Phoenix and the New Satellite Paradigm Created by HISat

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ABSTRACT

A satlet is a satellite architecture component into which the functional capabilities of a conventional spacecraft are decomposed and can then be aggregated back together to provide desired subsystem capabilities. NovaWurks has successfully developed satlet prototypes for the DARPA Phoenix program. These smaller disaggregated subsystem building blocks are called HISats, or Hyper-Integrated Satlets. By reassembling a sufficient amount of HISats and payloads, a spacecraft with the required capabilities can be formed by aggregation of their resources. HISats are distributed across a platform and interact through a variety of links. Removing some of the physical location dependencies between the resources of a spacecraft brings several attributes, such as reliability and flexibility. Building capabilities by aggregation of resources provides rapid scalability and robustness. A spacecraft bus which is composed of resource modules can be readily fit together to support a variety of payloads. However decomposing and disaggregating a spacecraft, and letting the different resources manifest separately, leads to several architectural and technological concerns which are related to the shared resources within the aggregated satlet network. Investigation of these challenges, solutions, and demonstration results from Phase 1 of the program are presented. Concepts for future space systems are discussed.

The views expressed are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>ADCS</td>
<td>Attitude determination and control subsystem</td>
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<tr>
<td>Comm</td>
<td>Communications</td>
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<td>DoF</td>
<td>Degrees of freedom</td>
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<td>ELV</td>
<td>Expendable Launch Vehicle</td>
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<td>HISat</td>
<td>Hyper-Integrated Satlet</td>
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<tr>
<td>I&amp;T</td>
<td>Integration and Test</td>
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<td>NRE</td>
<td>Non-Recurring Expenses</td>
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<td>PAC</td>
<td>Package of cells</td>
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<td>POD</td>
<td>Payload Orbital Delivery system</td>
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<td>RWA</td>
<td>reaction wheel assembly</td>
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<td>SYS</td>
<td>system satlet</td>
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<td>SWAP</td>
<td>size, weight, and power</td>
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<td>UDS</td>
<td>user defined space</td>
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INTRODUCTION

As the new frontier to be explored in the 1950s through 1970s, space mission costs were understandably high. However, unlike other new technologies introduced in the latter half of the 20th century, space mission costs have remained high. High costs have limited humankind’s access to space and the beneficial services it can provide. Cost drives almost all space systems and strongly influences whether programs will proceed or not. With the drive towards increased commercialization of space, cost will be the key to establishing a credible, profitable business case for space products and missions. A space system’s cost is a function of its size, complexity, level of technology maturity, design life, schedule, risk tolerance, and project’s structure (i.e. number and size of organizations, documentation and review requirements, management style and controls). Many approaches have been proposed to reduce space system costs by addressing one or more of the key drivers (e.g. “design-to-cost” reduces some combination of size, complexity, technology, and lifetime to achieve the targeted cost). This paper delves deeper into a cost reduction approach based on a novel morphology using findings from Phase 1 of DARPA’s Phoenix program. A review of satellites developed from the 1960’s onward indicates that all share nearly identical morphology (where we
take morphology to mean the architecture of the elements that comprise a spacecraft. This static spacecraft morphology is not only observed through time, but is also observed across all satellite size/mass scales. An example of static morphology is seen in comparing a large satellite Reaction Wheel Assembly (RWA) to a Cubesat RWA; they both employ the same methodology and occupy identical positions in the system’s architecture (as an actuator in a spacecraft subsystem). This paper presents the results from Phoenix Phase 1 research that provide insight into the key parameters of a cellularized satellite architecture.

A cellular satellite architecture allows the disaggregation of typical space vehicles into as many or as few cardinal pieces (called satlets) as required to achieve cost savings, flexibility, and reliability while maintaining the required mission performance. The term “Satlet” is intended to define either a single cellularized subsystem (e.g. a propulsion satlet) or a single standalone satlet-based system. The extent of cellularization can vary between the following two extremes:

(a) **Single Function Satlets.** Each Satlet can incorporate one individual satellite subsystem function and aggregate multiple units to increase the required performance (e.g. spatially distributed miniature RWAs that together provide total momentum control). Space systems built from single function satlets are referred to as heterogeneous, since several diverse satlet types would be required to complete a space vehicle equivalent system.

(b) **System Satlets.** Each Satlet constitutes a complete stand-alone system that contains requisite individual components such as processors, solar cells, batteries, attitude control sensors and actuators, etc. that can be aggregated together to serially increase performance with increased numbers. (A simple example might be today’s Cubesat, which is a system Satlet without the ability to aggregate performance.) Space systems built from system satlets are referred to as homogeneous, since identical satlets are aggregated to complete a space vehicle equivalent system.

A previous paper by the authors compared a spectrum of cellularization levels for a representative mission with respect to SWAP, flexibility, reliability, and cost. This paper answers the questions, “Is there an optimum level of cellularization?” and if so, “What are the cellular elements of an optimum system?”

**OPTIMUM DISAGGREGATION – PHASE 1 STUDY RESULTS AND KEY OUTCOMES**

**Disaggregation Defined**

The simplest disaggregation scheme, certainly the one that first comes to mind, is a division by the standard set of spacecraft subsystems; attitude determination and control (ADCS), communications (Comm), command and data handling (C&DH), electrical power (EPS), thermal control (TCS), guidance, navigation, and control (GN&C), propulsion, and structures and mechanisms (S&M). This level of disaggregation serves to allocate specific functional requirements (e.g. attitude control) to each satlet type, as this is how the subsystems came to be grouped and identified in the first place. Carrying this approach one step further, the subsystem satlets could be disaggregated into component satlets. For example, an ADCS satlet could be disaggregated into specific attitude sensor and attitude actuator satlets. As mentioned above, this type of heterogeneous system has been optimized historically in spacecraft design as the number of each subsystem or component (instantiated as a satlet type) can be determined based on the performance and reliability requirements. We’ll refer to these two intuitive types as Single-subsystem satlets and component satlets. Figure 1 illustrates the concept.

**Figure 1. Levels of Disaggregation from Traditional Monolithic to the Component Level**

Perhaps a more interesting question is, can better SWAP efficiency be realized by combining more than one subsystem functionality in a single satlet? Such a satlet might provide ADCS and propulsive functionality, or perhaps Comm and C&DH. We’ll refer to this genre of satlets as multiple-subsystem satlets.

At the far end of the multiple-subsystem satlet spectrum are satlets possessing every subsystem functionality. This satlet type is essentially a satellite in the nano to small size category but with the ability to be aggregated for resource sharing and improved performance capability. This type of satlet is referred to as a system satlet. The homogeneous space system resulting from aggregating system satlets exhibits a high level of flexibility in that any satlet can provide any resource to...
the aggregation as needed (some quantitative limits may apply due to a specific satlets position in an aggregation such as a blocked sensor or dedicated actuator).

**Previous Findings**

An excellent study using model-based design exploration was performed during Phoenix Phase 1. The study captured satlet design and aggregated satellite design trade spaces using the Systems Modeling Language (SysML), imposed requirements as parametric constraints on acceptable solutions, conducted automated searches of the trade space and generated pareto-optimal satlet architectures that satisfied mission requirements while maximizing a value metric, expected profit. The study’s findings are presented in Figure 2. The results shown in the figure use as a baseline a revenue model with two missions—one for a large 12m aperture (referred as mission 1), and a second one for a smaller 2m aperture (referred as mission 2). Figure 2 shows the general trade space distribution in the mission 1 profit vs. mission 2 profit space. This plot shows the profit distribution for solutions for the two different missions in terms of number of satlet types in the aggregate architecture. The most flexible solutions are those that can provide a good profit for both mission cases (the pareto-optimal region at the top right corner of the trade space shown in Figure 2). Note in the expanded plot, 2b, that all satlet architectures studied (containing 1-4 satlet types) are respectably represented in the 92nd percentile rank for both mission 1 and 2.

![Figure 2a. Two Mission Profit Space Showing the Number of Satlet-Types in the Architecture](image)

**Key Outcomes**

While Figure 2 may show an optimal solution plotted, because of the assumptions used to scope the trade space, the limited size of the automated exploration of satlet combinations, and the inherent uncertainty in the inputs to the analysis, one can safely postulate that any solution in the 92nd percentile can be considered a near-optimal if not possibly the optimal disaggregation solution for the mission being considered.

In terms of factors not considered in the study but discussed in the authors’ previous work, system satlets provide advantages in their flexibility to respond to changing requirements, particularly requirement changes occurring late in a mission’s life cycle and cost savings achieved by single-type production quantities. Thus the existence of system satlets in the pareto front called for a previously unexplored optimal spacecraft paradigm to be pursued. This paradigm is utilized by the Phoenix program through the HISat satlet as described in previous work and is now been instantiated by the development of the HISat and selected variants derived from the efforts explored in Phase 1.

**THE CHALLENGE OF HISAT VARIANTS**

Disaggregation of the basic satlet building block is discussed in the preceding section but Phase 1 also brought development for other specialized satlet system elements. The myriad of possible specialized variants was evident in Phase 1 but which ones were the best was less obvious. A set of challenges were put forth to cull out the most promising solutions. These challenges began to identify variants to answer the question posed earlier, “What are the cellular elements of an optimum system?”
**UDA – Solution to the Challenge of Accommodating Specialized Devices/Payloads**

An early Phase 1 specialized variant concept investigated was the ‘User-Defined Space’ (UDS) for non-satlet device accommodation (e.g., solar arrays, RF payloads). The UDS was an accessible internal satlet volume available to payloads. The UDS provided power, data, and thermal support to the payload. Phase 1 revealed that significant NRE was going to be required to accommodate typical payloads in the volume (form and size) allotted. Also, integrating the payload device into the satlet reduced the flexibility and exchangeability of satlets in I&T and on-orbit.

Instead of the UDS approach, NovaWurks showed that a less constrained suite of payload devices, many already existing in the small sat industry, could be accommodated externally mounted to a satlet. Inherent to the NovaWurks satlet design, the HISat, are edge connectors that allow HISats to be aggregated together and share resources. A working approach was found to use the inherent HISat connectors to attach payload devices to HISats on any of five available sides. Figure 3 shows a cutaway of a satellite (built with HISats, attached to a yellow ESPA ring) with a payload (small yellow unit) attached to a UDA (orange).

**Figure 3** HISats Using UDAs to Easily Attach Devices

The UDA is composed of a ‘flat plate’ fitted with four edge connectors. The payload device is mounted directly to the UDA plate. The UDA, once connected to a HISat, can exchange power and data, and employ thermal management as required. This configuration concept supports the notion of the satlet keeping overall system costs down by not providing custom interfaces but a common programmable ‘space ready’ support system that increases its utility for users and maintains production volume of the adapter plate in a cellular architecture. The payload accommodation capability of the UDA approach scales well to large payloads by attaching multiple UDAs to the payload which can be interconnected via HISats. This concept is the basis of the NovaWurks conformal spacecraft being developed in Phase 2.

**HIMast – Solution to the Challenge of Very Large Structures**

The Phoenix mission of large aperture repurposing helped solidify the need for long reach on large apertures for remotely placed satlets and thrusters. Storable tubular extendable member technology was demonstrated during Phase 1 to meet the needs of required reach. The initial deployment mechanism was large in order to house a large diameter boom to handle loads and rotational stiffness was needed. NovaWurks developed the utility of a long deployable element as an integral part of its HISat system. NovaWurks has worked with a Phoenix team member, Roccor, to prototype an improved dual-boom (counter-rotation smaller diameter pair) deployable structural element, HIMast (figure 4), that addresses both shortcomings and has the added advantage of being housed in the HISat form-factor. The HIMast design will provide the following benefits: variable deployment length and >4m overall reach means a single version of HIMast can meet a range of “long reach or large structure” requirements; power and data lines embedded in the structural layup, provide connectivity to the distal end; the HIMast is driven by a HISat carousel using a simple internal gearing system, eliminating the need for additional internal motors/controllers; and the HIMast fits into the HISat form factor for ease of launch packaging. Additional forms of this basic space “2x4” are being developed to further optimize the utility of this HISat variant.

**Figure 4** Double-C HIMast Element

**Articulated Positioners – Solution to the Challenge of Fine Position Control and Long Reach**

The Phoenix mission of aperture repurposing advanced another proposed satlet system element: multiple DoF precision positioners with long reach capability. The Phoenix repurposed aperture required precision adjustable placement of an RF feedhorn at the aperture focal point. NovaWurks recognized the utility of this type of system element for a variety of applications including deployments and positioning of optical payloads. NovaWurks developed a concept drawing upon the same miniature motor and connector technology used in a HISat, a simple 3-DOF arm (1 axis of rotation and two axis of translation) is constructed. When two pairs of arms are aggregated...
between three HISats and the end HISat is used as a gimbal (as shown in Figure 5), an accurate wide range 6-DOF mechanism is formed through cellular components.

**Figure 5. Six-DoF Articulated Positioner Design and Three-DoF Optical Demonstration System**

Though slow moving, this precision near-zero backlash design creates a dynamic and accurate aggregated device. Constructing the articulated positioner arms with HISat connector technology allows fluid, power, data, and thermal to pass through the arms extending basic HISat resources to payloads mounted at the end. Thus the HISats/arms/gimbaled payload combination can be thermally managed which is key to fine positioning control and payload operation.

**METHODS OF AGGREGATION AND THE IMPACTS**

Satlet aggregation to achieve better performance metrics and reliability is one of the cornerstones of the cellular concept. Aggregation concepts and their resulting requirements were considered early in Phase 1. Several obvious options present themselves; a) prelaunch aggregation where satlet PACs (packages of cells) are configured prior to launch, b) on-orbit telerobotics or human PAC assembly, and c) PAC self-aggregation. Option c) is under development. Items a and b are discussed below.

**Prelaunch – Fixed**

Prelaunch assembly of PACs in their final configuration is a valid option for any mission whose requirements can be met with a PAC configuration that meets launch vehicle payload volume and mass constraints and can withstand launch vehicle environments. The PAC must be configured such that all HISat connections can meet the launch load and vibration environments. Additionally, launch vehicle providers require that separable connections be protected with an inhibit feature that precludes inadvertent commanded release or disconnects. The HISat design has addressed these concerns with a connector design that is launch lockable and mechanically switched separation switches that inhibit operations in the HISats. While the Phoenix mission does not require final mission PACs to be launched, satlets are required to be attached to the POD and Servicer/Tender vehicle for ELV launches driving most of the requirements discussed above.

**On-orbit Assembly**

Generally the launch vehicle requirements described in the paragraph above for fixed configurations are applicable to most systems. However, in missions where an on-orbit assembly capability exists, compliance with those requirements may be more easily accomplished due to other launch packing options (e.g. soft pack of individual HISats in bags). On-orbit assembly does impose additional requirements on HISats particularly in the connector and external handling features areas. Phoenix telerobotics requirements related to satlet assembly were developed for: a) remote center compliance, b) optical fiducials, c) connect/disconnect forces and torques, d) connect/disconnect verification, and e) electrostatic discharge.

An additional aspect of telerobotics handling for any item is compatibility between the available tools and object to be manipulated. Figure 6 shows two notional satlets and a grasping tool. As a system, satlet connectors and sides are needed for attachments to other satlets and to storage or work platforms, basically reducing the number available for tool handling. While Figure 6 appears to show several available sides for grasping, tool accessibility to all those sides may be constrained by obstacles and robot arm dexterity or reach.

**Figure 6. Block Diagram of Satlet and a Grasper Tool Interfaces (S-S satlet to satlet, S-P satlet to platform, RA robot arm)**

Phoenix telerobotics requirements related to satlet handling by tools were developed for allowable satlet handling surfaces and applied pressure. HISat integrated all these requirements to allow for both pre-launch and on-orbit flexibility of handling and assembly.
PAC DESIGN FLEXIBILITY

One of the benefits of a cellular architecture is its flexibility throughout its lifecycle. The inherent flexibility during the design phase has been found very useful to date. PACs can be constructed to satisfy mission requirements fairly rapidly, their performance can be evaluated, and the metrics of multiple PAC options compared. The Phoenix “FedEx™ to GEO (POD PAC) is a simple example of how HISats can be densely packaged to create a container and still provide spacecraft operations such as GNC and communications.

Figure 7 Densely Packaged HISats on a Payload Orbital Delivery system

The ‘greening’ of the GEO disposal belt and repurposing of apertures is a goal of the Phoenix program. Using HISats and their on-orbit assembly features allows this mission to be easily configured and flown.

Figure 8 Notional Phoenix Aperture Repurposed with Satlets

During the first phase of HISat development over 83 different flight configurations for 11 missions were investigated in a matter of months. Such system engineering capability has been developed by using HISats and a standard building block approach to mission development. The ability to rapidly conform to launch vehicles, fairings, payloads, and mission constraints provides a unique opportunity to explore a variety of solutions to spacecraft and spaceflight.

Figure 9 A Sampling of the Range of HISat-based Configurations Developed to Satisfy Varying Mission Needs

Space vehicles, both exploration and Earth-serving, imagined in science fiction but historically unfeasible to construct are now practically launchable, built, and configured as needed for the mission in both time and space. Cellular architecture on a large scale for a Solar Power Satellite (SPS) was the subject of a NASA NIAC Phase 1 project. The concept of the “SPS-ALPHA” utilizes modular “satlet” assembly to enable the scale required analogous to the concept explored by NovaWurks for the Phoenix program.

Figure 10. Depiction of SPS-ALPHA, a Solar Power Satellite via Arbitrarily Large Phased Array

While this ease of design flow for various missions and multiple configurations has become somewhat standardized during the course of Phase 1, an effort has begun to apply more automation into the process even...
to the extent that payload providers and mission designers can perform rapid configuration trades with reasonable accuracy. This work will be ongoing during Phase 2.

CONCLUSIONS

Phoenix Phase 1 served as a beneficial catalyst that explored cellular architecture issues and challenges that could finally be identified, investigated in depth, and practically solved. As a result a new paradigm for space has been established. Through the means of HISat, a high production space vehicle building block, and the appropriate toolset of HISat variants, low-cost rapidly configurable space systems of any size are becoming possible. It is envisioned that as this new cellular building block approach is utilized, even more concepts and possibilities will be uncovered as scientists, entrepreneurs, and space explorers dare to dream, no…design and build, in a manner not possible before.

ACKNOWLEDGMENTS

The authors thank the DARPA Phoenix Advanced Technologies Program for funding the research presented in this paper.

The authors wish to acknowledge the contributions of Roccor and Altius in providing the technical support and drawing for HIMast.

REFERENCES


