SSC15-II-1

DARPA Phoenix Payload Orbital Delivery System: Progress towards Small Satellite Access to GEO

Larry Gunn
DARPA Tactical Technology Office
larry.gunn@darpa.mil

Jeremy Palmer
DARPA Tactical Technology Office
jeremy.palmer@darpa.mil

Joanne Leung, Andrew Ogilvie
MDA Robotics and Automation
9445 Airport Road, Brampton, ON L6S 4J3, Canada; 905-790-2800
joanne.leung@mdacorporation.com

Alfred Tadros, Laurie Chappell
Space Systems/Loral
3825 Fabian Way, Palo Alto, CA; 650-852-4791
alfred.tadros@sslmda.com

Ken Weldy
Naval Research Laboratory
4555 Overlook Ave SW, Washington, DC 20375-5320; 202-767-6998
ken.weldy@nrl.navy.mil

Erin Fowler
ManTech International Corporation
erin.fowler.ctr@darpa.mil

James Eagen
KSH Systems Engineering
james.eagen.ctr@darpa.mil

Brook Sullivan
Sullivan Analytics and Technical Services LLC
saatsllc2015@gmail.com

ABSTRACT

The emerging practice of hosting payloads on commercial geosynchronous Earth orbit (GEO) satellites is gaining traction throughout the space community because of the flight opportunities and budgetary savings that it offers. Using the hosted payload model, the DARPA Phoenix Payload Orbital Delivery (POD) system is meant to enable a higher tempo to GEO for small-mass hardware items.

The POD system proposes a departure from the typical hosted payload. The POD would provide a controlled release of the hosted payload from the commercial host near GEO. The POD standard user's guide developed under the Phoenix program ensures compatibility with most of the approximately 15 commercial launches to GEO each year. By hosting with a standard user’s guide, commercial satellite providers would be capable of bringing hosted payloads quite late into the typical launch integration cycle. The combination of high-tempo commercial launches and late integration would create an “express delivery” capability to GEO orbit. This POD capability would continue the paradigm shift of working with the commercial satellite provider directly to leverage the efficiencies of mass to orbit, reducing interactions with the launch provider. Phoenix is completing the

design and ground testing of the POD system to help make access to new orbits more affordable and more routine for small-mass systems.

INTRODUCTION

History of the Payload Orbital Delivery (POD) System

Under the DARPA Phoenix program, the Payload Orbital Delivery (POD) system was conceived as an "express delivery to GEO" logistical mechanism for launching hardware such as mission-specific tools and satlets to GEO, where they would be available for collection and use by a robotic servicer/tender spacecraft already in orbit.[1,2] Space Systems/Loral (SSL) and MacDonald, Dettwiler and Associates (MDA) Robotics and Automation studied the feasibility of the concept and settled on mass, volume and power allocations and mechanical, electrical and data interfaces that would support a sustained use case for POD access to orbit. Safety, concept of operations, provisions for limiting the burden of integration on the host, and contractual, regulatory and insurance processes were addressed early as part of the initial study.

The POD would be a key enabler of a future advanced space logistics infrastructure, providing hardware and potentially fuel for a robotic spacecraft to use for servicing on-orbit assets, but it can be used in the nearer term for launching small satellites to GEO, where they would normally encounter multiple barriers to entry including high cost and prohibitively long launch integration timelines. These barriers to entry have often limited mission concepts for small satellites to exclude consideration of missions and payloads that would benefit from or could not be performed without access to GEO, near-GEO, geosynchronous transfer orbit (GTO) and beyond. The POD would open the door to new missions, payloads and concepts of operation for small satellite projects with lower budgets and shorter schedules than typical GEO satellite projects. More regular access to orbit would also enable the integration of more current and capable electronics and other technologies to space assets by limiting time spent "on the shelf" before launch.

The first launch of a POD would serve as a proof of concept for the capability and demonstrate the processes of integration and safe ejection from the host spacecraft.

POD Comparison to Other Hosted Payload Opportunities

The Hosted Payload Guidebook[3] summarizes the cost and timeliness motivations for the hosted payload concept: "The two principal advantages for a hosted payload owner of flying on a commercial mission versus a government-sponsored mission are: (1) the faster tempo of commercial programs, and (2) the lower cost. Typical schedules for commercial satellite deployments from concept definition to operations are around 32 months. Comparable government schedules could be five to seven years, and sometimes longer if the primary government mission is complex. And while many science missions have been limited to low earth orbit (LEO), given the expense of getting to geostationary orbit (GEO), the use of hosted payloads on commercial GEO satellites provides a relatively low-cost opportunity for access to higher orbit."

To date, hosted payloads have remained integrated with their host spacecraft for the duration of the host spacecraft life. The Phoenix program proposes to release the POD with its payload from the GEO host spacecraft. While the POD mass range is similar to an ESPA class delivery (180 kg on a standard ESPA ring slot), the availability of multiple launches per year for a POD, versus the ESPA cadence of one launch every 3-4 years, would provide great flexibility, timeliness and economies of scale to support sustainable hardware delivery to a valuable orbit regime. Also, the ability to release a payload from the host anytime during its transit from its upper-stage separation in GTO to its arrival in GEO would help to reduce launch costs of small satellite planetary and exploration missions, which are gaining interest in the era of reduced agency budgets.

Tables 1 and 2 show prices and mass allocations for other rideshare options to GTO and GEO as reference models for services to these orbits that are offered or could conceivably be offered based on existing technologies. *The larger Atlas 541 allows fairing volume for a secondary, so there is the potential for an ESPA or the ULA DPAF, although these are not currently offered as options to GEO. The pricing figures provided for ULA secondary access to GEO use a rough estimate of 50 percent mass penalty for the delta-V required for GEO insertion.

Table 1: Comparison of Mass and Cost of Some Options for Rideshare to GTO

Rideshare Capability to GTO	Mass (kg)	Cost ($k)	$k/kg
Spaceflight Services SHERPA[4]	100	5,950	**60**
ULA ESPA[5,6]	180	52,869	**294**
ULA Primary[7,8]	4450	164,000	**37**
SpaceX Primary[9]	4850	61,200	**13**

Table 2: Comparison of Mass and Cost of Some Options for Rideshare to GEO

Rideshare Capability to GEO	Mass (kg)	Cost ($k)	$k/kg
Spaceflight Services SHERPA	100	9,950	**100**
ULA ESPA	*90*	*52,869*	***~587****
ULA Primary	*2225*	*164,000*	***~74****
SpaceX Primary	*2400*	*61,200*	***~26****

The requirements that traditional hosted payloads place on their hosts vary widely, as evidenced in Table 3. The fact that the POD is a *releasable* hosted payload would bring benefits to the host spacecraft in that the host would not have to expend the stationkeeping propellant for the additional POD mass during its entire life in orbit; the POD would be ejected before the host arrives in its GEO slot, relieving the host of the burden of the POD mass before the host begins its useful life.

Table 3: Summary of Some Commercially Hosted Government Payloads[10]

Payload	Mass (kg)	Power (W)	Volume (m^3)	Payload Type
WAAS	60	300	1	L-Band Comm
AIS	3	8	0.003	VHF Comm
IRIS	90	450	0.127	IP Router
CHIRP	115	275	0.3	IR Sensor
ADF UHF	320	2000	8	UHF Comm

Planned Flight Testing

The first Hosted Payload Assembly (HPA) is scheduled for launch in March 2017 on board a host spacecraft provided by Space Systems/Loral, LLC (SSL). The Hosted Payload Assembly is made up of a POD Ejection Mechanism (PEM) and a POD Chassis provided by MDA Robotics and Automation and a POD payload. The payload for the first POD mission has not been finalized.

The host spacecraft would carry the HPA from the launch pad to near geosynchronous orbit. Once the host spacecraft arrives at the appropriate location near GEO for drop off of the POD (POD chassis plus POD payload) and performs the necessary checks, the host spacecraft would send the command to release the POD launch locks. After the launch locks are released, the POD would still be restrained at one location by the Universal Docking System (UDS), developed by MDA US Systems LLC. The UDS separation mechanism would then be released, causing the POD to separate from the host spacecraft. This release would be monitored by cameras on board the host spacecraft to document the safe release of the POD from the host spacecraft.

Once free from the host spacecraft, the POD would be activated and begin its journey as an independent spacecraft. The host spacecraft, meanwhile, would continue to maneuver to its operational orbit location, leaving the POD far behind. After this point, the host spacecraft and POD would perform each of their missions independently from one another.

POD ACCOMMODATION ON GEO SATELLITES

Process for Developing POD Volume, Mass and Power Allocations

The goal of the DARPA POD development is to develop cost-effective, frequent access to GTO/GEO for small payloads. In order to develop a cost-effective approach, it is generally necessary to define a standard so that the non-recurring engineering cost for each flight opportunity is kept to a minimum. To that end, the DARPA POD team worked together to define a standard mass and volume allocation that would target a "sweet spot" within the user community.

The first step in this process was to define a rideshare location on the GEO host that would frequently be available in order to meet the goal of having frequent ride opportunities. SSL performed a survey of past, present and future SSL satellite configurations and identified two locations that are frequently available for use (Figures 1 and 2). Once these "standard" and "extended" POD locations were identified, SSL surveyed other willing satellite manufacturers to ensure compatibility with other potential hosts.

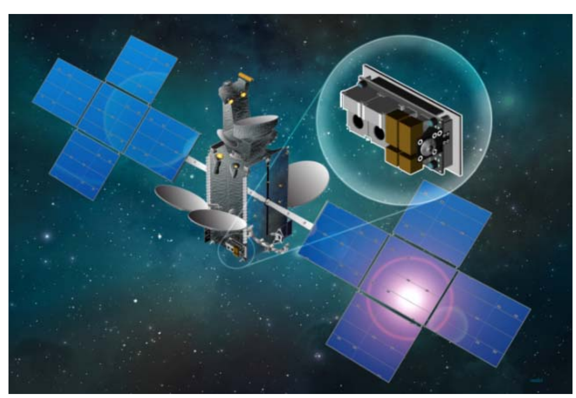

Figure 1: SSL Satellite Locations Frequently Available for POD RideShare – Unused Battery Compartments on East/West Faces (Standard Size)

Figure 2: SSL Satellite Locations Frequently Available for POD RideShare – Mid-Panel on East/West Faces (Extended Size)

The next step in this process was to survey the potential user community in order to find out whether the proposed standard and extended form factors are a good fit for user needs. SSL met with many interested parties across government, industry and academia and received feedback that was supportive of the proposed standard. In addition, SSL has developed a POD-compatible satellite bus that can execute a variety of missions in this class—further validation that the proposed form factor will meet the needs of many potential users.

The standard for power availability during GEO host orbit-raising was also validated through a survey of the user community. The survey concluded that most POD payloads would require very little power during the ride to GTO/GEO—a small amount to trickle-charge a battery or provide heater power would be sufficient in most cases because the POD would not be operating during this time.

Annual POD Hosting Opportunities

Figure 3 shows the results of the FAA's 2014 Commercial Space Transportation Forecast,[11] which indicates that launches to GSO are forecasted to remain relatively steady at ~15 launches per year through 2023. Not all of these launches will be compatible with a POD rideshare; however, SSL expects that roughly half of the launches could accommodate a POD, resulting in a steady stream of ~5-7 launches per year. The first POD launch is scheduled for March 2017, with several immediate opportunities that follow. Interested users are encouraged to contact the authors with their mission needs.[12]

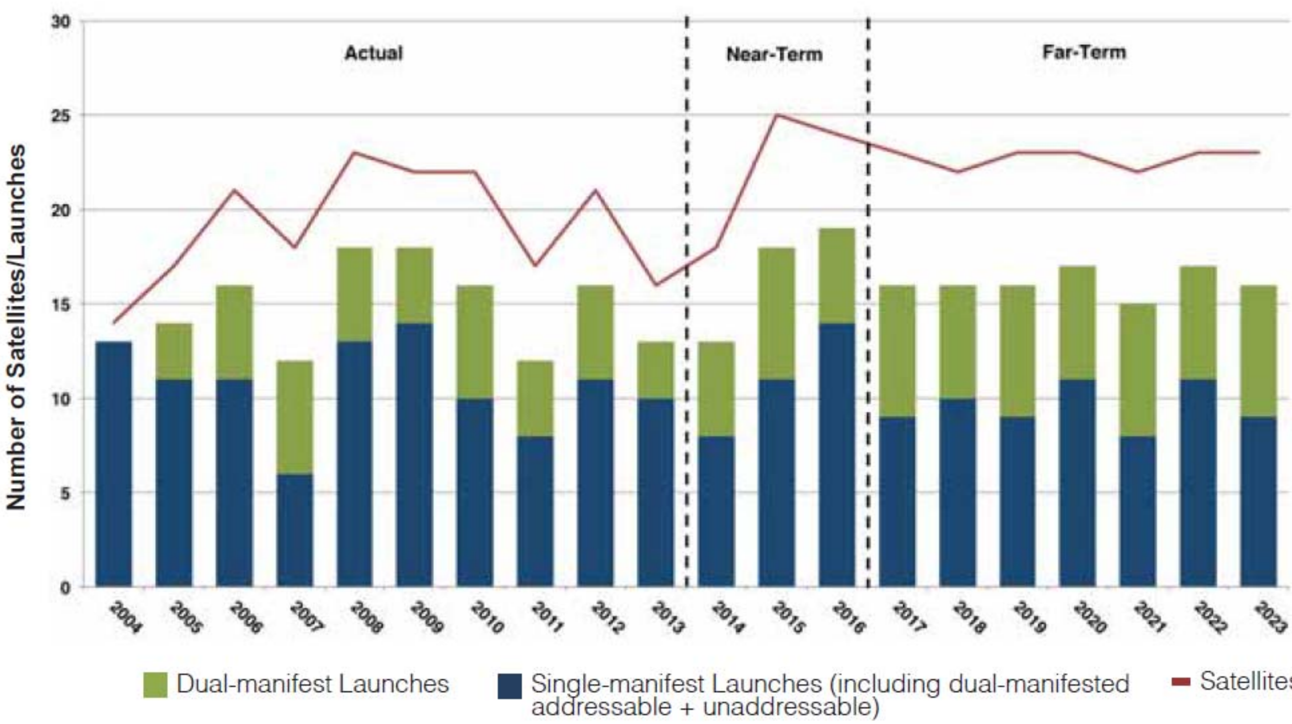

Figure 3: FAA Satellite Launch Demand Forecast 2014-2023

POD Launch Integration Cycle

One of the common difficulties with rideshares is that the schedules of the two or more spacecraft sharing a launch do not line up—Often smallsats want to wait until their program is well under way to sign up for a specific launch, or their development timeline is very short relative to the GEO host. A benefit of the POD program is that the existence of an established standard would enable a GEO host program to proceed with a POD implementation while the details of POD payload are negotiated.

In general, a Launch Service Agreement for a POD would be executed at Launch-24 months. A typical timeline for a POD launch is shown in Table 4.

Table 4: Typical POD Launch Mission Timeline

Event	Milestone Date
Contract Signing	Launch – 24 months
Separation System Delivery	Launch – 12 months
POD or POD mass model delivery	Launch – 9 months
PODS Final Integration to Host	Launch – 2 months
Ship to Launch Base	Launch – 1 month
Launch	Launch

POD Accommodation Status

SSL's near-term activities on POD accommodation are focused on completing the design and test of elements in support of the March 2017 flight. In parallel, SSL continues to solicit input from potential POD users and is actively working to book POD flights beyond March 2017.

HOSTED PAYLOAD ASSEMBLY (HPA) DESIGN

HPA Interfaces

To accommodate a range of payload sizes, there are two versions of HPA, Standard and Extended. The mass and volume of each option are summarized in Table 5. The primary function of the HPA's Payload Ejection Mechanism (PEM) is to safely dispense the POD from the GEO host spacecraft with benign tumble rates within a defined trajectory corridor. The PEM is identical for both the Standard and the Extended HPA. The Standard POD, shown at the PEM release point, is illustrated by Figure 4. The Extended HPA configuration incorporates a wider POD with additional launch tie-downs. Figure 4 illustrates the main components and interfaces of the PEM and a Standard POD chassis. The PEM was originally designed to dispense a POD with multiple payloads attached to it, but it could also dispense a payload that interfaces directly to the PEM without a POD chassis.

Table 5: HPA Mass and Volume Options

HPA Option	HPA Maximum Mass	HPA Volume [L x W x H]
Standard HPA	90 kg	90.9 x 45.7 x 40.0 cm^3
Extended HPA	150 kg	90.9 x 90.9 x 60.0 cm^3

The PEM's standard interface to the dispensed payload consists of four launch tie-downs and their associated hardware (i.e. bolt catchers and launch tie-down brackets), four cup/cone ejection push points and a centrally located tie-down interface called the Universal Docking System (UDS). The UDS has an active half and a passive half. The active half is attached to the PEM, while the passive half is attached to the dispensed payload. The UDS includes a fastener (and its release actuator) to keep the two halves mated, as well as two electrical pin pads that provide a power/data interface between the Payload and GEO host spacecraft. The central UDS serves as the final in-flight disconnect. After the four launch tie-downs have been released, the central tie-down is released to initiate ejection of the Payload from the GEO host spacecraft by the PEM.

The PEM to GEO host spacecraft interface consists of a PEM baseplate and four spacecraft-to-HPA connectors. The baseplate allows for easy integration with the spacecraft's mounting structure via 16 standard fasteners installed from the underside of the baseplate. The HPA ICD captures requirements for the GEO host mounting structure such as baseplate bolt pattern, structural stiffness and flatness, interface loads and cutouts/keep-out zones to accommodate access to HPA tie-downs.[13] The tie-downs are designed to be easily removed/reinstalled from/to the PEM baseplate for in-situ reset and refurbishment. All electrical signals and power from the host to the HPA pass through the four spacecraft-to-HPA 25-pin D-sub connectors situated on the side of the PEM baseplate.

The POD chassis is the standard pallet for payloads dispensed by the PEM. The standard POD chassis can support a payload manifest of up to 60 kg. The HPA mass is a total of 90 kg, including the payload manifest and the chassis and ejection mechanism. The POD chassis includes all features required to interface to the PEM and provides a flat mounting surface with fastener holes spaced on a 50 mm x 50 mm grid for mounting payloads. A payload can also directly incorporate the features required to interface to the PEM without the use of the POD chassis. The HPA ICD allows for two options, one with a POD Chassis and one without. The following preliminary guidelines have been established for HPA payload developers.

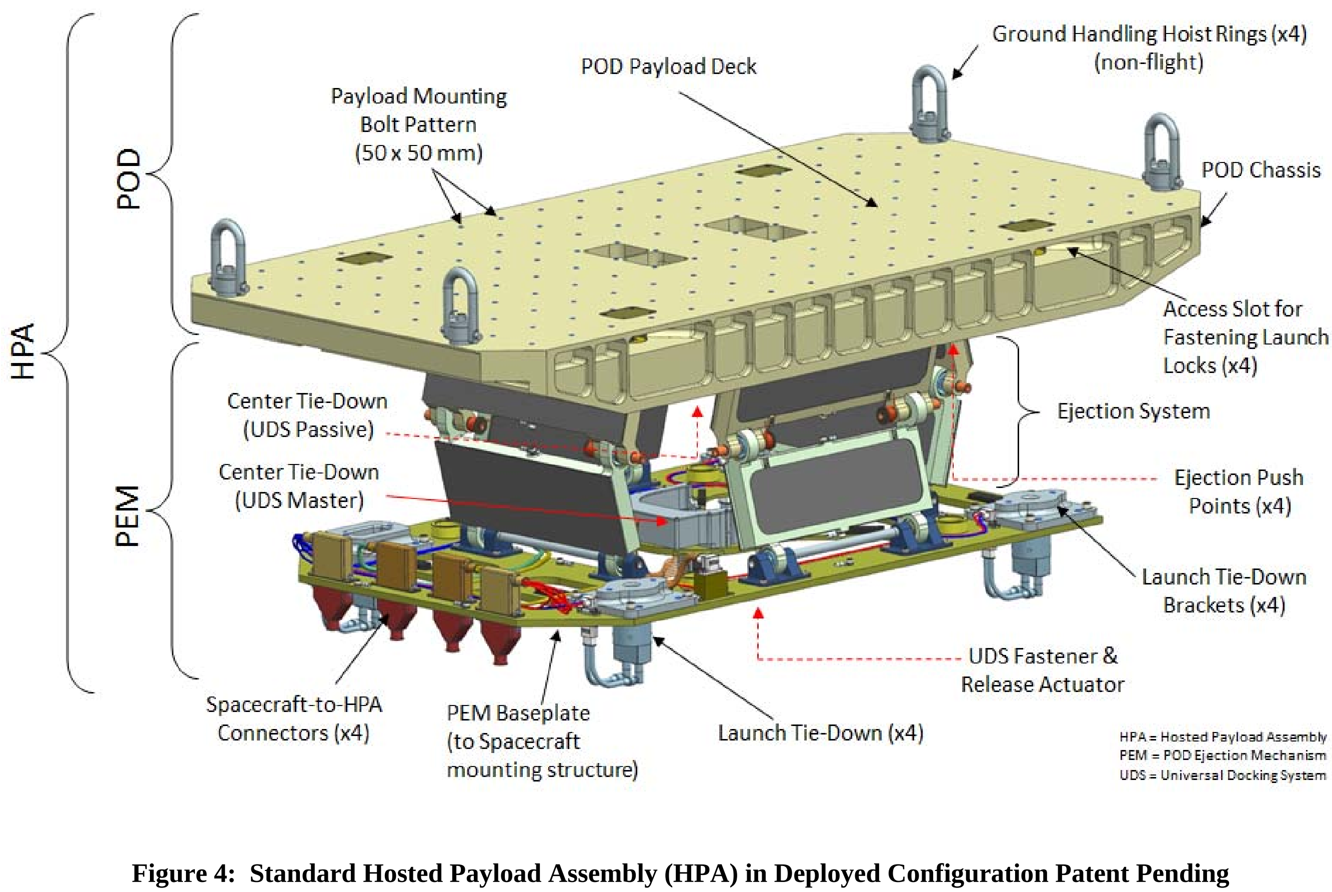

Figure 4: Standard Hosted Payload Assembly (HPA) in Deployed Configuration Patent Pending (PCT/CA2015/050451)

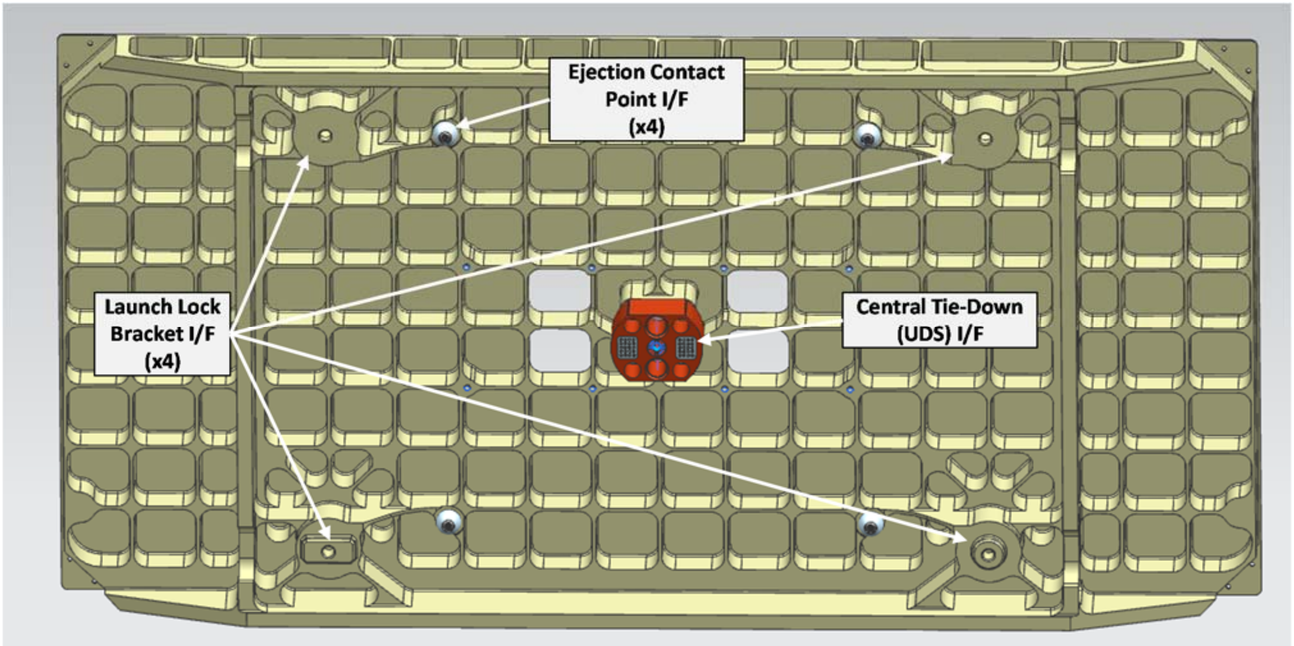

Figure 5: Standard POD Chassis (Underside) to PEM Interfaces

A payload designed to withstand the dynamic environments defined by the HPA ICD does not require mission specific analysis if:

- The payload mass is between 15 kg and 60 kg (inclusive)
- The payload CG is within 15 cm radius of POD Chassis center and within 15 cm of the POD Chassis Payload Deck
- The payload is well fastened to the POD chassis (one fastener for every 5 cm of payload mounting edge distance)
- The payload has a fundamental frequency >= 200 Hz, or between 50 Hz to 75 Hz
- The payload footprint follows the mass-dependent guidelines in Table 6:

Table 6: Payload Mass to Payload Footprint Guidelines

Payload Mass Range	Payload Footprint
15 Kg – 30 Kg	20 cm x 20 cm (minimum)
30 Kg – 60 Kg	30 cm x 30 cm (minimum)

The payload dynamic environment in the HPA ICD will increase and mission specific analysis is required to determine resulting increased payload sine and random vibration levels if:

- The previously listed constraints describing the nominal HPA payload are not met
- The payload is very flexible or includes kinematic mounts in the primary load path
- The payload has a first natural frequency with significant mass participation between 75 Hz and 150 Hz

The underside of the POD chassis (Figure 5) is equipped with the following interfaces to the PEM:

- Launch lock brackets
- Final central tie-down
- Ejection contact points

The launch lock brackets located at the four corners of the PEM baseplate are designed to withstand launch environment shear loads and to provide PEM-to-chassis alignment. To ensure a balanced ejection, all launch locks are released/actuated before the final central tie-down is released for POD separation. The central tie-down is a POD UDS that is both a mechanical interface and an electrical in-flight disconnect (IFD) between the POD and the PEM. The active half of the UDS resides at the center of the PEM and houses the tie-down actuator. The passive half of the UDS resides on the POD chassis. The UDS provides the capability of up to 40 pass-through signals, eight of which offer ESD protection on both sides of the UDS IFD. The cable harness from the passive UDS to the payload are flying leads, offering payload providers flexibility in connector selection. In a robotic mission where the POD requires relocation and temporary stowage, the passive UDS can be reused to dock and undock with any other active robotic UDS.[14]

Once all five tie-downs are released, the preloaded PEM would unfold and push the POD away from the host spacecraft. The PEM would push on the POD via the four cup-cone interfaces (ejection push points) between the POD chassis and the PEM ejection frame until the POD separates from the PEM at the PEM's end of travel. After the PEM has dispensed its payload, it would remain preloaded against its hardstops so that it would not impact the attitude dynamics of the GEO host over its operating life.

In the case where a payload interfaces directly to the PEM without a POD chassis, the payload would be equipped with a set of components from a PEM interface kit.

The HPA User Guide for spacecraft and payload providers will capture the ICD, installation and operational details required to design for the HPA service. The guide will include a set of general hosted payload requirements that payloads would have to satisfy to ride on a commercial host spacecraft.[15]

HPA Ground Test Results and Design Status

A test rig has been fabricated to characterize the ejection performance of the HPA, as shown in Figure 6. The stationary portion of the test rig allows for the attachment of a PEM, while the mobile portion supports the POD chassis that is to be ejected by the PEM. Operating on a flat granite surface, the mobile test rig ("Air Bearing Test Rig") is equipped with air bearings to minimize friction as the POD chassis slides across the granite slab so as to mimic on-orbit ejection along three degrees of freedom (two translational DOF in the plane of the granite surface, one rotational DOF about the gravitational axis). Performance in a fourth DOF can also be evaluated by unlocking a pitch shaft to provide rotation about the shaft. The Air Bearing Test Rig is designed to represent the POD payload and can therefore be adjusted to vary payload mass, inertia and CG location. The Air Bearing Test Rig is also fitted with a gyro sensor and optical targets for accurately determining position, velocity and acceleration of the POD during ejection. Both the fixed and mobile halves of the performance test rig are designed to accommodate PEM and POD chassis mounting in the horizontal and vertical configuration (a rotation of 90° about the ejection axis).

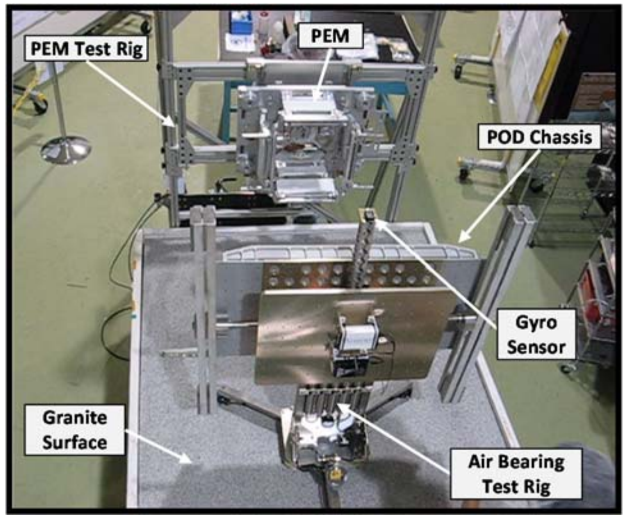

Figure 6: Engineering Models on the HPA Performance Test Rig

In parallel, an engineering model PEM and POD chassis were developed to prove the HPA design concept. Green-run trials of POD ejection were recently performed with the engineering models installed on the HPA test rig, as shown in Figure 6. The central fastener and its release actuator were installed to hold the passive and active halves of the UDS together for an ejection test. The release actuator was powered and subsequently broke the central fastener as expected. The POD was dispensed by the PEM smoothly with benign tumble rates and an acceptable ejection trajectory error. Breaking the central fastener did not produce any observable disturbances to PEM/POD dynamics, and the fastener severed cleanly at the expected separation interface, as shown in Figure 7.

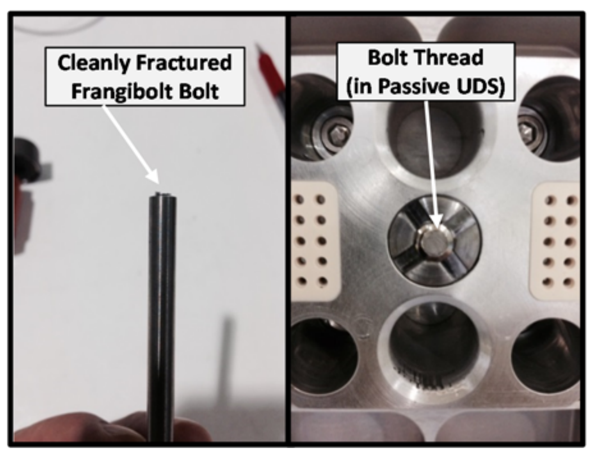

Figure 7: UDS Fastener Release Test – Severed Fastener

Following these successful green runs, a full suite of engineering model performance tests will be conducted to characterize the PEM and POD chassis design using data collected from the gyro sensor and external vision system.

The HPA design effort is advancing towards a critical design review of the PEM and POD chassis in June 2015. The flight model PEM and POD chassis will then be subjected to a qualification program and an acceptance program. Both the Qualification Model and Flight Model will undergo functional, performance and environmental testing. This testing includes subjecting the HPA to its launch and on-orbit environments, as well as testing the actuation of its tie-downs and ascertaining that the PEM functions as expected at appropriate points in the test sequence. Once acceptance tested, the PEM and POD chassis will be available for spacecraft and payload integration. Several HPA and spacecraft simulators will also be developed throughout the program to assist in HPA and spacecraft testing. The inaugural flight of the HPA is planned for the first quarter of 2017 and would complete its flight qualification.

CONCLUSION

The emerging practice of hosting payloads on commercial GEO satellites is gaining traction throughout the space community because of the flight opportunities and budgetary savings that it offers. Using the hosted payload model, the DARPA Phoenix POD system could enable a high delivery tempo to GEO for small payloads. This goal would be achieved by designing and verifying the POD system to a standard user's guide that would ensure compatibility with most of the approximately 15 commercial launches to GEO each year. Once the fundamental POD system capability is established, a POD could be integrated into a host spacecraft quite late in the integration flow, creating an "express delivery to GEO" capability. Because the initial Phoenix POD hosting study took into account the results from a survey of existing GEO communications satellite providers' mass and power margins, other satellite providers besides SSL should be able to accommodate PODs with limited development and impact to existing bus designs. The intention is that the POD would be proliferated throughout the industry as a new method for delivering small-mass hardware items, small spacecraft and potentially fuel to GEO at a higher tempo than has previously been possible.

The goal of the POD approach is to begin to address a sustainable ecosystem model of on-orbit services, similar to any number of Earth-based logistics and re-supply services that use and rely upon fast delivery to create new business and markets. As this on-orbit servicing ecosystem emerges, new concepts of operation could be considered. Depending on the design of the POD-to-host interface, the mechanical, power and data interface connections could serve as access points to augment or repair a GEO host. Not only could a host satellite interface with a POD and then eject it, but afterwards it could conceivably also take advantage of on-orbit robotic services to have a new electronics box attached via the empty POD connections where the POD was ejected. This concept raises the entirely novel possibility of adding new capabilities, providing external diagnostics or adding fresh revenue streams to existing on-orbit spacecraft.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of the many people on the Phoenix teams at each of the organizations involved. The views, opinions and/or findings contained in this article/presentation are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

REFERENCES

[1] Barnhart, David, et al. "Phoenix Project Status 2013." Proceedings of the AIAA SPACE 2013 Conference and Exposition, San Diego, CA, September 2013.

[2] Sullivan, Brook, et al. "DARPA Phoenix Payload Orbital Delivery (POD) System: 'FedEx to GEO.'" Proceedings of the AIAA SPACE 2013 Conference and Exposition, San Diego, CA, September 2013.

[3] "Hosted Payload Guidebook," Futron Corp., August 2010.

[4] http://spaceflightservices.com/

[5] http://www.defense.gov/contracts/archive.aspx

[6] http://www.ulalaunch.com

[7] http://www.defense.gov/contracts/archive.aspx,

[8] http://www.ulalaunch.com

[9] http://www.spacex.com/

[10] Andraschko, M., Antol, J., Horan, S., Neil, D., "Commercially Hosted Government Payloads: Lessons from Recent Programs," 2011 IEEE Aerospace Conference.

[11] http://www.faa.gov/about/office_org/headquarters_offices/ast/media/2014_GSO_NGSO_Forecast_Report_FAA_COMSTAC_July_15_2014.pdf

[12] http://sslmda.com/downloads/payload/hosted_payload_fact_sheet.pdf

[13] Francetic, B., Ratti, J., Cass, M., Lyn, C, "MDA Space Missions Generic HPA Assembly ICD," STDMEC-21187, Rev P2, May 2015.

[14] DARPA SN-14-51 GEO Robotic Servicer RFI, https://www.fbo.gov/index?s=opportunity&mode=form&id=a5ba9b924872fe7f6b2169e4e2a73bcc&tab=core&_cview=0

[15] "MDA Robotics and Automation Hosted Payload Assembly (HPA) User Guide," MDA-STD-SGSD.13157, Rev P1, May 2015.