CELLULARIZED SATELLITES – INITIAL EXPERIMENTS AND THE PATH FORWARD

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ABSTRACT

Small satellites are an exciting technology in the space industry today. For example, over half a dozen private companies have announced plans to build large networks of smallsats to provide remote-sensing imagery data to customers. While smallsats can provide advantages over traditional large satellites, satellites assembled from "building block" cells called satlets add to those advantages. NovaWurks is developing the cellularization of satellite technology as a way to dramatically decrease the cost of new space assets, while also enabling these assets to be incrementally upgradeable and easily repairable. Basically, a small number of nanosat-scale satlets serve as building blocks for assembling a fully functional satellite, analogous to how living organisms are made up of basic cell types. Novawurks has developed satlet technologies in HISats™, to be configured and aggregated as reliable, flexible spacecraft for a variety of space purposes. An initial set of HISat-based experimental missions are either underway or planned for the near future. These experimental missions seek to provide on-orbit verification of the satlet concept, the HISat™ instantiation of that concept, and verification of key payload accommodation features. The spectrum of space access utilized to execute the experimental missions serves to demonstrate the flexibility of the cellularized architecture concept. One mission is scheduled to be assembled in space aboard the International Space Station (ISS) enabling a deployment. A second, the experiment for cellular integration technology (eXCITe), is planned for launch as a pre-launch assembled payload on an Expendable Launch Vehicle (ELV) to be deployed from a SHERPA. The third experimental mission aims to utilize HISats™ to fly a Payload Orbital Delivery (POD) system after deployment from a host satellite in geosynchronous Transfer orbit (GTO). The path forward for HISat-based missions promises to push the envelope into the capabilities once thought only achievable by much larger traditional buses.

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INTRODUCTION TO CELLULARIZED SATELLITES

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. *Single-function satlets* incorporate one individual satellite subsystem function per satlet and multiple units are aggregated together to increase the required performance (e.g., spatially distributed miniature Reaction Wheel Assemblies (RWAs) that together provide total momentum control). Several diverse satlet types are required to complete a space vehicle-equivalent system. *System satlets* are designed so each satlet constitutes a complete standalone 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. For this type, identical satlets are aggregated to complete a space vehicle-equivalent system.

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. NovaWurks has been investigating the cellularization of satellite technology and has developed a hyper-integrated satlet, named HISat, that provides complete satellite functionality in a nanosat-scale package. The HISats can be aggregated and share resources such as electrical power, attitude control sensors and actuators, data processing, etc. With their flexible assembly options resulting in multiple possible configurations, HISats provide a building-block bus (called a PAC – Package of Aggregated Cells) that can conform to and accommodate many different payload sizes and shapes. The potential benefits to payload designers are obvious. HISats provide an app-based, open-source approach to core resource-sharing cellular firmware that provides for simple user-created applications to coordinate the requisite individual HISat hardware. This enables HISats to be aggregated together informationally so that satlet resource exposure and sharing is transparent to the operation of the system. This critical resource-sharing software provides for basic capability that tailors performance by varying the number of HISats interoperating without skipping a beat. This aggregation of information adds reliability to a cellularized design. The HISat software approach allows the payload user/developer hands-on design, development, and operation of an app to create a specific functionality desired on a HISat cell (like a cell phone). The application building provides a common building block paired with an easily accessible operating system. The benefit is lower-cost software life cycles because application development can be instantiated, maintained and updated in the cloud by researchers and mission clients alike.

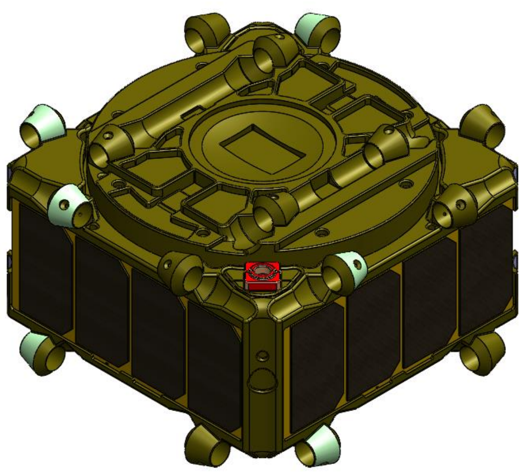

Exhibit 1: System satellite example – HISat (Hyper-Integrated Satlet)

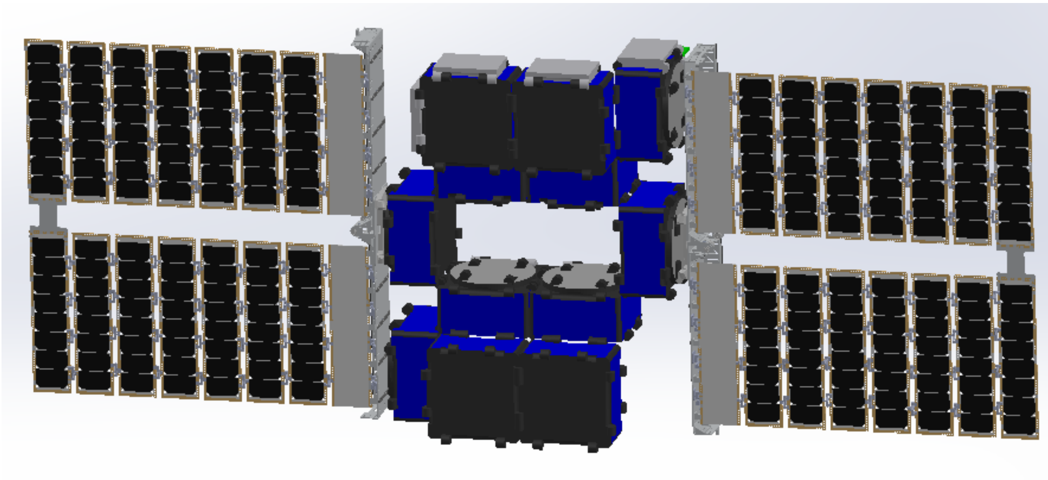

Exhibit 2: Payload Testbed-2 – A PAC of twelve aggregated HISats shown with two deployed solar arrays

Cellular space systems, like HISats, are an approach, already in space today, for truly low-cost space operations. One proven method of achieving real cost reductions is by mass production, which could reduce costs by two or more orders of magnitude and allow custom tooling and automation to be exploited while their costs are dissipated among units. The satlet cellular approach is a means to reach the promise of increased production to lower costs in the space vehicle business. Satlet production runs of as few as 50 units are predicted to significantly lower cost per satlet. Low production costs, combined with low-cost access to space through flexibility, would enable many space-based services to be competitively offered relative to today's market.

FINDINGS IN DESIGN, ASSEMBLY, AND TEST

As noted above, cost savings are expected to be realized in a cellular architecture due to mass-production efficiencies. What is not as immediately apparent is the savings that could be realized in the design and testing phases. This section discusses initial findings in all three product phases.

Design

One imagines the design process as an unalterable, logical, sequence of iterative steps that can be found with some small variations in any systems engineering handbook. A typical sequence of the fundamental systems engineering activities for a space system are: definition of mission goals and concepts, the identification and allocation of required functions, definition of key requirements to achieve the required functionality (and performance), development and execution of design trade studies, iteration of the trade studies and associated operational concepts until one or more system design solutions are found, and then selection of an optimal system. Once this point is reached, the next level of functionality, requirements, and design trade spaces are addressed. Sufficient depth must be reached to support product baselining and cost estimation.

Cellular space system design, while requiring the same basic inputs as a traditional space system, mission goals and concepts, is a very repeatable and flexible process. The functional analysis is minimized as each system satlet provides a broad set of indentical functions as resources for the PAC to use. In fact, there is considerable temporal flexibility as to which satlet, or satlets, would provide a particular resource to satisfy a required function. A list of key requirements is still needed, but satisfying those requirements, in many cases, is a matter of sizing the number of satlets required rather than allocating, sizing, and chosing hardware for each subsystem. The trade space for cellular systems becomes focused on the physical configuration of the satlets that comply with the requirements. Mass and power budgets are simplified since each satlet brings a standard unit of mass and power storage and internal usage-based consumption. For a cellular system, there is no need to repeat the design process at successively lower levels (e.g., from system to subsystem to assembly, etc.) as the satlet is the lowest reducible unit.

NovaWurks has exercised the design cycle for its HISat and PACs over 80 times during the last three years. Initial baselines are produced by a small team of two or three engineers in two or three days for a new concept and frequently changes can be accommodated in a single day. Changes are relatively easy to implement, even after the design phase, as occasionally happens due to launch vehicle volume, first fundamental frequency, or center-of-mass requirement updates, and large payload power demands.

Assembly

NovaWurks has gained considerable experience in the assembly area having assembled over 100 HISats to date. Immediately realizable and apparent are the savings achieved in utilizing selected commercial off-the-shelf (COTS) parts and standard materials. In many uses, satlet reliability is not impacted and in cases where it is, the inherent redundancy of a cellular system where many satlets are available to perform multiple functions mitigates the impact to space system reliability.

Satlet assembly is a repeatable process of assembling essentially identical units over and over again. Parts kitting prior to assembly is standardized as well. Lessons are learned on early units, captured in procedures, and applied to subsequent assemblies in an iterative process. While robotics are envisioned to play a role in future satlet assembly lines, NovaWurks is presently using a skilled workforce to perform the assembly tasks. The assembly teams become more efficient in their techniques and task flows due to our human capability to learn and make things better and easier to do. Experience is gained in common failure modes and points, and early intermediate testing can many times be implemented to detect those failures before additional assembly resources and time are wasted. Assembly quality control efforts are focused on the technically difficult areas, resulting in the reduction of satlet acceptance failure rates.

Admittedly, NovaWurks HISat production is still in its infancy where a high learning curve is to be expected, but the results are encouraging in that an estimated 5x reduction in assembly time has been achieved for the HISat product.

Test

Following assembly, satlets undergo acceptance testing for workmanship. Similar to assembly, testing is also a repeatable process of testing identical units through a standard sequence of tests meant to provide satlet units ready to be assembled into a PAC for flight. Commonality is achieved in required test equipment and test procedures. As with assembly, lessons learned are applied to subsequent testing, resulting in an increasingly efficient and effective test campaign. While presently a skilled workforce is performing the test tasks, a robotic approach has been established to perform future satlet acceptance testing. Testing has allowed experience to be gained in common test setup, execution, and data collection, allowing focus on quality control measures and on those areas resulting in the reduction of satlet acceptance failures due to improper testing.

INITIAL CELLULARIZED SATELLITE EXPERIMENTS

Three experiments have been initiated to test celluar space systems in orbit. All utilize the NovaWurks satlet design, the HISat. One is in orbit while the other two are undergoing ground testing. A brief description of the three space systems and their experimental goals follows.

SIMPL

Satlet Initial Mission Proofs and Lessons (SIMPL) is a six-HISat PAC with two deployable solar arrays that was launched atop a United Launch Alliance (ULA) rocket on December 6, 2015, from the Cape Canaveral Air Force Station in Florida. SIMPL rode in Orbital ATK's Cygnus spacecraft. Berthing with the ISS was completed on December 9, 2015. SIMPL was delivered to the ISS disassembled into its eight components. SIMPL received ISS program office approval for stowage in the ISS and subsequent assembly by an ISS crew member. SIMPL is currently in stowage awaiting ISS crew time for assembly. The SIMPL experiment provided a proto-qualification run for satlet environmental and functional testing in addition to meeting ISS safety and operational standards for assembly and deployment.

eXCITe

The eXperiment for Cellular Integration Technology (eXCITe) is a 14-HISat PAC currently undergoing environmental testing. eXCITe is scheduled to launch on a SpaceX Falcon 9 rocket and be deployed by Spaceflight's SHERPA auxillary payload accommodation system sometime in mid-2016. Unlike SIMPL, eXCITe would launch fully assembled in its flight configuration. The eXCITe experiment seeks to provide a proto-qualification run for satlet and PAC environmental and functional testing in an expendable launch vehicle environment. A prime goal of the eXCITe experiment is to demonstrate payload accommodations. The NovaWurks cellular space system utilizes a User Defined Adaptor (UDA) to provide a standard but customizable interface for payloads. eXCITe plans to host a range of payloads to accomplish this goal. To provide payload supprt for power and high-data-rate communications, eXCITe includes two deployable gimbaled solar arrays and two S-band space-to-ground link radios. eXCITe also includes a multi-core processor experiment that has not flown before. From the eXCITe perspective, the multi-core processor operation aims to provide data points on payload thermal management using the UDA. Three radiation science experiments are included in the payload suite. These experiments intend to introduce a longer operational cycle (~24 hours) to eXCITe's accommodation requirements while maintaining specific tempertures to maximize measurement precision.

A frequently touted feature of the cellular architecture is its suitability for on-orbit assembly and reconfiguration. While eXCITe would not be assembled in orbit, it would undergo a reconfiguration. The eXCITe experiment plans to host a free flyer payload which would be deployed via a PSC Mark II motorized lightband. eXCITe's Attitude Determination and Control System would mitigate attitude deviations from the deployment (the payload is ~20 percent of the total mass), return to its nominal attitude, and resume operations. This deployment would demonstrate the ability of cellular systems to undergo a significant mass-property change and autonomously regain attitude control with new PAC mass properties in effect – a technical capability required for future assembly and reconfiguration missions.

PODSat

The Payload Orbital Delivery system Satellite (PODSat) is a four-HISat PAC nearing the start of assembly, integration, and test. PODSat is intended for launch on a to-be-determined expendable launch vehicle in 2017. PODSat is designed to be the free-flying element of the DARPA-funded Hosted POD Assembly (HPA), which seeks to provide a platform (the POD) and a separation mechanism for it be deployed by a host spacecraft. Conceived to take advantage of under-utilized launch vehicle payload mass and reliable, frequent launch opportunities, the initial HPA would be hosted on a geostationary communications satellite, with the PODSat deployment occurring in a subsynchronous geostationary transfer orbit.

PODSat would provide a demonstration of the ability of cellular architecture to incorporate a structural element, the POD chassis, into a PAC. Similar to the way app-based software architectures allow easy integration of new software, celluar architectures could offer that same feature to a variety of hardware options.

The PODSat experiment would also provide valuable in-orbit data on an orbit environmental regime outside of the first two experiments.

CELLULARIZED SATELLITES ENABLE FLEXIBILITY IN CHOOSING SPACE ACCESS OPTIONS

Key to low launch costs for nanosatellites and small satellites is acceptance of secondary manifest opportunities on a broad array of launch vehicles providing delivery to a wide range of Earth orbits. Small satellites that are also cellular would add to the inherent advantages of small satellites as secondary payloads.

Small Satellites as Secondary Payloads

Primary payloads that do not utilize a launch vehicle's entire mass-to-orbit capacity provide an opportunity for secondary payloads to be added. To qualify, a secondary payload must meet mass, size, safety, and environmental requirements. Small satellites, by definition, easily meet mass and size requirements and by standard spacecraft design practices can meet safety and environmental requirements. Commercial launch vehicle service and integration providers have developed standard interfaces and integration processes that accommodate payloads ranging from CubeSats to satellites of several hundred kilograms.

Cellular Satellites as Secondary Payloads

Cellular satellites share small satellites' ability to meet mass and size requirements. The cellular design adds the ability to upsize or downsize the mass in unit satlet mass increments to increase or decrease respectively the satellite's capability or redundancy. The adjustment can be made at initial mission/payload design or well after launch contract start as the launch vehicle's overall payload mass budget changes. Similarly, a cellular design has the ability to accommodate various size envelopes as the satlet units can be assembled in multiple configurations while maintaining the same mass, functionality, and performance. As with mass, the configuration options are considered and downselected as an initial payload design but can be altered if the launch vehicle's payload envelope is changed during the course of the payload integration process.

Similar to traditional small satellites, cellular satellite units, the satlets, are designed and tested to meet safety and environmental requirements. The final assembly, or PAC, undergoes the same considerations for safety and environment for the final flight configuration.

HISat Missions Substantiate Cellular Flexibility

The three HISat-based experiments described above substantiate the assertion that cellular architectures are adaptable to wide range of space access options. The eXCITe PAC seeks to use two very common standard secondary payload interfaces available in the commercial market, an EELV secondary payload adaptor and a motorized light band separation system. In addition to having the ability to be deployed by a motorized light band, the eXCITe PAC plans to host an additional smaller one to deploy a free-flyer payload itself, with the goal of demonstrating compatibility with both sides of the separation system. PODSat seeks to utilize a payload delivery system primarily intended to make use of excessive capacity on launch vehicles delivering a primary payload to geostationary orbit. In this case, the HISats would make use of the structural platform and separation system provided by the HPA, which presents configuration requirements very different from eXCITe. The HPA would be hosted in an unused recess on the host spacecraft and not released until a geostationary transfer orbit is attained. Both are very different environments from the eXCITe experiment. SIMPL demonstrates the ability of a cellular space system to be launched unassembled and then be assembled in orbit. The eight SIMPL subassemblies were packaged separately for the launch aboard a Cygnus cargo vehicle. The smaller subassembly packages eased cargo vehicle loading relative to a single package of comparable size and mass. SIMPL was fully certified by NASA for ISS storage, crew assembly, transfer through the Japanese Experiment Module (JEM) to an external platform, and deployment safety via an ISS robotic arm. SIMPL arguably met the most stringent safety requirements of the three experiments since a crewed vehicle was being utilized. SIMPL was designed and tested to use yet a third separation system provided by NanoRacks, the Kaber.

In terms of orbits, launch-driven configurations, and separation systems, the first three HISat PACs display a flexibility to use a wide spectrum of space access options.

INITIAL RESULTS INDICATE CELLULARIZED SATELLITES ARE PROVING THEMSELVES TO BE AN ADVANTAGEOUS SPACE SYSTEM

Through the development of its first three cellular space systems, NovaWurks has realized benefits in the design, assembly, and test of its HISats and PACs. The three PACs utilize very different launch approaches that demonstrate the flexibility of cellular systems to access space via multiple means. Experience has been gained in hosting six payloads and nine external resources across the three experiments. All payloads and resources interface with a PAC through a single HISat, making integration and test very focused on the simple standard but customizable interface hardware, the UDA. Payload provider feedback on the interface has proved very favorable. Following successful integration of payloads onto HISats, integration and test at the PAC level have been seamless. Because of this simplicity, the result has been very short periods of time from payload commitment to flight readiness. HISats offer a potentially cost-effective and flexible performance level above single and multiple-U cubesats and traditional small satellites. Future missions could push the cellular space system envelope into the upper mass regimes of small satellites and even beyond.