Platform (ORUPP) is to be launched as an auxiliary payload to GTO. It is equipped with an AKM and sufficient propellant to transfer to GEO, as well as a small low-power beacon so that the Servicer can locate it. A maximum total mass requirement of 120 kg was derived from a typical piggyback launch opportunity on the Ariane 5 (ASAP5 User's Manual 2000), but this size of payload could be delivered on other launch vehicles as well. Therefore the useful mass of 65 kg was calculated based on the delta-v budget and an assumed inert mass fraction of 15%. The size of the ORUPP was estimated based on the mass using a form factor (Larson 1999). Assuming that the ORUPP is much denser than traditional spacecraft, the size of the and ORU and ORUPP is estimated as 80 x 80 x 50cm^3 and 80 x 80 x 100cm^3, respectively.

The ORUPP Mass Budget is as follows:

- Launch Mass: 120 kg
- Dry Mass: 83 kg
- Useful ORU Mass delivered to GEO: 65 kg

It is absolutely critical that the inert mass of the ORUPP is kept low, to maximize the useful ORU mass launched to GEO. The resulting design is very minimalist; the ORUPP does not need most of the subsystems found on a typical spacecraft, such as attitude control, thermal control, etc. However, it must be oriented properly and spin stabilized prior to separation from the launch vehicle, because if the ORUPP is tumbling, it is impossible for the Servicer to capture it. To fulfill these requirements the carrier could have its own ACS, but this would significantly increase the inert mass fraction. Instead, the final stage of the launch vehicle can orient the direction of the carrier prior to separation, and it provides the initial angular velocity to stabilize the orientation of the ORU spacecraft (Ariane 5 User's

Manual 2004). Thus the ODORU Servicer shall be able to capture the ORU and ORUPP by approaching along the rotational axis.

The ORUPP takes advantage of ongoing launches to GTO, which are on the order of 20-30 per year (Sullivan 2005). As spacecraft are optimized for mass, and not for the launch vehicle, nearly every launch has excess capacity that could be utilized for a secondary payload. Currently though, the opportunities for piggyback launches are on the order of 2 per year (Wiens 2000). It is not unreasonable to assume that given the excess capacity, contracts can be negotiated with launch vehicle companies to guarantee at least 4 piggyback launch opportunities/year, as this represents an additional revenue source for the launch vehicle company. Concurrently, it represents a relatively cheap opportunity for the launch of an ORU.

Finally, two options for disposal of the spent ORUPPs were considered: the "trash can" concept and the "individual" concept. In the "trash can" concept, the ORUPPs would be deposited and connected together at specific places near GEO, and then transferred to graveyard all together at the end of the Servicer's mission. The "individual" concept involves the Servicer removing the AKM from the new ORU, attaching it to the spent ORU, and thus each ORU can bring itself to graveyard. The individual concept is simpler as it requires fewer rendezvous, and reduces the delta-v budget of the Servicer considerably. It is technically more difficult as it requires the AKM of the ORUPP to be restartable. It also requires the inert mass of the ORUPP to be larger at launch, and it requires slightly more fuel. The two options were traded, and it was found that the trash can concept was the best option.

7.3.4 Mission Timeline

The ODORU Servicer has an initial design life of 7.5 years, and it conducts an average of four servicing missions per year. Each servicing mission consists of discarding an old ORU at the trashcan, picking up a new ORU that has been launched and transferred to GEO in the meantime, and performing a service to the Client spacecraft. At the end of the Servicer's initial lifetime, additional ORUPPs can be launched allowing the Servicer to self-service, providing additional years of life. This can be continued indefinitely provided the Servicer remains operational. When the Servicer reaches the designed EOL it uses the remaining fuel to rendezvous with the trash can. After that it will transfer the trash can to graveyard orbit. Thus no orbital debris remains in GEO, and a new Servicer can be launched. The Servicer is launched into GTO and then uses low thrust ion propulsion to transfer to GEO. Once in GEO it performs approximately 30 servicing missions, each consisting of unloading an old ORU, loading a new ORU and servicing a client. At the end of its lifetime, the Servicer transfers itself and all old ORUs into a graveyard orbit.

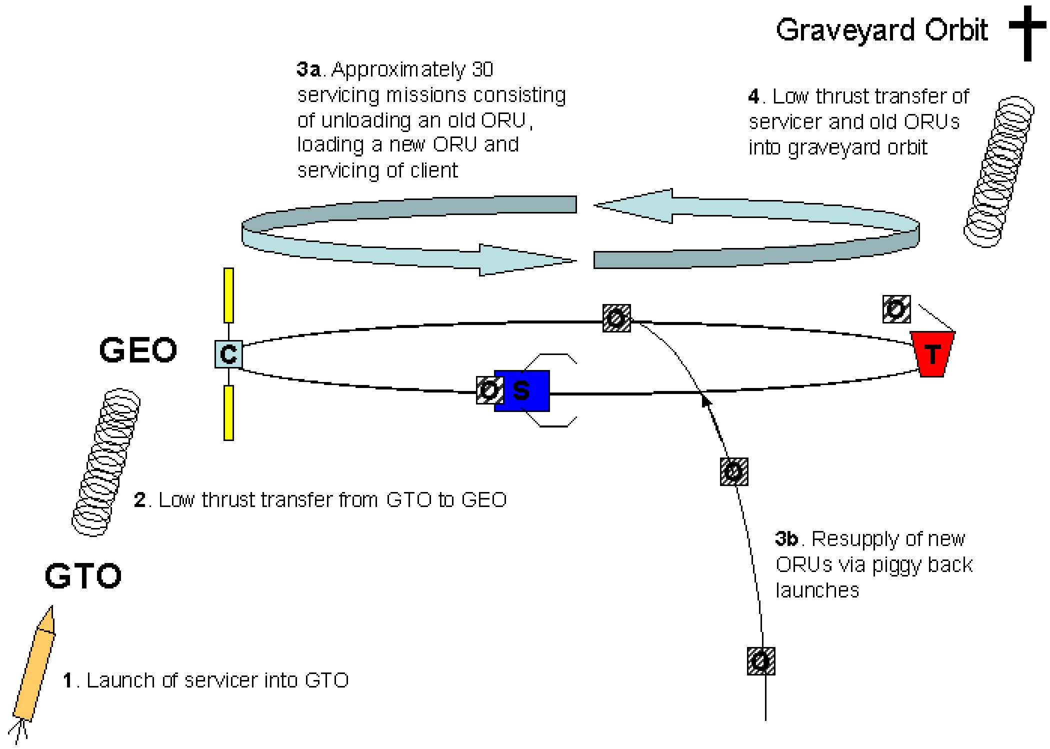


Figure 7-4: Outline of the ODORU mission.

Timeline

Table 7-2 shows the timeline, required maneuvers, and delta-v budget during the spacecraft's lifetime along with the evolution of its mass:

Table 7-3: ORU Lifetimes

Event	dT (days)	t (days)	dv (m/s)	$M_{s/c}$ (kg)	ΔM_f (kg)
Launch into GTO	-	0		2550	-
GEO Acquisition	130	130	1800	2460	90
First servicing mission					
Drift	3		0		
Phasing to Client (10 deg)	8		14		
Rendezvous with client	4		5		
Docking to and servicing of client	4		0		
Letting go	1		1		
Drift	3		0		
Stationkeeping total			3		
Total	23	153	20	2459	1
Average subsequent servicing mission					
Drift	2		0		
Phasing to trashcan (90 deg)	19		48		
Rendezvous with Trashcan	6		8		
Docking to trashcan and unloading of ORU	1		0		
Letting go	1		1		
Drift	3		0		
Phasing to ORU (90 deg)	19		48		
Rendezvous with ORU	5		8		
Docking to ORU	1		0		
Drift	1		0		

Event	dT (days)	t (days)	dv (m/s)	$M_{s/c}$ (kg)	ΔM_f (kg)
Phasing to Client (90 deg)	19		48		
Rendezvous with client	4		8		
Docking to and servicing of client	4		0		
Letting go	1		1		
Drift	3		0		
Stationkeeping total			14		
Total	**90**	**243**	**183**	**2450**	**9**
Servicing missions 3-30	**2435**	**2547**	**4936**	**2220**	**230**
Deorbit					
Phasing to trashcan (90 deg)	19		48		
Rendezvous with trashcan	6		8		
Docking to trashcan	1		0		
Mass with old ORUs				+ 30* 65	
Deorbit	1		7		
Stationkeeping			4		
Total	**27**		**67**	**4166**	**1**
TOTAL	**2705**	**2705 (=7.4 years)**	**7006**		**331**

Event	**dT (days)**	**t (days)**	**dv (m/s)**	**$M_{s/c}$ (kg)**	***ΔM_f (kg)***
Launch into GTO	-	0		2550	-
GEO Acquisition	130	130	1800	2460	*90*
First servicing mission					
Drift	3		0		
Phasing to Client (10 deg)	8		14		
Rendezvous with client	4		5		
Docking to and servicing of client	4		0		
Letting go	1		1		
Drift	3		0		
Stationkeeping total			3		
Total	*23*	*153*	*20*	*2459*	1
Average subsequent servicing mission					
Drift	2		0		
Phasing to trashcan (90 deg)	19		48		
Rendezvous with Trashcan	6		8		
Docking to trashcan and unloading of ORU	1		0		
Letting go	1		1		
Drift	3		0		
Phasing to ORU (90 deg)	19		48		
Rendezvous with ORU	5		8		
Docking to ORU	1		0		
Drift	1		0		
Phasing to Client (90 deg)	19		48		
Rendezvous with client	4		8		
Docking to and servicing of client	4		0		
Letting go	1		1		
Drift	3		0		
Stationkeeping total			14		

Total	90	243	183	2450	*9*
Servicing missions 3-30	2435	2547	4936	2220	*230*
Deorbit					
Phasing to trashcan (90 deg)	19		48		
Rendezvous with trashcan	6		8		
Docking to trashcan	1		0		
Mass with old ORUs				+ 30* 65	
Deorbit	1		7		
Stationkeeping			4		
Total	27		67	4166	*1*
TOTAL	***2705***	***2705 (=7.4 years)***	***7006***		***331***

Stationkeeping

Stationkeeping in GEO costs 50-55 m/s per day on average (TU Delft, 2006). A conservative assumption of 55 m/s per day was used.

Launch and Orbit Acquisition

The required delta-v to transfer from GTO to GEO is 1800 m/s which includes the gravity losses that result from thrusting during almost the entire journey as well as an inclination change of 28 degrees. (TU Delft 2006). Using the simple estimation that the travel time is equal to the delta-v divided by the initial acceleration (i.e. worst case, because the spacecraft is heaviest at the beginning of its journey) of 0.4N/2550kg, the journey from GTO to GEO will take approximately 130 days.

Servicing of First Client

Once the Servicer reaches its target orbit it can begin nominal operations. The first client it services will not be far away since the transfer trajectory from GTO to GEO will have been designed such that the Servicer arrives in the vicinity of the client. We assume a difference of 10 degrees in true anomaly from the first client.

If the Servicer is 10 degrees ahead of the client, it will maneuver into a higher orbit (i.e. an orbit with a larger semi-major axis) in order to reduce its orbital period and thus allow the Client to catch up with it. If the Servicer is 10 degrees behind the Client, it will go into a lower orbit (i.e. an orbit with a smaller semi-major axis) in order to rendezvous with the Client. The former maneuver takes slightly less delta-v than the latter since delta-v is a function of semi-major axis ($a^{-0.5}$). The Servicer is assumed to be behind the Client as a conservative estimate, and therefore undergoes the more expensive maneuver that reduces its semi-major axis.

The dimension of the maneuver depends on the number of desired phasing orbits. If the time spent in the phasing orbit is small, the delta-v spent to reach that phasing orbit is larger than the delta-v spent to reach a different phasing orbit in which the spacecraft would stay for a longer period of time. A trade therefore has to be done between the time taken to phase and the delta-v spent on acquiring the phasing orbit.

In theory, it is possible to reach any spacecraft within one single orbit, even if the client is 180 degrees away. In practice though, due to the large difference in semi-major axis between GEO and the necessary phasing orbit (15679 km), which entails a delta-v of 1100 m/s, this obviously exceeds any realistic budget.

In addition, a delta-v of 1100 m/s can only be imparted upon the spacecraft instantaneously with a chemical engine. Using ion thrusters, accelerating to overcome 1100 m/s difference in velocity takes 55 days. Even if the delta-budget permitted spending 1100 m/s on a phasing maneuver, the decrease in phasing time would be more than outdone by the time necessary to accelerate the spacecraft.

This relationship holds regardless of the angular separation. If the phasing time is long, little delta-v is required to reach the phasing orbit and it takes the spacecraft only a few days to accelerate. If the phasing time is short, more delta-v has to be spent to reach the phasing orbit, and it takes the spacecraft longer to accelerate. A certain minimum time is therefore always necessary to overcome a given angular separation. In the case of an angular separation of 10 degrees as assumed for the first client, this minimum time is 8 days. For the average angular separation of 90 degrees this minimum time is 18 days.

We assume that at the end of any phasing maneuver, the Servicer uses two orbits to approach the client in increments of 0.01 degrees. This is done for safety reasons as it gives the ground personnel enough time to validate the Servicer's correct position and velocity with respect to the client. Once the Servicer has reached an angular separation of 0.01 degrees, phasing is over and the rendezvous maneuvers begin.

An autonomous rendezvous in LEO costs 30 m/s on average (Bounova 2003). Maneuvers in GEO are cheaper by approximately a factor of 0.06, derived from comparing the delta-v necessary in GEO to change the semi-major axis by 20 km to the delta-v necessary in LEO to change the semi-major axis by the same amount. This leads to a rendezvous cost of 1.75 m/s. With considerable margin, we assume an average cost of 5 m/s for every rendezvous. We further assume that every rendezvous maneuver lasts on average 4 orbits, which in GEO is equivalent to 4 days (Yamanaka 1997).

Once the Servicer has acquired the same position and velocity as the client, docking and servicing takes place. It is assumed that it is the client that undertakes all stationkeeping and attitude control during this phase. No fuel is therefore consumed by the Servicer.

The estimate of docking and servicing time is within four days. In 1982, the Russian Servicer Progress needed only 10 days to complete its task of servicing Salyut 7 (Wade 2007). This study looks 50 years into the future, so four days are considered to be a very conservative estimate.

Once servicing is completed, the Servicer undocks from the Client and maneuvers into a slightly lower orbit. There it can drift without interfering with other GEO spacecraft while the next change in orbital position is prepared. In case the orbital position is less than 180 degress behind the Servicer, it would maneuver into a slightly higher orbit than GEO. Again, for reasons of simplicity and because it takes less delta-v to increase the semi-major axis than to decrease it, we disregard this option.) A delta-v of 1m/s was allocated for this maneuver which can easily be completed within 1 day.

Subsequent Servicing Missions

If the next service requires an ORU that is already on board, the Servicer can move directly on to the next client. If the ORU is not on board, the Servicer has to pass by the trashcan to unload the used ORU from the previous client and then pick up the new ORU that has been launched into orbit in the meantime.

To assess the delta-v budget and timeline for the remaining mission, an average of 90 degrees angular separation was assumed between the Servicer and the next ORUPP, the Servicer and the trash can, or the Servicer and the next Client.

Unloading an old ORU at the trashcan differs only slightly from servicing a Client spacecraft. More time and delta-v is allocated for the rendezvous maneuvers, since the trashcan's orbital parameters may not be known as accurately as those of a client spacecraft. Once the Servicer is docked to the trashcan, however, it needs less time to perform its tasks, since it only offloads the old ORU but does not load a new one. Just as with a client spacecraft, the Servicer then lets go of the trashcan by performing a small maneuver to change its semi-major axis toward the next required phasing orbit.

Having discarded the old ORU, the Servicer can now load a new one. It again phases to overcome an average of 90 degrees of angular separation with the new ORU. The rendezvous with the new ORU also takes longer than a rendezvous with a client spacecraft, because the ORU is just like the trashcan a very simple spacecraft. Its orbital parameters may therefore not be known to a high accuracy and the Servicer needs additional time and delta-v to search for it. Once it has met with the ORU. No other tasks have to be performed at this point. The Servicer can directly move on to phasing towards its next client.

The steps to perform the next services are identical to those described for the very first servicing, thus the same delta-v budget and response time as for the second servicing missions described above are used.

Deorbit

At the end of the Servicer's lifetime, the Servicer itself and the old ORUs collected at the trashcan have to be put into a graveyard orbit. The Servicer therefore maneuvers to the trashcan and docks onto it. It then fires its ion engines to move itself with the trashcan into an orbit approximately 200 km above GEO. The required delta-v for such a maneuver is 0.73 m/s. Even though the Servicer has to move a large mass to the graveyard orbit, its fuel reserves are sufficient to do so.

Given a mass budget of 420kg, the required task to perform at least 30 services within 7.5 years and maneuver the Servicer and all ORUs into a graveyard orbit afterwards is easily achieved. Based on the above calculations, 90 kg of fuel remain at the end of the ODORU mission. This leaves ample room for contingencies, especially as the calculations are based on very conservative assumptions. Meeting the target response time of three months is slightly more difficult, albeit possible. As explained above, phasing to a new orbital position in GEO takes a minimum amount of time because the Servicer uses solar electric propulsion. Only if the angular separation is small and the required ORU is already on board, a response time of less than one month is feasible.

7.4 Subsystem Design

This section describes in further detail the various subsystems of the ODORU Servicer. The subsystems are shown in Figure 7-5.

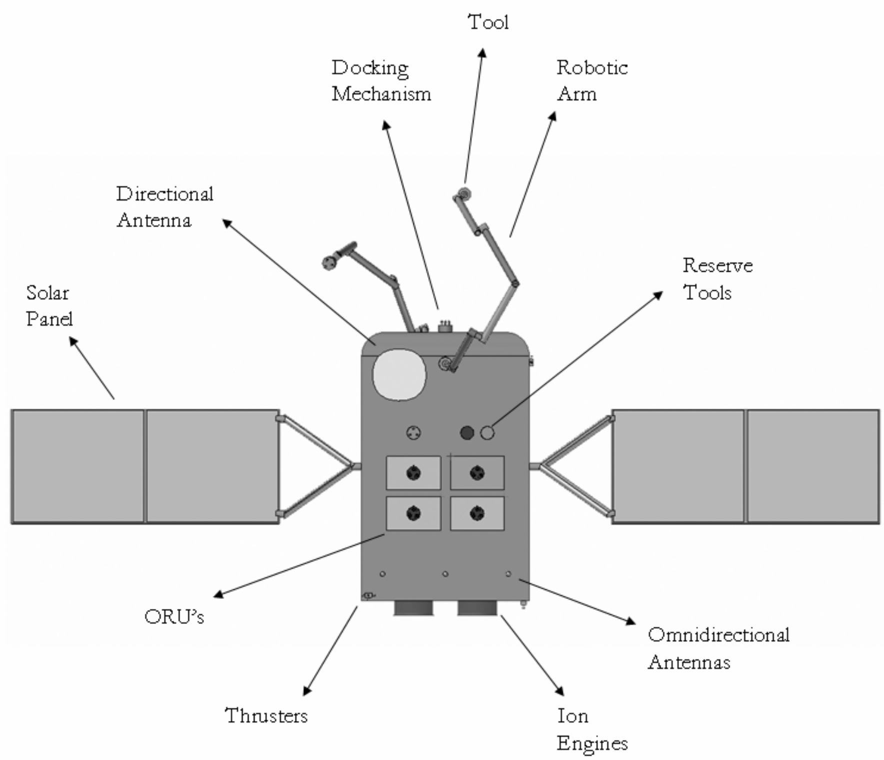


Figure 7-5: Subsystem Overview

7.4.1 Propulsion: Ion engine

The ODORU Servicer uses an ion engine propulsion system with Xenon as propellant. Two ion engines, each with a thrust of 200 mN and I_{sp} of 5000 s, operate in parallel, while two others are onboard for redundancy. The performance of the engines (see Table 7-4) was based on conservative estimates of the evolution of current ion engines, such as those used on Bepi-colombo (ESA 2006).

Table 7-4: Ion engine performance.

Parameter	Performance	Example: Bepicolombo
I_{sp} [s]	5000	3000
Thrust [N]	0.4	0.17
Power Consumption [kW]	2.5	2.75
Mass per engine [kg]	100	120
Number of Engines	4 (1 or 2 in operation)	3 (1 or 2 in operation)

The Servicer has two tank systems: one main propellant tank, and two replaceable propellant ORUs. These two systems are internally connected so that propellant can be supplied from either. A large amount of fuel is used for the initial transfer from GTO to GEO, thus future life extensions can be performed with the fuel provided by ORUs.

7.4.2 Guidance, Navigation and Control

The GNC system consists of attitude determination sensors including sun sensors, star trackers, and inertial measurement unit and attitude control actuators. Considering that the Servicer is designed to perform precise attitude control in order to dock to clients as well as to capture the ORUPP, the GNC sub-system shall be equipped with a Control Moment

Gyroscopes (CMG) having a large torque capacity (10-30 times that of a reaction wheel). It is expected that the robotic arms can be used for fine control, and to desaturate the CMG. As well, thrusters will be needed for additional momentum dumping and slewing.

The ORUPPs that the Servicer collects in orbit will be spinning. In order to dock to them the Servicer has to acquire the same spin rate. S uch a spin-up maneuver costs on average 5-10 m/s (TU Delft 2006). Once the Servicer has docked to the ORU, it has to despin again requiring another 5-10 m/s. For the spin-up and despin maneuvers, a conservative estimate of 20 m/s per collection of an ORU was assumed.

7.4.3 Power

One of the key design challenges of the Servicer is the power system, due to the large power required for operation of the ion engines and the robotic arms. The power consumption of the propulsion system and payload, as well as an estimated power consumption rate of each subsystem is summarized in Tables 7-5 and 7-6. For the estimation of the power consumption of the subsystems, the high power requirements of the ion engine are taken into account.

Table 7-5: ODORU Power Budget

	Power [kW]
Ion engine	5
Robotic Arms	0.3

Table 7-6: Power Consumption of Subsystems

	Power Consumption [%]
Attitude Control	5
Communication	1
Command and Data handling	1
Thermal	1
Power Supply	5
Margin	3

With the assumption that the robotic arm and ion engines are not used at the same time, the power requirement of the whole Servicer spacecraft is estimated as 6 kW. In Table 7-6 the area of the solar panels and its mass are calculated using a solar panel efficiency of 28.3%, which is based on today's technology, and 40%, which is recently accomplished in the laboratory environment at the University of Delaware (2007). For the calculation of mass, the current specific performance is assumed as 47 W/kg at the EOL. A 5% performance degradation over 10 years is assumed.

Table 7-7: Solar Panel efficiency

Efficiency	23.3% EOL (recent)	35% EOL (Mid-term)
Area [m^2]	18.8	12.5
Mass [kg]	127.7	90.3

7.4.4 Docking Mechanisms

Depending on the nature of the Client satellite, different docking mechanisms can be considered. Figure 7-6 compares the different docking concepts for a cooperative client satellite (such as ETS-VII and Orbital Express), and for an uncooperative Client. According to Yoshida (2007, pers. comm. 10 August), the docking mechanism for a cooperative target (Figure 7-7a) is simpler and safer than the target capture mechanisms (Figure 7-7b and Figure 7-7c). Indeed, in the case of a target capture, instead of a docking, the manipulator arm should track and grasp a fixture mounted on the target satellite (visual servo-tracking of the grasping point) while maintaining its proximity to the target, which increases complexity and risk of the mission. The choice of a docking mechanism is highly related to the target spacecraft, and risk and simplicity would be derived from that. Standardization of the great majority of serviceable satellites in the mid-future will enable the use of the docking mechanism for cooperative targets (Figure 7-7a).

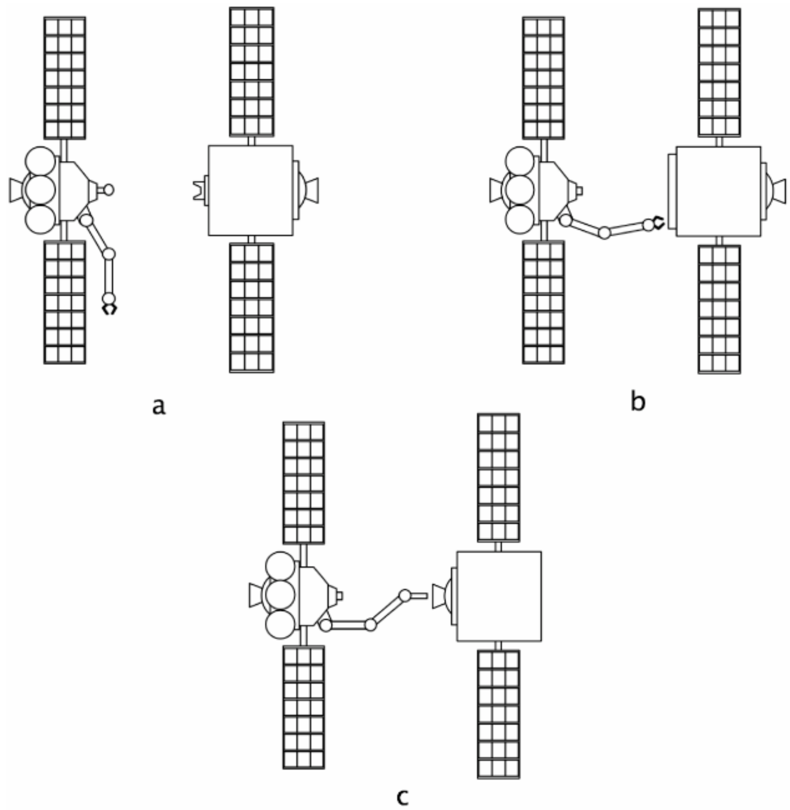


Figure 7-6: Docking configurations

Comparison of docking concepts with (a) a cooperative target, and capture concepts for a non cooperative target: (b) grasping a fixture and (c) inserting a probe in the thruster nozzle cone.

7.4.5 ORU Sequence of Operations

"The most complex space application of robotics is on-orbit servicing" (Ellery 2000, p. 49).

Unlike planetary robotic rover operations, and unlike basic teleoperated grasping operations, Mid-Term ORU missions will require more complex autonomous robotics operations, such as precision cutting, drilling, tool swapping, screwing, etc. To ensure the performance of such dexterous operations, the robot must be equipped with several degrees of freedom (DOF), typically six or seven (Rovetta 2001). In order to illustrate the level of complexity inherent to ORU robotics mission, a typical high-level ORU sequence of operations is described:

- Initial positioning of the arm in front of the old ORU (using visual sensors)
- Latch the end-effector to the old ORU
- Use the drill tool and loosen the bolts
- Remove the old ORU by pulling the arm back
- Stow the old ORU on to the Servicer spacecraft
- Find the replacement ORU and latch to it
- Orient the new ORU for insertion to the client spacecraft
- Install the new module on the client

- Use drill tool and tighten the bolts
- Wait for the new ORU check-up

In order to enable these complex and high dexterous operations, the following enabler technologies, which are high-level needs for Mid-Term future robotics, can be defined as follows (PiedBoeuf 2004):

- Manipulator and end-effector: The level of dexterity of the robotic manipulator and end-effector must be high enough to perform human-type operations
- Autonomy: In order to limit the communication bandwidth, reduce complex ground operations and chance of failure due to erroneous commands of ground controllers, and to enable more accurate operations, fully autonomous rendezvous and docking as well as ORU operations are baselined. Moreover, autonomous operations reduce the training of ground operators. Teleoperated operations also suffer from a communication delay of 1-7 seconds, depending on the space and ground segment architecture.

Although autonomous replacement of ORU has been demonstrated in orbit (ETS-VII and OE), most on-orbit satellite servicing operations are currently carried out manually, i.e., by an astronaut. However, manned missions are usually very costly, and there are human safety concerns too. Furthermore, it is currently impossible to carry out human OOS missions for satellites in GEO, as no current human space vehicles can reach them. The trade-off of autonomous vs. teleoperated operations is summarized in Table 7-8.

Table 7-8: Trade-off of Autonomous vs. Teleoperated Operations

	Autonomous	Tele-operated
Susceptibility to error	LOW	HIGH
On-board computational resources	HIGH	LOW
Communication bandwidth	LOW	HIGH
Operating cost	LOW	HIGH
Transmission delays	NONE	HIGH
Range sensors	REQUIRED	NOT REQUIRED
Robustness to uncertainties	HIGH	LOW

7.4.6 Robotic Requirements

Based on the mission requirement, detailed system requirements have been derived, and are listed below.

R-R1 Autonomy: Each ORU mission shall be performed in a fully-autonomous mode, without any ground support, from the completion of the docking maneuver, to the undocking maneuver from the Client spacecraft.

R-R2 Safe Mode: If, for any reason the robot become unable of completing the ORU exchange, the autonomous system shall be able to stop the on-going operation and trigger a safe mode, where ground control take over the command of the robot.

R-R3 Number of Robotics Arms: Two robotics arms shall be used on the service spacecraft.

R-R4 Robotic Arm Dexterity: Each robotic arm shall be equipped with 7 DOF.

R-R5 Mass: The mass of each robotic arm, including their manipulator, shall be no more than 250 kg.

R-R6 Tools: The Servicer shall be able to perform every ORU-related task and docking operations with only two different tools.

R-R7 Combined Arm Capability: Both arms shall be able to connect to each other.

R-R8 Vision Sensing: Vision sensing shall be accomplished by three video cameras located as follows: one camera on each robotic manipulator for autonomous navigation purposes and one camera on the Servicer itself for general video monitoring of the on-going tasks. The frame rate of the arm-mounted camera shall be of at least ten frames/sec and the frame rate of the third camera shall be of a least 2 frames/sec.

7.4.7 Robotic design

Robotic Arm

To determine the length of each robotic arm, it is assumed that, due to standardization, no ORUs will be located more than six meters away from the docking port (which corresponds to about 75% of the total length of the largest possible client satellite). Therefore, the robotic arm won't need to replace ORUs beyond that distance. Using the assumed dimensions shown in Figure 7-7, it can be easily determined that an 8.5 meter robotic arm is necessary. However, taking into account the requirement of combined arm capability with seven DOF, it means that this distance could be reached by combining two arms of about 4.5 m, to one 14 DOF robotic arm of 9 m. The proposed 4.5 m robotic arm is illustrated in Figure 7-7.

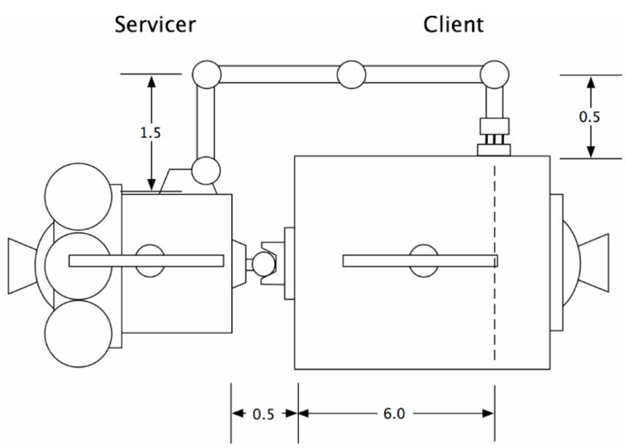


Figure 7-7: Sizing the Robotic Arm

Finally, the arm is also equipped with force/moment sensors and uses reactionless manipulation to avoid attitude disturbances of the client satellite during manipulations, as used in the client spacecraft is fairly small, the two arms can combine the tasks of removing the old ORU from the Client and removing a new ORU from the Servicer at the same time. With a large spacecraft, where the two arms are combined to reach for the ORU connector, the arm will have to take out the old ORU first, and then temporarily stow it. This allows it to retrieve the new ORU and install it on the Client spacecraft, before stowing the old ORU on the Servicer spacecraft. This storage of the ORU might also be made possible by adding an additional ORU storage platform on the Servicer spacecraft, similar to what has been installed on the SPDM.

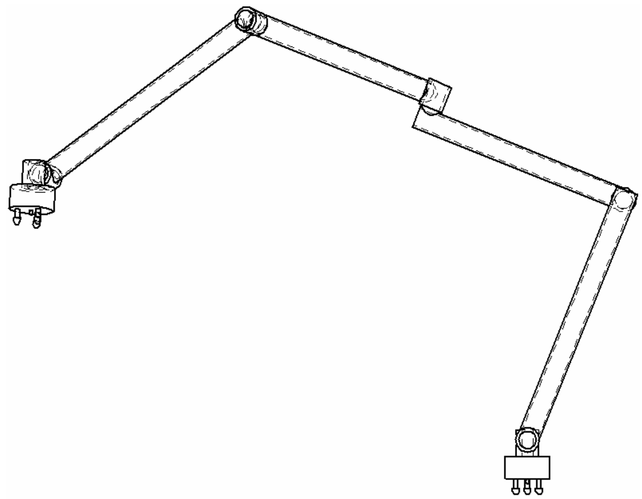


Figure 7-8: Proposed 7DOF Robotic Arm

Finally, the arm is also equipped with force/moment sensors and uses reactionless manipulation, to avoid attitude disturbances of the Client satellite during manipulations (such as what has been done in the ETS-VII mission).

Tools

Since both arms shall be able to connect to each other in order to enable potential longer reach, only two tools are allowed for this mission. It is also recalled that from this requirement, these two tools shall be able to accomplish all the docking and ORU replacement operations. The proposed baseline design consists of a male and a female tool, which are illustrated in Figure 7-9 and Figure 7-10.

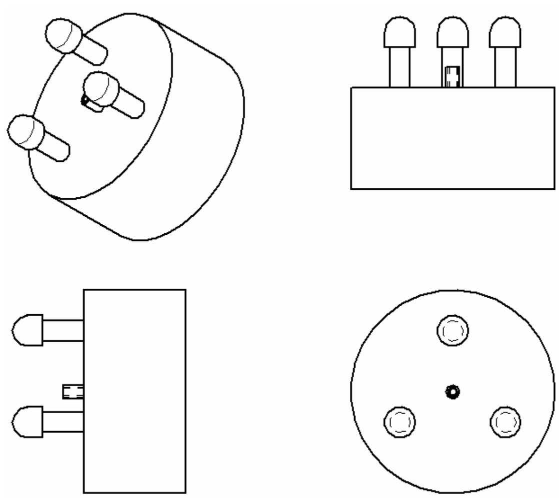


Figure 7-9: Proposed Male Tool

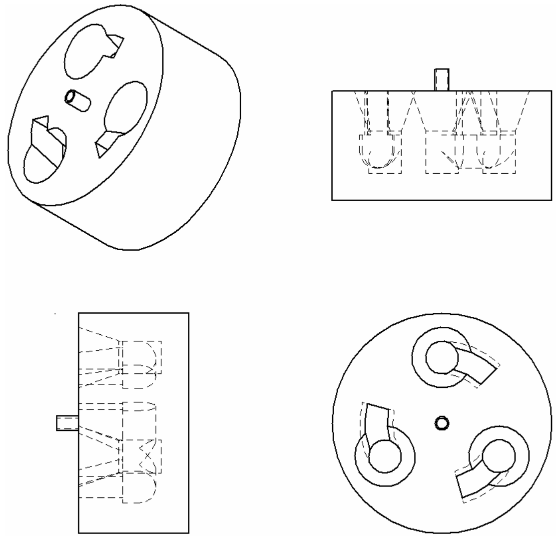


Figure 7-10: Proposed Female Tool

These tools are compatible and can be used on the ORUs as a latching/unlock and lock/release mechanism, where a female tool is mounted on each ORU. Latching the male tool to the female tool and unlocking the ORU happens when the pins are inserted into the holes of the female tool and then rotated clockwise (CW), which triggers a mechanism that unlocks the ORU from its storage area. Once the male and the female mechanisms are latched together, the ORU is then free to be taken out to another storage area. Once the ORU is installed to its new storage area, the locking mechanism is triggered by rotating the male tool counter clockwise, which releases the ORU at the same time. That same procedure can also be used as a docking/undocking mechanism to attach both arms to the Servicer spacecraft and to combine the two arms into a single arm. Finally, the male tool also acts as a robotic hand by having the ability to grasp objects with three fingers actuated by one motor. Indeed, one motor is sufficient since it is not necessary for all three fingers to close independently (all fingers will close to grasp an object as firmly as possible). This capability enables the grasping of a spinning re-supply ORU or of a tumbling client in order to guide it to the docking mechanism.

Video Monitoring and Manipulator Alignment

Vision sensing shall be accomplished by three video cameras located as follows: one camera on each robotic manipulator for autonomous navigation purposes, and one camera on the Servicer itself for general video monitoring of the on-going tasks. The frame rate of the arm-mounted camera shall be of at least 10 frames/sec, and the frame rate of the third camera shall be of a least 2 frames/sec. The first two are mounted on each arm, next to each male tool. These two cameras will be mainly used to autonomously track a target marker and align the manipulator with it. The target marker will be a reference triangle symbol, located next to each female mechanism, positioned in a way that it would be centered in the camera CCD when the male and the female tools are properly aligned.

Target Illumination

A pulsed xenon flash lamp, similar to SUMO's flash lamp, will be mounted next to each camera, in order to illuminate what each manipulator's field of view. These devices will then facilitate the detection of the target marker and alignment of the male and the female tool.

Proposed Sequence of Operations

In the case that the client spacecraft is small enough so that both robotic arms can reach the ORUs of interest, the arms can perform different tasks at the same time. If however the client spacecraft is too big, the two robotic arms will have to combine into a single larger arm. To accomplish this, one of the arms will swap its male tool with a female tool, connect with the other arm and release the other side from the Servicer spacecraft. This will have consequences regarding the sequence of operations, as listed below.

Possible sequence with 2 separate robotic arms of 4.5m

1. The first arm goes to the old ORU on the Client spacecraft, while the other arm goes to the new ORU on the Servicer spacecraft
2. Both arms use the male tool to connect with the female tool on the ORU's
3. Turning the male tool into the female tool will release the mechanism at the backside of the ORU, as well as releasing the ORU
4. Take out the ORU
5. The first arm moves to the Servicer spacecraft while the second arm moves to the Client spacecraft
6. Put the ORU's into place
7. Turning the male tool to the other side will connect the mechanism at the backside of the ORU, as well as locking the ORU
8. Retract the arms

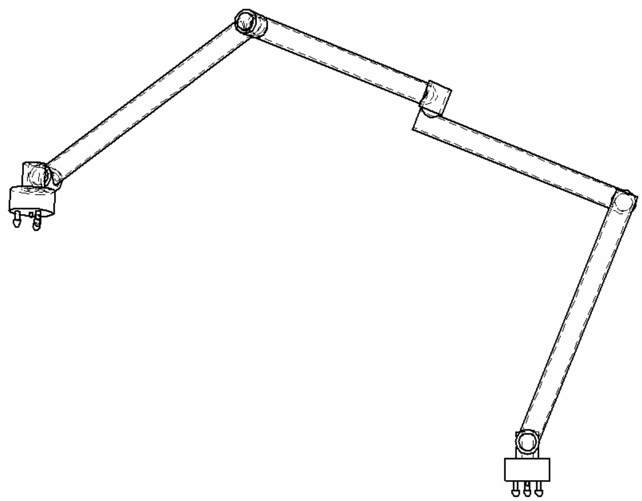


Figure 7-11: Proposed Robotic Arm with Seven DOF

Possible sequence with one big robotic arm

1. Move the arm towards the old ORU on the client spacecraft
2. Use the male tool on the arm to connect with the female tool
3. Turn it in order to release the ORU
4. Take out the old ORU
5. Go to the storage connection on the Servicer
6. Attach the ORU on the Servicer spacecraft
7. Go to the new ORU
8. Use the male tool to connect with the female tool
9. Turn it in order to release the ORU
10. Take out the new ORU
11. Go to the Client spacecraft
12. Put the new ORU in the client spacecraft
13. Turn the male tool in order to fix it.
14. Go to the old ORU on the Servicer spacecraft
15. Use the male tool to connect with the female tool
16. Turn it to release the ORU
17. Take the old ORU to the Servicer hull
18. Put the ORU in the Servicer hull
19. Turn it to fix it

20. Put the second arm back on its original place with the right tools
21. Retract both arms

7.4.8 Communication

Due to the unique nature of a maneuverable Servicer spacecraft that must rendezvous with spacecraft operated by other companies, as well as rendezvous with the ORUPPs, communication is a difficult and critical component of the ODORU system. The system architecture includes provisions for sending data and commands to and from the Servicer, as well as ensuring the Servicer has the ability to find and rendezvous with the ORUPP.

Ground Segment

As the Servicer will maneuver throughout all of GEO, three ground stations will be needed to maintain contact and operations, as shown in figure 7-12.

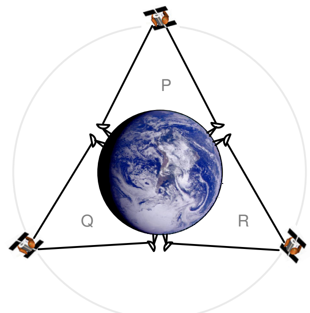


Figure 7-12: Ground Facilities

Space Segment

The communication system on the Servicer consists of four antennae: one for the uplink to receive commands from ground; two downlink antennas: one to transmit telemetry and another to transmit real time video data; and one antenna to locate the signal from the ORUPP. The antenna used for the video downlink has a diameter of 80cm and can be controlled using a two-axis pointing mechanism, while the other three are Omni-directional.

Communication coverage between the Servicer and the ground station is continuous, especially when the Servicer and Client are docked and undergoing ORU exchange operations. Even though the robotics is designed to be fully autonomous, the whole service mission will be monitored, such that in case of needed teleoperations, the up-link bit rate is high enough to perform this intervention from ground.

There is also a need for communication between the Servicer and the ORUPP. The ORUPP contains a small, low-power beacon which continuously sends out a signal, such that the Servicer will be able to detect it (see Table 7-9.)

Table7-9: Requirement of Servicer System (ITU 2007; SLBC 2007)

	Description	Concept and parameter
Uplink	Control the bus sub system	9600bps
	Emergency Teleoperation of Robotic Arms	Autonomy is used nominally Teleop: 9600 bps
Downlink	Telemetry	9600 bps
	Real-time video image of at least two cameras and other sensor data	10 Mbps for each camera, Video transmission
Crosslink	To locate the ORUPP	100bps

Communication Frequency

The Servicer will require frequency allocations from the ITU for each of the transmissions. The carrier frequency bands were chosen based on data rate requirements and the communication parameters are outlined below. For uplink communication, the frequency will be 2000 MHz (LS-band), and the total bandwidth will be 128 kbps. This is enough for all uplink control commands and it will meet the ITU standards and the Servicer requirements (see Table 7-10). The choice for Servicer telemetry parameters communication is in the 2180 MHz range (LS-band) with a total bandwidth of 64 kbps. The real-time video image must use a higher frequency, because there is a much higher data rate. Thus 3600 MHz range (S-band) for real-time video communication was chosen, and the total bandwidth is 80 Mbps, as shown below:

Table7-10: Frequency bandwidth and antenna type

	Description	Frequency	Bandwidth	Antenna type
Uplink	Uplink commands and data	2000 MHz	128 kbps	Columnar helical
Downlink	Telemetry	2180 MHz	64 kbps	Columnar helical
	Sensor data(include Real-time video, radar data, and other sensors)	3600 MHz	80 Mbps	Dish
Cross link	Localize the ORUPP	900 MHz	100 bps	Columnar helical

Link Budget

The BER (Bit Error Rate) of each link must be less than 10-6 (ITU 2007), and the link budget design is listed in Table 7-11, using the Link Budget Calculator (SLBC 2007).

Table7-11: Result of link budget calculation

	Up-link	Down-link	Video Comm.	Cross-link
Transmitter [W]	50	5	10	0,01
Transmitter Antenna diameter [m]	9	0,5	0,8	0,2
Channel frequency [MHz]	2000	2180	3600	900
Bit rate [kbps]	128	64	80000	0,1
Link margin [dB]	28,80	22,3	7,2	8,1
Reciever Antenna diameter [m]	0,5	9	15	0,3
Signal to Noise [K]	500	500	500	500

7.5 Market Analysis

Businessmen and academics continue to identify a large commercial market for OOS services. Sullivan (2005) has identified over $2.3 billion USD in servicing opportunities per year, while Caswell (2006) estimates that every year $3.8 billion USD in GEO satellite investment is retired through lack of propellant. Satellite executives continue to express interest in OOS and are willing to embrace the technology if it impacts the bottom line (Butler 2007, pers. comm. 20 July).

The insurance industry also has a vested interest in the success of OOS. In the GEO market alone, Sullivan (2005) estimates that from 1994 –2003, 7.4 insurable events occurred per annum valued at a total of $748 million USD, or about $100 million USD per event. If commercial OOS options existed, the insurance industry could reclaim a portion of this $7.5 billion USD in payouts. Rescuing satellites suffering early failures is frequently an issue for satellite insurers, as they take ownership of stranded or damaged satellites they have insured (Caswell 2006). To the extent, if insurance companies can salvage damaged and/or wrong-orbited spacecraft, insurance rates are likely to be reduced.

In determining our target client base and the payloads they will need, we have performed a detailed market analysis. This analysis is important for two reasons:

- It determines the payload of our spacecraft, with an emphasis placed on servicing events that occur the most frequently, and offer the highest revenue per servicing event
- It sets an upper boundary on the lifecycle cost of our servicing missions which means that this is a financially sustainable scenario i.e. we are a private company seeking to make a profit.

Sullivan (2005) has estimated the annual break-even servicing fees form OOS to exceed $2.3 billion USD, with the greatest-value market segments to be refueling, removing inactive satellites from GEO, and ORU Exchange. We have reproduced Sullivan's table, adjusted to 2007 dollars, and added with a column for our defined mission categories. If we do not include the "Remove Inactive" category, which represents a hazard fee avoidance for an operator rather than the purchasing of a service (Sullivan 2005), our ORU system architecture addresses over 60% of the market.

Table 7-11: Estimated OOS Annual Market Value

Sullivan Service Category	Team DOCTOR Service Category	*Break-Even Servicing Fee ($m 2007)*	*Average Annual Opportunities*	*Annual Market Value ($m)*
Refuel	**2D, 2E, 2F - Refuel**	**43.0**	**20**	**859.5**
Remove Inactive	3A, 3B - Deorbiter / Reorbiter	45.0	10.5	472.6
ORU Replacement	**2B - ORU Remove/Replace**	**87.0**	**4.4**	**382.9**
General Repair	2G - Depot with Spares & Tools	87.0	3.8	330.7
GEO Retirement	3A, 3B - Deorbiter / Reorbiter	21.5	10.9	234.2
LEO to GEO Transfer	3A, 3B - Deorbiter / Reorbiter	1.1	131	140.7
Relocation in GEO	3A, 3B - Deorbiter / Reorbiter	14.0	4.6	64.2
Deployment Monitoring	1B - Proximity Ops	21.5	1.4	30.1
Deployment Assistance	2G - Depot with Spares & Tools	0.3	84	27.1
Health Monitoring	1A, 1B - Flyby, Proximity Ops	0.0	200	0.0
Total				2,542.0

(Sullivan 2005; Inflationdata.com 2007)

7.5.1 Estimating ORU Service Fees

In assessing what a satellite operator is likely to pay for an ORU mission, two approaches can be taken:

1) Estimate the depreciated value of the satellite that will no longer function if it is not serviced (book value approach)
2) Estimate the value a satellite operator places on the continued operation of the satellite that needs to be serviced (cash flow approach).

While Sullivan (2005) takes the book value approach due to its conservative nature, we have chosen the latter due to its increased focus on the potential for servicing to improve cash flow generation, rather than sunk investment cost. When an operator determines that a specific satellite will not meet its design life, or if the operator wishes to investigate life extension though refueling, he or she assesses the following trade:

1) Likely cash flow generation from procuring a new satellite
2) Likely cash flow generation from procuring a service mission, followed by procuring a new satellite.

Depending on its configuration, a commercial GEO satellite typically costs $300 million USD or more, including the cost of the satellite, launch and insurance (Saleh et al. 2005). The typical life of a GEO satellite is 10-15 years (Tech-faq 2007). Before a satellite goes out of service whether it is projected to reach the end of its design life, or an anomaly is projected to shorten the life of the satellite, the satellite operator must make a decision on whether or not to replace the old satellite with a new satellite. In the course of normal operations, it is rare for an operator not to replace the old satellite, as even if the operator's revenue growth is stagnant, it will want to preserve the orbital slot for future growth opportunities.

In the event that the operator has the opportunity to repair or extend the life of satellite, the operator will make an economic and technical assessment of whether or not life extension could enhance the profitability of the company. If an otherwise healthy satellite is running out of propellant, or if an ORU replacement could restore satellite health, it could make economic sense to consider life extension. The following chart illustrates this trade-off:

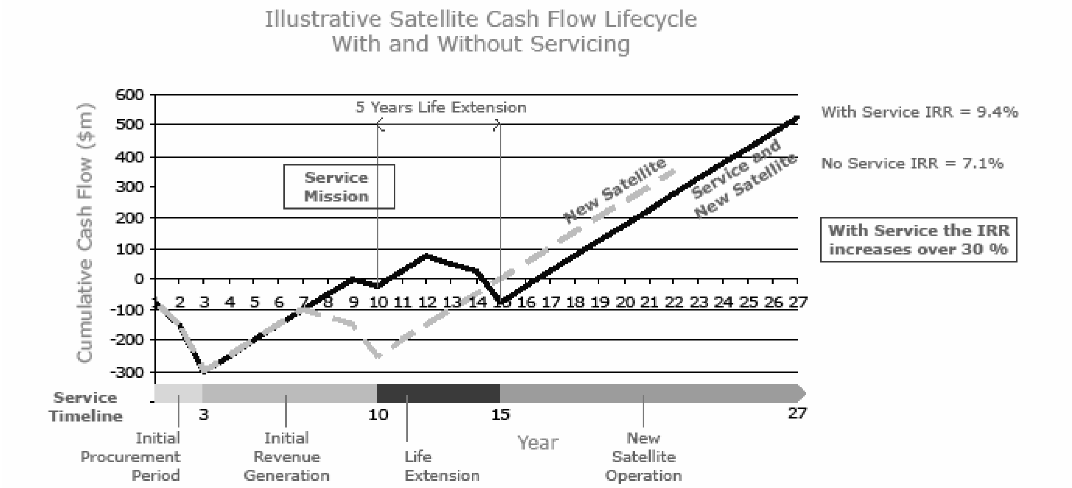


Figure 7-13: Illustrative Satellite Cash Flow Lifecycle

The above figure represents two scenarios, with each scenario assuming that an operator initially procures a $300 million USD satellite with a design life of 12 years. The satellite generates $50 million USD of revenue per year, and operates for seven years before an ORU needs to be replaced. In year seven, the operator will need to decide between:

- Replacing the ORU in year 10 for a fee of $75 million USD. The replacement enables five years of additional operation, allowing an additional $250 million USD of revenue. Following this five year period, the operator will procure a new satellite for $300 million USD to replace the retiring satellite.
- Procuring a new satellite and forgoing the ORU Exchange, to require $300 million USD of procurement.

In determining the fee a satellite operator may pay for an ORU Exchange service, we have calculated two Internal Rate of Returns (IRR). The first IRR measures the return a satellite operator could achieve with the purchase of a service mission followed by a new satellite procurement. The second IRR measures the return the operator could achieve with the procurement of a new satellite only. We have assumed the operator will only purchase the ORU Exchange service if the former exceeds the latter by a minimum of 25%.

The improved IRR is necessary when taking into consideration the risk of a potential servicing mission, as well as the opportunity cost of not purchasing a state-of-the-art satellite. We have adjusted the service mission fees until the IRR improvement of purchasing an ORU Exchange service exceeds this 25% hurdle. Results are indicated in Figure 7-14 below.

Table 7-12: Trade-off Analysis for ORU service mission prices

Fuel ORU Trade-off Analysis	
new satellite cost (USDm):	$300
new satellite lifetime (years):	12
satellite revenue per year (USDm):	$49
service mission price (USDm):	$36
years of extension:	2
IRR of a new satellite:	10.6%
IRR of service mission + new sat:	13.2%
IRR improvement over new satellite:	2.7%
% improvement	**25.3%**

Other ORU Trade-off Analysis	
new satellite cost (USDm):	$300
new satellite lifetime (years):	12
satellite revenue per year (USDm):	$49
service mission price (USDm):	$139
years of extension:	5
IRR of a new satellite:	10.6%
IRR of service mission + new sat:	13.2%
IRR improvement over new satellite:	2.7%
% improvement	**25.2%**

Our overall ORU mass of 120 kg, yielding a payload mass of 65 kg, allows us to provide a fuel ORU allowing two years of life extension, or other ORUs that on average will allow five years of life extension. Figure 7-14 estimates the following service mission prices:

1) Fuel ORU: $36 million USD for two years of life extension, or $18 million USD/year
2) Other ORU: $139 million USD

7.5.2 Refueling Market

Refueling represents over 1/3 of the estimated break-even OOS market, with 20 servicing opportunities occurring every year. This is largely composed of satellites that have run out of propellant, but are otherwise fully functional. As refueling opportunities are likely to occur four to five times more often than other ORU-like failures (Sullivan 2005), we will offer a fuel ORU replacement service despite its lower revenue per kilogram. It is important to note that Sullivan's break-even annual servicing fee of $43.0 million USD represents the potential maximum annual fee, and is capped in theory by the average annual revenue per satellite of about $49.0 million USD (SES Global 2007; Intelsat 2007; Eutelsat, 2007). Our cash-flow focused fee is significantly lower, due to our estimation of IRR improvement that the customer will require.

It is important to note that by the time our ORU exchange comes into service, semi-permanent docking refueling services are likely to exist (similar to the SMART-OLEV concept) (Caswell 2006). These services will most-likely target the market for longer-term fuel-based life extension missions, leaving a market opportunity for shorter-term refueling missions.

7.5.3 Other ORUs

Sullivan (2005) has estimated that there will be 4-5 annual opportunities for ORU-like replacement. However, historical data suggests these opportunities will be spread across a range of ORU-like failures:

Table 7-14: ORU-like failures in GEO (Sullivan 2005)

ORU Failure	Occurrences 1994 – 2003
Solar array	15
Control processor	7
Wheel	7
Battery	6
Transponder	4
Antenna	4
Payload sensor	1
Payload sensor	1

The data strongly suggests that our initial ORU suite should contain the following four ORUs, with our first ORU replacement to be contracted before the Servicer launch:

- one (1) Fuel ORU
- one (1) Solar Array ORU
- one (1) Central processor ORU
- one (1) Wheel ORU

The sale of the first ORU will create an ORU vacancy on the Servicer. The next specific ORU request can then be filled through:

- The three remaining ORUs on the Servicer
- An "on-demand" ORU launch from an assortment of ORUs on the ground ready to go up on the next available piggyback GEO launch

Our non-fuel ORU opportunities have the potential to significantly increase satellite lifetime. For example, replacing a faulty battery one year after launch could extend the life of a satellite by over 10 years. Sullivan (2005) has estimated that on average, GEO satellites that experience ORU-like failures have a remaining book value of about $100 million USD. For a $250 million USD satellite with a 12-year design life, this infers that ORU-like failures occur at the seven-year point, with five years of design life remaining. In practice, the bathtub mortality curve suggests that this average is composed of several early failures, where the operator is likely to place a high value on servicing, and several later failures, where the operator will place a lower value on servicing (Sullivan 2005).

Based on an IRR analysis of cash flows, we have assumed that the client will be willing to pay significantly more than Sullivan's estimated break-even servicing fee of $87 million USD, which is based on remaining book value. If an operator is able to extend satellite life by five years, the satellite could generate nearly $250 million USD in additional revenue.

7.5.4 Project Market Share

According to Sullivan (2005), considering the refueling and ORU-replacement markets only, there are 24-25 annual servicing opportunities per year. We have estimated the size for each market below (see Table 7-14):

Table 7-15: ORU-replacement market (Sullivan 2005)

Team DOCTOR Service Category	Estimated Service Fee Per ORU ($m 2007)	Average Annual Opportunities	Annual Market Value ($m)
2D, 2E, 2F - Refuel	**36.0**	**20.0**	**720.0**
2B - ORU Remove/Replace	**139.0**	**4.4**	**611.6**
Total		24.4	1,331.6

As the ORU-replacement market is estimated to far more lucrative than refueling, we will attempt to take maximum market share in this segment. We have assumed we will be able to achieve 33% ORU-replacement market share, on a per-mission basis, which equates to 1.5 service missions per year. The remaining 2.5 missions will be refueling missions, which represent 12.5% of the refueling market on a per-mission basis. These assumptions provide the average annual revenue per mission and total annual revenues, see table 7-15.

Table 7-16: ORU-Replacement projected annual revenues

Team DOCTOR Service Mission	Revenue Per Mission ($m)	Annual Revenue ($m)
ORU Replacement	139.0	
ORU Replacement	139.0	
Refuel	36.0	
Refuel	36.0	
Year 1 of Operation:		350.0
ORU Replacement	139.0	
Refuel	36.0	
Refuel	36.0	
Refuel	36.0	
Year 2 of Operation:		247.0
Average	74.6	298.5

7.5.5 Timeline and Net Present Value

An aggressive schedule was produced for the ODORU plan to develop to fruition. The development costs for the spacecraft and the ORUs were spread out over five years, with production beginning in year five. The Servicer is launched in year six with the first four ORUs onboard, and ORUs are continually developed and launched at a rate of four per year. The Servicer has enough fuel onboard for 7.5 years, however it is capable of self-servicing, thus it can extend its life in year eight and every two years subsequently with fuel and/or battery ORUs as needed. It services four satellites per year nominally, though some years it will be assumed only three due to uncertainties, and times it has to self-service (a piggybacked ORU will be used as fuel for the Servicer rather than for a Client).

The NPV of the ODORU architecture was calculated using the development and production costs, the expected revenues, the development and mission timeline, and the following assumptions:

- Launch to GTO costs of $40,000 USD per kilograms (Larson 1999; Sullivan 2005)
- Operations cost of $10 million USD per year
- 95% learning curve for ORU production
- 10% discount rate
- Launch insurance costs of 13% of value of Servicer and launch
- Liability insurance costs of $10 million USD per year

With the assumption that the Servicer is capable of delivering four ORUs per year, the NPV of the project over the entire 15 year life cycle is $327 million USD, which corresponds to an IRR of 18%. The breakeven point occurs about 9.5 years into the lifetime of the project, or about 4.5 years after the Servicer has been launched. Thus any life extensions the Servicer is able to do through self-servicing, will significantly increase the NPV of the project as revenue continues to be generated in the later years (see Figure 7-15).

Table 7-17: Project Cost and Revenue until Breakeven

$ million	Develop				Build	Launch!	Launch 4 ORUs each year after				
Year	0	1	2	3	4	5	6	7	8	9	10
Non-recurring servicer	(62)	(111)	(91)	(46)	(10)						
Non-recurring ORU	(10)	(19)	(15)	(8)	(2)						
Servicer production					(86)						
Servicer launch						(102)					
Servicer launch insurance						(24)					
ORU production					(37)	(33)	(32)	(31)	(30)	(29)	(29)
ORU launch						(19)	(19)	(19)	(19)	(19)	(19)
ORU launch insurance						(8)	(8)	(8)	(8)	(8)	(8)
Liability insurance						(10)	(10)	(10)	(10)	(10)	(10)
Operations						(10)	(10)	(10)	(10)	(10)	(10)
Total cost	(73)	(130)	(106)	(54)	(134)	(207)	(79)	(78)	(77)	(77)	(76)
Total cost cum	(73)	(203)	(308)	(362)	(496)	(703)	(782)	(860)	(937)	(1,014)	(1,090)
Discounted @ 10%	(73)	(191)	(278)	(319)	(410)	(522)	(566)	(606)	(642)	(675)	(704)
Total revenues					0	75	298	298	298	298	298
Total revenues cum					0	75	373	671	970	1,268	1,567
Discounted @ 10%	0	0	0	0	0	46	215	368	507	634	749

This analysis includes reductions in revenues in Year Eight due to self-servicing. This assumes that all servicing missions are successful, whereas if a servicing mission is unsuccessful, there will be no revenue obtained for that ORU. Interestingly, if we assume one failed servicing mission each year, i.e. only three ORUs per year, the NPV is still positive, albeit quite low at $64 million USD, and the breakeven point occurs much later in the project, at about Year 13. This failure rate estimate is overly conservative, but it shows that even with a few failed missions, there is a potential business opportunity for the ODORU.

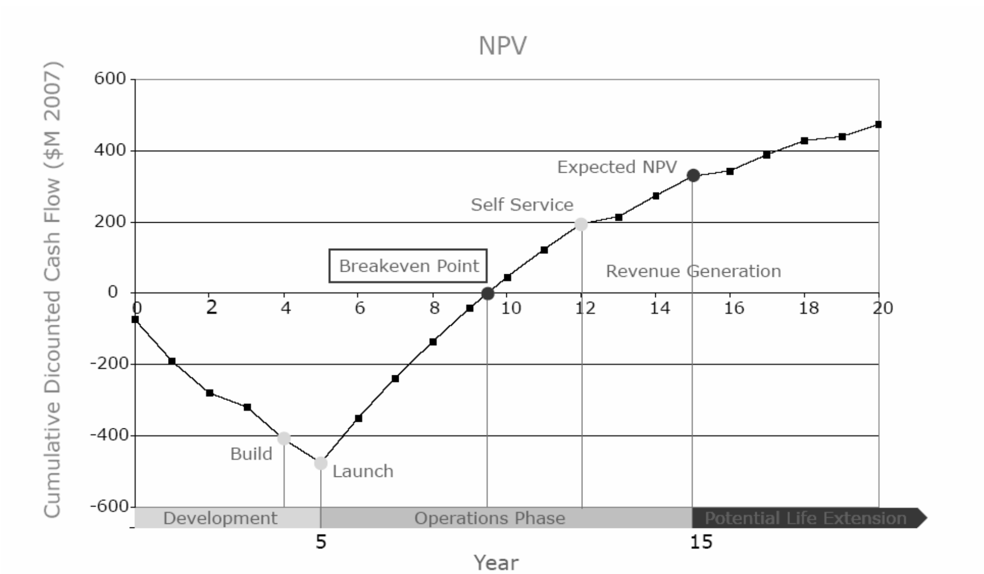


Figure 7-16: Cash flow

7.6 Conclusions

Looking at the thorough analysis presented in this section it is clear that there is a great potential for ORU missions. Although our mid-term mission still requires certain technological advancement, it was shown that there are economical benefits that a company can gain by implementing these kinds of missions. Taking into consideration the bigger picture of the future of space exploration, we need to remind ourselves that although technological innovation comes along with a big price tag attached, there is still a market need for these developments. This market does not only represent the scientific community but mainly represents already existing businesses that make a lot of money with their communication satellites. Due to this, notice that our financial case is not based on assumptions that governments would spend more money, but strongly takes into account the current market situation and trend analysis reports. Looking at the market situation and at potential options out there makes a very strong economic argument for implementing this in real life.

OOS is an important technology that enables a range of future missions. Keeping in mind the hazard environment that would be dangerous to humans, or would be performed inefficiently if carried out by humans. Space based assembly plants would be one of many projects that would need OOS technology in order to work. Because it takes too much effort, involves a lot of risk, and is too expensive, you need robots instead of humans to assemble bigger space structures. Security issues involved are another aspect that supports plants/habitats that are built by robots and run/inhabited by humans. Furthermore there will be a future with many more satellites in orbit that might all need a service in one way or the other. A company/agency that would like to offer this kind of service should not rely on flights from Earth; instead it would be useful to maintain a spare depot in orbit. Further down the road the exploration and utilization of the solar system will need a supportive infrastructure that enables these tasks. Without OOS all of these missions and scenarios will be very difficult to achieve and economical benefits will most likely only remain in the communications sector.

Chapter 8
Far-Term Vision

If humanity is ever to expand the horizons of space exploration beyond Earth's immediate vicinity, the ability to reliably support space missions will play an integral role in that expansion. The next 30-50 years will most likely witness a profound transformation of humanity's ability to utilize space. In order to achieve this vision, OOS must be considered a requisite step. Detailed below is the Team's vision for the future of space applications and exploration enabled by OOS. In this period, new OOS missions will emerge from those developed in the Near- and Mid-Terms. In the Far-Term, the Team envisions the addition of a single OOS mission: the Fuel Depot plus ORU Spares in Earth orbit (see Figure 8-1).

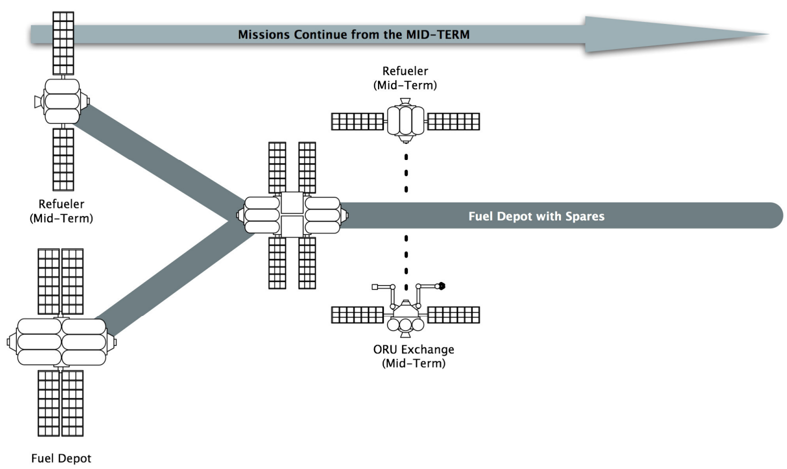


Figure 8-1: Far-Term Roadmap

8.1 Potential Customers

In the Long-Term vision, all prior Near- and Mid-Term clients will also remain as customers into this period, in addition to new ventures. Numerous agencies and companies have proposed the creation of outposts and colonies on the Moon and Mars. If the Mid-Term vision as described in Chapter 6 becomes a reality, private and public activity may substantially increase, as will the need for OOS of these customers and assets.

8.2 Key Considerations and Enablers

8.2.1 Technological Aspects

In the Far-Term, unforeseen and revolutionary technologies may be significant enablers of OOS missions. Furthermore, another driver of OOS will be exploration missions to both the Moon and Mars. Therefore, the exploration plans of civil space agencies may very well be the primary enablers of OOS in the Far-Term.

8.2.2 Economic and Financial Aspects

The Far-Term vision includes commercial enterprises such as lunar surface and orbital tourism. Similar economic considerations apply to the Far-Term vision where OOS may include large spacecraft acting as fuel depots and providing ORU spares to provide more cost effective and reliable space applications. In the Far-Term, the accumulation of space debris due to a century of space activities will likely become a major concern for spacecraft operators. The 400-800 km LEO orbit and GEO graveyard orbit are expected to be densely populated with uncontrolled collisions exponentially increasing the amount of space debris in these orbits. LEO debris may pose a major safety risk for launch operators and human spaceflight. The GEO graveyard orbit may become a hazard to GEO itself as uncontrolled collisions spiral into this orbit. A new OOS industry serving the need of space debris removal may emerge based on Space Tug OOS technologies. Clients for this industry may include military, civil government space agencies, commercial satellite operators, and the commercial space insurance industry.

8.2.3 Policy and Social Aspects

As highlighted in the Chapter 6 discussion of the Mid-Term, policy and legal barriers may decrease over time. In particular, in the Far-Term, OOS will have become a central activity to enable and enhance space applications and exploration missions, as well as one of the possible solutions to space debris. The development of ever more complex and capable OOS missions can be facilitated by forward-thinking international policies and inter-governmental agreements.

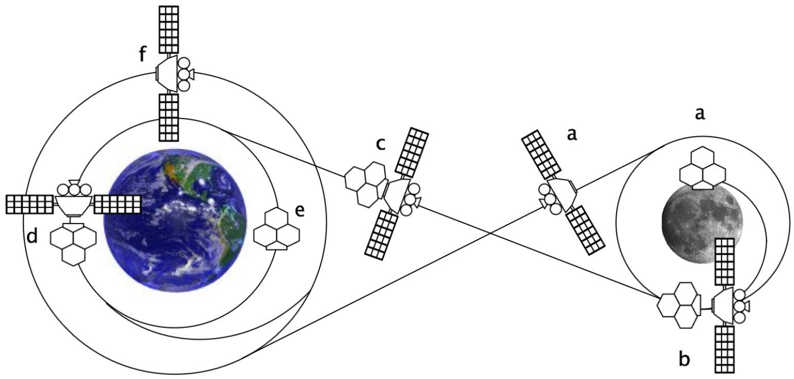
8.3 Missions and Activities Enabled

By the time the Far-Term is reached, the Team envisions a robust on-orbit infrastructure will be in place to support the continued development of space. In this time period, a number of ambitious missions and activities around the inner solar system may become a reality.

NEO ISRU: NEOs are a potential source of resources that can be mined and utilized multiple in-space applications (Valentine 2002). The Space Studies Institute (SSI) has proposed a NEO utilization program that would feature on-orbit robotic construction of solar power satellites using metals obtained from NEOs.

Deep Space Manned Missions: The initial steps that have been made thus far with human missions have largely been constrained by fuel and supply limitations. A deep space human mission to destinations deeper in the solar system could make use of require regular and established supply depots and refueling services. Prior placement of fuel and supply depots at various points along the vehicle's path will dramatically reduce the required carrying capacity of a crewed deep-space vehicle. These depot stations should also be able to inspect and perform maintenance on the spacecraft at each stop.

Lunar Construction and Manufacturing: A significant portion of the Moon's regolith consists of valuable resources such as Iron and Titanium (Taylor 1997). Utilization of these resources will require extraction and perhaps processing capabilities on the Moon. The question remains how these products will be transported to where they are needed in lunar or Earth orbit. A space tug-based transportation system with the ability to rendezvous with cargo launched from the Moon would be capable of transporting the material back to Earth orbit, where it could be used in orbital construction facilities to manufacture solar satellites or even other spacecraft (see Figure 8-2).



a. Tug en-route to moon, where cargo from surface is ready to launch
b. Tug and cargo rendezvous and dock in lunar orbit
c. Tug transfers cargo back to Earth orbit
d. Cargo undocks from Tug
e. Cargo emplaced in Earth orbit
f. Tug moves back into parking orbit awaiting next lunar transfer mission

Figure 8-2: Space Tug Lunar Cargo Transfer Mission

Space Elevator: In the Far-Term, space elevators present a promising method for accessing Earth orbit. However, there are a number of factors that can be expected to degrade the elevator structure, such as radiation, debris and atomic oxygen (Edwards 2002). A dedicated Servicer will have the ability to monitor the elevator and make repairs and modifications when necessary.

8.4 Summary

In the Far-Term there are numerous customers with missions that will be enabled or enhanced by OOS. Figures 8-3 and 8-4 show these customers and missions integrated with those from the Near- and Mid-Terms. These customers include lunar hotels, Mars outposts, scientific installations, lunar archives, space transportation infrastructures like space elevators, etc. By this period, OOS technologies will have evolved to encompass industry standards and enable multiple activities such as on-orbit construction and ISRU. Through the application of OOS, space applications, utilization and exploration may become realized as a dynamic human sphere of activity.

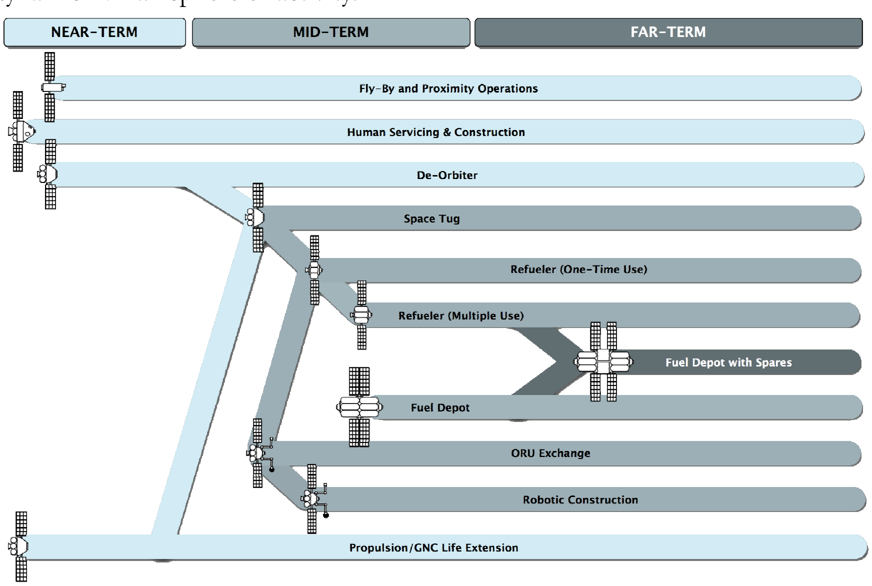


Figure 8-3: Integrated OOS Roadmap

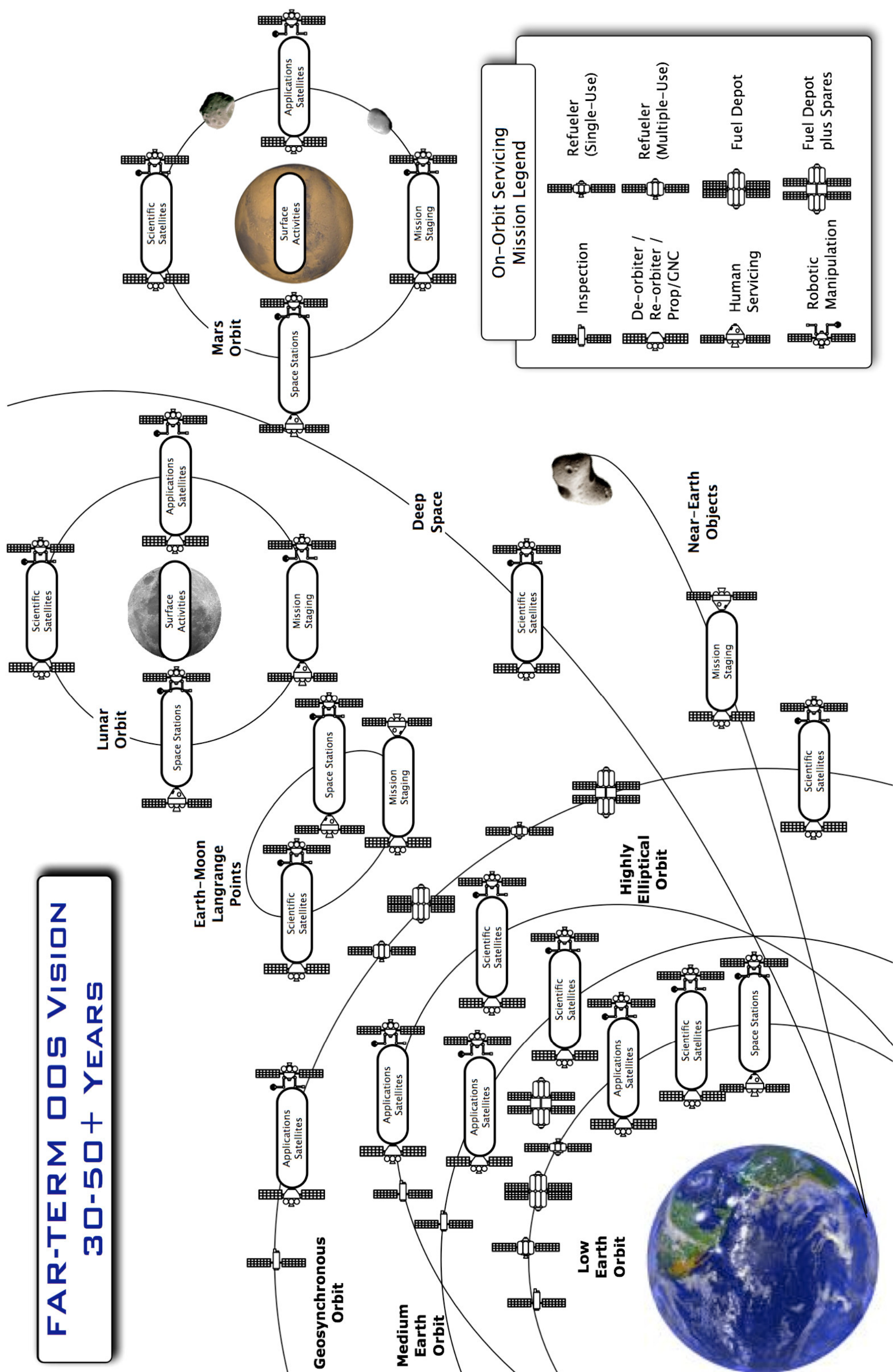


Figure 8-4: Far-Term Vision

Chapter 9

Conclusions and Recommendations

Over the course of the past few months, Team DOCTOR has interviewed commercial satellite executives from five companies on the topic of OOS. Here are some of their responses:

"We've seen great advances in docking – we are getting good at this." – Executive #1

"We will want to launch new technology." - Executive #2

"It would be very attractive to make our older satellites last longer." – Executive #5

"Electronics on my 15-year satellite may last 20 years, but it's probably still better to buy a new satellite" – Executive #1

"If we can extend the lives of our satellites, the manufacturers will find a way to charge more!" – Executive #5

"Watch this space!" – Executive #3

"We need to start building satellites with a grappling point, but it will be tough to get manufacturers to do this." – Executive #1

"Make sure you call your insurance provider first!" – Executive #4

"It's a great idea for a satellite with a bad launch that has used all of its fuel to get to orbit." – Executive #1

As can be seen from the above quotes, the current state of opinion on the feasibility, or even desirability, of OOS is mixed. Yet, soon after the launch of the world's first GEO communications satellite in 1963, governments begin to investigate the feasibility of OOS (Boeing 2007; Macchia and Skeer 1969; Keating 1966). This is not surprising, as the concept of maximizing the utility of multi-million or billion dollar assets is the very staple of economic theory. GEO satellites alone represent an investment in space infrastructure of nearly $70 billion USD, with approximately $5 billion USD spent on additional infrastructure each year. The sheer size of investment in space is too large to not continually reassess if the timing is right for OOS to enhance the value of society's investment in space. Yet, despite numerous feasibility studies, experiments, and successful demonstrations that provide the rationale for the wider adaptation of OOS, it has yet to take-off in a widespread manner. Our report has attempted to identify these disconnects and provide recommended courses of action.

We can learn from observing the evolution of serviceability design in space telescopes. Even with the success of several manned HST servicing missions, in which its capabilities have been increased multiple times over, often times the economic justification to incorporate serviceability features into telescope design cannot be made. In the short term, designing a system for serviceability increases cost, while benefits are not likely to be realized until the Mid- or Far-Terms (Baldesarra and Miller 2007). Longer-term perspectives need to take increased precedence over shorter-term profitability motives. This leads to our first recommendation:

1. **To reap the benefits of on-orbit servicing, the space industry should focus more on "systems design" rather than "spacecraft design".**

While standardization is not a prerequisite for the OOS to continue to grow, it can help propel the efficiency and speed of the integration of OOS into spacecraft architectures. We have identified several paths to standardization, initiating from both government and commercial sources. Satellite manufacturers in isolation cannot be expected to implement spacecraft standardization without insistence from their customer base, as first-movers are likely experience short-term losses in profitability. Solutions to standardization are likely to be international, as national markets alone are unlikely to reap the economies of scale that standardization could supply. Technology leaps are not required – it would cost little to incorporate features like docking interfaces. However, the long-term success of standardization initiatives will depend on the perception that standardization allows more than extending the life of old technology – it must make it easier to incorporate technical advances without complete overhauls. Our second recommendation is directed at both commercial entities and governments:

2. **Satellite operators, both government and commercial, must insist that manufacturers begin to incorporate elements of standardization into spacecraft design.**

However, operators will not insist on standardization unless then can see a clear path to increased profitability, and this has yet to be demonstrated beyond paper studies. Until now, the commercial space industry has mixed track record in allocating capital to promising projects. For example, in the 1990s, over $10 billion USD was invested in unprofitable LEO telephone systems (Hesseldahl 2001). The success of OOS depends on interdisciplinary interaction between technical engineers and business managers, or better yet, the proliferation of professionals that are able to wear both of these hats. In the last decade, the increased involvement of profit-seeking shareholders has resulted in financially focused management teams who may be more willing to embrace servicing over throw-away designs. As cheaper system designs are proposed that serve identifiable market needs, we believe commercial OOS projects have a better chance of succeeding than previous stalled attempts (Xue 2007, pers. comm. 1 August; Sullivan 2005). It should not be surprising then, that one of our recommendations is directed squarely at the business community:

3. **Space entrepreneurs must demonstrate that on-orbit servicing can be profitable.**

Commercial profitability is only one of the initial steps on the roadmap we have identified for the progressive integration of OOS into the space industry. We first have stated our desired long-term future: a robust, expanding space infrastructure. In this future, OOS will be a necessity to maintain such systems as lunar outposts, space tourism, and interplanetary exploration. Our roadmap then lays out key events along the critical path to our desired long-term future, including the further development of ORU technology and space tugs in the Mid-Term. Our proposed ORU architecture demonstrates the profit-enabling potential this standard could offer, and hopefully will provide the space industry with an incentive to take the steps now required to reach this critical milestone as soon as possible. Thus, our fourth recommendation:

4. **The Space Industry should consider implementing our proposed roadmap, making OOS an important enabler for our future in space.**

People from many countries and cultures have worked on this project to develop on-orbit concepts, assess technology options and provide a robust roadmap. Going into the project, team members had widely-divergent visions of OOS and its implementation, from government professionals focused on space exploration, to entrepreneurs with a focus on near-term feasibility and profitability. Working as a team, we have realized our visions are the same, just focused on different parts of our roadmap. This leads to our final recommendation:

5. **To reap the benefits of a vibrant space industry we are all responsible to continually assess the role on-orbit servicing can play in achieving this goal.**

To date, several successful human OOS missions have been performed. Robotic OOS has begun to move beyond the academic battleground, and with each successful demonstration, moves a step closer to operational reality. Team DOCTOR is looking forward to working with our fellow space professionals in making OOS an integral part of our space future.

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Annex A
Feasibility Matrix

A.1 Introduction

The feasibility matrix is a flexible and concise tool used to provide a feasibility estimate for each of the possible mission scenarios described in Section 2.3. Critical criteria in four categories; policy, economic, technical and interdisciplinary, were identified and mission feasibility evaluated for each. Weights are assigned to each criterion, and a feasibility score is calculated for each mission. A detailed description of the selected criteria and their justifications is given herein.

The feasibility matrix can be used to assess mission achievability for various future segments (e.g. Near-, Mid- and Far-Term). The feasibility matrix is also capable of evaluating each mission under a general criteria category such as policy, economic, and technicality. The baseline feasibility matrix was filled out from the viewpoint of current and near-term space environment (0-5 years).

The scores used range from 1 to 3, 1 meaning that a certain criterion is infeasible for the specific mission or that the criterion hinders this mission (as this might be the case for policy or economic considerations), 2 standing for an indifferent score, and 3 indicating that the mission is feasible with respect to the selected criterion or that it is even enabled/promoted by it.

For the weighting (w_i), a number between 1 and 5 was assigned to each criterion, using a higher value for criteria that are considered to be more important and have a larger impact on the mission feasibility. The individual mission ratings (s_i) were assigned based on literature research, technical estimations, cost-benefit analyses, and expert judgement. The score for each group of criteria (S) is calculated per Equation A-1.

$$S = \frac{\sum_{i=1}^{n} s_i \cdot w_i}{\sum_{i=1}^{n} w_i}$$

Equation A-1: Group Criteria Scoring Equation

where n is the number of criteria in the criteria category. The overall mission feasibility score (F) indicating the relative feasibility within the range of 0 to 200, is calculated per Equation A-2.

$$F = \left(\left(\sum_{i=1}^{m} g_i \cdot S_i \right) \cdot 100 \right) - 100$$

Equation A-2: Relative Feasibility Equation

where g_i is the weight assigned to each group of criteria, S_i is the score resulting for this group and m is the number of criteria groups. It is required that the summation of the g_i equals 1.

A.2 Policy Criteria

National and international policies are an important component of the social, technical, and economic environment that determines the feasibility of space missions, including OOS. In our feasibility analysis we consider the importance of policy by evaluating potential OOS missions against four critical criteria:

- Intellectual Property and Technology Transfer;
- Liability, Insurance, and Licensing;
- Space Traffic Management and Debris; and
- Potential for Dual-Use

These criteria were selected due to their current or potential impact on public or private OOS missions. In weighting these criteria our team emphasized dual-use; technology transfer; and liability, insurance, and licensing since current policies in these areas provide significant barrier for some space applications.

A.3 Economic Criteria

In addition to technical and engineering development costs, any economic analysis will need to consider non-development costs of any OOS mission or system. This includes ground facilities, communication links, operations, insurance and other financing costs, licensing and legal/regulatory costs. While economic considerations cannot be looked at in complete isolation form technical, policy, and interdisciplinary criteria, our economic criteria categories will attempt to provide fidelity in assessing the commercial and economic rationale for OOS, whether through government funded programs, PPP, or commercial ventures serving the commercial and governmental space sectors.

The following economic indicators were considered:

- Financial and Legal Costs
- Regulatory Costs
- Insurance Costs
- Potential Market Size
- Profitability
- Timing

A.4 Technical Feasibility

The aim of this paragraph is to devise a specific method for evaluating the technical feasibility of the different OOS missions. Technical considerations are a vital part of assessing the various mission scenarios. Several technical analyses has been performed in the past beginning with comprehensive databases of satellite characteristics and studies of past satellite failures (Sullivan 2005; Sullivan and Akin 2001).

The following criteria were considered:

- Development and Operation Costs
- Schedule
- Risks
- Support Requirement
- TRL
- Technical Innovation

A.5 Interdisciplinary Criteria

Team DOCTOR organized the analysis criteria presented above into three disciplines; however, many external influences on OOS feasibility cannot be segregated into economic, technical, and policy concerns. In order to address the interdisciplinary nature of OOS mission, we created a fourth working group with four additional feasibility criteria:

- Standardization;
- Value to Civil, Military, or Commercial Customers
- Divergence of Customer Requirements; and
- Potential for Added Value.

These criteria help to integrate the disciplinary requirements for OOS missions. In order for an OOS mission to be technically, economically, and politically feasibility it will have to satisfy customer criteria in each of the disciplines and some or all of the integrated interdisciplinary criteria.

A.6 Analysis

The feasibility matrix provides a good background for a gap analysis, thus supporting the roadmap definition phase by identifying the most feasible missions for different orbits in the near-term future.

Filling out the feasibility matrix as outlined above, considering an equal weight of 0.25 for each criteria group, it turns out that technically already mature missions have the highest final scores and thus can be assumed to be viable within the next 10 years. Missions still needing technological development or having major drawbacks from policy or economic points of view have lower scores. The complete feasibility matrix is shown in Figure A-1 and the results for the different mission categories are described below.

Figure A-2 highlights the feasibility score for missions both in LEO and GEO. In many aspects these two orbits are very similar; however, there is the significant difference emerging from human related missions being restricted to LEO. Successful previous human OOS missions in LEO have increased the TRL for this type of application, at the same time lowering risk and decreasing time constraints.

The rationale for selection the ORU Exchange mission is due to the high feasibility rating for potential missions in LEO and GEO for ORU Exchange per Figure A-3. It can be shown that economic considerations have a large impact on the mission feasibility for the GEO orbit, and policy/law regarding intellectual property and technology transfer as well as liability; insurance and licensing do not pose significant resistance.

The Space Tug is a slightly more complex mission that can latch onto spacecraft, transfer the spacecraft to a desired orbit location, and return to a specified orbit location. In addition to de-orbiting missions the space tug can perform transfers of raw materials for construction and provide orbital injections for operational satellites. These mission types are interrelated with the Space Tug being the logical extension of the De-Orbiter. Moreover the space tug enables future OOS missions and other space applications. This study assessed the feasibility of a single use De-Orbiter and the Space Tug with the results shown graphically in Figure A-4.

Mission Category	Mission	Orbit	Policy Criteria					Economic Criteria							Technical Criteria							Interdisciplinary Criteria							Final Feasibility Score
			Intellectual Property & Tech Transfer	Liability, Insurance & Licensing	Space Traffic Management & Debris	Potential for Dual Use	**Policy Feasibility**	Financial & Legal Cost	Regulatory Cost	Insurance Cost	Potential Market Size	Profitability	Timing Considerations	**Economic Feasibility**	Development & Operation Cost	Schedule	Technical Risk	Current Technology Readiness Level	Technological Innovation	Support Requirements	**Technical Feasibility**	Short Term Lack of Standardization Hinders Mission	Long-Term Benefits from Standardization	Divergence of Customer Requirements	Value for Civil Use	Value for Military/Intel Use	Added Value	**Interdisciplinary Feasibility**	
		Criteria Weight >	4	4	2	5	0.25	4	4	2	5	4	2	0.25	5	3	4	5	1	3	0.25	4	4	3	5	5	4	0.25	
1. Inspection	1A. Fly-By	LEO	1	3	3	1	1.80	3	2	1	3	1	2	2.14	3	3	2	3	1	3	2.71	3	2	3	3	3	1	2.52	129.43
		MEO	1	3	3	1	1.80	3	2	1	1	1	2	1.67	3	3	2	3	1	3	2.71	3	2	3	2	3	1	2.32	112.52
		HEO	1	3	3	1	1.80	3	2	1	1	1	2	1.67	3	3	2	3	1	3	2.71	3	2	3	1	3	1	2.12	107.52
		GEO	1	3	3	1	1.80	3	1	3	3	2	3	2.43	3	3	3	3	1	3	2.90	3	2	3	3	3	1	2.52	141.33
		EXP	2	3	2	1	1.93	3	3	1	2	1	1	2.00	3	1	2	2	1	3	2.19	3	2	3	1	1	1	1.72	96.10
	1B. Proximity Ops	LEO	1	2	3	1	1.53	3	2	2	3	2	3	2.52	3	3	2	3	2	2	2.62	3	2	3	3	3	1	2.52	129.90
		MEO	1	2	3	1	1.53	3	2	2	1	1	3	1.86	3	3	2	3	1	2	2.57	3	2	3	2	3	1	2.32	107.05
		HEO	1	2	3	1	1.53	3	2	2	1	1	2	1.76	3	3	2	3	1	2	2.57	3	2	3	1	3	1	2.12	99.67
		GEO	1	2	3	1	1.53	3	1	2	3	3	3	2.52	3	3	3	3	1	2	2.76	3	2	3	3	3	1	2.52	133.48
		EXP	2	2	2	1	1.67	3	3	2	2	1	1	2.10	3	2	2	1	2	2	2.00	3	2	3	1	1	1	1.72	87.05
2. Manipulation	2A. Human Servicing	LEO	1	2	2	2	1.73	1	1	0	2	1	3	1.33	2	3	2	3	2	2	2.38	2	3	2	3	1	2	2.16	90.19
		MEO	1	1	2	2	1.47	1	1	0	1	1	1	0.90	1	1	1	1	2	1	1.05	2	2	1	2	1	3	1.84	31.48
		HEO	1	1	2	2	1.47	1	1	0	1	1	1	0.90	1	1	1	1	2	1	1.05	2	2	1	1	1	3	1.64	26.48
		GEO	1	1	2	2	1.47	1	1	0	1	1	1	0.90	1	1	1	1	2	1	1.05	2	2	1	1	1	3	1.64	26.48
		EXP	1	1	2	2	1.47	1	2	0	1	1	1	1.10	1	1	1	1	3	1	1.10	2	2	2	3	1	3	2.16	45.43
	2B. Orbit Replaceable Unit Remove & Replace	LEO	2	2	1	1	1.53	2	2	1	3	2	1	2.05	3	2	2	3	3	2	2.52	1	3	2	3	3	2	2.40	112.62
		MEO	2	2	1	1	1.53	2	2	1	1	1	1	1.38	3	2	2	2	3	2	2.29	1	3	2	3	3	3	2.56	94.00
		HEO	2	2	1	1	1.53	2	2	1	1	1	1	1.38	3	2	2	2	3	3	2.43	1	3	2	3	3	3	2.56	97.57
		GEO	2	2	1	1	1.53	2	1	3	3	3	3	2.43	3	2	2	2	3	3	2.43	1	3	2	3	3	3	2.56	123.76
		EXP	2	2	2	1	1.67	2	3	1	2	1	1	1.81	3	1	2	1	3	1	1.76	1	3	3	3	1	3	2.28	87.95
	2C. Propulsion / Guidance, Navigation, Control Extension	LEO	2	1	2	1	1.40	2	2	1	3	2	3	2.24	3	2	2	2	2	2	2.24	1	3	1	3	3	2	2.28	103.90
		MEO	2	1	2	1	1.40	2	2	1	1	1	3	1.57	3	2	2	2	2	2	2.24	1	3	2	3	3	2	2.40	90.24
		HEO	2	1	2	1	1.40	2	2	1	1	1	2	1.48	3	2	2	2	2	2	2.24	1	3	2	3	3	2	2.40	87.86
		GEO	2	1	2	1	1.40	2	1	3	3	3	3	2.43	3	2	3	2	2	2	2.43	1	3	2	3	3	2	2.40	116.43
		EXP	2	1	2	1	1.40	2	3	1	2	1	1	1.81	3	1	2	1	3	1	1.76	1	3	3	1	1	2	1.72	67.29
	2D. Refueler (One-time Use)	LEO	1	2	2	1	1.40	3	2	1	3	2	3	2.43	3	3	2	2	3	2	2.43	1	3	1	3	3	2	2.28	113.43
		MEO	1	2	2	1	1.40	3	2	1	1	1	2	1.67	3	2	2	2	3	2	2.29	1	3	2	3	3	2	2.40	93.81
		HEO	1	2	2	1	1.40	3	2	1	1	1	1	1.57	3	2	2	2	3	2	2.29	1	3	2	3	3	2	2.40	91.43
		GEO	1	2	2	1	1.40	3	2	3	3	3	3	2.81	3	2	2	2	3	2	2.29	1	3	2	3	3	2	2.40	122.38
		EXP	1	2	2	1	1.40	3	3	1	2	1	1	2.00	2	1	2	1	2	2	1.62	1	3	2	3	1	3	2.16	79.48
	2E. Refueler & Depot	LEO	1	1	2	1	1.13	3	2	1	3	3	2	2.52	1	2	2	1	3	2	1.57	1	3	1	3	3	3	2.44	91.71
		MEO	1	1	2	1	1.13	3	2	1	1	1	2	1.67	1	2	2	1	3	2	1.57	1	3	1	3	3	3	2.44	70.29
		HEO	1	2	2	1	1.40	3	2	1	1	1	1	1.57	1	2	2	1	3	2	1.57	1	3	1	3	3	3	2.44	74.57
		GEO	1	2	2	1	1.40	3	2	1	3	3	3	2.62	2	2	2	1	3	2	1.81	1	3	2	3	3	3	2.56	109.71
		EXP	1	2	2	1	1.40	3	3	1	2	2	1	2.19	1	1	2	1	3	2	1.43	1	3	2	3	1	3	2.16	79.48
	2F. Stand-Alone Fuel Depot	LEO	1	1	2	1	1.13	3	2	1	3	1	2	2.14	1	1	1	1	3	2	1.24	1	3	1	2	2	2	1.88	59.86
		MEO	1	1	2	1	1.13	3	2	1	1	1	2	1.67	1	1	1	1	3	2	1.24	1	3	1	2	2	2	1.88	47.95
		HEO	1	2	2	1	1.40	3	2	1	1	1	1	1.57	1	1	2	1	3	2	1.43	1	3	1	2	2	2	1.88	57.00
		GEO	1	2	2	1	1.40	3	2	1	3	2	3	2.43	1	1	2	1	2	2	1.38	1	3	2	2	2	2	2.00	80.24
		EXP	1	2	2	1	1.40	3	3	1	2	1	1	2.00	1	1	1	1	3	2	1.24	1	3	1	1	1	2	1.48	52.95
	2G. On-Orbit Depot with spares and tools	LEO	1	1	1	1	1.00	2	2	1	3	3	1	2.24	1	2	2	1	3	2	1.57	1	3	1	3	2	3	2.24	76.24
		MEO	1	1	1	1	1.00	2	2	1	1	1	1	1.38	1	2	2	1	3	2	1.57	1	3	1	3	2	3	2.24	54.81
		HEO	1	2	1	1	1.27	2	2	1	1	1	1	1.38	1	1	2	1	3	2	1.43	1	3	1	3	2	3	2.24	57.90
		GEO	1	2	1	1	1.27	2	1	1	3	1	2	1.76	1	2	3	1	3	2	1.76	1	3	2	3	2	3	2.36	78.76
		EXP	1	2	2	1	1.40	2	3	1	2	1	1	1.81	1	1	3	1	3	2	1.62	1	3	1	1	1	3	1.64	61.71
	2H. On-Orbit Robotics construction	LEO	1	2	1	1	1.27	2	2	1	3	1	3	2.05	2	1	2	3	3	3	2.29	2	2	1	3	2	3	2.24	96.00
		MEO	1	2	1	1	1.27	2	2	1	1	1	1	1.38	1	1	2	2	3	3	1.81	2	2	1	1	2	3	1.84	57.43
		HEO	1	2	1	1	1.27	2	2	1	1	1	1	1.38	1	1	2	2	3	2	1.67	2	2	1	1	2	3	1.84	53.86
		GEO	1	2	1	1	1.27	2	2	3	3	3	2	2.52	1	1	3	2	3	2	1.86	2	2	1	1	1	3	1.64	82.19
		EXP	1	2	2	1	1.40	2	3	1	2	1	1	1.81	1	1	2	1	3	2	1.43	2	2	1	3	1	3	2.04	66.95
	2I. On-Orbit Human construction	LEO	1	1	1	2	1.33	1	1	0	3	1	3	1.57	2	3	2	3	2	1	2.24	2	3	2	3	1	3	2.32	86.57
		MEO	1	1	1	2	1.33	1	1	0	1	1	1	0.90	1	2	1	1	2	1	1.19	2	2	1	1	1	3	1.64	26.71
		HEO	1	1	1	2	1.33	1	1	0	1	1	1	0.90	1	2	1	1	2	1	1.19	2	2	1	1	1	3	1.64	26.71
		GEO	1	1	1	2	1.33	1	1	0	1	1	1	0.90	1	2	1	1	2	1	1.19	2	2	1	1	1	3	1.64	26.71
		EXP	1	1	2	2	1.47	1	2	0	1	1	1	1.10	1	2	1	1	3	1	1.24	2	2	2	3	1	3	2.16	49.00
3. Maneuvering	3A. De-Orbiter (One-time Use)	LEO	2	1	3	1	1.53	3	2	1	3	2	2	2.33	3	3	3	2	2	2	2.57	2	3	2	3	3	2	2.56	124.95
		MEO	2	1	3	1	1.53	3	2	2	1	1	2	1.76	1	2	3	2	2	2	1.95	2	3	2	3	3	2	2.56	95.19
		HEO	2	2	3	1	1.80	3	2	2	1	1	2	1.76	1	2	3	2	2	2	1.95	2	3	2	3	3	2	2.56	101.86
		GEO	2	2	3	1	1.80	3	1	3	3	3	3	2.62	3	3	3	2	2	3	2.71	2	3	3	3	3	2	2.68	145.33
		EXP					0.00							0.00							0.00							0.00	0.00
	3B. Re-Orbiter (Multiple Use)/Space Tug	LEO	2	2	3	1	1.80	2	2	2	3	1	2	2.05	2	1	2	2	2	2	1.86	1	3	1	3	3	3	2.44	103.62
		MEO	2	2	3	1	1.80	2	2	2	1	1	2	1.57	1	2	2	2	2	2	1.76	1	3	1	3	3	3	2.44	89.33
		HEO	2	2	3	1	1.80	2	2	2	1	1	2	1.57	1	2	2	2	2	2	1.76	1	3	1	3	3	3	2.44	89.33
		GEO	2	2	3	1	1.80	2	1	1	3	3	3	2.24	2	2	2	2	2	3	2.14	1	3	2	3	3	3	2.56	118.52
		EXP	2	2	2	1	1.67	2	3	1	2	1	1	1.81	2	1	2	1	3	2	1.67	1	3	1	3	3	3	2.44	89.57
	3C. Human Capture & Return	LEO	2	1	2	2	1.73	1	1	0	1	1	3	1.10	2	1	1	3	1	2	1.86	2	3	2	3	1	3	2.32	75.14
		MEO	2	1	2	2	1.73	1	1	0	1	1	1	0.90	1	1	1	1	2	1	1.05	2	3	1	1	1	3	1.80	37.14
		HEO	2	1	2	2	1.73	1	1	0	1	1	1	0.90	1	1	1	1	2	1	1.05	2	3	1	1	1	3	1.80	37.14
		GEO	2	1	2	2	1.73	1	1	0	1	1	1	0.90	1	1	1	1	3	1	1.10	2	3	1	1	1	3	1.80	38.33
		EXP	2	1	2	2	1.73	1	1	0	1	1	1	0.90	1	1	1	1	3	1	1.10	2	3	2	2	1	3	2.12	46.33

Figure A-1: Feasibility matrix

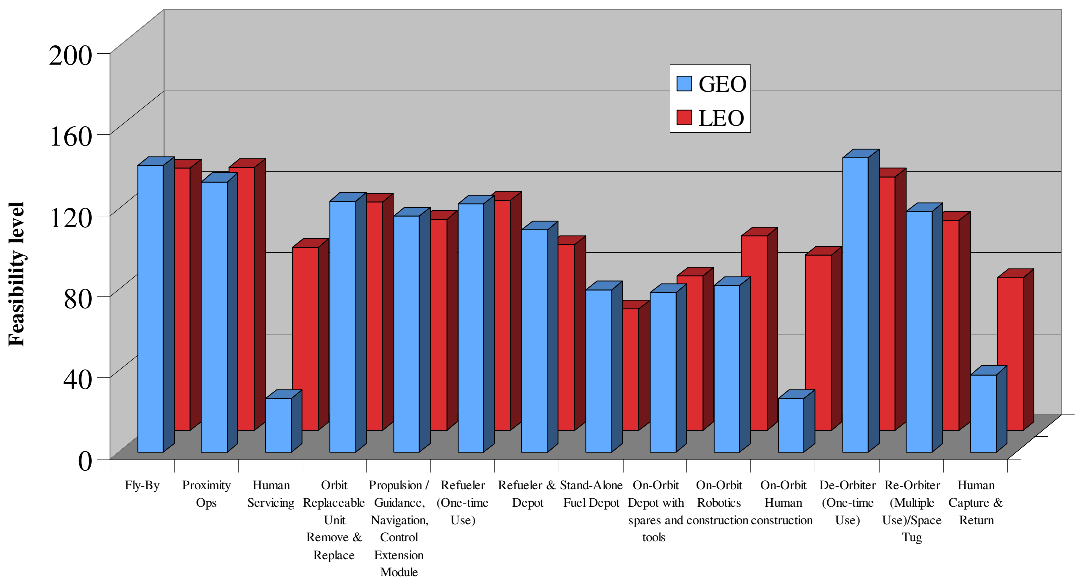

Figure A-2: Feasibility Scores for the Servicing Missions in GEO and LEO.

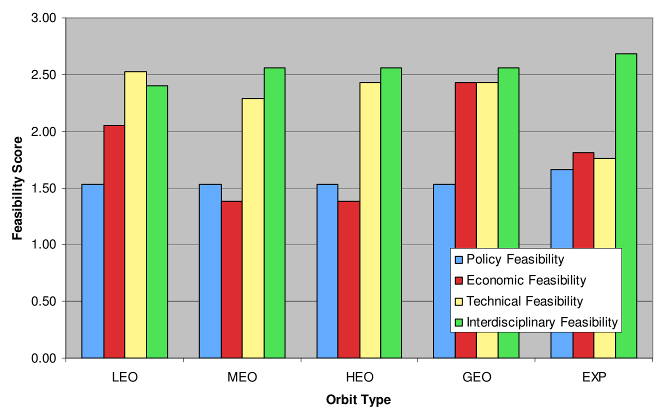

Figure A-3: Near-term Feasibility Rating for ORU Exchange for Various Orbit Types

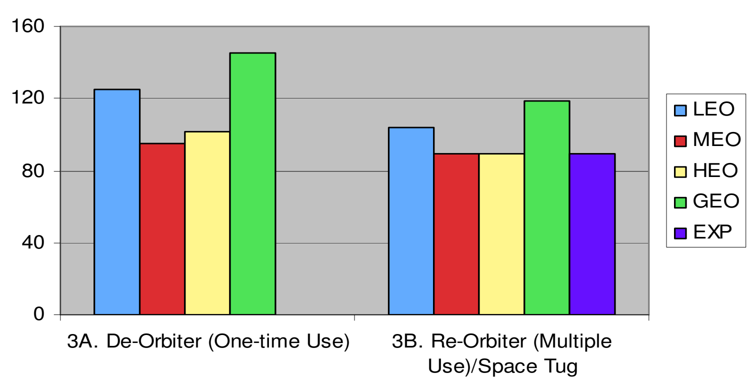

Figure A-4: Feasibility of the Space Tug and De-orbiter

A.7 Matrix Sensitivity

As outlined above, the feasibility matrix can be used in different ways to look through different lenses at the feasibility of OOS missions. One possibility is to fill out the matrix for different time frames, e.g. to compare near-, mid- and far-term considerations. Figure A-5 shows a possible change in the weights for different criteria for different time frames.

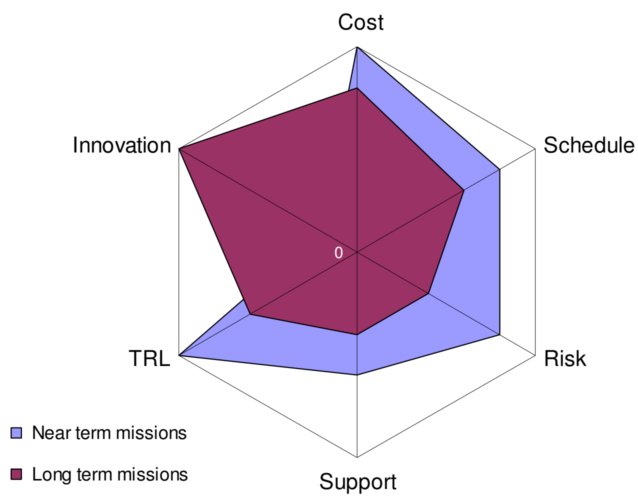

Figure A-5: Weighted Criteria for Near and Long Term Mission

Another way of working with the matrix is to use it for different view points, such as an economic perspective, excluding policy and technical considerations. A third possibility is an analysis from the perspective of different organizations. As an example, we tried to adjust the weights and scores for four different scenarios: civil, military, commercial and academic applications. The results of this analysis for three selected missions are shown in Figure A-6. It depicts the deviation of the feasibility scores from the general near-term analysis in Figure A-3. The chart clearly shows that for example human servicing is not viable at all from a commercial perspective, whereas refueling missions would be highly interesting from this point of view. On the other hand, looking at the missions from a civil standpoint, human servicing turns out to be more feasible than refueling missions.

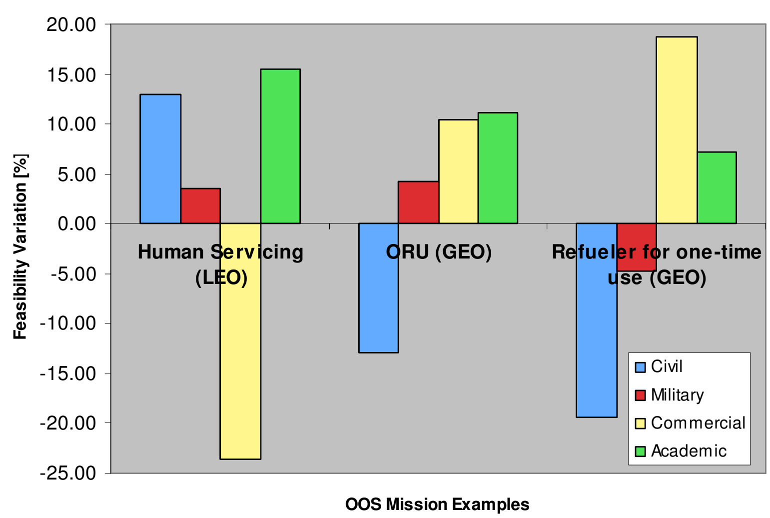

Figure A-6: Analysis Results for Selected Missions