

On Spaceflight Instrument Adaptive Electrical and Electronics Subsystem Functional Framework

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Abstract—Near-earth heritage spaceflight missions and contemporary large observatories such as the NASA Hubble Space Telescope (HST), future James Web Space Telescope (JWST), or planetary fly-by (Cassini with its 12 instruments) and orbiting deep space observatories like the Mars Reconnaissance Orbiter (MRO) have carried large electronics subsystems. The Kepler cosmology observatory 95 mega pixels focal plane servicing electronics comprises some 50 electronic boards. The future cosmology mission Wide Field Infra-Red Survey Telescope (WFIRST with 2 instruments) envisions a focal plane with 18 large 4Kx4K sensors totaling 4.8318e+09 bits also serviced by a multitude of electronic boards. On the other hand, a new class of NASA Earth small satellite missions (SmallSat), the Department of Defense Operationally Responsive Space small satellites (ORS) and planetary surface mission instruments require smaller scale electrical and electronics subsystems. These are challenged with unique external space launch technology requirements for ever-smaller mass and volume, constraints on power and communications bandwidth, in addition to the requirements of space extreme environment of temperature variations and cosmic radiation. Within this wide range of space exploration and earth remote-sensing missions there is a need to revisit these external and internal spaceflight instrument science requirements from the point of view of developing the future spaceflight instrument scalable and adaptive electrical and electronics subsystem (IAEES) conceptual framework. We consider these instrument requirements and conceptual functionality framework on the precedent of the two future Decadal missions – the flagship cosmology observatory WFIRST pre-cursor study and proposal DESTINY [1] and the proposed Mars-2020 mission instrument – the Pulsed Neutron Generator and Gamma Ray Spectrometer (PING). Both proposals are now history with the first materializing as the winning WFIRST [2] and the PING destined to fly on some other than Mars-2020 mission. The purpose of this paper is to delineate the IAEES framework in proposal phase broad enough to be scalable and adaptive for future implementation. Representative top-level requirements - each originating in science definition and the instrument's other subsystems and the spacecraft needs constitute the basis of such a framework. A representative IAEES conceptual framework is elaborated on the precedent of the two future mission instruments' proposals and is analyzed as a reference scalable adaptive IAEES and its simulators.

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1. SPACECRAFT AVIONICS' ARCHITECTURES AND STANDARDS

All spacecraft have much in common, carrying similar subsystems – propulsion, thermal, mechanical, guidance navigation and control (GNC), command and data handling unit (C&DH), mass storage (MSS), communications and power. Because of such commonalities and spacecraft adaptable to external requirements, the spacecraft architectures are presently susceptible to a common framework and standardization.

Considerable effort is underway to standardize spacecraft avionics architectures by the Air Force Research Laboratory Modular Open Network Architecture (MONARCH), Spacecraft Onboard Interface Services (SOIS), Sandia National Laboratories, the Office of the Director of National Intelligence Space Universal Modular Architecture (SUMO), NASA Core Flight Executive (cFE)/Core Flight Software (CFS), SpaceCube, SpaceAGE Bus and ESA. The recent efforts and ideas are described in “Common Avionics Approach SpaceAGE Bus and cFE/CFS, Software and Hardware Component Based Architecture” by Jonathan Wilmot and Glenn Rakow, NASA-GSFC 7-25-12. The approach to standardization of the spacecraft avionic interfaces is summarized in the report “SpaceAGE Bus: New Avionics Building Block Concept” by Alex Kisin, Glenn Rakow, Eric Gorman, NASA Goddard Space Flight Center Flight Data System and Radiation Effects Branch.

2. INSTRUMENT SCALABLE AND ADAPTIVE ELECTRICAL AND ELECTRONICS SUBSYSTEM FRAMEWORK

While spacecraft avionics architecture state-of-the-art is mature and susceptible to standardization, present instruments are very different and the future spaceflight instrument electrical and electronics subsystem architecture candidates' commons are in embryonic state. The goal of this paper is to first delineate a representative framework at instrument proposal phase that would allow its future scalability and adaptability at implementation. There are different views where to begin. Given that the *science problem statement had been formulated*, we begin with top-level requirements for two IAEES in recent instrument proposals – the WFIRST Imager pre-cursor DESTINY proposal and the proposal for the Mars-2020 or other planetary mission instrument called PING. This is followed by *nominal and bottleneck operational concepts, life of a measurement exposure and its timing diagram slice and the IAEES framework in two styles – textual and picture-oriented* with various levels of detail and abstraction. These constitute the elements of a proposal EE subsystem framework, allowing for its future implementation scalability and adaptability.

In this paper we are interested in a similar to spacecraft avionics standardization approach, but for the on-board instrument electrical and electronic subsystem. Here the variety of architectures and components far supersedes those of spacecraft avionic and we are compelled to delineate instrument IAEES common requirements and conceptual functionality first:

- *The PING instrument science problem to solve* is to facilitate Mars-2020 mission samples identification and selection for a future sample retrieval mission. This is done by using a neutron pulse generator (NPG) illuminating the marcian soil and return of a resulting Gamma Ray signal measured by the Gamma Ray Detector (GRD). The GRD together with on-board processing constitutes the Gamma Ray Spectrometer (GRS) that identifies the soil and its surrounding material's composition. PING is to fit into Curiosity's Rover DAN [4] instrument volumes on Mars-2020 Rover with comparable mass, power and cost.
- We must begin with top-level science requirements while external space extreme requirements are well known. Here we begin with the PING science top-level requirements (Table 1) followed by
- The instrument operational concept and
- Measurement exposure time diagram of a scientific phenomenon of interest. We define the PING Life Cycle of an Exposure in its few, but different modes of operation, from the IAEES point of view (Figure 1).

Table 1. PING external & science top-level instrument requirements – Compliance (C, Y-Yes, N-No) by Verification (V) at concept level by computer Model (M)

Req ID & name	Requirement Text	C	V
1 Read-Out Electronics Circuitry (ROIC)	The EE shall be able to ingest row science measurements from 1 Channel GRD at channel rate of 30K to 50K <i>asynchronous</i> events and digitize to 12 bits outputting a maximum of 600Kbs in science active mode of operations for 15-min exposures and science passive mode of operations for a 150-min exposure; It should be able to ingest signal at 1Mhz in diagnostic mode;		M
2 Processing	On-board instrument data system data processing using bounded histogramming to 2048 energy bins each being a 16-bit wide counter. 64 Histograms in science active mode of operations making GRD a – Gammas Ray energy spectrometer. (GRS) On-board processing of diagnostic mode of operations producing event-by-event 20-bit events vector for a 5-minute exposure. M2020 Preliminary Instrument Standard Electrical JPL D-79821 Rev. – And Software Interface Specification September 18, 2013	Y	M
3 Performance	EE Subsystem Components Survival $T_1 = -45^{\circ}\text{C}$ to $+65^{\circ}\text{C}$	Y	M
4 Performance	EE Subsystem components operation at temperature range $T_2 = -40^{\circ}\text{C}$ to $+60^{\circ}\text{C}$	Y	M
5 Platform	Provide platform for the PING instrument algorithms firmware implementation for all 6 applications	Y	M
6 Power	Provide instrument power distribution and switching	Y	M
7 ICD	Comply with AO and PIP for volume	Y	M
8 ICD	Comply with AO and PIP for mass	Y	M
9 ICD	Comply with Sept. 15 2013 AO and Sept. 18 2013 PIP, and Preliminary Instrument Standard Electrical JPL D-79821 Rev. and Software Interface Specification September 18, 2013	Y	M
10 Reliability	IC&DH Box-Level firmware redundancy	Y	M
11 Interface to Robot	Effective interface speed of 0.8Mbps over an 8Mbps interface channel being pulled for 0.1 sec each second.	Y	M

3. INSTRUMENT SCIENCE MODE OF OPERATIONS AND OPERATIONAL CONCEPT

The empirical base of science consists of measurements by the science instrument detector subsystem. The science top-level requirements can be also visualized through the required detector system modes of operations. For each of the detector system mode of operations there is a need for a 1-page timing diagram. All operational modes timing diagrams can still fit on 1-page diagram. For example, for PING there are 3 major modes of operations, including the *nominal* and *bottleneck* cases:

- Science Active Mode of Operations (SAMO) using the PNG with 3 to 15 minutes exposures over a total of 2h per Mars' solar day (sol) is the *nominal mode of operations*

- Science Passive Mode (SPMO) using the Cosmic Ray Background and rover RTG as neutron stimulus; an exposure is 1h exposure and a single 2048-bin histogram of 16-bit energy level counts
- Science Diagnostic Mode (SDMO) comprises the NPG pulsed with 100-microsecond pulses at 10KHz and sampling during each pulse 100 times for 5 minutes. Each measurement is stored as a 20-bit event comprised of the 12-bit measurement and 8-bit time tag. This is the *bottleneck mode of operations*.

The detector system mode of operations is at the heart of science and engineering implementation. However, it appears that the definition of the modes of operation is difficult for the science team at proposal time and it remains implied till later times of design, when it already becomes an engineering implementation problem. Extracting the modes of operation information from the science team is an arduous task.

We will concentrate here on the *science active mode of operations* when the PING stimulus comprises a 100 μ s duration pulse fired at 10KHz. The EE Subsystem ADC is digitizing the analog signal asynchronously governed by the pulse shape discriminator output TTL pulse with some 30Kss to 50Kss measurements expected by science. These are distributed into 64 histograms each 2048 bins wide with each bin implemented as a 16-bit counter. This allows to store maximum 64 x 2048 x 16 science events per science mode of operations exposure or 2^{21} science events per $3 \times 60 = 180$ seconds = 2^6 seconds. $2^{21} / 2^6 = 215$ and a 16-bit counter will work. 2^{15} is approximately equal to $2^{10} \times 2^5$ or 32000 science mode measurement events per second or samples per second that is less than 50Kss. The Timing Diagram within an exposure may be a periodic function, like for PING with a period of a stimulus pulse P. The Timing Diagram shall depict one such period P within an exposure.

3.1 Life of an exposure and timing diagram for the science nominal active mode of operations

An observation, a space-time dependent measurement of phenomena of scientific interest ω , originates in the mind of a scientist and measured signal digital representation end on the scientist desk for analysis. The time dependent measurement ω comprises a specified by a scientist time interval τ during which the measurement(s) of the signal ω is conducted by detector(s). Detector can be passive or active. Passive detector is just “listening”. Active detector, like radar, is probing and then listening to return signal of interest. Another example is a detector system that illuminates target with high-energy neutrons and “listens” to return gamma rays response ω . In active detectors the time of the activation beginning t_0 is the beginning of the exposure interval τ .

In any case, we have $\{\omega, t_0, \tau\}$ parameters and we are interested in a diagram depicting what happens within the time interval $[t_0, t_0 + \tau]$ when the measurement sequence within an exposure is complete.

The measurement sequence within τ can be elementary –

the signal is accumulated (integrated) and a single measurement is performed at τ end or at $t_0 + \tau$.

In a more complex case as is with the measurements of PING induced gamma rays, the measurement sequence is *structured*. Namely, many measurements are conducted in a predetermined time sequence within an exposure τ .

The Timing Diagram depicts, in its 1st part the *measurement sequence* within an exposure $[t_0, t_0 + \tau]$. For example, in PING science requested 64 histograms that are built up from 64 measurements at times $t_1, t_2, t_3, t_4 \dots t_{64}$, digitized by the Analog-to-Digital Converter (ADC) and digital data read-in by the Field Programmable Gate Array (FPGA) for the on-board “histogramming” application. The durations of each histogram time interval are $\delta_1, \delta_2, \delta_3, \delta_4 \dots \delta_{64}$. Note, that since the histograms are generated sequentially in time we may need some on-board Random Access memory (RAM) only for one Histogram on FPGA Card 1 before switching to a its buffer, while this time point histogram is downloaded to the FPGA Card 2 card larger memory.

For the PING proposal the time diagram just included the Timing Diagram Slice of 4 Histograms, as an example. This Diagram is augmented with 4 parameters $\delta_1=D_1, \delta_2=D_2, \delta_3=D_3, \delta_4=D_4$.

At the end of the exposure the resulting digital data frame is transferred to the spacecraft. This frame is then downlinked to the Ground Station with its final destination to the instrument science team. This completes the life cycle of an exposure for remote sensing. The timing diagram can also be developed as text, explaining what is going on or as a graph.

If the science team does not provide the time sequence we can hypothesize our own sequence $t_1, t_2, t_3, t_4 \dots t_{64}$ point in time and complete the timing diagram using the Slice as a guiding example.

The timing diagram importance is paramount since it guides the evaluation of needed resources and design of the EE Subsystem. If not completed some surprises may remain hidden in the entire instrument resulting in schedule and cost overruns.

In conclusion, the timing diagrams is not much different from our daily routine of events we follow – {wake up at 5 AM, shave, brush, coffee, carpool, meeting1, meeting2, meeting3, meeting4...meeting #k, report at 5 PM} – a 12-hour exposure. It is similar to a Thermal Test profile diagram. The Timing Diagram depicts a controlled science measurement concept.

3.1.1—Structure of PING Science Mode of Operations Exposure and Timing Diagram

The exposure comprises a sequence of PNG structured timed pulses (P) each 1ms long or 1KHz pulses. Within a 3-min exposure there are $n=3 \times 60 \times 1\text{KHz} = 180\text{KGz}$ pulses P_i where $1 \leq i \leq n$

$$[P_1 P_2 P_3 \dots P_i \dots P_n]$$

Within each pulse P_i there is a period of the exposure timing diagram depicting the 64 histograms timing sequence $t_1, t_2,$

$t_3, t_4 \dots t_{64}$ in relation to exposure each pulse P_i beginning t_0 . An example of a time diagram slice is presented below in Figure 1 for the PING instrument.

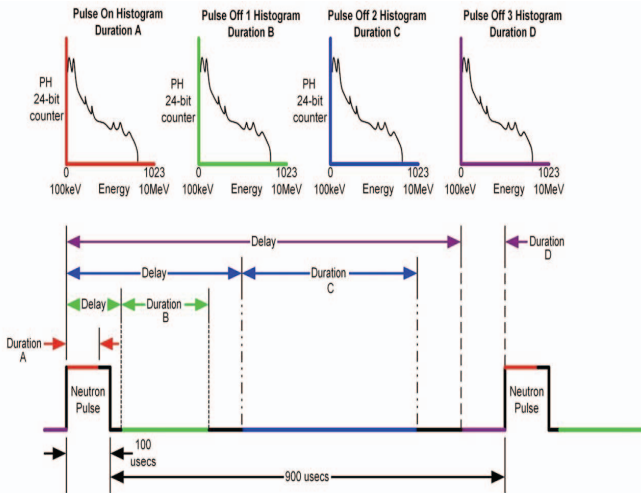


Figure 1. Timing Diagram Slice

4. WFIRST PRECURSOR DESTINY STUDY ELECTRICAL AND ELECTRONICS EXTERNAL AND SCIENCE REQUIREMENTS

The WFIRST pre-cursor was the Joint Dark Energy Mission (JDEM) charged with making precise measurements of expansion rate of the universe to reveal vital clues about the nature of dark energy - a hypothetical form of energy that permeates all of space and tends to increase the rate of expansion. One of three JDEM concept studies - the Dark Energy Space Telescope (DESTINY) was conducted in 2008 at the NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

DESTINY's electronics are primarily tasked with the readout and control of two large arrays of large format detector assemblies in two focal planes and with pointing the boresight precisely and repeatably. These two focal planes, one for science and one for precision guiding, are passively-cooled and maintained at two different temperatures but share common optical and structural paths. The science array is sampled multiple times within an exposure. The electronics feature a fast readout and onboard processing using large external memories, followed by data compression, formatting and interface to the spacecraft solid-state recorder, C&DH and PDU.

For the Destiny Electrical and Electronics (EE) Subsystem the principal challenge is the large number of science detector elements ($32 \text{ } 2\text{K} \times 2\text{K}$ sensors or $1.28 \cdot 10^8$ pixels) and the short time in which these elements must be read out on multiple 100 kHz channels and have their data processed and stored ($\ll 10^2 \text{ s}$). The fine guidance detector elements (8×8) $1\text{K} \times 2\text{K}$ sensors or $3.2 \cdot 10^7$ pixels) must be read out at 2 Hz ($6.4 \cdot 10^7$ pixels per second). These correspondingly require digitization at 16 bits and 12 bits, resulting in order of magnitude larger volumes of digital data bits to ingest and process science data and to store

exposure frames. The fast processing of such large volumes (1.6 Gbs science and or 0.768 Gbs fine guidance data for 12-bit digitization and 1.09 Gbs for 14-bit digitization) of data using advanced algorithms (based on the up-the-ramp algorithm by Offenberger, Fixsen and Mather) is at the core of this challenge.

The solution to the Destiny requirements is both technically and fiscally feasible. The Destiny EE Subsystem does not require new inventions prior to the design phase. It leverages the HST, JWST and Spitzer EE technologies and heritage in Science Sensors, FGS Sensors, ASICs and ROICs, onboard data processing by using reconfigurable computing (RC) Network and Instrument Sensor Web (ISW) topologies, Fine Thermal Control Sensors, interfaces – such as Spacewire, High-Speed LVDS, Harness radiation protection and large 3 GB SDRAM.

The science focal plane's large array of $8\text{K} \times 16\text{K}$ or 128M pixel elements are of a proven technology with readout electronics. The science sensors are controlled individually by high-performance small ASICs grouped into packages. Each ASIC package multiplexes digital signals into four powerful processing cores with built-in full redundancy. The FPGA-DSP based cores ingest the ASIC data by a switchable mixed electronics card which conditions the data and prepares it for ingesting by the primary digital card of each processing core. The digital card comprises four FPGAs running the pre-processing and processing functions in firmware. The output of a processing core's digital card is a sequence of packetized sensor frames comprising an operational mode exposure. The processing cores are internally interconnected by Spacewire network interfaces. These packets are networked over Spacewire interfaces to the Instrument Command and Data Handling Unit (ICDH) for compression and CCSDS packets formats encapsulation and forwarded to the Spacecraft SSR over high speed LVDS and Spacewire interfaces. The ASIC/ROICs selection and configuration architecture addresses the signal/noise readout requirements. The instrument flight firmware of FPGA-DSP based RC Cores (nodes) addresses the volumes, rates and computational complexity requirements. The RC hardware compression modules card architecture (assisted by RAD750 and the instrument flight software in the ICDH) implements the required throughput requirements to the spacecraft SSR.

4.1 DESTINY space environment and science top-level requirements

Weak Lensing (WL), Baryon Acoustic Oscillations (BAO) and Supernova Type Ia (SN Ia) measurements are the known techniques to probe dark matter and energy. The JDEM DESTINY Near Infrared Instrument employs two of these three techniques. Although many JDEM requirements are still in the processes of change, evolution and refinement, some are known and mature at this time and sufficient to develop the EE subsystem concept and architecture. Among these are: Probe of Faint SN Ia Sources in Near Infrared Band, requiring long exposures, but also integrating noise

- Probe for Weak Lensing
- Precise Pointing and distant-in-time Re- Pointing within a few milli-arc seconds
- Fine Guidance System (FGS) – precise pointing and re-pointing at more than 3000 SN. HST has more stringent pointing requirements, but fewer targets
- FGS Sensors readout by the EE subsystem and on-board processing within the EE subsystem or Spacecraft Attitude Control System (ACS) or both
- EE subsystem Signal and Data Processing on an FGS Control Pulse at Pointing-for-Exposure Completion
- Large Science Focal Plane and Sensor/ASIC Mosaic Fast Readout Control - Use of SIDECAR ASIC [3] in Focal Plane Electronics (FPE) (cold electronics)
- Reduce on-board stored data volume for constrained downlink channels - SUTR real-time data processing resulting in compression larger than 150:1 ratio, followed by Lossless Data compression in ICDH at 2:1 ratio
- Reduce on-board Sensor/Readout noise and reject cosmic rays affects and saturated pixels SUTR processing in Image Frame Processors within the Off-Focal Plane Electronics in the EE subsystem (warm electronics) while Cosmic Ray Rejection is an Integral Part of Noise Reduction in SUTR processing
- Science Sensor Readout on maximum number of channels (32 channels) to reduce frame clock- out, rate and reduce readout noise to 6e
- Maintain Focal Plane and cold electronics at stable cryogenic temperatures; Active thermal control electronics by ICDH; Appropriate harness materials to minimize parasitic heat loads
- Detectors cutoff is at $\sim 1.7 \mu\text{m}$. This allows the detector to operate at relatively warm temperatures ($\sim -120^\circ\text{C}$) with acceptable dark current. This simplifies the instrument by allowing the use of thermoelectric cooling systems instead of the heritage cryogenics or mechanical cryogenics coolers that are typical in other NIR instruments and thermal control by the EE subsystem ICDH
- Operate reliably at the Lagrange 2 Point (L2) environment for three years. Thorough modeling of L2 radiation environment. Use of proven radiation hardened Electrical, Electronic, and Electromechanical (EEE) parts. Use of radiation mitigation schemes (spot shielding, redundancy, etc.) where necessary
- High performance on-board data processing. FPGA-based hardware processing in multiple Image Frame Processors. HyperX Experiment on MISSE-7, carrying super-computing hardware. Proven RAD750 general-purpose processor in ICDH. Dedicated image compression ASICs in ICDH at 2:1 ratio and data formatting for storage in SSR
- Warm electronics boxes are housed in spacecraft bay. Ambient temperature for warm boxes
- The FGS carries its own star catalog of some 3000 stars, each described by 5 double-precision floating-point

numbers and requiring 120,000 bytes of memory, upgradeable from the ground.

- All on-board processing within the EE subsystem is synchronized with an FGS Timing Control Pulse of Completion of Precise Pointing for an observation exposure. If FGS is part of the SC ACS there must be a timing control pulse interface from SC to the EE Subsystem.
- SUTR boards carry large Synchronous Dynamic Random Access Memories (SDRAM). A few Giga bytes of SDRAM and its management is required to support SUTR boards
- There must be an option for real-time downlink. Critical science and calibration raw telemetry subset storage or bypassing SSR, for real-time downlink
- For a single string design the SC SSR, FPGAs, ICDH Processor and External SDRAM memories must be radiation hardened. Radhard SDRAM-based boards. With 5 1.85Gbs modules per board the SSR is populated with some 100 boards and weighing more than 50 kg.

Three Processing Cores, similar to the science focal plane, handle the Guidance Focal Plane sensors' full frame readouts. Ground testbeds will be used for design rapid prototyping and interface validation, system-level performance demonstration and integration and test procedures development. The EE Subsystem also interfaces to the instrument mechanisms control electronics by passing to it the conditioned spacecraft power and for commands and telemetry over a 1553 Bus. It also collects the instrument housekeeping signals and data, and provides thermal control of the focal planes. The flow of analog signal and digital data is organized in packets identifying the data source, the frame boundaries, the frame unit of information – line beginning and end codes for analog signals and heritage packet encapsulation for digital data. The EE Subsystem concept was developed to the DESTINY Program requirements. The ten top-level requirements for the EE Subsystem were presented above. The EE Subsystem architecture is presented in the following Figure 2 and Figure 3. It depicts the EE Subsystem Architecture; EE Subsystem Boards (primary and redundant) and Boxes' Size, Mass, Power, Data Volumes, Rates and Boxes' Placement. The total mass (53.4 kg) and the power (192 W) taking into account the 30% contingency margin on board levels. Masses of the focal planes and focal plane electronics were not included, but estimated as 4.0 kg per focal plane. The DESTINY EE subsystem was then characterized by its most critical components – its data flow of large and fast data streams. It didn't contain any pictures and a well-placed metaphor is worth many pictures. When the Figure 2 was analyzed by the Aerospace Corporation it was found the most representative of the EE subsystem descriptions in the proposal process. The top-level requirements must be understood and the technology to meet them must be asserted in text or pictures allowing for implementation flexibility. References 1-3 provide the instrument science problem definition and mission requirements evolution.

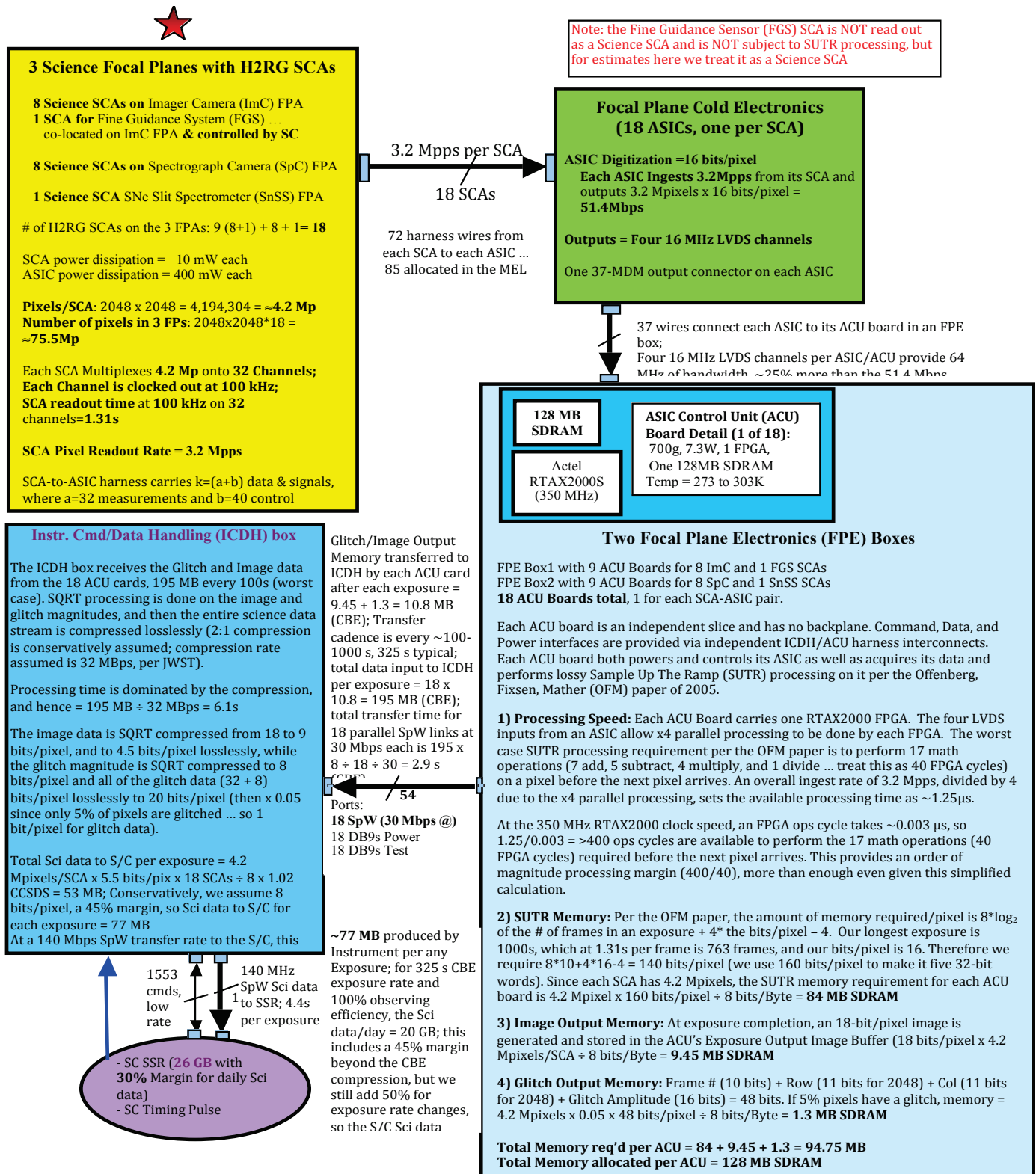


Figure 2. DESTINY Signal flow for 18 parallel signal-processing chains

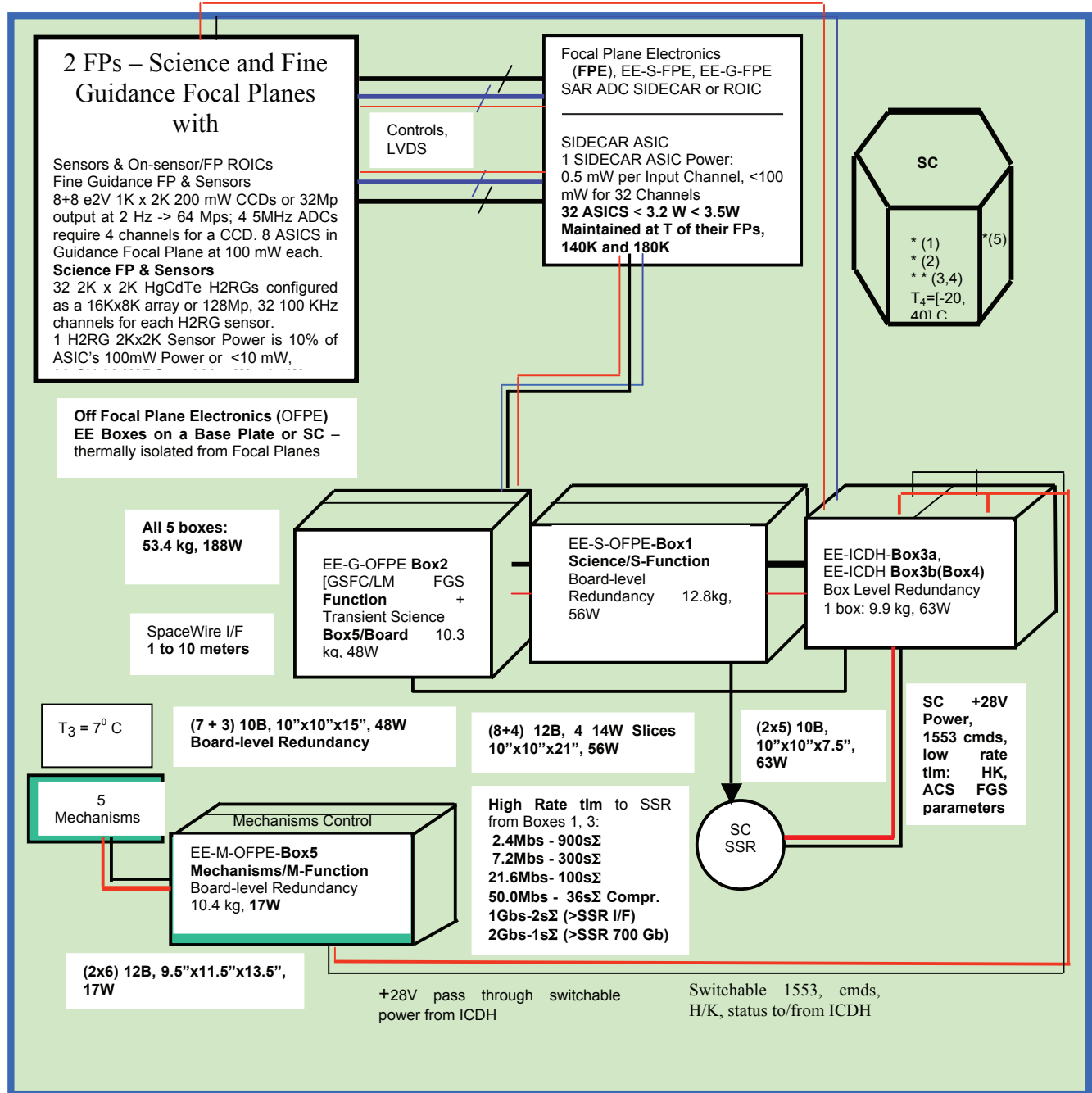


Figure 3. EE Subsystem Architecture; EE Boxes' Size, Mass, Power, Placement

5. PING EE SUBSYSTEM FRAMEWORK

The PING EE subsystem framework is structured differently from DESTINY – by describing the functionality of its core cards while for DESTINY we provided its EE subsystem framework by the way of the critical data flow diagram. Table 2 provides the PING data volumes and effective data rates specific to Mars rover computational elements polling each of the prospective 10 instruments each second for a time window of *0.1 seconds* for each instrument to respond to the polling command by a data transmission and for a total of *100Mb per sol*. This results in effective transmission rate equal to selected interface divided by 10 or 0.8Mbs. In a proposal one of the main component is cost based on instrument size, volume, mass and power, as well as data volume and rates. As much as abstraction is allowed in proposal phase, these must be categorized in order to arrive at cost using cost models. This is why we provided preliminary parameters in the figures.

PING Front End Electronics Card (GRD I/F)

The Front End Electronics (FEE) card performs the following functions:

- Receives science data inputs from the Gamma Ray Detector
- Creates event triggers for the Science Data Acquisition Card
- Amplifies and converts electrical pulses from the PMT to digitized amplitude data
- Sets the thresholds for event detection under control from Science Data Storage Card
- Creates test pulses for injection into the signal chain, under amplitude control from Science Data Storage Card and timing control from Science Data Acquisition Card.

PING Data Storage Card

In the event of an inadvertent application of high voltage during ground testing, there is a protection network at the input to the PMT signal preamp. This is followed by the preamp itself, whose output is an analog voltage pulse. The pulse goes through a shaping amplifier, resulting in a higher signal to noise ratio and a signal $v(t)$ with characteristics that are suited to the ability of discriminators, a peak detector, and track-and-hold circuit to process the signal. The circuits for these are identical in form to such circuitry as was used in the Low Energy Matrix Telescope (LEMT), still functioning on board the WIND spacecraft, which was launched in 1994. Digitizes housekeeping data and sends it to Science. The shaped pulse creates a trigger for the FPGA when its amplitude exceeds a Lower Level Discriminator threshold. If the amplitude also exceeds an Upper Level Discriminator threshold, that information is used by the FPGA to reject the event. Thresholds are set by DACs, which are controlled by FPGA #2. These can be the same DAC devices, which were flown in the GLAS instrument (ICESAT1). A peak detector comprised of a constant fraction discriminator, also used in the LEMT, establishes timing for the track-and-hold to capture the peak amplitude

of the shaped pulse, as well as timing for the start of digitization by the ADC. Once digitization is complete, the ADC sends an End of Conversion signal to FPGA #1 and waits for the FPGA to collect the data.

A Test Pulse Generator is included whose level and timing are controlled by the FPGAs and DAC. This is useful for performing aliveness checks and testing that the discriminator thresholds are providing the desired event acceptance or rejection. Housekeeping data (temperatures, voltage, and current monitors) are multiplexed into a separate ADC. The analog multiplexer and ADC are controlled and read out by FPGA #1. The circuitry for this has ubiquitous heritage, Mercury Laser Altimeter (MESSENGER) and Lunar Orbiting Laser Altimeter (LRO) are two examples.

Digital Electronics Boards (Science and Housekeeping Data Acquisition and Storage) CCA's #1 and #2

The CCA1 and CCA2 perform the following functions

- Time stamping. The analog signal $v(t)$, resulting from a GRD event, is digitized by the Front-End-Electronics (FEE) card at 12-bit resolution, and up to 1 MSPS (mega samples-per-second) in diagnostic mode. In science mode, this rate can be reduced to 200 kSPS (kilo samples-per-second). Samples are only generated upon triggering from the FEE, which instructs the FPGA to activate the analog to digital converter (ADC) to acquire the amplitude of $v(t)$ for histogramming. The 12-bit digital value is transferred from the FEE to FPGA Card 1. A 2048-bin histogram is generated using the 11 most significant bits of the 12-bit word as an address into the histogram computation memory. The data at this address is read into a 16-bit register, where it is incremented by 1. The incremented data is then written back to the same address, before a new ADC sample is acquired, and the entire process is repeated over again. The histogram generated resides primarily in this histogram computation RAM, until an integration time is completed. Afterwards, the entire histogram is read from the memory and sent to the second FPGA card via FPGA-to-FPGA digital interface, and stored in science data storage memory with other histograms. Science data is then downloaded to the rover upon command over a redundant RS-422 interface. The PING architecture is depicted in the following Figures 4-6 and its principal components are as follows:

CCA #1

Receives GRS event trigger

Acquires A/D samples

Computes histograms of the A/D samples for –

a) science active mode,

b) science passive mode and

c) diagnostic mode of 1MHz event-by-event operations

GRD and NPG pulse and power control interface Test Pulse Generator control

CCA #2

Science data storage

Housekeeping data acquisition and storage

Rover C&DH interface

Power supply control

1 PPS (1 pulse per second from Rover).

PING EE Subsystem Architecture

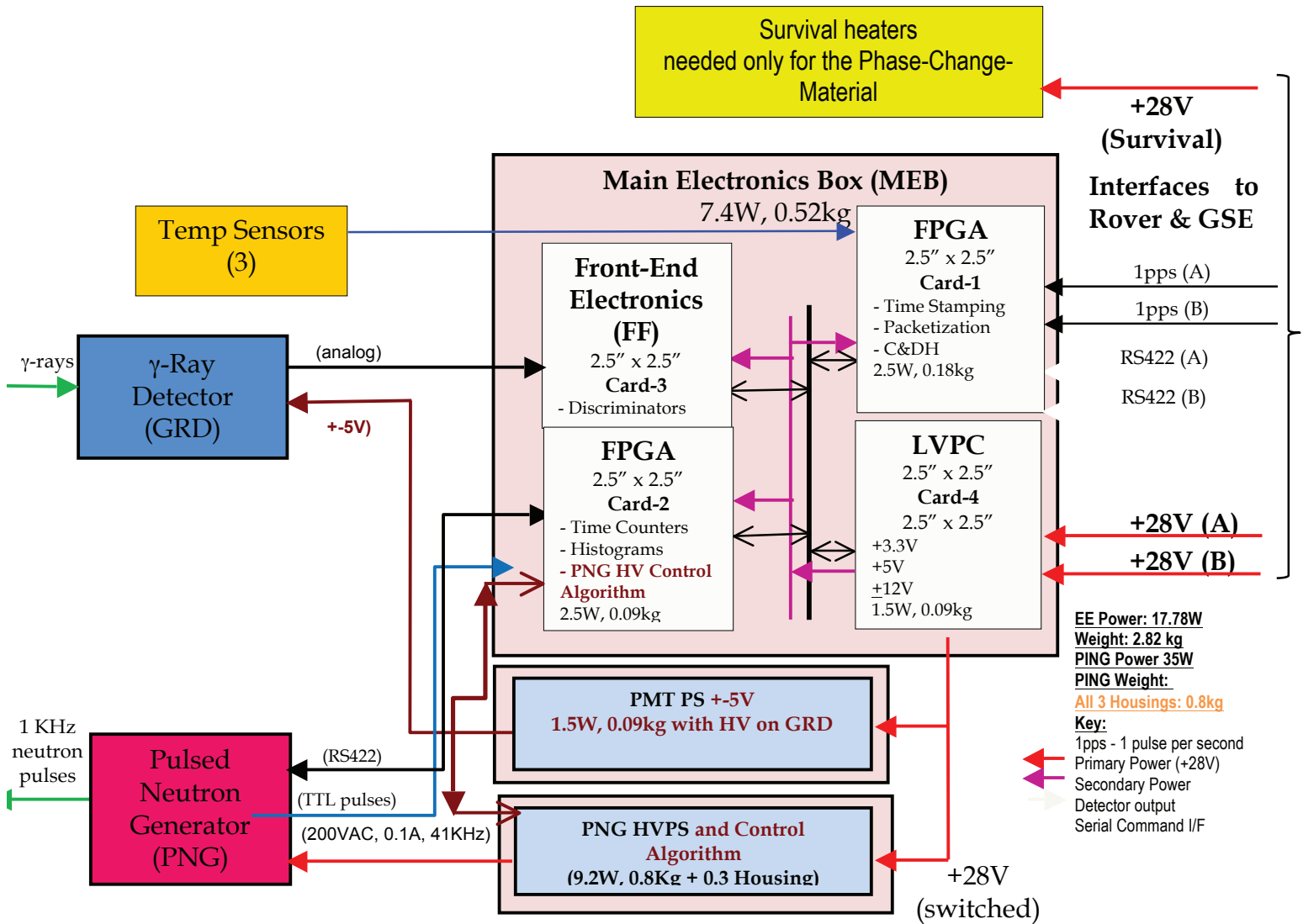


Figure 4. Ping EE Subsystem Conceptual Block Diagram

PING EE Subsystem Simulators

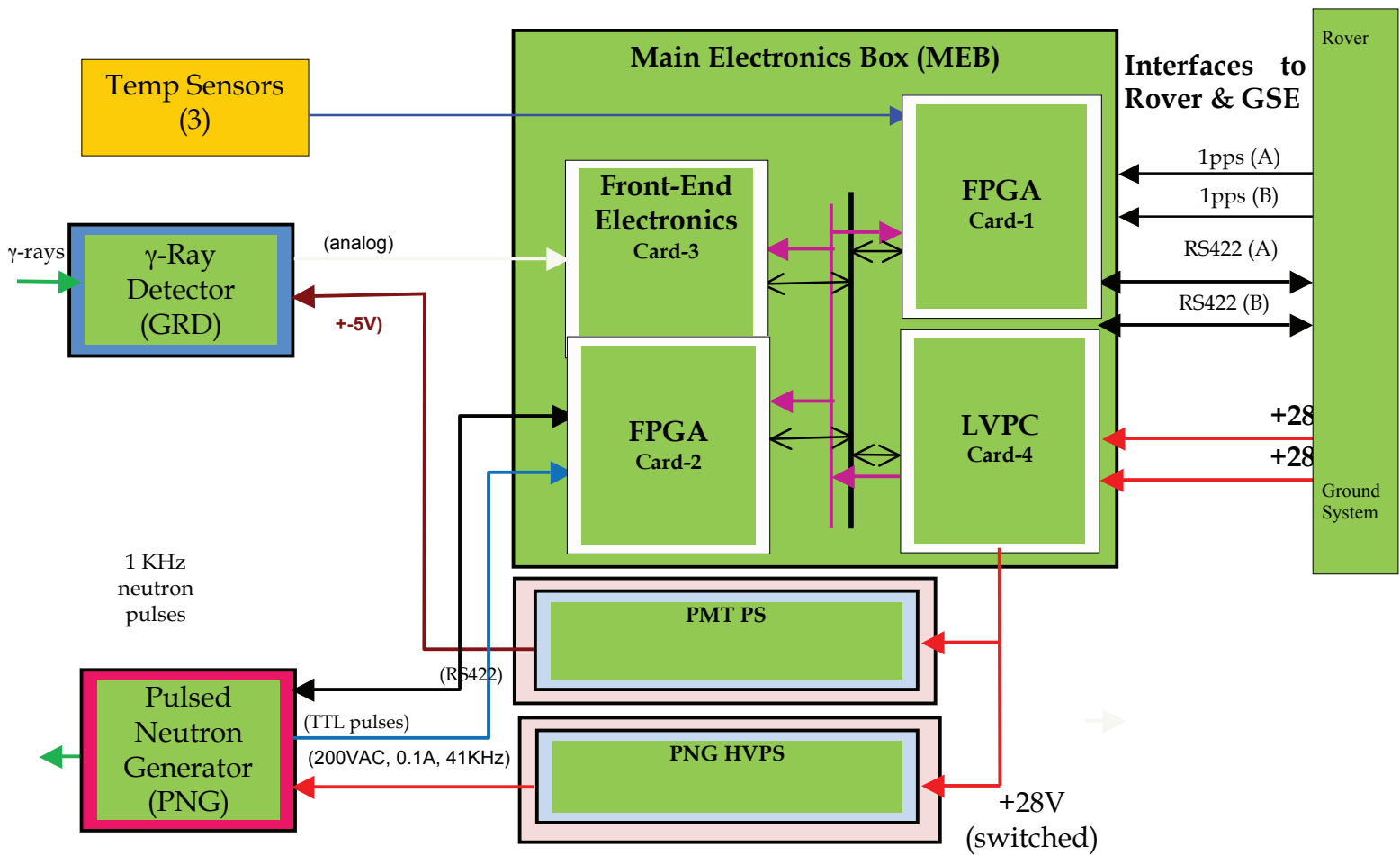


Figure 5. Six Simulators (in green) – Main Electronics Box (MEB), GRD, NPG, Rover, Ground System and High voltage power supplies.

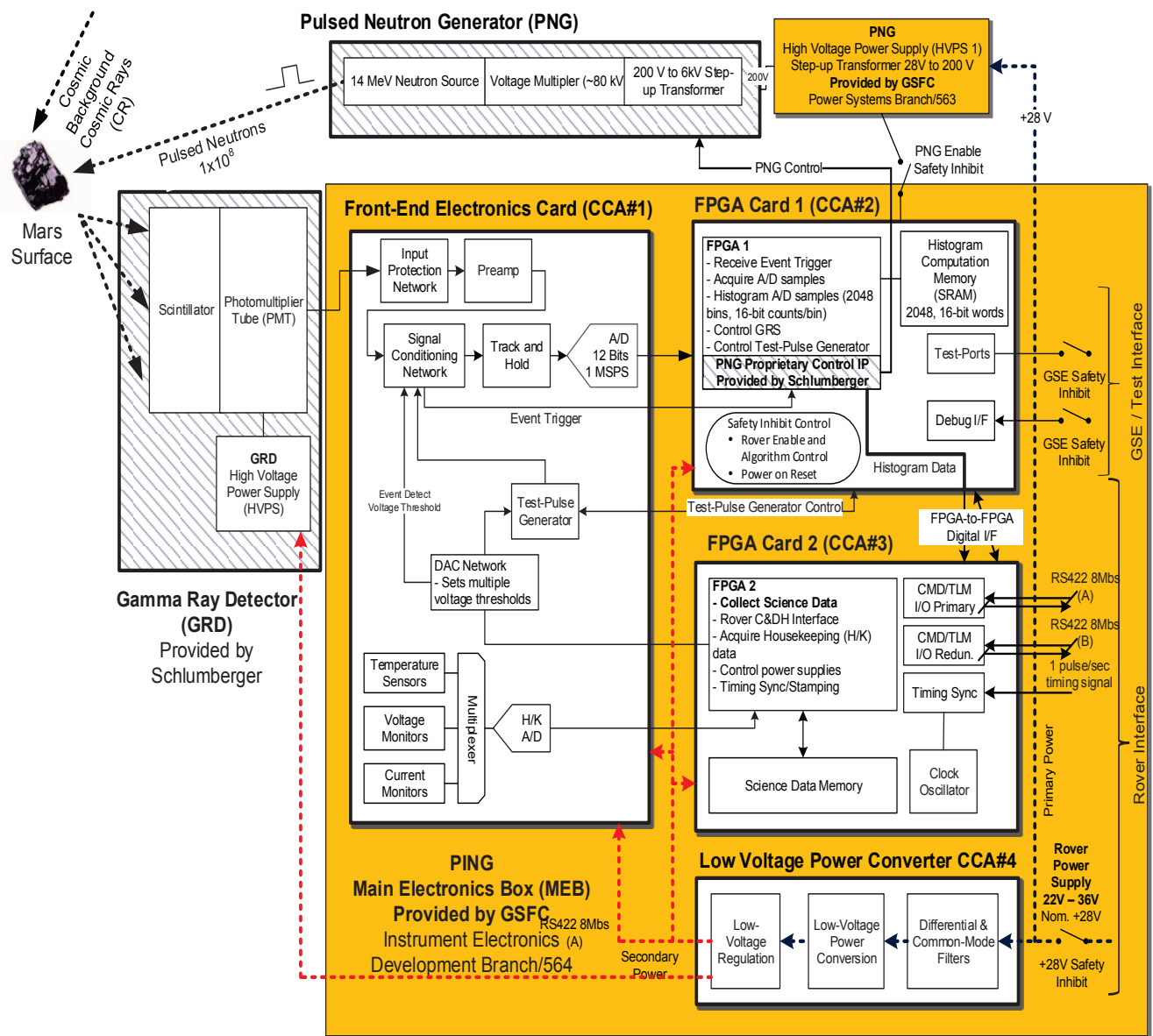


Figure 6. PING EE subsystem block diagram

Table 2. PING Data Volumes and Data Rates by Mode of Operations – Science Active Mode of Operations (SAMO), Passive (SPMO), Debug Events (DEMO)

PING Mode of Operations	RAM for 1 Exposure	PING/Rover CE Channel Throughput	Channel 1Mb Frame Time-Window	Effective Data rate	Number of Frames for Exposure	Total Data Volume per sol (<i>constraint is 100Mb</i>)
SAMO	2Mb	8Mbps	0.1s	0.8Mbps	2 (sequence of 2 1Mb frames)	51Mb
SPMO	32Kb	8Mbps	0.1s	0.8Mbps	1	<<51Mb
DEMO	2000Mb	8Mbps	0.1s	0.8Mbps	2000 (select a few 1Mb frames to transmit)	Small volume of selectable frames

The second FPGA card primarily handles CCSDS packetization of data and communication of science data over the rover interface. In addition, the card handles timing, time-stamping, as well as system synchronization, housekeeping data collection and power supply control. In addition, the second FPGA card drives a series of digital-to-analog converters, which set various analog voltages used for the test-pulse generator and thresholds for the event detection in the FEE signal- conditioning network. Schlumberger will also provide the PNG Proprietary Control IP to interface with the Pulsed Neutron Generator control interface. The Science Data Acquisition Card also controls multiple safety-inhibit switches. The safety inhibits protect the instrument, as well as human life and property. The safety inhibit protects against inadvertent firing of the PNG.

Flight heritage for the Digital Electronics Cards is based on the Spacecube v2.0 form factor [5] and baseline the Microsemi RTAX2000 FPGA that has heritage on many NASA missions including, Lunar Reconnaissance Orbiter, Global Precipitation Measurement, Magnetosphere Multiscale (MMS) mission, Soil Moisture Active Passive (SMAP) mission and many others. These do provide the computational platform for all six on-board applications in absence of a CPU and operating system with heritage flight software.

The PING instrument electronics on-board algorithms include: The Instrument Flight System Firmware (IFSF) that controls computational arithmetic and external memories access, Instrument C&DH Firmware, Instrument on-board science application 5 algorithms' firmware and instrument signal and digital controls firmware. The application algorithms are – (1) Histogramming all measurements for science active mode of operations, (2) Histogramming for science passive mode of operations, 3) Even-by-event processing in diagnostic mode with storing huge a large vector of events but on-board processing and analysis of only a small movable window of data without transmission to spacecraft, (4) NPG gamma-ray signature analysis for power control, (5) Communications information formatting and packetization for transmission to the rover over an RS-422 I/F at 8Mbps and within 0.1s transmission window of frames $\leq 1\text{Mb}$ in length and control of multiple thresholds.

The GSE comprises *six simulators* (Figure 5) in support of the entire instrument development sequence, using off-the-shelf components and spare flight components for precision timing.

Empirical lessons were the bases for framework segments weight estimates– for PING each IEES board square inch weights approximately **9 grams** and for cost modeling - flight segment cost estimate is approximately equal to $\text{segment_weight} \times \1.5M . This cost should be combined with the cost of GSE and its simulator that is approximately **\$1.5M**. Each card depth is assumed as **1.5"** with aluminum enclosures having of **0.1"** depth wall. For

DESTINY the computational weight factors were **700g** for a digital board and **900g** for an analog board. For cost estimates the cost of an FPGA implementation of an application algorithm was **\$400K**.

6. CONCLUSIONS

We have described a spaceflight instrument scalable and adaptive electrical and electronics subsystem IAEEES conceptual framework by enumerating its components on the precedence of two NASA future flagship missions' instrument proposals, WFIRST and PING. The instrument scientific problem to solve statement, top-level technical requirements to its EE subsystem, the science modes of operation and sensor exposure diagram constitute the framework for the few pages of a proposal EE subsystem section. These are supported by the interleaved figures of block diagrams and data volume and rates table and facilitate a scalable and adaptable implementation.

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BIOGRAPHY



Semion Kizhner is an aerospace engineer with the National Aeronautics and Space Administration at the Goddard Space Flight Center. He proposed the development of the Hilbert-Huang Transform Data Processing System (HHT-DPS) for one dimension (1-D) and has been leading the HHT-DPS development team. He also proposed in 2013-2014 and as Principal Investigator developed the HHT2 system for 2-D. He participated recently in evaluation of the NASA Advanced Space Technology proposals, was recently the EE subsystem lead for the DESTINY/Joint Dark Energy Mission/WFIRST concept studies and Mars-2020 PING instrument proposal EE subsystem. He is the lead for the SMAP radiometer science data processing code development. He published two dozens of technical papers and mentored numerous undergraduate, graduate and doctoral students in the NASA Education Programs. He graduated from Johns Hopkins University with an MS degree in computer science and holds a Bachelors degree in applied mathematics and cybernetics.



David Sohl has 35 years experience in the development, testing, and operation of space flight instruments and instrument electronics. This experience includes all aspects of instrument and electronics development, fabrication, assembly, and test. He has worked as a technician, design engineer, test engineer, lead engineer, chief engineer, integration and test manager, and instrument manager. He worked on multiple types of instruments in all wavelength ranges (UV, IR, Visible, X-ray, Gama Ray) that operate from 30°C down to 0.25°K. These instruments have flown on all platforms (aircraft, balloons, sounding rockets, space shuttle, and satellites). He has also worked on all phases of project lifecycle from proposal through development and on-orbit operation. He recently supervised the development of the JWST NearSpec instrument electronics, SMAP radiometer electronics and science data processing system development, and the development of two instrument electronics boxes for the ASTRO-H mission. He is currently serving as the Branch Head of the Instrument Electronics Development Branch at the Goddard Space Flight Center. He graduated from Johns Hopkins University with a degree in Electrical Engineering.



Dr. Ann Parson had great experience applying new instrumentation technology to real space science missions. From involvement in the extremely successful Swift Gamma Ray Burst Explorer launched in 2004, she had the opportunity to participate in the full life cycle of a space science mission. Dr. Parson began the Cadmium Zinc Telluride gamma ray detector technology development at Goddard in 1993 that eventually led to the successful Swift mission proposal in 1998. Her scientific interests have since broadened to include the study of the origin and evolution of the planets. Dr. Parson was the Principal Scientist for the Mars-2020 PING proposal.



Jeffrey Smith is an Optical Engineer at NASA Goddard Space Flight Center and the Associate Branch Head – Optics Branch. He graduated from University of Tennessee, Knoxville (TN) with a bachelor's degree in electrical engineering and holds an MS degree from University of Maryland College Park. He was a NASA summer intern and was hired by NASA upon graduation from TN. He was instrumental in setting up at NASA Goddard Space Flight Center the super-computing platform based on a network of DSPs for testing the James Web Space Telescope (JWST) compound mirror controls. He authored numerous papers on JWST optics and is currently leading the JWST systems testing at Johnson Space Flight Center in Huston.



Ms. Renee Reynolds received her Bachelor of Science degree in Electrical Engineering from the University of Maryland College Park in 2000, and her Masters of Science degree in Electrical and Computer Engineering from Johns Hopkins University in 2007. Ms. Reynolds has worked as an Electrical Engineer at NASA's Goddard Space Flight Center since 2000 and now serves as a Supervisory Electrical Engineer within the Instrument Electronics Development Branch. Renee's history of designing and testing flight electronics hardware includes the following launched NASA missions: Swift Burst Alert Telescope, Solar Dynamics Observatory, Lunar Reconnaissance Orbiter (LRO), Hubble Space Telescope – Servicing Mission 4, Global Precipitation Measurement and Mars Organic Molecule Analyzer Mass Spectrometer.