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差出人 George Maeda

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Attachment(s):

(1) "Swenson_International_Space_Station", 714 KB pdf, 6 pages.

: Re:
: ISS, small satellites and
: space weather
:

Dear ISWI Participant:

The attached item comes from Dr Hans Haubold (UNOOSA at Vienna, Austria) with the following comments: "I recall that Professor Yumoto was thinking about using small satellites for space weather research. The UN Programme on Space Applications implements ISWI through the line of action ISWI/GNSS/ICG. Our programme has actually three initiatives: HSTI focusing on ISS, BSTI focusing on small satellites, and ISWI focusing on space weather. The attached paper is illuminating the link between ISWI + BSTI + HSTI. Very interesting!" [end of quote].

For tomorrow:
"April2011 IRGGEA Letter", from Dr Christine Amory in France.

Most cordially yours,
: George Maeda
: The Editor
: ISWI Newsletter

The International Space Station as a Launch Platform for CubeSats to Study Space Weather

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The lower ionosphere/thermosphere region (150 to 350 km) is the boundary between the sensible atmosphere of the Earth and space. Conceptually it is a beach-like region of the upper atmosphere where both electro-dynamic plasma and fluid-dynamic processes operate. This region receives energy and momentum contributions from the sun in the form of solar ultra-violet light and electromagnetic energy coupled via the earth's magnetosphere. The lower ionosphere/thermosphere region also receives energy and momentum from the lower atmosphere via waves that break and terminate turbulently in this beach-like region. The various processes, acting both as system drivers and feedback elements in the lower ionosphere/thermosphere region, are still poorly understood and the weather of the lower ionosphere/thermosphere region cannot be predicted. It is also the area where satellite drag ensures a quick end to satellite lifetimes and it has thus become known as the "inaccessible region." Few observations of the fields or state variables and their coupling are available, and hence no validation of the fundamental neutral or plasma processes has been accomplished. As the terrestrial populations wrestle with the question of "change" (global, climate, etc) our need to continue making long-term measurements is crucial, but is frustrated by cost and launch opportunities for even smaller dedicated satellites. The lower ionosphere/thermosphere region itself has been identified as a region where almost un-measurable atmospheric changes have very measurable consequences. The International Space Station (ISS) orbiting just above this "inaccessible region" is an ideal platform from which CubeSats can be launched to study the region below. In this paper we explore how the ISS can be used to advance our understanding of the ionosphere/thermosphere region.

Key Words: Ionosphere, Thermosphere, CubeSat, International Space Station, Constellation

1. Introduction

The most significant advances in solar and space physics, or Heliophysics, over the next decade are most likely to derive from new observational techniques. The connection between advances in scientific understanding and technology has historically been demonstrated across many disciplines and time. There are clear ties between advances in our understanding of Heliophysics processes and the deployment of new sensing techniques, from new vantage points, which fuel new discoveries. The study of the Heliophysics system requires multipoint observations on a planetary scale to develop understanding of the coupling between disparate regions: solar-wind, magnetosphere, ionosphere, thermosphere, and mesosphere as illustrated in Fig. 1. Multipoint measurements are also needed to develop understanding of the various scalars or vector field signatures (i.e gradients, divergence) that arise from coupling processes that occur across temporal and spatial scales and also within localized regions. The need for a better understanding of the ionosphere and thermosphere processes and their role in bridging the dynamics between the Earth's atmosphere and geospace has been highlighted in the NASA 2009 Heliophysics science Roadmap¹⁾. Four inherently ionosphere and/or thermosphere centric science question mission targets have been identified (i.e., ONEP, INCA, CISR, and DGC) as key future investigations. It is clear that the Heliophysics community

now needs multi-point measurements from within the space environment to make progress on important scientific questions within the ionosphere-thermosphere-mesosphere region.

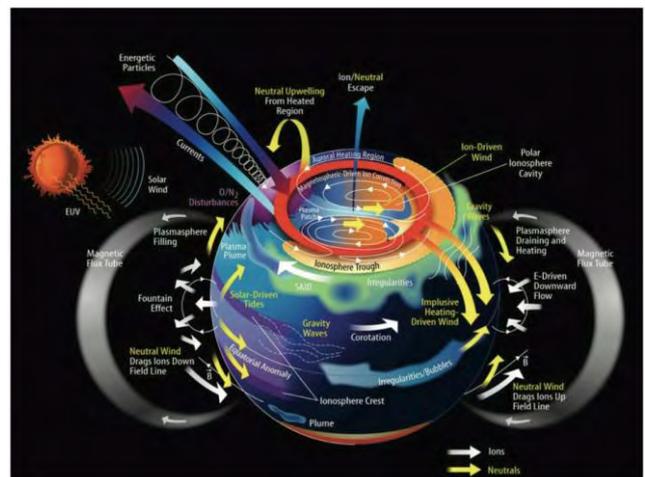


Fig. 1. System view of dynamics and processes due to coupling with drivers from the Sun and Earth's atmosphere (courtesy NASA¹⁾).

Remote imaging is one source of multi-point measurements of Heliophysics systems but not all measurement parameters of interest can be observed through remote sensing techniques. Some examples that are not well observed by remote imaging

are electric field patterns and currents flowing along magnetic field lines both of which are important quantities for understanding the coupling of regions. The details of atmospheric composition are difficult to observe remotely but are an important parameter for the chemical dynamics of the lower ionosphere/thermosphere. It is also clear that significant scientific advances can be made by placing remote imaging sensors at multiple points to make distributed observations of globally coherent phenomena such as atmospheric tides and auroral storms, or to improve the observations through advanced signal processing methods such as tomography or improved temporal/spatial resolutions.

The resources that will be available over the next decades for all areas of Heliophysics research have limits and it is therefore important that the scientific and technical community find ways to leverage the costs of developing new technologies to advance science. The high cost of access to space, at first review, is a serious impediment to making multipoint measurements within the space environment or in other words in deploying constellations of traditional satellites. It is therefore desirable to develop much smaller and lower-cost sensor/satellite systems such that the largest number of distributed measurements can be economically made in the space environment. The smaller the mass and volume of the sensor/satellite the larger the number will be that can be deployed from a single launch vehicle. The prospect of creating miniaturized sensors and satellite systems is good given the enormous investment of commercial, medical, and defense industries in producing highly capable, portable and low-power battery-operated consumer electronics, in-situ composition probes, and novel reconnaissance sensors. The advancement represented by these technologies has direct application in developing small sensor/satellite system for Heliophysics research.

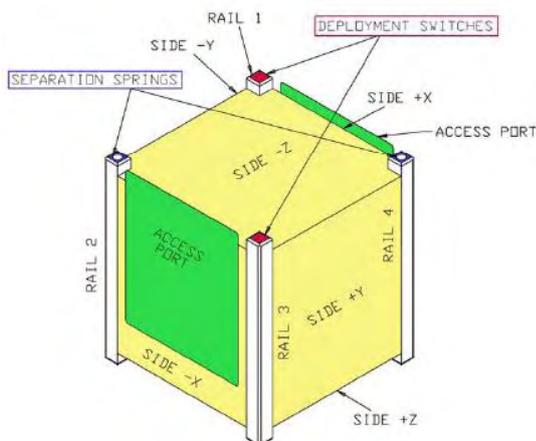


Fig. 2. The one unit CubeSat standard as defined in the Poly Picosatellite Orbital Deployer (P-POD) interface control document²⁾.

Affordable constellations are not the only observational tool enabled by smaller and lower-cost sensor/satellite systems. With them it becomes feasible to put "almost disposable" platforms into heretofore sparsely or un-sampled locations or

regions where it is currently not economical to place a larger more expensive satellite. Deployed into very low Earth orbit, these small low-cost platforms could carry instruments into the lower ionosphere/thermosphere, for example. The region between 150 km and about 350 km in the Earth's atmosphere is not conducive to long lifetime orbits but could be monitored nearly continuously by periodically deploying small satellites from the International Space Station, for instance. This lower ionosphere/thermosphere is a region in which the full complexity of electro-dynamics and fluid-dynamics is exhibited, but where satellite drag ensures a quick end to satellite lifetimes. It has thus become known as the "inaccessible region". Small low-cost satellites can be placed into short lifetime trajectories lasting only a few weeks or months for scientific purposes which would not be feasible for larger more-expensive satellites.



Fig. 3. The Poly Picosatellite Orbital Deployer (P-POD) used for containerized launch services of CubeSats (Courtesy Cal Poly)

The CubeSat standard for picosatellites was developed in the late 1990's for the use of the academic community in teaching space systems engineering to the next generation. It has since become widely accepted both internationally and by a broad spectrum of organizations due to the low-costs and relatively easy access to launch services which promoting the standard have engendered. The distinguishing characteristic of CubeSats is the mechanical standard for containerized launch services and how the picosatellites are opportunistically paired with those launch vehicles that provide deployment containers. The Poly Picosatellite Orbital Deployer (P-POD) developed by Cal Poly is an example of a widely accepted containerized launch system for secondary payloads²⁾. Most launch vehicles in the United States have designed support for multiple P-Pod containers which each delivering a 3 liter (10 x 10 x 30 cm) volume weighing no more that 4 kg to orbit. The basic CubeSat (1U) form is 10 x 10 x 10 cm (see Fig. 2) and three fit within a P-POD but other form factors have been deployed including 1.5U (10 x 10 x 15 cm) and 3U (10 x 10 x 30 cm). Current estimates place the number of CubeSat developers at over 100 worldwide including governments, industry and academia. The CubeSat is becoming recognized as a viable spacecraft but for scientific investigations and a number of institutions are developing miniaturized space weather sensors for CubeSats^{3,4,5,6)}.

2. The International Space Station as a Launch Platform

The International Space Station (ISS) has the potential to play a major role in facilitating the studies of the lower ionosphere/thermosphere region and many of the science targets identified in the NASA 2009 Heliophysics Roadmap¹⁾. The ISS is expediently located in the middle of the lower ionosphere/thermosphere region; hence, it could become a permanent launch platform for regular or responsive deployment of the small satellite fleet. For example, a group of satellites could be launched in response to a storm or stratospheric warming. It would also be the ideal location from which to routinely launch probes into the inaccessible region below or to maintain a long-term multi-point observational capability. The unique advantage of ISS is that deployments of these small satellites is not contingent on finding a suitable ground based launch opportunity, whose scheduling could never be triggered by a storm type scenario. The relatively high ISS orbit inclination also provides complete mid-latitude and equatorial coverage; during geomagnetic storms, the areas of interest are exactly these. The ability to deploy on command enables the scientific study not just of the ionosphere/thermosphere but other area such as astrophysics or Earth science could benefit from this capability.

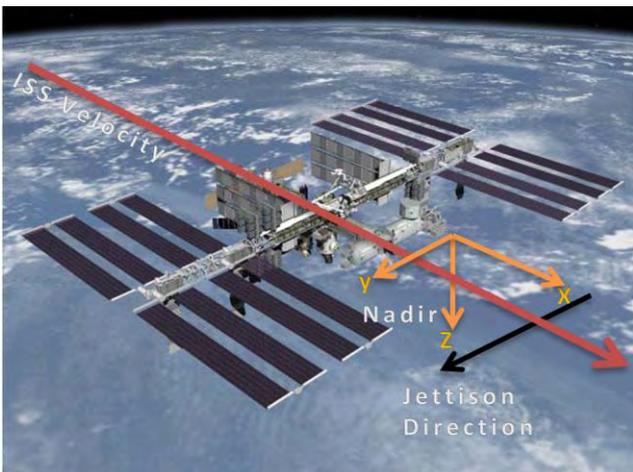


Fig. 4. The International Space Station has an established jettison policy, PDD 1001, for releasing objects (courtesy JAXA⁸⁾).

The ability to regularly deploy satellites on weekly to monthly time scales or during a specific geophysical event is the distinguishing compelling capability for locating a large number of CubeSats on the ISS. This is a distinctly different approach than simply deploying CubeSats from various resupply vehicles just before their arrival at the ISS, which would be useful, but it does not allow for the long term monitoring, constellation development or launch in response to scientific phenomena of interest. The ISS has an established jettison policy (PDD1001) that outlines a procedure under which objects released from the ISS are not a concern for re-contact with the ISS as illustrated by Fig. 4. The vector for the jettison velocity is 45° (nominal) aft from ISS nadir with a minimum magnitude of 5cm/s⁷⁾. What is needed to make use

of the ISS as a host platform for a large number of Nanosatellite is a well-established deployment system that is consistent with the ISS jettison policy. This deploder could be developed to hold large numbers of CubeSats, a recognized standard, for metered deployment from the ISS. Our group is currently studying a ISS CubeSat Ejection System (ICES) to fulfill the needs of the scientific community in studying the lower ionosphere/thermosphere.



Fig. 5. The Japanese Experiment module has both ram and wake facing attachment points for exposed facilities (courtesy JAXA⁸⁾).

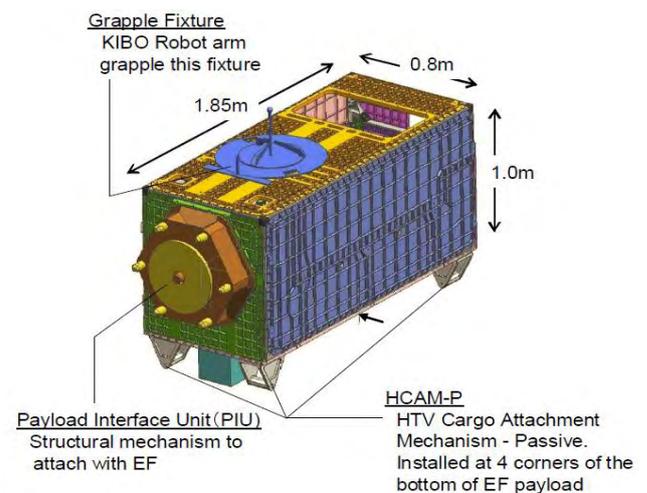


Fig. 6. An Exposed Facility payload for the Japanese Experiment Module on the International Space Station (courtesy JAXA⁸⁾).

A concept for attaching ICES to the ISS is to make use of the Japanese Experiment Module (JEM) as illustrated in Fig. 5. This element of the ISS, also known as Kibo, has the ability to attach Exposed Facility (EF) modules for user defined payloads (see Fig. 6). Each EF can weigh up to 500kg and is provided both low and high rate telemetry and up to 3 kW of power⁸⁾. Kibo has twelve attachment points for EF modules of which five lay in the wake side. These wake side locations are prime sites for ICES and current plans have them free of payloads for the 2013-2018 time frames⁹⁾. ICES and its load of CubeSats would be transported to the ISS using established resupply vehicles. As a practical example, the Japanese H-II Transfer Vehicle (HTV) would be used as the transport vehicle for ICES. ICES would then be installed external to the ISS using the Kibo Remote Manipulator System⁸⁾. Each

P-POD would be oriented within the ICES such that upon command deployments from the P-PODS would occur nadir and aft (opposite and down from RAM) from the ISS in accordance with the ISS jettison policy. Over a two year period the contents of ISCS would be ejected to achieve the scientific objectives of the CubeSat mission. The 350-400 km projected altitude of the ISS allows for a reasonably accurate prediction of orbit lifetime (< 1.5 years) and the timely reentry of each deployed CubeSat.

An initial study of placing modified P-Pods (See Fig. 3) in the volume of an EF shows on the order of 75 to 200 1U sized CubeSats could be easily accommodated. ICES mounted on a wake Kibo site would eject spacecraft in the down and aft direction consistent with the ISS jettison policy due to the placement of P-Pods ejecting towards the end of the EF as illustrated in Fig. 7. If an EF position on the end of Kibo were used then modified P-Pods would eject out of the side to be consistent with the jettison policy as illustrated in Fig. 8. We expect that a scientific study might make use of 3U sized CubeSats allowing 25 to 66 picosatellites to be stationed on the ISS. Many of these spacecraft would be identical copies for space weather or other scientific purposes and several different scientific CubeSat missions could be accommodated.

CubeSats stored within ICES would need to have their batteries recharged on orbit given a possible two year period before ejection. These CubeSats also would have to comply with all ISS safety requirements and materials properties. Finally, the P-Pods illustrated in Fig. 7 and Fig. 8 makes use of a proposed 6U ejector to efficiently use the volume of an EF for the storage of CubeSats. ICES could provide the ability to communicate with the hosted CubeSats through the ISS and Kibo communication systems during the extended stay at the ISS. All of these capabilities require a modification to the existing CubeSat and P-Pod standards to define recharging and communications connectors as well as the safety inhibit schemes. For instance the ability to recharge batteries on orbit will require a system for charge termination. Our team is exploring if this functionality should be part of the individual CubeSat or the ICES systems.

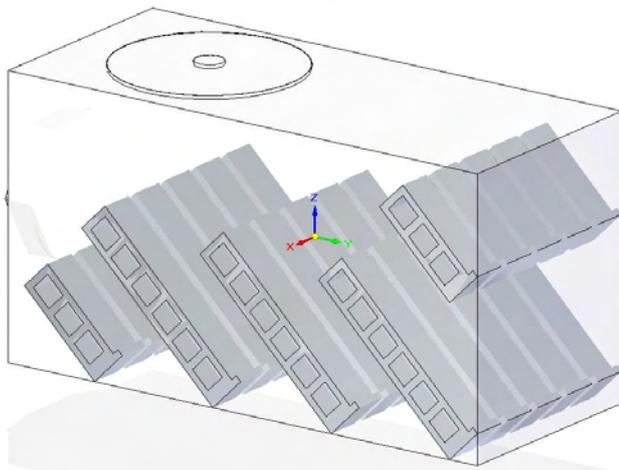


Fig. 7. A study of placing 3U and modified 6U P-Pod like deploders within the volume of an Exposed Facility achieving 120U of storage.

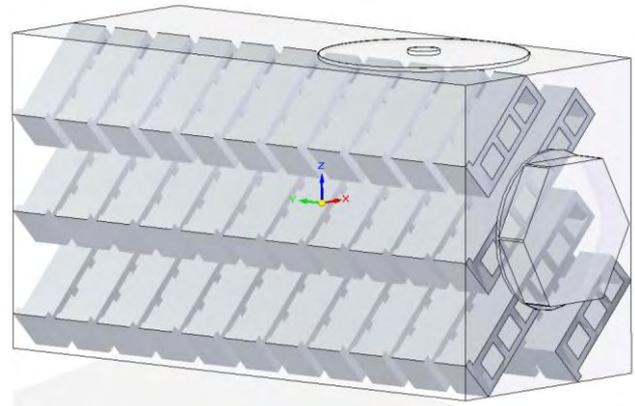


Fig. 8. A study of placing 3U and modified 6U P-Pod like deploders within the volume of an Exposed Facility achieving 198U of storage.

3. Example Space Weather CubeSat

An example of a type of scientific CubeSat that might be deployed from ICES for studying the lower ionosphere/thermosphere region is the “Dynamic Ionosphere CubeSat Experiment” or “DICE” mission. This mission was selected and funded by the US National Science Foundation in October 2009 in response to a cooperative proposal from Utah State University’s Space Dynamics Laboratory (USU/SDL), ASTRA Inc, and Embry Riddle University. DICE is one of several missions currently in development under NSF’s CubeSat-based Science Mission for Space Weather and Atmospheric Research program. DICE consists of two identical CubeSats that will be launched simultaneously into Low Earth Orbit (LEO) to study the formation and evolution of geomagnetic storm enhanced density features that occur in the Earth’s Ionosphere. Each spinning CubeSat has three science instruments, a Langmuir Probe to measure *in-situ* ionospheric plasma densities, an Electric Field Probe to measure DC and AC electric fields and a Three Axis Magnetometer (TAM).

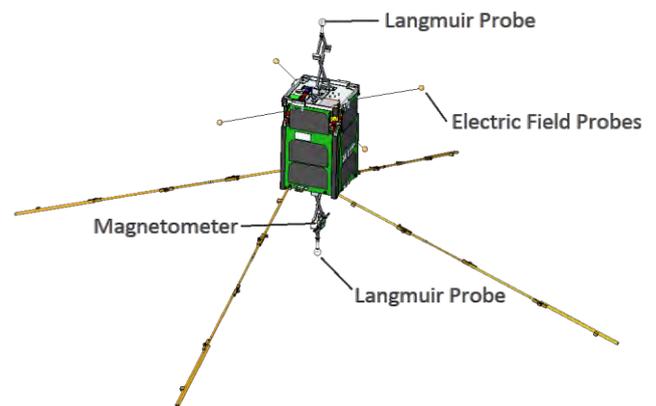


Figure 9 The DICE spacecraft with electric field wire booms in partial deployment.

Figure 9 illustrates the DICE spacecraft and instrumentation configuration. Each of the two DICE spacecraft is identical in design and function, and both conform to a 1.5U CubeSat form factor (10x10x15 cm). Sixty of these spacecraft could be accommodate by ICES as depicted in Fig. 7. The four electric

field booms each extend 5 m from the spacecraft with spheres on the ends of the wire booms. The four shorter booms on the bottom-side of the spacecraft comprise the UHF communications turnstile antenna and are 0.2 m in length. The UHF booms also provide balance for the controlled spin of the spacecraft about its major moment of inertia. The DCP sensor spheres are supported on the top and bottom of the spacecraft by extending scissor booms that extend 8 cm away from the spacecraft. The electronics for the EFP and DCP are housed in the spacecraft on the science board.

The DICE mission is not using amateur radio systems and frequencies, but is instead using government radio bands and high speed downlink rates that are consistent with a NSF funded mission. A half-duplex UHF modem developed for DICE provides a 1.5 Mbit/s downlink and a 19.2 kbit/s uplink. Each DICE modem will be continuously listening for ground station commands, which will switch it into transmit mode for a short period of time after which it returns to listen mode. Both spacecraft will use identical up- and downlink frequencies but will have unique logical addresses decoded by the modem. The ground stations are proposed to be at Wallops Island on the east coast and/or at SRI on the west coast.

3. Example Constellation Mission

Our team has completed a preliminary simulation of a notional small satellite constellation that can be created from the ISS using a long-term deployment strategy. This study has been focused on developing a constellation that will permit global measurements, including considerable observation time in the “region of low accessibility” of the lower ionosphere/thermosphere region. The simulation was performed in Satellite Tool Kit (STK) and is based on ephemeris and environmental data applicable to a January 6th, 2010 deployment initiation. Fifteen small satellites (3U CalPoly CubeSat form factor) were deployed regularly every three days from the ISS over a 45-day period. The deployments occurred in the anti-ram direction at ~2m/s delta V from the ISS. The same solar and geomagnetic constants were used through the year-long simulation.



Fig. 10. The constellation state following the deployment of the first four satellites ten days after initial deployment.

Fig. 10 illustrates the localized leader-follower or “string of pearls” constellation that has been developed following the deployment of the first four spacecraft along with the ISS. Fig.

11 illustrates the development of the constellation after all 15 of the CubeSats have been deployed. At this point, global temporal and spatial coverage has been well-established. Fig. 12 provides an overview of constellation evolution after the in terms of altitude. Precession, orbit overlapping, and altitude distribution occurs, facilitating a global view that includes measurements in the “inaccessible region” as well. Fig. 12, portraying the constellation altitude decay with time, reinforces the concept of global measurements in the lower ionosphere/thermosphere “region of low accessibility.”

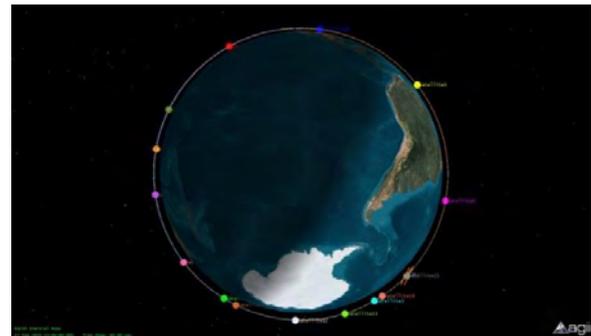


Fig. 11. Constellation state following deployment of all fifteen satellites or 45 days after the first CubeSat deployment.

These initial simulations demonstrate that the ISS is an ideal platform for the study of the open science questions in the lower ionosphere/thermosphere that are critical to Heliophysics Roadmap. Both localized and global constellations can be developed from the lower ionosphere/thermosphere in a very timely manner, enabling long-term and responsive observations. The ISS’s established accessibility provides for refurbishment of the small satellite deployment system, and for responsive deployment scenarios based on manual control from within the ISS or the ground. This simulation is in no means comprehensive, with many variables and options such as the varying altitudes of the ISS (e.g., after a burn to higher altitude) and the solar cycle contributing significantly to possible constellation profiles that can be developed and modified through minimal mission operation activities.

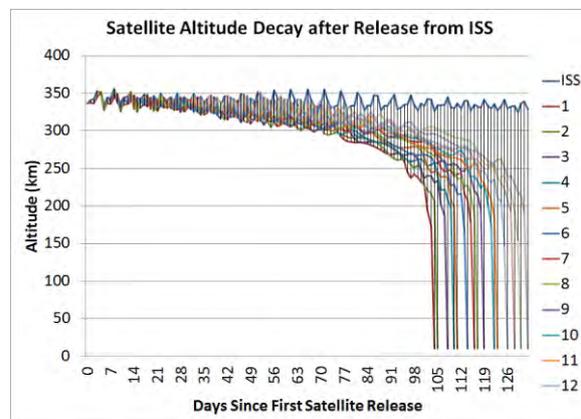


Fig. 12. The altitude evolution of the CubeSat constellation over its lifetime.

5. Summary

Utah State University – Space Dynamics Lab (USU-SDL), in close collaboration with multiple NASA institutions and the geospace community at large, is developing a detailed study targeting the viability and use of the International Space Station (ISS) as a launch platform for phenomena of interest in the lower ionosphere/thermosphere region. The science and technology demonstration viability study is in collaboration from the Goddard Space Flight Center Heliophysics Division Space Weather laboratory. The study includes a launch vehicle and International Space Station integration and deployment process systems engineering design and trade study with collaboration from the Johnson Space Center Space Environments group and Payload Office. The ICES (e.g., CubeSat) storage container interface and on-orbit operations engineering design and trade study is in collaboration with the AMES Research Center Small Satellite Technology group. The study is also being used as the design project for the spring 2011 Space Systems Design course at Utah State University. Fourteen students are enrolled in the course and are participating in the study.

The purpose of the effort is the verification that it is feasible to launch large numbers of small satellites from the ISS. In so doing, the stage will be set for a unique method to address outstanding space-weather issues as well as advance our knowledge of the ionosphere's interactions with the mesosphere, thermosphere, and magnetosphere. Establishing the feasibility involves three separate issues: 1) that indeed the technology to deliver a canister to the International Space Station that contains many dozens of small satellites and which can be attached via an external attachment point is possible; 2) that the subsequent remote deployment operations is consistent with ISS safety protocol; and 3) that most significantly the overall pro-rated cost per launch is defensively affordable. To address these questions the team is meeting with the ISS stake holders as well as the broader technical and scientific community. The strategic location of the ISS makes it an ideal platform from which to address science questions that need in situ measurements to be made in both a difficult altitude range, 125 to 250 km, and in rapid response to space weather phenomena such as a Superstorm or a stratospheric warning.

The broader impacts of this effort lie in several directions: 1) new access to space capability; 2) an international openness due to the nature of ISS, and 3) a dramatically improved capability for a large number of student teams engaged in small satellite development to have their payloads launched. By verifying that indeed a cost effective and technically feasible method to use the ISS external payload capability to launch “constellations” on demand will provide national agencies, as well as commercial and educational entities, a new launch capability for LEO. This concept significantly enhances the recently announced NASA plans to establish a Flight Opportunities Program, which will reside within the NASA Office of the Chief Technologist and focus on the use of commercial reusable suborbital research (CRuSR) vehicles and the ISS to conduct future research and education.

Although the proposed study focuses on the lower ionosphere and thermosphere and ultimately magnetosphere science, the new access capability is not so restricted and science and technology missions covering a broader range will be enabled. The ISS platform itself is already an internationally accepted resource. Hence, use of this potential resource has few international limitations. This is most certainly true for the international educational pursuits of either core science or the small satellite technology demonstrations. The successful outcome of the proposed work would result in a launch platform from which numerous satellites would be deployed with no recognition of payload or national priorities.

Acknowledgments

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