Practical Aspects of On Orbit Servicing in the Commercial Marketplace

Abstract

It is the contention of Orbital Recovery that the era of practical on orbit servicing is at hand. The reasons for this are straightforward. The value of commercial spacecraft in the GEO communications satellite market is high enough that a cost effective system for extending their lifetimes now make financial sense. Parallel to this, recent advances in technology in terms of propulsion, power generation, robotics, and software make it possible to develop a system that is truly cost effective. This paper will examine the market for commercial spacecraft life extension and describe some of the technologies that make for a cost effective approach to on orbit servicing.

Introduction

Today there is no viable mechanism for extending the life of a geosynchronous (GEO) communications spacecraft beyond the normal "end of life" brought about by fuel depletion. Almost all GEO comsats retain all or the majority of their revenue generating potential until that end of life and would continue to operate well beyond the end of life if supplied with enough fuel to continue to maintain their position in the GEO arc. With the rapid advances in spacecraft subsystem technology over the past ten years it has become possible to think about the servicing of existing spacecraft in orbit in a cost effective manner

The question of servicing and extending the lifetime of a GEO comsat is as old as the industry itself. The U.S. National Aeronautics and Space Administration (NASA) did extensive studies on this concept in the 1960's and 70's. Indeed the original space station Freedom had a hanger incorporated along with an Orbital Transfer Vehicle (OTV) that could accomplish this task from a technical sense.

There have been other commercial and government efforts in this area and we take advantage of the government efforts that have developed technology that we can use. We also have learned from the mistakes of previous commercial efforts where we have found them to be too costly to be economically viable. A lot of money is currently being put into orbital servicing for government spacecraft and there is considerable government interest in our SLES. All in all the time seems to be right for our business.

Costs and technology go hand in hand in entrepreneurial space efforts. It is absolutely necessary that costs be contained in order to have a product whose price point is accepted by the market. There is no doubt that the technology exists to do what we want to do. However, if it cannot be done at a level that makes sense then the business is a failure and we should not invest the time and effort to make this work.

The Market for Commercial On Orbit Servicing

The market served by SLES™ is restricted to assets of maximum value that serve the commercial market. The vehicle that we propose will not refuel, augment electrical power, or provide an interface to the electrical systems of a comsat. It will be kept in mind that the SLES™ can evolve into a vehicle with more functions but for now, in order to contain costs, we will restrict the design to the absolute minimum necessary to do its job.

Establishing the Baseline Market

When discussing the life extension of a spacecraft we have to place a number of restrictions in order to narrow the scope of the business and technical aspects to a minimum reasonable number in order to maximize the potential for a successful business. The narrowing of the field that is enumerated here is based upon an extensive survey of spacecraft known to be in orbit today. This survey was conducted on the Internet as well as from the personal knowledge of the industry by the author.

LEO Spacecraft

First of all we eliminate all Low Earth Orbit or LEO spacecraft based upon the value proposition. All LEO spacecraft that we know of are generally research or government/military spacecraft. The ones that are commercial such as the Iridium or Globalstar constellation spacecraft are inexpensive enough that we would have a very difficult time reducing the cost to an acceptable level for a profitable business. Also, LEO spacecraft outside of the military have little need of life extension from a propulsion viewpoint. Therefore we eliminate this category.

MEO Spacecraft

Second of all we eliminate Medium Earth Orbit (MEO) spacecraft for the same reasons. Exceptions would be spacecraft in the Molniya orbits that are commercial comsats but they do not need much in the way of excess fuel supplies over a very long lifetime, much less than Geosynchronous (GEO) spacecraft. Many MEO spacecraft in the commercial sector are quite valuable but not cost effective for our Mk 1 system. An exception that interests us would be GEO spacecraft stranded in a LEO or MEO orbit. However, this is a subclass of the GEO market.

GEO Spacecraft

There are several different types of spacecraft in GEO orbit, some of which are not of interest to Orbital Recovery due to their function or lack commercial value. This paper will focus only on GEO communications spacecraft due to their commercial value and the ability of investors and the banking community to accurately access return on investment associated with their life extension. We do not preclude other types of satellites but the commercial ones offer the best chance in our opinion to create a truly commercial market for on orbit servicing.

GEO Communications Satellites

When we whittle down all of the spacecraft and their orbits that we are not going to save we end up with a subset that makes for a great opportunity and vital business plan. For almost 40 years companies and national programs have lofted communications satellites to this orbit. Billions upon billions of dollars worth of communications satellites (comsats) are in operation today and there is a continuing demand for future business. It is this market that we seek to address.

Orbital Recovery is also narrowing of focus for the business today in that we will only address the market provided by 3 axis stabilized spacecraft.

Market Statistics on GEO Comsats

According to statistics kept active on a daily basis by www.lyngsat.com there are approximately 286 comsats active as of this date in GEO or inclined orbits. Table 1 gives the distribution of spacecraft in the four regions as broken down by Lyngsat.

Region	Number In GEO	Number Inclined
Asia Pacific (160°W-71°E)	65	19
Europe (71°E-0°E)	59	25
Atlantic (0°W-61°W)	36	14
Americas (61°W-160°W)	60	8

Table 1: Number of Operational Sats In GEO

This is a total of 220 GEO birds and 66 inclined birds. Not all of these comsats are customers for ORC. Some of these satellites are too near the end of their life for us to be able to save if we started today. Some of these satellites are spin stabilized. Some are "too small" or of not enough value to be cost effectively saved. Also, many of these spacecraft have been launched since 1995 and have 15 year lifetimes. This means that they are not customers till the 2008 timeframe. This leaves a subset of 43 spacecraft that are potential customers for ORC between now and 2008. This does not include any comsats that are launched between now and then that are stranded. It is expected that one per year on average will fall into this category based upon historical statistics.

The Economics of Orbital Recovery's SLES™

Economic viability, i.e. PROFIT is the key to success of any commercial orbital recovery system. In order to have a profitable business costs must be not only less than, but significantly less than the price we charge our customers.

The spacecraft that are our target market carry a lot of transponders and therefore considerable value. Boeing 601's usually carry 48 to 60 mixed C and Ku band transponders. Boeing 702's usually carry upwards of 80 transponders and they are the higher power versions used in DIRECT TV and other direct broadcast applications.

A way to determine the value of the spacecraft in our target market is to examine the revenue of the major satellite operators divided by the number of spacecraft in their fleet. While this is an inexact measure due to their associated ground services revenue it is still a valuable metric. This metric tends to level out the costs of new birds not yet launched balanced by the ancillary revenue of their associated services. Table 2 gives the revenue of the world's 20 largest satellite operators.

Operator	Country	2001 Revenue	2000 Revenue	Sats	Sats Ordered	Average Revenue
1. Intelsat	U.S.	$1.1B	$1.1B	22	4	$50M
2. PanAmSat	U.S.	$870.1M	$1B	21	5	$41.4
3. SES Astra	Luxem	$655.5M	$665.9M	13	1	$50.3
4. Eutelsat	France	$593.5M	$650.5M	18	6	$40M
5. SES-Americom	U.S.	$506.7M	$522M	16	6	$31.7
6. LoralSkynet	U.S.	$388.9M	$324.6M	7	3	$55.6
7. JSAT	Japan	$298.2M	$332.8M	8	1	$37.3
8. New Skies	Holland	$209M	$198.3M	6	2	$35
9. Telesat Canada	Canada	$201.6M	$197.8M	5	2	$40
10. Space-Com	Japan	$170.8M	$204.6M	4	1	$42.5
11. Arabsat	Saudi	$155M	$132.4M	3	0	$51.7
12. Star One	Brazil	$130.5M	$125M	5	1	$26.1
13. Satmex	Mexico	$128M	$136.4M	2	1	$64
14. AsiaSat	Hong Kong	$124.3M	$128.6M	3	1	$41.4
15. Telenor	Norway	$121.6M	$113.9M	3	0	$40.5
16. Shin Satellite	Thailand	$116.8M	$97.4M	3	1	$40
17. Hispasat	Spain	$94.9M	$81M	3	2	$31.6
18.SingTelOptus	Australia	$85.9M	$73.3M	5	1	$17.8
19. Korea Telecom	South Korea	$76.3M	$53.5M	3	1	$25.4
20. Russian	Russia	$61M	$56M	11	5	$5.5

Table 2: Top 20 Satellite Operator's Revenue 2000-2001 and Per Sat Average

Taking the average of the top 17 players and ignoring the obvious last three laggards the average revenue per satellite of the operators is approximately $42.3M dollars. The numbers include satellites that have too few transponders for our target such as a Boeing 376, Russian satellites, or the Orbital Sciences lightsats.

If you take numbers from the per transponder pricing and apply that to the large birds the result is an average revenue of at least $50M dollars. What this implies is that with an average per satellite cost of around $250M dollar and revenue per year of $50M the orbital recovery system can be profitable to the satellite operators if the price is a number between $50-$80M dollars. This means that in order for our business to be profitable we need to be able to build and launch our birds for $40-$70M dollars. This is an obvious challenge. However, at this time the number for the price is elastic and can change upward as the market for satellites continues to improve.

Another factor is the orbital salvage service. We can price that service at a premium over the normal price as the insurance companies are liable for far more than our price and the target spacecraft retain their full lifetime and value. The author estimates that we could charge as much as $100M dollars for short term service for stranded comsats.

GEO Spacecraft Aging Issues

A legitimate issue about GEO spacecraft to be life extended is the extended reliability of their on board systems not associated with the propulsion system. This issue can be dealt with by an examination of spacecraft that have been put into inclined orbits to extend their lives. There are three primary subsystems that are subject to aging of geo comsats that we will address here.

Solar Arrays

In the very early 1990's solar arrays for geo comsats began a transition from silicon cells to those made with Gallium Arsenide (GaAs). These cells exhibit a much lower degradation curve relative to silicon cells and was a primary driver in the manufacturers offering a greater life than the norm of ten years at the time. Data that we have obtained from NASA indicate that the degradation is less than 15% over a fifteen year lifetime with the decay rate leveling off in the out years. This indicates that, barring component or subsystem failures the arrays should be able to provide full power or nearly that throughout the extended life of the satellite. Also, the host spacecraft will have a lower power demand by the ability of the SLES to take over station keeping as well as attitude control. This merely shifts the power draw from the host spacecraft to the SLES™.

The spacecraft that have GaAs solar arrays have dominated the industry since the early 90's and therefore they power the vast majority of spacecraft that are potential customers of ORC.

Batteries

The batteries on a geo comsat are necessary to power the spacecraft during eclipse periods during equinox periods. Again a trend started in the late 80's through early 90's to shift from Nickel Cadmium batteries to Nickel Hydrogen. Either way there are spacecraft in orbit that are still operational over almost 20 years with their batteries intact. Information that we have obtained from Eagle Picher[1] Industries indicate that under accelerated testing Nickel Hydrogen batteries have exceeded 22.5 years of life even under accelerated testing conditions more severe than normal operations.

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[1] http://www.tech.epcorp.com/index.htm

Transponder Power Amplifiers

Transponder power amplifiers (PA's) are the final subsystem that is subject to aging degradation due to usage and time. Most PA's are Traveling Wave Tubes (TWT)'s that degrade over time due to cathode erosion and other effects. However, this is the system that has the most redundancy in modern communications satellites. Usually there is one redundant PA for each four transponders. Reliability information that we have indicates that most of this redundancy is not used and therefore is available for the life extended satellite. Again, the satellites that remain in operation in inclined orbits provide the data that we need to verify this statement.

GEO Spacecraft Summary

Our survey of European, Russian, and American built spacecraft has revealed that all of them have common design elements and a level of economic value that make them suitable for the SLES™. The purpose of the preceding sections was to establish the design parameters and that there are representatives of each that are at the time of their life that are suitable for the SLES™ system. The economic considerations are easily ascertainable by a simple counting of the number of transponders with more obviously being of greater value.

Orbital Servicing for Life Extension

First, it must be stressed that what ORC is proposing for life extension does not meet the classical definition of on orbit servicing. In a recent thesis[2] by MIT grad students Elisabeth Lamassoure and Daniel Hastings defined orbital life extension in the following way

> ***Life Extension includes any on-orbit servicing aimed at extending the operational life of the system in its original design; this involves refueling, refurbishing, and repairing***.

This definition is identical to the historical one used by NASA and other space agencies. This is not what ORC is proposing.

In initial discussions with Mr. Walt Anderson, founder of ORC and long time space investor it was stressed that the current cost structure for orbital servicing of spacecraft was too expensive and that a lower cost method had to be developed in order to build a business to operate in the real world. Since cost is usually exponentially proportional to complexity, simplicity is essential in order to meet cost targets. Therefore the SLES™ Mk 1 will not refuel, refurbish, or repair the existing space asset. We offer the following recast of the definition of spacecraft life extension.

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[2] http://www.ssl.umd.edu/space/servicing.html

***Life Extension includes any on-orbit servicing aimed at extending the operational life of the system; this involves refueling, refurbishing, repairing, and or the addition of auxiliary elements*.**

The ORC concept uses the simplest interface possible to a GEO comsat in order to reduce cost as well as deal with the fact that none of the manufacturers have any provision for servicing of these assets after launch. Our system is not dependant upon any "help" in the form of friendly interfaces, ranging targets on the comsat or any other aids.

Spacecraft Life Extension System Design

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We have in our initial discussions and informal trade studies sought to determine the simplest interface possible that will enable the successful execution of the technical side of the business plan. Below in Table 3 is a list of the key design issues of our system.

SLES™ Key Design Issue	Design Solution
Target Spacecraft Interface	Utilize Apogee Kick Stage Nozzle
Propulsion System	Stationary Plasma Thrusters
Docking	Softdock with Hard Capture
Target Spacecraft Extended Lifetime	Inclined Birds Give Lifetime Indication of Ten Years Max
Launch Vehicle	Light Enough for Secondary or Cheap LEO Primary
Technological Integration	Simulation and Testing

Table 3: SLES™ Key Design Issues

The slow progress in the development of spacecraft technology has reached the point to where new designs for on orbit servicing can be considered that are not based upon traditional chemical designs. Also, with the proliferation of heavy lift launch vehicles such as the Ariane V, Delta IV, Atlas V, and Sea Launch a competitive stable of launchers that can handle heavy secondary payloads exists.

SLES™ Top Level Requirements

The SLES™ must operate as a stand alone spacecraft as well as a companion payload attached to a nominally much larger GEO communications satellite. Below in bullet form are the top level requirements for SLES™

- Spacecraft Lifetime
- 12 Years Total Life
- 10 Years Attached to Largest Existing Comsat
- Must be Capable of Flying as Secondary or Primary Payload
- Launch Weight Target (<1000 Kg Wet Weight)
- Spacecraft Operating Environment
- Geosynchronous Transfer Orbit (GTO)

- Low Earth Orbit (LEO with upper stage)
- Geosynchronous Orbit
- SLES™ Spacecraft Interface to Parent Spacecraft
- Mechanical (Physical Attachment to Existing Propulsion System)
- Electrical (None for version 1)
- Target Satellite Vendors Products
  - HS601 (Boeing 601)
  - HS601HP (Boeing 601HP)
  - Boeing 701
  - Boeing 702
  - Lockheed Martin A2100 Series
  - Alcatel SpaceBus 2000/3000 Series
  - Loral 1300 Series

SLES™ Design Elements

The fact that today's commercial spacecraft do not have servicing friendly interfaces was a primary design driver in the development of the SLES™. In a perfect world GEO comsats would be designed for servicing but this is certainly not the case today. This forces a set of design trades on the combined system that tend to increase the complexity of operations as well as the docking system.

The Host Interface

Large GEO comsats share for the most part a common design feature. This feature is a liquid apogee kick motor. These kick motors share propulsion fuel with the on board station keeping thrusters. Most of these systems use a Hydrazine monopropellant thruster and most are in the range of 220 to 490 Newtons thrust. Figure 1 shows one of these thrusters integrated on a GEO comsat.

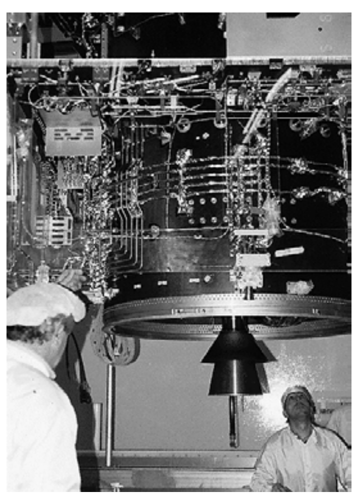

Figure 1: Apogee Kick Engine For the Artemis Experimental Comsat

A decisive advantage of the Orbital Recovery design is that the SLES™ is guaranteed to be aligned with the center of gravity of the spacecraft along the X and Y axes of the spacecraft. This does introduce an issue in the Z axis and this is dealt with in the following sections.

SLES™ Capture Tool

The SLES Capture tool is the only truly unique part of our system design. The conceptual design for the capture tool is that it will insert itself into the apogee kick motor module where it will lock to the nozzle. The German space agency DLR[3] have developed a design that meets our specifications. Figure 2 gives an illustration of the DLR developed capture tool.

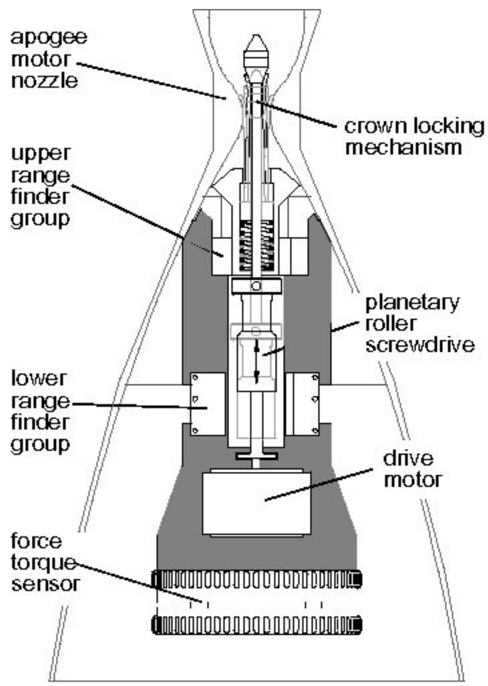

Figure 2: DLR Capture Tool

Orbital Recovery is in discussions with DLR to license this hardware for our use.

Propulsion System Sizing and Design

Obtaining the absolute maximum efficiency from the propulsion system is the critical to the SLES™ design. A cursory look immediately eliminated a chemical propulsion system as being far too heavy to meet our weight requirements. GEO comsats typically carry several thousand pounds of Hydrazine for the standard lifetime station keeping requirements. The standard delta V provided by a chemical system and other parameters over a ten year period are as follows:

[3] http://www.robotic.dlr.de/TELEROBOTICS/ess.html

- North/South Station Keeping 430 m/s
- East/West Station Keeping ~30 m/s
- Propulsion Isp 230 seconds
- Thrust 4-22 Newtons

In the 1990's several American companies signed license agreements with Fakel to bring this technology to the western market. The companies that we have been dealing with are Busek[4] and General Dynamics[5]. Figure 3 provides a picture of one of these thrusters.

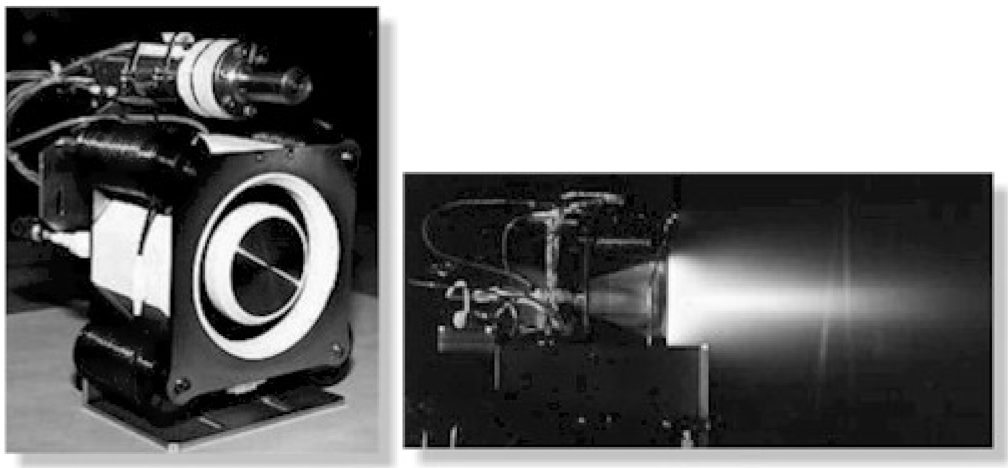

Figure 3: Busek/General Dynamics Stationary Plasma Thrusters

There are SPT thrusters available in a range of power levels that are suitable for our purposes. The thruster shown above is a flight version that is going to fly on a Defense Department satellite in 2004. This version is available to us and has been qualified for up to 7000 hours of operation, which is plenty for our application. Various versions of these thrusters have been flying on Russian satellites for station keeping for over 30 years.

Semi Autonomous Rendezvous and Capture Subsystem

The SAR&C (SARC for short) is the most complex aspect of the SLES™ system. The SARC design is straightforward but the hardware and software implementation for the subsystem has changed dramatically over the past ten years. Some of the components of the SARC have flown in space in experiments conducted by the Japanese space agency NASDA in cooperation with DLR. Figure 4 gives an illustration of the GETEX[6] experiment flown in 1999 on the Japanese ETS VII spacecraft.

[4] http://www.busek.com/el_propulsion.htm
[5] http://www.rocket.com/
[6] http://www.robotic.dlr.de/Klaus.Landzettel/getex.html

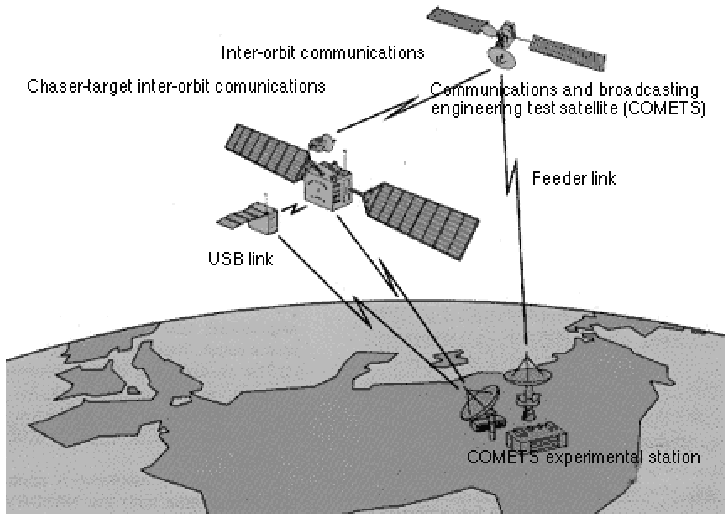

Figure 4: GETEX experiment on the ETS VII Mission

The SLES™ system design significantly takes into account the requirements imposed by the SARC. The requirements imposed on the SLES™ in order to operate as the primary control for the coupled host/child system results in a free flying SLES™ design that will have incredible sensing and control capabilities. The components that make up the SLES™ SARC are shown in table 4 below.

SARC Component	**Purpose**	**Comment**
Attitude Control System	Fine Positioning	~5 arc-minute control
Star Field Sensor	Very Fine Attitude Knowlege	15 arc-second knowledge
GPS Sensor	Onboard Orbit Determination	Navigation from LEO/GTO to GEO
Inertial Sensor	Measure Accelerations in X/Y/Z	Rendezvous fine control
Video Guidance Sensor	Visual Docking Control	Provide operator control
SLES™ Probe	Provide Docking Latch	
Momentum Wheels	Fine Attitude Control	~1 arc-minute control
Software	Integrate All of the Above	Provided via license from DLR

Table 4: SARC System Components

Almost all of the SARC components in the table are available off the shelf today. We are currently in discussions with DLR for the licensing of their technology.

Design Summary

The technologies developed over the past fifteen years in hardware and software developed for on orbit servicing have worked to lower the cost of such systems for the integrator. The work undertaken by DLR in the development of a capture tool for the rocket nozzle of a comsat and their extensive work in developing software for telepresence makes for a considerable retirement in risk for Orbital Recovery. Hardware developed by the Russians in the form of the SPT's help to dramatically reduce propellant needs to carry out our mission. Additionally, advances in solar cell technology and power system efficiency makes for a more compact system that can traverse the distance between GTO and GEO in a shorter period of time, thereby reducing the risk of hardware failure during the traverse through the radiation belts.

Market Summary

In developing a space business practicality is paramount. The perceived risk of a business of on orbit servicing is so high that the business plan absolutely must make plain sense to a potential investor. This business plan must meet or exceed all of the parameters associated with the typical criterion of investment including ROI, risk, management team, and the intangible of confidence. The best way to establish that confidence is to be able to clearly indicate the benefits and rewards to the customer and investor. These parameters are best shown when political decisions are taken out of the equation of business. We do not disregard the government market but the purchasing decisions of governments are based upon political considerations that cannot be managed by a company.

When dealing with a purely commercial environment the political considerations do not rank as high as the financial considerations associated with the introduction of a new technology. Although the business world is conservative they understand the relative weighing of risk and reward. Our SLES system then becomes a simple risk Vs reward decision. Business lives with this every day and the satellite market is no stranger to risk. With commercial GEO comsats we can clearly enumerate the value proposition in a way that is obvious to all concerned. The key then becomes execution. For Orbital Recovery that is the fun part.