Reimagining Test Bed Development for "Build-to-Print" Modular Electronics Designs

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In 2007, the APL Space Electronic Systems Group began developing the power distribution unit (PDU) for NASA's two Radiation Belt Storm Probes (RBSP, now known as the Van Allen Probes) spacecraft. The RBSP PDU was a new, slice-based, modular design that was intended to be used for multiple missions as a reconfigurable "build-to-print" solution. In keeping with the PDU design philosophy, the PDU test bed needed to meet the typical autonomy and reliability requirements, with the additional challenges of future PDU configurations and mission-to-mission reuse with minimal redesign effort. The RBSP PDU test team extended the APL mini–mission operations center (mini-MOC) concept to slice-level testing to facilitate mission-to-mission reuse and to leverage autonomous testing during the slice qualification. The culmination of design philosophy, execution, and forward thinking resulted in the development of a PDU test bed that is baselined for use on future missions with a significant savings in both cost and schedule versus new development, as well as successful early delivery to the integration and test phase of the two RBSP PDU boxes in late 2010.

INTRODUCTION

APL has been successfully using the concept of mini–mission operations centers (mini-MOCs[1,2]) to perform subsystem (box)-level testing on multiple missions for more than a decade. These mini-MOCs typically utilize a COTS telemetry and command (T&C) product, in addition to APL-developed software, to provide a subset of full MOC capabilities. The test team decided to bring the mini-MOC concept to the slice (board)-level testing for power distribution unit (PDU) development. This was intended to facilitate mission-to-mission reuse and to leverage streamlined, autonomous testing during the slice qualification.

Each test bed (TB) design fully utilized a subset of the COTS instrumentation suite, which was supplemented by well-defined TB hardware modules for unique requirements. A certified TB wire harness implemented the complex network of interconnections between TB elements. The primary goal of this design paradigm was to reduce TB cost by localizing complexity into one-time-cost COTS instrumentation and T&C systems. A secondary goal was to develop in-house hardware for real-time, unique test requirements. While the wire harness was used to interconnect the hardware modules, the glueware (software interface programs) was used to interconnect the COTS instrumentation modules to the COTS T&C system. The standard APL ground support equipment (GSE)-to-MOC interface control document was implemented as on all APL missions.

A large number of test scripts, often containing thousands of lines, was required to perform the various board- and box-level tests. The TB hardware was intentionally developed to be flexible and generic, which increased script length because of the added script complexity and configuration requirements but also allowed for adaptation to changes in PDU configuration with little impact to TB hardware. The result was a benefit to the TB schedule. The PDU scripts also used only basic script language constructs so that they can be easily reused on future COTS T&C systems regardless of the complexity of the target language.

BACKGROUND

As a result of the efforts made during the design of the Radiation Belt Storm Probes (RBSP, now known as the Van Allen Probes) PDU, a flexible, modular PDU system was developed. This architecture accommodates various configurations of the three board designs to meet both RBSP and future mission requirements from a single "build-to-print" box. Three distinct slice designs were developed to implement the PDU system: the command/telemetry (CT) slice, the relay/capacitor (RC) slice, and the MOSFET switching (FET) slice. The RBSP PDU, pictured in Fig. 1, utilized one CT slice, two RC slices, and three FET slices, which resulted in six safety buses, 75 switched output services, and 12 unswitched output services.

The two main functions of the CT slice are to provide (1) the PDU external control interfaces, and (2) a DC/DC converter for the secondary power functions on the RC and FET slices. Command and telemetry are handled within the CT slice field programmable gate array (FPGA), along with separation acknowledgment and some other system control requirements. The secondary power, the inter-integrated circuit (I^2C) bus, thruster pulse, and other signals are routed internally from board to board using an inter flex interface (rigid flex) board. In a redundant system, there would be two CT slices. One would operate the A-side of the box and the other would operate the B-side. (For the FET, RC, and interslice harness, a redundant control path is included within the single card.) The Control and Low-Voltage Power Supply blocks in Fig. 2 are included on the CT slice. From the TB view, this board has the most complex real-time external interfaces, utilizing low-voltage differential signaling (LVDS) transceivers, an I^2C bus, and universal asynchronous receiver/transmitter (UART) data links.

The main functions of the RC slice are to implement the following: bulk bus capacitance, unswitched power services, safety bus relays, umbilical power diode isolation, autonomy relays, safety plugs, single point ground, and some housekeeping telemetry. These functions encompass the Power Input and Umbilical block in addition to some of the Power Services block shown in Fig. 2. The only differences between the two copies of the RC slice design in the RBSP PDU are the single-point ground connection, the I^2C bus addresses, and the power service sizing (current sensing and fusing). The RC slices, as well as the FET slices, utilize an APL application-specific integrated circuit (ASIC), and the power remote input/output (I/O) 2 chip, which implements A/D conversion, telemetry, pulse generation, and switch commanding from the I^2C interface. From the TB view, the external interfaces to the instrument are I^2C control, input power, integration and test (I&T) plug, and output power services.

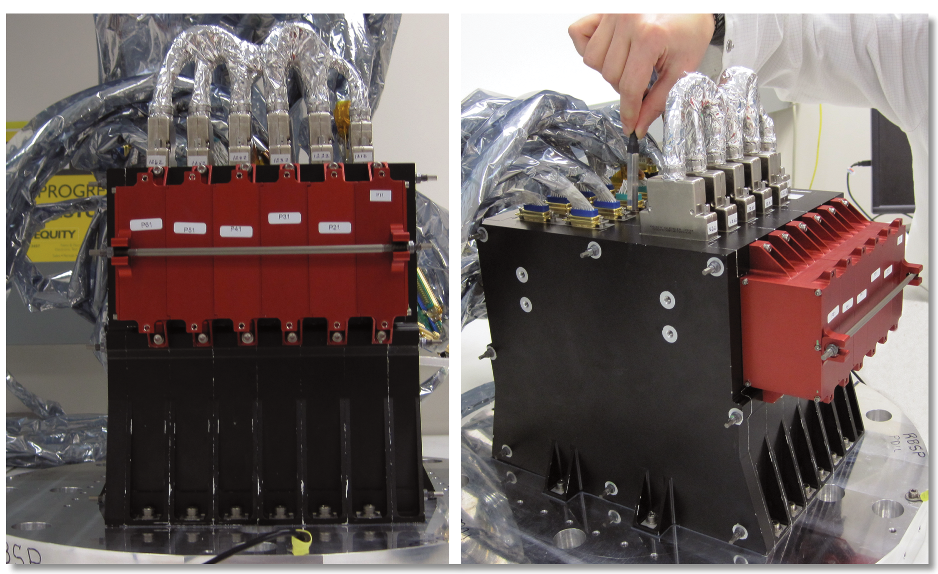

Figure 1. Flight PDU box with nonflight fuse modules.

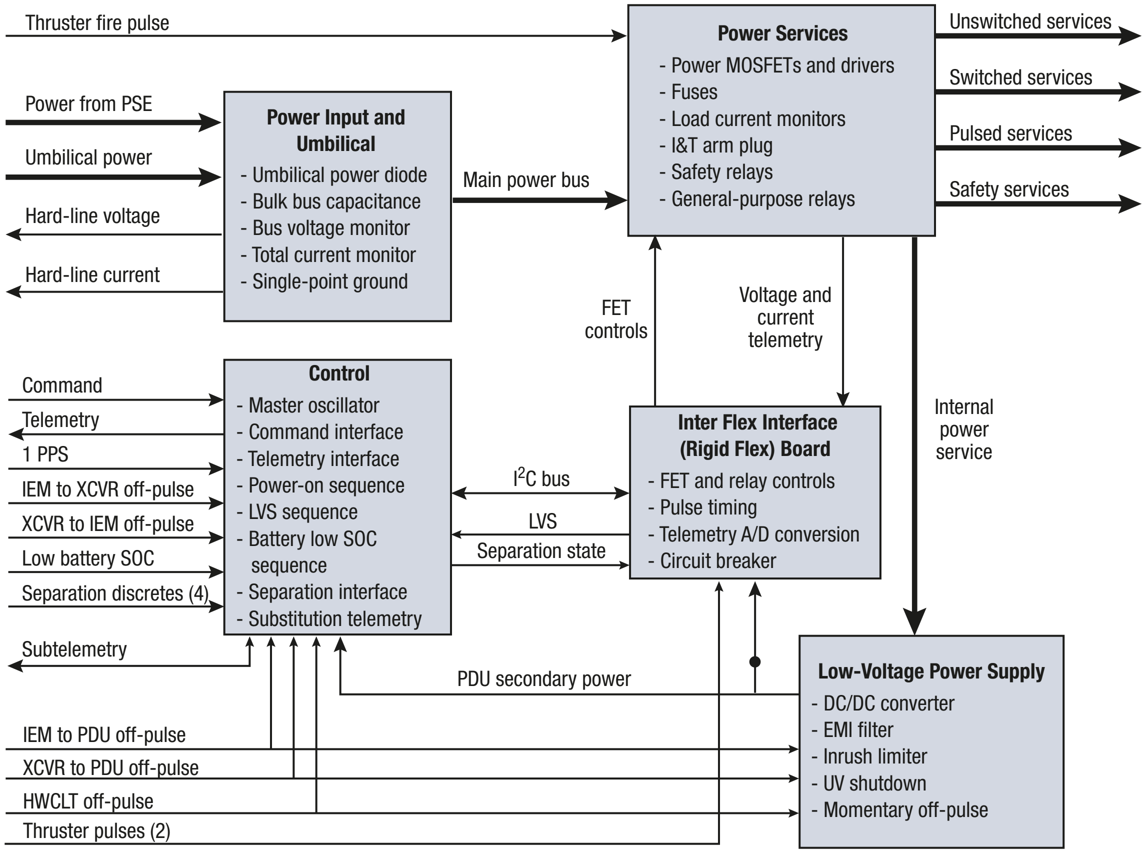

Figure 2. RBSP power subsystem block diagram. 1 PPS, 1 pulse per second; EMI, electromagnetic interference; HWCLT, hardware command-loss timer; IEM, integrated electronics module; LVS, low voltage sense; PSE, power system electronics; SOC, state of charge; XCVR, transceiver.

The only function of the FET slice is to implement the many switched power services for the spacecraft while drawing power from the appropriate safety or general power buses for each set of output services. Every FET slice included the same number and type of switched services; however, the size of each power service (fuse size and current sense range) was unique to the loads on each card. The only other difference between the FET slices is the I^2C addresses for the power remote I/O 2 ASIC, which provides the current sensing, voltage monitors, pulse generation, and switch control functions. The FET slice functions reside solely in the Power Services block of Fig. 2. The PDU design configurability was based on the ability to expand both the power delivery concept and the interslice signal transmission with minimal design effort. By modifying the connections in the interslice power harness (wrapped harness on the top of the box) or adding/reconfiguring cards, the PDU can be adapted to new output service and safety bus requirements for reuse on future missions.

TB design was required to facilitate testing at both the slice and box levels while maximizing reuse of TB components for cost savings, schedule reduction, and TB maturity acceleration. The decision to include the mini-MOC at the slice level was driven by the goal of TB reuse on future missions and by the schedule to qualify all six flight FET slices. The mini-MOC increased slice qualification autonomy and repeatability, accelerated the test schedule, and allowed all applicable slice-level hardware, software, and scripts to be reused at the box level of testing.

INTELLIGENT DESIGN TO LOCALIZE ENGINEERING COMPLEXITY

To keep the complexity and cost of the TB down, with a subsequent increase in reliability, each interface was analyzed at the requirements level to target COTS measurement and stimulus equipment. Although this did not work in all cases, it served to minimize the nonrecurring engineering (NRE) costs for the TB design effort. By widely utilizing COTS equipment, the team was presented with as much reliable, functional, and documented COTS test hardware as possible, including an application programming interface to control integrated logic. The overall goal of the interface design effort was to localize complexity within the Measure-

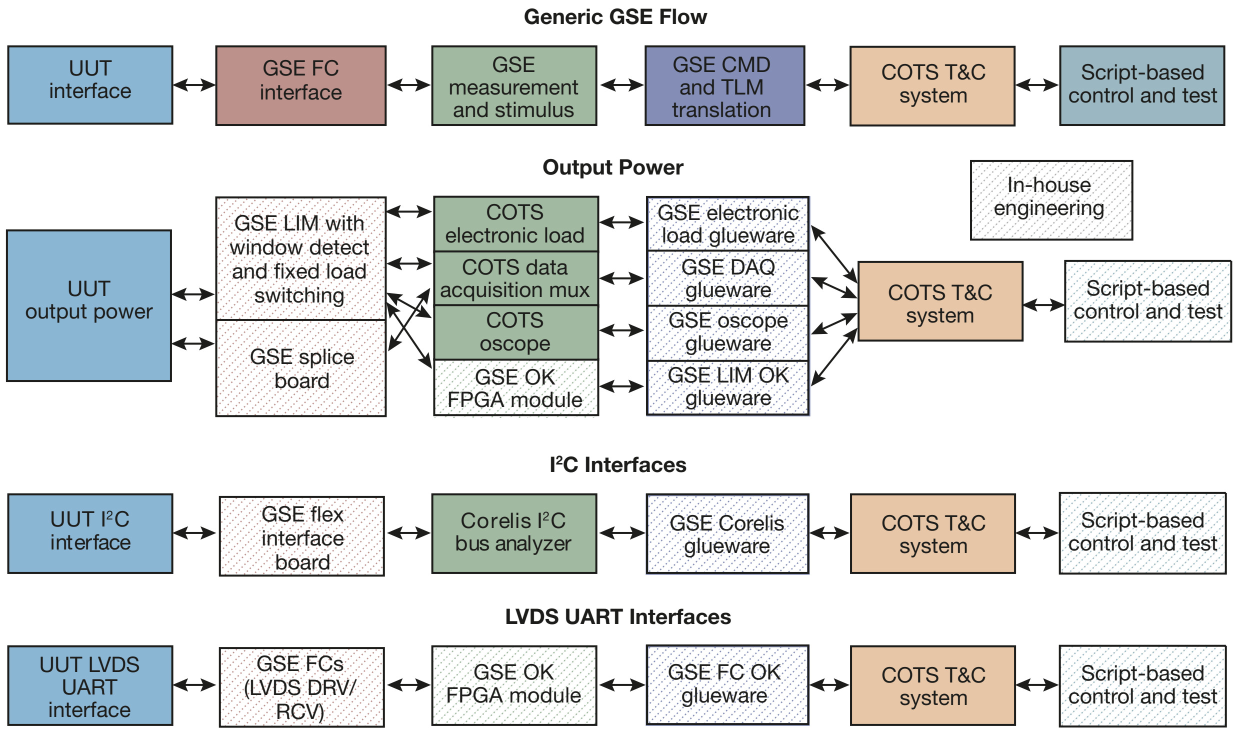

Figure 3. Use of COTS equipment within the GSE test flow to reduce in-house engineering complexity. CMD, command; DAQ, data acquisition; DRV/RCV, driver/receiver; FC, first circuit; LIM, load interface module; OK, Opal Kelly; TLM, telemetry; UUT, unit under test.

ment and stimulus, COTS T&C system, and Script-based control and test blocks of Fig. 3. The green GSE measurement and stimulus functionality blocks include a significant number of COTS test hardware elements, and the orange COTS T&C system blocks are a representation of the EPOCH ground system used for T&C for the RBSP spacecraft. The scripts were designed to be a complex element to allow script developers to have complete control over all software-controlled elements. This also minimized redesign of GSE hardware by allowing open script-based control. The pink GSE FC interface blocks and purple software GSE CMD and TLM translation blocks are designed to be primarily simple hardware and software interface translation blocks, respectively.

The team developed custom in-house hardware to fill vacancies in the test suite where COTS implementation was not suitable to meet unique TB requirements, in addition to development of hardware to provide safe FC interfaces to the unit under test (UUT). In many cases, the FC interfaces, shown in pink in Fig. 3, are minimized to LVDS protocol receivers, or PDU input power switches. When unique requirements existed for measurement and stimulus, an Opal Kelly-integrated FPGA platform with USB interface was utilized to provide command, telemetry, and control functionality. The firmware development process was defined to meet outlying test requirements and segregated into a load interface module firmware design and FC firmware design. Whereas the load interface module firmware was always common and fully utilized, the FC firmware was a superset of FC test requirements, which were used as needed for each unique FC board.

In addition to unique requirements, the TB was designed to provide simple hardware translation from the UUT to the COTS test hardware, along with a simple software translation from the COTS test hardware to the COTS T&C software. Pushing complexity into COTS hardware, COTS T&C software, and in-house scripting assisted the development of a generic, reconfigurable platform with the necessary flexibility to support a build-to-print product across multiple missions with minimal hardware redesign. Utilizing the TB for future missions would require mostly script modification to reconfigure for new services sizes or additional slices, thereby reducing TB development costs on a similar order to the build-to-print UUT NRE savings. Although the script complexity is increased to manage TB configurability, embedded software and especially the cost of hardware circuits and schedule impacts could be reduced, resulting in an overall benefit.

INCREMENTAL DESIGN WITH THE SLICE-LEVEL MINI-MOC

Slice-level testing in the mini-MOC significantly reduced GSE/test engineering cost and scheduling time.

	Slice-level testing	Box-level testing
Previous missions	Implemented using one of the following: - Manual testing - Labview instrumentation - QNX chassis with custom code - Distributed test instrumentation - TBs with custom code	Implemented using: - SC COTS T&C system - Autonomous scripts in T&C language - Dedicated TB instruments (rack) - Certified TB harness - Instrument to T&C glueware
RBSP PDU TB concept	Implemented using: - SC COTS T&C system - Autonomous scripts in T&C language - Dedicated TB instruments (rack) - Certified TB harness - Instrument to T&C glueware	Implemented using: - SC COTS T&C system - Autonomous scripts in T&C language - Dedicated TB instruments (rack) - Certified TB harness - Instrument to T&C glueware

Figure 4. Mini-MOC to the slice-level design concept. SC, spacecraft.

The effort for the RBSP PDU was front-loaded—avoiding the informal slice-level test setup that has been previously used to test flight slices—and moved directly to the design and deployment of a capable GSE system to test the first engineering module (EM) slices. This required more foresight and a higher level of effort from the GSE team in the early phases (Fig. 4). Every piece of the slice-level TB design, scripts, hardware, software, and databases were derived from modules from which the box-level TB was built, leading to a streamlined approach in which early efforts produced long-term results.

All scripts, databases, and hardware within the TB were vetted through the debug process of the EM boards, and later, the EM box. Any script changes could be directly verified by testing with the EM slices. In this manner, the maturity of the TB was always at a very high level when it was needed to test flight slices or boxes. The flight slices were tested only within a controlled, autonomous, and verified test system, which was able to produce consistent, repeatable results just like the PDU box TB environment.

Finally, the front loading of the GSE effort reduces risk to the box-level TB development. When new elements are needed to produce test results at the box level, or especially in the case of an entirely new system, there is the risk that chosen hardware, software, or test methodology will not function. With no earlier heritage, and no available test object until the EM box, there is some level of risk that the box TB will not fully function and the problem will not be found until the EM box is available to interrogate the box TB. With the PDU mini-MOC TB design, every element of the box-level TB was a direct copy, or built on existing hardware, software, and test methodology within the slice-level TBs. Because of this heritage, the TB is exercised earlier in the EM test schedule, so any anomalies can be investigated and remedied at all levels earlier in the test schedule. Once again, this is front-loading of the GSE design, which reduces risk as the test program moves from the slice- to box-level testing.

MODULAR DESIGN AND REUSE

The PDU design, in its modular style, provided simplified external interfaces and confined more complex control functionality to certain blocks of the design. Figure 5 illustrates the major I/O functions of the PDU slices and illustrates how the PDU test team was able to develop groupings of I/O signals. Some of these groupings required specialized signaling or real-time control, so they were handled in a TB firmware design (Specific control logic). However, given the functionality required in power distribution, many of the functions required of the TB were input power switching and output power service monitoring.

Output power service monitoring is one example in which modular design and COTS instrumentation were leveraged within the TB. The measurement, monitoring, and loading requirements were analyzed to determine which COTS instrumentation could be utilized to accomplish the test program. What remained was creation of a four-wire measurement of the output voltage and switching between the two fixed loads for each output service. The TB design team successfully developed custom hardware to provide for the unique test requirements so that the same platform could be used for every FET and RC output service. The same load interface module was used in the RC slice, FET slice, and box-level TBs. Every service was only differentiated in hardware by the value of the resistor on the fixed load plate. Harnessing provided the appropriate connections, so that the scripts could command complete control of the TB system for voltage measurement, glitch detection, current measurement, transient waveform capture, and load switching.

The output power services are an example of how the TB team resorted to in-house hardware design only to meet unique requirements and ensure that it was applicable to multiple TB designs. With variations in PDU loading, the same architecture is fully applicable, with possible replacement of fixed resistors and script modifications due to service size changes. This is a prime example of how the PDU TB was designed to be modular and flexible to provide the same benefits to future missions as the PDU box itself.

Considering the EM/flight total of nine FET slices, six RC slices, and three CT slices, the testing load at the slice level was high for the RBSP PDU test team and could likely increase for future missions. The focus of a

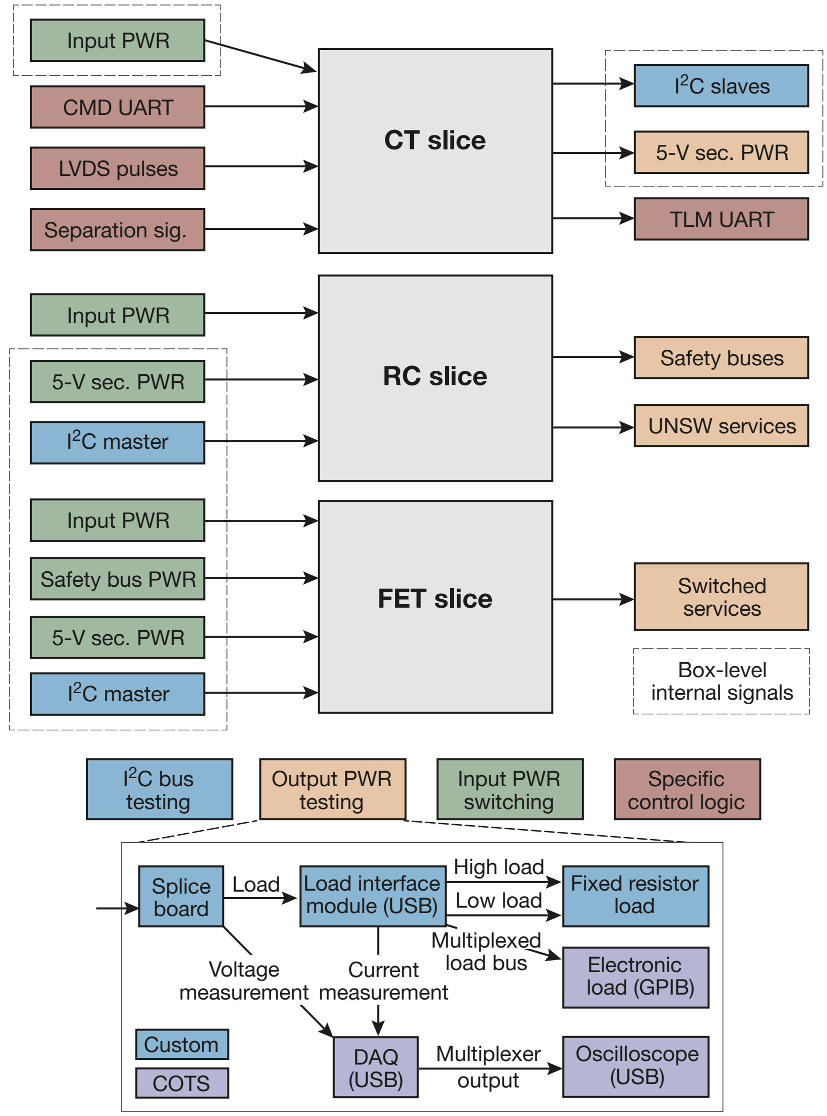

Figure 5. PDU major test interfaces. GPIB, General Purpose Interface Bus; sig., signal; sec., secondary; UNSW, unswitched.

build-to-print design effort was to reduce NRE costs and cycle time for future developments. To maximize that goal, the PDU TB must streamline the flight qualification efforts and reduce the engineering support requirement. By introducing the COTS T&C system and investing in a repeatable, autonomous slice test suite, not only was the RBSP PDU slice qualification cost reduced, but the same hardware, software, scripts, and databases can be reused to test future PDUs with minimal NRE cost. Changes in configuration, load sizing, etc., may drive some load plate changes, script modifications, or TB growth, but the base-level modules create a generic platform matched to the flexibility of the PDU design. When those future PDUs are qualified, they will do so with minimal reconfiguration NRE cost and the schedule acceleration afforded by an existing autonomous test suite.

TELEMETRY AND COMMAND DATABASE

APL has been consistently improving its spacecraft database capabilities incrementally with each new mission.[3] The overall goal has been to have database tools that function independently of the ground software, making it easier and quicker to update specific portions of the database at any given time. A naming standard was devised for each subsystem as their individual workbooks were developed. This ensured naming consistency and ease of comprehension for team members.

The command database was kept at a high level for the slice- and subsystem-level testing. Instead of defining a large number of specific commands, a select number of text string commands were defined. Each contained multiple variables, providing the full range of command availability required for the testing. This method reduced the database management cost and also reduced the potential for operator error. The team could now easily test any configuration of the UUT at any given time.

The mnemonic names were more specifically defined for the telemetry database. Because the database allowed for the aliasing of different names, multiple designations for mnemonics could initially be defined for individual pieces of hardware; in some cases the definitions were down to the individual bit level. This eliminated the need to redefine the bit pattern in the telemetry stream. As the project continued, alias names could be modified so that they better described the data being displayed, as the telemetry was tailored for the specific mission (for example, which service was being powered, which switch was enabled, etc.). Essentially, each mnemonic could have multiple names but share the same bit location in the telemetry stream.

The naming convention allowed the test engineers and the subsystem engineers later in the project to understand exactly what telemetry was being displayed according to their own tailored names. Once the PDUs were delivered to the I&T team, the database was easily adjusted to reflect the use of the spacecraft's specific functions for the PDU. At this point, the command database was also expanded to provide more specific command names and definitions, reflecting only the variable combinations required for commanding the PDU on the ground and in flight.

SCRIPT DEVELOPMENT

The initial consideration for this effort was to make every facet build-to-print at the lowest cost possible and at the highest quality, all while meeting an aggressive delivery schedule. Our approach was to complete all tasks such that our test results were as repeatable and reliable as possible. This approach was implemented in all aspects of the design, including the approach to writing the test scripts.

While developing the scripts and ground system, mechanisms were added to allow for easy output of test-related data such as characterization data, quantitative values, and pass/fail results. The oscilloscope was automated to supply snapshots of waveforms, which proved to be valuable in validating the EM and flight units. This approach nearly eliminated the need for engineering dumps, as all of the pertinent data were available in log files that were easy to manipulate. This step proved critical in documenting failures, and information allowed for quick debug and retest failures, as needed, using the scripts to maintain consistency. The log files were also vital for trending and validating environmental tests results. The files generated by the scripts were also beneficial in generating data packages for quality assurance. The data collection process was almost completely automated. This capability required some special commands and glueware to be written to allow the ground system, COTS, and scripts to work perfectly together at a small, up-front cost.

Test scripts were written in a linear fashion to be simple, easy to read, and easy to convert from individual board testing to subsystem-level testing using automated text substitution. This method was also used to convert scripts between different ground system languages of differing command set complexities. Conversion was required because the initial test scripts were written for each individual board of the PDU. Once board-level testing was completed, all scripts had to be converted for testing of the complete integrated PDU. The scripts were written with this reuse in mind. The scripts were structured in a modular manner in order to receive user inputs at the start of the testing, so little user interaction was required thereafter. This proved to be beneficial because it saved time and money because technicians could conduct the testing with little to no special training. Equally advantageous was the fact that the scripts would notify the test conductor of any errors encountered and would provide guidance if further investigation was required by the cognizant engineer. This resulted in very repeatable results. The scripts were version controlled by using a server repository for configuration management so differences between versions and their results could be more easily understood.

Several rounds of EM testing had to be completed for all of this to function as envisioned. The template was an EM FET slice script used to perfect this method. Once the scripts functioned autonomously with the first configuration of the EM FET slice, the template was modified for the second and third configurations. This was continued when possible for the remainder of the EM FET slice-level scripts. After the test script package was completed, all EM FET slice boards were tested with full confidence that everything was controlled, repeatable, modular, and dependable. The flight FET boards were then tested, with very few changes required to complete the testing and with minimal risk to the flight units. This procedure was then expanded through text substitution to generate scripts that would and did function at the full PDU box-level testing.

The decision to make the test scripts linear and simple made it possible to use them across multiple UUTs. This led to savings in cost and time, which allowed us to meet our very aggressive schedule.

CONCLUSION

By taking the APL mini-MOC COTS-based testing concept from the box level to the slice level, the PDU team was able to deliver its product to the spacecraft in a timely manner. In addition to serving the immediate PDU effort, the design and methodology were tested, proven, and documented and are now preserved for application to future missions. The early efforts to localize complexity, retain complete script-based control, and design reusable modules were successful in fostering a TB solution ideally suited to validate both current and future PDU configurations.

Although the PDU was only one of many components of the spacecraft, its timely delivery was essential to the start of the I&T phase of the mission. It was successful during spacecraft integration and performed all of its intended functions throughout environmental testing. The Van Allen Probes were launched from Cape Canaveral on 30 August 2012, and all instruments were deployed during a 3-month commissioning phase. At the time of this writing, the spacecraft are continually and successfully performing prime science operations.

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