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Reverse Engineering of Juno Mission

Homework 7

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Group 5

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Notation

SRU	Stellar Reference Unit
SSS	Spinning Sun Sensor
JEDI	Jupiter Energetic-particle Detector Instrument
JADE	Jovian Auroral Distribution Experiment
REM	Rocket Engine Mount
HGA	High Gain Antenna
MGA	Medium Gain Antenna
LGA	Low Gain Antenna
TLGA	Toroidal Low Gain Antenna
JIRAM	Jovian Infra -Red Aurora Mapper
UVS	Ultra Violet Spectrograph
MAG	Magnetometer
Ax	Array # x
AR	Anti Reflecting
ME	Main Engine
IC	Inner Cruise
OC	Outer Cruise
EGA	Earth Gravity Assist
CG	Center of Gravity
AOCS	Attitude and Orbit Control System
TCS	Thermal Control System
TMTC	Telemetry and TeleCommand
RCS	Reaction Control System
DSM	Deep Space Manuever
SEP	Sun Earth Probe
EPM	Earth Pointing Mode
SPM	Sun Pointing Mode
FOV	Field of View
MLI	Multi-Layer Insulator
S/C	Spacecraft

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.

2 Shape and appendages

The main body of the S/C has the shape of a regular hexagonal prism with sides of 1.77 m and and high 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 on 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 Microwaves Radiometer. 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 suites of instruments is mounted. The aft deck, aligned with the -Z-axis, features the ME cover, the last two REMs for the ADCS, the aft LGA, the TLGA and JIRAM.

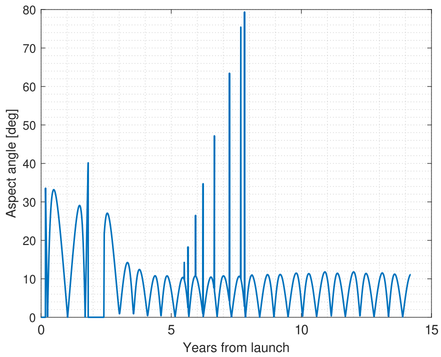

Figure 1: Juno in packed configuration

3 Configuration inside the launcher

As mentioned in section 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 as an option a fairing 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 difficult on 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. Every honeycomb panel is used to divide the 6 bays where the tanks are placed and they all converge in a central column, probably made of titanium, that guarantees internal rigidity. 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. 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,

Figure 2: Juno in packed configuration

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. Attention must be paid to A1, where the MAG is mounted. 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.

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.

4.1 Propulsion subsystem - exterior

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 nor with the solar arrays nor with the antennas.

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.

4.2 TMTC 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 requirements of 0.25° are 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 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, on on the forward deck, on the same structure of the MGA, and one on the aft deck. The two antennas are coupled together as are not independently controllable and are only used during the EGA due their limited power.[8]

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

4.3 AOCS subsystem

The **RCS** used to control the attitude of the S/C is presented in subsection 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 of Spinning Sun Sensors are positioned on the edge of the forward deck amd 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 in working conditions and allow for a fail safe recovery.[12]

4.4 TCS 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 shied the body and the instruments from the radiation present around Jupiter.

Solar Arrays: this massive structure is composed by eleven panels of different sizes. The panels are composed by a carbon fiber support on which solar cells are placed. 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 th +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, ≈ 80°C, is present.[13] The MAG boom and the MOBs are thus thermally decoupled via titanium made 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 × 0.8 m × 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 it 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 be 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 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 blanket are present.[18] Particular attention had to be take into account as the instruments on the forward deck had to not be placed in front of the louvers positioned on the vault.

4.5 EPS 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 maintain a stable inertia matrix and improving platform stability due 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 unshadowed by instruments to ensure consistent power generation. The panels' backsides face deep space for most of the mission, aiding in heat dissipation and efficiency. The MAG suite on the edge of panel A1 includes SRUs 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 behind Earth and during perijove passages when solar array power is insufficient.[20] They are positioned on the forward deck and are connected to the electronics of Juno with satellites coming from the main body and via shielded cables 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].

5 Internal configuration

Only considerations about the internal structure and the Propulsion subsystem can be made, as all the important instruments are or placed on the outside of the satellite or inside the vault.

5.1 Propulsion subsystem - interior

Six propellant tanks are located inside the main body, four of fuel and two of 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 thanks 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 ones are cylindrical with domed ends. Propellant lines are located on the outer part of the thanks 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.[23][1] 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.

Bibliography

[1] *Advanced Global Optimisation Tools for Mission Analysis and Design*. NASA press kit. Site: https://www.jpl.nasa.gov/news/press_kits/JunoLaunch.pdf. 2011.

[2] NASA JPL. *Juno Quick Facts*. Site: https://www.jpl.nasa.gov/news/press_kits/juno/facts/. 2011.

[3] William McAlpine et al. “JUNO Photovoltaic Power at Jupiter”. In: (2012).

[4] Site: https://www.jpl.nasa.gov/news/juno-solar-panels-complete-testing.

[5] Site: https://www.ulalaunch.com/docs/default-source/rockets/atlasvusersguide2010.pdf.

[6] Site: https://spaceflightnow.com/atlas/av029/fairing/.

[7] Thomas A. Pavlak et al. *Maneuver Design for the Juno Mission: Inner Cruise*. AIAA space forum. Site: https://arc.aiaa.org/. 2018.

[8] Anthony P. Mittskus et al. “Juno Telecommunications”. In: (2012).

[9] Anthony P. Mittskus et al. “Telecommunications Antennas for the Juno Mission to Jupiter”. In: (2012).

[10] A. Carmel Mary Esther et al. “A study on degradation of germanium coating on Kapton used for spacecraft sunshield application”. In: (2015).

[11] Leonardo S.p.A. *AUTONOMOUS STAR TRACKERS*. Site: https://space.leonardo.com/documents/16277711/19573187/Copia_di_A_STR_Autonomous_Star_Trackers_LQ_mm07786_.pdf?t=1538987562062.

[12] Adcole Maryland Aerospace. *Fine Spinning Sun Sensor*. Site: https://satcatalog.s3.amazonaws.com/components/362/SatCatalog_-_Adcole_Maryland_Aerospace_-_Fine_Spinning_Sun_Sensor_-_Datasheet.pdf?lastmod=20210708050522.

[13] Stephen F Dawson Paul Stella William McAlpine Brian Smith. *Juno Photovoltaic Power at Jupiter*. Site: https://ntrs.nasa.gov/citations/20130010565. 2012.

[14] Installing Juno’s radiation vault. *Radiation vault characteristics*. Website. Site: https://www.nasa.gov/image-article/installing-junos-radiation-vault/. 2024.

[15] Sierra Nevada Corporation. *Passive thermal louvers*. 2017.

[16] D.J. McComas et al. “The Jovian Auroral Distributions Experiment (JADE) on the Juno Mission to Jupiter”. In: (2012).

[17] S.E. Jaskulek et al. “The Jupiter Energetic Particle Detector Instrument (JEDI) Investigation for the Juno Mission”. In: (2013).

[18] B.T. Mokrzycki et al. “The Juno Waves Investigation”. In: (2017).

[19] Eaglepicher technologies. *Proven battery technology utilizing high energy, long-cycle life, low weight and small volume lithium-ion cells*. 2022.

[20] Various. *Spacecraft Information*. Website. Site: https://spaceflight101.com/juno/spacecraft-information/. 2024.

[21] Site: https://www.eaglepicher.com/blog/batteries-enabling-planetary-and-deep-space-exploration/.

[22] Jeff Lewis. “Juno Spacecraft Operations Lessons Learned for Early Cruise Mission Phases”. In: (2014).

[23] Nammo. *Leros 1b engine*. Journal of Geophysical Research: Planet. Site: https://www.nammo.com/wp-content/uploads/2021/03/2021-Nammo-Westcott-Liquid-Engine-LEROS1B.pdf.