Concept for a Distributed, Modular, In-space Robotically Assembled, RF Communication Payload in GEO

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Abstract—**In this paper, we discuss a concept for a Radio Frequency (RF) Ka band communications payload that is robotically assembled and serviced in space using a servicing vehicle such as the Robotic Servicing of Geosynchronous Satellites (RSGS) vehicle being developed by the Defense Advance Research Projects Agency (DARPA). Our work focuses on how to modularize a representative Ka band communications payload into discrete modules that are hosted on a persistent platform. In our concept, each module consists of a primary aperture and the associated RF and electronics required to serve a particular coverage area or type. These modules are notionally packaged in a form factor capable of launching as a secondary payload via an EELV Secondary Payload Adapter (ESPA) ring or a Payload Orbital Delivery System (PODS) module. The overall payload consists of an earth coverage module, regional coverage modules, high gain regional coverage modules, and a host interface unit (HIU). We discuss the notional capabilities and requirements of each module. We present two different architecture concepts corresponding to two different persistent platform concepts. In one concept, the persistent platform is made up of small, independent spacecraft that are connected together with structural members with communication channels. The payload modules are hosted on the individual spacecraft. In the second approach, the platform consists of a large central spacecraft with a structural truss that has power, communication and thermal loops. The payload modules are hosted on the truss through standard interfaces. We present aspects of the mission concept on how the payload may be modularized, launched (as secondary launch elements), acquired by the RSGS vehicle in space and assembled on to the persistent platform. We discuss the robotics aspects of assembly and servicing of the payload modules. A key aspect of this concept is the serviceability of the payload. Central to the modular and discrete payload design is an intent to refurbish the payload incrementally as technology evolves or the components fail. Existing geosynchronous communication satellites are designed and built as monolithic spacecraft which makes any servicing beyond refueling fairly complicated. This makes it hard to take advantage of the post launch evolution in technology, particularly in the electronics elements. Our concept is aimed at modularizing the payload such that the modules, particularly the electronics elements, can be easily serviced using the RSGS vehicle. Our concept attempts to take advantage of the long service life of high reliability system components in the core satellite bus while allowing rapid expansion and upgrading of the communications payload through the addition and replacement of individual payload modules.**

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1. INTRODUCTION

Under the current paradigm, it may take a government program over 10 years to progress from capturing customer needs to delivering the on-orbit asset and the resulting spacecraft may then operate for 15 or more years. This results in customers having to forecast their coverage and capacity needs many years into the future, making it very difficult to rightsize the communications payload or respond to changing technology. Furthermore, since the spacecraft must operate for 15+ years and is not intended to be serviced, it needs to be designed and built with extremely robust and/or redundant

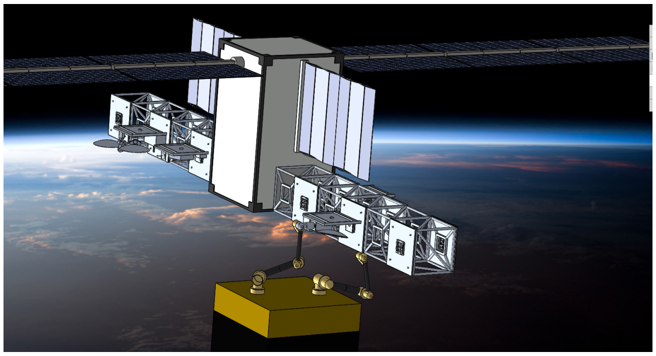

Figure 1. **Concept rendering of a payload module being installed on the persistent platform by a robotic space craft servicing vehicle**

components. Lastly, due to the rapid pace of development of digital electronics and the difficulty of assuring proper operations in the space environment, payloads are often built with tried and tested parts that lack state of the art capabilities. In addition, these parts are expensive since there is limited demand. More capable and cost-effective payloads may be built using state of the art COTS components but this may assume more risk to the functionality of the payload. The added risk brought by the use of COTS components may be mitigated through redundancy and on-orbit servicing and replacement of the smaller electronics modules, without replacing the overall system.

Therefore we propose an alternative architecture for a communications satellite where the communications payload is modularized so that it can be easily installed and removed from a host platform while in orbit. The host spacecraft or persistent platform can be designed for long life in orbit since the technologies required to provide basic services including power, thermal regulation, and attitude control to the payload are improving much more slowly than the payload systems. In contrast, the individual payload modules may be removed and replaced more frequently to adapt the payload to the current user needs or to replace faulty components. Furthermore, because the design, launch, and life cycle of the payload and the bus are decoupled, multiple different payloads, potentially from different customers may be hosted by a single platform and individual payloads may be added or removed as needed, building off of the existing hosted payload model. Lastly, in the case of a communications satellite, an initial capability may be launched and then as user demand grows or evolves, additional modules may be added to grow the capabilities of the system in conjunction with evolving demand.

A concept for this kind of system is shown in Fig. 1: the central bus or platform contains the payload agnostic systems including the power generation and distribution, attitude control, and thermal control systems. It also has a number of standardized payload interfaces that provide a structural, thermal, electrical, and data connection between the platform and each hosted payload. Then, payloads conforming to the interface specification may be added or removed from the platform by a robotic system such as the Robotic Servicing of Geosynchronous Satellites (RSGS) vehicle as needed. The overall concept for servicing the platform is shown diagrammatically in Fig. 2. After placing the platform and servicing vehicle in orbit, payload modules may be launched as secondary payloads and then captured by the servicing vehicle. The servicing vehicle then rendezvous with the platform and anchors itself to the platform with one of its manipulators. Then it can install the new payload in an available payload bay on the platform and/or remove a defunct payload before departing from the platform to serve another customer.

In the remainder of the paper we begin by discussing the state of the art of spacecraft robotics, in orbit assembly, spacecraft interfaces, and communications satellites. We then analyze the communications coverage and capacity that we may provide with our proposed system based on the specifications of commercially available very small aperture terminals (VSATs) and target data rates derived from commercial trunking technology rates. Next we discuss the system components that we propose to use to deliver these capabilities and how they may be packaged into individual modules for launch and in orbit installation. We then discuss two possible architectures for the persistent platform and how the payloads may be installed and serviced on the platform. Next, we discuss the electrical components and reference signal processing approaches that could be used in the system. Lastly we discuss how our proposed system compares to a more traditional communications satellite and propose a scaled down version of our system that could serve as a proof of concept technical demonstration.

2. Related Work

Various concepts for robotically serviceable and in space assemblable spacecraft have been considered for many years and various component technologies are undergoing development or have been demonstrated in orbit include robotic manipulators and servicing vehicles, modular interfaces, and payload deliver systems [1, 2]. A wide range of communications satellites have also been launched and operated demonstrating various system architectures and ever improving capabilities. Below we discuss the various technologies that may be required for our proposed modular serviceable communications spacecraft.

Robotic manipulators and interfaces

Many of the flight proven robotic systems have been used in manned space flight, including the Shuttle Remote Manipulator, Space Station Remote Manipulator System, Special Purpose Dexterous Manipulator, Japanese Experimental Module Main and Fine arms, and European Robotic Arm [3, 4]. These have been used to aid astronauts in deploying and servicing satellites and in the construction and operation of the International Space Station. Robotic arms have also been demonstrated on unmanned spacecraft including the Orbital Express Demonstration Manipulator and ETS-VII Robot Arm both of which were used to demonstrate various berthing manuvers and orbital replacement unit (ORU) transfer and installation operations [5–7]. The Front-End Robotics Enabling Near-Term Demonstration (FREND) robotic arm has also been developed to enable autonomous servicing of satellites and has been demonstrated in a number of ground tests [8]. Currently, multiple agencies are developing manipulators and integrated robotic servicing vehicles to refuel, reposition, or modify existing satellites including the Robotic Servicing of Geosynchronous Satellites (RSGS) and Restore-L vehicles [2, 9]. These vehicles integrate robotic manipulators, general purpose tools, and sensors for proximity operations onto a spacecraft bus and will be capable of rendezvousing with, grappling, and servicing client satellites.

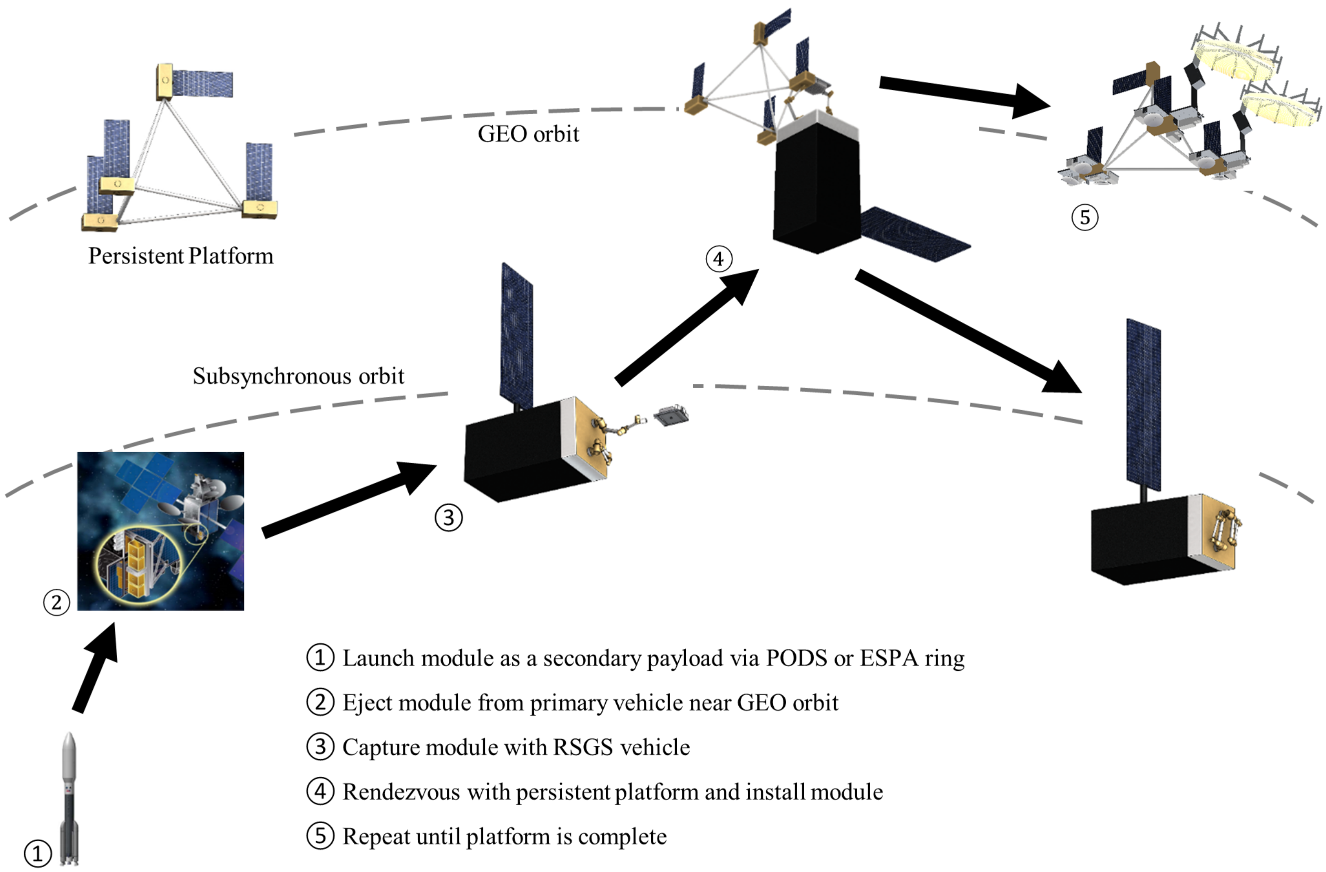

Figure 2. Concept of operations for payload installation.

Spacecraft interfaces

A standardized, error tolerant, and easily actuated interface may be used to facilitate assembly and servicing of a modular satellite by a servicing vehicle that is incapable of performing more intricate operations. A number of different interfaces have been implemented on the ISS including the Japanese Experimental Module Experimental Exchange Unit (EEU) [10]. Other interfaces capable of providing a structural, electrical, thermal, and/or data connection, are undergoing development including the intelligent Space System interface (iSSI), Oceaneering GOLD-2, and TUI axon connectors [11–14].

Secondary payload launch standards

Also key to realizing an in space assembled and serviced spacecraft is a affordable and flexible means of launching the individual components. A number of different secondary payload launch interfaces are currently available or undergoing development that will facilitate delivery of payloads for in orbit assembly or servicing. The Northrop Grumman EAGLE-S, Moog Orbital Maneuvering Vehicle, and Spaceflight Inc. SHERPA are all Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring derived vehicles. Like traditional ESPA rings, they are designed to carry over 1000 kg of total payload mass in the form of a number of payloads ranging from 10 cm^3 cube satellites up to 320 kg small satellites on a single launch. Unlike existing ESPA rings, they also can include attitude control, propulsion, and power generation and distribution systems and can provide survival power and basic communications to payloads while delivering them into specific orbits [15–18].

The Space Systems/Loral Payload Orbital Delivery system (PODS) is another secondary payload standard that may be used to launch secondary payloads to geostationary adjacent orbits. This system defines a standard payload that may weigh up to 90 kg and must fit in a 90.9x45.7x40.0 cm volume and an extended payload that may weight up to 150 kg and must fit in a 90.9x90.9x60 cm volume [19, 20]. The secondary payload can be attached to the host geostationary spacecraft via the standardized PODS interface before launch and is then ejected into a geostationary adjacent orbit after the host spacecraft has circularized its orbit.

Communications Satellites

Communications satellite technology has advanced rapidly over the last few decades based on advances in power systems, digital electronics, and antenna technologies. To support and enable the higher data rates users need, the use of the RF spectrum has also evolved and relies more on higher frequencies, specifically in the K-band. At higher frequencies strong signals can be achieved with relatively small directional antennas and more spectrum is available for higher data rate usages. Space-based antennas can also be built with low side-lobe levels which allows for spatial reuse of the same spectrum across the visible earth surface. Lastly, advances in digital electronics have facilitated the shift from analog to digital transponder architectures on spacecraft. Programmable logic can allow significant adaptation of the capability by simple digital reprogramming.

In addition to the more sophisticated antenna suites being supported, the signal structures and resource management required to support it have also evolved. Initially, the majority of the resource management and signal processing was performed at the ground station due to to the high development costs, rapid technology evolution, and low reliability of these systems. However, with advances in digital electronics and operational fielding history, these functions have begun to be integrated into the spacecraft. Notably the demonstrated ability to reprogram these functions after the spacecraft has launched has allowed payloads to adapt to a wide range of user requirements and waveforms. This trend increases system autonomy and reduces the ground footprint and operational costs. To the degree mobile-to-mobile communications are involved, this also translates to a reduction of ground hub site assets and increases system capacity.

The growth in capacity enabled by these technologies may be seen in a number of different commercial and military satellite systems that have been deployed over the last 30 years. For example ViaSat Inc.'s Anik F2 satellite that was launched in 2004 delivers downlink speeds up to 1.5 Mbps while ViaSat-1, launched less than eight years later, delivers downlink speeds up to 25 Mbps. Furthermore, ViaSat Inc. advertises that ViaSat-2, launched in 2017, will have double the capacity and seven times the coverage area of ViaSat-1 [21]. Military systems have also demonstrated significant capability improvements. The MilStar satellite constellation represented one of the most advanced robust and reliable systems when it was launched between 1994 and 2003. These satellites provided global coverage from 65° N to 65° S and delivered data rates from 75 bps to 1.544 Mbps to users [22]. This system is now being replaced by the Advanced Extremely High Frequency System (AEHF) which will provide 10 times the total throughput of the MilStar system and data rates of up to 8 Mbps to individual users [23]. Similar advances can be seen in the Defense Satellite Communications System (launched between 1982 and 2003) and its replacement, the Wideband Global SATCOM launched in 2007 [24, 25].

3. Communications Payload Assumptions and Requirements

To focus our design, we assume that a perspective customer will require global coverage (±65° latitude) in the commercial, military, or scientific Ka-bands for a broad community of users. For analysis purposes, we focus on the military Ka-band (30-31 GHz up, 20-21 GHz down) since this is the most cited band for the available VSAT systems. Since we are not working from actual user requirements, we instead analyze the coverage and capacity capabilities that might be provided by the system we envision. We assume that our system will support hub sites and deployed communications sites including maritime users, airborne users, vehicular users, and man-portable systems for mobile users. Various groups of users may also be clustered in geographic regions and could consist of a group of ships, vehicles, airborne users, or personnel as shown graphically in Fig. 3. The capabilities of various user types are then based on a survey of commercially available VSAT systems examples of which are shown in Fig. 4 and Table 1. Although we believe these assumptions result in a reasonable basis for stating system capacity, they should be seen as a reference point based on which a comparison can be made.

We assume that each spacecraft will need to provide high and medium rate data services, and low rate voice and text services. The target data rates are based on commercial trunking technology rates, where the high rate service is 6 or 44 Mbps, the medium data rate is 1 Mbps, and the low rate voice and text services are at 2.4 kbps. To deliver the services we describe, we assume that global coverage can be delivered by a minimum of three spacecraft. Each spacecraft will operate in a 1 GHz band and support left and right hand polarization. Lastly we model the link budgets based on 95% world wide availability and summarize our link budget assumptions in Table 2. Although most analysis is focused on these numbers, it is assumed that there is some adaptability of rate and that the overall capacity of the system will depend on the user mix, distribution and connectivity. These services can be delivered via an earth coverage horn, gimbaled dishes, and larger multi beam antenna (MBA) reflectors. To summarize, we expect to be able to provide global coverage to all users at a minimum of 2.4 kbps and higher data rates, up to 44 Mbps, in regional coverage areas depending on the size of the ground terminal's aperture and spacecraft resources dedicated to the particular user. In total, with the described mix of users, the proposed communications system may provide up to 1.8 Gbps of regional traffic supported with 765 Mbps of hub site traffic.

Payload pointing requirements

Individual payloads can tolerate relatively high pointing errors in their initial pose since the alignment of the gimbaled antennas may be refined through calibration prior to operations if there is sufficient additional gimbal range of motion. Therefore we will assume that the initial alignment of the interface for each payload element will be repeatable within 1°. Subsequent alignment stability is assumed to be a more slowly changing effect (with the possible exception of thermal snap occurring during the eclipses), and is set at 0.1° 3-sigma. The payloads will also be subject to higher frequency disturbances that manifest themselves as pitch/yaw or roll jitter at the antenna boresight. This must be limited to ±0.03° 3-sigma for the gimbaled dishes and 0.01° 3-sigma for the MBA reflectors. For the gimbaled dishes, where the 3 dB beam width of the baseline 70 cm primary aperture is 1° on the uplink, corresponding to an approximately 600 km in diameter coverage area, the impact of the jitter can be booked by advertising a smaller coverage area (565 km) to accommodate the ±0.03° jitter or to book the effect as pointing loss on top of the 3 dB edge-of-coverage booking.

Although either of these approaches may also be applied to the pointing requirements of the aggregate coverage of the multibeam antennas, since the coverage area is comprised of sub-beams, the sub-beams need to be considered separately. We assume that the 3 dB beam width of a sub-beam is approximately 0.23° or less if a lower roll-off is used. Therefore, excessive jitter may cause users to move between sub-beams, resulting in undesired repeated handoffs between adjacent sub-beams. To avoid this a lower disturbance level of 0.01° 3-sigma is desired. Lastly, if the spacecraft is unable to provide the desired pointing accuracy, it may be able to provide its attitude knowledge to the payloads which can then actively compensate for any pointing errors through their gimbals.

4. System Architecture and Modularization

We propose to provide the communications capabilities and coverage areas outlined above through nine individual antennas: one fixed global earth coverage antenna, one gimbaled reach back hub site antenna, five gimbaled regional coverage antennas, and two high gain multi beam antenna regional

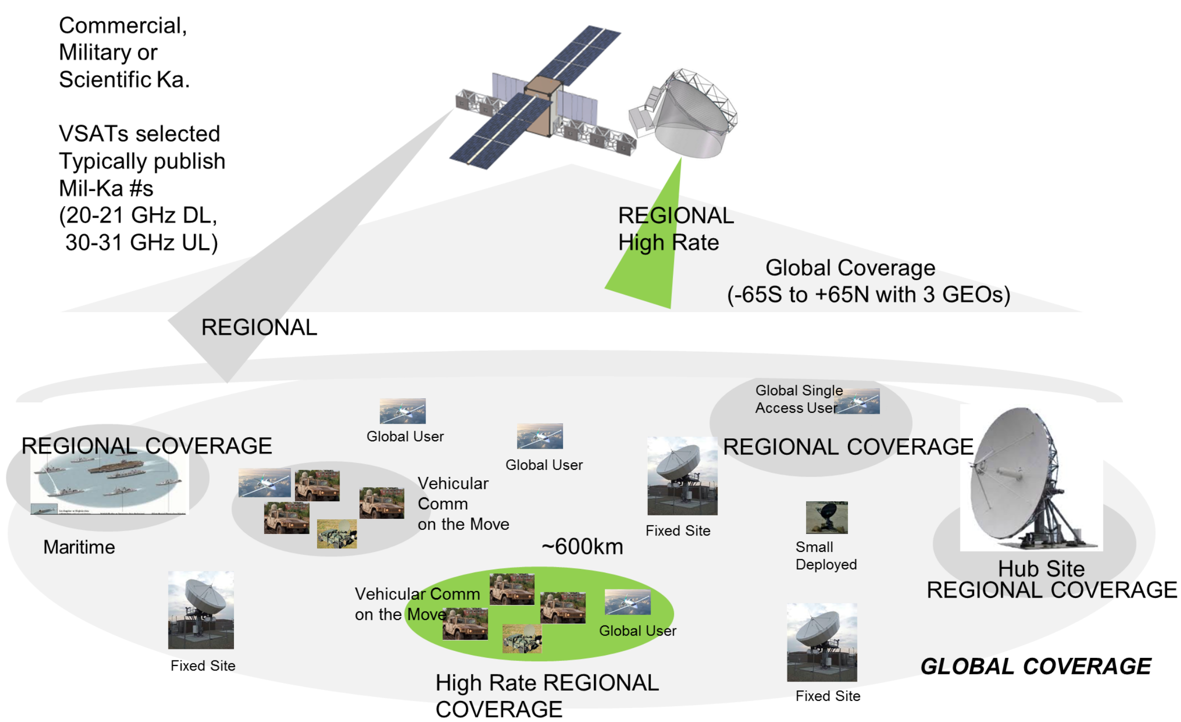

Figure 3. **Potential system coverage areas and user communities. We assume that the system will cover a range of users including hub sites, deploy-able communications sites, maritime users, airborne users, and smaller vehicular and man-portable systems for mobile users. We also assume that multiple users will be operating in a single geographic region and may be covered by a single coverage area.**

Figure 4. **Examples of very small aperture terminals that may be use to access the proposed system**

coverage antennas. In addition to these region specific components, we expect to require a centralized host interface unit (HIU) module responsible for the configuration of the overall system and managing the switching of signals. The requirements and capabilities of each module are summarized in Table 3.

To facilitate incremental launch and servicing of the system, we propose to discretize the payload into individual modules that can be launched as secondary payloads and installed on the platform via a standardized interface. Each module must fit in a 90.9x90.9x60 cm volume and weigh less than 150 kg to ensure that it may be launched via the PODS standard or on a propulsive ESPA ring. The payload interface

Table 1. Summary of the notional user community used as a reference point for the capacity analysis

User	Terminal	Services	Aperture	L.EIRP	G/T	Reference terminal
User 1	Hub site	High rate data, voice, and messaging	7.2 m	81.5 dBW	34 dB/K	Standard 7.2 m MET terminal [26]
User 2	Large deployed	High rate data, voice, and messaging	2.4 m	69.5 dBW	28.7 dB/K	Hawkeye III 2.4 m [27]
User 3	Medium deployed	High rate data, voice, and messaging	1.6 m	66 dBW	25.2 dB/K	Hawkeye III 1.6 m [27]
User 4	Maritime	High rate data, voice, and messaging	1.6 m	66 dBW	25.2 dB/K	Hawkeye III 1.6 m [27]
User 5	Vehicular	Medium and high rate data, voice, and messaging	0.46 m	47.4 dBW	12.8 dB/K	Datron FSS-4180-LC [28]
User 6	Airborne	Medium rate data, voice, and messaging	NA	52.5 dBW	12.5 dB/K	Global Aero 5530 [29]
User 7	Small deployed	Medium rate data, voice, and messaging	0.6 m	51.8 dBW	15.2 dB/K	Manpack Panther [30]

Table 2. Link budget assumptions

	uplink, downlink
Rain margin	4 dB, 3 dB
Atmospheric margin	1 dB*, 0.5 dB*
Loading margin	4 dB
Transmitter/receiver IMP loss	3 dB
Polarization mismatch	0.25 dB
Earth terminal pointing loss	1 dB
Aperture efficiency	60 % - 70 %
Radome losses	1 dB
Feed, slip ring, and flange losses	2 dB
Eb/No (1/2 QPSK)	1 dB
Eb/No (2/3 8-PSK)	3.6 dB

*Atmospheric loss margin reduced for airborne users

on the persistent platform must be positioned to provide a unobstructed view of the earth and sufficient clearance for the payload's gimbaled and deployable antennas. The interface (such as the TUI Axon or iSSi connectors) must also provide electrical bonding, primary power, heat rejection, and data transfer interfaces. Electrical bonding of the payload to the persistent platform for primary power and return lines as well as primary structure ground (chassis ground) is needed to avoid a noisy environment and also to address space plasma charging and electromagnetic compatibility (EMI/EMC). The interface must also deliver 600 watts of electrical power to each module and accept 450 watts in returned heat by maintaining the the thermal interface at a nominal temperature range (e.g. between $-20°$ and $50°$C). Lastly a data interface connecting the individual modules with a data rate of between 1 Gbps and 100 Gbps is needed depending on how the waveform is processed.

Based on these requirements and constraints, we have developed notional models of each module that show how the substantive components could be packaged for launch and operations. All of the modules are based around a standardized back plane that includes the primary structure, spacecraft interface, launch vehicle interface, and servicing vehicle grapple fixture. For reference, we have modeled these components on the manufactures specifications for commercially available or under development components. The structure is based on the standard (90.9x45.7 cm) or extended (90.9x90.9 cm) PODS chassis depending on the size of the module. The spacecraft interface is based on the specifications for the iSSI connector which is 220 mm in diameter, 48 mm thick, and weighs 2.5 kg. The grapple fixture is based on the Probe Fixture Assembly used on the orbital express mission. Lastly, the launch vehicle interface will depend on how the module is going to be launched. If launched via the PODS based system, the module can be mounted to the PODS payload ejection mechanism on the host spacecraft. If launched on an ESPA ring, the module can be attached to one of the ports via a separation system such as the Planetary systems motorized lightband that is mounted to the bottom of the back plane.

Concepts of the earth coverage, regional coverage, and high gain regional coverage modules are shown in Figs. 5, 6, 7, 8, and 9 respectively and the subsystems and their estimated mass and power requirements are summarized in Table 4. Each module includes the aperture, pointing mechanism (if required), and analog and digital electronics mounted to the structural back plane. The components are arranged so that they fit within the 90.9x90.9x60 cm bounding box dictated by the PODS standard when stowed in the launch configuration so that it may be launched on a ESPA ring or PODS system. The earth coverage module is composed of a 4 cm aperture, low noise amplifier, RF power amplifier, and RF and digital electronics module. These components can be mounted to the smaller standard PODS back plane as can be seen in Fig. 5.

The notional design of the regional coverage module consists of a 70 cm diameter primary aperture that includes a feed horn and low noise amplifier, a two axis antenna gimbal based on the NEA P3[5] actuator, gimbal drive electronics based on the Motiv Space Systems Bravo motor controller, and four TWT and EPC based RF power amplifiers paired with four RF and digital electronics modules [34–37]. These components can be easily packaged into the requisite form factor as shown in Fig. 6. Although we have not conducted a detailed design of the feed or sub reflector, in this configuration, there is a ⌀30 by 37 cm tall volume available for these components. We also consider a version of this module where the aperture is rigidly mounted to the back plane and the whole module is gimbaled as shown in Fig. 7. This approach is attractive since it eliminates the complexity and signal losses of the wave guide slip ring between the amplifier and antenna but adds the technical challenge of the heat transfer across the gimbal.

Table 3. Module coverage capabilities, antenna technologies, and general specifications

Coverage Type:	Regional	High Resolution	Earth	SC Interface	Total
Module Name	Gimbaled Antenna	MBA	Earth Coverage	HIU	
Coverage	1°	1°	17.5°	NA	NA
UL 3 dB beam width	1°	0.23°	NA	NA	NA
EIRP	57 dBW	57 dBW	-12 dBW	NA	NA
G/T	12 dB/K	24 dB/K	-12 dB/K	NA	NA
Sidelobe level	-17@1.5 Th3dB, -30 (O)	-17@1.5 Th3dB, -30 (O)	NA	NA	NA
UL band	30 - 31 GHz	30 - 31 GHz	30 - 31 GHz	NA	NA
DL band	20-21 GHz	20-21 GHz	20-21 GHz	NA	NA
Spectrum	1 GHz in Ka-band	1 GHz in Ka-band	1 GHz in Ka-band	NA	8 GHz
Instantaneous BW	125 Mhz - 1 GHz	125 Mhz - 1 GHz	10 MHz	NA	NA
Pointing uncertainty	$0.03°, 3\sigma$	$0.01°, 3\sigma$	$1°, 3\sigma$	NA	NA
Mass allocation	120 kg	120 kg	120 kg	120 kg	1200 kg
Power allocation	600 W	600 W	600 W	600 W	6 KW
Thermal allocation	450 W	450 W	450 W	450 W	4.5 KW
Count	6	2	1	1	10

Table 4. Module breakdown

	Module Type			Properties*	
Module components	Gimbaled Antenna	MBA	Earth Coverage	Mass	Power
Structure	interface, structure, and heat spreaders	interface, structure, and heat spreaders	interface, structure, and heat spreaders	25 kg	NA
Antenna Suite	70 cm dish, gimbal, LNA	3 m dish, gimbal	4 cm dish and LNA	25 kg	NA
Power amplifier	4x TWT + EPC	MBA Feed	TWT + EPC	25 kg	400 W
Electronics	one 125 MHz transponder per digital module (four digital modules total) to support digital transponder or fully processed payload [31, 32] .		one transponder and digital module configured for low rate services	25 kg	150 W
Alternative COTS electronics	Use of more capable COTS electronics may allow for flexible processing of the full 1 GHz spectrum with ganged TWTs instead of one TWTA per 125 MHz channel			12 kg	85 W

*Mass and power estimates based on the scaled spacecraft Mass/Power model developed by SSL [33]

Since the single dish configurations do not fully utilize the available volume and mass, we also have considered a version of the regional coverage module that packages two apertures into a single module capable of serving two coverage areas as shown in Fig. 8. In this configuration, the two reflectors must be folded together for launch and then can unfold using the gimbal actuators for operation. This module will require approximately 1 m of clearance on either side to accommodate the deployed reflectors. The stowed configuration also has limited space for the antenna feed and sub reflector (approximately $\varnothing$20 by 20 cm tall) and therefore may require a deployable feed or subreflector. Lastly, although two antenna's may be packaged into one module, it may not be possible to fully duplicate the electronics payload due to the combined volume, power, and thermal requirements of eight amplifiers and digital electronics modules. Therefore, this version of the regional coverage module may not provide increased capacity in comparison to the single dish but would allow the system to serve additional geographically separated coverage areas with some mass savings since only one structural backplane, spacecraft interface, and grapple fixture would be needed.

The high gain regional coverage module consists of a 3 m deployable reflector and boom (for example the TENDEG KaTENna, [38]), an antenna gimbal and drive electronics similar to that used on the regional coverage module, a MBA feed and SPA based amplifiers, and RF and digital electronics module. A notional configuration of these components mounted to the module backplane is shown in Fig. 9. When stowed for launch, the reflector and boom fold up and occupy approximately 40x40x90 cm. The other components can then be arranged on the other half of the backplane. When deployed, the antenna will require clearance behind and to either side of the module since it will occupy an approximately 3x3x3 m cube outboard and behind the module.

5. Persistent Platform Concepts

We have considered two different concepts for the host platform: a monolithic platform based on an existing large geostationary spacecraft bus such as the SSL 1300 and a modular platform such as Tethers Unlimited Inc.'s Constructable

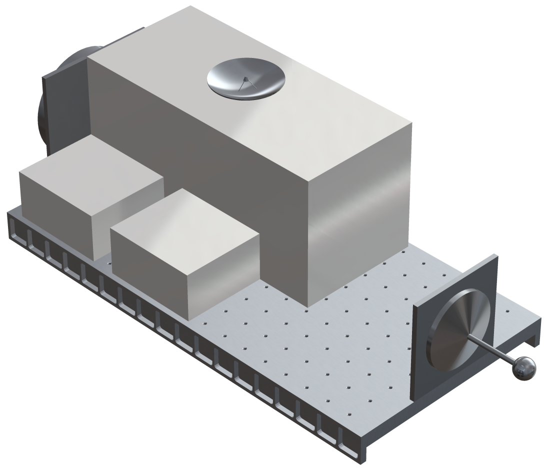

Figure 5. **Single 1° Earth coverage module**

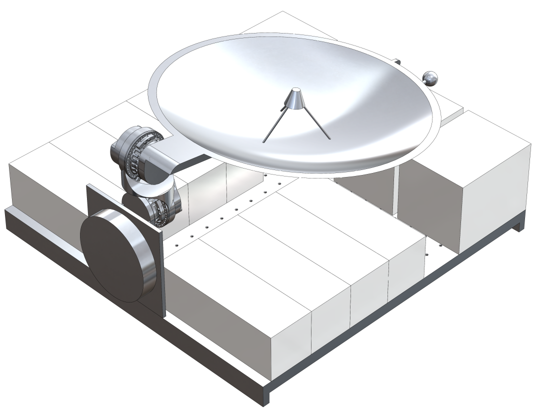

Figure 6. **Single 1° gimbaled spot beam coverage module**

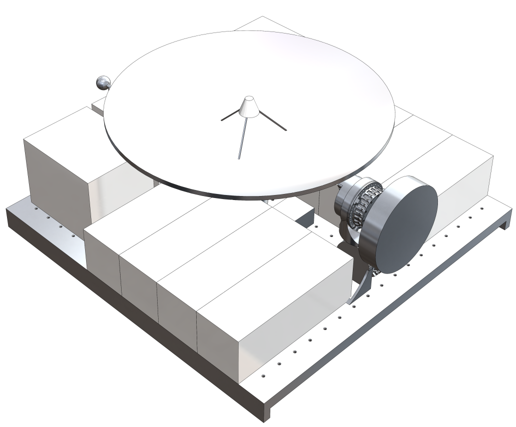

Figure 7. **Single 1° spot beam coverage module where the entire module is gimbaled**

Persistent GEO Platform [39, 40]. The monolithic platform concept (shown in Fig. 11) is based around a traditional spacecraft bus that hosts the solar arrays, radiators, attitude control system, and other basic services. Two trusses extend from either side of the center structure and each truss has

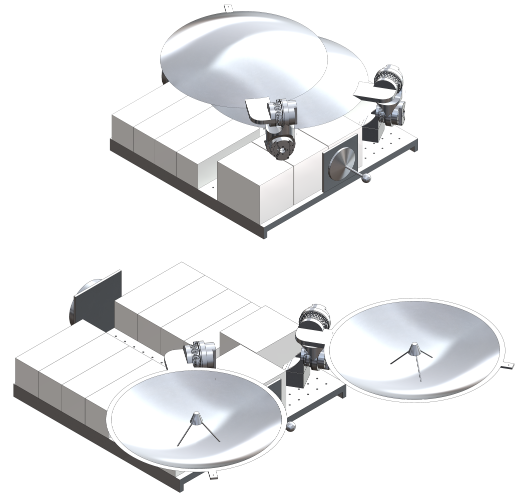

Figure 8. **Dual gimbaled spot beam module. This shows a concept for how two 1° gimbaled spot beams and their associated electronics may be packaged into a single module for launch (left) and when deployed (right).**

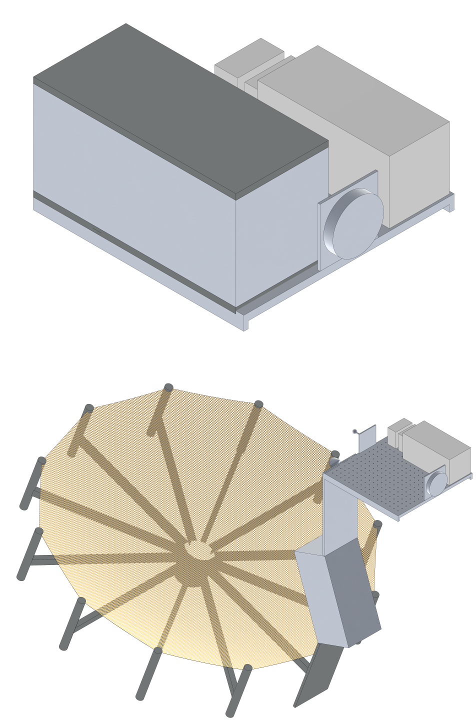

Figure 9. **High gain multi beam antenna module consisting of a 3 m deployable dish and its associated electronics in the stowed (left) and deployed (right) configurations.**

multiple payload mounting sites, each of which is equipped with the standard payload interface. Although payloads may be replaced, we assume that the basic capabilities of the platform such as its power generation and heat dissipation would not be expandable or upgradable; instead additional platforms would need to be launched once one reached its capacity.

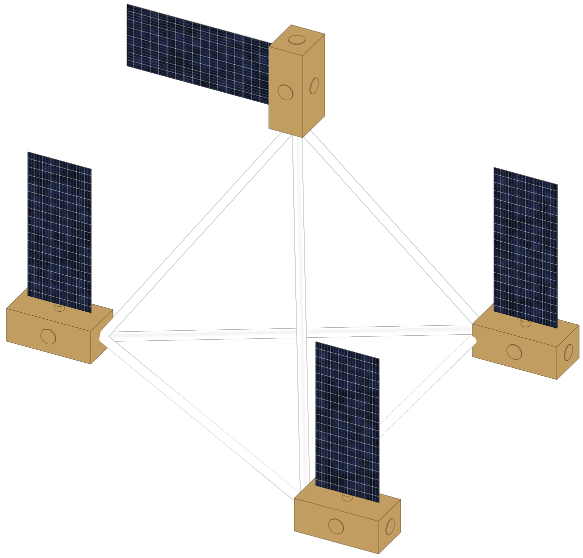

Figure 10. **Modular persistent platform**

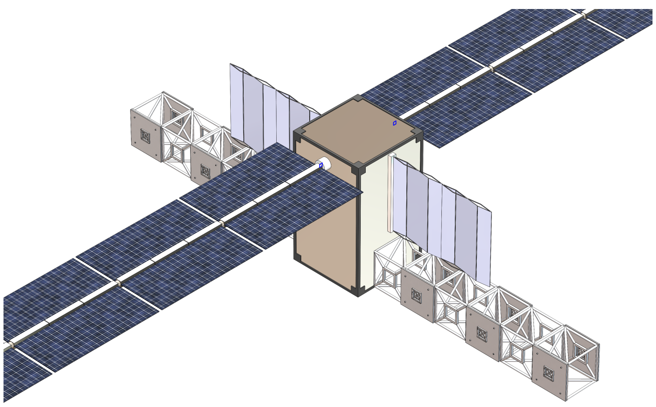

Figure 11. **Monolithic persistent platform**

The modular platform concept (shown in Fig. 10) is based around a small standardized spacecraft that can be launched as a secondary payloads and assembled in orbit into a larger structure. Each module includes a solar array, power distribution, thermal regulation, and attitude control systems, payload interfaces, and three long masts. After launch, four of these modules can then be linked together by their masts to form a tetrahedron. Electrical, data, and thermal connections through the masts allow the individual module to share power and other resources. If demand merits, additional tetrahedrons may be assembled and linked together to further expand the size and resources of the platform. Conceptually, this modular approach allows the capabilities and size of the platform to grow as needed based on the payload demands. However, the initial capabilities of a single tetrahedron may be limited in terms of the electrical and thermal power and mass of a payload that can be supported.

6. Assembly and Servicing

The concept for the overall payload deployment is shown in Fig. 2, the detailed concept for payload installation is shown in Fig. 12, and a dynamic simulation of these operations is presented below. We assume that the platform and robotic servicing vehicle (such as RSGS) are already in orbit and

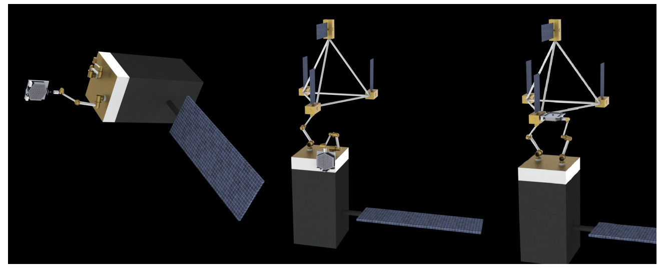

Figure 12. **Installation of the payload onto the platform**

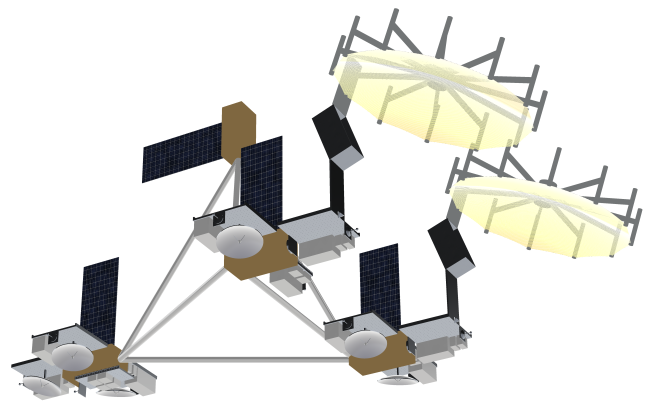

Figure 13. **Modular persistent platform with proposed GEONode payload**

functional when we begin launching the payloads. Payload elements can then be launched either individually via the SSL PODS interface or in batches via a secondary launch vehicle adapter such as the SHERPA, OMV, or EAGLE-S systems and inserted into a near geostationary orbit. Then, individual payloads may be captured via a standardized grapple fixture by the servicing vehicle. The servicing vehicle can then rendezvous with the platform, execute a r-bar approach to its nadir face, and capture a grapple fixture on the platform. We chose this approach since we do not expect any of the payloads to project in-front of the platform after installation or otherwise obstruct this the servicing vehicle if it approaches from below. Once anchored to the platform, the servicing vehicle can install the payload on the platform using its other arm. Positioning the interface on the side of the platform and payload allows the servicing vehicle to visually monitor both halves of the interface during the installation. After installing the payload, the servicing vehicle will first release its grasp on the payload and then the platform and then depart. Next, the payload can be brought online via commands sent by the platform and the apertures may be deployed. This operation may be repeated to install additional payload modules until the complete payload has been installed. Concepts for the complete payload installed on the modular and monolithic platforms are shown in Figs. 13 , 14, and 15. This process can also be reversed if a payload needs to be removed from the platform. The payload would first stow its antenna. Next, the servicing vehicle would anchor itself to the platform and grasp the payload. Then the payload interface would be commanded to disconnect and the payload would be moved away from the platform and berthed to the servicing vehicle. The servicer can then release its grasp on the platform and depart. Lastly it can boost the defunct payload into into a graveyard orbit for final disposal.

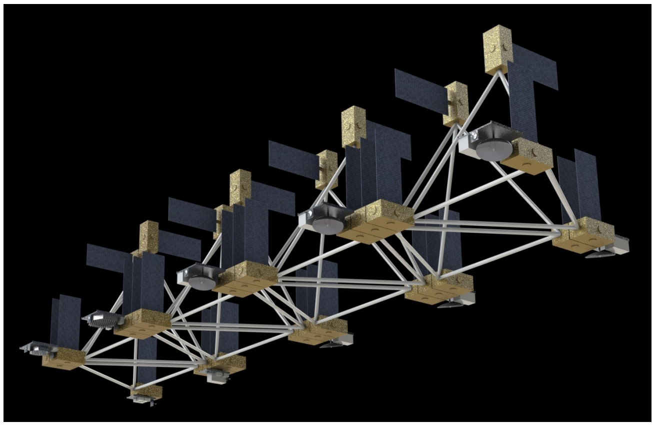

Figure 14. **Concept for a expanded modular persistent platform hosting the GEONode payload. The Expanded platform is composed of multiple tetrahedrons linked together and may be required to provide sufficient power generation and heat dissipation to the payload.**

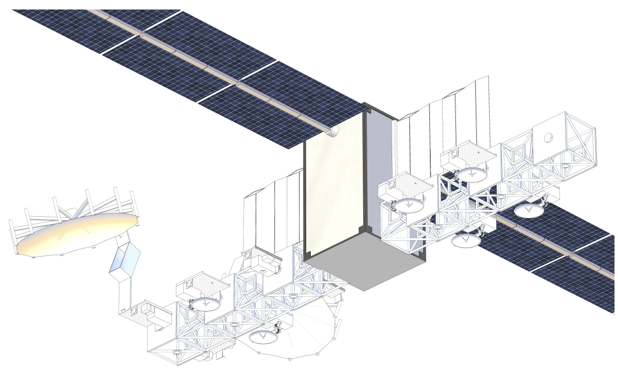

Figure 15. **Monolithic persistent platform with proposed GEONode payload**

Simulation Setup

The proximity operations and payload installation was simulated with the JPL M3tk (robot Mobility and Manipulation Modeling Toolkit) multibody dynamics simulation library [41]. M3tk allows dynamics problems to be set up using `.m3in` files that define the details of the simulated scenario including the gravity, bodies, points, joints, controllers, navigators, loop closures, joint loads, body loads, inter-body loads, materials, and contact models. Controllers are used to exert control over the degrees of freedom of the joints, and navigators are used to plan the action of the controller at a higher level of abstraction. CAD files can be provided for the bodies as `.stl` files. Contact models can be created using either the surfaces of the `.stl` files or primitives such as cylinders, disks, and spheres, together with a file specifying the material properties of the bodies. Figure 16 shows a graphical representation of how input to the dynamic simulation is structured.

Herein, the servicer spacecraft is controlled exclusively with with 12 notional chemical 10 N thrusters, implemented as body loads and controlled using pulse width modulation (1 s control period, 40% duty cycle). PID position and attitude control is used to track interpolated trajectories generated by a spacecraft navigator. PID motor control is used to control individual joints on the servicer's robotic arms. An arm navigator issues commands to the arm's revolute joints in

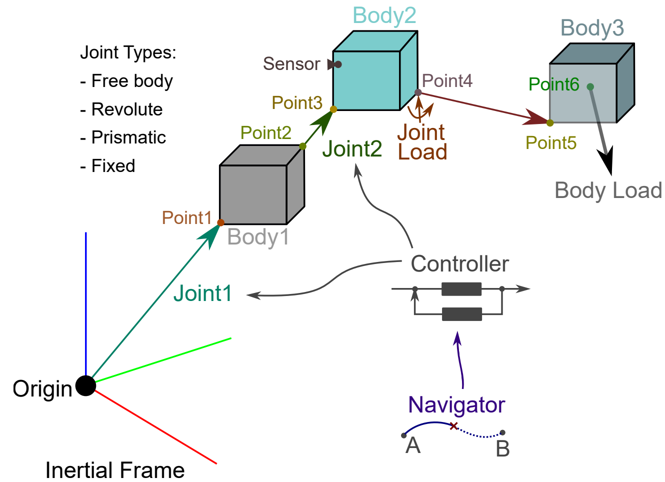

Figure 16. **A topological diagram of an M3tk model.**

Table 5. **Masses of the major simulated components.**

Component	Mass
RSGS Servicer Vehicle	4500 kg
Payload	150 kg
Host Spacecraft	2000 kg

one of two ways: explicitly as target joint angles (referred to herein as explicit commands); or implicitly through the specification of target end effector pose (referred to herein as pose commands). For the latter case, inverse kinematics are performed using the algorithm described in [42]. Typically, explicit commands are used herein for approximate positioning, whereas pose commands are used when the end effector must follow a specific Cartesian trajectory. The notional masses of the major components used in simulation are shown in Table 5.

Simulation of Proximity Operations

Approach and Grapple—To simulate the approach and grapple phase, the servicer spacecraft is commanded to a position near the payload. Once it is close to the payload, the arm navigator issues an interpolated sequence of explicit joint commands to bring the arm's end effector close to the grappling feature on the payload. A contact model is implemented on the "ball" of the grappling feature and the "cup" of the arm's end effector using the sphere, cylinder, and disk collision primitives (see right hand side of Figure 17). In order to avoid unnecessary contact, the arm navigator then issues interpolated pose commands to the grappling tool. The objective of this final maneuver is to translate the grappling tool so that it encapsulates the payload's grappling feature without colliding with it. During the motions of the arm, the thrusters are used to keep the servicer's center of mass stationary. Figure 17 illustrates the simulation during the final motion of the arm to grapple the payload.

Stow and Depart—To simulate the stowing of the payload, an explicit sequence of joint commands is used to get the payload close to the stowing location on the servicer. Then, pose commands are issued to the end effector to stow the payload using the stowing feature on the servicer and payload. Thrusters are fired to depart toward the host spacecraft. Figure 18 illustrates the simulation during the stowing of the payload.

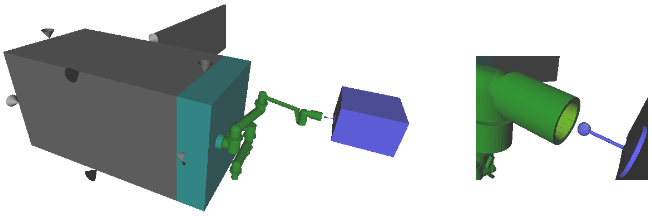

Figure 17. A snapshot of the M3tk simulation as the servicer grapples the payload (left). A closeup of the grappling interface with the collision model shown in yellow (right).

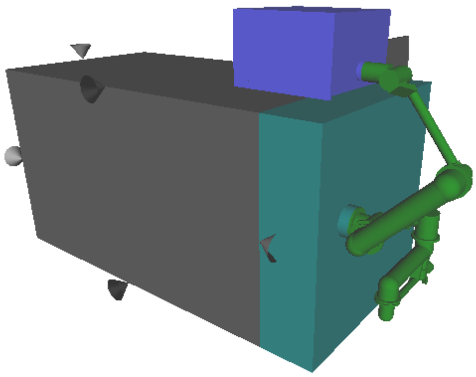

Figure 18. A snapshot of the M3tk simulation as the servicer stows the payload.

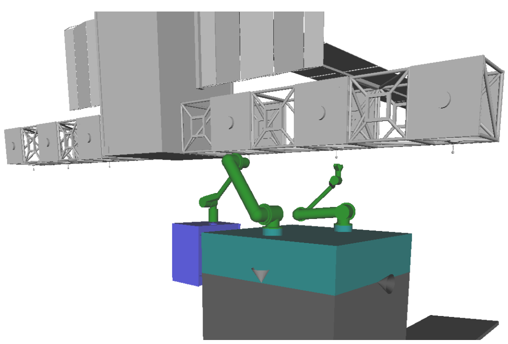

Figure 19. A snapshot of the M3tk simulation as the servicer docks with the host.

Approach and Dock—The servicer spacecraft is made to approach the host from below along the r-bar. The docking arm is deployed into a ready position using a set of explicit joint commands. Once at close range, the docking arm navigator issues pose commands to perform a Cartesian move, which attaches the servicer to the host. Figure 19 illustrates the simulation during the final docking maneuver.

Install and Depart—The payload is unstowed using pose commands to cleanly detach the payload from its stowed position. It is then brought near to the installation feature on the host using a series of explicit joint commands to the servicing arm. The final approach of the payload toward the installation feature is performed using pose commands. Thruster control is used to prevent orientation changes in the docked spacecraft assembly. The unstowing and installation phases are illustrated in Figure 20.

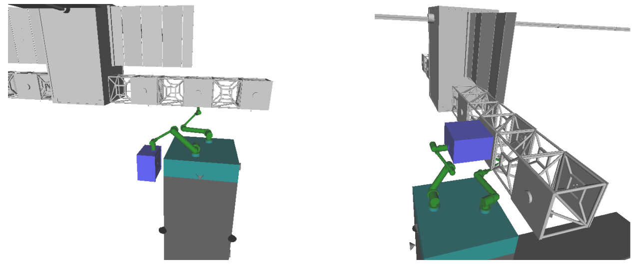

Figure 20. A snapshot of the M3tk simulation as the servicer unstows the payload (left) and attaches it to the host spacecraft's truss (right).

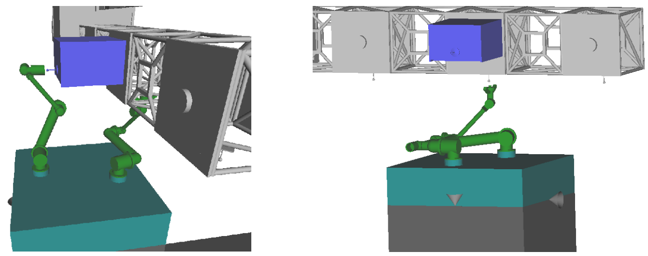

Figure 21. A snapshot of the M3tk simulation as the servicer releases the payload (left), and demates from the host spacecraft (right) before departing.

In preparation for departure, the servicer releases its grip on the payload, retreats the servicing arm using pose commands, and then stows the arm in its original configuration using explicit joint commands. Following this, the docking arm is released, backed away using pose commands and then stowed in its original configuration using explicit joint commands. The spacecraft then translates away from the host along the r-bar and departs. Figure 21 shows the servicer demating from the payload and docking feature.

7. Electronics and Signal Processing

Advances in COTS electronics capability provide a number of opportunities including more compact payloads, augmented payload functionality (reducing ground footprint and operational costs as discussed earlier), and even the possibility of reprogramming the payload function in orbit (addressing evolving protocol requirements for augmented payloads). More compact payloads may be built by performing more of the payload functions in digital rather than analog circuits, i.e. moving the digital/analog boundary closer to the antenna. In this context, one of the advances in satellite communications technology has been the shift from analog transponders to digital transponders facilitated by improvements in digital electronics [43, 44]. This transition to a digital architecture also simplifies controlling the intermodulation product problem and allows greater system flexibility since the system can be reprogrammed while in orbit. However, transitioning front-end analog functions to digital systems can demand significantly more powerful digital infrastructure.

In this study we attempt to touch on all three of these opportunities in the described concept. The digital electronics module is reprogrammable in that it uses field-programmable gate arrays (FPGAs), it supports both more compact payloads as a digital transponder and can be reprogrammed for augmented functionality adapting and integrating popular DVB-S2 waveform and protocols.

Signal processing architecture

We considering two different digital signal processing architectures: a digital transponder and a fully processed payload. For the digital transponder, the analog signal can be digitized and transmitted over a packet network as a digital intermediate frequency (IF), leveraging the DigitalIF work that has been done for ground terminals and apply it to the space segment [31]. The fully processed payload takes this further and fully recovers the data which can then be routed via data switching technologies. The digital transponder allows waveform processing and resource management to be performed on the ground, simplifying the spacecraft somewhat. In contrast, the fully processed payload allows this to be controlled on board the spacecraft, eliminating the ground footprint. It also has advantages both in terms of the flexibility of routing individual signals and noise since the up-link and down-link noise may be treated separately. An example of the on-board processing utilization and link budget advantage is a mobile to mobile communications case where good data rates are achieved via on-board full processing without having to waste resources to provide per mobile user forward and return links to a large ground hub. Block diagrams that show how the signal may be handled in each case are shown in Fig. 22.

Digital Electronics Module Design Concept

In order to better understand the mass and power required to deliver the desired capabilities, existing spacecraft systems and COTS electronics are evaluated. The reference capabilities are a digital transponder and a fully processed DVB-S2 like waveform implemented on the payload [32]. An assessment of data interconnects between modules and resource management are included with each of these capabilities. The capability and mass/power estimates are based on a scaled spacecraft Mass/Power model developed by SSL [33]. These results also align with an extrapolation from similar heritage electrical systems developed at JPL for the NISAR spacecraft Ka-Modulator [37]. Finally, a design based on flying state of the art COTS parts was assessed and led to the consideration of a Xilinx Ultrascale based Architecture. The desired processing capability for each approach is to support 360 Mbps of user traffic in a region, support inter-region traffic, and provide the equivalent of four 125 MHz transponder channels. The channelization on a transponder used to support a reference mix of users would be a combinations of either two high rate (44 Mbps), 14 high rate (6.3 Mbps), 14 medium rate (1 Mbps), or 200 low rate (2.5 kbps) users. Subchannelization is envisioned in the sense that a high rate channel could be repurposed as 7 medium rate channels or some number of low rate channels. We estimate that a traditional space qualified system capable of delivering these capabilities would weigh 25 kg and draw 150 W. In comparison, the COTS based system has the potential to weigh as little as 12 kg and only draw 85 W but must also take into account the repackaging needed to meet launch and space environmental requirements for thermal, shock and vibe.

Data interconnect

User data must be transferred both within a module and between modules as shown diagrammatically in Fig. 23. Therefore, high rate interconnects between the individual module are required to facilitate communications between different coverage areas. Since the modules are only connected via the platform which we assume can't be upgraded after it has been launched, implementing a flexible and robust interface between the modules is key. Therefore we have surveyed a number of different methods for data transfer within the platform and through the payload interface all of which are summarized in Table 6. The simplest interface we consider is low voltage differential signaling (LVDS) and a protocol such as SpaceWire. Although this is straightforward to implement, low powered, and light weight, the data rate is limited to 1 Gbps, constraining the bandwidth available for between region communication and future system growth. Although implementing LVDS based communications that support the desired 40 Gbps data rate may be feasible, we expect that doing so would require many more twisted pairs and add significant mass to the system. 10GigEBASE-T can support data rates up to 10 Gbps over four twisted pairs and cable runs up to 55 m. To achieve the desired 40 Gbps, we propose to use four Ethernet interfaces in parallel. We also consider a fiber optic interface that that would be capable of data rates up to 40 Gbps. However because of the difficulty of making fiber optic connections, we assume that a direct fiber optic connection to the payload through the interface is impractical. Instead we propose using either a free space optical connection or a short range, high rate copper interface. The free space optical connection such as that proposed for the iSSi connector eliminates insertion, provides galvanic isolation, and is less prone to electromagnetic interference but lacks flight heritage to the authors knowledge. In contrast, copper based interfaces are well understood but the electrical connector may be susceptible to damage during installation and may add additional complexity to the interface. Lastly, we consider short range module to module wireless communication since this could eliminate the dependence of the intermodule communication on the platform itself [45]. Although this would simplify the interface and allow for future upgrades to the module to module communications, at this time, the technology is relatively immature and the initial data rate is lower than desired.

Table 6. Module interconnect

Interconnect option	Data Rate	# of twisted pairs
LVDS (SpaceWire)	1 Gbps	4
4x 10GigEBASE-T	40 Gbps	16
SERDES to Bus optical	40 Gbps	
Free space optical to bus optical	1+ Gbps	NA
802.11ac	1 Gbps	NA

8. DISCUSSION

Comparison of the serviceable platform to a traditional spacecraft

Based on an existing analytical model, we estimate that a traditional satellite capable of delivering the desired capabilities discussed here would require a 7 KW solar array and weigh approximately 3700 kg [33]. This mass estimated is based on 750 kg of primary structure, 100 kg of propulsion hardware, 1250 kg of fuel, 150 kg of solar panels, a 200 kg battery to operate through eclipses, 250 kg for the thermal control system (TCS), telemetry tracking & command (TT&C) system, attitude control system (ACS), and command and data handling (C&DH) system, and approximately 1000 kg for the communications payload. In comparison, we estimate that the communications payload can be broken down into 10 modules and that the mass of the interface, structural backplane, and protective/thermal hardware required for the modular approach will be approximately 25 kg per module. This will increase the overall system mass of the serviceable satellite by 250 to 300 kg. Although the initial launch mass

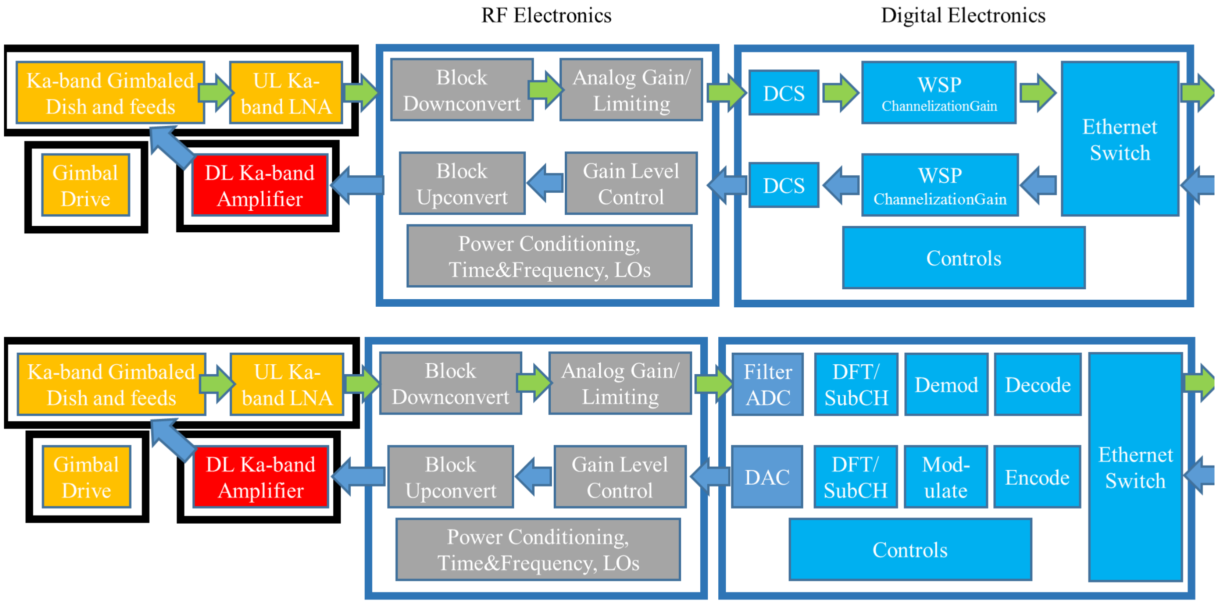

Figure 22. **Module electronics diagram for the digital transponder (top) and fully processed payload (bottom)**

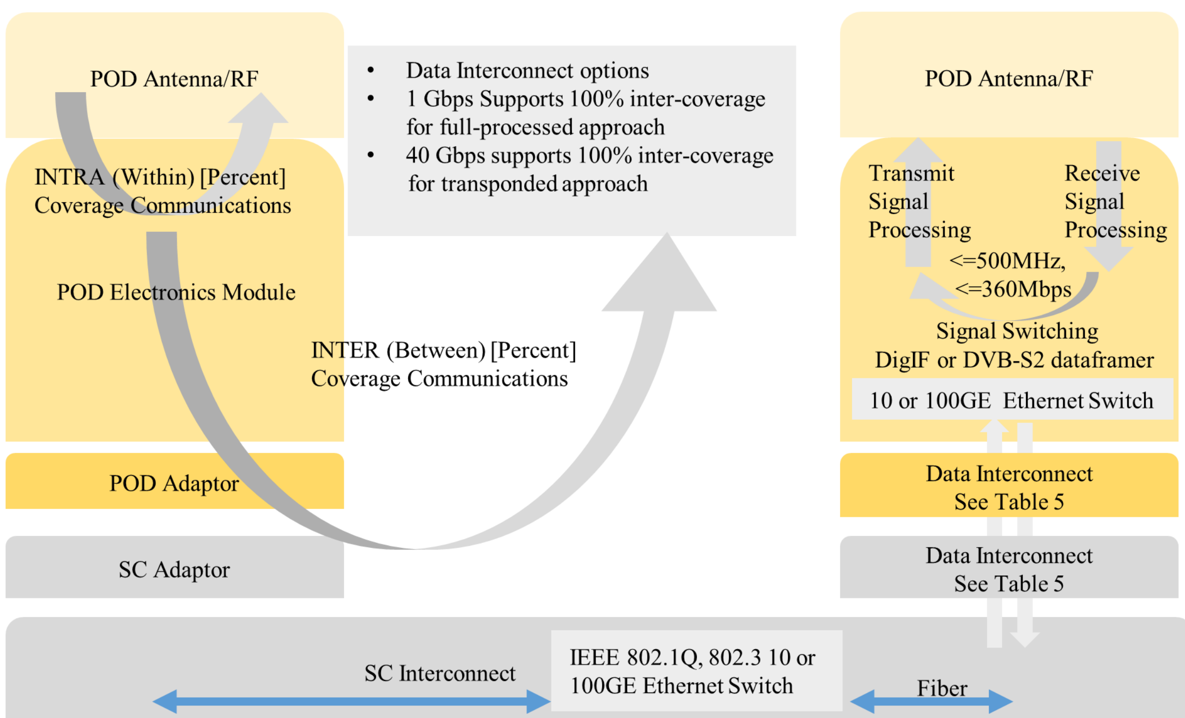

Figure 23. **Diagram showing within module and between module data flows and proposed interconnects**

may be up to 10% greater for the modular system, the mass required to fully replace the payload when a more capable communications payload is developed is approximately 1/3 the mass (approximately 1200 kg) of launching a completely new spacecraft, a significant savings that could translate into much more frequent upgrades when new technology is available or greater capacity is needed. Furthermore, the payload may be further modularized so that the electronics modules within each module may be replaced in orbit without replacing the antenna suite or amplifiers. Doing so may further reduce the launch mass and overall cost of maintaining the system since we expect that the COTS digital electronics will be the least robust components of our system with the shortest operational life. Although not directly captured in this mass comparison, one of the other significant advantages of the modular approach is that individual payload modules may be replaced when they fail or an upgraded capability becomes available, allowing for more incremental evolution of the payload.

Table 7. Estimated launch mass of a traditional satellite and the modular platform

7 KW Platform	Launch mass to GTO (kg)
Traditional approach	3700
Proposed approach	4000
Payload upgrade	1200*
Electronics upgrade	250*

*Fuel requirements for GTO to on-station not included in antenna suite upgrade mass estimate since this will be provided by the propulsive ESPA ring or POD host satellite

Tech Demo Concept

Here we have proposed an unproven approach to building, launching, and operating a communications satellite and recognize that there is significant risk associated with this. Therefore, we propose a simplified version of this modularized communications payload as an in orbit assembly technology demonstration. The demonstration system would consist of a single heritage space rated TWTA [36] used in conjunction with a microwave switch to either power an earth coverage horn or deployable regional coverage antenna. The digital electronics would rely on COTS components where possible and would consist of highly efficient power converters, high rate ADC/DACs and Xilinx Ultrascale FPGAs. The overall system may only draw 200 W of power and dissipate 100 W of heat. These components would be packaged into a self contained module that could be launched on an ESPA ring, via the PODS system, or permanently installed on a spacecraft as a secondary payload.

In order to demonstrate the in orbit assembly and servicing aspect of our proposed system, a standardized spacecraft interface such as the iSSI can be included in the demonstration module and on the host spacecraft. Then, we can demonstrate the installation of the module on the host spacecraft using one of the spacecraft robotic construction and servicing systems currently under development. For example, the payload could be launched via the PODS interface on a spacecraft equipped with the SSL dragonfly robotic arm that also includes the spacecraft interface and is capable of providing the necessary power, thermal, and attitude control [46]. Once in orbit the robotic arm could detach the payload from the PODS interface and reconnect it in its deployed location via the iSSI interface, demonstrating successful installation of the payload in orbit. Alternatively, it may be launched on a vehicle like the EAGLE-S that could also serve as the host spacecraft. After reaching orbit, the module may be released from the host and then captured by the servicing vehicle like RSGS. After berthing the payload, the servicing vehicle would then rendezvous and dock with the host spacecraft and install the module via the interface. This would demonstrate all aspects of the servicing paradigm that we have proposed including payload launch and delivery to the target orbit, payload capture by the servicing vehicle, servicing vehicle docking with the host satellite, and payload installation on the host platform by the servicing vehicle. In either case, after payload installation, payload operation would demonstrate the ability of the interface to provide the required utilities and the capabilities and functionality of the proposed communications suite.

9. SUMMARY

Here we have presented the concept for a modular spacecraft that can be assembled and serviced while in orbit by a spacecraft servicing vehicles such as RSGS. This concept breaks the spacecraft down into a long lived host bus responsible for basic spacecraft functions and a number of smaller payload modules that can be easily launched as secondary payloads, installed on the host bus by the servicing vehicle and removed and replaced when desired. Each module is designed so that it only relies on the host bus for power, thermal regulation, attitude control, data interconnects to other modules, and coarse pointing. The communications payload of a high capacity satellite is then distributed throughout the replaceable modules. Each module contains all of the components necessary to host a single steerable beam and its associated digital and RF electronics. Based on the launch constraints and reasonable assumptions about the kinds of users that the payload may serve, we have identified three different module designs that when combined on the host platform will deliver low rate global coverage and moderate rate regional coverage to many users and high rate coverage to a limited number of users in a few regions simultaneously. If the full payload of six regional spot beams, two multi-beam antenna's, and one earth coverage antenna were launched and high data rate interconnects were implemented on the platform, the resulting system may support up to 1.8 Gbps of regional traffic and 765 Mbps of hub site traffic. Furthermore, based on spacecraft mass models, the modular approach may only incur an initial mass penalty of 10% in comparison to a traditionally built equivalent spacecraft and require less than 1/3 the mass to fully replace the communications payload. Lastly, in addition to facilitating reuse of long lived spacecraft components, this approach may allow the capabilities of the spacecraft to evolve with user needs since individual modules may also be replaced or added to the platform if it is initially built with excess capacity.

ACKNOWLEDGMENTS

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