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A Further Look at Potential Impact of Satlets on Design, Production, and Cost of Satellite Systems

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ABSTRACT

For the past 50 years, the morphology for satellites has remained fundamentally unchanged despite evolutions in manufacturing, communications, and software occurring in other industries. Primary spacecraft support systems—power, attitude control, and others—are designed in the same way, whether in space telescopes, large communications satellites, interplanetary spacecraft, or Cubesats. This paradigm has been the status quo in spacecraft design and construction and has precluded any industry-wide, large-scale cost savings while maintaining performance. To change this trend and ensure performance and utility at low cost, that can scale, DARPA postulated the concept of a cellularized satellite, or “satlet,” as a satellite architectural unit. In this new morphology, each satlet would provide some fraction of the overall functions that, when aggregated via hardware and software, provide spacecraft space system with its complete required capabilities. The DARPA Phoenix program has developed this satlet morphology in Phase I and plans to validate and demonstrate it in a series of steps that exercise various applications and levels of configuration flexibility enabled by a satlet architecture. The first system experiment is planned to be conducted on orbit in 2015.

This paper aims to take a deeper look at the potential impact of space systems with cellular based designs, and using historical data showcases how design, production and ultimately cost can form the foundation for next generation spacecraft opportunities. A first order analysis conducted in a previous paper indicated that U.S.-launched satellites alone could create a market demand for 2,000-8,000 satlets flown per year, while the overall annual world satellite market could create demand for 10,000-40,000 satlets. This paper explores the instantiation of a cellular morphology to design, production and development to further quantify the impact of this revolutionary space system capability.

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Nomenclature

CONOPS = Concept of Operations
DARPA = Defense Advanced Research Projects Agency
DOF = Degree Of Freedom
GEO = Geostationary Earth Orbit
GSO = Geosynchronous Orbit
GTO = Geosynchronous Transfer Orbit
LEO = Low Earth Orbit
PAC = Package of Aggregated Cells, or satlet system
POD = Payload Orbital Delivery system
RPO = Rendezvous and Proximity Operations
Satlet = an individual "cell" that would provide one or more traditional satellite functions and that could be aggregated into a satlet system without additional elements

I. Satlets and Cellularization in Phase II of the DARPA Phoenix Program

THE goal of the Phoenix program is to challenge the historical mass-cost-performance equation for space systems and pursue a redefinition of the cost architecture for all future space efforts[i]. Three pillars defined the original Phoenix mission: developing and demonstrating various *robotic capabilities* necessary for assembling and manipulating satellite parts on orbit; enabling a *Payload Orbital Delivery system* (POD) to increase the tempo of space access (or "FedEx™ to space" model)[ii]; and developing and demonstrating an innovative *satlet morphology* that would enable assembly of systems on orbit. This third pillar also has the potential to change the fundamental economics for all satellites, including those fully assembled on the ground, and it forms the primary driver for technical change in satellite design discussed in this paper.

While the Cubesat standard provided an excellent platform for driving miniaturization of spacecraft hardware and now payloads, it has done so at the expense of limiting physical system performance.[iii] The very attributes that makes a Cubesat attractive, mass and cost to launch, ultimately constrain its effectiveness as a performance space system. Similarly, modularized spacecraft designs have identified some value for certain standards and interfaces, but suffer from the lack of a an agreed upon interface standard between Government partners organizations. This is due in part to the additive nature of the testing required given the numerous different modules, and also because the challenges in getting a standard adopted by industry are exacerbated by low unit volume production and lack of acceptance across vendors and suppliers.[iv] However, if Cubesats and new modularized solutions could be scaled to any size, mass and performance they could begin to challenge large space systems and ultimately enable revolutionary next generation space capabilities such as large assembled optical systems or space solar power stations.

This third and central pillar of Phoenix aims to respond to this very challenge; i.e. to enable space systems of any size, shape or performance to be built using a cellular design morphology. The satellite community could reap the benefits of commercially driven hardware and software interfaces, commercial scale high-volume production, and the ability to flexibly accommodate any payload, regardless of size or orbit, via the satlet morphology. During Phase I, the Phoenix program explored various methods to decompose, collect, and connect satellite functions as part of the satlet trade space evaluation. The program considered what type and level of cellularization is both achievable and optimal in a new cyber/electrical/mechanical satellite system and definitions of a "satlet" in the context of a cellular morphology applied to real satellite systems were proposed.[v,vi,vii] Spacecraft functions were redefined into fractional units or cells, which then needed to be collected into functional groupings to satisfy typical spacecraft operations. Groups could be of multiple types, ranging from heterogeneous, wherein each group performs a different function or functions, to homogeneous, wherein all groups are identical and contain a fraction of every required spacecraft function.

Phase II, which is currently underway, is refining both the nomenclature and the execution methodology for how a cellular space architecture can be realized. Physically connected functional groupings of cells (satlets) are referred to as Packages of Aggregated Cells (PACs), where a satlet is a "cell" consisting of hardware, software and space applications of a traditional satellite. The PAC then functions via a combination of internal devices (intrinsic to the cells, providing typical spacecraft component functions), external devices (devices extrinsic to the cell which fit the typical definition of payloads) and resources (elements either intrinsic or extrinsic to the cells that are dynamically and temporally aggregated by software). A "mission" is then a set of applications that utilizes the internal, external, and resource functions through software to execute a predefined goal. (In most cases this goal is to support a payload, such as pointing an optical camera to capture images.) Phase II efforts are also working towards a hardware instantiation that supports production as well as ground and on-orbit validation of the methodology. Key to the instantiation of a satlet systems is an executable connection methodology that reliably interconnects satlets together and to external devices and resources.

The Phoenix program plans to validate this new satlet morphology in a series of experiments both on the ground and in orbit, which will serve to incrementally demonstrate the various capabilities and applications of the satlet morphology. For a space demonstration, an experiment involving a PAC of satlets assembled on the ground with two payloads will be launched to low earth orbit (LEO) for initial validation of the satlets' basic functionality, both as individual cells and as an aggregated group. An initial configuration of this eXperiment for Cellular Integration Technology (eXCITe) is depicted in Figure 1.

The specific type of satlet (that will fly on eXCITe) is the Hyper-Integrated Satlet (HISat) developed from NovaWurks in Los Alamitos, CA.[vi] The NovaWurks solution is a homogeneous approach, where each individual satlet contains a fraction of every required spacecraft bus function. The eXCITe PAC is then defined as a number of satlets and resources configured to support one or more

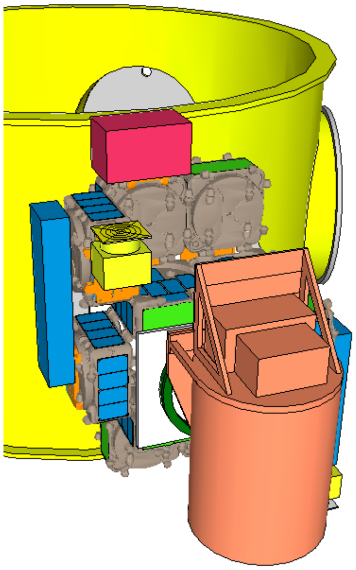


Figure 1. One configuration of satlet LEO experiment (eXCITe). *The satlets (shown here as tan boxes with green and blue sides) would provide all functions usually performed by a spacecraft bus in orbit.*

payload experiment(s). External devices to be tested with the PAC may include items such as solar panels for additional power generation, fuel tanks for additional consumables and longer life on orbit, and radios for telemetry and command of the PAC. The HISats, running software applications, provide traditional spacecraft resources of attitude determination and control, thermal regulation, internal power generation, a small propulsion capability, data storage and handling, and a stiff structure for payload support.

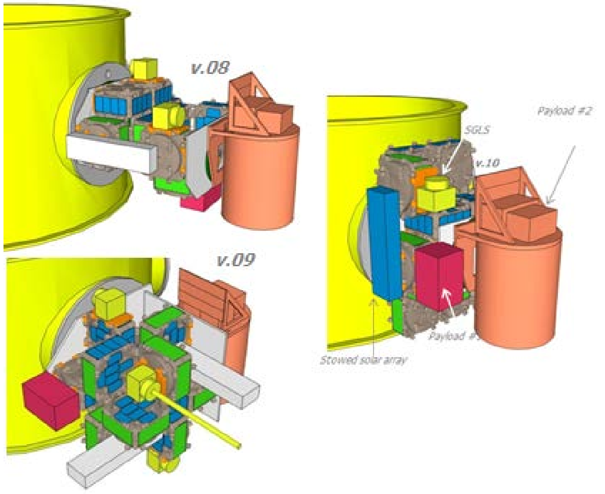


Figure 2. Snapshot of several configurations for the Phoenix satlet LEO experiment (eXCITe). *Over two dozen configurations were evaluated in less than two weeks using the satlet morphology.*

II. New Design Approaches for Satlet-based Space Systems

The concept of cellularization and aggregation provides a unique method to change the technical performance execution and thus the "design" of what we consider today to be traditional spacecraft.[viii] Design, as it is traditionally described, includes the physical configuration of an object, the resultant performance of that object including its reliability and resilience, and the ease of hardware integration which ultimately includes production.

Today, the typical design process for satellites consists of an iterative execution of first principles and established rule sets that must generate both detailed technical specifications as well as a specific geometric configuration. Work has been done to automate the selection, integration and execution of piece parts into a satellite geometry, while optimizing for a particular "payload" and "mission" based on traditional satellite morphology.[ix,x] Even with this automation, however, there is a need at each design stage to perform system analysis of thermal behaviors, structural resonance, RF interference and pattern, etc. in order to validate that the geometric design can support a viable space mission. In a satlet-based morphology, design is done at the cell level, where the power, thermal and data flow architectures are built into the geometric design intrinsically, allowing for a much higher number of potential configurations to be generated and validated early in the design cycle.[xi] As an example of this in practical terms, Figure 2 shows a subset of the more than two dozen configurations considered by NovaWurks in the course of the eXCITe experiment configuration layout. Each conforms to the launch constraints driven by the selected launch vehicle interface ring.

Today's design tools have graduated from dedicated design facilities to distributed workstations to tablets as technology's march has allowed physically smaller computing systems to process problem sets with higher complexity. A touchscreen "app" under development in the Phoenix program combines 2D tactical inputs on a flat surface with the ability to manipulate a 3D object on the screen to allow a user to design a configuration of satlets quickly and easily. The user interface is combined with rigorous analytics which quickly evaluate the configuration against various measures of goodness to allow virtually anyone to "design" a satellite using cell-based morphology. Figure 3 shows screenshots of a beta version of a graphical user interface for

Figure 3. Screenshots of Beta version of an initial "app" for Satlet based design. *The left image shows how various "resources" can be supplied to the satellite designer, and the right image shows how the graphical interface is able to "slide" satlets onto the screen, and rotate the image in 3D to "create" a new satellite around any payload.*

an iPad-based system that allows for design of a cellularized satellite with a payload of any type, size, shape and mass. The full app should be available in 2015.

III. Cellularization and the Interface Challenge

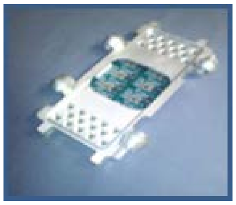


Figure 4. First look at a user defined adaptor that is being developed for the eXCITe flight experiment.

It has been noted previously that every function of a satellite may not lend itself to be cellularized.[v] Cellularization of satellites will require connectivity not only of communication and data,[xii] but also of power, thermal management, structural stability, maneuverability, and sensing. The principal value of aggregation in this context is the ability to achieve different geometries and aggregated system behaviors with satlet "building blocks" that enable flexibility to accommodate varying physical constraints and mission operations. A critical test of viability of a cellular solution is not in the decomposition or collection of a particular satellite function but rather in the potential for reconnection and aggregation. From a practical standpoint, central to any instantiation of aggregatable elements, initially built or reconnected down-stream, is an "interface": a piece of hardware and/or software that links the separate elements together to act as a whole or to support a unique piece of equipment (typically a "payload" that is an external device attached to a PAC of satlets). NovaWurks has instantiated a specific method to allow for cross-satlet connection and external device and resource connectivity into a PAC. Figure 4 shows a geometric configuration of a user defined adaptor (or UDA) which is being used on the eXCITe experiment, to connect resources and "payloads". At a minimum, the interfaces between satlet variants that may eventually be produced by multiple vendors could provide structural connectivity, but to enable performance in certain key areas of satellite operation, these interfaces would also provide aggregation of other decomposed satellite functions, including power, data, thermal management, and propulsion. To encourage implementation throughout the wider space industry, public release of user guides detailing how to connect a payload, resource or other type of satlet to a satlet system as designed under the Phoenix program are planned for later in the program.

IV. New Perspectives on Reliability and Manufacturing

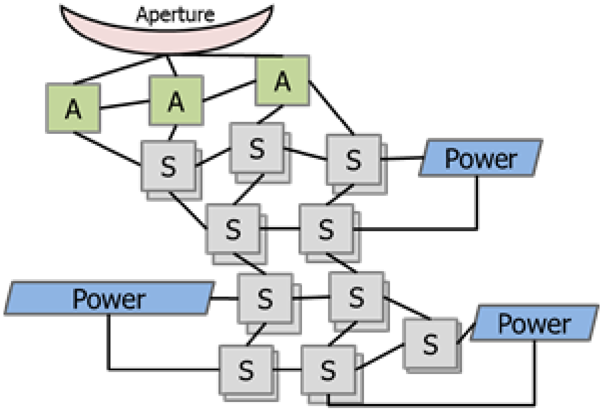


Figure 5. Simplified diagram of a "satletized" system applied to a representative aperture. *"A" represents payload or external device, "S" represents a satlet, and "Power" represents a power resource.*

While satlet morphology offers many intriguing new design attributes and performance characteristics when compared to traditional satellite designs, one particularly attractive feature is the opportunity to trade system reliability against other desired system traits. An individual satlet's reliability is of great interest in the satlet development process, as it influences not only the overall satlet system (or PAC) reliability but also the resulting cost/benefit valuation of the system.[xiii] Figure 5 is a depiction of a simple, generic example of a cellularized satellite system, using various instantiations of satlets that are aggregated together. In the figure, "A" represents a payload or an external device that provides connectivity to a payload. The "S" represents a satlet. "Power" represents a power resource that serves to collect and distribute power into the PAC. Together, these individual payloads, resources and satlets act as a satellite with a completely new architecture.

A previous paper demonstrated how satlet morphology would fundamentally change the relationship between satellite performance and reliability.[v] The satlets labeled with an "S" in Figure 5 were assigned various reliability ratings which in combination dictated the minimum number of each satlet type required for the mission (i.e. to support the payloads to execute a specific set of functions on orbit). Initial analysis showed in one case that adding only four redundant satlets beyond the minimum number needed for success (20 total vs. 16 minimum) resulted in a vastly increased system reliability at the end of five years. The implication is that a higher overall reliability could be achieved either by aggregating a larger number of satlets with lower individual reliability or by aggregating fewer satlets with higher individual reliability. As unit reliability is a crucial cost driver, designing satlets with lower individual reliability could enable a lower individual satlet cost but require additional satlets in the aggregated satlet system, while designing satlets with higher individual reliability could potentially drive higher individual satlet costs but reduce cost at the system level.

The system reliability attribute of the satlet morphology has several potential impacts on the end user market for satellites. First, the ability to increase system reliability via redundancy would have an effect on the manufacturability of the satlets. Typical satellite designs drive high reliability into component designs because the satellite bus can accommodate few, if any, spare components. This pressure to produce highly reliable components comes at a high cost and also limits the number of viable vendors to those with the skills to deliver such high-fidelity hardware. Limited options for suppliers in turn drives the cost up even more. The use of the satlet architecture may allow for much lower reliability at the cell level, which would reduce cost and enable existing commercial processes and manufacturers that do not traditionally build space hardware to be involved in the production of satlet components or even entire satlets.

A second impact of satlets on the satellite market could result from the fact that the reliability of any given satellite is “selectable,” meaning that the satellite buyer could choose system performance based on the satlet variants available, the price of those satlets, and the number that can fit in the launch vehicle with the payload. The satlet system solution could be configured and reconfigured by varying the number and types of satlets, resources, and payloads using known satlet performance and behaviors. This flexibility would also enable nearly real-time mission trades. This design knob is part of the ongoing Phoenix architecture evaluation, and the potential exists for the spectrum of reliability to manifest in different versions of satlets, provided to different customers based on their preference or mission.

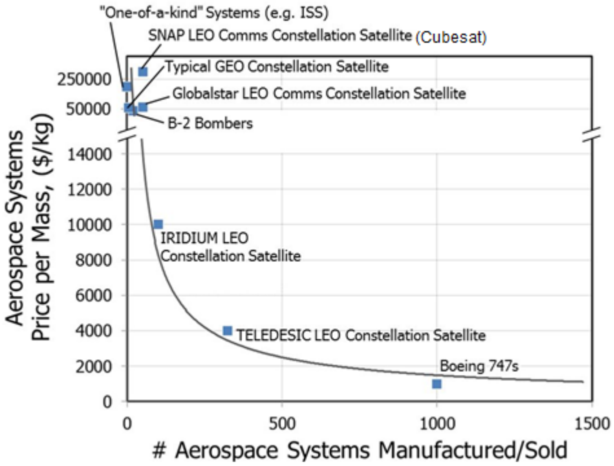


Figure 6. Example plot of specific cost/mass of aerospace systems. *The “production” effect occurs with higher number of units manufactured.*

A final key aspect of design is the ability to manufacture a high number of cells at the lowest possible cost point. The continuously escalating global consumer need for data on demand is driving significant advances in networking, software and electronics design and fabrication. Based on this consumer market pressure, advanced products are now manufactured at high unit volumes, including advanced low-power processors, battery technologies, novel networking schemes, operating systems, software constructs, and additive manufacturing systems. These products and their high-volume production can be leveraged to support satlet development. In particular, the prior discussion on reliability provides background on the unique opportunities to leverage such commercial parts in aggregate at their existing performance and reliability levels, rather than use the conventional and costly custom design and build processes for space hardware and software. Likewise, their commercial production capability means that a satlet morphology could rely on and be designed to exploit these ground-based, high volume, consumer-driven design and performance evolutions to achieve ongoing evolution of satlet technologies at an unprecedented rate. Figure 6 shows how the number of units produced affects price per mass for aerospace systems. A previous paper

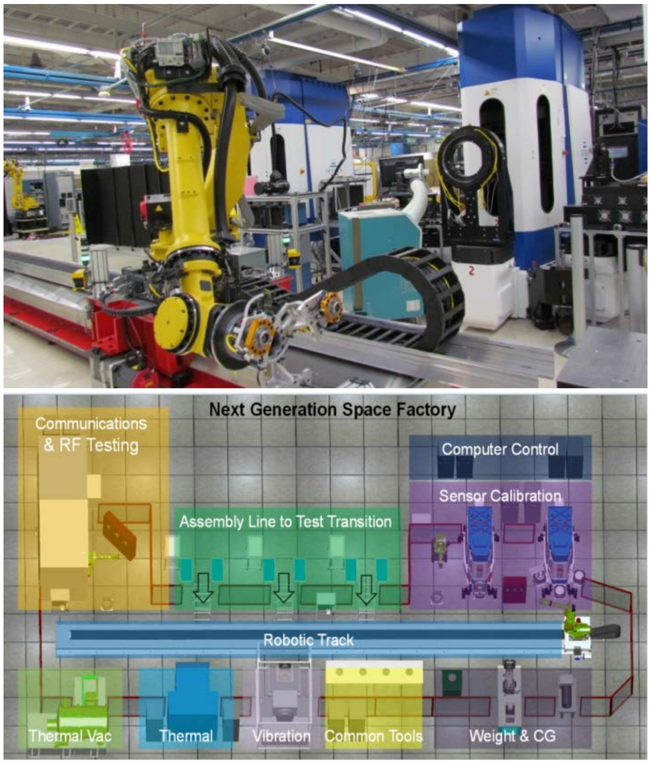


Figure 7. Space factory at Raytheon. *Current development pictured on top, future capability on bottom. Photo and artists concept courtesy of Raytheon.*

postulated that satlets could leverage the typical manufacturing production cost curve if the unit cost is low enough.[xxiv] Phase II of Phoenix is creating an initial capability to manufacture large numbers of satlets through both pre-production prototyping at NovaWurks, and a unique capability under development by Raytheon in Tucson, AZ.[xiv] Figure 7 shows a new "space factory" currently under development that will not only apply to Phoenix satlets, but will be used to assemble any number of other small satellite configurations. As the capabilities of this new factory concept are leveraged for satlet manufacturing, the readiness of the satlets for robotic handling and assembly will be demonstrated in the ground scenario of the assembly line. This early ground experience with satlet robotic assembly will be key to enabling a future space architecture in which satlets are reliably, efficiently, and safely assembled on orbit.

V. Next Generation On-Orbit Capabilities Enabled by Cellularization of Space Systems

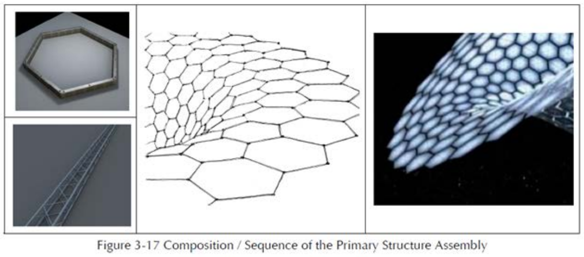


Figure 8. Example of an "aggregated" space solar power concept. *From SPS-ALPHA NIAC Phase 1 Report to NASA. Artemis Innovation Management Solutions LLC.*

The concept of cellularization applies not only to the traditional functions of a spacecraft bus (where Phoenix concentrated on initially), but the community is engaged in ongoing research on how to leverage cellularization in the payload arena as well. For example, space-based optical telescopes with large primary mirrors or lenses hold promise for expanding human knowledge of Earth and the universe.[xv] Larger primary optics allow telescopes to gather more light and peer farther into the cosmos. Currently, there is a desire to develop space-based telescopes with primary optics larger than 10 meters in diameter. (In comparison, the Hubble Space Telescope's primary mirror has a diameter of 2.4 meters.) NASA's Astrophysics Roadmap[xvi] highlights as high priorities technologies such as large focal plane arrays; low-cost, large-aperture precision mirrors; and distributed apertures. The industry is reaching a limit on the intricacy and complexity possible for deployable components, and in the absence of precision on-orbit assembly or manufacturing, the size of future mirrors is limited by the diameter of the launch vehicle fairings available today. The UK Royal Astronomical Society recently announced its desire to unite the world's space agencies to build a telescope ten times larger in diameter than the current Hubble Telescope called ATLAST (Advanced Technology Larger-Aperture Space Telescope).[xvii] The plan acknowledges that this new very large aperture device will have to be built from individual assembled elements, in this case with humans constructing the telescope up to one million miles from Earth.

Advocates of space-based solar power have long heralded the useful energy that could be beamed to Earth from orbit, but the development of such a system has been thwarted by the sheer cost not only of developing on-orbit assets to send power to earth, but of launch itself. As in the ATLAST concept, the ability to disaggregate the mass that is required to assemble something as massive as a solar power station on orbit could enable both lower cost launch options and use of mass on orbit in an assembleable and reconfigurable modality. Mankins et al has explored Space Based Solar power for many years, and through a recent NIAC study revealed a technical instantiation that is also "cellular-based" that may shift the economics of development within reach.[xviii] Figure 7 shows an example of how the NIAC study created a "hexbus" that postulates aggregating elements together to form a very large energy collection and transmission aperture. Phoenix satlets represent a promising hardware solution for an aggregable energy collection and transmission construct that has not previously been affordable or executable in space.[xix]

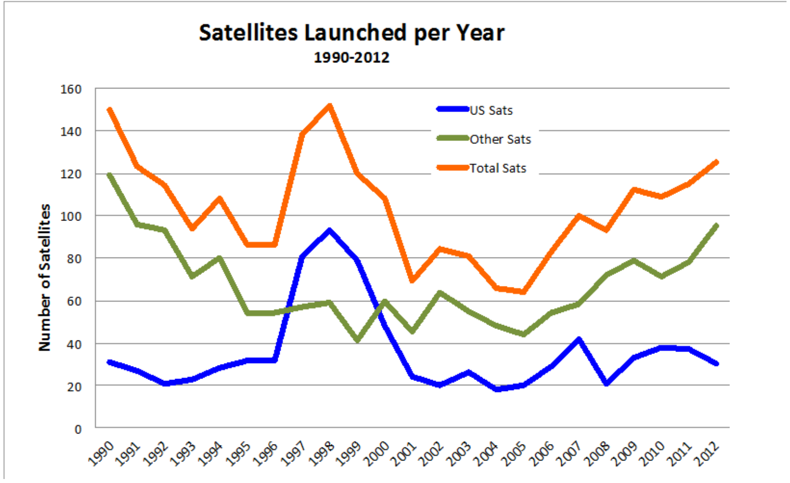
Development of the satlet architecture is a critical first step towards a new space ecosystem which creates opportunities for much larger assembled systems and, eventually, systems that can be reconfigured and improved after they have reached orbit. From a commercial perspective, the concept of changing how a company capitalizes on its expenditures for platforms on orbit was discussed in a previous paper, along with an example of an "infinite antenna structure that uses very long life structural mass to 'assemble' higher value electronics into a functioning communications node."[viii] In this example, not only would replacement of parts allow for space systems to take advantage of Moore's law improvements in electronics that are commonly used on the ground as soon as they are made available, but a new market approach to "leasing" structure on orbit could be enabled to address multiple companies' needs to use a very large aperture over a geographic location by sending up just the "payload" to be assembled onto the structure as needed. This scenario would allow costs to be amortized across multiple companies and many years.

VI. Market Impact: A Deeper Dive into Production and Cost Evaluations for Cellular vs Traditional Space Systems

The Phoenix program is pioneering the development of satlet hardware, software, production technologies and a public standard to enable cellular morphology, but a key question remains: Will it matter? How can we assess if this cell-based morphology is capable of impacting the space industry as a whole? Achieving a shift within the industry would require that this architecture support a variety of payloads and resources for different missions (e.g. electric propulsion units, optical elements) and have well-defined, open hardware and software interfaces, thereby creating sufficient economic demand for satlet units with an associated supply chain (i.e. in thousands of units).

As has been described in this paper, the Phoenix program is addressing the challenges of hardware and software connectivity between satlets and from satlets to other components such as traditional payloads, external devices, and resources through Phase 2 activities. A fundamental goal in solving these design challenges is not to create a required or static configuration but to create an architecture with inherent configurability and flexibility, where changes can be implemented during design *as well as during on-orbit operation*. This adaptive-by-design hardware and software solution is in development today by NovaWurks under the Phoenix program, and, if successful, it will ensure applicability of satlets to a wide variety of payloads and launch vehicles and enable scaling of systems from very small to very large without time-consuming and expensive traditional redesign. As identified in Section II, DARPA seeks to develop technology that could result in a paradigm shift in the demand number of units (thousands, year in and year out) that would enable industry-wide cost reductions and minimize the number of new modules or interactions that need further definition and additional engineering cost.

Figure 9. Satellites per year used in the initial analysis.



The previous market analysis paper attempted to begin answering whether the satlet morphology could create a new paradigm and provide the means for the evolution of a self-sustaining market and whether the annual economic demand represented by current and future space activities supports a need for satlets that could truly change the cost equation.[v] A historical database was developed using a combination of resources to provide a reasonably complete picture of satellites launched between 1985 and 2013 and includes details like satellite mass, power, country of original ownership, launch vehicle, launch date and orbit, to name a few.[xx] Figure 9 shows the number of satellites launched each year from 1990 to 2012 by the United States, by the rest of the world (indicated by Other), and by the U.S. and Other combined. Since the peak in the late nineties that was driven by communication satellite constellation launches, the United States has fielded an average of ~30 satellites per year, while the rest of the world launched on the order of two times that number. Recent years (2005 and later) have seen the world cumulative satellite launches on an upswing.

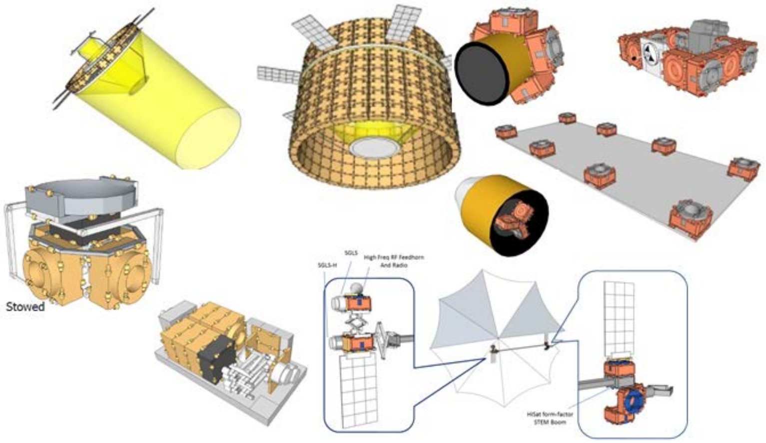
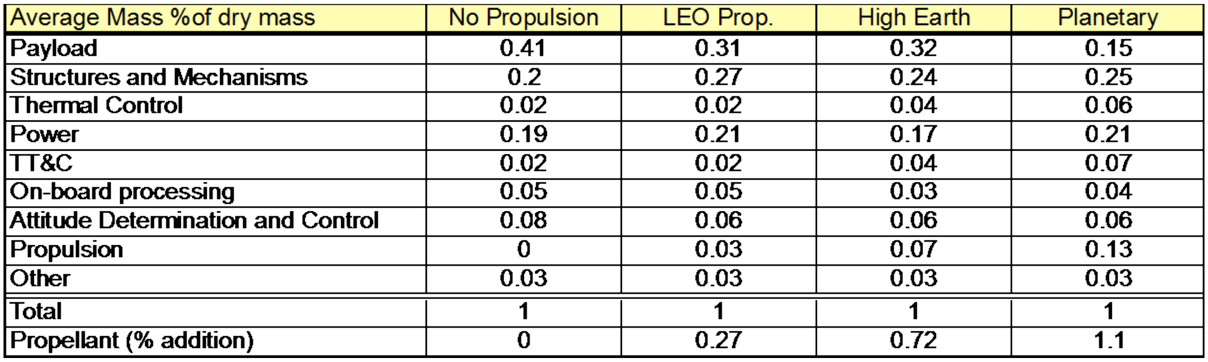


Figure 10. Examples of new geometric configurations for a cell based satellite design. *Each design represents a different way to "use" mass which has performance embedded in the geometric design.*

This database is fairly complete from the perspective of identifying the satellites and the launches; however, many data items that would help in creating notional "satletized" designs for these spacecraft (e.g. payload-specific mass and power, spacecraft bus and power, pointing and slew rates, etc.) are not readily obtainable. Additionally, it is not apparent that commonly accepted metrics to evaluate a cell-based design exist. While mass is generally used as the benchmark for comparisons in space systems, a cell-based design values reduction in mass versus performance differently because geometries can be markedly different from traditional monolithic structures. Figure 10 shows an example of how radical new space systems may be geometrically configured given a cellular architecture.

To do first order evaluations on a cellular architecture that is grounded in traditional metrics, some simple models from Space Mission Analysis and Design (SMAD)[xxi] are used to provide some approximation of the capabilities, where mass is the metric. Table 1, reproduced from Wertz Table 14-18, provides a model of spacecraft that can be used to separate the spacecraft mass into functional mass.[xxi] This table provides a mass percentage for different subsystems based on spacecraft dry mass and a fractional multiplier for propulsion mass for each of four spacecraft mission categories: no propulsion, low earth orbit with propulsion, high earth orbit, and interplanetary. For this analysis, only two types of the four spacecraft types were used – low earth orbit with propulsion and high earth orbit. This SMAD model was used on each satellite data point in the database to define the payload mass, spacecraft-only mass, and power subsystem mass for each spacecraft.

Table 1. SMAD Table with % of dry mass per subsystem (Wertz Table 14-18).



Average Mass %of dry mass	No Propulsion	LEO Prop.	High Earth	Planetary
Payload	0.41	0.31	0.32	0.15
Structures and Mechanisms	0.2	0.27	0.24	0.25
Thermal Control	0.02	0.02	0.04	0.06
Power	0.19	0.21	0.17	0.21
TT&C	0.02	0.02	0.04	0.07
On-board processing	0.05	0.05	0.03	0.04
Attitude Determination and Control	0.08	0.06	0.06	0.06
Propulsion	0	0.03	0.07	0.13
Other	0.03	0.03	0.03	0.03
Total	1	1	1	1
Propellant (% addition)	0	0.27	0.72	1.1

Some assumptions are made in order to approximate the number of satlets per mission spacecraft identified. First, the launch vehicle used for each of the historical satellites would not change if the satellite were made of satlets instead of traditional components, nor would the satlet morphology change the options available for launch. (In actuality, it is anticipated that using satlets to build satellites with the same or better capabilities would provide additional launch options, whether providing opportunities for more satellites for launch or driving a new launch market.) Second, the analysis assumes that the total satellite mass launched in any given year would remain the same, as the typical desire to fill the launch vehicle to capacity with more payload (e.g. larger telescope, more transponders), more resources (e.g. fuel, sensors, power), or more satlets would still prevail. Third, the analysis assumes that the aggregated satlets used for any given satellite would be sufficient to reconstitute at least the minimum capability required to support the historical satellite’s payloads, which includes the use of deployable solar arrays. Phases I and II of the Phoenix program have provided evidence of full subsystem capabilities for the satlet cells in development, with the actual level of performance in the testing process. Fourth, the satlets are capable and carry propellant, but this function is not used in the analysis, meaning that the propellant mass is separate and no advantage taken from individual satlets (a conservative approach).

The mass of a typical satlet from Phase II of Phoenix was used to determine the potential number of satlets that could be required to reconstitute these historical satellites using cellularization. Phoenix satlet variants range in mass from 4 kg to 10 kg, with an average of 7.5 kg for the current state of the art. This analysis used 7.5kg as the satlet mass, where each satlet provides a fraction of necessary system functions for each spacecraft. Using the SMAD equations, we then apply this 7.5 kg to the historical spacecraft mass, exclusive of power and propellant subsystems, and the result is intended to be a conservative assumption for satlets needed per year.

Figure 11. Satlets required per year for flight spacecraft, based on "satletizing" a percentage of original satellite mass.

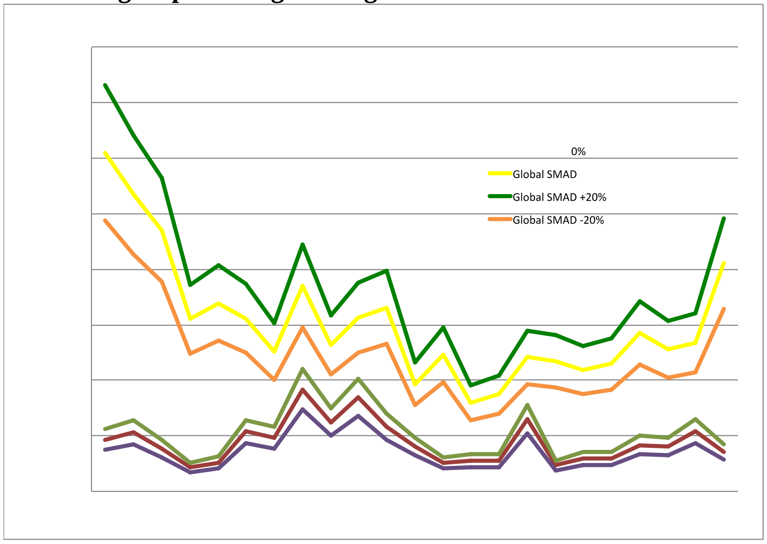


Figure 11 shows the result that if the United States and the rest of the world "satletized" all of their spacecraft, the predicted number of satlets that could be flown per year ranges from 1,000 to 4,000 satlets per year and from 3,000 to 15,000+ satlets per year, respectively. These numbers represent a unit demand approximately two orders of magnitude higher than that of the historical and current annual satellite production market. (The Iridium constellation is an outlier with approximately 100 satellites in its system). This projected level of demand for satlets would have significant implications on the production, manufacturing, and adoption of standards in the industry and would also support the concept of reliability via redundancy discussed earlier. Note that this data only includes satlets that would be actually launched and used on orbit. It is expected that a larger number of satlets would be required for new payload developments, existing payload testing, and software development test platforms. One can also project that, if cost has been the limiter on the number of launches per year, then a significant overall decrease

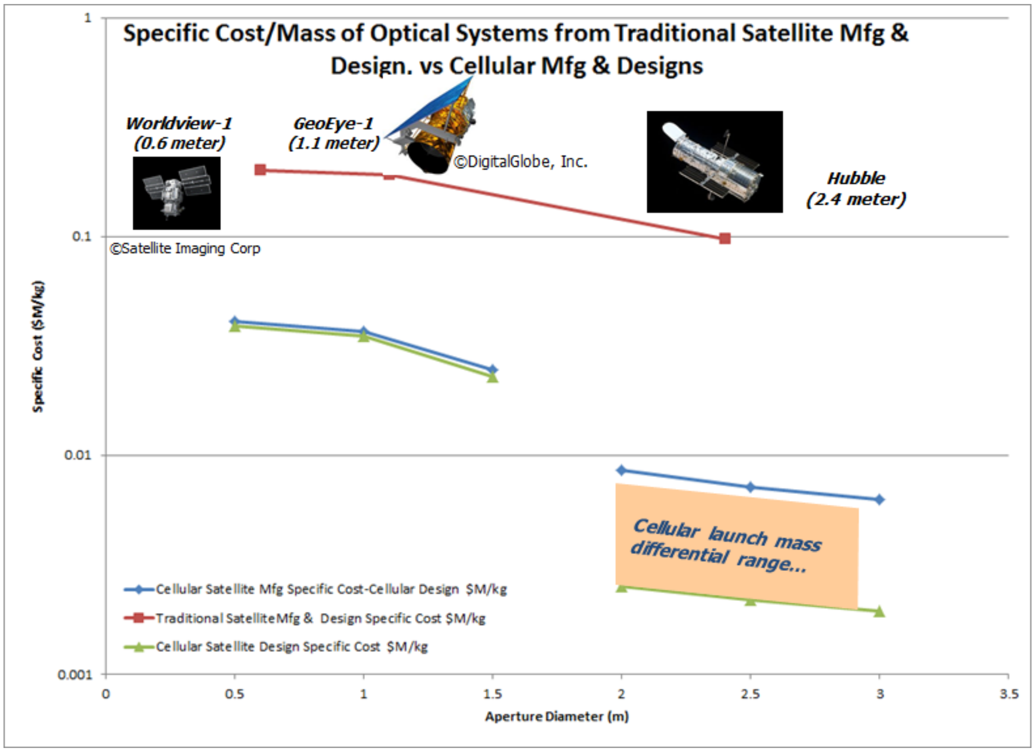


Figure 12. First order comparison of satletized spacecraft costs to traditional systems for a specific mission area (optical systems) relative to mass and aperture size.

in cost per launch could result in an increase in launch tempo per year and allow the demand for satlets per year to increase. Hence, the expectation is that these estimates for satlet demand per year are conservative.

A deeper dive into the cost/benefit analysis was applied to comparisons of legacy optical systems for both traditional and cellular architectures.[viii] Figure 12 shows an interesting trend where “satletizing” traditional satellites with larger primary monolithic payload elements (e.g. an optical aperture) results in higher satlet manufacturing numbers and thus greater savings. The cost savings, to first order, outweighs the loss of efficiency in mass due to cellularization, even when potentially higher launch costs to put the cellularized elements into orbit are considered.

Phase II is expanding upon the results for the number of satlets required to create “satletized” optical systems, expanding to “satletized” communications systems based on existing high-performing RF systems (e.g. the Advanced Extremely High Frequency (AEHF) and Wideband Global SATCOM (WGS) systems).[xxii, xxiii]

Preliminary estimates of satlet cost have also been developed as part of Phoenix Phase I program and are ongoing in Phase II. Predicted unit costs are still in the range of $50,000-100,000+ for production quantities of the current hardware design. Table 2 shows a notional comparison between existing traditional satellite designs and conceptual satlet morphology equivalents.

Future Phase II Phoenix satlet design activities will include development of specific use cases and hardware demonstrations. In addition, a more detailed assessment of Table 2 will be made based on historical and forecasted data using current pipelined payloads. Improved performance estimates via ground testing will offer better insight into the number of actual satlets required for different classes of payloads and provide the basis for evaluating launch vehicle sizing and payload support.

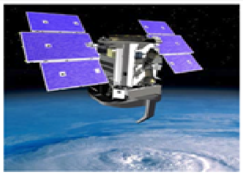
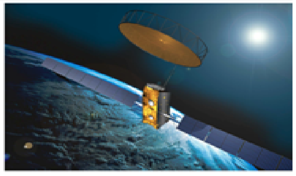
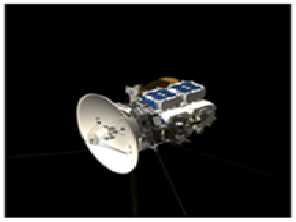
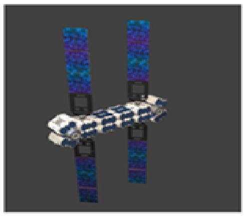
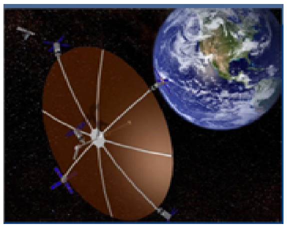
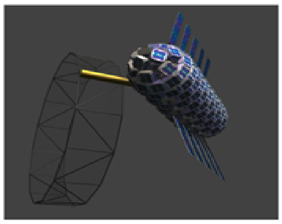
Micro Satellites	Mini Satellites	Medium Satellites	Large Satellites
 Planetary Resources (~50kg)	 SSTL 300 S1 (~350kg)	 NASA CloudSat (~850kg)	 Inmarsat (>5000kg)
Traditional Satellite Examples (cost includes representative bus and payloads)			
10-100 kg $2-$10M*	100-500kg $10-$50M	500-1000 kg $50-$100M	>1000kg $100M-$1B+
			
Cellular Examples (cost and cell count payload dependent)			
3-15 cells $500K-$5M *	15-40+ cells $5-$20M	40+ $10M+	80+ $25M+

Table 2. Comparison of typical satellites at various sizes, with traditional above and satletized below. *Note that the number of satlets is only an estimate based on representative payloads, and the cost is variable based on type of payload and satlets used.*

VII. Conclusions

The DARPA Phoenix project is driving forward in the development, verification, and validation of the satlet morphology. Satlets are being designed to exhibit here-to-fore unseen flexibility and performance, enabling the support of any payload, on any launch vehicle, at any altitude. An analysis of historical data, coupled with reasonable assumptions and Phoenix Phase I estimates for satlet mass, power, and capability, shows that proliferation of the satlet morphology could drive industry demand for 1,000-16,000 satlets per year, based on historical annualized satellite data. This number of units manufactured annually is one to two orders of magnitude higher in production quantity than any space satellite system to date and lends credibility to the low cost point that is predicted for the “cells” in this cellular architecture. In addition, with the forecast price points for satlets and the benefits from implementing the architecture (trivialized integration, flexible design, open architecture software applications), the total cost to field these satellites could be impacted by as much as two orders of magnitude.

The construct of a cellular morphology for space systems may well encompass more than just the production of hardware in the thousands of units in an industry that is typically restricted to numbers on the order of tens to hundreds. This market instantiation of satlets may also offer opportunities to develop software applications to enable satlets to host a variety of space payloads and create new on-board applications that leverage the significant processing and data storage capability of a multi-unit PAC. There are both significant challenges to multi-processor operations and a potential new field of research that could be explored to develop second generation space capabilities and possibly apply them to terrestrial platform domains. The eXCITe testbed flight will provide proof of concept for key satlet behaviors and a foundation for implementation of the satlet design approach. Cellularization of space systems lowers the barrier of entry for new entrants into space and enables resultant systems to exhibit very high performance and capability, through the advent of aggregation. It is feasible that consortia could be formed at much lower levels of investment that could begin to create the framework and infrastructure for very large-scale platforms and capabilities in space, following a pace of technological democratization that has begun on Earth in many other areas such as electronics and computational systems.[xx]

The views, opinions, and/or findings contained in this article/presentation are those of the author/presenter and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

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