SOLID STATE POWER SWITCHING FOR NASA'S DEEP SPACE MISSIONS

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ABSTRACT

JPL has focused the development of solid-state power switches to meet the challenging environmental requirements of deep space missions. Three developments have infused the latest technology and advance the capability of the design. The Cassini Solid State Power Switch (SSPS) utilized hybrid packaging technology and digital gate arrays. The New Millennium Programs Deep Space One development used mixed signal ASICs and multi-chip-module (MCM) packaging. The X2000 development increased the functional and environmental capability using mixed signal ASICs and MCM packaging. Each development has enhanced the functional and environmental capability for deep space missions.

INTRODUCTION

The purpose of the solid- state switch developments at JPL has been to improve the reliability and performance of the power system for deep space missions. An initial goal was to eliminate all of the relays and fuses on the spacecraft and replace them with a more reliable solid switch with the capability to detect, control and isolate a fault in flight as well as provide reset capability. Some objectives were to reduce the overall fault containment region and improve the visibility into the health of the power system. Three developments at JPL met these goals and objectives and gradually improved the overall performance of the power system.

The Cassini development was the first attempt by JPL to provide power distribution using solid-state power switches. The Solid State Power Switch (SSPS) was developed to provide power switching, fault detection and isolation. The SSPS provided command status and current telemetry for every load. Hybrid packaging was used to combine a gate array, analog control circuits and a power MOSFET die in a single package. Each switch was a separate fault containment region.

Based on the SSPS development, JPL proposed to develop the next generation power switch utilizing the latest technology available and validate it on the NMP Deep Space One. The purpose of the development was to combine the digital and analog control functions into a single mixed signal ASIC and package it with a power MOSFET in MCM packaging. The Power Actuation and Switching Module (PASM) was developed by a team of JPL, Boeing and Lockheed Martin.

Once the technology of the PASM had been validated as an experiment on Deep Space One, a new development started to expand the overall capability of the PASM. The X2000 development utilized the same technology, but improved the radiation tolerance to survive the Jovian-Europa environment. The capability to fire pyrotechnic devices and actuate valves was added to the PASM.

Some of the challenges for these developments are the requirements of deep space missions that include long life, low system power resources, temperature extremes, radiation levels and single event effects.

CASSINI SSPS DEVELOPMENT

The SSPS replaced a relay and fuse combination that had been the standard for the previous JPL missions. The SSPS is series redundant and was designed to switch a 30V power bus. The switch provides a current limit and trip function, dV/dt soft start and current telemetry. The switch design was optimized for switching electrical loads without energy storage on the main power bus.

The Cassini command path (figure 1) utilized a Honeywell (HR1060) one-mega-rad-hard gate array for the power distribution command interface. The power distribution subsystem contained a custom serial data bus on every board. The main command interface from the spacecraft was through a Remote Engineering

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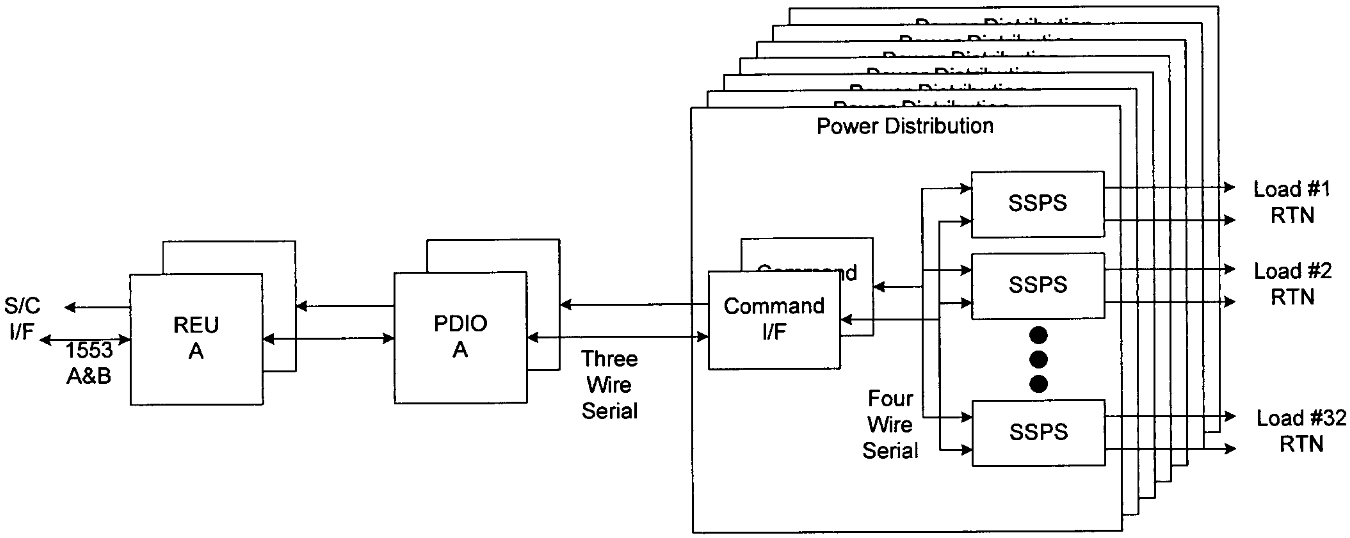

Figure 1: Cassini Command Path

Unit (REU) providing a 1553 data bus to the spacecraft and a parallel interface to the power subsystem.

The SSPS (figure 2) utilizes a combination of a radiation-hardened digital ASIC with discrete analog and power components in a class K hybrid package. CTS Microelectronics produced the SSPS under contract from JPL. For the digital command interface, United Technologies Microelectronics Center (UTMC) developed a gate array.

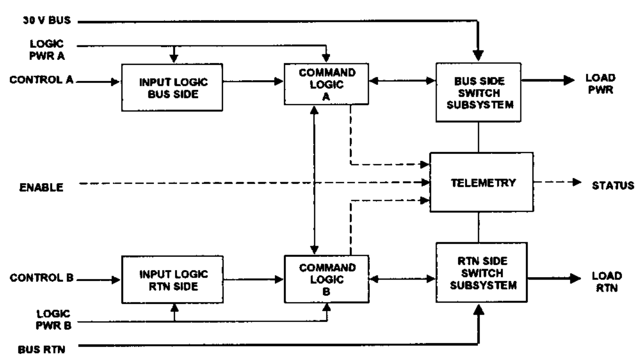

Figure2: SSPS Functional Block Diagram

The Cassini SSPS Hybrid contained the following components:[1]

- 2 UTMC gate arrays
- 35 active devices (IC dice)
- 26 chip resistors and capacitors
- 181 screened resistors
- 12 actively trimmed resistors
- 466 bond wires (396 are 1 mil gold)
- 72 pin package

The SSPS and command interface components were used on every power distribution board (see figure 3). The use of these custom parts on every board reduced the number of piece parts and assembly time of each board. Cassini was able to provide more functionality in a smaller package by investing in Hybrids and gate arrays.

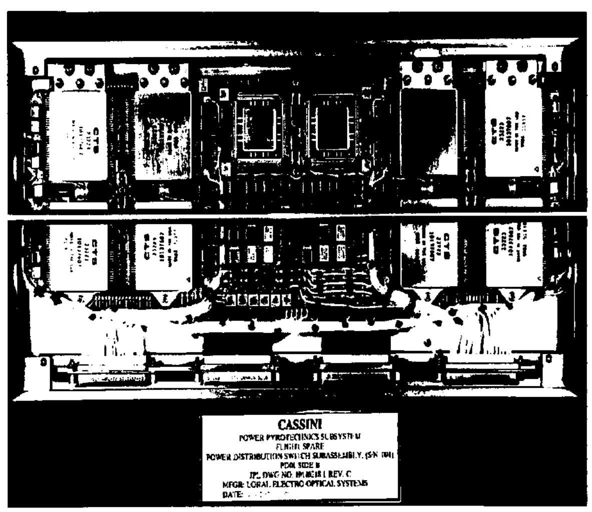

Figure 3: Cassini Power Distribution Board

Cassini was successful at infusing new technology to improve the overall performance. The development schedule was long enough to develop the designs and target the new technologies. Cassini had enough electrical loads (192) to justify the added development costs. The SSPS improved the overall risk to the project by providing more functionality per load reducing the fault containment region to a single load. Other benefits were displayed in spacecraft integration when some switches were tripped during checkout. Previous designs would have required a fuse change, but in this case the switch performed as designed and there was no impact to integration.

NMP PASM DEVELOPMENT

The Power Activation and Switching Module (PASM) is an experimental development, which flew on the NMP Deep Space 1 mission. The PASM was a joint development between Lockheed Martin, Boeing and JPL. The goal of the PASM experiment was the flight validation of three promising technologies for the power system electronics. The three technologies are the high voltage mixed signal ASIC, Power High-

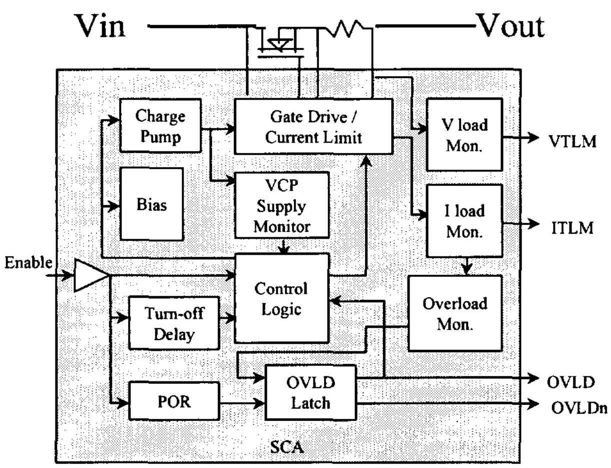

Figure 4: PHDI Power Switch

Density Interconnect (PHDI) packaging, and the dual rate 1773 data bus interface.

After the development of the SSPS for Cassini, several lessons learned and functional improvements were identified. Higher levels of integration could be achieved by the use of a mixed signal ASIC technology. The mixed signal ASIC would reduce the number of analog components just as the digital gate array accomplished for the SSPS. The PASM would take advantage of the capability of the mixed signal ASIC needing only a few passive components outside of the ASIC for complete control of the power MOSFET.

The PASM has four power switches that are current controlled for soft start current limiting and tripping functions. The PHDI switch module was designed by LM-CPC utilizing a General Electric (GE) technology. The PHDI packaging technology combines the mixed signal ASIC, power MOSFET and discrete components of four switches in a single package. The PHDI packaging technology enables high-density packaging for power applications.

The high voltage mixed signal ASIC technology is used for the Switch Control ASIC (SCA) inside the PHDI Switch Module. The SCA was fabricated on the Harris Radiation Hardened SiGate (RSG) process. The process became QML-V qualified in June 1997. The process was selected for the high breakdown voltage capability of the transistors. The total dose radiation level met the Cassini level of 100 Krad.

The SCA provides the control function for the power switch. The ASIC contains the digital command and telemetry interface, current control loop, charge pump and level shifting functions (figure 4). The switch is capable of switching from 3 to 40 V and up to 3 A steady state. Analog current and voltage signals are provided for telemetry. The high voltage process enables the wide range of input voltage to the switch.

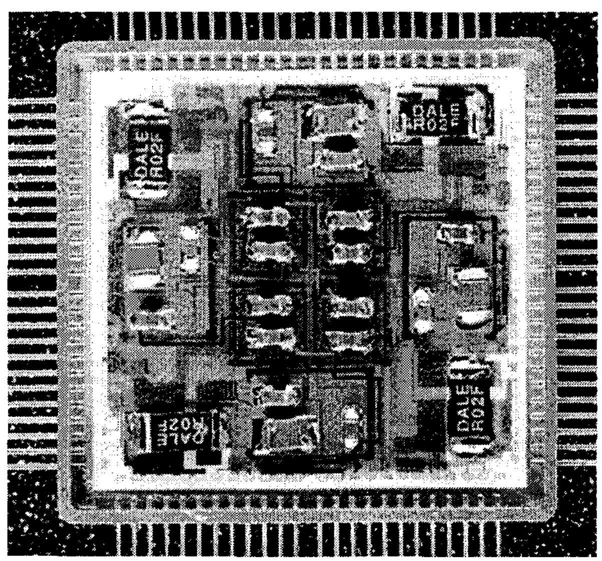

Figure 5: NMP PASM

Another lesson learned from Cassini was the number of different command interfaces between the spacecraft computer and the SSPS. A custom digital ASIC was design by Boeing to interface directly to the spacecraft 1553 or 1773 data bus. The level of visibility to the switch would increase and the fault containment for the command path would become smaller reducing the risk.

The 1773 interface, designed by Boeing, includes the transceiver and the Smart I/O protocol ASIC. The Smart I/O ASIC provides a remote terminal to the 1773 data bus.

The Dual Rate 1773 data bus is very promising for the power system due to the isolation of the fiber optic interface. The isolation is a great advantage within the power system to simplify the grounding tree.

Although the Smart I/O was designed for the 1773 data bus, the DS1 experiment was implemented using the spacecraft 1553 data bus. This change of implementation demonstrated the flexibility of the Smart I/O design.

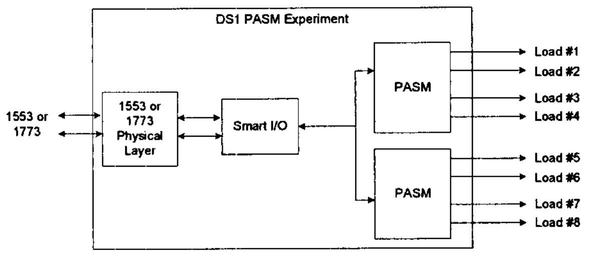

Figure 6: DS1 PASM Experiment

The purpose of the validation program was to validate the design and production processes for mixed signal ASICs and the HDI packaging technique and materials by exercising the electrical functions of the switches in the space environment. The validation program included flying two PASM modules as Category 3 (not essential to the mission) experiment on DS1. The test program included switching 5-volt-power to a 1 ampere resistive load through each of the eight switches (4 per module). The switches were also operated in parallel (2 at a time) to switch 5-volt-power to the same 1 ampere resistive load.[2] The PASM telemetry showed no degradation throughout the mission.

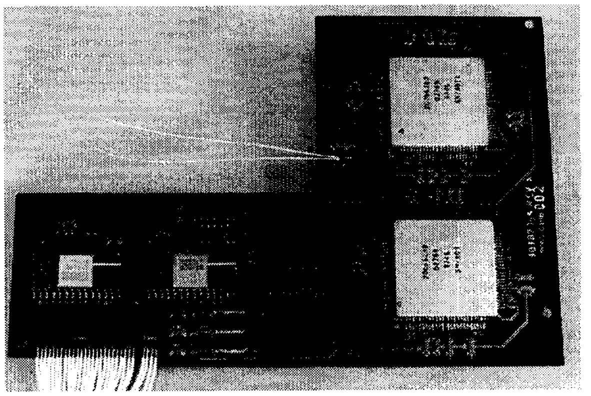

Figure 7: DS1 PASM flight experiment board

X2000 PASM DEVELOPMENT

The **Europa Orbiter Project was** managed by JPL for NASA took the prime initiative to deliver an orbiter to the Jupiter moon Europa. The Europa Project managed the X2000 development. The Europa Orbiter no longer exists as a stand-alone project and the mission goals have moved to the Jupiter Icy Moon Orbiter project. The requirements of the mission are what drove the X2000 design.

The key requirements for EO were as follows:

- 1 Mega-Rad Total Ionizing Dose capability for parts
- 14 year life
- Low Mass and Power

The X2000 Avionics primary focus was on the delivery of a flight avionics package for the Europa Orbiter. The package will include a new and innovative distributed architecture in both hardware and software. The architecture must be capable of integrating different instruments, propulsion modules, power sources and telecommunication into a multiple mission platform. A significant part of the avionics is the Power System Electronics (PSE). The PSE provides the power control and distribution.[3]

A key building block for the X2000 PSE is the Power Switch Slice (PSS) (see figure 8). Adding these slices can scale the power system.

The PSS provides the interface to all of the loads on the spacecraft. Each power switch can be commanded to drive a steady state or momentary/pulse load. Each switch can be configured in the high or low side, and series or parallel. No single failure shall cause more than one switch to be stuck ON. Telemetry is provided for each load. Every switch in the PASM

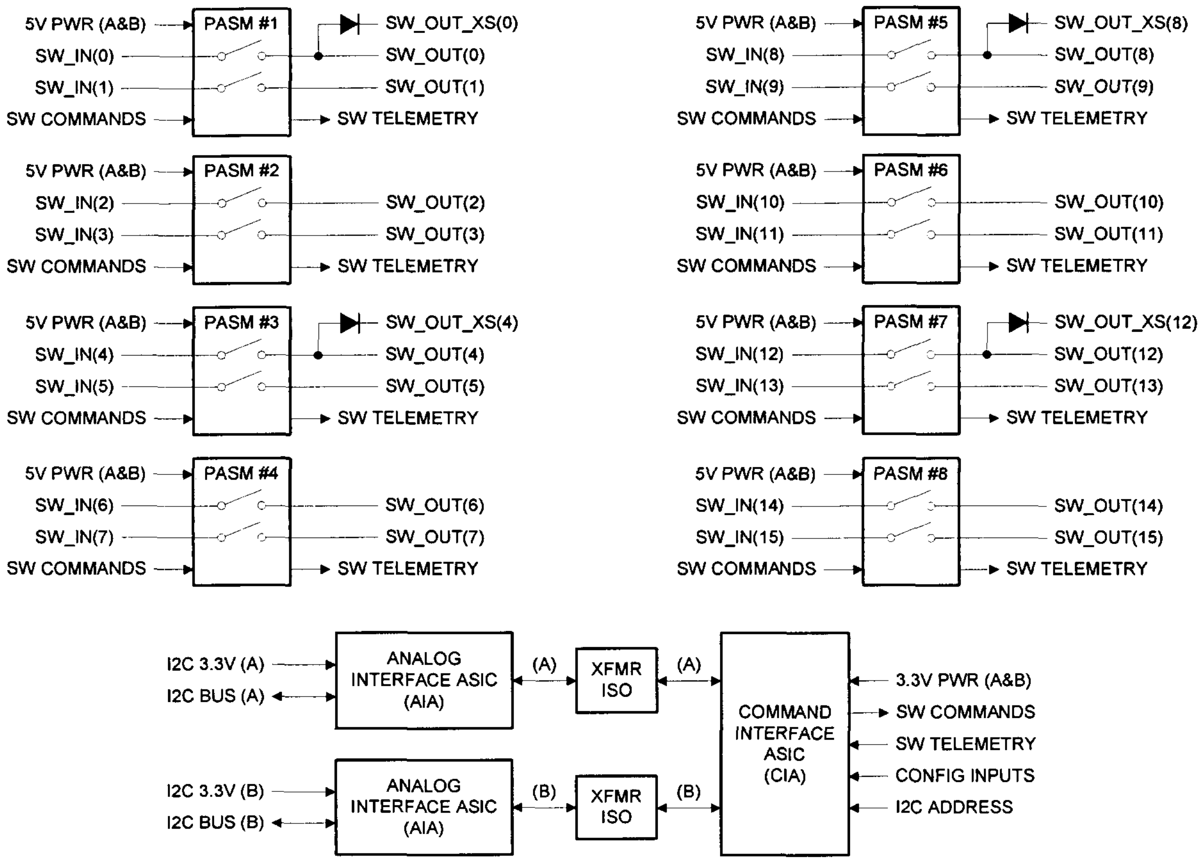

Figure 8: PSS Functional Block Diagram

provides controlled turn-on and protects the power bus from load faults. The command interface provides the command and telemetry interface. The PASM provides the power switching.

The PSS provides the power and command interface to the valves on the spacecraft. The command interface can synchronize and provide accurate timed commands. The same protection and telemetry is also provided per valve interface.

The PSS provides the interface to the pyro devices. The PSS provides an interface for safety inhibits, and has separate enable commands for groups of switches. Each switch provides current limiting to allow for simultaneous firing of multiple initiators.

The development of the DS1 PASM provided significant feedback on the development process and design issues. The X2000 PASM development would benefit from the feedback and advance the design to reduce power and provide more functionality over the DS1 PASM. One such improvement was to expand the capability of the switch to be able to fire pyrotechnic devices and actuate valves. Another improvement was to increase the total dose capability to meet the Europa mission requirements of 1Mrad.

The second generation PASM is very similar to the DS1 version. It provides basically the same funcitonality but with a 1 mega-rad-hard rating. The PASM contains two independent solid state power switches in a single package. The following is a list of switch parameters for the PASM.

Overload Trip Current	1 A, 3 A (selectable)
Overload Trip Delay	20 ms
Current Limit	2 A, 5 A (selectable)
di/dt	180 A/s
Voltage Telemetry	0.075 V/V
Current Telemetry	1 V/A
On resistance	60 mOhms

Input Voltage Range	0 – 40 V

Some changes have been made to make it more compatible with the X2000 products. The SCA is on the Honeywell RiCMOS IV Line, therefore the PASM is now one-mega-rad hard. Another change is that the package has changed to fit three PASMs on a side within a Compact PCI 3U card.

Power Load Application

The Power Distribution Function uses the PSS to provide load switching, telemetry, and fault protection. The number of slices will depend on the number of loads and total power of the spacecraft.

The command interface is via the standard interface to the spacecraft data bus. The I2C data bus is isolated between the physical and link layers.

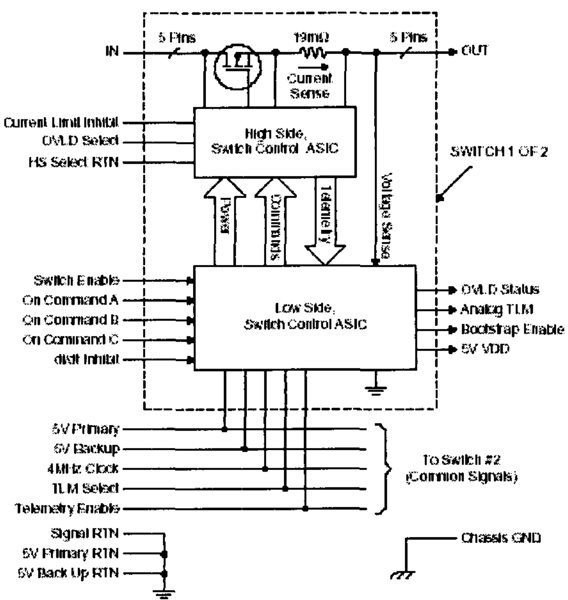

Figure 9: PASM Block Diagram

The PSS provides the capability to individually command sixteen switches on the board. Switches assigned to loads can be classified as loadshed or non-loadshed. The switches can be commanded in steady state mode or pulse mode. The steady state command turns the load on or off indefinitely. The pulse mode turns ON the switch for a specified duration after a specified delay. Pulse loads can be continued indefinitely with repeated commands.

The switch fault protection is composed of a current limit function and a selectable trip level. With current limit, other loads on the same power converter are not affected during the isolation of the fault.

Load current telemetry is available for each switch. The analog load current telemetry can be converted to digital telemetry by the command interface. Since telemetry is available on every switch, the power converter efficiencies can be calculated in flight as well as the identification of load variations, drifts and incipient failures.

The PASM can be used in different configurations. Switches can be connected in parallel to reduce the voltage drop for high current loads. It is configurable in series/parallel or bi-directional connection to the load. Additionally, these switches can be configured in various ways to meet critical load requirements or to provide needed cross strapping between loads.

Each switch is individually commanded. This allows for tighter power management in flight, which is necessary, when the power from the source is limited.

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The power MOSFET is an N-channel device with a typical on-state resistance of 50 mohm. The internal charge pump and level shift circuits allow the switch to be used in different configurations

Valve Drive Application

The Valve Drive Electronics application is a new addition to the power system. Traditionally, Attitude Control provided this module for most of the JPL spacecraft. The application was added to the power system architecture to take advantage of the commonality with the Power Distribution.

Some key additions to the PASM design the back EMF suppression clamping. This clamp allows for the PASM to switch up 700mH loads making it ideal for valve actuation. The clamps have been implemented by placing zener diodes to the gate drive in order to use the power MOSFET as the clamping device. The switch is configurable in any series parallel switch configuration without risk of damaging the switch.

The command interface provides a direct link to the engineering data bus (I2C) for the timing critical valve commands.

Pyro Drive Application

The power system traditionally provides the pyrotechnic commanding function on the spacecraft. The design will take advantage of commonality with the Valve Drive and Power Distribution functions.

The PASM has been designed to interface directly with a NASA standard initiator (NSI). Each switch is current limited to enable simultaneous firing of multiple events from the main power bus. The switch has also been designed to reduce shoot through current to less than 20dB below the guaranteed no fire current of the NSI for dV/dt less than 10V/us.

The command interface provides the precise timing and synchronization with the spacecraft. A command interface can be loaded into the CIA and verified prior to the execution at a set time. Several interfaces for safety inhibits have been added for many layers of protection.

Current Status

The PSS prototype will be complete by the end of 2004. The SCA has completed fabrication at Honeywell and is currently being integrated with the PASM brass board at Lockheed.

SUMMARY

The solid-state power switch development at JPL has been spread consecutively over three developments with lessons learned feeding into the next. The X2000 PASM represents the third generation power switch. Each development has increased the functional and environmental capability.

ACKNOWLEDGEMENT

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