

Department of Defense (DoD) Space Test Program (STP) Payload Design Criteria for the STP Standard Interface Vehicle (SIV)

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ABSTRACT

The Space Development and Test Wing (SDTW) of the Space and Missile Systems Center (SMC) is midway through the development of a new means of spaceflight access for the science and technology (S&T) community. The goal is to make available to the entire space community a standard spacecraft (SC) to payload (PL) interface on which to base PL designs and enable access to space in a shorter timeframe, with less cost and reduced risk. Rather than designing a unique SC for each payload; the STP Standard Interface Vehicle (SIV) is a recurrent SC bus with adaptable interfaces to accommodate a range of payloads. The SC will accommodate one to four payloads totaling up to 60 kg mass and 100 watts orbit average power mounted to an external payload interface plate. The space vehicle is designed for orbits ranging from 400 to 850 km and inclinations of 0 to 98.8 degrees. The program offers a Payload User's Guide which defines the mechanical, thermal, power and data interfaces to help facilitate PL design and integration. This paper focuses on the PL design criteria to meet the standard interface and the adaptable capabilities of the SC to perform a variety of low earth orbit (LEO) missions.

INTRODUCTION

The purpose of this paper is to briefly describe the SC to PL interface for the STP-SIV. First, the paper will describe the capabilities of the SDTW and then the STP-SIV characteristics. The majority of the paper covers the PL design criteria for the mechanical, thermal, power, and data interfaces. Greater detail of the interfaces can be found in the STP-SIV Payload User's Guide. It is expected that utilizing a standard interface and disseminating this information to the S&T community will increase spaceflight opportunities, lower cost, and reduce risk for SDTW missions and potential customers.

SDTW CAPABILITIES

In the past year, SDTW has successfully launched and operated several SC including STPSat-1, Orbital Express, TacSat-2, and NASA's CloudSat. This reflects the SDTW's ability to satisfy various user/customer requirements while maintain our focus on future missions such as STPSat-2 which is the first STP-SIV with two national laboratory experiment.

Mission

The SDTW "develops, tests, and evaluates Air Force space systems, executes advanced space development

and demonstration projects, and rapidly transitions capabilities to the warfighter." To accomplish this mission SDTW has two groups, the Space Test Group (SDTG) and the Space Development Group (SDDG) each with specific core competencies. Two of SDTG's competencies including procuring various types of launch vehicles and conducting satellite operations. A portion of the SDDG mission is to develop advance space systems which demonstrate DoD S&T and new capabilities for our warfighters. One component to accomplishing the SDDG mission is to increase the number of spaceflight opportunities for the S&T community. STP-SIV is one method to accomplish the SDDG mission in a more cost effective manner.

Spaceflight Access

SDDG has several methods available for spaceflight access depending upon user requirements. It can integrate PLs to human platforms (i.e. space shuttle or international space station), to satellites or launch vehicle with existing mass margin, or develop a custom bus with a dedicated launch vehicle. STP-SIV provides SDDG a more cost effective option than the custom "one-off" satellite. STP-SIV looks to lower cost via reduction of non-recurring engineering cost and reduction of PL integration cost. The former is achieved through procuring multiple SIVs where

lessons learned are applied and restricting requirements growth. Integration cost reduction is achieved with a broad, comprehensive adoption of the standard interface amongst the S&T community.

To begin a mission, the mission design division of the SDDG builds space-flight missions from a yearly, prioritized list of 40-45 DoD-sponsored space experiments. Due to SDDG's level-of-effort funding, new missions are only started when sufficient funds are available after budgeting for all current missions. This makes the timing and number of space vehicle acquisitions difficult to determine resulting in inefficiencies in the process. Together, the experiment list, which changes each year, and the uncertainty of SDDG's funding timeline makes the nature and timing of missions very difficult to predict. The STP-SIV program helps to minimize some uncertainty for the mission design division because the STP-SIV contract allows for purchasing of up to six space vehicles. Currently, the first STP-SIV is funded through launch in October 2009 with one year of on-orbit operations. SDDG expects to have additional funding for a second and possibly third STP-SIV in the near future depending upon availability of PLs designed to meet the standard interface.

Before the start of a new STP-SIV acquisition, the mission design division conducts a PL bundling study using the list of 40-45 DoD experiments. Then Ball Aerospace and Technologies Corporation (BATC), the STP-SIV prime contractor, will conduct a PL compatibility study. This study examines interdependences between PLs and the STP-SIV focusing on the utilization of the standard interfaces and concepts of operation. Once successful compatibility is determined, the PL developer will participate in generating memorandums of agreement between organizations. Finally, a space flight plan is signed to officially state a PL is manifested for space flight.

SPACECRAFT STANDARDS

The conceptual meaning of SC standardization can have different methodologies based upon standard parts, modules, architectures, interfaces, or the combinations of each of these methods. SDDG previously pursued standardization with the Space Test Experiments Platform (STEP) missions. SC manufacturers offer product lines of SC with common design characteristics for communication, science, and weather satellites. The Centre National d'Etudes Spatiales (CNES) developed the Myriade and Proteus standard SC and have successfully adapted specific PLs to accomplish a variety of scientific missions. Each of these efforts would define the "standard" in a slightly different manner. STP-SIV is also defining a standard

in the sense of an interface between SC and PL and an interface between SC and launch vehicle and applying a variety of lessons learned from previous "standard" SC developments. The two most significant lessons are to design for some flexibility early in the program and once the design is complete plan missions within the capability of the SC design to minimize STP-SIV program changes.

Benefits and Limitations

A standard interface provides programmatic benefits, yet operations and PLs receive benefit as well. Although the ground support equipment (GSE) and ground operations systems may need modification due to PL specific requirements (i.e. state of health and science data), the core GSE and ground systems, which interfaces to the SC should not change. Operations training for personnel will remain consistent across multiple SIVs and operators will achieve a greater familiarity with the SC and ground system. Hence, GSE, ground system and operations costs are reduced as the number of SIVs increase.

Various publications^{1,2,3} reveal the cost benefit of SC standardization. The STP-SIV design implements standardization at the interface between the SC and PL and the SC and launch vehicle. In order to incorporate the benefits of standardization, STP-SIV engineers work with experiment designers early in the development process. By designing to a standard, the PL developer will understand the resources that are available on STP-SIV and the requirements necessary for PL to SC interface. As part of the STP-SIV program, a STP-SIV Payload User's Guide is published and available to the entire S&T community as well as other government and industry organizations. Also for potential PLs, several questionnaires are required to understand an experiment's design and operational requirements. In turn, the experimenter will benefit from pre-defined SIV interfaces and components to help bound their interface designs.

There is the potential for design modifications due to obsolescence of parts and the desire to take advantage of improved technology. The STP-SIV program is monitoring the availability of parts and components and is prepared to change the design if necessary. New SC technology may also be desired at some point in the program. It is understood that any design changes will affect the cost benefit of maintaining the original design.

STP-SIV DESCRIPTION

The basic design drivers for the STP-SIV are derived from an analysis of PLs submitted to the Space Experiment Review Board (SERB) and the desire for

Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adaptor (ESPA) compatibility. A significant number of small PLs that come to the SERB for flight opportunity have a high degree of flexibility in orbit inclination and altitude and typically can be “bundled” into a suite of PLs that a single 180kg class SC can support. By providing small PL designers with a defined interface in which to develop their systems it will make it easier for SDDG mission planners to bundle the various experiments.

Vehicle Objectives

The basic rationale for standardization is the ability to reduce non-recurring cost of subsequent vehicles by performing the majority of the bus engineering and design only once. SDDG shares a fundamental goal with other government organizations to lower costs and increase speed of access to space. SDDG’s approach is to concentrate on achieving lower costs and shorter acquisition schedules for small satellite bus development. The primary program objectives are:

- Develop an agile, repeatable, ESPA-Class space-flight capability for DoD space technology demonstrations with a targeted launch readiness date of 2009.
- Develop a non-proprietary standard PL to SC interface (mechanical, thermal, data and power) for use by all experiments hosted on STP-SIV.
- Develop flexible capability to launch on a Minotaur-I, Minotaur-IV, other commercial vehicles, or attached to an ESPA.
- Reduce non-recurring costs through the life of the program through the use of a repeatable space-flight capability, a standard PL interface and overall mission costs through launch vehicle flexibility.

Vehicle Capabilities

The STP-SIV design supports the program goal of a low-risk bus by using flight-proven components, a simple structural design, and significant design and software reuse from prior missions. The design balances a low-cost and low-risk approach with significant SC capability and flexibility.

The STP-SIV capabilities support a variety of potential small PLs. The standard capability SC operates over a range of low earth orbit altitudes and inclinations. The SC design as shown in Figure 1 provides the required power over the full range of sun angles. Mission-tailored multi-layer insulation blankets provide the

appropriate radiator coverage for the particular orbit and PL suite. A single star tracker is a key element of the attitude determination and control system. It is mounted directly on the PL interface plate to minimize alignment errors between the bus and PL. Table 1 highlights the threshold requirements and performance goal characteristics for the SC.

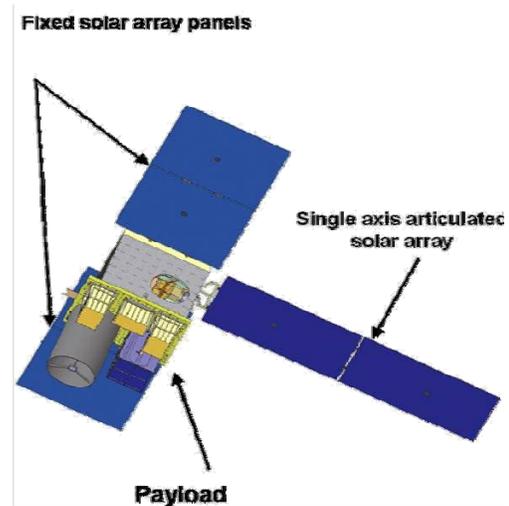


Figure 1: STP-SIV in Deployed State

Table 1: STP-SIV Capabilities

Parameter	Threshold Requirement
Orbit Altitude	400 – 850 km
Orbit Inclination	0 – 98.8°
Launch Mass	≤ 180 kg
Space Vehicle Volume	≤ 60.9 x 71.1 x 96.5 cm
Launch Vehicle Compatibility	Delta IV ESPA, Atlas V ESPA, Minotaur I, Minotaur IV, Pegasus (anticipate compatibility with Falcon 1)
SV Lifetime	1 year
Reliability (at 7 months)	0.90
Stabilization Method	3-axis
Pointing Modes	Nadir, Sun Pointing, Safe
Attitude Knowledge	0.03° 3σ (goal 0.02° 3σ)
Attitude Control	0.1° 3σ (goal 0.03° 3σ)
Bus Voltage	28 V
Communication Frequency	L-Band Uplink, S-Band Downlink
Command Rate	2 kbps uplink
Telemetry Rate	2 Mbps downlink

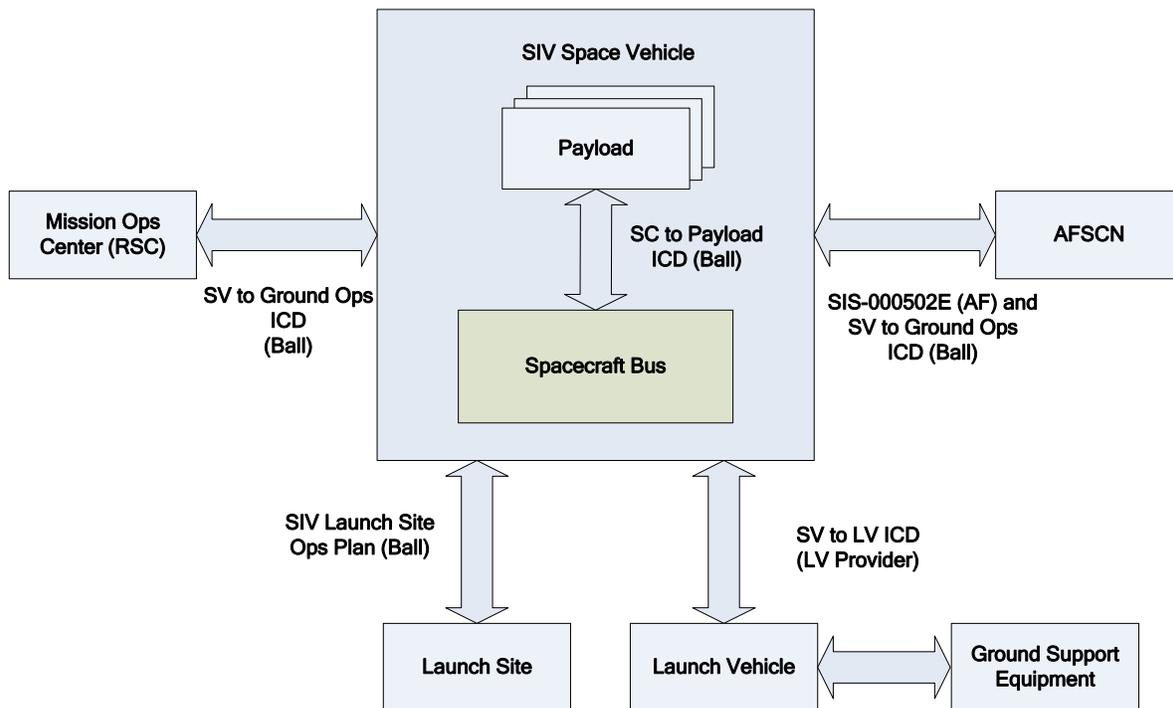


Figure 2. External Interfaces of the STP-SIV Spacecraft

Standard Payload Interfaces

There are many interfaces that STP-SIV must be compliant with as seen in Figure 2. The PL is primarily concerned with the SC to PL interface but many of those requirements are flowed down from SIV's external interfaces.

Spacecraft to Payload Interface

Mechanical Interface

The STP-SIV supports up to 60 kg of total PL mass. PLs mount to the SC using a standard PL mechanical interface (Figure 3 & Figure 4). The PLs mount to the aluminum plate using #10 fasteners to holes on 2.54 cm (1 inch) centers. See Appendix D of the STP-SIV Payload User's Guide for a complete drawing of the PL interface plate (PIP). The PL supplier shall make all mounting points compatible with the standard mounting grid. PL locations on the PIP will be determined by BATC to ensure requirements of each individual PL are satisfied.

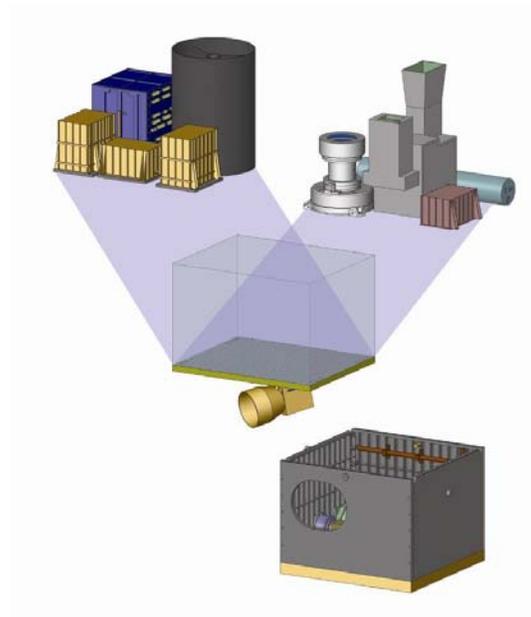


Figure 3: The STP-SIV Spacecraft Bus and Payload Module

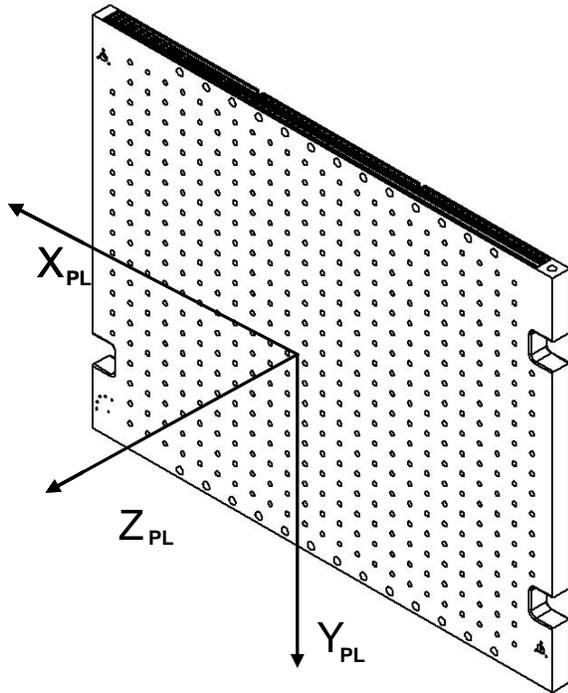


Figure 4: Payload Interface Plate with Payload Coordinates

SIV provides a total PL volume of 0.14 m^3 . The allowable PL envelope in the launch configuration is shown in Figure 5. PLs will be mounted ‘on-top’ of the SC and must fit within this volume for launch. Once the SC is on orbit and deploys the solar arrays, PLs may deploy elements as necessary to perform their missions. All deployed elements shall remain above ($+Z_{PL}$) the PL interface plane.

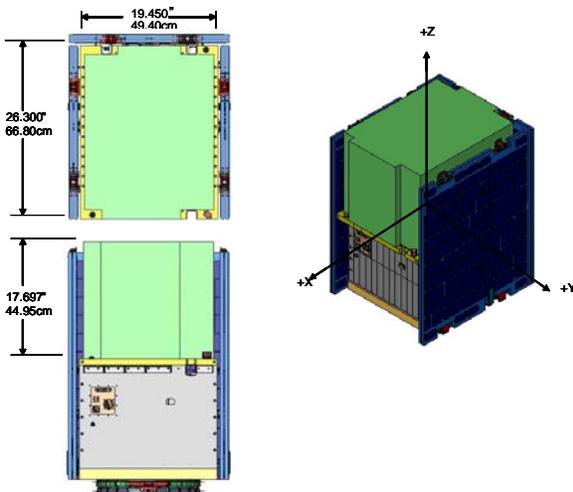


Figure 5: Payload Envelope for Launch Configuration

PLs are provided an unobstructed field of view of 2π steradian, oriented towards the $+Z_{PL}$ (nadir) axis and originating at the PL interface plane. Additionally, the PLs are provided a 2π steradian unobstructed field of view towards the $+X_{PL}$ (velocity direction until seasonal yaw flip), originating 55 cm from the leading edge of the PIP in the $+X_{PL}$ direction. This provides nearly 3π steradians of unobstructed views for PLs as shown in Figure 6.

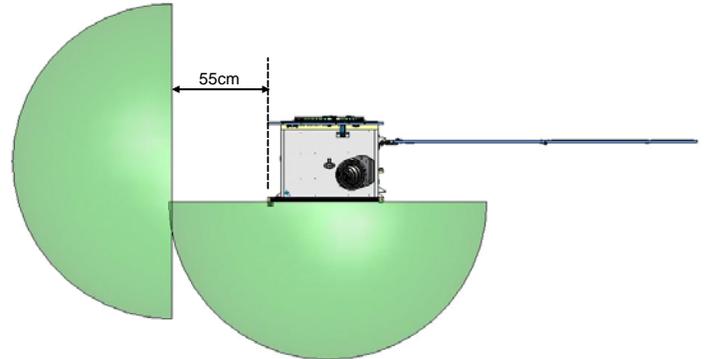


Figure 6: Payload Field of View

Power Interface

During normal mission operations, the SC will provide a minimum 100W orbit average power (OAP) to the PL suite. This power will be allocated between the different PLs on each mission. If the total power draw for all PLs combined exceeds 100W, it may be necessary to duty cycle PL operations in order to reduce the PL suite power consumption to within the capability of the SC.

Each PL is provided three switched power feeds. Each power feed provides unregulated $28 \pm 6 \text{ Vdc}$ from the SC. PLs which have multiple power modes of operation, may wish to divide up the three SC power services among the differing modes. For example, if the PL has a nominal or idle state of operation and occasionally powers up focal plane arrays, the PL may dedicate a single SC power service to that nominal mode and a separate power service to the focal plane electronics.

The SC provides over-current protection on each of the power lines provided to the PL. Each switch providing power to the PL is equipped with a circuit to actively disable the switch if the current exceeds 5.94 amps. After the initial 40 milliseconds from switch turn-on, if

PLs exceed the 5.94 amp limit for greater than 20 microseconds, the fault protection will turn the power switch off, removing power from the PL. The current on these switches is also monitored by the SC software. The software can be configured to remove power if the current exceeds a pre-determined current less than 5.94 amps.

Thermal Interface

The SC monitors the temperature of the PIP using four temperature sensors mounted to the underside ($-Z_{PL}$ side) of the PL interface plate. Each PL will receive the temperature read by these sensors once per second as part of the SC status message. The temperature measurements will also be provided to the ground as part of SC state of health (SOH). The PIP is maintained to temperatures between -9 and $+39^{\circ}$ C.

Data Interface

The SC Integrated Avionics Unit (IAU) functions as the main data and command interface between the PLs. All PL command, data collection, and data storage is via the PL Interface Board (PIB) which resides within the IAU. The PIB provides each PL one data port which consists of a 62 pin high density d-sub (HDD) connector on the PL module. All PL commands and collection of high rate data, real-time data, analogs and discretely is through the single 62 pin Data Port. All PL data (high rate and real-time) is polled and ingested in a "round robin" scheme ensuring that no PL can monopolize the bus. Both the PL high rate and real-time data is time-stamped at the time of receipt.

The PIB ingests PL high rate mission data, encapsulates this data in a Consultative Committee for Space Data Systems (CCSDS) compliant Channel Assess Data Unit (CADU) format and stores the formatted CADU for subsequent transmission to the ground. All high rate data is transferred via either an asynchronous UART EIA-422 link or a synchronous EIA compliant RS-422 link. The choice of synchronous or asynchronous data transfer method is selectable for each PL and is fixed prior to launch. The total high data rate available is 2 Mbps shared amongst all the PLs.

The PIB provides for collection of PL real-time data. One EIA-422 UART is provided on each PL data port. PL real-time data is collected and interleaved into the real-time SC downlink and is also stored on the PIB for retransmit. Each PL's real-time data is limited to 240 bytes/sec.

The PIB provides to each PL data port; 8 analog inputs, 8 discrete inputs, and 8 discrete outputs. The term "input" or "output" used throughout this section is referenced from the SC point of view (i.e. input refers to data from a PL into the SC). The PIB samples the analog and discrete telemetry channels once a second. Analog data is converted to a digital format using a 12 bit A-to-D converter. The PIB interleaves the discrete and analog data into the SC real-time telemetry. The PL real-time serial data is formatted with a CCSDS Path Protocol Data Unit (CP_PDU) header and then transferred to solid state memory for storage and subsequent transmission to the ground. SC data (high rate, real-time, analog, discrete) is identified using an application id (APid) and virtual channel id (VCid). SC real-time data is assigned its own APid and VCid for each data port, while analog and discrete data is included into the SC state of health data and uniquely identified by APid for each data port.

The PIB also functions as the gateway for commands issued to the PLs and delivering SC status message (time, SC ephemeris, SC attitude and PL interface temperature) information to the PLs. Each PL data port is provided one EIA-422 UART command link.

Each PL data port is provided a 1 PPS signal, slaved to the SC master clock. The 1 PPS signal is an EIA-422 compliant differential pulse providing accuracy better than 1 ms. Once a second, SC time (seconds since epoch) is delivered to each PL via the EIA-422 command gateway. Thus the PLs may synchronize to the SC master clock with a high degree of precision.

The PIB provides total mass memory storage of 8 Gbit of EDAC validated memory space. The memory is shared amongst all 4 PLs for high rate, real-time and stored state of health data. The PIB design allows for four software partitioned buffers corresponding to storage of each PL's high rate data. Memory partition size is allocated by flight software (FSW) and sized to fit individual PL's storage needs. Mass memory allocations are assigned to each PL by BATC and may be resized during flight. PL real-time data is also archived and managed by FSW. Archived data is available for retransmission via ground command. PL memory storage is physically arrayed as a circular buffer, for which PLs are responsible for not exceeding their data storage allocation and overwriting previous data. Memory partitions are in place to ensure that even in error conditions such as a PL exceeding their data storage allotment, each PL's data will remain inviolate.

The PIB system block diagram is shown in Figure 7.

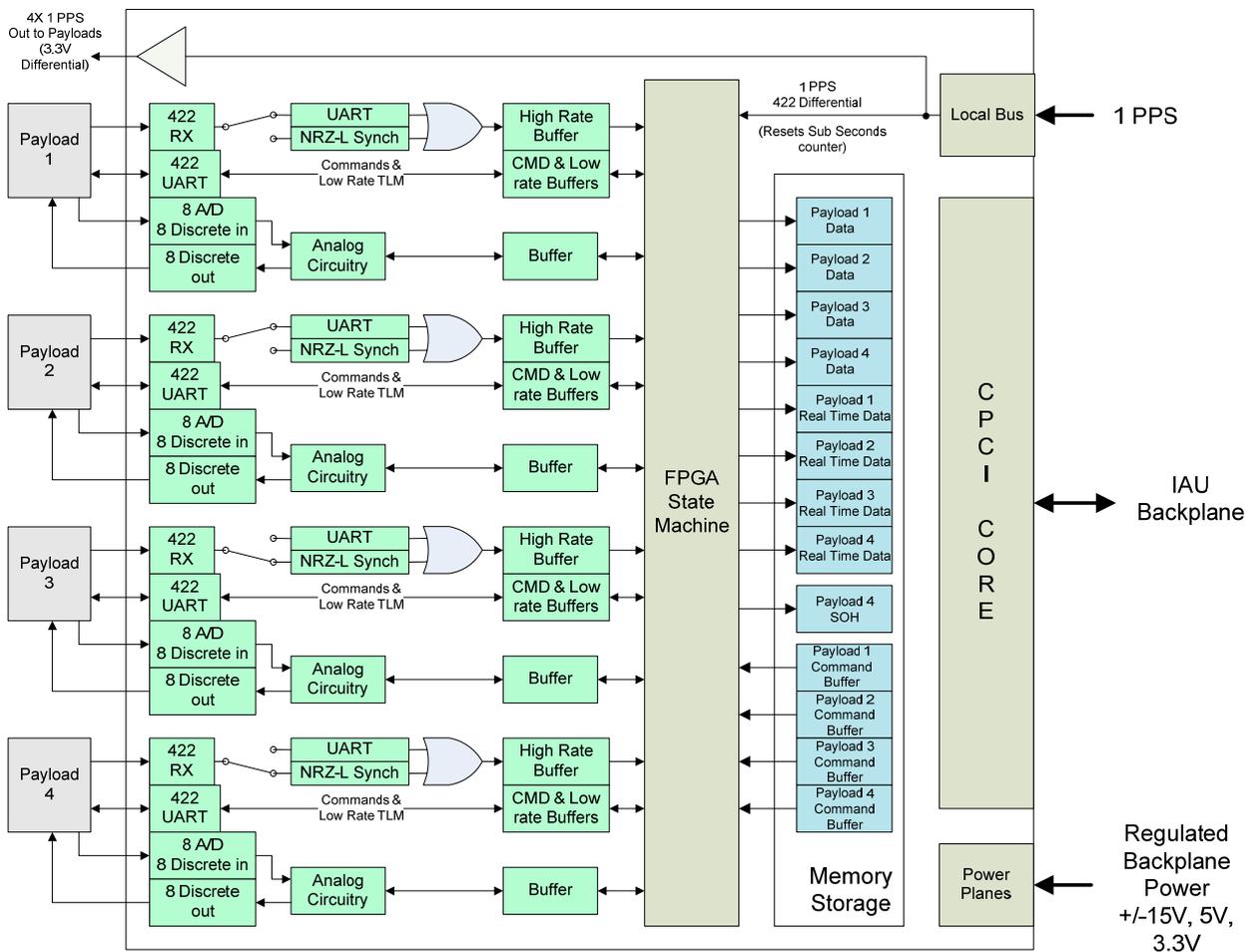


Figure 7: PIB System Block Diagram

Design Environments

The STP-SIV User’s Guide defines the environments the PLs will be exposed to during system level test, launch and on-orbit. These environments include vibration, acoustics, shock, acceleration, radiation, and electromagnetic.

Space Vehicle to Launch Vehicle Interface

STP-SIV is designed to launch a variety of launch vehicles, including Pegasus, Minotaur I, Minotaur IV and the ESPA on either Atlas V or Delta IV. This flexibility maximizes launch manifest opportunities as a secondary PL or as a rideshare partner.

Compatibility with multiple LVs requires the SV be designed to bounding launch environments that envelope all candidate LVs. Although volume and mass were easily bounded, other factors such as a realistic LV shock and EMI environment require thorough analysis.

A minimal set of electrical interfaces have been identified to provide safety monitoring and battery charging of the SC. The SC and PLs will be powered off when mated to the LV until SC separation, keeping the required number of umbilical interfaces at a minimum.

Spacecraft to Ground System Interface

The interface between the STP-SIV and ground operations is also controlled by two documents; an Interface Control Document (ICD) and the Standardized Interface Specification for the Air Force Satellite Control Network (AFSCN), AFSCN SIS-000502C. SIS-000502 defines the types of service provided by the AFSCN and the design requirements for the space vehicle RF system. The ICD describes the specific characteristics employed by the space vehicle RF system to show compliance with these requirements. This includes defining the exact operating frequency, subcarrier frequencies, modulation scheme, etc.

Space Ground Link Sub-System (SGLS) transponder consists of a command/ranging receiver with embedded decryptor and power converter and a telemetry/ranging transmitter with embedded encryptor and power converter. The STP-SIV RF system is based on a single string L3 COM CXS-810C transponder. The transponder provides command reception, telemetry transmission, encryption/decryption, and ranging data turn-around consistent with the Standard Interface Specification between Air Force Control Network Common User Element Comm/Range Segment and Space as described in AF SCN SIS-000502E. The following graphic (Figure 8) provides an overview of the ground system architecture.

Commands and Schedules

Commands are stored on board the SC in one of two schedules. The real-time schedule is an absolute time execution sequence. The script schedule is a relative time execution sequence. The real-time schedule and the script schedule have the same data format and structure. Each is a linked list ordered by scheduled time and priority. Each item in each schedule includes the command header, the data, and the cyclic

redundancy check (CRC). The maximum total length a command on any schedule is 256 bytes.

Real-time Command Processing

When the schedule target field indicates that the command is destined for the real-time schedule, the scheduled time field is compared with the current SC time. If the field's value is less than or equals to the SC time, the command is immediately executed. If the scheduled time is greater than the SC time, the command is placed on the schedule and executed when its scheduled time becomes equal or less than the SC time.

Every second, the real-time schedule is checked for commands that are to be executed. The scheduled time field of the first command on the schedule is compared with the SC time. The command is executed if its scheduled time field is either current or in the past. The scheduled time of the next command on the schedule is then checked and executed if appropriate. This is continued until the command being checked has a scheduled time that is in the future.

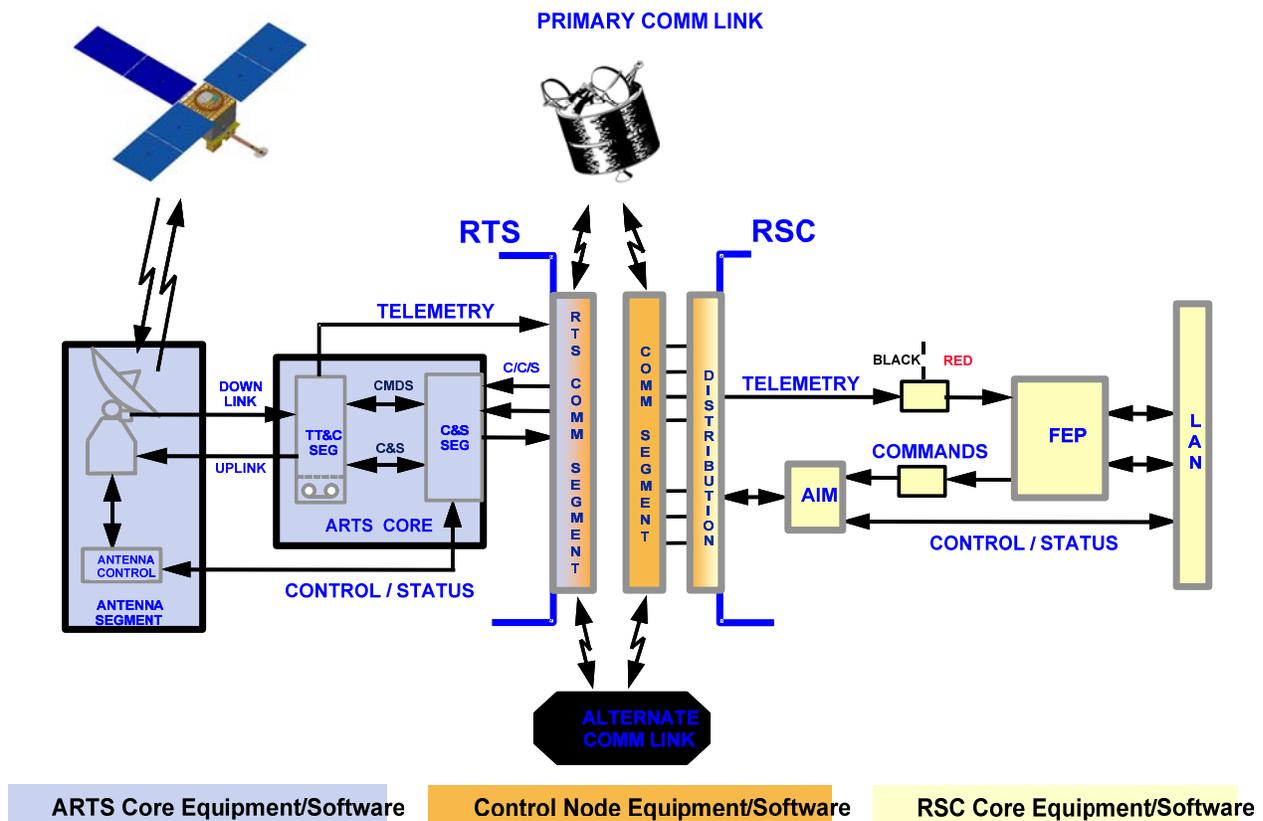


Figure 8: STP-SIV Ground System Interfaces

Script Command Processing

Script schedules have many of the same features as the real-time schedules. They can be manipulated in the same fashion as the real-time schedule. By command, script schedules can be loaded onto the real-time schedule. The script schedule persists after being loaded onto the real-time schedule so that it can be subsequently manipulated, reloaded, etc.

Script schedules have the same structure as the real-time schedule; they are linked lists ordered by scheduled time and priority. When the schedule target field indicates that the command is destined for one of the script schedules, it is placed on the script schedule by inserting it into the linked list.

When the script schedule is to be executed, a command is sent which loads the script schedule onto the real-time schedule. As the script schedule is being loaded, a time offset (either a command parameter or the current SC time) is added to the scheduled time field of the command. Thus the script schedule is a "relative time" schedule that can be used at many different times. Since each command retains the value of the target schedule field when it is loaded onto the real-time schedule, any inadvertently loaded script schedule can be deleted from the real-time schedule.

Interface Control Documentation

Although the STP-SIV Payload User's Guide describes the superset of interface capabilities, BATC and the PL developer must agree to the specifics of how each PL will use the interfaces. This non-ambiguous agreement is documented in the form of interface control document (ICD) and is the single source for interface requirements. The ICD specifies not only the requirement but also the method of requirement verification and provides traceability to supporting verification documentation.

Since PL developers and SDDG will partner to successfully fly DoD experiments, SDDG will suggest PL design changes that both increase the PL probability of mission success and decrease the risk of detrimental effect to the SC or other PLs. It is a balance between PL and SC requirements. However, PL developer must realize in most cases another PL will accompany them into space and both PLs must have the opportunity to

conduct its mission. In addition, developers must be vigilant of elusive effects to such things as outgassing and electromagnetic interference and apply design guidance supplied in the STP-SIV Payload User's Guide.

CONCLUSION

Over the last several decades, there have been many efforts with varying approaches to standardization of SC design. Standard parts and modular architectures have all been applied to SC designs by during previous STP missions. STP-SIV is taking advantage of the lessons learned from that experience and applying them to this program. Flexibility must be planned for from the beginning and missions must be adapted within range of the SC's capability. Development of SC standards requires upfront investment in order to achieve a return on investment once multiple missions have been built and flown. The more PL providers are willing to adopt the STP-SIV interfaces and develop experiments applicable to the capabilities of the SC the more successful this program will become for the SDTW.

Acknowledgements

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