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**COMMERCIAL GEOSYNCHRONOUS SATELLITE  
SERVICING**

by

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**COMMERCIAL GEOSYNCHRONOUS SATELLITE SERVICING**

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Submitted in partial fulfillment of the  
requirements for the degree of

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## **ABSTRACT**

On-orbit servicing (OOS) of satellites has been a significant goal since the early 1980s. Once considered feasible for satellites operating in low earth orbit (LEO) when the space shuttle program was operational, providing OOS for satellites operating in geostationary orbit (GEO) always has been beyond reach. The advancement of robotics and artificial intelligence (AI) has finally opened up the possibility of OOS for all orbital regimes. The aim of this thesis is to investigate what has been already proposed for OOS, identify the initial satellite subsystems that could benefit from OOS missions, and determine whether or not OOS can be made to be cost effective. By tracking and categorizing on-orbit satellite failures, a pattern begins to emerge about which subsystems are more likely to fail on orbit. From there, subsystem hardware components can be identified for potential replacement on legacy satellites and for design modification. Proving the ability to service legacy satellites will pave the future of satellite design and capability. Ideally, as the technology progresses, all satellites will move to a more modular design thus saving money and materials. By using current models and cost analysis, the feasibility of OOS can be demonstrated.

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## LIST OF ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control System
ADCS	Attitude Determination and Control System
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
AOCS	Attitude and Orbit Control System
AL	Actual Life
BOL	Beginning of Life
CAD	Computer-Aided Design
C&DH	Command and Data Handling
CMG	Control Moment Gyros
CER	Cost Estimating Relationship
CONFERS	Consortium for Executions of Rendezvous and Servicing
COSTAR	Corrective Optics Space Telescope Axial Replacement
CPF	Cost-per-function
CSA	Canadian Space Agency
DARPA	Defense Advanced Research Projects Agency
DL	Design Life
D/L	Downlink
DOD	Department of Defense
EO	Electro-Optical
EOL	End of Life
EPS	Electrical Power System
FDV	Fill and drain valve
FREND	Front-end Robotics Enabling Near-term Demonstration
GEO	Geostationary Orbit
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
HST	Hubble Space Telescope
ID	Inner Diameter
IR	Infrared

IRR	Internal Rate of Return
IRU	Inertial Reference Unit
ISS	International Space Station
LED	Light-emitting diode
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
MEO	Medium Earth Orbit
MEV	Mission Extension Vehicle
MRT	Marman Ring Tool
NASA	National Aeronautics and Space Administration
OD	Outer Diameter
OOS	On-Orbit Servicing
ORU	Orbital Replacement Unit
POD	Payload Orbital Delivery
R/D	Rendezvous and Delivery Vehicle
RF	Radio Frequency
RPO	Rendezvous and Proximity Operations
RSO	Resident Space Object
RSGS	Robotic Servicing of Geosynchronous Satellites
RSV	Robotic Servicing Vehicle
SA	Solar Array
SC	Spacecraft
SSMIS	Special Sensor Microwave Imager Sounder
TDM	Technology Demonstration Missions
TECH DEMO	Technology Demonstration
TT&C	Telemetry, Tracking, and Command
TTO	Tactical Technology Office
US	United States of America

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## I. INTRODUCTION

In the United States, the satellite industry has an estimated value in the billions of dollars. In 2016, the U.S. space economy had an estimated value of \$158 billion with the majority of profits in satellite communications, specifically satellite services and manufacturing [1]. In 2018, the global space industry was reported to be worth \$414.8 billion with commercial entities representing 79% of the profits [1]. As demand for space-based technology and services continues to increase annually, the global space industry is expected to grow in the construction, information, and government sectors. As defined by the Bureau of Economic Analysis, the space economy covers “the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilizing space” [1]. The space industry is defined as the “economic activities related to the manufacture and delivery of components that go to Earth’s orbit or beyond” [1].

While the global space industry continues to expand, the possibility of unexpected satellite failure continues to be a concern. It is a well-documented fact pertaining to different satellite missions that Tech Demonstration platforms are reported to have the highest possibility of suffering catastrophic failures, followed by remote sensing and communications satellites. In contrast, navigation satellites retain the highest rate of success due to having the highest “repeat-in-series” numbers [2]. Satellite failure can be caused by any number of issues, ranging from a single subsystem failure that cascades into a mission critical failure to complete irreversible satellite damage. A failure is defined as “an incident that could lead to permanent or temporary mission degradation” [3]. A mission critical failure is when a “premature loss of a satellite or loss of its ability to perform its primary mission” before its designated end of life [4].

When serious satellite damage or failure occurs, related costs can be significant for satellite development companies and the insurance companies. Not only is the initial cost of satellite construction lost, but any future profits are now null and void. The most recent example was the damage of Intelsat 29e, causing a loss of onboard propellant, and resulting in a total loss of the satellite [5]. A total loss is when a satellite fails in a way that prevents

it from performing the mission or causes it to be “taken out of service due to an anomaly” [4]. The Intelsat 29e construction cost was estimated at between \$400 and \$450 million, and this satellite had an expected 15-year operation span [5]. While this initial loss is still below Intelsat 2019 second quarter earnings (\$509.4 million), over its 15-year economic lifespan, Intelsat 29e would have earned a projected profit estimated at \$3 billion [6].

While major corporations such as Intelsat can occasionally afford to absorb losses of this magnitude, smaller corporations or government programs have limited capacity to do so. This high failure cost is a considerable barrier for any small space program. Although insurance companies can help mitigate the price of failure, other options could become available to help companies reduce catastrophic losses and satellite failure.

The new and emerging capability of refueling satellites on-orbit begs the question, what other activities could be conducted on-orbit? This study considers the feasibility of on-orbit servicing, repair, and upgrade possibilities for satellites currently located in geostationary orbit (GEO) to possibly provide scheduled maintenance, reduce costs, and insure against risk of failure.

## **A. BACKGROUND**

What is on-orbit servicing? On-orbit servicing (OOS) refers to any activity conducted in space by a space vehicle on a cooperative client satellite. These activities can vary widely depending on the service being offered. Some services that potentially could be offered, as defined by the Consortium for Executions of Rendezvous and Servicing (CONFERS), are inspection, capture, docking, berthing, relocation, refueling, life extension, combined stack control, repair, upgrade, assembly, undocking, unberthing, release, and departure [7]. While this newly emerging space activity is largely unregulated, CONFERS, the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), and the American Institute of Aeronautics and Astronautics (AIAA) are working to create guiding principles [8].

Current guiding principles for OOS have the space vehicle providing the servicing operation designated as the servicer and the space vehicle receiving the service as the client satellite [7]. Going forward, commercial OOS will be conducted between two consenting

parties in a responsible and transparent manner to promote trust and confidence in the servicer.

There are two types of clients currently defined in OOS operations: cooperative and non-cooperative clients. A cooperative client is defined as a fully functional satellite that can place itself into a mutually beneficial orbit for both the client and servicer [7]. A cooperative client can aid the servicer in its attempts to rendezvous with the client. For example, a cooperative client can maneuver their satellite into a more favorable orbit to receive the servicer. A non-cooperative client is a satellite that for either known or unknown reasons cannot control its flight or cooperate with the servicer in any way [8]. Most legacy satellites are designated as non-cooperative, since most satellites are not yet built upon specifications to readily receive servicers. As the capability to service satellites improves, it is possible to look to future designs with built in features to receive servicer satellites.

## **B. HISTORY OF ON-ORBIT SERVICING**

The concept and design of on-orbit servicing is not new. Since the beginning of mankind's first substantial foray into space, the concept of being able to fix, correct, or update space objects has been thoroughly discussed. Historically, the majority of these studies were focused on the International Space Station (ISS) and the space shuttle as potential platforms through which to conduct the servicing [9]. Before the prevalence of advanced robotics, any servicing missions, such as the Palapa B2 and Westar 6 salvage missions in 1984, and the numerous Hubble servicing missions from 1993 to 2009, were done by astronauts [10]. With the loss of the space shuttle program, however, it seemed that the ability to conduct on-orbit servicing too would be lost. However, with the new advancements in robotics and artificial intelligence (AI), OOS has become plausible allowing for corrections of satellite failures, or extending satellite services while on-orbit.

### **C. CURRENT ON-ORBIT SERVICING PROJECTS**

Before April 2, 2020, OOS was still a technological concept. Northrup Grumman's Mission Extension Vehicle (MEV) has now proven that it is a possibility. The MEV-1 is designed to perform rendezvous and proximity operations (RPO) with the client satellite and provide propulsion and attitude control to extend service life [11]. As of February 25, 2020, MEV-1 had docked with Intelsat IS-901 and proceeded to provide services. By April 2, 2020, Intelsat's IS-901 was returned to active duty [12]. MEV-1 demonstrated that OOS can provide life extension to defunct satellites. MEV-1 will provide an extra five years of propulsion and attitude control to IS-901 [13]. This event is just the tip of the iceberg for all the future possibilities OOS missions can provide.

### **D. PROBLEM DEFINITION**

As Northrup Grumman has now demonstrated, it is possible to conduct safe RPO with legacy satellites in order to provide life extensions services on-orbit. It bears further investigation into this new satellite mission area to further explore the potential capabilities of OOS missions.

This thesis will examine the different services that OOS spacecraft can provide at GEO. It will delve into the feasibility of developing an open standard that will enable commercial satellite developers to benefit from on-orbit servicing capabilities. The focus will be on identifying high failure components in each subsystem, ease of on-orbit replacement, and potential standardization of each subsystem. The goal will be to first identify the most profitable subsystems for OOS and how to start implementing modular design into those subsystems. The focus will be on current satellites in geosynchronous (GEO) orbit, how these legacy satellites can be serviced, while investigating which components across all platforms could be initially serviced and what needs to be changed to a modular design as an industry standard.

## II. IDENTIFICATION OF HIGH FAILURE COMPONENTS IN GEO SATELLITES

### A. INTRODUCTION

Since the early 2000s, several studies have been undertaken to study on-orbit satellite failures in order to identify and quantify different reasons behind satellite failure. Identifying when satellites fail and what components have failed can build the basis to start incorporating design modularity and on-orbit serving capabilities. In this chapter, several studies have been incorporated to gain an overarching view on which components have the highest failure rates and the level to which these failures contribute to total mission loss. These data have been broken down and arranged into the major satellite subsystems to highlight which subsystems would benefit the most from an on-orbit replacement capability.

By analyzing satellite failure data from 1980 to 2018, the majority of satellite failures can be attributed to either electrical or mechanical failure. As seen in Figure 1, 45% of all satellite failures were electrical in nature, while 32% were mechanical failures [3]. Combined, these two factors make up more than 75% of all satellite failures.

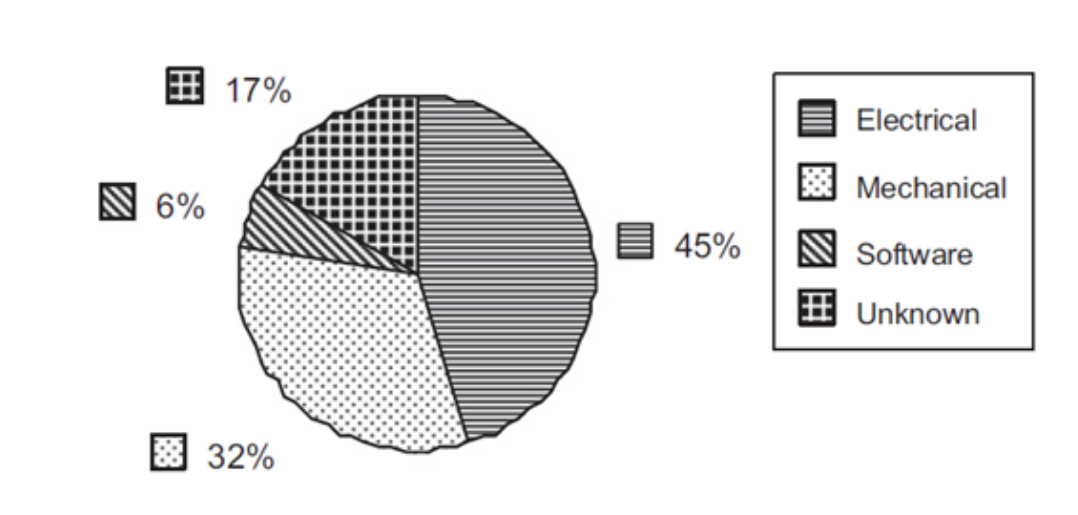
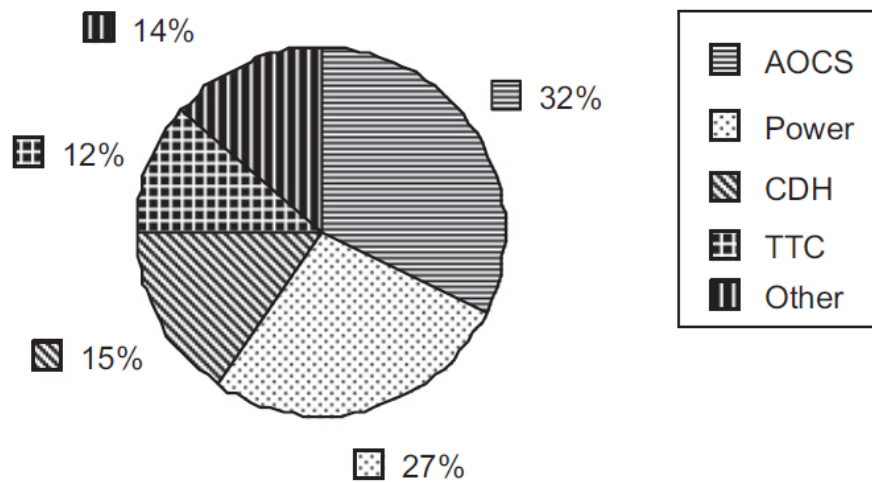


Figure 1. Spacecraft Failure Type. Source: [3].

Satellite failures were further broken down into which subsystems experienced the most failures. As seen in Figure 2, Attitude and Orbital Control System (AOCS) and Power accounted for more than half of the anomalies in a study done by the Canadian Space Agency (CSA) [3]. While it would seem that the AOCS failures would account for the high percentage of electrical failures in Figure 1, the majority of AOCS failure are mechanical [3]. The Power subsystems conversely, suffers more from electrical failures than mechanical failures due to the nature of its hardware composition. The exception is the solar array (SA) failures as seen in Figure 3, which are a combination of mechanical and electrical faults [3].



Study done from 1980 to 2005 identified 156 satellite failures on 129 civilian and military spacecraft.

Figure 2. Spacecraft Subsystems Affected. Source: [3].

Further reduction is necessary to identify the particular components in each subsystem that failed. Figure 3 illustrates the distribution of satellite component failures. Solar arrays, batteries, the power bus, and power circuitry all fall under the Power subsystem [3]. The AOCS counts the control motion gyroscopes (CMG), control processor, GPS, gyroscopes, reaction wheels, momentum wheel, thrusters, and tracking instruments as part of its hardware components [3].

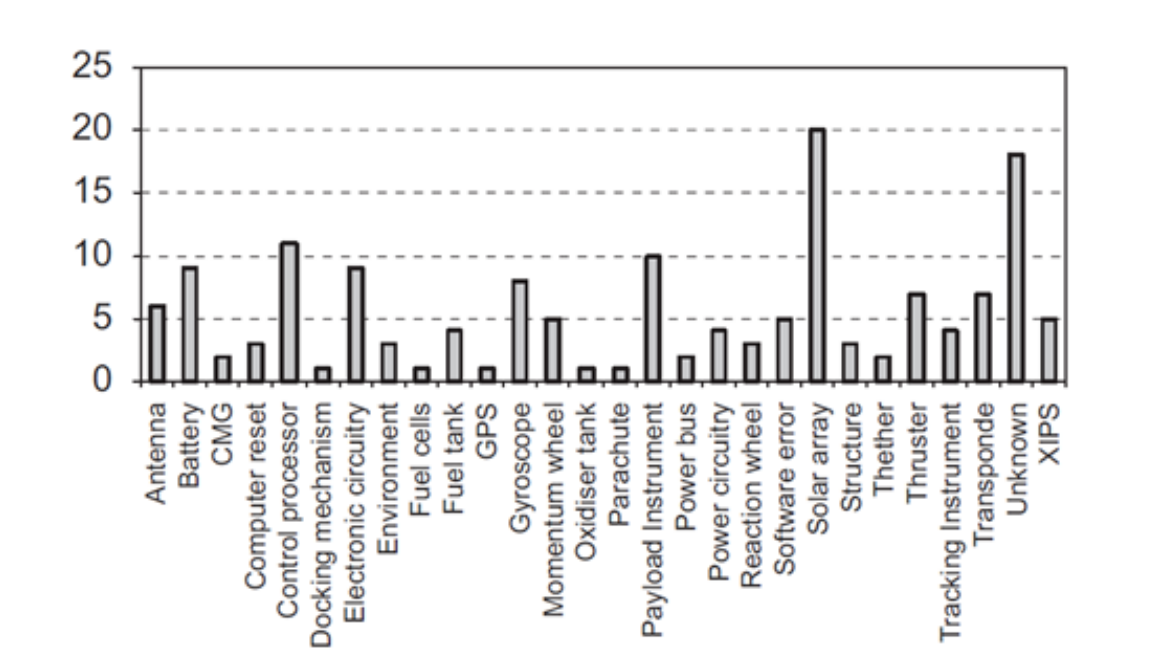


Figure 3. Spacecraft Component Failures: Source: [3].

Additional analysis of satellite failures over time indicates that 40% of all failures were considered a total loss and 65% of all failures caused significant mission degradations [3]. By considering all the different subsystems and the common failures associated with their respective hardware components, determinations can be made about which subsystems and components could benefit from OOS capabilities.

## B. TELEMETRY, TRACKING, AND COMMAND (TT&C) SYSTEM FAILURE ANALYSIS

The telemetry, tracking, and command (TT&C) subsystem is responsible for communication and radiometric tracking between the satellite and its respective ground stations [4]. Radiometric tracking uses the Doppler shift and ranging signal in a spacecraft (SC) downlink signal to measure the SC earth-relative velocity and distance to calculate the SC position relative to the Earth [4]. The TT&C subsystem allows the SC to receive commands from the ground station via its uplink radio signal and send telemetry and

mission data to the ground station via its downlink radio signal. Hardware components included in the TT&C subsystem are antennas, transponders/transceivers, power amplifiers, radio frequency (RF) network, and wideband transmitters [4].

The TT&C subsystem sees the smallest percentage of failures. As seen in Figure 2, only 12% of all satellite breakdowns fall into this category [3]. This small percentage is most likely due to the robust nature of this system and built in redundancies. The majority of failures in this category caused temporary mission degradation as opposed to mission failure [3]. The industry standard is to also have an “emergency mode recovery” where at least two antennas are designed to be always pointing at the ground station in-case of communication anomalies, thus allowing the ground station to maintain constant communication with the SC to troubleshoot any anomaly [4]. These low failure rates speak to the success of the redundancies present in this subsystem. The largest percentage of failures that do occur are attributed to electrical component failure, any software failures have been attributed to human error [1].

### **C. COMMAND AND DATA HANDLING (C&DH) SYSTEM FAILURE ANALYSIS**

The command and data handling (C&DH) subsystem is responsible for the on-board data processing for the SC. This subsystem incorporates the central processors, system management software, control system software, payload management software, and fault detection software [4].

The C&DH subsystem sees about 15% of all satellite failures, as depicted in Figure 2. While the percentage of system anomalies due to a C&DH failure are low, it can have devastating effects on the satellites mission capability and completion. Approximately 56% of all CDH anomalies lead to a total satellite loss. This can happen due a failure in the primary processor, in the electrical connection between the two processors, or a cascading failure in both the primary and secondary processor [3]. Since most satellites have primary and secondary processors designed to high software and hardware standards, the failure rate trends on the lower side.

#### D. STRUCTURES AND MECHANISMS SYSTEM FAILURE ANALYSIS

The structures and mechanisms subsystem consists of the physical SC structure, thermal protection, docking mechanism, and tether [4]. The CSA study included the payload instrument within this section; however, for this study, it will be broken out into the next section, II.E, due to the large percentage of failures in that category.

As seen in Figure 4, most of the satellite failures for this subsystem are caused by an anomaly with the payload instrument. The majority of failures in this category occur within the first year of operation and are of a mechanical nature; the rest of the anomalies are attributed to the space environment [3]. The CSA's study concluded that when the structural and mechanical subsystem suffered an anomaly, approximately 75% of the time it leads to mission failure [3].

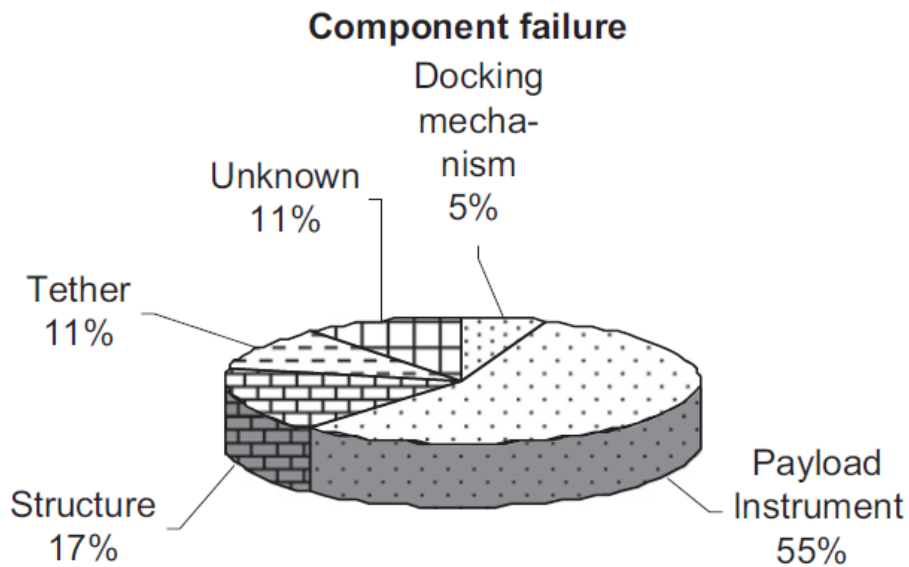


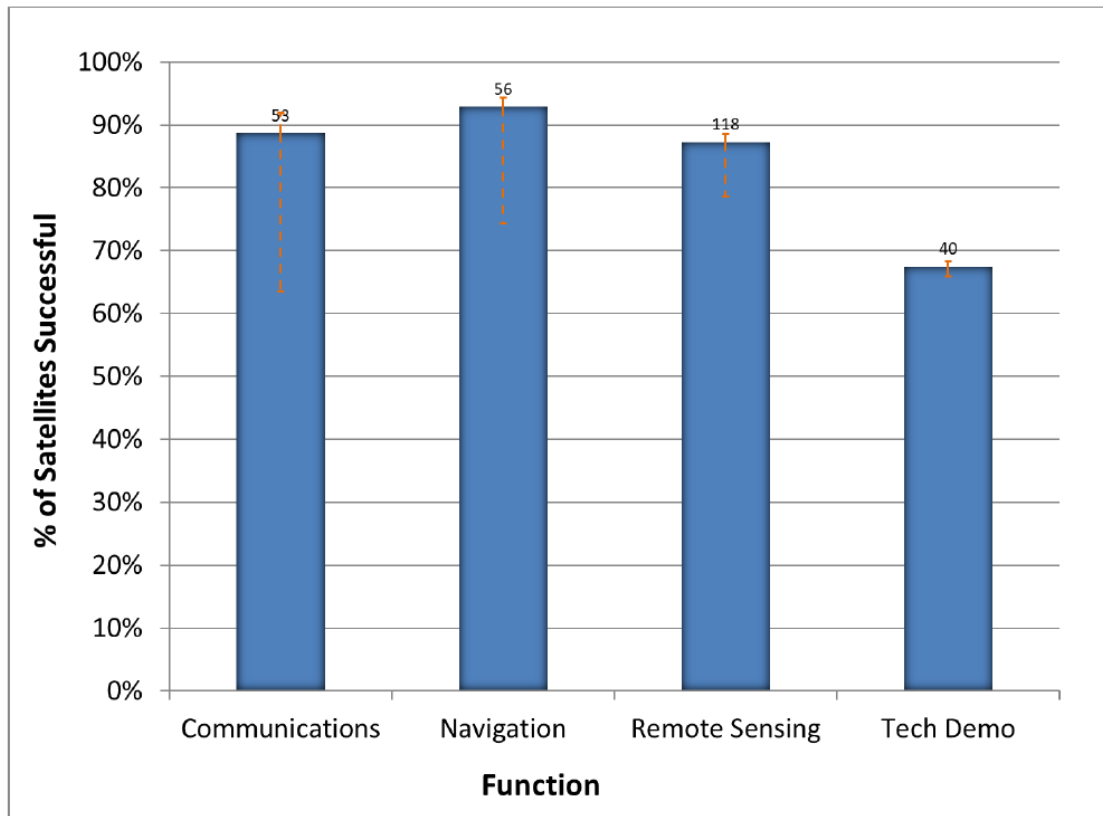
Figure 4. Failure Impact and Mechanical Component Failure: Source: [3].

#### E. PAYLOAD SYSTEM FAILURE ANALYSIS

While some satellite payloads are developed in limited numbers, other payloads are allocated as a part of a larger series. Navigation and communications satellites are often

built to be a part of large, global constellations. This is necessary to maintain global coverage as well as reducing the production cost of a single satellite.

Navigation and communication missions see the most robust payloads, due to the high series number produced for each constellation, reducing the potential for parts failure [14]. As seen in Figure 5, technological demonstration satellites have the lowest success rate simply due to the fact that they are often demonstrating unproven technology.



This graphic only depicts satellite data from 1980 to Dec 31, 2018, unclassified data only from only U.S. military and civilian satellites in GEO.

Figure 5. Rate of Satellite Success by Payload Type: Source: [14].

While not all payload types could benefit from on-orbit servicing capabilities, there is potential for satellites in large series to benefit from on-orbit servicing.

## **1. Communications Payloads**

Communications payloads at GEO allow for continuous coverage over a fixed region on earth. Depending on the company and the demand for service they are trying to fill a communication constellation can contain anywhere from 3 to 30+ satellites as seen in the Eutelsat constellation [15]. Standard to a communication mission is the antenna package tailored to the specific frequencies used by that satellite. Any type of servicing done on a communication payload would have to take into account the specific antenna design.

## **2. Remote Sensing Payloads**

Remote sensing payloads can be divided into two main categories based on how they are receiving and interpreting data. The first category being passive collection, where the SC collects the emissions it can pick up passively with its own sensors and does not rely on any active emissions by the SC instruments. If the SC instrument is measuring direct or reflected radiation it is considered a passive sensor [4]. Passive collection can be done by collecting solar reflectance, microwave radiation, X-ray radiation and gamma-ray radiation [4]. Examples of passive payloads are GeoEye and DigitalGlobe observation satellites or the U.S. DOD Special Sensor Microwave Imager Sounder (SSMIS) [4].

The second category is active collection, where the SC uses its own energy output to collect data like radar or LIDAR [4]. Active collections can be done with radar, LIDAR, scatterometer, laser altimeter, or sounder [16]. Examples of active sensor payloads are DLR's TerraSAR-x or the Global Ecosystem Dynamics Investigation (GEDI) on the ISS [16].

The precise calibration and instrument sensitivity required for each sensor on an observational payload makes it a difficult candidate for on-orbit repair. However, these satellites could potentially benefit from receiving on-orbit upgrades

## **3. Technology Demonstration Payloads**

Technology Demonstration Missions (TDM) due to the nature of their mission are not planned for an extended design life (DL). The average DL for a tech demo satellite is

approximately 1–2 years. As seen in Figure 6, since 1980 the DL for TDM satellites has remained constant and as such does not make it a good candidate for an OOS mission.

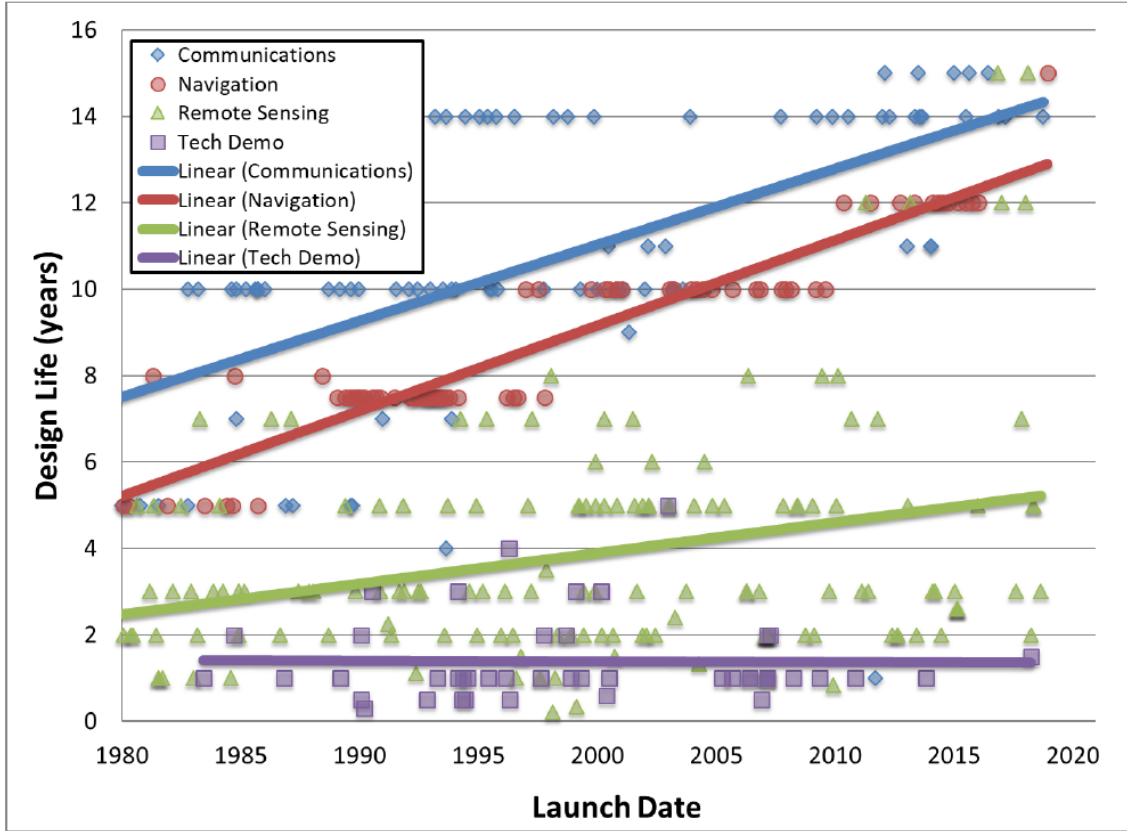


Figure 6. Design Life by Function: Source: [2].

## F. POWER SYSTEM FAILURE ANALYSIS

The Electrical Power System (EPS) provides, stores, regulates and distributes power to all other subsystems on the SC, without the EPS nothing will function [4]. For GEO satellites the power system accounts for roughly one-third of the entire spacecraft dry mass [4]. This subsystem is made up of four basic EPS groups; energy storage, power regulation and control, power distribution, and the power source [4]. Energy storage hardware is primarily composed of batteries, super-capacitors, fuel cells, and flywheels [4]. Standard aerospace batteries types and designations are shown in Figure 7.

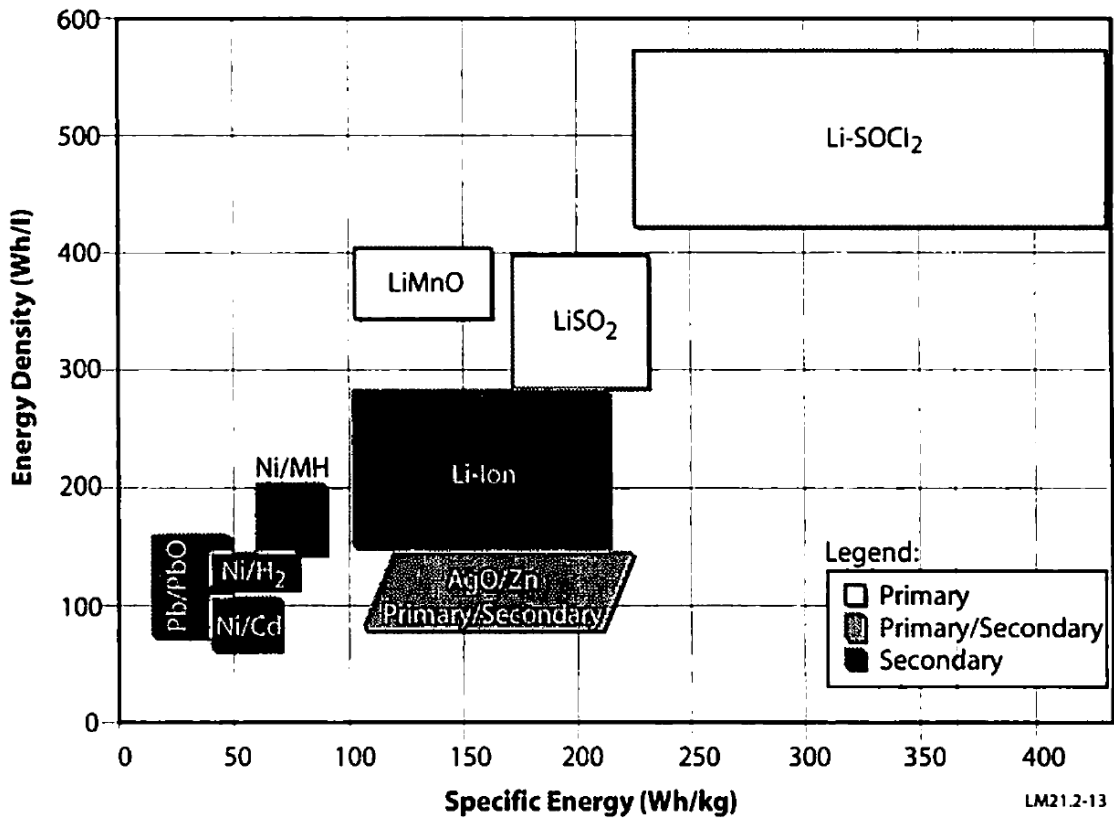


Figure 7. Aerospace Battery Types: Source: [4].

Power regulation and control are required to maintain a steady flow of power to each subsystem without allowing for an overcharge or negative current flow. The most common power source for satellites is solar photovoltaics, which are traditionally arranged on a panel and built into arrays. The size and shape of the array depends on the power requirement for each satellite mission.

From 1980 to 2019, EPS failures accounted for at least 80 documented satellite anomalies [2], [11]. As seen in Figure 2, from 1980 to 2005 approximately 34 satellites suffered from a significant EPS anomaly. The majority of the EPS failures were due to electrical malfunction (67%), and occurred during the first year of operation, 45% of all failures were critical to the satellite resulting in a loss of mission [1]. The majority of these failures can be attributed to solar array failures.

Further breaking the EPS down into its component parts from Figure 8, solar arrays (SA) account for 49% of all power systems failures, followed by battery failures constituting 22%, making both an ideal candidate to receive OOS.

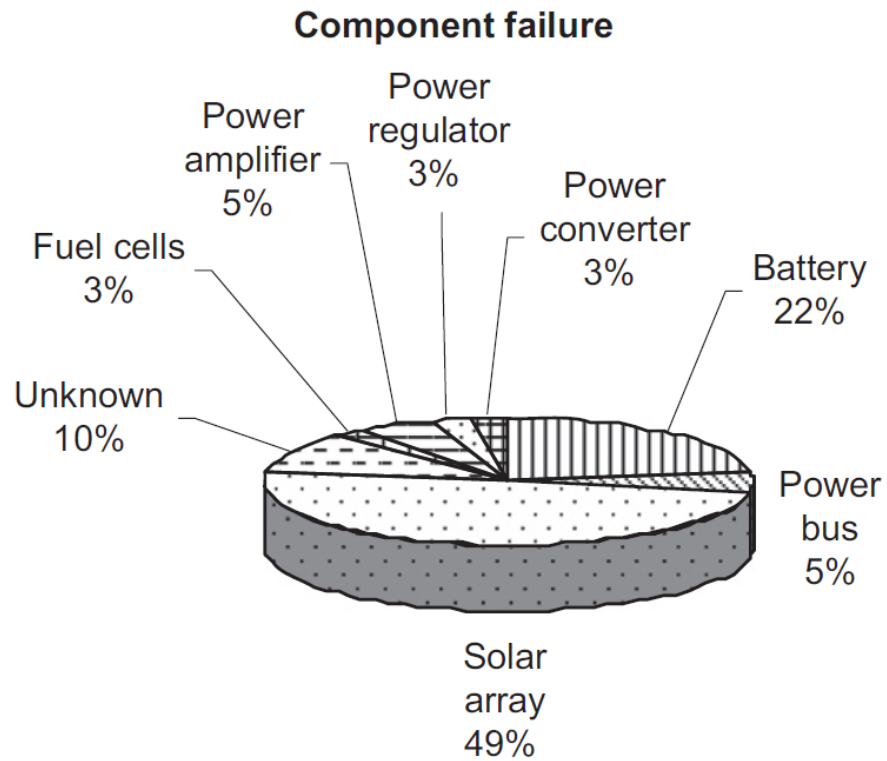


Figure 8. Failure Impact and Component Failure for Power Subsystem: Source: [3].

A more recent study, conducted from 2000 to 2019, on Axa XL insured satellites at GEO indicates at least 41 satellites were lost due to EPS failures [17]. Similar to the previous study solar arrays account for the majority of the anomalies. Figure 9 shows the accumulation of data from the AXA XL insurance study.

## Causes of Losses

GEO satellites launched since 2000

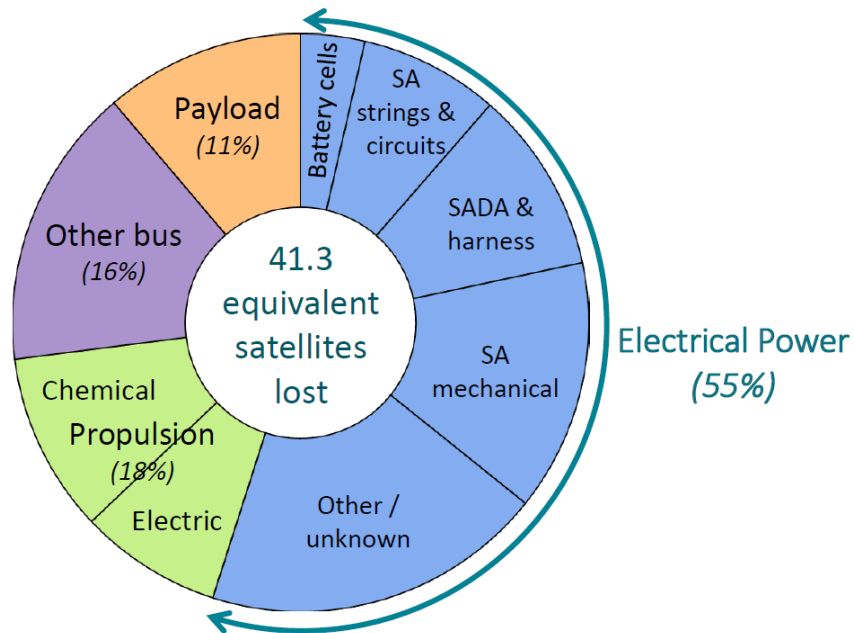


Figure 9. Satellite Failures from 2000 to 2019 at GEO: Source: [17].

A solar array can fail for numerous reasons. It can fail to deploy properly, in which case it can be counted as a SA mechanical failure, or due to the space environment it can experience arcing causing short-circuiting [3]. Solar arrays are also extremely prone to failure within the first year of life, 55% of SA failures will happen during the first year of life, generally during flight check-out [3]. The large failure rate experience by both SA and batteries make both good candidates to examine further for OOS possibilities. Also, over time the solar arrays will decrease in efficiency due to darkening caused by the space environment, which makes this system a potential candidate for a midlife servicing mission.

### G. CONTROL SYSTEMS FAILURE ANALYSIS

The attitude and orbit control system (AOCS) is broken down into two subsystems; “the attitude determination and control system (ADCS) and the guidance, navigation, and control (GN&C)” [3]. The ADCS stabilizes the SC and corrects the orientation to the

correct attitude per the mission requirements [3]. The GN&C system determines the satellites position and velocity. The AOCS is made up of actuators and sensors that are used by both subsystems. Actuators are used to maintain orbit and provide mission necessary attitude adjustments. Actuators can be any combination of reaction wheels, momentum wheels, control moment gyros (CMG), magnetic torquers, and thrusters [4]. Sensors are used for calculating SC attitude and position, and can be any combination of sun sensors, gyroscopes, star sensors, horizon sensors, magnetometer, and GPS receivers [4] .

The AOCS carries the brunt of satellite failures on-orbit. These failures account for 32% of all system failures, as shown in Figure 10. Breaking the AOCS into different failure categories, in Figure 10, 54% of AOCS failures are mechanical, 20% are related to an electrical failure, an additional 20% are seen due to a software failure, and the last 6% are due to an unknown failure [1]. Mechanical components consist of the CMG, momentum wheels, gyroscopes, reaction wheels, and thrusters.

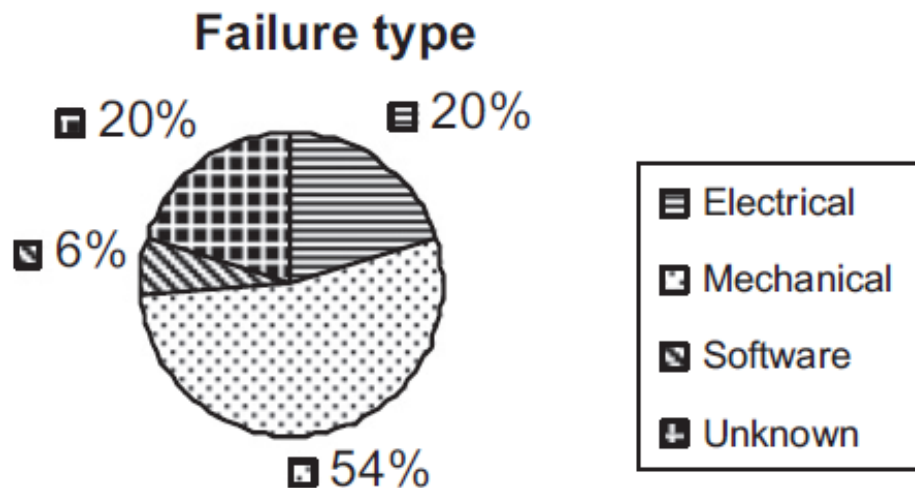


Figure 10. AOCS Failure Type: Source: [3].

Further analysis of specific component failure identifies gyroscopes, momentum wheels, and thrusters as the main culprits of a majority of AOCS failures (Figure 11).

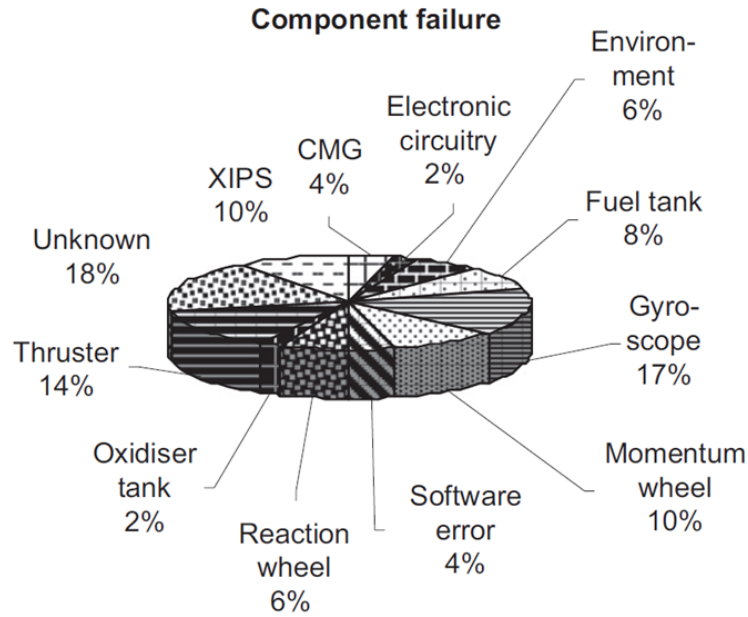


Figure 11. Failure Impact and Component Failure for AOCS: Source: [3].

In a study done by the NASA Goddard Space Flight Center from 1990–2001 into strictly guidance, navigation and control system failures, the leading causes of failure in GN&C were attributed to hardware and design problems. As seen in Figure 12, hardware failures were the cause of 45% of all GN&C failures in satellites [18].

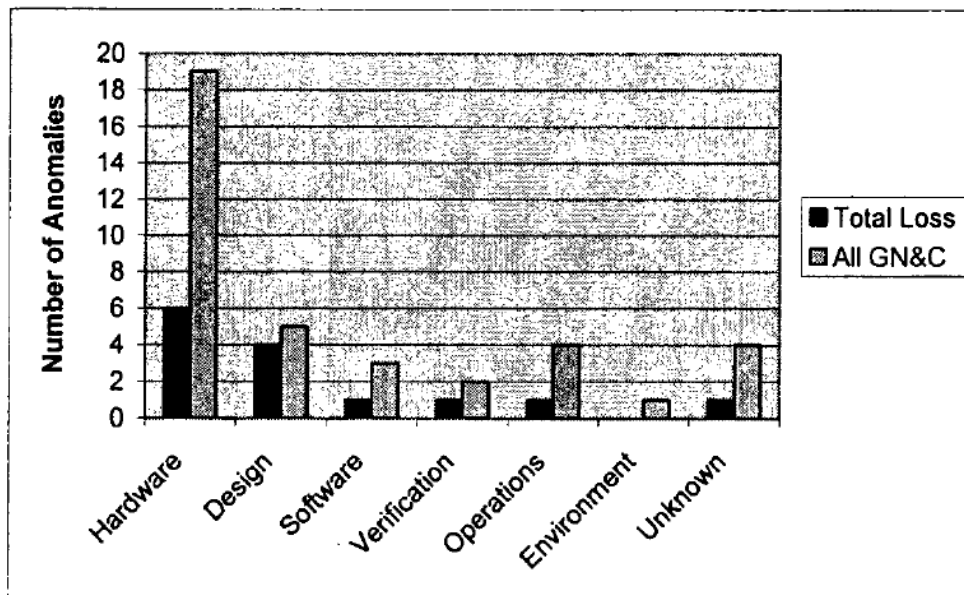


Figure 12. GN&C Anomalies vs. Cause Category: Source: [18].

The study goes on to conclude in Figure 13, which hardware has historically caused the most failures in the GN&C. Reaction wheels hold the leading cause of failures in GN&C hardware followed by pyrovalves [18]. Reaction wheel failure can be caused by a myriad of reasons; however, the leading cause is due to fatigue or overstress of said wheels. With the proper adjustments to satellite construction it may be possible for these high failure rate items to be replaced. Pyrovalves failures, due to their single use design are most commonly either due to a firing caused by human error or a pre-existing design flaw [19].

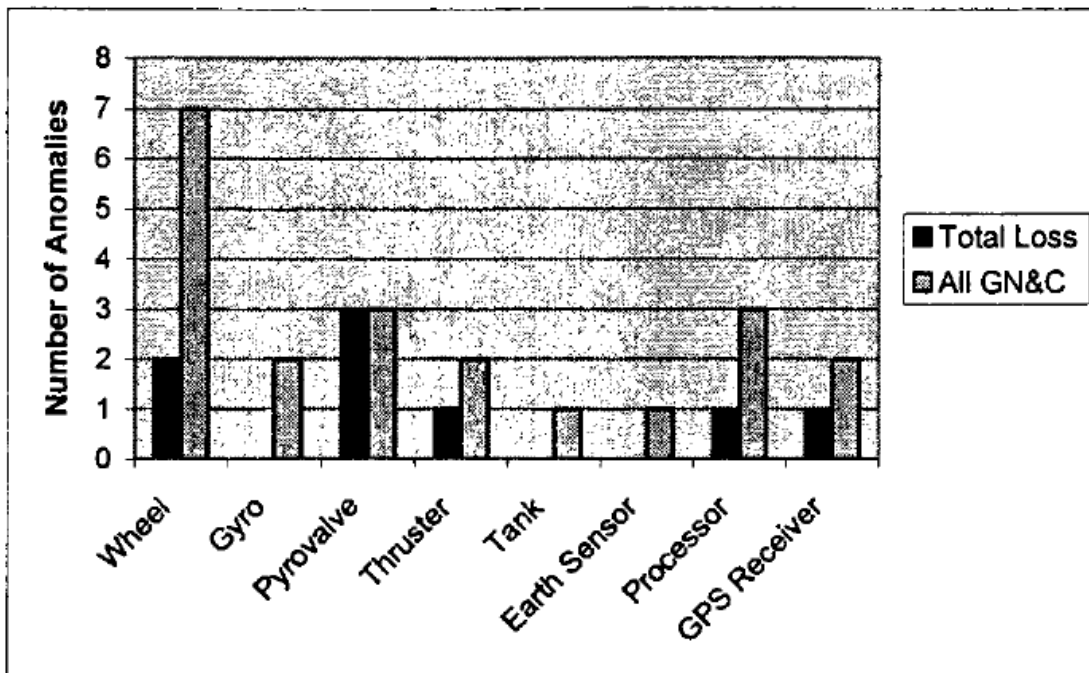


Figure 13. GN&C Anomalies vs. Equipment Type: Source: [18].

## H. TIMELINE OF SATELLITE FAILURES

Not only is it important to know what subsystems are most likely to experience failures, but when in their design life they can be expected to fail. The majority of satellites have the potential to experience what is called infant mortality, where the spacecraft's actual life is less than 10% of its design life [18]. This infant mortality is caused by the aforementioned multitude of system anomalies. However, if a satellite manages to make it past the first three years of its operational life, it will more than likely survive past its original design life [3].

In a study done by Aerospace Corporation in 2019, it was discovered that 20% of satellites launched failed to meet design-life expectations [14]. However, that data does not indicate when in the design lifetime that the satellite failed. Further investigation shows that 41% of satellites failures occur within the satellites first operational year [3]. After that the failure rate is roughly even as seen in Figure 14, with a 17% failure rate between years 1 and 3, a 20% failure rate during years 3 through 5, and from years 5 through 8 a 16% failure rate [3].

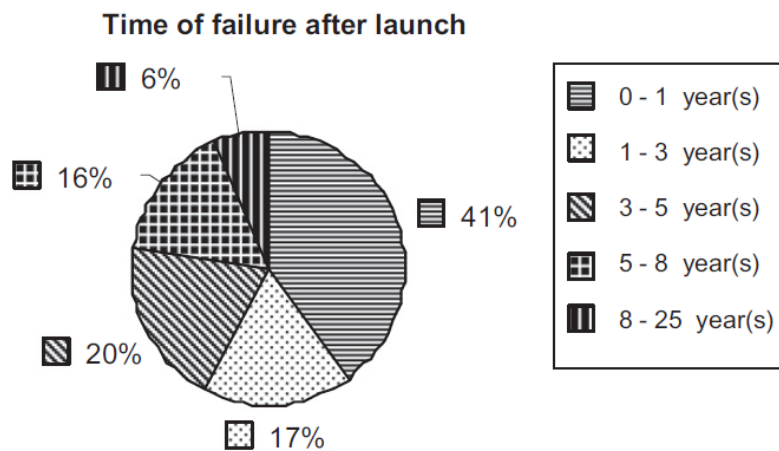


Figure 14. Time of Failure After Launch: Source: [3].

Some subsystems are especially vulnerable to this infant mortality, 56% of all GN&C anomalies occur within the first 10% of mission life, as seen in Figure 15 [18].

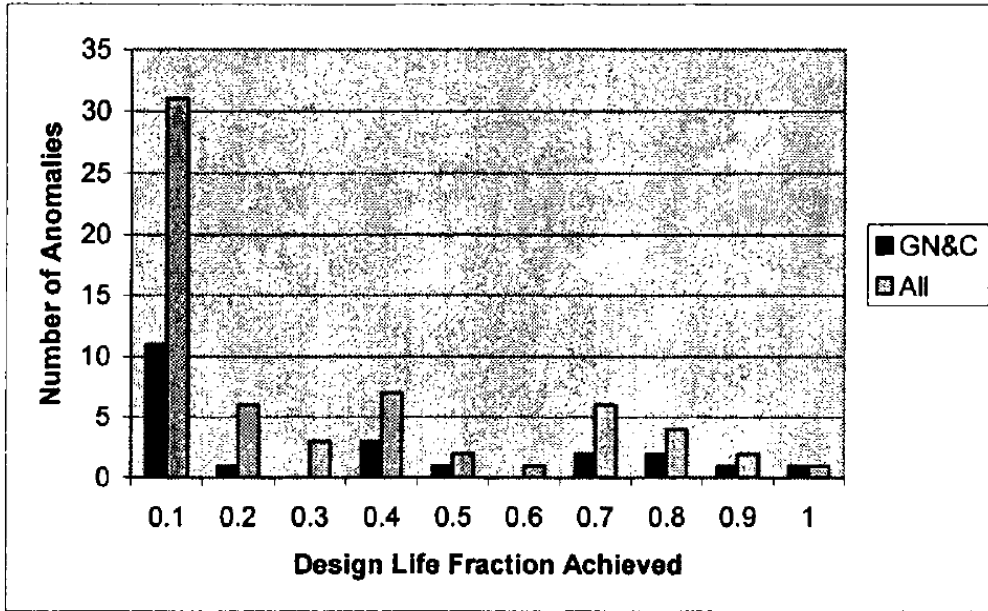


Figure 15. Anomaly Occurrence in Satellite Design Life: Source: [18].

The rate of infant mortality decreases as design life increases as seen in Figure 16 [2]. The majority of satellite failures within the first year belong to satellites with a design life of 5 years or less [2]. This high failure rate can be attributed to the lack of robust testing and hardened components included in this category of satellite [17]. While designing a more reliable component or adding redundancy to the satellite would decrease the failure rate it would also exponentially increase the cost of the satellite.

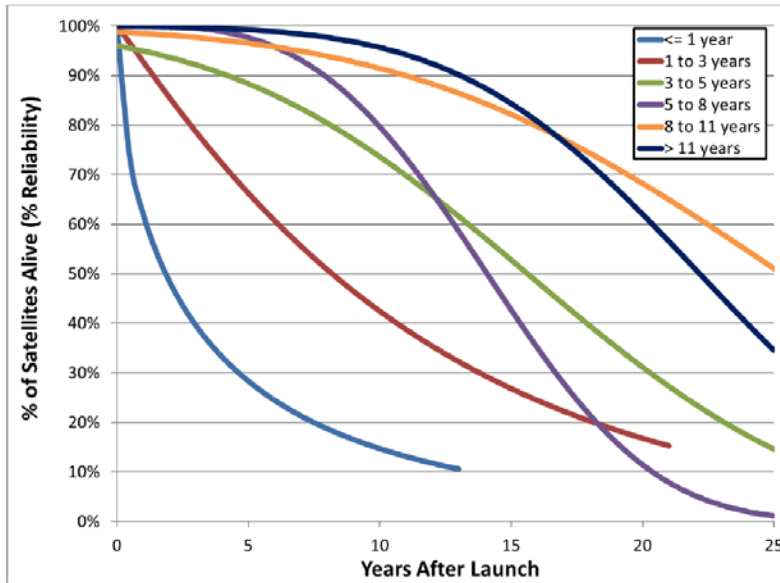


Figure 16. Satellite Reliability by Design Life Range: Source: [2].

For satellites with a design life of 8 to 11 years, 3.6% will suffer from infant mortality [2]. As seen in Figure 17, it is more common for a satellite failure to occur in the first year of operation. However, as the satellite ages the failure rate does decrease but it does not vanish entirely. Satellites that suffered from infant mortality would be the ideal category to begin initial on-orbit servicing test.

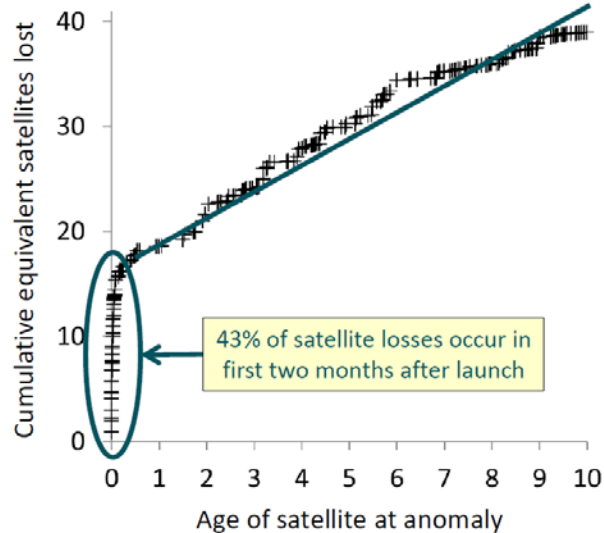


Figure 17. Satellite Anomalies and Losses vs. Age: Source: [17].

There are two types of satellite anomalies that do not follow this pattern and occur within the first year of satellite design life. Propulsion failure and central processor anomalies tend to fall outside the infant mortality timeline. For propulsion failures, 50% of the failures will occur within year 1 to 4 of design life, but can continue to happen up to year 10 of design life [20]. Central processor failures tend to begin after year 6 of operational life, and they will continue to fail up to year 8 or 9 of operational life [21].

Figure 18 indicates the year and percentage of anomaly occurrence broken down by subsystem. The subsystems most grievously affected still follow the similar pattern established earlier in this chapter. The AOCS and EPS systems, despite design improvements within the last 25 years, are still prone to a large percentage of system anomalies. These critical subsystems are prime candidates to benefit from on-orbit servicing.

Year	Antenna	Battery	Control Processor	Payload Electronics	Propulsion	Solar Array	Structures	Transponder	Total Claims	% of Total Anomalies
1	5/100.0%	1/17.0%		5/71.0%	2/25.0%	8/38.0%	1/100%	2/67.0%	24	44%
2		3/50.0%			2/25.0%	6/29.0%			11	20%
3		2/33.0%		2/29.0%		4/18.9%			8	15%
4					1/12.5%	1/4.7%			2	4%
5						1/4.7%			1	2%
6			1/33.3%		1/12.5%			1/33.0%	3	5%
7					1/12.5%	1/4.7%			2	4%
8			1/33.3%						1	2%
9			1/33.4%						1	2%
10					1/12.5%				1	2%

Source: Frost & Sullivan and Airclaims

Figure 18. Annual Anomalies by Type of Claim: Source: [21].

### **III. SATELLITE MODIFICATIONS TO FACILITATE ON-ORBIT SERVICING**

#### **A. INTRODUCTION**

Servicing satellites on orbit is a notoriously difficult challenge that has been discussed and researched since the early 1980s. Many satellites in orbit today that could benefit from on-orbit servicing fall into the category of non-cooperative satellites, mostly due to a lack of design to allow for servicing. However legacy satellites and satellites undergoing construction can both benefit from future servicing options. Some modifications can be made with only a low cost and minor design change, while other modifications will need to be delineated to future designs [22]. By starting with the little steps now, it will pave a future path for more sophisticated servicing options. The ultimate goal being the ability to upgrade old satellites with new technology and significantly cutting the cost to satellite construction.

There are six core reasons to invest in on orbit servicing technology: reduction of life cycle expenses, increased payload capability, extended orbital lifetimes, increased spacecraft capabilities, enhanced mission and operational flexibility, and increased pre-launched spacecraft flexibility [9]. OOS will help reduce satellite life cycle cost and help increase payload sensor availability [9]. It will extend spacecraft orbital lifetimes, capabilities, and mission flexibility and readiness [9]. Additionally, OOS can enable more last-minute flexibility and operational readiness in the pre-launch spacecraft, especially if that spacecraft has been built upon a modular design, allowing for potential payload change out before launch [9].

To provide the most economical option it is ideal if the satellite servicer can provide multiple services to multiple satellites. To facilitate this idea a proposed servicer design is the Orbital Replacement Unit (ORU) [23]. Historically the ORU was used first in the 1993 mission to service the Hubble Space Telescope (HST) and was used as a blanket term for any part that had to be replaced on orbit [23]. For servicing legacy satellites and satellites that have not been specifically designed to be modular or serviced, an ORU could be docked to the client satellite by a servicer satellite with the needed repair components

inside. Without implementing a modular design “approximately one-third of all satellite components can be practically replaced” [9].

Before servicing a satellite, fault identification on the client satellite is critical. By identifying either the exact nature of the fault or the piece of hardware associated with it, precise calibrations can be done for the repair parts [9]. System operators will need to prepare for satellite downtime during repairs and have the satellite enter into a safe mode for servicing operations. System engineers will need to verify that the ORU will not interfere with the client satellites thermal control and will operate within the power margins of the host satellite [9].

## **B. RENDEZVOUS AND DELIVERY VEHICLE**

The rendezvous and delivery (R/D) vehicle is the first part need to facilitate OOS operations. In order to service multiple satellites, the R/D vehicle will need to carry at minimum 2 ORU, enough fuel to complete its mission, and the tools to install the ORU onto the client satellite [9].

Ideally due to transmission delays the R/D vehicle would be able to conduct RPO and OOS operations in a fully automated mode with a manual safety override feature for emergencies [9], [22]. Figure 19 demonstrates one concept of the R/D vehicle design to service multiple satellites. Each replacement component would be an ORU designed to repair a specific satellite. As future satellite design trends tend toward a more modular system the ORU can also become a standardized model easily replacing common failed parts.

Several methods can be used to attach the ORU to the client satellite, however, for legacy satellites since they were not designed for servicing, the easiest method would be to attach the ORU to the Marman ring. The Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office has developed a prototype Marman Ring Tool (MRT) to assist in attaching to the client satellite body [23]. Figure 20 demonstrates how the prototype MRT would notionally attach to the satellite’s Marman ring.

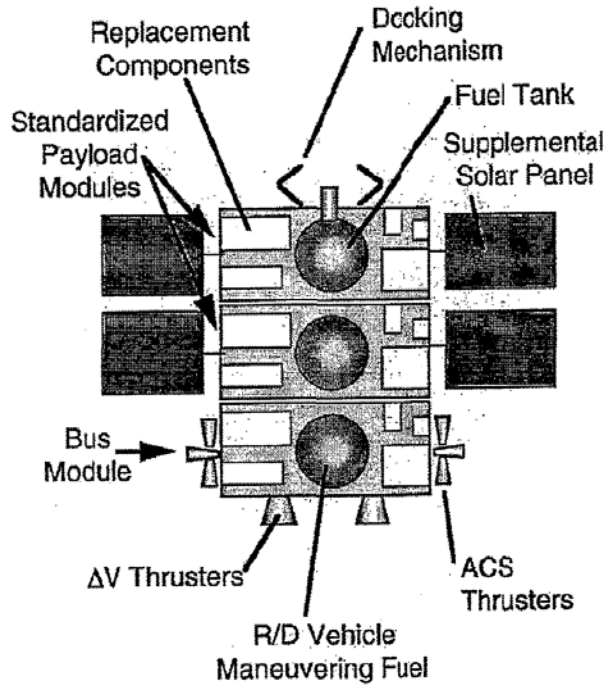


Figure 19. R/D Servicer and Module Configuration: Source: [9].

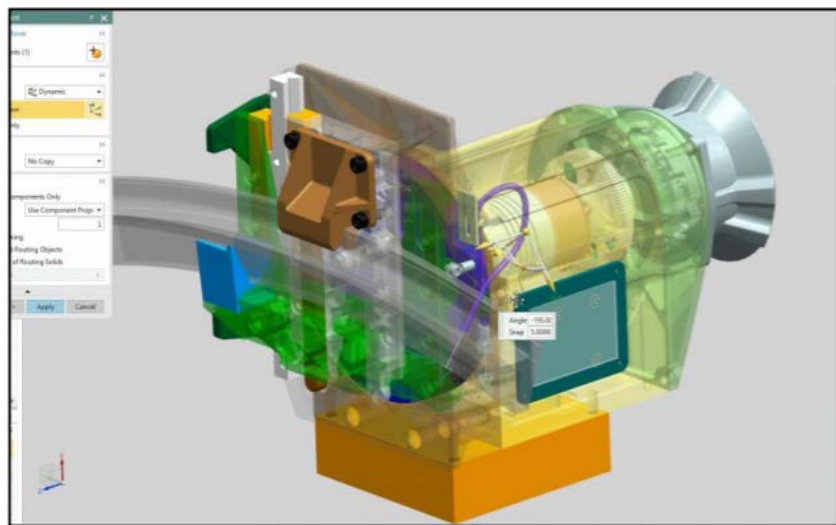


Figure 20. DARPA Prototype Marman Ring Tool CAD Demonstration: Source: [23].

Figure 21 shows the constructed MRT prototype displaying the outer diameter (OD) jaw and inner diameter (ID) jaws used to attach to the client satellite's Marman ring. Once the R/D Vehicle has docked with the client satellite the ORU will need to be

connected into the client's bus to interface with the subsystems it will be replacing. Seen in Figure 22 is a notional example of how the ORU could interface with the client satellite, as demonstrated with the 1553 bus; however, the concept can be applied to multiple bus structures as long as the ability to interface with the client satellite and isolate the broken component is present [9].

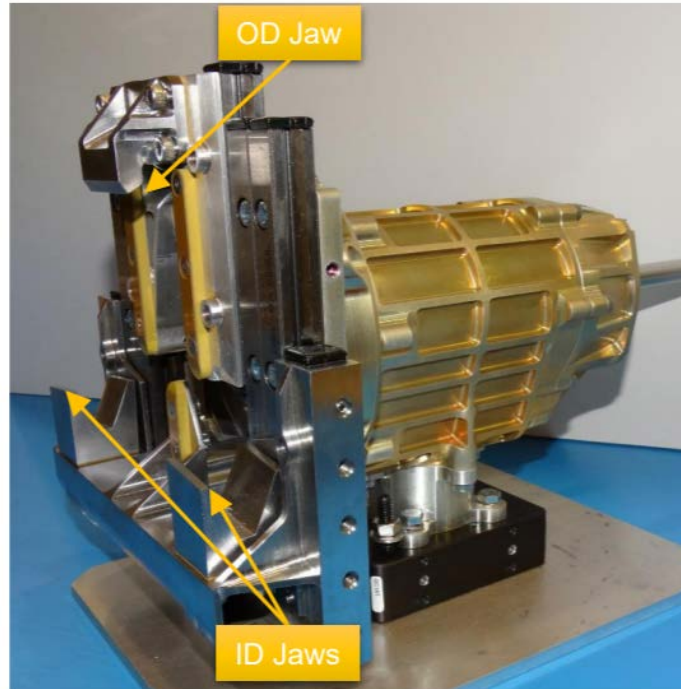


Figure 21. DARPA Prototype Marman Ring Tool: Source: [23].

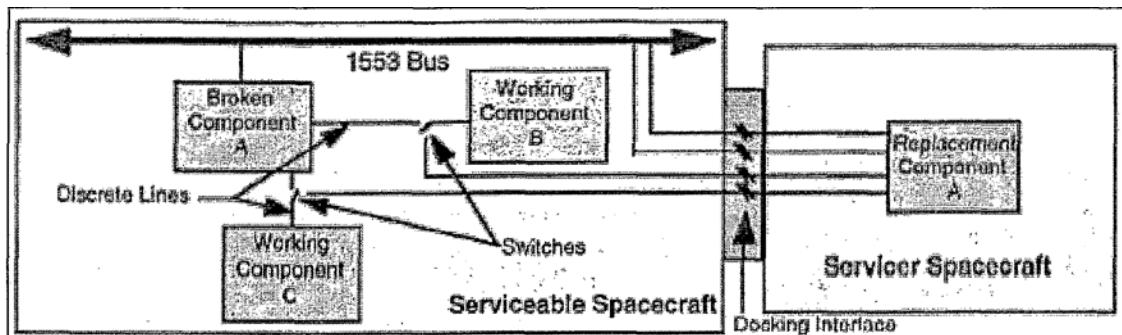


Figure 22. Wire Routing to the Docking Interface Enables Functional Replacement of a Component: Source: [9].

As satellite designs switch to a more modular architecture similar to Figure 23, the ability to conduct OOS with a standard ORU will become more common place.

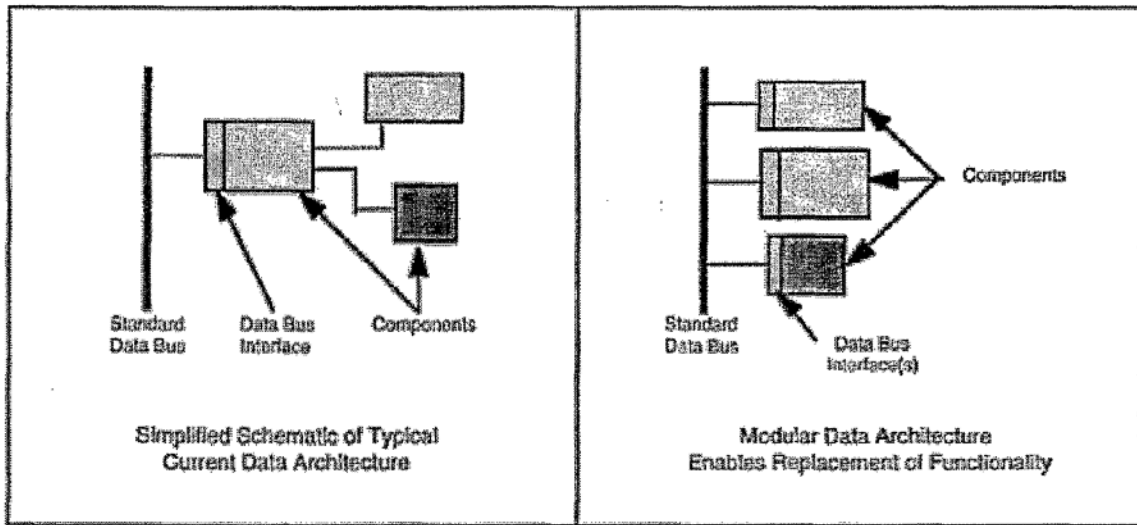


Figure 23. Typical Data Architecture and Modular Data Architecture: Source: [9].

While the R/D vehicle will be a new construction, there are many modifications that can be made to the external structure and internal subsystems on the potential client satellites without a significant design change or increase in cost. Most of these modifications would be superficial additions to the outer structure of the spacecraft and would aid in RPO for the client satellite [9].

### C. STRUCTURES AND MECHANISMS

To promote safer RPO the following modifications in Table 1 could be implemented. They range from low cost exterior only modifications to the high cost modifications associated with design changes. The low-cost exterior additions could be implemented while the satellite is still on the production floor [22]. The majority of the changes in Table 1 in the left side column can be implemented without the need for additional testing or qualifications. The modifications postulated in the middle column in Table 1 will need be run through the same qualifying test as the rest of the spacecraft's components to make sure they are radiation hardened and can survive the space environment. The final column will require major changes in the satellite design and will

need to be implemented during the initial design phase [22]. The first push to making a satellite serviceable should focus on implementing the service aids that cost little and add little extra mass, for example taking closeout photos and dimensions of the final structure could pay dividends when it comes time to service the satellite in orbit [22].

Table 1. Structure Modifications to Promote Safer Rendezvous and Proximity Operations. Adapted from [22].

<b>Level of Spacecraft Bus Modifications</b>		
<b>Low Cost: Exterior Additions</b>	<b>Medium Cost: Minor Modifications</b>	<b>High Cost: Redesign and Design Changes</b>
Add optical/reflective target on docking/capture axis (adhesive decal)	Install hemispherical retroreflectors for long-range targeting by the RPO sensors	Add Omni-directional, low-power RF beacons
Leave optical positioning aids used on the ground in place	Add solar-powered LED beacons to aft end of the satellite	Add external status indicators to visually indicate spacecraft readiness for capture
Take closeout photos using LIDAR or IR imaging	Add truncated-cone navigation aid (to provide pitch and yaw information)	Add RF crosslinks that can provide ranging information
Take additional closeout photos of aft end of spacecraft at launch site with servicing in mind	Install specific servicing sensors with telemetry (thermocouple on the fill-and-drain valve [FDV] mounting plate)	Add aperture door to sensitive optics to prevent contamination during servicing
Document dimensions of flight ready systems (with blankets in place, etc.)		
Provide network access to closeout photos (archive with searchable keywords)		

To facilitate ease of capture of the client satellite by the R/D vehicle the modifications listed below in Table 2 could be implemented. New technology designed and demonstrated by DARPA includes the Marman ring capture tool seen in Figure 21

which can grapple with 1194, 937, and 1666 Marman rings. Also in the current design process with OOS in mind, is the development of the FRENK MKII robotic arm system (RAS) and the Payload Orbital Delivery (POD) module which work together to complete the Robotic Servicing of Geosynchronous Satellites (RSGS) project [23].

Table 2. Structure Modifications to Increase Ease of Capture by R/D Vehicle. Adapted from [22].

<b>Level of Spacecraft Bus Modifications</b>		
<b>Low Cost: Exterior Additions</b>	<b>Medium Cost: Minor Modifications</b>	<b>High Cost: Redesign and Design Changes</b>
Add reference markings around the Marman ring (i.e., clock-face tic marks)	Standardize Marman ring for capture (DARPA’s current prototype can grapple 1194, 937, and 1666 Marman rings [23])	Add grapple features on the spacecraft bus aft end
Standardize blanket dressing around Marman ring (i.e., trim existing blankets to fit)	Add external grounding point to equalize electrical potential between spacecraft	Add standardized docking features
Take additional closeout pictures of Marman ring (and surrounding area) at launch site	Analyze deployables to accommodate on-orbit loads (thermal and mechanical)	Design deployables to accommodate on-orbit loads (thermal and mechanical)

To assist in on-orbit satellite repairs the following modifications in Table 3 can be implemented to the client satellites structure. The most focus being paid to the thermal blankets that traditionally are taped onto the satellite at the end of the build process. By strategically changing some of the adhesive from tape to Velcro it will be possible to still provide the thermal protection required while allowing for easy and repeatable access to the client satellite [22].

Table 3. Structure Modifications to Facilitate Repairs to Satellites.  
Adapted from [22].

<b>Level of Spacecraft Bus Modifications</b>		
<b>Low Cost: Exterior Additions</b>	<b>Medium Cost: Minor Modifications</b>	<b>High Cost: Redesign and Design Changes</b>
Close thermal blankets with Velcro instead of tape	Add external cameras to observe all deployments in case of anomaly	Design deployable mechanisms with external robotic overdrive feature (hex drive)
Add Velcro to back of all existing thermal blanket flaps to hold open when repairs are being conducted	Design thermal blanket flaps (with Velcro on back) for all external interfaces	Incorporate modular design for unit replacement (similar to what was done on the HST [10])
Provide loops on thermal blanket edges to facilitate manipulation with robotic arm	Add external connector that provides access to major spacecraft bus systems	Add external ORU interface with power and data connections
Add thermal blanket flaps over existing ground test ports	Position ground test ports at aft end (or in an area that a robotic arm can easily reach)	Combine mechanical and electrical connectors (blind mates)
Add external labels that identify location of ground test ports		

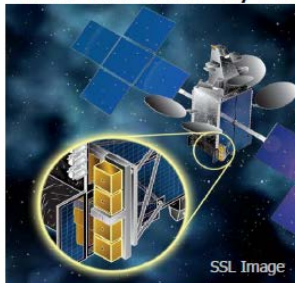
The structural modification suggestions in this section are just the tip of the iceberg, meant to be a launching point to begin transitioning satellite design to a modular construct that enables and promotes mission and design flexibility.

#### **D. PAYLOAD MODIFICATIONS**

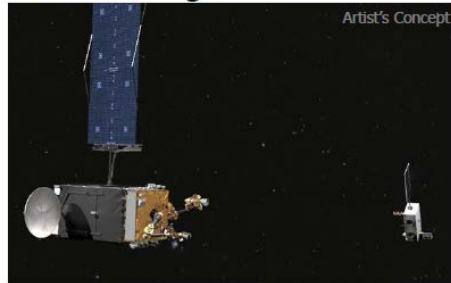
Besides modifications to the exterior structure of the bus, other modifications can be added to the satellites payload components to allow for repairs and upgrades. While most payload modifications to incorporate modular design would have to be incorporated at the start of the design process, some modifications can be still made on the production floor without significant extra cost depending on the mission set. For example, the direct downlink (D/L) is critical to communication missions, if this fails it will be catastrophic to

the satellites ability to function. To facilitate the direct downlink (D/L) becoming a repairable item a visible label should be added to the exterior of the spacecraft so that the D/L can be identified during OOS [9]. Future modifications could include designing modular payload sets that could be built into ORU and replaced on-orbit as needed for updates or repair [24]. DARPA’s RSGS project includes a prototype ORU specifically for adding a new payload upgrade called the Payload Orbital Delivery (POD) system [23]. It was flight proven in 2018 as an On-orbit attachable capability (OAC) where it is launched into space as a ride along on a host satellite via the POD system. Once released by the host, the OAC will then be retrieved by the RSGS to be installed on a client satellite, as seen in Figure 24.

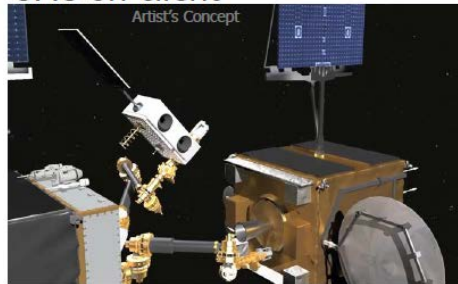
1) OAC delivered to GEO via POD system



2) RSGS retrieves free floating OAC



3) RSGS installs OAC on client



4) Client with new capability

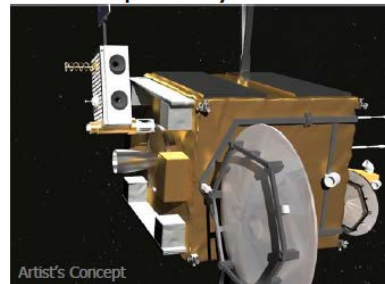
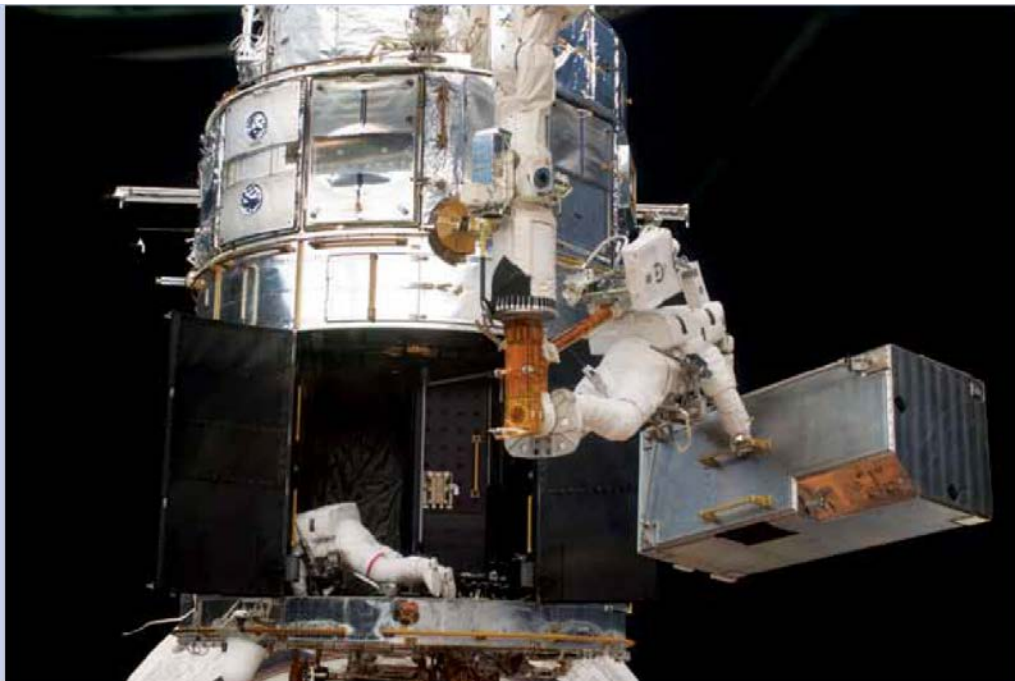


Figure 24. OAC Enable Space Architecture Adaptability:  
Source: [23].

## E. POWER SYSTEM MODIFICATIONS

The electrical power system (EPS) over the last couple of decades has seen a total failure rate of 27% as seen in Figure 2, and since 2000 has accounted for at least 80 total mission failures (Figure 9) [3], [17]. The main hardware components that failed before EOL are solar arrays and batteries, and both parts could see benefits from OOS and repairs [3]. Minimal cost modifications can include keeping the power test port available externally and adding the Velcro adhesive to allow for easy access on-orbit [9]. Mid-cost modifications could include reconfiguring the solar array connection to optimize for attachment and removal via a robotic tool and designing an ORU with spare batteries to interface with the client satellite [24]. Major modifications would include the redesign of the power distribution unit (PDU) and battery configurations.

Again a redesign to include a design similar to what was seen on the HST repair missions (Figure 25) could also be used to promote OOS operations [9], [24].



Installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) on the HST. The modular instruments were designed to be replaced on-orbit by astronauts from the ISS using the space shuttle.

Figure 25. HST First Servicing Mission: COSTAR Installation: Source: [24].

**F. ATTITUDE AND ORBIT CONTROL MODIFICATIONS**

The AOCS anomalies on-orbit account for 32% of all on-orbit anomalies and account for the majority of all satellite mission losses. Unlike the previous section, adding modifications to the AOCS will require a varying degree of minor to major design modifications to truly become a modular system on a spacecraft.

The change proposed by Table 4 in the left side column can be implemented without the need for additional testing or qualifications. Any inertial reference unit (IRU) that needed replacement could be replaced with a new IRU inside an ORU [23]. The modifications postulated in the middle column in Table 4 will need to be done in three parts, first for legacy satellites modifying the components to work inside an ORU. Secondly changing the satellite design so future iterations are modular, and finally run the new components through the same qualifying test as the rest of the spacecraft’s components to make sure they are radiation hardened and can survive the space environment. The final column will require major changes in the satellite design and will need to be implemented during the initial design phase [21]. Key to spacecraft servicing will be the design and implementation of a spacecraft software “servicing mode” to be implemented before OOS is conducted to place the satellite into a safe mode for RPO [24].

Table 4. Ease of Replacement for AOCS Components. Adapted from [9].

<b>Level of Spacecraft Modifications</b>		
<b>Minor Design Modifications</b>	<b>Minor Design Modifications</b>	<b>Major Design and Modifications</b>
Inertial Reference Unit (IRU)	Three Axis Magnetometer Sensor	Digital Sun Sensor Electronics
	Star Tracker	Gimbal Control Electronics
	Reaction Wheels	
	Electromagnetic Torque Rods	
	GPS Receiver	

For the hardware that suffers an anomaly in the AOCS system the repair process has the potential to be costly. While some parts can be replaced via an ORU, the more fragile electronics may need to wait until modular design has been implemented to repair due to their position inside the spacecraft [9].

#### **G. PROBLEMS THAT WILL NEED TO BE ADDRESSED**

While adding modifications and redesigning satellite parts will take time and money these are easy problems to solve while the satellite is still in the design process or even on the production floor compared to the puzzle of correcting on-orbit anomalies. Critical to making timely and accurate repairs is the exact knowledge of what has suffered a failure on the satellite. Each legacy satellite due to its unique nature will likely require a unique solution. For example, to replace an ADCS component, the replacement ORU will need to be precisely aligned to the client satellite reference coordinate systems, or allow for the new ADCS component to be calibrated while on-orbit [9]. Also, especially for repairs on legacy satellites, the ORU's electrical and attitude control systems will need to be designed and calibrated with the enough margin so that the client satellite can support the extra load of the ORU or the ORU will need to be designed so it can provide its own power [9]. Thermal studies will also need to be conducted so the ORU does not negatively affect the client satellite. Ultimately the customer will also need to prepare for adequate downtime on the client satellite for the repairs to take place.

## **IV. COST BENEFIT ANALYSIS OF ON-ORBIT SERVICING VS. SATELLITE REPLACEMENT**

### **A. INTRODUCTION**

Satellite program cost are driven by three main factors; the mass of the satellite, complexity, and the project timeline [4]. Increase either the mass or complexity of the spacecraft and you will increase the cost. Also, if the project timeline is reduced the satellite cost will increase. These three factors have to be taken into careful balance to maintain an appropriate budget but still produce a reliable satellite. Currently “space systems are designed primarily to have a high parts reliability” but they are still “inherently fragile because any failure can lead to major consequences” including but not limited to a loss of constellation capacity [4].

Right now, lower cost missions are classified as a lower risk since less resources are wasted in the case of a spacecraft mission loss. To date, satellite companies strive to build satellites as cost effective and as reliable as possible. However, satellites still have the potential to suffer from major anomalies, and while the design process continues to improve there will never be a time any system achieves 100% reliability. Spacecraft, especially those at higher orbits, are the only technology that do not benefit from routine maintenance and servicing. By filling this technological gap, the satellite industry can remodel the way it designs spacecraft to benefit from this cost saving measure.

### **B. BASIC COST ASSESSMENT MODEL**

The basic model looks at just the pure price difference between three cases. Case one is where the satellite lasts for its entire design life and then is replaced by a new satellite. For case one, the total cost ( $C_T$ ) is calculated by taking  $C_i$  the cost of a new satellite,  $C_g$  the cost of launch to GEO, and  $N$  as the number of launches needed [25]. For case one,

$$C_T = N(C_i + C_g). \quad [25] \quad (1)$$

This model will give us the cost to insert two satellites into orbit regardless of whether the initial satellite failed at end of life or before. This is the “sunk cost” and is the current method of satellite operation today [26].

The second model is launching the initial satellite and then at EOL time Y contracting for a life extension service at cost  $C_r$  [25]. The current model for this is Northrup Grumman’s MEV-1 that is extending IS-901 lifespan for 5 years [13].

$$C_T = C_i + C_g + C_r \quad [25] \quad (2)$$

Further cost  $C_u$  will be added to repair/upgrade a satellite on-orbit in conjunction with the life extension services giving us Equation 3.

$$C_T = C_s + C_g + C_r + C_u \quad [25] \quad (3)$$

The cost difference ( $\Delta C$ ) will be calculated by

$$\Delta C = [2(C_s + C_g)] - [C_s + C_g + C_r + C_u]. \quad [25] \quad (4)$$

If the cost of extending life and repairing/upgrading can be priced in such a way that  $\Delta C$  is significantly less than Equation 1 then OOS can be economically feasible [25]. Essentially, if the required servicing costs are less than the cost of a new satellite plus the launch to GEO it will be economically viable strategy.

### 1. Communication Satellite Example

While the equations above are a basic model of how to calculate the potential cost savings of OOS it does not take into account the potential for on-orbit anomalies that would require servicing or replacing the satellite. By taking into account the reliability of a satellite a more realistic cost estimate can be used. A communication satellite has an average reliability ( $R(DL)$ ) of 89% and an average design life ( $DL$ ) of 15 years [2]. If  $N=2$  and the statistical average life span is  $R(DL)*DL$ , then the expected lifetime ( $EL$ ), when a new replacement satellite is used, can be written as

$$EL = [R(DL) * DL + R(DL) * DL] = 2R(DL) * DL = 2R(15) * 15. \quad [25] \quad (5)$$

If an OOS system is used instead, where  $R(DL|r)$  is the reliability given replenishment, then

$$EL = [R(DL) * DL + R(DL|r) * DL]. \quad [25] \quad (6)$$

For 30 years of service with a replacement satellite,

$$\text{Cost per year} = 2(C_s + C_l) / 2R(15) * 15. \quad [25] \quad (7)$$

For 30 years of service with satellite replenishment,

$$\text{Cost per year} = (C_s + C_l + C_r + C_u) / 15 * [R(15) + R(15|r)]. \quad [25] \quad (8)$$

The goal to making this a feasible option is that the replenishment service needs to fulfill one of two factors; make the client satellite “as good as new” and extend the lifetime an appreciable amount or be cheap enough to act as a stop gap measure before another satellite is launched [25].

For example, Northrup Grumman’s MEV-1 is currently providing a life extension service to IS-901 for \$13 million per year for a max of 5 years [13]. Intelsat 901 was in operation for 18 years, with an initial design life of 13 years, and other than its lack of propellant is still operational [27]. IS-901 cost of construction was \$300 million with a launch cost of \$109 million [28]. In total Intelsat paid ~\$474 million for 23 years of satellite service. Conversely if they instead chose to replace the satellite with a new spacecraft it would have cost them another ~\$362 million, including current launch cost aboard a Falcon 9 rocket, bringing the total for 26 years of design life to ~\$771 million [29], [30]. Thus saving Intelsat \$297 million, which is almost the cost of a new satellite.

While this is a viable case for a functional satellite that has consumed all onboard propellant, what about a satellite that has suffered an anomaly? Unlike the service provided by Northrup Grumman the price tag on an ORU and the OOS mission will be a one-time fee. If the cost of servicing and parts can be marketed to be 10–20% the cost of a new satellite while extending the life span that could be an attractive option. However, this

model only takes into consideration the current method of designing satellites for a 10–15-year design life.

### C. A DIFFERENT APPROACH

The approach above while demonstrating that OOS has potential, based solely on its price tag, it does not take into account the full breadth of options available to the satellite industry with an OOS capability. A servicing mission can be compared to an information transfer network and evaluated on a cost-per-function (CPF) metric [31]. By using a CPF the satellite servicing cost can be compared over its total lifetime cost against different factors as a “quantitative measure of cost effectiveness” [31]. The ultimate goal of an on-orbit servicing mission is to deliver an ORU to enhance the lifetime and capabilities of the spacecraft.

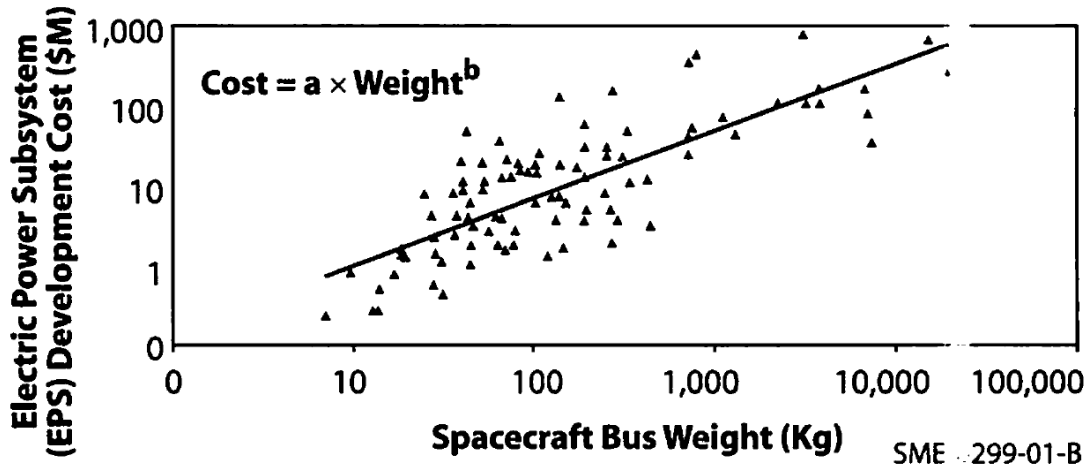
Using an information transfer network evaluation of OOS mission can be determined cost effective if its CPF is less than a traditional approach [31]. OOS can reduce the CPF by decreasing the cost of the theoretical first unit (TFU) by reducing the need for redundancy and thus reducing the dry mass of a spacecraft. By designing a spacecraft to be serviced at the 8, 10, or 13-year mark instead of designing a satellite to survive for 13–15 years a significant savings can be realized. By comparing the ratio of dry mass of a nominal satellite design life ( $T_D$ ) to the dry mass of the planned serviced lifetime ( $T_S$ ), where  $k \approx 2.75\%$  per year, produces Equation 9 [31].

$$M(T_D) / M(T_S) = 1 + k(T_D - T_S) \quad [31] \quad (9)$$

A satellite designed for 15 years has roughly 22% more dry mass than the same system designed for 8 years. The cost of the TFU ( $C_{TFU}$ ) is directly proportional to the dry mass of the satellite [4].

$$C_{TFU} / M_{dry} = \$77,000 / kg \quad [31] \quad (10)$$

So, by reducing the dry mass of the satellite by 22%, the  $C_{TFU}$  is also reduced by 22%. This applies across all spacecraft subsystems as well, in Figure 26 the weight of the spacecraft bus is directly and linearly proportional to the expense of developing the EPS.



This dataset provides the basis for deriving a statistical cost estimating relationship (CER).

Figure 26. Example of a Development Cost vs. Weight Database: Source: [4].

The second reduction of CPF is the change in failure calculations and compensations cost [31]. With servicing as an option after a satellite anomaly the cost can change from a total loss or reduction in performance to the cost of servicing and repair. Currently satellites are notoriously over designed due to the lack of serving options. To overcome an anomaly a spacecraft must have built in redundancies or suffer the consequences. This overbuild manifest itself not only in cost but also survivability. While 58% of satellite failures happen in the first 1–3 year, if a satellite does not experience a failure it will more than likely exceed its original design life [2], [3].

Figure 27 illustrates the percentage of satellites that lived past their intended design life. At the time of this study 80% of the satellites had reached their design life of >11 years, however if the majority of recently launched satellites with a planned lifetime of > 11 years reach their design life, that number will increase to 96% [2]. By incorporating satellite servicing into the CPF calculations you can reduce the cost over a more traditional approach [31].

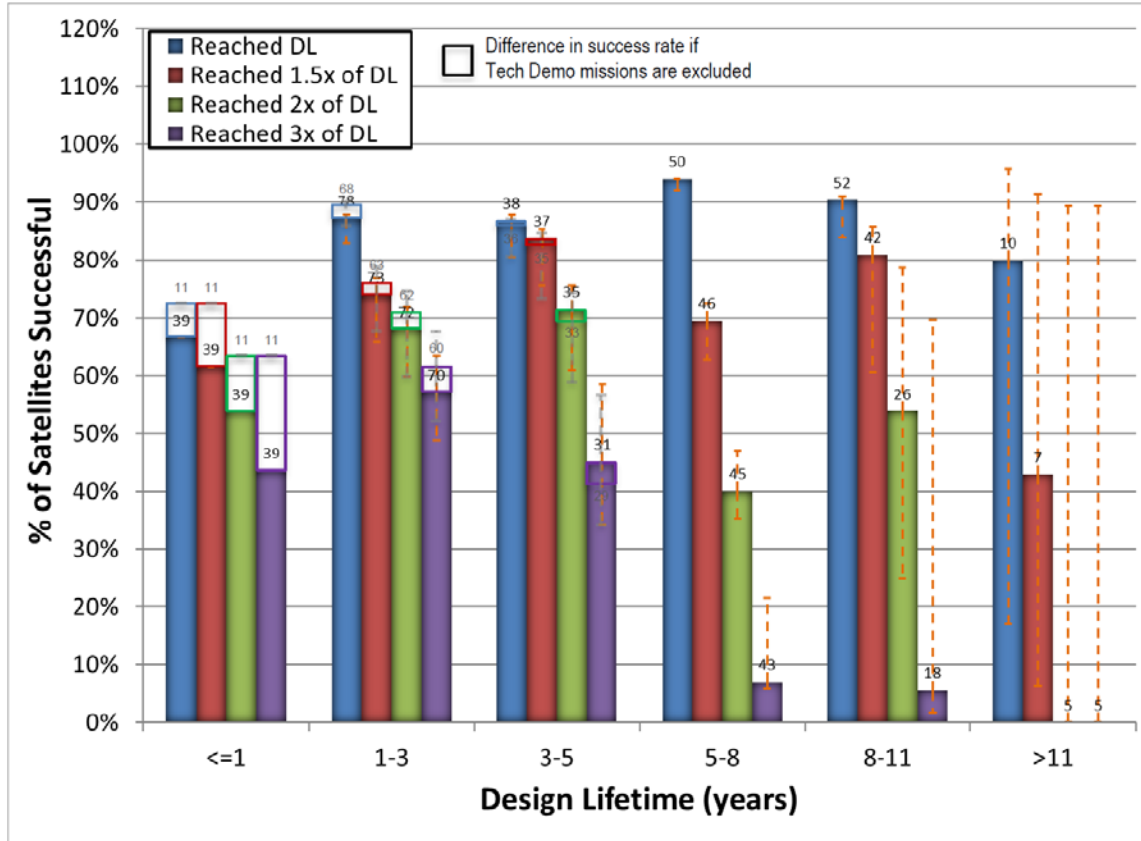


Figure 27. Success Rate by Design Life Range: Source: [2].

### 1. Communication Satellite Example

Let us use the Intelsat example again. The average Intelsat satellite cost between \$275 - 400 million, and requires a Falcon 9 class rocket to boost it into GEO costing an average of \$62 million, and is expected to have a design life of 13–15 years with an average life span of 18–20 years [28], [29]. On average in 2019 a communication satellite earned about \$60 million in revenue, as seen in Table 5.

Table 5. 2019 Revenue of Commercial Satellite Companies

Satellite Operator	Country	2019 Revenue (\$M)	Number of Satellites	Avg. Revenue per Satellite (\$M)	Source
SES Global	Luxembourg	\$2,161.33	50	\$43.22	[33]
Intelsat	US	\$2,061	52	\$39.63	[34]
ViaSat	US	\$684.2	4	\$171	[35]
Eutelsat	France	\$1439.1	37	\$38.89	[36]
SKY Perfect JSAT Group	Japan	\$963.91	18	\$53.55	[37]
Thaicom	Thailand	\$146.09	8	\$18.26	[38]
Average		\$1242.6	28	\$60.75	

All prices are in U.S. dollars, any currency conversions were done using data provided by Morningstar for Currency and Coinbase for Cryptocurrency [32].

For the purpose of this example OOS cost was estimated to be \$50 million. By calculating the cost pro forma for the four different scenarios the cost benefits to on-orbit servicing can be seen. Table 6 is the current spacecraft model without the access to any OOS missions. With this model around year 7 the initial cost of satellite development and launch has been paid off and they rest of the gross revenue earned from the spacecraft is pure profit. When a satellite company investigates building a new satellite it looks to gain an internal rate of return (IRR) of 15 to 20%, which is achieved around year 11 as shown in Table 6 [6]. The IRR is a metric used, to estimate the potential profitability of a new investment and to calculate future growth and expansion [39]. It was chosen for this scenario as it allows for comparison on an even basis since, in its calculations it omits external factor like inflation or cost of capital [39]. For tables 6 through 9 all IRR calculations were done using the built-in IRR excel calculator.

Table 6. Communication Satellite without Servicing

<b>Years</b>	<b>Gross Revenue</b>	<b>Cost Coverage and Profit</b>	<b>Internal Rate of Return</b>
0	\$0	- \$362	-
1	\$60	- \$302	-
2	\$60	- \$242	-
3	\$60	- \$182	- 44.40%
4	\$60	- \$122	- 22.00%
5	\$60	- \$62	- 8.60%
6	\$60	- \$2	- 0.22%
7	\$60	\$58	5.26%
8	\$60	\$118	9.00%
9	\$60	\$178	11.63%
10	\$60	\$238	13.52%
11	\$60	\$298	14.92%
12	\$60	\$358	15.98%
13	\$60	\$418	16.78%
14	\$60	\$478	17.40%
15	\$60	\$538	17.88%
16	\$60	\$598	18.26%
17	\$60	\$658	18.56%
18	\$60	\$718	18.81%
19	\$60	\$778	19.00%
20	\$60	\$838	19.16%

All dollars are in millions

Table 7. Communications Satellite with Servicing due to Mission Loss at Year Two

<b>Years</b>	<b>Gross Revenue</b>	<b>Cost Coverage and Profit</b>	<b>Internal Rate of Return</b>
0	\$0	- \$362	-
1	\$60	- \$302	-
2	-\$50	- \$352	-
3	\$60	- \$292	- 63%
4	\$60	- \$232	- 36.33%
5	\$60	- \$172	- 20.53%
6	\$60	- \$112	- 10.59%
7	\$60	- \$52	- 4.02%
8	\$60	\$8	0.52%
9	\$60	\$68	3.76%
10	\$60	\$128	6.14%
11	\$60	\$188	7.93%
12	\$60	\$248	9.30%
13	\$60	\$308	10.36%
14	\$60	\$368	11.20%
15	\$60	\$428	11.87%
16	\$60	\$488	12.41%
17	\$60	\$548	12.85%
18	\$60	\$608	13.21%
19	\$60	\$668	13.50%
20	\$60	\$728	13.75%

All dollars are in millions

Table 7 demonstrates the second case where a spacecraft experiences an anomaly at year 2 but instead of suffering a total mission loss and being counted as forfeit, it is repaired by an OOS mission correcting the anomaly. While ultimately the spacecraft does not generate as much revenue as the case in Table 6 without the servicing mission it would have been a total loss, this way the satellite is still a viable asset.

Table 8 provides an example of the third case where the spacecraft is still designed for a 13-year lifespan but has planned for a servicing mission at year 13 which extends the spacecraft’s functional life for another 13 years. Profits are still realized at year 7; however, the life extension services at year 13 allow for a greater rate of return extending out to year 25.

Table 8. Communication Satellite with Servicing at Year 13

Years	Gross Revenue	Cost Coverage and Profit	Internal Rate of Return
0	\$0	- \$362	-
1	\$60	- \$302	-
2	\$60	- \$242	-
3	\$60	- \$182	- 44.40%
4	\$60	- \$122	- 22.00%
5	\$60	- \$62	- 8.60%
6	\$60	- \$2	- 0.22%
7	\$60	\$58	5.26%
8	\$60	\$118	9.00%
9	\$60	\$178	11.63%
10	\$60	\$238	13.52%
11	\$60	\$298	14.92%
12	\$60	\$358	15.98%
13	\$10	\$368	16.12%
14	\$60	\$428	16.80%
15	\$60	\$488	17.32%
16	\$60	\$548	17.74%
17	\$60	\$608	18.07%
18	\$60	\$668	18.33%
19	\$60	\$728	18.54%
20	\$60	\$788	18.71%
21	\$60	\$848	18.85%
22	\$60	\$908	18.96%
23	\$60	\$968	19.05%
24	\$60	\$1,028	19.12%
25	\$60	\$1,088	19.19%

All dollars are in millions

Table 9 demonstrates an example of the final case presented as a potential with OOS missions. In Table 9 the spacecraft is only designed for 8 years reducing the initial TFU cost by 20% to \$240 million. Due to the reduction in design life the planned servicing will now take place at year 8 extending the satellite life to 17 years. Using this design generates a final 22.74% rate of return which is greater than all cases presented in Table 6, Table 7, and Table 8. Table 9 represents the optimal solution to employ OOS missions. By fully incorporating the capabilities that a servicing mission can provide, spacecraft can be

designed to less stringent standards saving money and time while seeing a greater rate of return.

Table 9. Communication Satellite Designed for 8 Years with Servicing

<b>Years</b>	<b>Gross Revenue</b>	<b>Cost Coverage and Profit</b>	<b>Internal Rate of Return</b>
0	\$0	- \$302	-
1	\$60	- \$242	-
2	\$60	- \$182	-
3	\$60	- \$122	- 36.29%
4	\$60	- \$62	- 13.46%
5	\$60	- \$2	- 0.33%
6	\$60	\$58	7.62%
7	\$60	\$118	12.68%
8	\$60	\$178	13.31%
9	\$60	\$238	16.13%
10	\$60	\$298	18.08%
11	\$60	\$358	19.44%
12	\$60	\$418	20.44%
13	\$10	\$428	21.18%
14	\$60	\$488	21.74%
15	\$60	\$548	22.16%
16	\$60	\$608	22.49%
17	\$60	\$668	22.74%

All dollars are in millions

By implementing the full capabilities of an OOS missions into both the profit calculations and design considerations it can be shown that CPF of an OOS capable satellite is less than that of a traditional approach. Commercial and military satellites can both benefit from this capability.

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## V. CONCLUSIONS AND FUTURE WORK

As demonstrated in the chapters above there is ample opportunity for servicing missions for satellites at GEO. From 2000 to now, AXA XL has identified at least 82 satellites (Table 10) that could benefit from some form of servicing [17].

Table 10. GEO Satellites Servicing Opportunities. Adapted from [17].

<b>GEO satellites that could benefit from servicing</b>		
<b>Type of Servicing</b>	<b>Opportunities</b>	<b>Annualized</b>
Re-Orbit/De-Orbit	17	0.9
Inspection	59	3.0
Repair	15	0.8
Life Extension	30	1.5
Power Augmentation	39	2.0

82 GEO satellite launched since 2000 have suffered major anomalies that could benefit from on-orbit servicing. Some satellites can benefit from more than one type of servicing.

The technology to perform these mission is almost ready for commercial use as well as seen with both Northrup Grumman’s MEV-1 and DARPA’s RSGS prototype [23], [13]. The last remaining step to realizing this technology as a viable commercial service is for a company to take the first step and contract with DARPA to be the first example of on-orbit repair. Similar to how Intelsat contracted with Northrup Grumman to extend IS-901’s functional life span a company could choose a satellite that otherwise would be counted as a loss for the first demonstration [27].

Once this first step is taken it no longer becomes a “chicken” and “egg” problem but a real and feasible option. It is only the beginning of a wide variety of options available once the doors of OOS missions truly open up. As shown in Chapter IV, it is more beneficial for a satellite company to design a satellite for 8 years and then pay for a life extension servicing at year 8 than it is for a 13–15 design life satellite that may last up to 18 years. However, what remains to be explored are the follow-on functions that OOS could provide. By reducing the need for redundancy in space it could reduce the cost for

access to space further opening up a commercial industry and further allowing for more economic growth in this sector [25], [40].

#### **A. FOLLOW-ON RESEARCH**

Further research will be needed to investigate what changes will be required to be made into the regulatory laws that govern outer space. Currently there is concern that OOS missions could fall under the scrutiny of the International Traffic in Arms Regulations (ITAR) or the Export Administration Regulations (EAR) [41]. Another concern is the imagery that is needed to conduct RPO would potentially need special licensing from NOAA [41]. Finally, the need for licensing from the FCC would be another consideration any new OOS company would have to take into account [41].

Another new field would be what the insurance policy could look like for both servicer and client satellite. Would insurance companies offer coverage within the first three years for GEO satellites that include OOS missions to correct anomalies [41]?

Could a mobile and flexible servicer become the solution to the issue of orbital debris [25]? How much further must the technology progress before companies can look to the GEO graveyard orbit for potential salvage missions [42]? Once we get to that point how much further is necessary to go until we can assemble satellites in orbit [25]?

Ultimately OOS is just the first steppingstone to a multitude of future capabilities. By pushing forward into this new technological capability, it will open the door for further space capabilities.

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