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Reverse Engineering of Juno Mission

Homework 7

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Group 5

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Notation

EOM	End Of Mission
ASC	Advanced Stellar compass
OBDH	On Board Data Handling
PS	Propulsion System
AOCS	Attitude and Orbit Control System
TMTC	Telemetry and Telecommand
TCS	Thermal Control System
EPS	Electric Power System
TRL	Technology Readiness Level
C&DH	Command & Data Handling
CPU	Central Processing Unit
SBC	Single-Board Computer
ROM	Read Only Memory
PROM	Programmable Read Only Memory
EEPROM	Electrically Erasable PROM
NVM	Non-Volatile Memory
SFC	Synchronous Fast Cycle
SEU	Single Event Upset
RAM	Random Access Memory
DRAM	Dynamic RAM
SRAM	Static RAM
SDRAM	Synchronous DRAM
DTCI	Data, Telemetry and Command Interface
EDAC	Error Detection And Correction
GIF	Guidance, Navigation & Control Interface
GN&C	Guidance, Navigation & Control
RCS	Reaction Control System
SDST	Small Deep Space Transponder
ULDL	Uplink and Downlink
LVDS	Low Voltage Differential Signaling
PCI	Peripheral Component Interconnect
cPCI	Compact PCI
P/L	Payload
FPGA	Field Programmable Gate Array
IPB	Instrument Processor Board
JSIB	JADE Sensor Interface Board
CH	Camera Head
CCD	Charge-Coupled Device
RISC	Reduced Instruction Set Computer
SPARC	Scalable Processor Architecture
JADE	Jovian Auroral Distribution Experiment
JEDI	Jupiter Energetic-particle Detector Instrument
MAG	Magnetometer
MWR	Microwave Radiometer
UVS	Ultraviolet Spectrograph
JIRAM	Juno Infra-Red Auroral Mapper
OS	Operating System
FFT	Fast Fourier Transform
WvFE	Waves FFT Engine
DPU	Digital Processing Unit
SRU	Stellar Reference Unit
SSS	Spinning Sun Sensor
REM	Rocket Engine Mount
HGA	High Gain Antenna
MGA	Medium Gain Antenna
LGA	Low Gain Antenna
TLGA	Toroidal Low Gain Antenna
Ax	Array # x
AR	Anti Reflecting
ME	Main Engine
IC	Inner Cruise
OC	Outer Cruise
EGA	Earth Gravity Assist
CG	Center of Gravity
DSM	Deep Space Manuever
SEP	Sun Earth Probe
EPM	Earth Pointing Mode
SPM	Sun Pointing Mode
FOV	Field of View
MLI	Multi-Layer Insulator
LILT	Low Intensity and Low Temperature
MOB	Magnetometer Optical Bench
KIPS	KiloInstructions Per Second
MIPS	MegaInstructions Per Second
IMU	Inertial Measurement Unit
D/L	DownLink
U/L	UpLink
I/O	Input/Output

1 Juno configuration

1.1 Introduction of Juno's configuration

Juno is the first spin-stabilized, solar-powered spacecraft to perform scientific operations around Jupiter, equipped with various instruments each having unique requirements and limitations. Due to Jupiter's harsh environment, special consideration was needed for the configuration of payloads, antennas, internal hardware, and power sources to ensure the mission's longevity and operational power. Accurate mass distribution is critical for precise measurements, as Juno spins at 2 RPM during science operations.[1] The following sections will detail Juno's general configuration and analyze its various payloads. The external appendages of Juno and its reference system is shown in Figure 1.

1.2 Shape and appendages

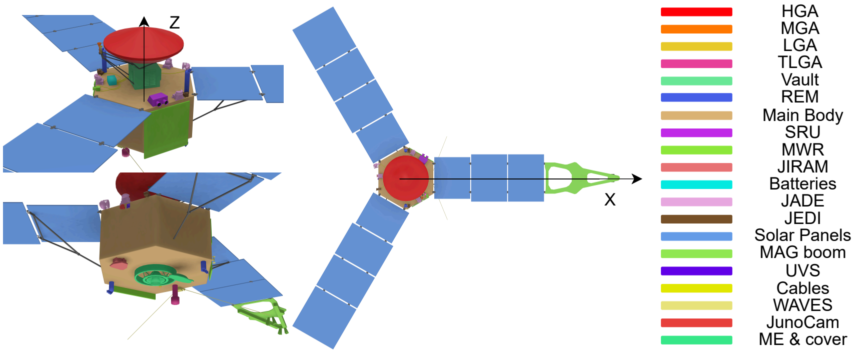

Figure 1: Juno's configuration and reference system

The main body of the S/C has the shape of a regular hexagonal prism with sides of 1.77 m and height of 1.52 m: in its interior the ME, tanks of fuel and oxidizer are stored. The interior of the prism is divided into six bays thanks to honeycomb composite walls that allow, together with MLIs and thermal blanket, to decouple each section from their surroundings. A tank is placed in each bay. On the top deck are installed the two 55 Ah Li-Ion batteries, the two SRUs, the SSSes, all the cabling for the instruments, JEDI and JADE. Moreover two of the four REMs are placed on the top deck along the Y-axis, the titanium vault is placed at the center of the prism, aligned with the Z-axis. Inside the vault all the important electronics is stored in order to keep it shielded from the radiations. At last, the 2.5 m diameter HGA to transmit and receive in X-band and Ka-band is mounted on top of the vault. Alongside the HGA, the front LGA and the MGA are placed. On three of the six lateral faces of the main body the three solar arrays are mounted and spaced 120° apart. Under the solar array along the +X-axis the WAVES antennas are placed, while on a fourth face both the JunoCam and the UVS instruments are mounted. The last two lateral faces are occupied by the MWR antennas. The three solar arrays are composed by a different number of panels: A1 has three panels while A2 and A3 are composed by 4 panels each. In fact on the edge of A1 the MAG suite of instruments is mounted. The aft deck, aligned with the -Z-axis, features the ME cover, the last two REMs for the AOCS, the aft LGA, the TLGA and JIRAM.

1.3 Configuration inside the launcher

Figure 2: Juno in packed configuration

As mentioned in subsection 1.1, the cross section of Juno's main body is an hexagon with 1.77 m sides. The circumscribed circumference has thus a diameter of 3.54 m. The solar arrays have a total area of about 60 m^2 and their total aperture when deployed is more than 20 m.[2] Given that the needed launcher, the Atlas V, has fairings of diameters up to 4.57 m, the three arrays had to be folded. A system of hinges and struts and a division in multiple panels had to be developed.[3] Dimensions of the arrays led to difficulties during ground testing: technicians had to fold and unfold the three arrays one by one and not all three together.[4] The adopted fairing features a maximum height of 10.18 m, that is the smallest fairing among the 5 m family.[5] Dimensions are coherent with the ones of Juno. The smallest possible fairing to be mounted on the Atlas V had an internal available diameter of 3.75 m and an available internal height of 1.58 m which was not compliant with dimensions of the S/C. The packed configuration features, in addition to the folded arrays, the Waves antennas to be retracted: together with the solar arrays they will be deployed soon after separation from the Centaur upper stage. The adapter used to connect the launcher to the spacecraft was found to be the type D1666, composed by two pieces of machined aluminum. Loads are transferred from the Centaur to the S/C via its internal panels and the central column: every honeycomb panel is used to divide the six bays where the tanks are placed and they all converge in a central column, made of titanium, that guarantees both internal rigidity and thermal insulation. Inside the column the ME is stored. The capabilities of the adapter vary depending on the position of the CG of the spacecraft with respect to the separation plane.[5] Due to the mass distribution of Juno at launch, the CG was found to be inside the main body, at around 1.4 m from the said plane. From the Atlas V user manual[5], this values imply a maximum payload capability of 6.5 tons, above the ≈ 3.62 tons of Juno at launch.[2] In Figure 2[6] it is possible to observe the S/C with the folded arrays and the adapter prior to the launch. A1 with the MAG boom is also visible. Separation of Juno from the adapter is carried out by a system of springs, a clamp band and a release mechanism: the system allows to safely separate the S/C and provides the needed energy to obtain positive separation, which in the case of Juno implies reaching an orbit with a specific energy of 31.1 km^2/s^2.

1.4 External configuration

Juno is a spin stabilized S/C that performs science operations in a LILT environment, with a trajectory ranging between 0.85 AU and 5.45 AU. The positioning of the instruments and the scientific payload is defined such that during science operations each face of the main body has a clear view of Jupiter twice a minute. All the on board subsystems will be analyzed.

1.4.1 Propulsion Subsystem

RCS: the twelve RCS thrusters are mounted on four REMs, three thrusters each, two REMs are on the forward deck (F-REMs) and two are on the aft deck (A-REMs). Each REM is mounted on top of a pylon: F-REMs are raised by 74 cm while A-REMs are raised by 26 cm from their respective decks. Each thruster features a different orientation with respect to the Z and X axis: axial thrusters are canted 10° from the Z-axis on the top deck. Lateral thrusters are canted 5° from the X-axis and 12.5° from the Z-axis. Axial thrusters can be utilized as an alternative to the main engine.[7] All this precautions are needed as plum from the firing of the thruster must not interact neither with the solar arrays nor with the antennas nor instruments.

ME: the Leros 1b main engine is stored inside the main body. On the aft deck its cover is visible: this device is needed to protect the engine from collisions with debris along the cruise.

1.4.2 Telemetry and Telecommand Subsystem

HGA: this antenna is both responsible for communications along the mission and for conducting science operations.[8] It is mounted on top of the electronic vault and has a diameter of 2.5 m. It is located along the spin axis, such that its pointing requirement of 0.25° is satisfied.[9] In addition to transmitting and receiving in X or Ka-band, the HGA also serves the fundamental role of thermally protecting the spacecraft from the radiations coming from the Sun during the IC: the whole antenna is covered with a highly reflective Germanium Kapton blanket.[10]

MGA: this antenna is mounted near the HGA on the forward deck and it is used for communications only. It serves as alternative to the HGA during the different manuevers as its beamwidth is larger at 10.3°.[8]

LGA: two of this type of antennas are present on Juno, one on the forward deck (on the same structure of the MGA) and one on the aft deck. The two antennas are coupled together as they are not independently controllable and are used during the EGA and for some critical manuevers.[8]

TLGA: this antenna serves a crucial role during all the ME manuevers that Juno performs and in the eventuality of a safe mode. It is mounted on the aft deck, aligned with A1, and has the peculiarity to be a bi-conical horn-style antenna. The TLGA transmits only tones that are necessary to assess the health status of the spacecraft. During the ME manuevers the SEP angle must be carefully monitored in order to not exceed safe operational values for this antenna.[8]

1.4.3 Attitude and Orbit Control Subsystem

The **RCS** used to control the attitude of the S/C is presented in subsubsection 1.4.1

SRU: two of this type of sensor are mounted on the forward deck of Juno, looking in the radial direction. They are responsible for the attitude determination of the S/C during all the ICs, the OC and science operations. Software calculations are required as the spin rate of Juno changes throughout the mission, from 1 to 2 RPM. The SRUs are turned off and covered during the two DSMs as a direct sight of the Sun would have damaged their sensible optics. While performing EPM or SPM no precautions are needed.[11]

SSS: two Spinning Sun Sensors are positioned on the edge of the forward deck and are oriented in such a way to include both the Z-axis and a portion of the XY plane inside their FOV. They are used during critical manuevers to provide accurate attitude determination while the SRUs are not being used and they allow for a fail safe recovery.[12]

1.4.4 Thermal Control Subsystem

MLI: this kind of passive thermal control is needed as the trajectory of Juno ranges between 0.88 AU and 5.45 AU. Active thermal control is not the only option as it requires power, a precious resource around Jupiter. Moreover, MLIs are also used to shield the body and the instruments from the radiation present around Jupiter.

Solar Arrays: these massive structures are composed by eleven panels of different sizes. The panels are composed by a carbon fiber support on which solar cells are installed. The cells are placed on a Kapton film and protected by an AR glass. The backside of the panels is covered in Black Kapton. This is done to ensure that the operability range of temperatures of the cells is met across the different phases of the mission, from the +90° C at the perihelion to the -146° C around Jupiter.[13] Moreover, the panels have to dissipate the excess of energy, stored as heat, that they produce during the first phases of the mission. On A1 the MAG boom is mounted: its instruments require special attention as a strong temperature gradient of about 80°C is present.[13] The MAG boom and the MOBs are thus thermally decoupled via titanium hinges and joints.[13]

Vault: this particular element, made of titanium, is positioned on the centre of the forward deck of the S/C and its dimensions are ≈ 0.8 m $\times$ 0.8 m $\times$ 0.7 m.[14] It houses all the electronics as it is able to shield it from the radiations around Jupiter. It also manages to keep its interior within the correct temperature range thanks to the presence of heaters and louvers. The position of the louvers is critical as they must radiate to the deep space and not face other instruments on the deck: thermal control prior the EGA and during science operation is critical as any loss inside the vault could lead to the loss of the mission. The elements inside the vault are placed in order to conduct the heat to the louvers via thermal straps.[15] During operations the vault is thermally shielded by the HGA. All the cabling coming from the electronics housed inside the vault exits from its lower face and it is linked to the batteries, in order to not create thermal bridges on the main body.

Instruments on the main body: all the instruments placed on the forward deck are thermally isolated thanks to MLIs and warmed up through electric heaters. During the ICs, when Juno is closer to the Sun, they are partially shielded by the HGA.[16][17] The elements on the aft deck are instead facing the deep space for the majority of the mission: heaters and thermal blankets are present.[18] Particular attention had to be taken into account as the instruments on the forward deck had to not be placed in front of the louvers positioned on the vault.

1.4.5 Electric Power Subsystem

Solar Arrays: Juno is equipped with ≈ 60 m^2 of solar panels, which generate up to 400 W of power at a distance of 5.45 AU from the Sun.[13] The placement of these panels is influenced by Juno's spinning architecture, helping to maintain a stable inertia matrix and improving platform stability thanks to their mass distribution.[3] Detailed reasoning for the cell arrangement within the panels is provided in a previous chapter. After separating from the Centaur upper stage, the solar arrays are deployed, reducing the spacecraft's spin rate from 1.4 RPM to 1 RPM for cruise operations.[1] These arrays are positioned using electrically actuated struts and hinges and must remain unshaded by instruments to ensure consistent power generation. The panels' backsides face deep space for most of the mission, aiding in heat dissipation and thus efficiency. The MAG suite on the edge of panel A1 includes ASCs to monitor any flexing of the array, essential for accurate readings of Jupiter's magnetic field.

Batteries: Juno's two 55-Ah[19] Li-Ion batteries are essential for providing power to the instruments during EGA when Juno is in eclipse and during perijove passages when solar arrays power is insufficient.[20] They are positioned on the forward deck and are connected to the electronics of Juno with cables coming from the main body or via shielded ones running on the outside of the deck. The batteries are positioned under the HGA in such a way to minimize the length of the cables running to the SRUs and not to interfere with the louvers.[21] Due to their size, the batteries couldn't be housed inside the vault or main body, as doing so would significantly increase structural mass. Thermally regulated and shielded with an MLI blanket over a beryllium box, the batteries are designed to withstand environmental radiation.[21]

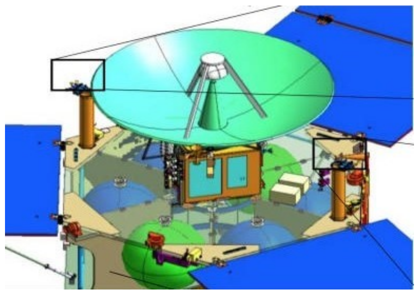

Figure 3: Juno's internal configuration

1.5 Internal configuration

Only considerations about the internal structure and the Propulsion subsystem can be made, as all the important instruments are placed on the outside of the satellite or inside the vault. A view of the internal configuration can be observed in Figure 3. Six propellant tanks are located inside the main body, four for fuel and two for oxidizer, one in each bay. This configuration allows to improve the stability of the spinning stabilized platform and allows to have a better control on the position of the CG, that will shift along the Z-axis throughout the mission. The tanks are all made of titanium to guarantee high specific strength and thermal insulation.[22] Moreover, the tanks are covered with MLIs and electrically heated. Fuel's and oxidizer's tanks have a sphere-like shape, while the two remaining tanks containing helium are cylindrical with domed ends. Propellant lines are located on the outer part of the tanks as while Juno spins, the fuel is naturally moved to the most exterior region. The main engine is stored inside the main body, in the center region where the six bays converge.[1][23] As the engine fires, heat must be dissipated to not overheat the nozzle. This constrain leads to the maximum operation of the engine of 42 minutes.[23] The same structure that is stressed during the launch is responsible for thermally decoupling the tanks and the ME's nozzle and, together with the thin panels that divide the bays, contributes to the torsional rigidity of the S/C.

2 Juno OBDH

2.1 Introduction of OBDH

Given the long term exposure of the S/C to extreme environments, such as the one around Jupiter characterized by high levels of radiation, Juno's OBDH system was designed to ensure proper functioning up to EOM. This was achieved by selecting radiation hardened hardware characterized by high TRL. The OBDH system also needs to constantly interact with all other subsystems to handle both telemetry and scientific data.

2.2 Architecture of OBDH

The OBDH system is based on two redundant, single fault redundant C&DH boxes, each including:

- **RAD750 Computer:** a 3U radiation hardened single-board computer by BAE systems[24] with 256 MBytes of NVM flash memory (as EEPROM) and 128 MBytes of SFC DRAM local memory.[25] The latter was chosen for its quick operations capabilities while EEPROM was selected due to its resilience to UV radiation. EDAC algorithms are employed on both kinds of memory to reduce data errors caused by radiation. The computer board is able to handle 100 Mbps of instrument throughput, much higher than needed for payloads requirements, and can operate at up to 200 MHz. It offers a substantial performance improvement over older rad-hard processors being capable of more than 400 MIPS (Dhrystone 2.1). The CPU itself can withstand a total radiation dose of up to 1 Mrad (Si) while the whole card has a much lower resistance of 50 Krad (Si). They are also characterized by a SEU rate of $< 1.6 \cdot 10^{-10}$ errors/bit-day and $< 3.62 \cdot 10^{-4}$ errors/card-day respectively.[26] Furthermore this computer has already been employed on various missions such as NASA's Mars Science Laboratory proving its effectiveness.[20] A general scheme of the RAD750 board is presented in Figure 4.

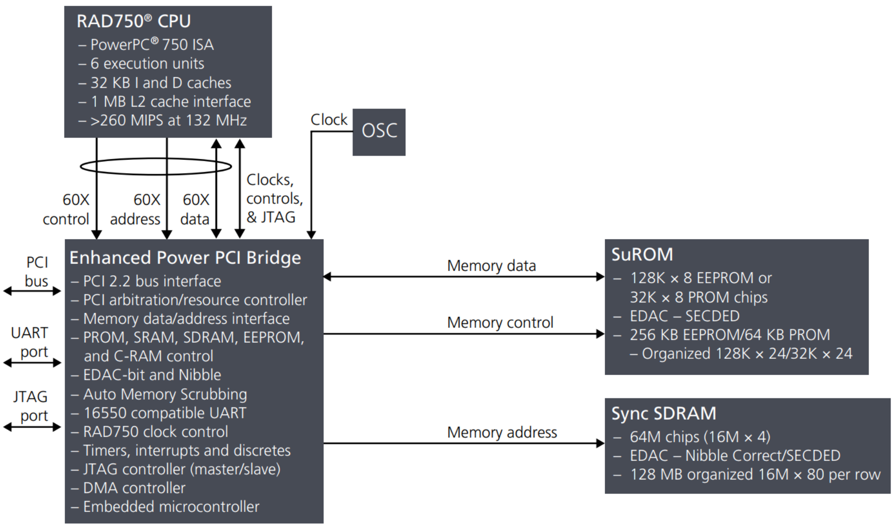

Figure 4: General scheme of RAD750 SBC

- **DTCI card:** it contains the interface between the C&DH box and all the instruments of the spacecraft, while also providing science data storage capabilities. In particular 32 Gbits are available for data storage with a further 8 Gbits dedicated to EDAC. This is sufficient both for all science orbit downlink data requirements and representative stress cases. Unlike all other cards present in the C&DH box it's characterized by a 6U format instead of a 3U one.[25]
- **GIF card:** similarly to the DTCI card it provides the interface between the C&DH boxes and all GN&C hardware, namely the various attitude sensors and the twelve RCS thrusters. As maintaining proper functionality of the AOCS is of critical importance, two GIF cards are present in each box, thus offering quadruple redundancy. Each card is also connected to both SDSTs through MIL-STD-1553[27] busses.[8]
- **ULDL card:** it also connects to the two SDSTs and, as the name implies, it's tasked with providing and controlling both the uplink (command) and downlink (telemetry and data) of the S/C. In this case only one card is installed in each box but, similarly to the GIF cards, both C&DH units are cross-strapped to both SDSTs. This connection utilizes LVDS interfaces instead of MIL-STD-1553 busses.[8]
- **cPCI bus:** an internal bus, comprised of an Eurocard-type connector and a PCI, that interconnects all of the C&DH box hardware, allowing multiple cards to operate in a single system. cPCI busses are long lasting components, hence particularly suitable for missions like Juno.

The two C&DH boxes are further connected to the rest of the spacecraft with two sets of redundant RS-422 busses:

a synchronous interface for science data and an asynchronous interface for telemetry and command, both capable of a transfer rate of 57.6 Kbps.[28][29] All P/Ls also feature individual computation capabilities and a certain level of local memory, with the only exception being the Gravity Science investigation since it relies only on the TMTC system. This architecture choice was made as both the high number of P/Ls and their complexity meant that a centralized processor couldn't handle the required workload. As a consequence the P/Ls only communicate with the central C&DH boxes to exchange processed data, commands and telemetry. A brief description of the internal data handling hardware of each P/L is shown below:

- **JADE:** its IPB is powered by both an Atmel AT697E SPARC8, RISC processor and a Actel RTAX2000S-1 FPGA, the first one handles data computation while the second houses the logic control of the whole board. Three separate memories are present: 128 KB of PROM for boot code, 512 KB of EEPROM to store flight software and look-up tables and 4 MB of SRAM for codes and data during execution. Further SRAM is employed on the JSIB as a buffer for the incoming measurements from the sensors.[16]
- **JEDI:** each sensor is wholly controlled by a single RTAX2000 FPGA together with a soft-core processor embedded in it. 64 KB of PROM and 256 KB of EEPROM function as NVM, while 8 MB of SRAM support the processor operations.[17]
- **JunoCam:** it makes use of two Actel RTSX FPGAs: one is inside the CH to drive the CCD sensor and extract data from it while the second is housed in the electronics assembly and oversees data storage and communication with S/C. 128 MB of SDRAM serve as an image buffer.[30]
- **MAG:** this instrument only requires basic logic functions supplied by two redundant radiation-hard Aeroflex UT6325 FPGAs which also provide 55 kbits of internal memory, sufficient for FGM data processing.[31]
- **MWR:** all logic and computations are carried out by an Intel 8051 microcontroller and an FPGA. The flight software is burned into a PROM which can be updated through the S/C interface.[29]
- **UVS:** all of the instrument's subsystems are controlled by an Intel 8051 processor implemented in a radiation-hardened FPGA with 32 kB of fuse programmable PROM, 128 kB of EEPROM, 32 kB of SRAM and 128 kB of acquisition memory for scientific data.[28]
- **Waves:** it relies on two SoC architecture implemented in separated radiation tolerant FPGAs responsible for data processing and handling. The primary FPGA is based on a single processor core, the Y180s, running a custom OS developed by the University of Iowa. 32 KBytes of PROM are available to store the boot code, while 2 MBytes of RAM are used to store the OS and data during execution. The second FPGA houses the Waves FFT Engine, a programmable general-purpose digital signal processor tasked with capturing and analyzing scientific data. It makes use of 8 Mbytes of independent local memory due to the bandwidth requirements of the WvFE processor, to store programs, data and raw waveforms.[18]
- **JIRAM:** it's characterized by two separate data channels: one for the imager and one for the spectrometer. Its electronics box contains the DPU, the proximity, the main electronics (CPU board), the power supply and the limited angle de-spinning mechanism driver board.[32] As for memory the instrument has both a 537 Mbit hard partition and a 4000 Mbit soft partition: the first is used to store data during observation while the latter houses the same data until the downlink process occurs.[33]

2.3 Reverse sizing of OBDH

For this sizing, an estimation by similarity has been conducted. This method grants a preliminary evaluation of the memory and the processor that are necessary for OBDH to handle the functionalities of the S/C along the mission. Some typical values have been considered by the method for each process, which include data, codes and instructions per second. Then, the acquisition frequency and the occurrences of each process is hypothesized by the knowledge of the various subsystems present on Juno.

The method has been applied for two main phases that have been identified: manoeuvering and telecommunication. The manoeuvering includes both the manoeuvres executed by RCS and by the main engine. A less conservative approach could have treated the two cases separately in terms of data budget. The payload contribution has not been considered since, as mentioned in subsection 2.2, every science instrument possesses its own data handling unit, which communicates with a central unit. The data budget has been computed and reported in the tables below.

PS							
Components	**Number**	**Code [words]**	**Data [words]**	**Typical KIPS**	**Typical freq. [Hz]**	**Acq. freq. [Hz]**	**KIPS**
Main engine	1	1200	500	5.0	0.1	0.1	5.0
Tank control valve	14	800	1500	3.0	0.1	0.1	3.0
Tank pressure sensor	8	800	1500	3.0	0.1	0.1	3.0

Table 1: Data budget for PS

AOCS							
Components	**Number**	**Code [words]**	**Data [words]**	**Typical KIPS**	**Typical freq. [Hz]**	**Acq. freq. [Hz]**	**KIPS**
Thruster control	12	600	400	1.2	2.0	2.0	1.2
Star tracker	1	2000	15000	2.0	0.01	10.0	2000.0
IMU	1	800	500	9.0	10.0	100.0	90.0
Sun sensor	1	500	100	1.0	1.0	1.0	1.0
Kinematic integration	1	2000	200	15.0	10.0	10.0	15.0
Error determination	1	1000	100	12.0	10.0	10.0	12.0
Attitude determination	1	15000	3500	150.0	10.0	10.0	150.0
Attitude control	1	24000	4200	60.0	10.0	10.0	60.0
Complex ephemeris	1	3500	2500	4.0	0.5	0.5	4.0
Orbit propagation	1	13000	4000	20.0	1.0	1.0	20.0

Table 2: Data budget for AOCS

TCS							
Components	**Number**	**Code [words]**	**Data [words]**	**Typical KIPS**	**Typical freq. [Hz]**	**Acq. freq. [Hz]**	**KIPS**
Thermal control	1	800	1500	3.0	0.1	0.1	3.0

Table 3: Data budget for TCS

TMTC							
Components	**Number**	**Code [words]**	**Data [words]**	**Typical KIPS**	**Typical freq. [Hz]**	**Acq. freq. [Hz]**	**KIPS**
Transponder U/L	1	1000	4000	7.0	10.0	10.0	7.0
Transponder D/L	1	1000	2500	3.0	10.0	10.0	3.0

Table 4: Data budget for TMTC

OS							
Components	**Number**	**Code [words]**	**Data [words]**	**Typical KIPS**	**Typical freq. [Hz]**	**Acq. freq. [Hz]**	**KIPS**
I/O device handler	1	2000	700	50.0	5.0	5.0	50.0
Test and diagnostics	1	700	400	0.5	0.1	0.1	0.5
Math utilities	1	1200	200	0.5	0.1	0.1	0.5
Executive	1	3500	2000	60.0	10.0	10.0	60.0
Runtime kernel	1	8000	4000	60.0	10.0	10.0	60.0
Complex autonomy	1	15000	10000	20.0	10.0	10.0	20.0
Fault detection	1	4000	1000	15.0	5.0	5.0	15.0
Fault correction	1	2000	10000	5.0	5.0	5.0	5.0

Table 5: Data budget for OS

For the PS, 14 control valves have been assumed, one for each thruster and two for the main engine. For the tanks 8 pressure sensors have been considered, one for each tank (of fuel, oxidizer and pressurizer).
For the AOCS, 12 thrusters are considered. The acquisition frequency of the star tracker[11] is relatively high and rises the KIPS. This value has been taken into account to size the processor, but in reality the star tracker has its own microprocessor.
For the TCS, the thermal control refers to the centralized unit that handles all the heaters in the S/C.
For each phase the total throughput, data and code are calculated and margined by 400%.
The total KIPS for each subsystem is calculated as follows:

$$\mathrm{KIPS}_{tot} = \sum_{i=1}^{n_{fun}} k_i \, \mathrm{KIPS}_i \tag{1}$$

The KIPS for each subsystem is then summed up in the data budget of each phase if the subsystem is active.

The results of the data budgets are reported in Table 6 and Table 7.

Manoeuvering						
	PS	AOCS	TCS	TMTC	OS	TOT
Active?	1	1	1	1	1	
Throughput	71	2366.4	3	10	211	2661.4
Margined	355	11832	15	50	1055	13307
Code	18800	69000	800	2000	36400	127000
Margined	94000	345000	4000	10000	182000	635000
Data	34500	34900	1500	6500	28300	105700
Margined	172500	174500	7500	32500	141500	528500

Table 6: Data budget for manoeuvering phase

Communication						
	PS	AOCS	TCS	TMTC	OS	TOT
Active?	0	1	1	1	1	
Throughput	0	2366.4	3	10	211	2590.4
Margined	0	11832	15	50	1055	12952
Code	0	69000	800	2000	36400	108200
Margined	0	345000	4000	10000	182000	541000
Data	0	34900	1500	6500	28300	71200
Margined	0	174500	7500	32500	141500	356000

Table 7: Data budget for communication phase

For the ROM sizing, the relevant value is the maximum total code (margined) expressed in Mb, for the RAM is the maximum total memory, which is the sum of both the code and the data, while for the processor is the maximum total throughput (expressed in MIPS). The architecture of the OBDH is assumed to be 32-bit in order to calculate the word size.

Total code [Mb]		
	Manoeuvering	Communication
Total	0.508	0.433
Margined	2.540	2.164

Table 8: Total code per phase

Total data [Mb]		
	Manoeuvering	Communication
Total	0.423	0.285
Margined	2.114	1.424

Table 9: Total data per phase

Total throughput [MIPS]		
	Manoeuvering	Communication
Total	2.661	2.590
Margined	13.307	12.952

Table 10: Total throughput per phase

Total memory [Mb]		
	Manoeuvering	Communication
Total	0.931	0.718
Margined	4.654	3.588

Table 11: Total memory per phase

In the tables above the sizing values have been enlightened. Comparing those with the real ones (subsection 2.2), the compliance is proved. It can be noticed that the real computer board has much higher performances in terms of memory and computational power with respect to the computed ones.

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