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Plug and Play - Small Satellite Solutions with Large Satellite Implications

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ABSTRACT

The Plug N Play concept has roots that reach back decades and has implications that reach decades into the future. The aerospace industry has tried to achieve a reusable modular satellite from time to time to leverage recurring design costs and by reusing them change them into nonrecurring costs. The Air Force Research Laboratory (AFRL) is working on a new approach to implement a modern version of a standardized bus definition. It started with standardization efforts for NASA and DoD MMS (Multimission Modular Satellite) missions of the 1970's and 1980's. It has evolved to today's applications in small responsive space satellite programs. The potential applications of Plug N Play concepts to large satellite programs can reduce costs as well as minimize assembly, integration and test timelines. Today we have to ask "Are the large satellite houses ready to adapt a new paradigm that will reduce satellite cost, and shorten the Integration and Test cycle?"

INTRODUCTION

Modular satellites are coming of age with the projects such as AFRL's Plug and Play Satellite (PnPSat). PnPSat is using standardized interfaces and interface plates to minimize development time and assembly, integration and test (AI&T) schedules. The history of modular satellites goes back to the 1970's when NASA developed the Multimission Modular Spacecraft (MMS) to be serviced using the space shuttle. The first MMS was Solar Max which launched in 1980. The benefits of commonality in interfaces and simplification of AI&T is applicable to large satellites as well. Standardizing instrument interfaces and spacecraft bus designs would allow NASA to build more large satellites for science missions for less money.

HISTORY OF MODULAR SATELLITES

In the mid 1970's NASA was starting to plan a new direction in a post-Apollo world. When Apollo was shutdown there was an exodus in the aerospace industry. There were very few people who in 1981 were between 25 and 35 years old. The new generation of engineers was entering an industry different than they had grown up watching on television. Instead of putting men on the moon, establishing a lunar colony, or sending men to Mars the space program had been

focused on Earth orbit science and exploration. NASA was building their Great Observatories - Hubble Space Telescope, the Compton Gamma-Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope. A new vision was taking off in parallel at NASA for manned flight. NASA set its vision on a reusable manned launch vehicle to re-capture the imagination of Americans. The Space Shuttle was taking shape. It would allow on-orbit servicing of satellites (Solar Max Mission, Hubble Space Telescope, etc) as well as providing a platform for on-orbit science experiments. At the same time NASA and their contractors developed the modular satellite to reduce the cost of science missions as well as to make the satellites serviceable using the new Space Shuttle. NASA and the DoD flew several MMS missions including Solar Max Mission (SMM)¹, Military MMS (M3S), Landsat D and D', UARS, Explorer Platform and Topex. Other programs such as CGRO, and HST used subsystems and concepts from the MMS satellite family.

¹ Shayler, D.J. "Walking in Space," Praxis Publishing Ltd., 2004, pgs 256 – 262.

The original intent of the MMS program was as much to provide readily serviceable satellites to exploit the capabilities of the coming Space Shuttle as it was to minimize re-design efforts for each satellite. Another benefit to using the same bus for multiple missions is the improved efficiency as each AI&T team learns how to integrate and test a mission they will be able to reuse all of that experience on their next assignment. Resolution times of bus related anomalies are greatly reduced because the team has seen the problem before or it has a thorough understanding of where to proceed to find the root cause of the anomaly.

The reuse of existing designs eliminated the need for traditional point designs to meet the performance requirements. The Solar Max Mission was used as the pathfinder for the MMS series. Problems encountered on SMM were corrected and to a large extent were not repeated on follow on satellites in the series. The AI&T team became experts in the MMS bus as they worked on multiple missions with nearly identical Fabrication time was minimized as the buses. fabricator re-built boards that they were particularly familiar with, and AI&T times were shortened due to the experience brought to each successive mission. Many of the above benefits were also seen on the Hubble Space Telescope and the Compton Gamma-Ray These programs leveraged the Observatory. standardized interfaces and hardware in the C&DH system.

Figure 1 shows the subsystems that are the parts of the MMS bus. The payload is mated to the bus at the instrument module interface. Nominally everything below the instrument module interface is the same for each mission except for the amount of propellant loaded.

THE END OF THE MODULAR SATELLITES OF THE 1970S/80S

The end of the MMS series in the 1980's was due to several factors. First there was a lack of flexibility within the modules, there was a drift away from satellites with only one large sensor or experiment, and multiple smaller experiments or instruments. For example the Communications and Data Handling (C&DH) module was based on the NSSC-I (NASA Standard Spacecraft Computer-I). While the NSSC-I was an excellent computer in the 1970's when it was selected for the first of the MMS satellites it did not have an evolutionary path from its basic configuration into the future. While the memory was expanded, and later a co-processor was added, there were no leaps in processor capabilities making the NSSC-I obsolete as science data needs expanded. A spacecraft computer can be expandable and upgradable with careful use of standard interfaces, form factors, etc (as we saw in the PC, XT, AT, etc versions of the home computer) providing a standardized upgradable platform.





Modern satellites use much more powerful on-board computers (OBCs) than were available during the MMS era. The NSSC-I was rated at 35 KOPS (thousand operations per second) and on SMM had 48k words of Core RAM, while Landsat D and D' and UARS had 64k words of Core RAM. The computer on the Gamma-Ray Large Area Space Telescope (GLAST) is a RAD750 (based on the PowerPC 750) VME based computer.

The three MMS bus modules were produced by three different companies. This allowed for each partner to do what they were expert at and brought the best of each company to the program.

² Falkenhayn, E, Jr. "Multimission Modular Spacecraft (MMS)", AIAA-88-3513, AIAA Space Programs and Technologies Conference 1988, Houston, TX.

Figure 2 presents the heritage of the MMS series of missions including a few missions where MMS related modules were used. The Hubble Space Telescope used

parts of the C&DH to provide the SI C&DH (Scientific Instrument Command and Data Handling System) for the HST payload.

	1976/1980	1978/1982	1983/1986	1980/1988	1984/1991	1980/1982	1987/2000	1992/1994
PROJECTS MSS SUPPORT	SMM	LANDSAT D & D'	GRO	HST	UARS	DOD	EXPLORER PLATFORM	TOPEX
C&DH	J	1	1	J	J	1	J	J
POWER SYSTEMS	J	J	J		J	J	J	J
ACS	J	J	J		J	J	J	J
FSS	J	J	J	J	J	J	J	J
PROPULSION		J			J			
STS INTERFACE	J	J	J	J	J	J	J	J
SPACECRAFT SERVICING	J	J	J	J	J	J	J	J
MECHANICAL SYSTEMS	J	J		J	J	J	J	J
ELECTRICAL SYSTEM SC/CU	J	J			J	J	J	J
THERMAL SYSTEMS	J	J			J	J	J	J
MISSION INTEGRATION GSE	J	J	J		J	J	J	J

MMS Projects and MMS Module Use on Other Projects

Figure 2 MMS Heritage and Life Cycle³

^{1. &}lt;sup>3</sup> Falkenhayn, E, Jr. "Multimission Modular Spacecraft (MMS)", AIAA-88-3513, AIAA Space Programs and Technologies Conference 1988, Houston, TX.

RESPONSIVE SPACE CONNECTION TO PLUG AND PLAY SATELLITE DEVELOPMENT

One of the main purposes of the Plug and Play Satellite is to allow satellites to be integrated, tested and launched quickly. The general opinion in the responsive space community is that the AI&T time normally associated with spacecraft takes too long. The question is "What is too long?" and how much time needs to be trimmed from a standard spacecraft program to meet the requirements of the responsive space community? AFRL's TacSat II spacecraft (see Figure 3) included several payloads that demonstrated new technologies for space operations. One of the mission requirements for TacSat II was to demonstrate was how rapidly an AI&T program could be executed. The goal of 12 to 18 months was given to the program to see if spacecraft AI&T could be done on a small spacecraft (less than 900lbs) within this timeframe.

At the beginning of the TacSat II program the AI&T activities were streamlined in order to meet this goal. Some of the streamlining included the reduction of paperwork. Plans and procedures included only the necessary information to successfully complete the AI&T task. Integration personnel were placed in small project teams that concentrated in performing an integration task. Quality assurance and configuration management were integrated into each of the integration teams so that the review process was streamlined. This meant that a higher level of risk was associated with some of the AI&T. The program understood the risk and determined it to be acceptable because it was considered more important to reduce the After component integration, integration time. specialized system teams were implemented based on what components the team members had worked on.

Another important time-saving resource used was the implementation of a FlatSat. The FlatSat was in effect an electrical test-bed that included engineering models and prototypes used to evaluate the electrical and software interfaces and performed as a pathfinder for component and system testing. This resource was also used to execute tests to verify the TacSat II mission operation concept. Testing components on the FlatSat demonstrated a reduction in component integration time onto the satellite by 15 to 25% versus components that were directly integrated onto the spacecraft.

The number of payloads associated with the TacSat II was higher than typical (TacSat had 11 payloads), it was considered to be a worst case condition for a spacecraft development program. Officially spacecraft integration started for TacSat II on 4/25/05 with performing the safe-to-mate of a few avionics components and completed on 10/26/06 with the last

operational scenario being performed on the integrated satellite. The TacSat II AI&T only exceeded the 18 month integration goal set for the program by two days. Since the desire by responsive space proponents is to be able to integrate and launch spacecraft with new technology in less than 12 months it is important to understand and to learn from the TacSat II program what can be done to reduce the AI&T and launch time to meet this goal.



Figure 3 TacSat II during Vibration Testing

One of the arguments often stated in reducing the development and integration time is to limit the number and complexity of the payloads or instruments to be integrated onto the spacecraft. The average delivery form the vendor was 5 $\frac{1}{2}$ months later than the date original promised. This delay was essentially proportional to the complexity of the instrument as one would expect. Instruments such as an imaging or complex RF sensor were normally delivered later than a simpler bus experiment. Looking at the data more closely shows that the impact of TacSat II's 11 payloads delivering late only resulted in an overall program delay of a little more than 2 ¹/₂ months. The reason for this discrepancy was that even though the payload was delivered late other AI&T operations were being performed during the delays.

An opinion often expressed by spacecraft management, is that if there is a delivery delay why can't the integration team complete the remaining integration then stand down to return when the delayed components arrive. This can be done but it is not in the program's best interest because the integration team would need to go to other programs until instruments arrive. The integration team needs to be reformed and in some cases new team members would need to be found (since not every integration team member would be available after this hiatus). So the integration manager has to slow down the existing work and/or start other integration activities that are scheduled later in the integration flow until the delayed components have arrived. In the case of TacSat II integration activities often had to be changed due to delivery delays, but the overall serial impact to the schedule was not over $5\frac{1}{2}$ months as expected.

What were the major factors that affected the integration time for TacSat II? The chart shown in Figure 4 is a compilation showing the percent of each type of integration activity of the complete AI&T effort. The data is based on the daily integration logs. This chart shows the activities' serial schedule impact to the program.



Figure 4 –Percentage of Time for Integration by Activity Type

The categories shown in the above chart include:

Mechanical – Assembly, mounting, fit checks, spacecraft lifts, applying thermal coating, blanketing, and other mechanical operations associated with the spacecraft and its components

Inspection – Physical inspections, measurements, and initial preparations associated with any component, structure, or instrument to be installed on the spacecraft

Interface Test – Safe-to-Mate tests, harness verification, electrical interface checks between the spacecraft and the component, initial command and telemetry checks, and ground support equipment verification

System Test – Subsystem and system testing: end-toend communication tests, orbit simulation, ACS polarity testing, overall spacecraft operations type tests, exercises, rehearsals, etc.

Software Integration – Regression tests, software functional tests, database verification, on-board spacecraft autonomous and commanded processes, and ground to spacecraft script integration and verification for operations

Environmental Test – Random vibration, modal verification, thermal vacuum operations, thermal balance, EMI/EMC, mass properties, etc.

Troubleshoot and Repair – Activities associated with mechanical, electrical, thermal, or software modification to resolve errors or anomalies

System Problems – Cases where troubleshooting and modifications were seen at the systems level. Often these problems would affect the overall operation of the spacecraft and may require a change to operation, modification to either spacecraft or ground software, or a modification to existing hardware.

Payload Problems – Problems and changes to various instruments to ensure the objectives of the mission are met. Payload unique software modifications installed on the spacecraft and/or ground system to meet the payloads mission objectives.

Based on the overall time associated with the integration of TacSat II, a 50% reduction in the time of the top four time-consuming activities the integration time would have been reduced by approximately 6½ months meeting the 12 month AI&T schedule goal. This reduction in schedule may be realized by standardizing component interfaces thereby reducing the time it takes to perform integration activities. If the Interface Test or all of the Troubleshooting and Repair, System Problems, and Payload Problems activities was eliminated for the TacSat II integration we still would not have met a 12 month delivery schedule.

PLUG AND PLAY SATELLITE

The AFRL development of the PnPSat is a significant step toward meeting the Responsive Space requirements for rapid assembly, integration and test. Standardization and implementation of plug-and-play techniques can simplify system design and reduce AI&T times.

Plug and Play Standardization Mechanical and Electrical interfaces

Some of the key standardization includes both the mechanical and electrical interfaces associated with components and how spacecraft panels are interconnected. The mechanical standardized interfaces that the Plug and Play (PnP) program has implemented is to use a grid pattern on spacecraft panels to allow the general placement of components. The grid simplifies both the mechanical design of components and allows the flexibility to place the component to meet the mission needs. To support integration the side panels are hinged on the bottom to the bottom panel and the top panel is hinged to one of the side panels. After the

integration is completed panels will be directly mounted to one another to increase the overall spacecraft rigidity. This is necessary to ensure that there is sufficient structural strength to survive the launch environment. Some of the concerns associated with this technique were that the fundamental frequency would be too low and the panel attachment would not have adequate structural strength. Sine burst and sine sweeps of a worst case mass loaded structure indicated both adequate strength and a high fundamental mode for the structure. Introducing this novel approach of hinging the panels the spacecraft can be unfolded to get unobstructed access to all component interfaces. This reduces the need of placing components in a sequence that is normally seen in the assembly of other small spacecraft. This mechanical standardization allows for the simplified removal of panels. Panels and the associated components can be removed in minutes, and after the rework or modification is complete the panel can be re-installed in minutes. The panels are also interchangeable by exchanging one or more end points from one side of the panel to the other depending on spacecraft configuration.

Electrical standardization for PnPSat includes the connectors, data signals, and power connections. These items simplify the design of the component to bus interface in that there is predominately one kind of connection between the components and the spacecraft. Power and data distribution is handled by a router located within each spacecraft panel. Panel-to-panel power and data communication is done at opposite sides of each panel which allow data and battery power to be routed to all six sides of the spacecraft. Component service points (known as end points) are located on either side of the panels. By implementing this approach several benefits can be realized: 1) routing components do not use up valuable spacecraft surface area 2) there is essential spacecraft data and power service located where needed on each panel, and 3) all the spacecraft services are available to any component located on the bus. Some of these standard services include: SpaceWire communications. unregulated 28V battery power, Time Synchronization, Signal Grounds, and support for Hardware-in-the-Loop (HITL) testing. This last feature allow for components to accept and provide data to perform on-orbit simulations. Current to the component is both monitored and regulated by the router. The router connection to an end point has the ability to act as a soft fuse when the user issues commands to set the maximum current limit going to the component. This allows each component maximum current to be set for safety reasons and to allow components to be power cycles to allow for the component to be brought back on-line.

The SpaceWire is based on the IEEE 1355 standard and is used to route data and commands to and from the component to the distributed C&DH function located throughout the spacecraft. This standard allows data to be routed throughout the spacecraft at up to 400Mbps. By using this as the standard communications several protocol issues such packetization, data transport and error handling, are defined to the user.

Integration Flow Options

The benefits of the standardization and self-realizing nature of PnP to AI&T is that an automated integration process can be developed for modules. The safe-tomate test can be executed by computer measuring ground continuity to spacecraft ground, verify signal and power line isolation from ground, and continuity of power return to bus ground, and stray voltage checks.

The use of a computer for these measurements and tests allows the creation of computerized and centralized fabrication logs, and provides traceability of all tests performed on the module. The system can also auto generate malfunction reports when measurements limits or performance requirements are not met.

PnP Software Architecture and Lessons Learned

Software is one of the most important components that enable the PnP technology. Software or firmware is included throughout the PnP architecture. This includes software/firmware within the components to provide to the spacecraft system software the capability and characteristics of the component. Components in the PnP architecture are handled as resources that are called from system level applications. In the current PnP architecture these components use a standardized electrical, software interface known as an Appliqué Sensor Interface Module (ASIM). In the PnP architecture the spacecraft functions such as guidance and navigation, command (GNC), and data handling, and communications are not tied directly to the spacecraft components. These functions provide system calls to use resources to perform an action. This means that the system software needs to be truly modular and adaptable based on the capability of resources that are available.

In the general case, software applications that perform specific functions such as momentum management need to be able to determine the limit and capability of its resources in a dynamic manner. Since computational elements may be distributed in the PnP architecture the software needs to be able to interact cohesively even though the software elements are located on different computational sites. Furthermore, these software elements may not be on the same computational element after a system reboot or in the event that software element needs to be restarted. There needs to be a robust central software process to match applications to resources, manage the timing of software functions on the various computational elements, provide a management of the start-up of applications, and a strong error recovery process within this software.

The current PnP architecture has extended the selfrecognition process to ground operations. The spacecraft can provide its capability to the ground during the pass. This allows that the ground system to determine the available command functions and spacecraft capability with only a minimum knowledge of the spacecraft. These software processes may improve reliability, reduce complexity, and reduce manpower needed to operate and maintain the spacecraft allowing the satellite users to concentrate on performing mission related activities.

The PnP Sat project has significant schedule constraints that have limited the ability of the team to produce optimized software driven in large part by the desire to launch as soon as practical. The end capabilities of this software architecture show great promise to the realization of Responsive Space. There are several items that could be handled differently or lessons that can be learned based on the development of this software on future PnP type missions. In general these items that should be incorporated for the next PnP spacecraft:

- 1. Software requirements must be definitized early in the process and requirements creep needs to be avoided. These requirements need to be agreed upon by all affected organizations and maintained by a central organization.
- 2. When using multiple software vendors, software configuration management needs to be universal and managed by a single organization.
- 3. The software change process needs to be managed and robust enough to handle problems and to allow other software organizations (and other effected functions) to review and approve quickly allowing timely changes.
- 4. Manage software in an organic manner taking evolutional steps versus expecting software elements to be delivered in whole without previously interacting with the other software and hardware elements.
- 5. Adequate simulators and test resources need to be available at the vendor site to support an integrated approach to software development.

6. A central test-bed that contains all approved software, firmware and necessary hardware so that integrated system test can be conducted. This resource needs to be available remotely to software providers so they determine if the integrated software functions correctly. This resource software can be modified in a controlled manner and after the test the software should revert to the approved versions (resist the temptation of approving software just because you got it to work, make sure changes are documented and verified on the vendors' simulator).

A number of these seem self evident however they are often difficult to implement correctly based on normal software development practices. With the PnPSat pioneering self realization and the highly complex resource driven distributed software architecture needed to support it leads to iterations that should not be necessary on follow on missions.

The challenge is in the implementation. For example requirements of where to put the friction model for a reaction wheel needs to be defined in this software intensive architecture (in the general GNC code or in the component software). What are the contingency modes associated with component failures or what software component formats the communication downlink to the ground? There is the possibility of misinterpretation of who is doing the work and how it is to be used. This will be minimized in future programs as these software processes become definitized. The application PnP software architecture will most likely be done by multiple software organizations. The control and validation of the software architecture as a whole needs to be carefully monitored and controlled to prevent unnecessary reworks that may fix one problem but generate a whole new set to problems for different organizations. Integrating software functions in an organic manner reduces the number of software interaction problems. A software element should be delivered early so that integrated tests can be done with other parts of the software and appropriate changes made to the software element to better allow the integrated PnP software to be developed within schedule. It is important to understand that this process may take a little longer than individual software vendors developing only in-house. A substantial timesaving can be realized by avoiding software redesign due to incompatibility with other software or problems associated with application speed and timing. By implementing these fairly simple rules the development of this highly complex software architecture can be accomplished within a reasonable schedule.

MID-SIZE AND LARGE SATELLITE APPLICABILITY

The Hubble Space Telescope showed that a well defined payload interface can provide for interchangeable scientific instrument packages. HST has four axial scientific instruments (SIs) and one radial SI. The SI Control and Data Handling system (SI-C&DH) was based on the MMS C&DH, and provided a well defined interface for the SI teams to use as a basis for their design. The new movement we are seeing to reduce wire bundle size (use of the PnP concepts) were not fully present in the Hubble design but the beginnings could be seen in the axial instruments.

All four of the axial instrument locations maintained the same electrical and mechanical interface to the Hubble bus; therefore any axial instrument could be installed into any of the four positions. This provided time and financial savings during the qualification, integration, verification, and installation of the replacement instruments on Hubble. One standard design of GSE could be utilized for the spacecraft simulator, and one set of test procedures. Only one carrier design was needed to carry any axial the instrument on the Shuttle to the Telescope. The Astronauts could use the same technique for installing any of the axial instruments.

Current PnP technology utilizes a main power feed that runs through all the bays of the satellite with individual pick off points for components. Larger satellites require increased component power demands potentially leading to significant voltage drops along the feed to the component. For the large satellite application an individual power distribution and small battery could be provided for a modular section, or bay, of the satellite. Power for the bay would be associated with only that bay reducing the effect of voltage drops. This adaptation of the PnP design applied to the power system would allow a modular approach with a complete standardized power system in each bay.

Using this approach each component bay would receive solar array power and have its own charge control system, battery, and power distribution system. All aspects of a typical Electrical Power System (EPS) would be scaled down to the lower requirements of only powering a pair of payload bays. Control and telemetry of the PnP power system would utilize the ASIM to set charge control settings, control power application and resettable power protection devices (i.e. Data Device Corporation's RP-21000 series) to payloads or resources. Redundancy would be handled by making two adjoining bays capable of powering either of the bay's payloads via standardized PnP boards. The redundant bay power distribution board could be held in cold or hot sparing depending on the payload requirements.

Blowing a discrete fuse such as the FM08 fuse as used on HST (due to incorrect connections or operator error) necessitates the rework and requalification of the power distribution board or box (or fuse plug) at a cost of schedule. This risk can be reduced by implementing solid state power controllers, such as Data Device Corporation's RP-21000 series as used on satellites similar to the GLAST. This device has the added advantage of being designed to trip like a FM08 or FM12 fuse, while being electronically resettable and it can act as the power switch for the feed to the payload or resource.

Making the power storage, charging, and distribution smaller will make the integration easier as the components will be smaller and easier to handle. Each module will have less input/output lines to test. System functionality can be demonstrated at a smaller less complex level, allowing modular system functional and qualification testing at survival levels to be completed prior to assembling the complete satellite power system. Smaller system components reduce the complexity of the test configuration, and ground support equipment thus reducing cost. The smaller environmental facilities required will open more options for test locations thus leaving the satellite less at risk due to test facility schedule.

The implementation of using a common communication protocol would simplify the spacecraft design and reduce the complexity of integration. Another difference that is seen with larger satellites is the data storage and computational resources necessary to operate the large satellite payloads. In some cases instrument data rates could exceed SpaceWire's 400 Mbps rate. If a common bus was used this would severely impact operational functions that are also using this bus. Here again if the high data rate component resources are confined to the same component bay as the data rate component we could isolate this data from the rest of the spacecraft system. That is to say that the computational service for an instrument such as an imager would be adjacent to the instrument with an appropriate storage module for that instrument. A second local SpaceWire router could be provided to the instrument segment to that bay or all the SpaceWire and data resources located in that bay could be dedicated to that instrument. There could be an external SpaceWire port that provides a connection to external spacecraft services. Using this approach the instrument team could be supplied with the flight bay(s) to perform instrument integration independent of the spacecraft. When it is time for the instrument to be integrated with the spacecraft then this bay could be simply added to the spacecraft since the external connection, mechanical, and functional interfaces are predefined in the PnP standard.

PnP would also allow the standardization of all connectors on the satellite harness. Thus there are only three unique connectors for each resource/payload, one connector for power and return and one connector each for input and output signals. The other grounds can be on any connector. The pin assignment for the signal input and output connectors would be the same, but polarization of the connectors would prevent misswiring. Payload or other components would have socket contacts on the signal output connector while the signal input connector would have pin contacts. The small PnPSat utilizes Micro D connectors, but due to the larger power requirements these would have to be changed to a connector with larger contacts for power. All data connectors could be D-Subminiature or micro-D connectors. Careful selection of the power and signal connectors would ensure they were of non-mating varieties (pin vs. socket, different number of contacts, or contact arrangement).

Keeping all harness interfaces identical in connector and pin assignment simplifies harness design, fabrication and test and greatly reduce the risk of applying power to a signal line or tying a signal to ground.

Automated testing and certification logs could be expanded to incorporate the work orders, travelers, and test logs so that the complete data package is immediately available via a web interface. This brings the data to the project and reduces delays waiting for the contractor or configuration management to scan in the test data, or for test engineers to fill our problem records, anomaly reports, or any of the other reporting paper work.

Mechanically the small PnPSat is designed so that its side panels fold down horizontal to gain access into the spacecraft. While this works for small satellites, with small side panels that are easy to work around, larger satellites will require side panels that could be 3 feet wide by 4 feet tall (the approximate size of a Hubble bay door). For this size of satellite, a method such as that used by Hubble for its electronics bays with hinged doors that open on a side hinge to allow access into the bay would be preferable. Utilizing hinged doors with replaceable captive fasteners, would also reduce the penalty testing on the satellite bus if a bay has to be opened to allow access to a payload or resource box. There is no reason that the standard 5 cm hole patterns used in the PnPSat should not be continued in the larger spacecraft. If the hole pattern on the mounting surfaces is standardized, then GSE and test fixturing can be shared by the various payload or other components preventing each box from needing its own handling equipment, vibration plate, etc.

The biggest challenge to growing the size of PnPSat concept is the software and firmware development and validation. Utilizing the software and firmware concept that has evolved in the current PnPSat will serve as a road map to successfully growing the size and complexity of the software and firmware that will be required for larger satellites. While the modularity of the software and firmware will facilitate growing single sided non-redundant systems into redundant software and firmware systems to enable the larger satellites to be more robust and fault tolerant. In the case of large satellites a standard needs to be adopted to develop, integrate and maintain flight software that is used for spacecraft services such as GNC and communications. This would allow for the re-use of software and allow for these software resources to be upgraded to better support spacecraft operations. Also there is an obvious need for mission specific software but this software needs to conform at the interface level to the PnP software standard and there needs to be some isolation (such as the mission specific software only being located on one computational resource) to ensure that the overall PnP software architecture remains stable.

The verification of this software and firmware will be very intensive, but by utilizing a FlatSat test environment the resources will be in place to successfully develop and deliver the complex system. Having FlatSat resources with increasing fidelity allows the software team to improve the testing of the system as the software grows and the different modules from different suppliers come together. This is exactly the process utilized by Hubble with software first being tested on software simulators, then on single sided Engineering Model (EM) resources, and then in the Vehicle Electrical Test Facility (VEST) with a full complement of flight, flight spare, qualification, and engineering model resources.

NASA could have a few standard busses for different size satellites and orbits resulting in a true off-the-shelf spacecraft bus procurement opportunity. It will often more satellite than is needed, but the savings realized through streamlined production, eliminating nonrecurring design cost and greatly reduced system engineering activities. It will also increase reliability as human errors are eliminated or greatly reduced.

If the manufacturers of large constellations of satellites can adopt PnP concepts then the reduced cost that they will pass on to the customers/users will allow the customers to fund additional missions.

Catalogs of standard busses could be developed where multiple companies propose satellite busses that provide standard interfaces and services to the customer. This would be analogous to the Mill Spec approach to part numbers for electronics. The satellites would be standard and interchangeable; this would allow the payload teams to work to a standard interface that has been tested in the real world thus reducing the number of Interface Control Document (ICD) violations. The direct competition would reduce costs, and the standard buss developed would also lead to simplified AI&T efforts saving time and money.

CONCLUSIONS

The history with MMS shows that there are several critical factors necessary to achieve long term success of "standardized bus systems". The first lesson is that if a concept is brought to the market before its time it will fail as a concept due to the inability of other organizations to adapt to the new paradigm. Secondly for long term survival flexibility and/or upgradability must be central to the modular architecture.

There will come a time when even the best conceived architecture will become out dated. As advances in technology continue the difference between the old modular or standardized bus was conceived and the current state-of the art becomes too large a gap to economically resolve. At this point either a major redesign or a fresh start will be needed.

The PnPSat has pioneered the self-realizing concept for satellites. This concept will minimize system engineering, design, and AI&T schedules. This concept will dramatically reduce ICD miscommunication driven anomalies. Manufacturing errors due to engineering errors or workmanship errors caused by one-of-a-kind designs. These technologies also have direct applicability to mid-size and large satellites. By implementing the PnP concepts the satellite designers can significantly reduce the amount of harness required saving mass, cost, and reducing the possibility of miswires.

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