Creating a Sustainable Assembly Architecture for Next-Gen Space:
The Phoenix Effect

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Nomenclature

ApSAT = Aperture Satellite
HPA = Hosted Payload Assembly
ISS = International Space Station
MAGE = Mechanical Assembly Ground Equipment
PMSE = Project Management and Systems Engineering
PEM = POD Ejection Mechanism
POD = Payload Orbital Delivery system
PCT = POD Capture Tool
RCA = Retired Candidate Asset
Satlet = cellularized satellite building blocks
S/T = Servicer/Tender
TRL = Technology Readiness Level

ABSTRACT

Despite gains in technology development and a strong motivation to reduce costs, current space systems that support military, civilian and commercial needs face rising schedule, complexity and cost challenges. All other terrestrial platforms, whether in the air, on land or sea, have adopted an “assemble, repair, upgrade, re-use” paradigm to maximize efficiency and minimize recurring costs in response to ever changing requirements or needs.

DARPA’s Phoenix project was created to rethink and re-architect how space systems are created to support DoD mission needs, shifting from on-Earth integration and assembly, to on-orbit. The primary objective is to demonstrate the ability to upgrade or create new space systems at greatly reduced cost, and support DoD mission needs in a new way that increases tempo and importance of high value mission payloads to orbit, allowing a much faster response to new challenges.

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I. Introduction

For the past 50 years, the overall architecture of satellites has remained virtually unchanged. In general terms a satellite consists of a bus (the platform that operates in space) that supports a payload designed to execute a specific mission. The customer, whether Government or Commercial, is interested only in the payload and its operation, but must pay the entire cost of the bus plus payload plus launch to realize the benefits. With few exceptions satellites are point designs. The exceptions are when a fleet of satellites is required, such as the Global Positioning (GPS) or Iridium constellations, or communications satellites in GEO that have multiple satellites operating simultaneously.

The Phoenix project is examining the feasibility of constructing satellites on-orbit, by investing in aggregation modules or cells, coupled with advanced robotics to allow various forms of assembly, repair, upgrade and reuse in space. Investments have been explored in showing cellular satellite building blocks made by modularizing monolithic bus functionality can match the requirements of a specific defined mission.[i,ii,iii]. These cellularized modules or satlets, are envisioned as being capable of providing some but not necessarily all of the functionality needed by the new satellite or space system, but full satellite functionality is achieved by aggregating multiple satlets (potentially multiple types of satlets) into a single system. The initial instantiation of on-orbit aggregation proffered by Phoenix to demonstrate the satlet-based construct was through a major investment in GEO-based robotics. Satlets and Geo robotics, through an ambitious representative demo mission, were designed to satisfy the major technical domain goals required to enter a paradigm of assemble, upgrade, repair and reuse capability.[i]

To substantiate a sustainable business case, Phoenix was envisioned as a holistic and sustainable ecosystem, with investments in specific technology areas needed to prove the viability of the new construct, with a goal to completely re-write the current satellite build cost model. As a technology architecture Phoenix comprises three key pillars of research that represent variables in current satellite cost models, shown as they relate to goals of cost reduction in Figure 1;

- A new way to design satellites via cellularization,
- Faster tempo to get the "cells" and/or low mass material to orbit, and
- A way to manipulate and assemble satellites on orbit by using highly capable robotics and end effectors handling and assembling using the cell based modules or satlets.

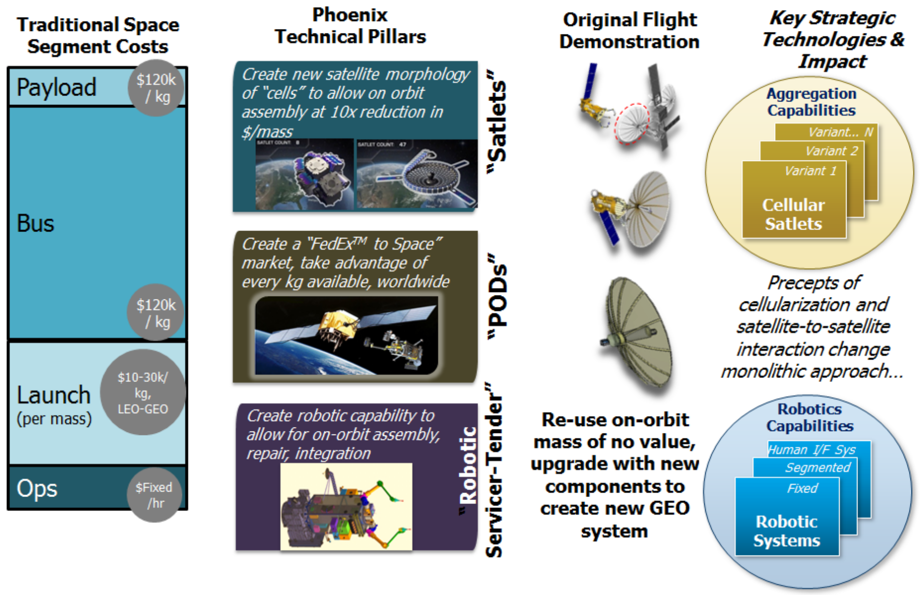

Figure 1. Technical investment area pillars behind DARPA Phoenix's goal to address the traditional "bus" costs in a new way.

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I. Examining precepts to sustainable market or demand justification development for Commercial/DoD investment

In business, once a market exists, market demand helps spawn entry motivation for new players and/or new technologies. There is an extra physical and perceptive risk barrier to experimenting with new technologies or entrants, in space applications either to develop new demand models or to change the current monolithic ship/shoot/forget approach to space platforms. Creating a new market also typically requires venture capital in some form; DARPA is supplying the initial investment for this new market via technology development specifically in space via Phoenix. Several specific "demand justification" metrics are also postulated through the interaction with current industry and economic analyses to show the feasibility for a new way of doing business in space (for both commercial and military users). It is instructive to define "market" in terms that relate the "demand" typical of market based economics, to the "need" relative to a requirements-based economics typical of the military domain.

The justification for bigger and more powerful commercial satellites is driven by end-use customer demand. The existence of millions of users in a geographic area translates to revenue; e.g. from streaming content (via data flow and RF communications). The justification in the military for bigger and more powerful satellites is driven by a need to amortize the capital expenditure of taxpayer dollars to meet projected threat profiles. This application has the form of data content streamed to thousands of users (as a relative weighting) who then use the information to affect the well-being and safety of millions. The cost models for both areas pre-suppose a build, launch and operate process to get the platform in space, without any chance of repair, upgrade or re-use. Coupled with limited availability and high price launch, this has tended to drive the need to validate the platform before launch with as minimal risk as possible, and as much oversight, redundancy, and fail-safes included, which in turn drives the end-platform cost higher.

Conventional spacecraft are manufactured to provide value over a specific time-frame. The business case closes when the value of the mission over time exceeds the cost to manufacture, launch, and operate the spacecraft. For military spacecraft the value is the ability to accomplish specified missions. For these traditional spacecraft, the capabilities are locked in during the design process and rarely can be changed once the spacecraft build is completed. Updated software is the main opportunity for up-grading existing systems on-orbit.

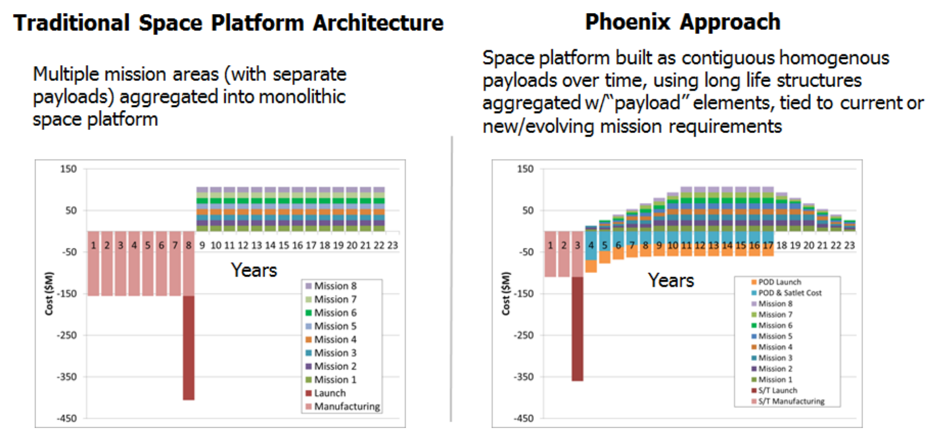


Figure 2. Example of space platform acquired as homogenous aggregated military requirements (via payloads) in left graph, into a heterogeneously build satellite platform over time in right graph.

To evaluate some level of "goodness" of this approach, the value of each platform can be compared to expected "revenue". In the commercial sector, revenue is in real dollars with the metric of profit from income versus amortized cost of the platform and operations, for providing service to the millions of customers who utilize data content delivery. For the military, there is no profit or cash based metric, but it is possible to quantify goodness on a "quasi-revenue" basis solely on the operational use over time divided by the life of the elements (i.e. payloads) on the space platform providing the service. The graph on the left of Figure 2 shows an example of how this is notionally actualized into value in a representative military satellite system, where each mission area is a separate "payload" that is providing input for a specific requirement (i.e. identified threat or need etc.).

Now let's look at a method that provides for an on-orbit assemble, repair and upgrade approach, where space robotics and aggregate-able modules offer a number of methods to add additional life and performance-based dimensional value to the space platform over time thus extending the mission in some defined way (i.e. the “Phoenix effect”). First examination of this is shown on the right hand graph of Figure 2, which shows the same two-dimensional representation of quasi-revenue versus time. However, the profile takes into account a constant step wise progression of increasing mission aggregation, through delivery of a base bus platform with subsequent deliveries of the payloads that are needed to address the requirements originally intended, over time. What is interesting is that this construct offers the possibility of a much faster delivery to orbit from start of the acquisition versus needs delivery on-orbit, to get some of the initial payloads operational, at almost 2-3x faster than the traditional monolithic designed and acquired approach (shown in the left graph of Figure 2).

Figure 3. Representation of alternative quasi-revenue profile over time and additional value metrics from the Phoenix effect.

But what the Phoenix effect also enables is a third axis representation of “goodness” shown in Figure 3; the ability to manipulate and assemble elements on orbit to allow current spacecraft to expand either the bandwidth of existing mission capabilities or expand the set of missions that can be accomplished. Robotics, and the ability to assemble on orbit, now allows a paradigm shift in the primary market of DoD systems – agility and nimbleness can be enhanced, enabling more responsiveness to new threats in almost real time (months as opposed to years). The ability to address emerging missions in a timely manner has always been a concern for both the DoD and the spacecraft acquisition community, given the long duration to build a large monolithic system. Furthermore, having robotic capabilities on-orbit would open up other value enhancements such as enabling repair or mission lifetime extension on other DoD spacecraft, avoiding critical mission availability gaps, and further expanding the value proposition from a 2D to 3D representation of value to the military, as indicated in the third axis.

II. Examining sustainable technology to enable demand justification

The precept proposed by Phoenix is that technology can be created to enable the assembly, repair, upgrade and re-use paradigm, which is used in all other terrestrial applications, to be extended profitably to space. To do this Phoenix starting at the beginning; looked at how satellites are built today, explored decomposing satellites into a much different morphology inspired originally by biology, and looked at how they could separately be sent to space to be assembled in-situ at a much lower cost. There are fundamental precepts used on Earth that need to be enabled in the space domain to affect this new approach successfully.

Mass production

The early 20th century saw the introduction of Taylorism and of Henry Ford's introduction of the moving assembly line. In these ideas, the cost of the production system and apparatus was shared across first many identical products, e.g. the Model T and then across a family of similar products. These methods of production work only if the number of units produced is large enough that the cost of the infrastructure per unit produced becomes vanishingly small. Unfortunately, satellite production quantity today is single unit or a low volume, except in the case of constellations[iv]. Since spacecraft are not modular today either in function selection or in modularization to reduce cost, the production run is too low. Thus one precept that was explored was the construct of high volume, low cost production, applied to satellites.

Modularity

A key element to enable high volume low cost manufacturing to apply to a space platform is in modularity. Modularity speeds up the design process, enables cost savings in re-use, and allows streamlined manufacturing processes. Scientific instrumentation is an example of highly complex elements that have used modularity for years. For instance, a modern instrument usually consists of a custom front end (the payload), a controller (one or several modern CPUs with communications capabilities), a keyboard and a display. The cost of computer, communications, keyboard and display are modules that are amortized over the family of products and the front end is application or "mission" specific to one instrument. The overall cost of the instrument makes good use of the reduction in cost of the electronics since it follows Moore's Law. Another instance of this precept of modularity combined with high volume low cost production is the proposed smart phone announced by Google where the customer has the ability to choose modules to personalize his/her phone[v]. DARPA has examined modularity in the past applied to other platforms both for ground use (through iFAB, META, AVM[vi]) and space use (via disaggregation in System F6[vii]) specifically to save cost, and decrease time from need to instantiation.

Phase 1 of Phoenix explored modularity and mass production in a new design methodology to increase the volume of modular aggregatable elements that could create a satellite. If modules suitable for use over a wide spectrum of satellites could be designed then sufficient volume to amortize the cost of design, procurement and manufacturing over many modules could become a viable way to build satellites[viii].

Aggregation of modular production volume-level cells compared to traditional approach

To explore the precept of mass production and modularity in detail, Phoenix has created the ability to build cellularized satellites where instead of the satellite bus containing the payload as part of the satellite, the payload drives the satellite configuration and resulting "bus". The system then needs just sufficient modules and just sufficient capability to achieve a closed design and to address the typical redundancies and inefficiencies in any cell based system, the cost of redundancy must be offset by a much larger reduction in cost of the individual cells. The first generation Phoenix satlets are being developed to take advantage of modern COTS technology such as Android based processors and medical supply service valves in order to take advantage of Moore's law and avoid the long development time of modern satellites where electronics generation lags COTS components often by many years. Thus Phoenix would follow the cost reduction curves of commercial-based development and production.

The concept of cellularization and aggregation also provides a unique method to change the technical performance execution and design of any individual satellite functional element. Consider the example a communications satellite with an antenna of approximately 16 meters in diameter and bus mass of about 3200kg, dry mass. Now consider the guidance, navigation, and control (GNC) subsystem design. Traditional attitude control is from reaction wheels or control moment gyros inside the bus with a maximum moment arm of about 30 cm diameter. If you were able to build a control scheme that took advantage of the radius or extremes of the antenna i.e. where the antenna carries the GNC devices and not vice versa, the moment arm of the reaction system would go from 30 cm to 30 meters or approximately 100 times the control authority. This factor of 100 can be used in many ways, to reduce the fuel needs, to increase lifetime, etc. Thus a small inexpensive satlet placed properly may be able to replace large expensive pieces of traditional monolithic functionality. The same argument applies to thruster placement, as an example. Figure 4 shows examples of the type of configurations possible with a satlet-based architecture that could take advantage of geometries atypical of today's traditional satellite designs.

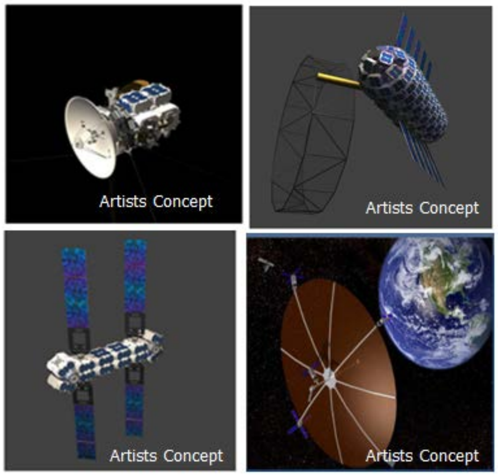


Figure 4. Examples of the type of geometric configurations possible for on-orbit assembled modular satellites.

But what about inefficiencies associated with cell design? Figure 5 shows an example of a “satletized” satellite morphology compared to legacy buses relative to mass and aperture size (as an application specific payload example). In the first order analysis both configuration methods were examined relative to mass, based on a specific aperture size. That is the blue line represents a “cellular based design” that was able to take advantage of a conforming geometric configuration to take advantage of leverage of distance (as described above with a GNC solution). The green line represents a geometric configuration that is the same as a traditional satellite. The first order analysis shows with a “cellularized” satellite design based on satlets, mass is less with a cellular architecture than with a traditional architecture at smaller apertures. As you get to larger apertures (and thus larger structural geometries) to support this type of monolithic payload element, depending upon the geometric configuration mass may be equal to a traditional design (as shown by the pink band between the blue and green lines of satletized satellites). But what happens to cost?

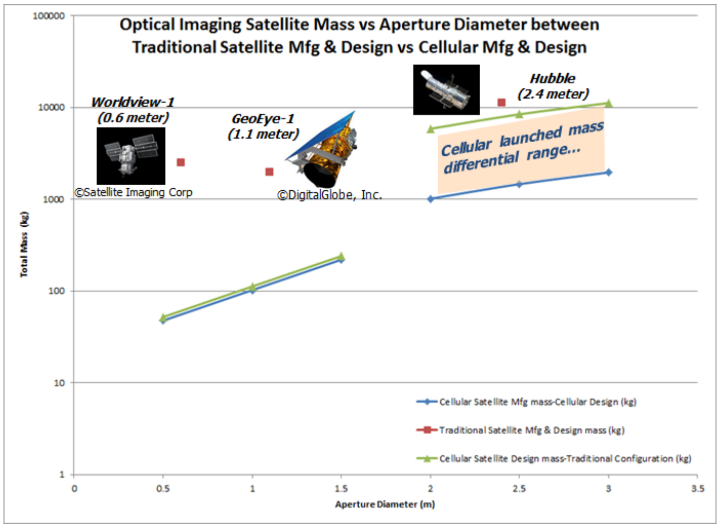


Figure 5. First order comparison of satletized spacecraft to traditional systems in mass and aperture size.

Figure 6 shows a graph of specific cost versus aperture diameter, based on the first order analysis described above. Taking into account true satlet module production benefits, the in-efficiency trend indicated in pure mass vs aperture size reverses itself when looked at via specific cost/mass. That is, the cellular satellite, either a traditional or custom cellular design configuration, drops in $/kg as the aperture size grows. The production cost numbers realize a higher savings for the same mass as a traditional satellite with a larger primary monolithic payload element (i.e. the aperture). The cost savings, to first order, outweighs the loss of efficiency in mass due to cellularization; even factoring in potentially higher launch costs to get up cellularized elements (i.e. more aggregate mass).

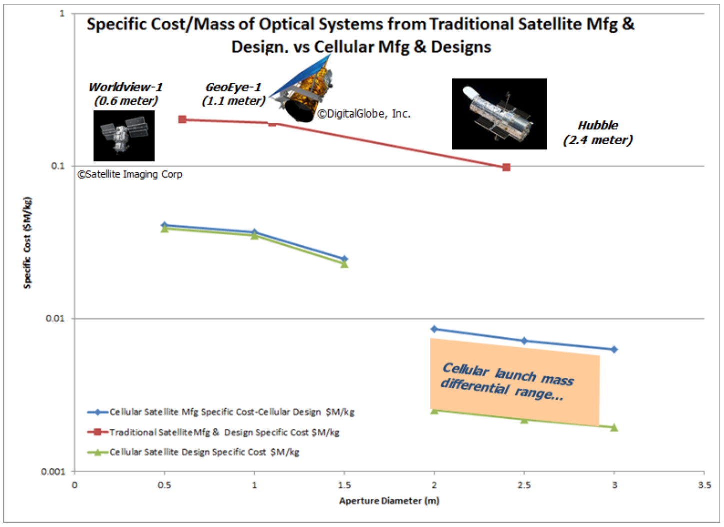


Figure 6. First order comparison of satletized spacecraft costs relative to traditional systems in specific mass and aperture size.

Cellularization does something else unique; it tends to shift the overhead of coordination and control of a set of distributed modules (satlets) from pure electro-mechanical design actions to computational focused actions based on software. This results in a shift from adding components that increases mass, to a “mass free” ability to change the configuration and thus resulting performance and functional execution of a typical satellite in space. If communication between each cell can be wireless, the new challenge then becomes research into aggregation of satellite functions, such as determining which of the many thrusters to fire at any given time, not adding additional thrusters (and thus mass). Cellularization may shift the current problem of cost of launch tied to mass, to a much lower cost of software development with no mass consequences (but acknowledging mass inefficiency upfront to cellularization). The shift in focus to software follows the industry trends today where advanced technology enables software applications to be democratized across a much wider user base, down to individuals who use, as examples, cell phones or wireless devices to either reconfigure or control for new applications. The challenge of spacecraft design then is not that satlets can possibly be appropriate, but rather what multiplicative factor would be produced by the use of satlets in fast ground design and on-orbit reconfiguration for new payloads (i.e. revenue or threat addressing pieces of hardware).

While cellularization offers intriguing possibilities to explore distributed systems on the ground, in the gravity-free space environment it allows almost unlimited sized platforms, where the ability to utilize the large free unencumbered volume is a significant advantage, and does not require limitation in geometry to fight restrictions due to launch loads against the 1-G environment. Cellularization may well open up application trade spaces that so far have eluded space architects; one specific example may be space based solar power systems. In a NASA NIAC report authored by Dr John Mankins it identified independently an instantiation of large structures enabled by the precept of “modular” aggregatable modules or cellularization directly.[ix] But to assemble on orbit requires technology for manipulation in space, namely robotics.

Manipulation and Control (Robotics)

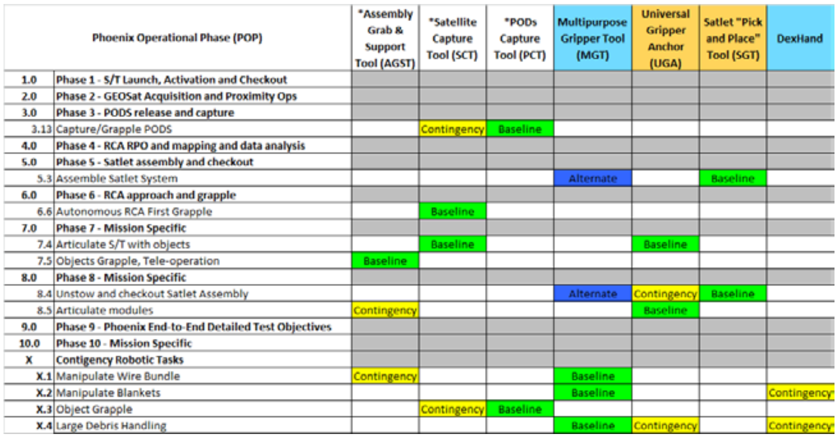
The assembly, repair, upgrade and re-use paradigm used ubiquitously today on Earth is only possible due to the ability to manipulate the component parts to build the platform. Construction sites are planned out as to how to schedule deliveries as needed, Just-In-Time (JIT) manufacturing, where to place materials and parts, how to assemble in sequence, and how to fasten all within a 1-G environment. Humans, tools and robots all affect construction and assembly via high degrees of manipulation that are taken for granted. In space this capability must be introduced separately. It is useful to look at how this is done today on the ground as context for the introduction of space robotics needs.

To use one or more robots in an assembly tasks requires obtaining a robot with suitable motion and sensory abilities (either built-in or added-on externally) and that has the requisite kinematic performance, laying accuracy and repeatability. In addition there needs to be proper tools and fixtures appropriate to the assembly being performed. In terrestrial applications, applications are performed on an assembly bench, fixtures and vises hold the parts during assembly and fastening tools are used. The exact type of tools and their capacity is determined by the application. In terrestrial applications a rough guide is to handle objects that are handled by humans, so applications of the size and weight of a bowling ball are often appropriate. (OSHA regulations top out at 75 lbs for one person lifts[x].)

Secondly in terrestrial applications, parts are presented to a robot in a prescribed order and in prescribed poses in order to maximize throughput and minimize cost per unit produced. They must also be made in the correct material (i.e. be of a high enough strength, proper previous use history, etc.)

Robots require basic functions to acquire sensory data and compute appropriate actuator drive commands to ensure stable servo operation of the joint in question. At the first (or lowest) level where each joint motor is controlled (joint level control), the object being manipulated moves in Cartesian space but the robot joints form its own robot geometric frame. The second level is where commands are given in the geometric frame and are then translated internally into joint level control. Again real-world sensors can be translated back to and from the various Frame levels as needed.

A third level is the application level where motions are specified with respect to objects in the application. For instance, if a hole in a plate was be designed relative to the edges of the plate, an action may be defined as 'put the bolt into the hole on plate surface 4 inches’, with the robot software taking care of the joint level actions to achieve the goal. Not all levels are needed in all applications and the choice of level is application dependent.



Phoenix Operational Phase (POP)		*Assembly Grab & Support Tool (AGST)	*Satellite Capture Tool (SCT)	*PODs Capture Tool (PCT)	Multipurpose Gripper Tool (MGT)	Universal Gripper Anchor (UGA)	Satlet "Pick and Place" Tool (SGT)	DexHand
1.0	**Phase 1 - S/T Launch, Activation and Checkout**							
2.0	**Phase 2 - GEOSat Acquisition and Proximity Ops**							
3.0	**Phase 3 - PODS release and capture**							
3.13	Capture/Grapple PODS		Contingency	Baseline				
4.0	**Phase 4 - RCA RPO and mapping and data analysis**							
5.0	**Phase 5 - Satlet assembly and checkout**							
5.3	Assemble Satlet System				Alternate		Baseline	
6.0	**Phase 6 - RCA approach and grapple**							
6.6	Autonomous RCA First Grapple		Baseline					
7.0	**Phase 7 - Mission Specific**							
7.4	Articulate S/T with objects		Baseline			Baseline		
7.5	Objects Grapple, Tele-operation	Baseline						
8.0	**Phase 8 - Mission Specific**							
8.4	Unstow and checkout Satlet Assembly				Alternate	Contingency	Baseline	
8.5	Articulate modules	Contingency				Baseline		
9.0	**Phase 9 - Phoenix End-to-End Detailed Test Objectives**							
10.0	**Phase 10 - Mission Specific**							
X	**Contigency Robotic Tasks**							
X.1	Manipulate Wire Bundle	Contingency			Baseline			
X.2	Manipulate Blankets				Baseline			Contingency
X.3	Object Grapple		Contingency	Baseline				
X.4	Large Debris Handling				Baseline	Contingency		Contingency

Figure 7. Example assignments for both generic and mission specific tools examined in Phase 1 for Phoenix.

Application command and control may also be done by using a human-in-the-loop (where the in-space applications are via humans from the ground). Human in the loop has been demonstrated from ground to space on the International Space Station (ISS) on a SPHERES experiment and the refueling demonstration by GSFC[xi,xii]. The above discussion on frames applies to human-in-the-loop application, but more important for control in space is the need to work in spite of the communications time delay to and from orbit to provide a safe set of operations.

Specific on-orbit assembly or servicing tasks require solid solutions and thus, need work in point cases. As an example of a point case for developing mission specific tools, Figure 7 shows the assignment table used for the tool kit assembled for Phoenix in Phase 1 which includes both multi-purpose and mission specific end affecters for the original repurposing mission proposed.

Parts Supply and Logistics.

Assembly in space will face the same fundamental issues of parts delivery, part pose, part manipulation, fastening methods in terrestrial applications, yet add in the complication of zero-g. Part of the challenge of space assembly is in finding good solutions to the analogous problems posed from terrestrial challenges. A powerful tool is to validate the parts before launch, place them in the correct sequence and hold them in the correct pose through launch to their use in space. This must be given strict attention and the Phoenix solution is to use piggy-back rides to orbit on commercial launches, where each "part" or "module" sent up is known and the ability to "unpack" on orbit is addressed.

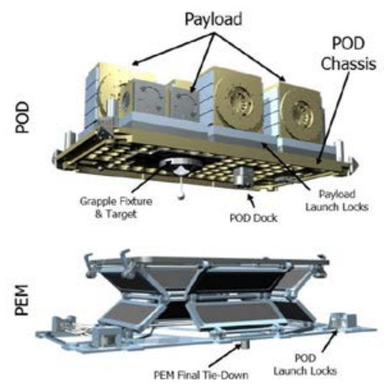


Figure 8. Initial design of a hosted payload assembly (HPA) that consists of an ejectable POD. (MDA image)

Assembly anywhere can proceed only after the parts for assembly are delivered to the production site, in the correct pose (described above). Translated to space, the production location is on-orbit, which also adds the challenging economics of space delivery. A big satellite normally needs a dedicated launch and that usually incurs a great expense. Delivery to the GEO orbit is normally of the order of 200 million dollars per launch. Methods of ameliorating this cost take various forms, including ride sharing and the use of the ESPA ring or other multi-satellite launch system. These methods rely on the catch-as-catch-can scheduling of finding a suitable launch. The Phoenix approach was/is to concentrate on making arrangements with the builders of commercial satellites to carry materiel to GEO orbit. GEO orbit was chosen because it is the most valuable commercial orbit and because there is regular delivery of satellites there. World-wide, there is a typically a launch more often than once per month thus supporting the possibility of a "FedEx^{TM}" or "UPS^{TM}" service to orbit.

To solve this, another technical pillar of Phoenix is design of a Hosted Payload Assembly (HPA) that would carry material to the vicinity of GEO where it is then safely ejected into a stable orbit position and condition. The intended use of this new delivery mechanism is through hosted payload services from commercial communications satellites. Safe ejection of this new payload ensures that both the ejection process (via a payload ejection mechanism or PEM) and the object ejected (the Payload Orbital Delivery (POD) module) do not interfere in any way with the more expensive communications satellite. Commercial customers have seen the value of PODS and on-orbit operations such as maintenance and commercialization of the PODs idea as a means to validate new revenue or use case.

The PODs that meet this stringent specification can carry a variety of material from earth to orbit at the cost that approximates the cost of the additional fuel to carry the mass to GEO. The Phoenix PODs are envisioned to carry satlets, tools, fixtures and other material needed for the intended mission specific application. Figure 8 shows the latest Phoenix POD design, whose current design is 1x1x0.4 meters and is sized between 65 to 135 kg of free flight capable mass.

III. Sustainable Orbit operations through domain knowledge and risk reduction

The Phoenix project decomposed the separate elements of planned on-orbit activities to accomplish its mission into Operational Phases (referred to as Phoenix Operational Phases or POPs). Most of the POPs are generally the same regardless of the end mission as each requires satellite-to-satellite interaction starting essentially at launch. What differentiates a specific end-use case is the mission specific event (i.e. assembly, servicing, augmentation, etc.) instantiated once the final rendezvous and dock of two separate satellites occur, where the fundamental differences are in specific tools or robotic end effectors (as examples) for a very focused application. Table 1 shows an example of ubiquitous actions mapped to a specific mission end-interaction case that was developed under Phase 1 for Phoenix.

TABLE 1. Mapping Operational Phases of Sat-to-Sat Interaction to Ubiquitous and Mission Specific Actions

Operational Phase	Ubiquitous Sat-to-Sat Actions	Original Phoenix OP's
Servicer Initiation and Support	Servicing Vehicle Launch and Activation on orbit	1) Servicer/Tender launch, activation and checkout
Logistics and Resupply Initiation and Support	Launch of Logistics and Resupply (i.e. tools, fuel, parts, new payloads etc.)	2) POD launch delivery via commercial hosted payload launch 3) POD RPO and capture
Client Spacecraft Validation for Interaction	Validation of On Orbit Satellite for/prior to Interaction, Far and Near Rendezvous prior to Interaction (e.g. inspection)	4) RCA RPO, mapping and analysis 6) RCA final approach and grapple
Satellite-to-Satellite Interaction	Mission Specific Interaction and End Use Application (i.e. refueling, repair, re-location, upgrade, assembly, re-use, etc.)	5) Satlet assembly and checkout 7-10) Mission specific satellite to satellite engagement and operations, S/T hibernation (transit to parking location as applicable)

During Phase 1 the Phoenix team has been working across the POPs to reduce mission risk through physical testing. A steady buildup of hardware-in-the-loop tests has been occurring at the component level to validate initial precepts in each POP during this Phase. Building upon the success of the various component tests, a set of combined validation tests ("Phoenix Technology Demonstrations" or PTDs) are planned to be conducted to more directly prove out the various techniques, technical hardware concepts and human-in-the-loop interactions that are required under the operational phases identified in Table 1, applicable to most sat-to-sat interaction missions (instantiated via the original POPs). These PTDs are planned during Phase 2 and the robotics efforts would be carried out at NRL's Space Robotics Lab. The PTD's are listed below and descriptions of each follow along with Phase 1 tests to-date that feed into each one.

PTD-1: Validation of Robotic Toolkit Ops and Resupply Logistics Demonstration

This demonstration set is meant to validate basic robotic toolkit operations and notional resupply logistics (via a POD capture and early unpack). The PTD would demonstrate pre-capture POD inspection, autonomous capture of a POD (Figure 9), securing the captured POD on a work bench hard point, and tele-operated unpacking of the POD. The goal is to perform POD capture operations fully autonomous. The subsequent POD manipulation tasks would be performed using a combination of scripting, partial autonomy, and tele-operated robotic modes. POD capture would be simulated using NRL's Contact Dynamics Test bed, and would exercise the visual servoing system, the compliance control system, and the inverse kinematics and obstacle avoidance system.

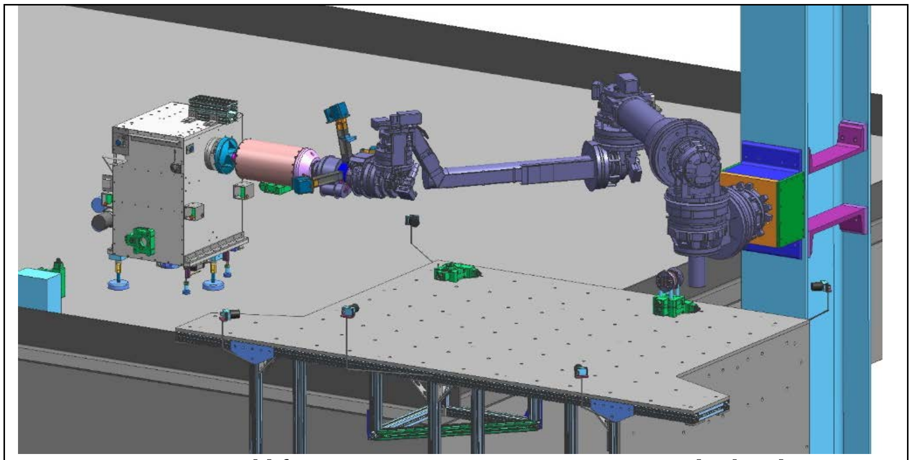


Figure 9: PTD-1 would focus on autonomous POD capture and related operations. (NRL image)

Key elements in the test would include the FREND arm, the MDA PCT (POD Capture Tool), and a POD simulator (mass, inertia, and PCT compatible grapple fixture). Each of these elements has already been proven separately in Phase 1. Figure 10 shows an MDA test of the PCT's ability to capture a simulated free flyer in off-nominal angle and rates, Figure 11 shows interactive tests with a moving POD that was conducted using the MEI test suite connected to the NRL robotic control arm to validate a latency compensation methodology.

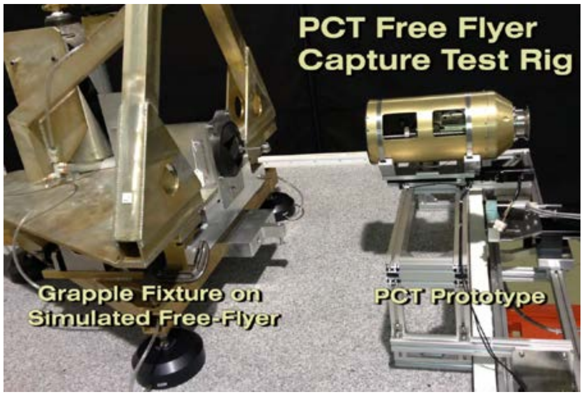


Figure 10: PCT capture test setup. PCT on right, free floating mass with Grapple Fixture on left. Various closure rates, approach angles, and approach offsets were tested. (MDA image)

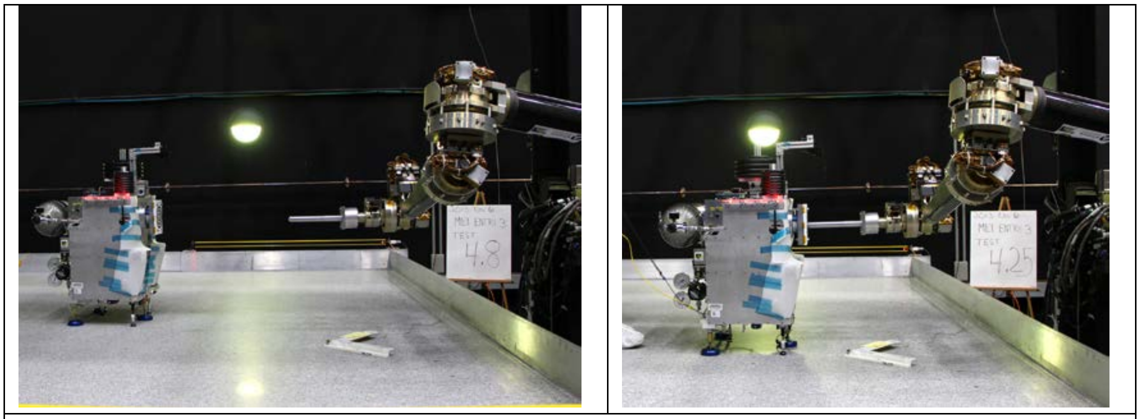


Figure 11: Moving POD tracking test, initial states (moving POD, active arm), tracking and contact. (NRL images)

Phase 2 also intends to include validation of the PEM (POD ejection mechanism) to verify low rotation normal separation of a POD from a host spacecraft (Figure 12). Phase 1 analysis completed and showed safe methods for on-orbit separation that would avoid the high value GEO region for logistics modules (POD's) and provide methods for navigation and tracking from ground and the Servicer vehicle for recovery[xiii].

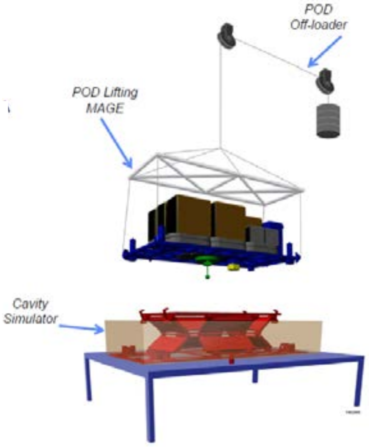


Figure 12: Notional PEM separation rig, including constrained volume on host spacecraft, PEM, POD, and POD off-loader to allow testing in 1g. (SS/L image)

PTD-2 Payload Refresh, Assembly and Installation Demonstration

The next series of demonstrations would concentrate on techniques of robotic assembly of an external payload and the installation of that payload onto a spacecraft mockup (Figure 13). This would primarily be tele-operated emplacement tasks, and would exercise the ability of the robotic workstation to provide sufficient situational awareness cues to the operator and the ability of the operator to precisely control the arm in the presence of realistic communications delay and simulated orbital lighting conditions.

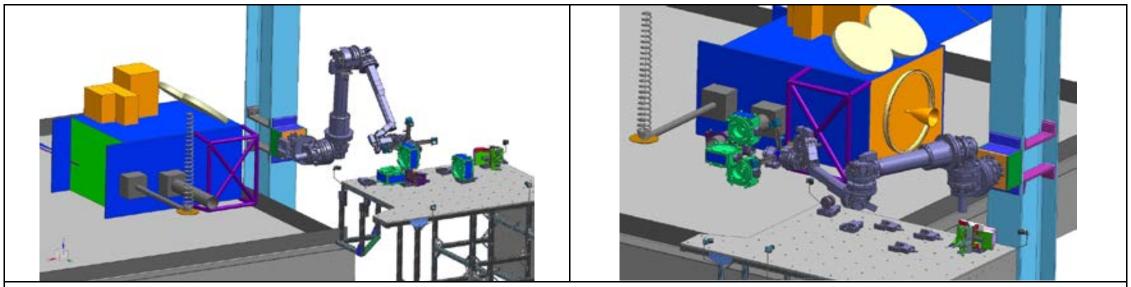


Figure 13: PTD-2 would focus on robotic tool change out operations, manipulation and assembly tasks. (NRL image)

PTD-3 Dexterous Servicing Demonstration

The goal of the last demonstration is to showcase end-to-end techniques required for sat-to-sat interaction, via dexterous robotic manipulation tasks. This may instantiate itself in a demonstration that steps through all the various phases of servicer to client rendezvous, grapple, and then mission specific application such as freeing a stuck deployable or repairing torn thermal blanketing. The precise goals of this PTD would be established based on lessons learned from PTD-1 and PTD-2 as well as from inputs from key GEO robotics stakeholders.

Phase 1 of Phoenix spent a considerable amount of time validating the various concepts for RPO techniques and sat-to-sat contact interaction through multiple HIL activities. As an example, all of the RPO sensor types under consideration for Phoenix were run through a simulated POP4 at the Smithsonian Udvar-Hazy facility in Chantilly, VA in March 2013. A rack supporting the RPO sensors was positioned, via boom lift, at a variety of approach angles and distances from a high fidelity mockup of a TDRS satellite suspended from the ceiling of the hall (sitting over a retired Space Shuttle), shown in Figures 14 and 15. Lighting conditions were varied as well to exercise a variety of optical sensors. Visual, LIDAR, and other data was collected and analyzed to generate point clouds which could be used to validate computer models on the ground for dexterous servicing action plans, show in Figure 16.

Figure 14: "Night at the Museum" setup includes high fidelity TDRS mockup and Phoenix sensor package on a boom lift. (NRL image)

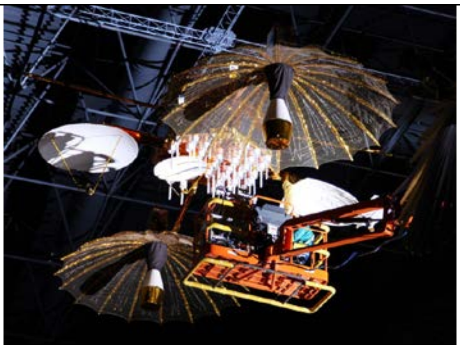


Figure 15: Closer view of the TDRS mockup and Phoenix sensor package on the boom lift. (NRL image)

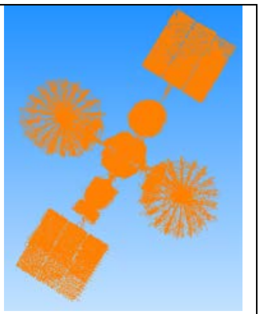


Figure 16: Example point cloud generated by LIDAR used during the testing. (NRL image)

Based on the information collected in a validation activity of a client satellite using various sensors, a servicing vehicle can then approach, grapple, and dock with a client spacecraft. Techniques to accomplish this with a primary arm were demonstrated previously at NRL using a simulated grapple fixture (Figure 17). Once the bus positions the robotic arm within a 2 meter pre-grapple box, the machine vision system demonstrated guiding the robotic arm to grasp a verified grapple point such as a launch vehicle interface (e.g. Marmon ring). Phase 1 also addressed a key consideration during first contact between two different satellites, that of differential charging, and was not found to be a major issue from results in actual condition tests in an NRL plasma chamber (Figure 18).

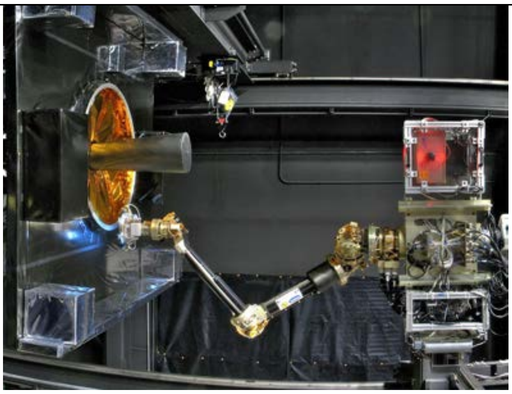


Figure 17: FREND arm at NRL equipped with Marmon ring grasping tool has been successfully demonstrated many times in a variety of configurations and lighting conditions. (NRL image)

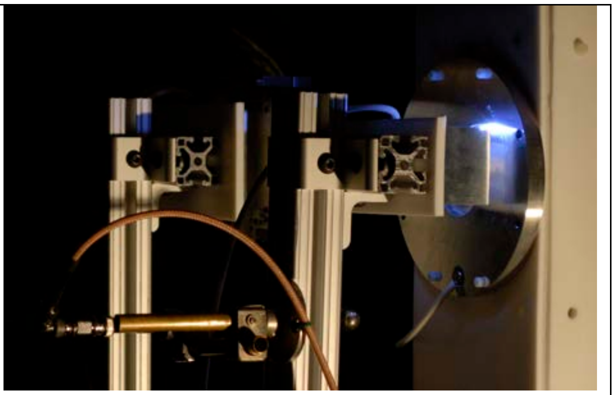


Figure18: Differential charge testing for first contact risk reduction (NRL plasma chamber image).

Phase 1 performers ATK and Honeybee specifically demonstrated tools that support spacecraft capture via a Marmon band (Figure 19/20) and grasp of a vertically mounted circular boom (Figure 21) respectively.

Figure 19: Spacecraft Capture Tool (SCT) pre-contact versus a Marmon ring. (ATK image)

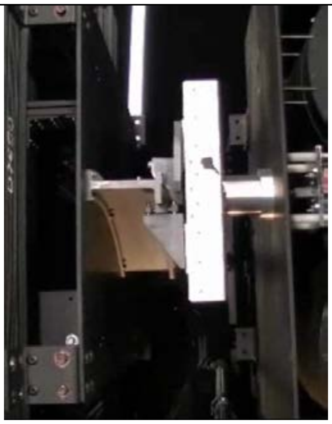


Figure 20: SCT at Marmon ring capture. (ATK image)

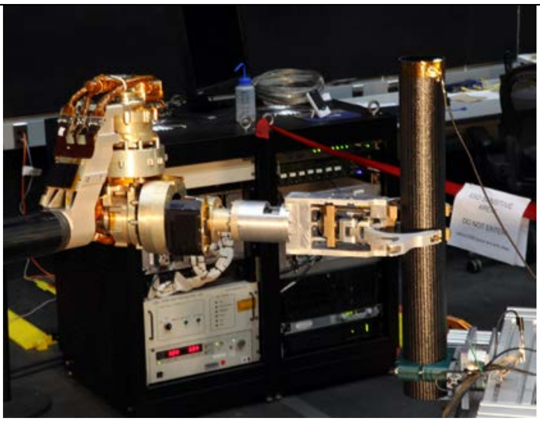


Figure 21: Universal Gripper Tool (UGT) mounted on FREND arm (left side) grasping a vertical boom (right side). (NRL image)

IV. **Addressing the Culture changes required for sustainable operations**

Technology changes are necessary requirement to enable new market openings, but acceptance of technical concept validity that may challenge existing culture is ultimately required for execution. There are two major areas of acceptance that apply to what Phoenix engenders; safety of operations for satellite-to-satellite interaction, and duality of the inherent technical capability.

A significant dichotomy exists in the precepts that Phoenix enables, since all space systems today represent a "dual-use" capability; what can be used for productive peaceful operations can also be used for non-peaceful endeavors. The domain of space suffers from much higher consequences (in the orbital domain) from satellite to satellite interactions that are accidental or not intentional than most terrestrial events, such as the collision between a Russian Cosmos and an Iridium bird[xiv]. The dichotomy of this duality challenge was acknowledged by the head of Air Force Space Command, Gen Shelton, when he commented that the advances in space that benefit the US and other nations now rely on "is a double edge sword"[xv]. Economics, access to data and communication are all enabled by satellite operations; yet reliance upon these platforms in space could become a potential target in future conflicts, thus putting the very attributes that enable the DoD and the world to rely upon at risk. DARPA and all new space technology lab goals are to take off the table technical inviolability to open up new arenas of operation and capabilities; ostensibly this includes area that may have duality of usage. So how does the US space technology sector balance development of potentially ground breaking capabilities in space that benefit the DoD and commercial sector, and maintain the US goals of protecting and defending freedom of navigation and maneuvering in this domain?

One approach is to announce and show intent of actions at the beginning of a mission specific application that utilizes robotics, under the new paradigm of assemble, repair, upgrade and re-use. Responsible, transparent behavior in the operations of the Phoenix demonstration has been a central theme from the beginning. The operations to affect satellite-to-satellite interaction are ubiquitous across any end-use mission area and are represented in the original POP's in Section III that start from launch through rendezvous and proximity operations to physical contact. Today there are no treaties or policies that explicitly restrict sat to sat interaction in this regards; however updates to their detailed write-ups may be required to address uncertainties that exist in exact adjudication of liability and indemnification for cooperative and planned events, and avoiding errors of intent perception by others. Phoenix's first foray into an application space for GEO robotics, i.e. reuse of components in space, also uncovered another area that is eventually required to be addressed, that of ownership rights and launching state identification related to liability and indemnification. As an "assembly" example, if a new space platform is created out of a combination of new and old parts, who then is identified as the "launching state" and ultimately "owns" the implied liability? Current treaties identify a launching state as the country of launch and/or ownership. If a new platform is created in space from two or more "launch state" party components, a new identification of ownership may be required to allow for continued operations of this new platform, to conform to existing treaties and to allow business to be performed with and from this platform. The panoply of treaties and agreements within the US to understand how to develop the documentation trail is in itself somewhat difficult, given the lack of clear definitions. Regulatory approval is another new area that has not yet been adjudicated inside the US, and is a topic of discussion within world community of space-faring Nations through the COPUOS "code of conduct" discussions.

V. **Projecting into the Future**

Projecting an economic "market" for both DoD and Commercial industry applications for GEO robotics has been looked at in the past focusing on specific single mission instantiations. Each identified the use of a "servicing" architecture to offset or change the cost equation in some way, whether through "high volume low profit" models (refueling e.g.) or "low volume high profit" models (repairing a stuck antenna e.g.). Mass is quite often used as the metric to quantify value, i.e. launching satellites with less fuel and fueling on orbit thus shifting mass costs from primary client to a new servicer[xvi]. Mass is tied to capital expenditure relative to the primary platform cost, i.e. satellite plus payloads that both DoD and commercial users are planning to address the market. Another approach to a sustainable market could be examined through the eyes of capital expenditures (CAPEX).

Today commercial space CAPEX (where the analogy in the military economics is the POM process) is calculated based on existing/projected market demand, i.e. customer base in commercial realm, threat or identified need base in military. Figure 22 shows an example of projected market "need" for use of bandwidth on-orbit by the US Military[xvii]. The high throughput satellite numbers are expected to grow almost exponentially in the 2020's and beyond. The typical method to address the projection of this type of growth is to build multiple satellites to address the demand over time, with expected replacements included in the CAPEX projections (for DoD, enough POM cycles etc.).

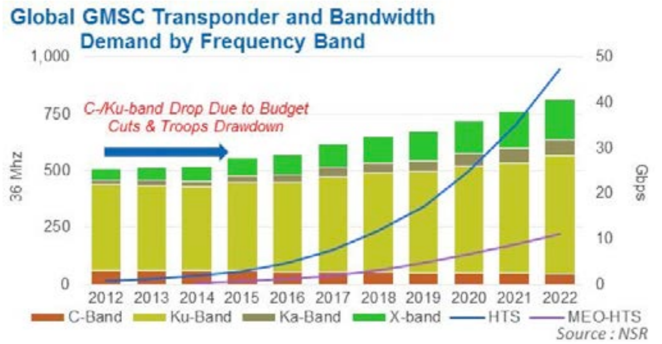


Figure 22. Satcom transponder and bandwidth demand by frequency band.

An alternative approach of having to launch multiple new satellites is to increase the CAPEX on the platforms going to space now (such as high bandwidth comms), to include future or projected possible customers (or needs in the case of the DoD) payload capacity. An example of this may be illustrated through Intelsat's EPIC[xviii] project; the next communication satellites they propose to purchase would be larger and hold more transponders that are not explicitly purchased at launch, but held in expectation that the market in the geographic region would grow into those payloads such that Intelsat can "sell" new business. The downside is higher mass and CAPEX expenditures initially, the upside is not having to spend more CAPEX on another space platform or launch in the future, when the market comes online in the middle of an on-orbit platforms life cycle.

The Phoenix effect posits an alternative approach where CAPEX and thus value of mass of the resultant platform on orbit is spread over a larger period of time (notionally quantified in Figure 3) at incremental lower costs per time period. As an example, a future extreme instantiation of the Phoenix concept would be to examine how to build a large platform (e.g. one on the scale of 100's of meters long) that can be mounted with antennae elements to form an observational structure for sensing in space in which full capability is built, over time. This construct would seek to take advantage of long duration structural platform components, and concentrate the high value electronics that tend to obsolesce (via Moore's law) and degrade (due to orbital environment) to be sent up at a higher refresh rate and lower mass over time to increase the platforms aggregated performance. Figure 23 shows a cross-shaped base mounted with a sparse aperture structure as an example.

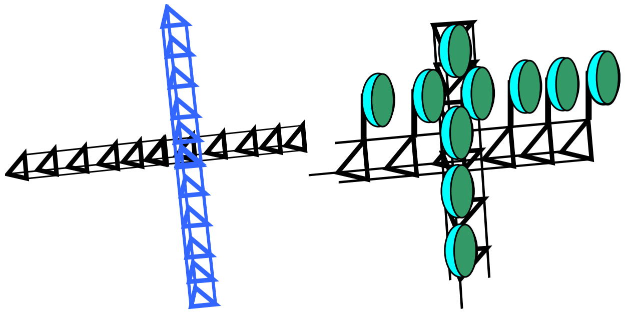


Figure 23. Notional "infinite" antenna structure that can be continuously built out or upgraded over time with new payload electronics and capabilities.

Here the focus is on assembling the base structure on which to mount the individual high value mass elements (i.e. payloads) sent to space in multiple launches. The specific payload elements (large optical elements or microwave or radar antennae e.g.) could be designed as modules such that they can be assembled easily onto the structure (very much like satlets are created to physically attach and aggregate together). The space structure would start as a small structure with minimal payload functionality but would be expanded as new PODs loads are delivered Just-in-Time and their contents used to increase the aggregated resultant "satellite" size and thus user capacity on orbit (i.e. bandwidth). The resulting platform could then morph into any type of payload modality (such as space based radar, segmented mirror telescope, super large RF aperture, etc.) just by sending up the mission specific payloads and tools to assemble them. The task is to make the structure and do it while minimizing cost and time including the launch or space access cost, by maximizing the life of the low value components (i.e. structures) and minimizing the high value mass components (i.e. payloads) onto smaller and lower cost launch vehicles or secondary's.

VI. **Conclusion**

The Phoenix project is an audacious enterprise to attempt to advance the US technological domain capability to change the cost calculus of creation and use of platforms in space by an order of magnitude less than what is done today. The approach engendered by the Phoenix effect pushed technology investments in Phase 1 to support a system architecture of assembly in space, and de-convolution of details in approach sequencing, robotic manipulation and control, collision avoidance, docking, fastening, flexible checkout, non-standard maintenance and repair-in essence a complete lifecycle of a new system in space. The precept of "assemble, repair, upgrade or reuse" that infuses our Earth based culture requires new approaches in platform design as well as manipulation and assemble-ability to allow this paradigm to translate into space. The "market" for just robotics may well be tied to applications to drive the need/demand beyond what to-date has been described as pure "servicing". To expand the base one approach is to completely change the underlying precept of satellite morphology to open up the manipulation technology demand, and thus drive a higher need for space based robotics capabilities. Phoenix cellular morphology via satlet constructs is exploring this new need justification in detail in Phase 2.

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