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Reverse Engineering of Juno Mission
Homework 4

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Group 5

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Notation

SRU	Stellar Reference Unit	**MIB**	Minimum Impulse Bit
TDI	Time Delay Integration	**AD**	Attitude Determination
SSS	Spinning Sun Sensor	**ME**	Main Engine
IMU	Inertial Measurement Unit	**FOV**	Field Of View
ASC	Advanced Stellar Compass	**RCS**	Reaction Control System
CHU	Camera Head Unit	**CMG**	Control Moment Gyro
DTU	Technical University of Denmark	**REM**	Rocket Engine Module
FGM	Fluxgate Magnetometer	**TRL**	Technology Readiness Level
SSIRU	Scalable Space Inertial Reference Unit	**HGR**	Hemispherical Resonator Gyroscope
HAMRR	High Accuracy Mode Rate Range	**HGA**	High Gain Antenna

1 Introduction of AOCS

The Attitude and Orbital Control System of Juno comprehends various sensors and actuators that are vital to maintain the satellite in operability conditions and to execute all the basic tasks. In this chapter, the main modes of the satellite are deduced through the analysis of the mission already done in previous chapters. These modes will be then arranged on the timeline consequently. Based on the identified modes and pointing budget, the architecture of the actual system will be presented and then progressively analyzed, verifying the compliance with the previously found requirements. Finally, a reverse sizing of AOCS will be carried out.

2 Breakdown of Juno modes

Throughout the mission phases, Juno has to accomplish different tasks through various modes. The principal ones that have been identified are here described.

2.1 Sun Pointing Mode (SPM)

This mode aims at pointing the spin axis of S/C (+Z axis) to the Sun. This mode is used in order to:

- keep the solar panels pointed to the Sun to provide energy; this is even more crucial in the initial phases of the mission, when all the system checkouts have to be performed;
- thermally protect the satellite's vault using the HGA as a shield when the satellite is relatively close to the Sun.

This mode is applied mainly when the SPE angle is too large to ensure the communication through the HGA. This condition occurs during the first phases of the mission and nearby the EGA, when the satellite is in proximity of Earth and relatively close to the Sun. The LGAs are therefore used during this mode to communicate with ground.

The pointing requirement for this mode is not very strict since the solar panels are sized for much higher distances and can provide enough energy, the LGAs have a wide beamwidth to communicate with ground and the HGA is large enough to protect the vault. The spin rate of the satellite is set to 1 RPM for this interplanetary mode. This improves the passive stability of the pointing, reducing the burden on the active attitude control.

2.2 Earth Pointing Mode (EPM)

The EPM is a contiguous interplanetary mode to the SPM, the +Z axis of the S/C is pointed to Earth. It triggers when the distance from the Sun is high enough to ensure a safe thermal dissipation without the aid of the HGA (≈ 1.4 AU) **REFERENCE** . Moreover, the S/C will be far enough from Earth to ensure both HGA communications and the fulfillment of power requirements, hence the SPE is low.

2.3 GRAVity science Mode (GRAVM)

2.4 MicroWave Radiometer Mode (MWRM)

2.5 Turn-Burn-Turn Mode (TBTM)

2.6 VECtor Mode (VECM)

2.7 Spin Change Mode (SCM)

2.8 Safe Modes

3 Architecture and rationale of AOCS

3.1 Sensors

Juno's AOCS employs the following main attitude sensors:

- 2 **Stellar Reference Units (SRUs)** custom built by Selex Galileo (now Leonardo S.p.A.) mounted on the forward deck of the spacecraft facing radially outwards. These units are based on the A-STR[1], modified with further radiation shielding to survive the harsh environment of Jupiter, bringing the total weight up to 7.8 kg. One of the most important characteristics of these sensors is the ability to operate in a Time Delay Integration (TDI) mode, which allows them to compensate for the spin of the spacecraft when capturing an image. Other specifications of the standard A-STR are reported in Table 1.

FOV [deg]	Update rate [Hz]	Bias Error [arcsec]	FOV error [arcsec]
16.4×16.4	4 or 10	8.25 (pitch/yaw) 11.1 (roll)	< 3.6 (pitch/yaw) < 21 (roll)

Size (L × W × H) [cm]	Mass [kg]	Power consumption [W]	Operational temperature [°C]
$19.5 \times 17.5 \times 29.1$	3.55	8.9 @ 20°C 13.5 @ 60°C	-30 to +60

Table 1: A-STR specifications

- 2 **Spinning Sun Sensors (SSSes)** by Adcole Maryland Aerospace[2], also positioned on the edge of the forward deck with a similar orientation as the SRUs. They are specialized for attitude determination on a spinning spacecraft and allow for a fail safe recovery. Sun sensors are required during ME burns, when SRUs might be pointing the Sun. Useful specifications are shown in Table 2.

FOV [deg]	Size of sensor (L × W × H) [cm]	Size of electronics (L × W × H) [cm]
± 64	$6.6 \times 3.3 \times 2.5$	$5.1 \times 8.2 \times 8.9$

Accuracy [deg]	Mass of sensor [kg]	Mass of electronics [kg]	Power consumption [W]
± 0.1 at 0° ± 0.6 at 64°	0.109	0.475 to 0.725	0.4

Table 2: SSSes specifications

- 2 **Inertial Measurement Units (IMUs)** by Northrop (Hypothesizing heritage from Cassini[3] and MESSENGER[4]) inside Juno's main body. One of their biggest advantage is utilizing Hemispherical Resonator Gyroscopes (HGRs) which, due to their construction and inner workings, are inherently radiation hardened and highly resistant to wear and ageing. In particular Scalable Space Inertial Reference Units (SSIRUs)[5] are used which were also modified for this specific mission like the A-STR. Their nominal specifications are shown in Table 3.

Power [W]	Size of sensor (L × W × H) [cm]	Weight [kg]
43 max	$28.9 \times 18 \times 14.9$	7.1

Operational temperature [°C]	Angle Random Walk [deg/$\sqrt{\text{hr}}$]	HAMRR [deg/s]
-55 to +85 (non-operational) -10 to +60 (full performance)	< 0.00015	± 7

Table 3: SSIRUs specifications

All of this sensors are doubled to provide cold redundancy, meaning that only one unit is powered during nominal operations while the other one is switched off.
An additional sensor, the **Advanced Stellar Compass (ASC)**, is present on Juno to support the MAG experiment suite. It's comprised of four **Camera Head Units (CHUs)**, two per each FGM for redundancy, mounted on the MAG boom pointing towards the -Z direction and inclined by ± 13° along the Y-axis. Their objective is to achieve an even more precise attitude determination near the instrument location with the help of the SRUs, which also function as a backup in case the ASC fails. These sensors were designed and built by the Technical University of Denmark (DTU) as largely off-the-shelf products.[6]

3.2 Actuators

As previously described in the analysis of the propulsion system (Homework 2) Juno utilizes twelve MR-111C RCS thrusters by Aerojet Rocketdyne[7] divided into four groups of three. Each set is housed on a Rocket Engine Module (REM) on top of four pylons, two on the forward deck and two on the aft deck, extending in the Z-axis and mounted along the Y-axis.

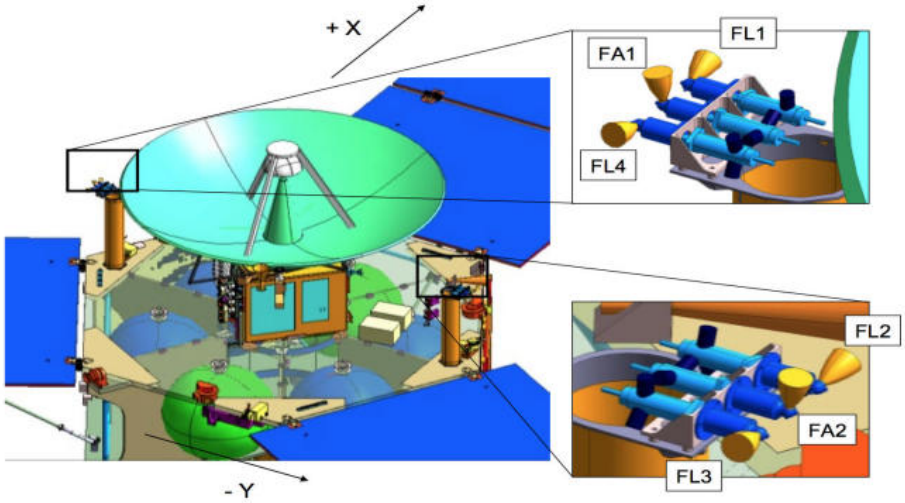

Figure 1: RCS mount direction

The pylons are raised respectively by 74 cm on the forward deck and about 26 cm on the aft deck. As shown in Figure 1 each cluster includes an axial thruster, denoted by the letter "A", and two lateral ones, denoted as "L". Axial thrusters are canted 10° away from the Z-axis while the lateral thrusters are canted 5° away from the X-axis and 12.5° toward the Z-axis[8]. The specifics of the MR-111C thrusters are presented in Table 4.[9]

Thrust [N]	Specific impulse [s]	MIB [Ns]
4.5	220	0.08

Propellant	Catalyst	Mass [kg]	Power usage [W]
Hydrazine	S-405	0.33	13.64

Table 4: MR-111C specifications

Additional hardware is present on the spacecraft to aid attitude control, while not being full-fledged actuators. In particular the supporting struts of the three solar arrays can be moved to adjust their position in order to align the principal inertia axis with the geometrical Z-axis. An active nutation damper is also installed on-board, able to reduce unwanted nutation by generating a controlled damping torque. Given the stringent pointing requirements an active system was chosen for its higher damping rate.

3.3 Rationale

All AOCS components were mainly chosen due to their high TRL, like in all other systems of the spacecraft. This due both to the complexity of the mission and the harsh environment of Jupiter. Further criteria for the selection and positioning of each unit can be highlighted:

- **SRUs:** star sensors are the most accurate and are capable of complete AD independently of any other sensor. Moreover magnetometers weren't really taken into consideration due to the lack of an accurate model of Jupiter's magnetic field. This leaves sun sensors and IMUs as possible options but neither could be used as the main source of AD due respectively to low accuracy or the need to be periodically realigned. SRUs positioning is dictated by the need of leaving their FOV unobstructed.
- **SSSes:** sun sensors are still needed since during ME burns since the orientation of Juno during this manoeuvre could point the SRUs towards the Sun, possibly damaging them. The SSSes main goal is thus to detect the Sun before it gets too close to the SRUs FOV, in order to shut them when needed. This also explains their proximity to the SRUs.
- **IMUs:** since the sun sensors aren't capable of a complete AD while the SRUs aren't being used, another component able to do so is required and IMUs were the only remaining choice. They are also employed during large precessions (larger than ~2.5°) and required for active nutation damping and spin control.
- **RCS Thrusters:** thrusters were chosen since they are able to provide a high control torque while remaining compact and integrated with the propulsion system. On the contrary reaction wheels and CMG would take up much more space to generate the same control action, thus being less space efficient and cumbersome. Magnetorquers, instead, weren't even considered for the same reasons as magnetometers. Regarding the

thrusters' positioning, their orientation presented in subsection 3.2 are due to the need of limiting the interaction of the exhaust gasses with the on board instruments, the HGA and solar arrays.

4 Reverse sizing of AOCS

Bibliography

[1] 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.

[2] 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.

[3] Sergei A. Jerebets. "Gyro Evaluation for the Mission to Jupiter". In: (2007).

[4] Daniel J. O'Shaughnessy et al. "MESSENGER IMU INTERFACE TIMING ISSUES AND IN-FLIGHT CALIBRATION RESULTS". In: (2006).

[5] Northrop Grumman. *Scalable SIRU™ Family*. Site: https://cdn.northropgrumman.com/-/media/wp-content/uploads/pdf/Scalable-SIRU-family-of-products-brochure.pdf?rev=57f1ba8ddcb44783b9e97f979b6e45d9.

[6] Patricia Lawton Jack Connerney. "Juno Magnetometer (MAG) Standard Product Data Record and Archive Volume Software Interface Specification". In: (2018).

[7] *Aerojet Rocketdyne Propulsion plays role in Juno mission*. Online Communication. Site: https://www.proquest.com. 2016.

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

[9] *MR-111C datasheet*. Site: http://www.astronautix.com/m/mr-111.html.