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Reverse Engineering of Juno Mission
Homework 4

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Group 5

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Contents

Notation

AOCS	Attitude and Orbit Control System
TCS	Thermal Control System
TMTC	TeleMetry and TeleCommand
PS	Propulsion System
P/L	PayLoad
S/C	Spacecraft
SPM	Sun Pointing Mode
EPM	Earth Pointing Mode
GRAVM	GRAVity science Mode
MWRM	MicroWave Radiometer Mode
TBTM	Turn-Burn-Turn Mode
VECM	VECtor Mode
SCM	Spin Change Mode
SM	Safe Mode
SPE	Sun Probe Earth
APE	Absolute Performance Error
EGA	Earth Gravity Assist
PJ	PeriJove
DSM	Deep Space Manoeuvre
JOI	Jupiter Orbit Insertion
PRM	Period Reduction Manoeuvre
OTM	Orbit Trim Manoeuvre
TCM	Trajectory Correction Manoeuvre
OC	Outer Cruise
D/L	DownLink
MWR	MicroWave Radiometer
SRU	Stellar Reference Unit
TDI	Time Delay Integration
SSS	Spinning Sun Sensor
IMU	Inertial Measurement Unit
ASC	Advanced Stellar Compass
CHU	Camera Head Unit
MAG	Magnetometer
FGM	Fluxgate Magnetometer
SSIRU	Scalable Space Inertial Reference Unit
HAMRR	High Accuracy Mode Rate Range
MIB	Minimum Impulse Bit
AD	Attitude Determination
ME	Main Engine
FOV	Field Of View
RCS	Reaction Control System
CMG	Control Moment Gyro
REM	Rocket Engine Module
TRL	Technology Readiness Level
SRP	Solar Radiation Pressure
GG	Gravity Gradient
HGR	Hemispherical Resonator Gyroscope
HGA	High Gain Antenna
MGA	Medium Gain Antenna
LGA	Low Gain Antenna
TLGA	Toroidal Low Gain Antenna
OT	Operational Temperature
PC	Power Consumption
ARW	Angle Random Walk
ΔV	Velocity change [m/s]

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 (mainly the TLGA) are therefore used during this mode to communicate with ground.
The pointing requirement (APE) 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.
To assess a preliminary APE for this mode, the thermal requirement has been interpreted as visible in Figure 1.
This condition has been selected since power generation results not to be critical at the distance at which this mode is triggered ($\lesssim 1.4$ AU)[1]. The shadow of the antenna shall cover entirely the vault below it as a first and conservative approximation. The resulting APE angle is reported in Table 1. This value is relatively high with respect to other more restrictive modes, hence it won't be the sizing factor for the choice of AOCS hardware.

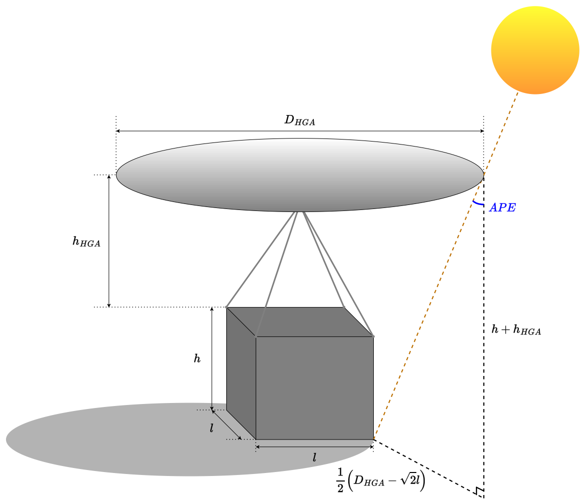

Figure 1: Sketch for APE evaluation

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)[1]. 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. The APE for this mode depends on the antenna that will be pointed to Earth: when the switch from SPM happens, the MGA is first pointed to Earth and subsequently the HGA is activated. The most restrictive APE is given by the beamwidth of HGA. This mode is always relative to the interplanetary phase and is the main one used throughout the cruise. The spin rate of 1 RPM ensures stability of the axis that is pointing to Earth.

2.3 GRAVity science Mode (GRAVM)

The GRAVM is the principal mode for science operations orbits around Jupiter. It aligns the +Z axis towards Earth in order to communicate and to perform the gravity experiment with the HGA. Hence, the APE is related to the antenna beamwidth specification, moreover the SPE angle is always low enough ($\lesssim 10°$)[2] to ensure enough power generation from the solar cells. The spin rate for this mode is fixed at 2 RPM to ensure payload requirements and also adds stability to the axis pointing, which is more perturbed due to the vicinity with Jupiter.

2.4 MicroWave Radiometer Mode (MWRM)

The MWRM is the secondary mode for science operations orbits around Jupiter. It aligns the +Z axis orthogonally to the orbital plane in order to nadir point the dedicated instrumentations, which are placed on the lateral surfaces of the S/C. The spinning axis is off-set from the Earth direction of 24°÷27°[3]. The MWR orbits are carried out at the early stages of the Juno mission due to the accentuated degradation of the MWR payload. Furthermore, the mode occurs only around the PJ passage to acquire data without D/L. To send the information, Juno switches to GRAVM at the end of the experiment in order to align HGA and MGA towards Earth[2]. The spin-rate is nominally set at 2 RPM since it comes from the payload requirements, in addition it augments stability to the pointing axis. The need to have a dedicated mode for the MWR experiment rises from the requirements on the payload itself. In particular, the MWR antennas shall follow the S/C ground track on Jupiter within an aperture of ±5.4°, which is imposed by the beamwidth of the smallest one[4]. The latter angle can be identified as the APE of this mode.

2.5 Turn-Burn-Turn Mode (TBTM)

The TBTM is performed when the alignment of the main engine (-Z axis) needs to be parallel with the ΔV direction of the ME manoeuvre (DSMs, JOI, PRM). In particular, a slew manoeuvre of approximately 90° with a rate of 0.1°/s is first performed. This is done to align the +Z axis with the interested direction of the burn. The thrusters are also activated to spin-up the angular rate at 5 RPM to ensure stability throughout the ME burn. During this time, the only communication link with Juno is through tones via TLGA. The end of the operation of the ME is followed by the decrease of the spin rate at 2 or 1 RPM, depending on the mission phase. The APE of this mode is related to the precision required by the alignment of the ME. Since from literature no specific requirement was mentioned, a numerical evaluation was conducted in order to enlighten the effects of a misalignment from the nominal ΔV. In particular, the manoeuvres affected by this uncertainty are:

- **DSM-1**: an error on this manoeuvre could be easily solved during DSM-2, so it is not critical in APE evaluation;
- **DSM-2**: an error on this manoeuvre could lead to a failure on targeting Earth for EGA, since the following TCMs could not be sufficient to correct the trajectory;
- **JOI**: a contained error in the direction for this manoeuvre unlikely could lead to a catastrophic failure of the mission; instead the error could be corrected later by OTM;
- **PRM**: as for the JOI, the error could be fixed easily during the next phases of the mission.

From these observations, the DSM-2 was selected as the most critical manoeuvre, hence it was better analyzed through numerical simulation. From ephemeris, the velocity vector after DSM-2 was taken as the nominal one. Then, in order to add the error due to APE, the nominal velocity was shifted within a cone of semi-aperture α_{APE} without changing the magnitude and then propagated until the date of the nominal EGA. Two values of α_{APE} were tested through this method, results can be seen in Figure 2 and Figure 3.
TCMs are performed throughout the interplanetary phase to correct the path, nevertheless their magnitude is limited to ≈ 9 m/s[5]. For this reason, a certain precision on TBTM is required.

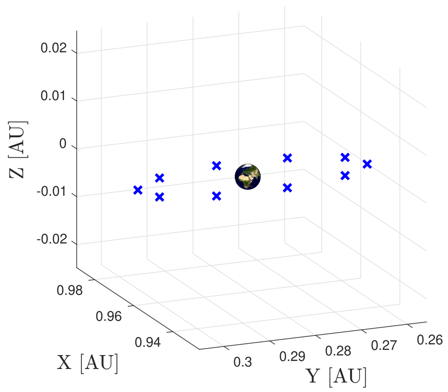

Figure 2: Simulation results for $\alpha_{APE} = 0.25°$

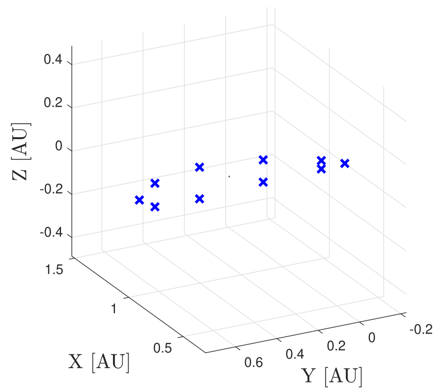

Figure 3: Simulation results for $\alpha_{APE} = 5°$

2.6 VECtor Mode (VECM)

The VECM is performed for OTM and TCM with RCS only. The +Z axis pointing is maintained (Earth or Sun depending on the phase) and the same for the spin rate (1 or 2 RPM for interplanetary or science phase respectively). The direction of the burn is then decomposed into two directions (axial and lateral). The APE during this mode is inherited from the current phase.

2.7 Spin Change Mode (SCM)

Due to the nature of the spin-stabilized S/C, a control mode on the angular velocity is mandatory. The SCM is performed through RCS and it can be requested by other modes (TBTM) or executed by itself during cruise (before and after the fly-by). The Juno nominal spin rates are:

- 1 RPM for the interplanetary cruise;
- 2 RPM for the science orbits and the EGA (for payload requirements and pointing stability respectively);
- 5 RPM for the ME manoeuvres (for stability of the ΔV direction).

The tolerance on the spin rate is ±0.05 RPM[3].

2.8 Safe Modes (SM)

Safe modes are mainly divided into two different types, depending on whether three-axis attitude knowledge is retained or not.

- **SM-1**: the attitude is known, so the satellite maintains its current pointing (Earth or Sun). The required APE is inherited from the particular pointing in which the mode was triggered.
- **SM-2**: the attitude knowledge is lost. In this critical eventuality, the +Z axis will cone within 2° around the Sun. The APE is not specified for this configuration since it cannot be assured. The LGAs could be used to communicate thanks to the large beamwidth.[6]

2.9 Pointing budget

	SPM	EPM	GRAVM	MWRM	TBTM	VECM	SCM	SM-1
TCS	$APE \leq 25°$	-	-	-	-	$APE \leq 25°$	-	$APE \leq 25°$
TMTC	-	$APE \leq 0.25°$	$APE \leq 0.25°$	-	-	$APE \leq 0.25°$	-	$APE \leq 0.25°$
PS	-	-	-	-	$APE \leq 0.25°$ $rate = 0.1°/s$	-	-	-
P/L	-	-	$APE \leq 0.25°$	$APE \leq 5.4°$	-	-	$APE \leq 0.05$ RPM	-

Table 1: Pointing budget for AOCS

Table 1 synthesizes the pointing requirements of the main subsystems of the S/C in terms of performance for the AOCS. The empty cells in the table indicate no influence of the subsystem in the pointing budget for the selected mode. It can be noticed that the most stringent APE is 0.25° (inherited by the beamwidth of HGA), which is compliant with the precision obtainable by the spin-stabilized thruster configuration of Juno coupled with the chosen sensors. For TBTM the same APE as the HGA was arbitrarily selected after the analysis described in subsection 2.5. In particular, this choice has consequences on the required precision for the sensors: since during TBTM the SRU must be deactivated, the other sensors have to be selected in order to keep the same precision.
In Figure 4 the sequence of the different modes for the nominal mission is correlated with the phases. The OTMs performed in VECM during science phase are not shown for sake of clarity.

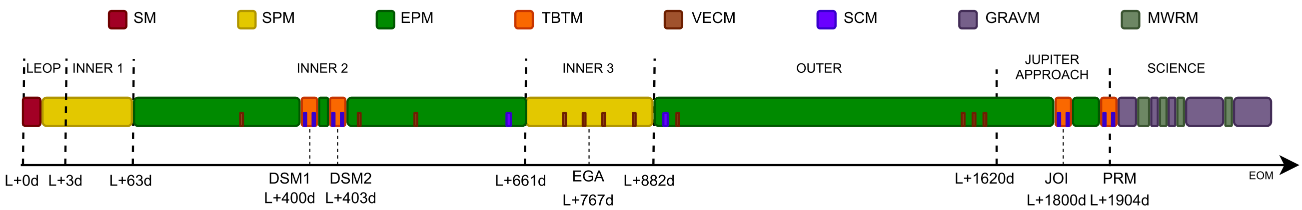

Figure 4: Timeline for mission phases (not in scale)

3 Architecture and rationale of AOCS

To achieve the required performance and capabilities of each mode, highlighted in section 2, Juno's AOCS is rather complex. It is based on the simple concept of a spin-stabilized spacecraft, but it's aggravated by the pointing requirements, the expected harsh environment and the required reliability for the mission. The choice for this particular design is due to several motivations: the possibility to grant visibility for more payloads with just one mode, the reduction of total mass and complexity, good stability for limited power consumption exploiting the mass distribution due to radial positioning of the large solar arrays. The on-board hardware and the rationale of its choice are presented here.

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[7], modified with further radiation shielding to survive the harsh environment of Jupiter, bringing the total weight of each one 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. Main specifications of the standard A-STR are reported in Table 2.

FOV [deg]	Bias Error [arcsec]	FOV error [arcsec]	Mass [kg]	PC [W]	OT [°C]
16.4 × 16.4	8.25 (pitch/yaw) 11.1 (roll)	< 3.6 (pitch/yaw) < 21 (roll)	3.55	8.9 @ 20°C 13.5 @ 60°C	-30 to +60

Table 2: A-STR specifications

- **2 Spinning Sun Sensors (SSSes)** by Adcole Maryland Aerospace[8], positioned on the edge of the forward deck oriented in such a way to include both the Z-axis and a portion of the XY plane in their FOV. They are specialized in attitude determination on a spinning spacecraft and allow for a fail safe recovery. Useful specifications are shown in Table 3.

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

Table 3: SSSes specifications

- **2 Inertial Measurement Units (IMUs)** by Northrop (Hypothesizing heritage from Cassini[9] and MESSENGER[10]) placed inside Juno's radiation vault. 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)[11] are used which were also modified for this specific mission like the A-STR. Their nominal specifications are shown in Table 4.

Power [W]	Weight [kg]	OT [°C]	ARW [deg/$\sqrt{\text{hr}}$]	HAMRR [deg/s]
43 max	7.1	-55 to +85 (non-operational) -10 to +60 (full performance)	< 0.00015	± 7

Table 4: 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 suite, 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 a 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.[12]

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[13] divided into four redundant 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. The pylons are raised respectively by 74 cm on the forward deck and about 26 cm on the aft deck. As shown in Figure 5 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[5]. The specifics of the MR-111C thrusters are presented in Table 5.[14]

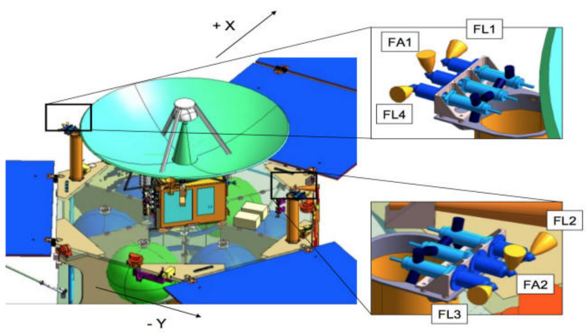

Figure 5: RCS mount direction

Thrust [N]	I_s [s]	MIB [Ns]	Propellant	Catalyst	Mass [kg]	Power usage [W]
4.5	220	0.08	Hydrazine	S-405	0.33	13.64

Table 5: 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.[15] An active nutation damper is also installed on-board, able to reduce unwanted nutation by generating a controlled damping torque.[16] Given the stringent pointing requirements an active system was chosen for its higher damping rate with respect to a passive one.

3.3 Rationale

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

- **SRUs:** star sensors are the most accurate and are capable of complete AD independently of any other sensor, they are used during most of the mission when Juno is pointing either the Sun or the Earth, so in all modes except for the TBTM and SM-2, during which they are shut down. 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:** one is always on to further enhance AD, while both of them are used during SM-2 to obtain a coarse attitude determination. Since a SM entry could happen at any point of the mission the SSSes FOV need to cover all possible orientations of Juno: Earth pointing, Sun pointing and the necessary pointing for ME burns.
- **IMUs:** since the sun sensors aren't capable of a complete AD while the SRUs aren't being used, so during TBTM, another component able to do so is required and IMUs were the only remaining choice. They are also employed during large precessions (larger than $\sim 2.5°$) and required for active nutation damping and spin control.[16]
- **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 is due to the need of limiting the interaction of the exhaust gasses with the on board instruments, the HGA and the solar arrays. Being the only actuators present on-board, thrusters are used during all control modes.

4 Reverse sizing of AOCS

In this section a reverse sizing of the AOCS is performed. The complexity of the dynamics of a spinning stabilized satellite only controlled via RCS required the use of a Simulink model, developed by us and presented in subsection 5.1.

4.1 Modeling hypothesis

The preliminary reverse sizing process is based on some reasonable assumptions:

- **Geometry**: Juno spacecraft has been modelled via SolidWorks software, simplifying its shapes but conserving the general dimensions, in particular the size of the solar panels, the vault and the central body. The mass of the system is assumed to be constant throughout the whole mission, at 3625 kg, so the propellant mass needed is overestimated. Principal moments of inertia, calculated from the centre of mass, are assumed to be aligned with the geometric axes of the model: this assumption is pretty compliant with the real satellite dynamics thanks to the actuators mounted on solar panel as described in subsection 3.2.
  The central body was designed as an hexagonal prism with an height of 1.48 m and sides of 1.79 m, the three solar arrays as thin panel of 8 m × 2.7 m × 0.03 m, one of them shorter at 6m due to the presence of the MAG boom, the vault as a rectangular prism of 0.8 m × 0.8 m × 0.7 m and the HGA as a rotational ellipsoid with a major semi-axis of 1.25 m and a minor semi-axis of 0.625 m. The view of the used shapes is presented in Figure 6.

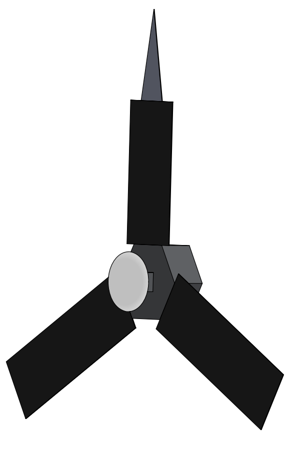

Figure 6: Juno CAD model

- **Sensors**: the attitude of the spacecraft is assumed to be correct at all times. No errors are present as nor SRUs nor IMUs nor SSSes were modelled.
- **Thrusters**: all twelve thrusters are decoupled one from the other. This assumption changes the dynamics of the spacecraft as the real satellite has to perform various burn via RCS in VECM while in the model only one burn is required. Different arms for each thrusters were considered as they are not symmetrical with respect to the centre of mass: 2.7 m for thruster controlling X and Y-axis, 3.2 m for the thrusters controlling the Z-axis.
- **Controller**: as the performance of the various manoeuvres is influenced by the chosen control law. Parameters as maximum angular speed and acceleration, total time of the manoeuvres are employed to verify the obtained results.
- **Phases**: only two phases have been considered for disturbances correction with different disturbances: IC from L+3 to L+822 and jovian planetary phase. OC was not considered as SRP lowers and no other significant disturbances act on Juno. However, the same amount of fuel consumed during ICs will be allocated for the OC to point Earth for telecommunications. For the IC phase three different sections are considered: IC 1, IC 2 and IC 3. Relations between this sections and different modes in shown in Figure 4. Sun pointing has been considered for all three sections as a worst case scenario sizing, even if IC 2 is a Earth pointing mode (Earth and Sun are almost aligned in this section so the reasoning is not that far off). During each section of the IC, the SRP is considered constant as the integral mean value calculated on the length of the section. For the correction manoeuvres, the following division was implemented: for 20 days only correction about the angular speed are considered as the attitude error is lower than the required as stated in section 2; then, a 20 minutes correction manoeuvre is performed to align the spinning axis with its nominal direction. Slew manoeuvres are also considered to take into account the movement of the spacecraft relative to the Sun as the pointing cannot be considered inertial. The simulation takes into account only one trial and assumes no difference are present between contiguous sections. Realignments of Juno's axis can be related to safe-modes and general to correction manoeuvres as the system is able to handle different disturbances from the nominal orbit.

  Jupiter planetary phase takes into account SRP, magnetic disturbances and gravity gradient (GG). The considered orbits for the simulation consists in a 11-days elliptical orbit, repeated for 33 times as the nominal mission required.
- **Manoeuvres**: two different kinds of manoeuvres were modelled. Slew manoeuvres at each DMS, where the TBTM is employed. A worst case scenario has been identified, within the DSMs requirements, with a change of 90° in angular momentum orientation. Observed rate of this manoeuvre from Nasa Eyes[17] shows an angular velocity of about 0.1 °/s[18]. This will be used as the maximum value allowed.

  To simulate SPCM only the spin of the spacecraft along the main spin axis (+Z-axis) is controlled and no attitude corrections are performed.

4.2 Perturbations

There are four attitude perturbations that need to be analyzed: solar radiation pressure (SRP), gravity gradient (GG), magnetic and aerodynamic disturbance. In the harsh environment of Jupiter some of those had a significant impact on the spacecraft, while others could be neglected.

- **Magnetic Torque**: this disturbance was considered only around Jupiter. The model used to describe its magnetic field consists in a dipole modelled based on the work of Acuña et al[19], and its value is shy of $4.3 \cdot 10^{-4}$ T. Juno's magnetic dipole was assumed from literature, considering an high value as a worst case scenario of 0.05 Am^2.
- **SRP**: this disturbance is considered both during the IC and the jovian phase, however, in the latter phase, had a less relevant effect as the intensity of the radiation coming from the Sun goes with the inverse of the distance squared. Values considered in the different phases and sections are reported in Table 6. As previously mentioned in section 2, solar radiation is higher during IC 1 and 3, where the spacecraft is closer to the Sun as can be seen in the first row of Table 6.

  SRP applies a torque on different surfaces: the cross section of Juno that faces the Sun is 70 m^2. This value was, as a first approximation, divided in three equal parts, as the number of solar arrays: the torque is computed by considering the SRP acting in the barycenter of each panel. The large area considered made the SRP the dominant perturbation throughout the whole IC phase, despite of the distance from the Sun. The total torque is only applied to the Y-axis due to the geometry of the spacecraft. Reflectivity was considered of 0.55 for all surfaces facing the Sun, while the arms of the torque were calculated from the CAD model.
- **Gravity Gradient**: this disturbance is considered only during the planetary phase around Jupiter. As can be seen from the last row of Table 6, it is various orders of magnitude lower than the SRP during the other phases. The value considered for the various IC is derived from the medium distance between Juno and the Sun, while value for the jovian phase is reported as the maximum found around the whole orbit, but it is not the value considered, in fact the dynamics of this disturbance was modelled around the real first nominal orbit of Juno around Jupiter, when the spacecraft is facing the Sun, so no worst case scenario was considered alone.

	IC 1	IC 2	IC 3	Jovian phase
F_s $[W/m^2]$	1225	413	1339	$4.08 \cdot 10^{-2}$
$Torque_{SRP}$ [Nm]	0.991	0.33	1.08	0.04
$Torque_{GG}$ [Nm]	$3.5 \cdot 10^{-10}$	$5.4 \cdot 10^{-11}$	$3.5 \cdot 10^{-10}$	$5.39 \cdot 10^{-4}$

Table 6: SRP and Gravity Gradient relevant values

- **Atmospheric Drag**: this disturbance is meaningful only in case of a dense atmosphere. During the IC phase, Juno is in the vacuum, so no atmosphere is present. For the planetary phase, the atmosphere can be neglected as at 1000 km of altitude, density is in the order of 10^{-11} kg/m^3 and Juno's lowest approach is above 4000 km. Supposing an exponential decay of the density with altitude, as in Earth's atmospheric model, the value of the density allows to not consider the atmospheric drag as a disturbance[20].

4.3 Propellant reverse sizing

Results of the control action in various scenarios are analyzed in this section.

- **SCM**: this control mode is employed 10 times to change the angular speed of the spacecraft in order to perform or ME burns or science operations. Nominally Juno is spinning at 1 RPM during every cruise phase, 2 RPM during science operations and Fly-by and at 5 RPM during all ME burns. A total of 10 manoeuvres of this kind were performed, 5 spin-ups and 5 spin-downs, distributed along the whole mission. A total of 33.14 kg of hydrazine was found to be consumed. A maximum acceleration of 0.05 °/s^2 was found. In Table 7 are reported the amount of fuel utilized for each single change in spin and the number of times it had to be performed, in one way or the other: first column spin change were performed before and after DSMs and before JOI; second column before and after the Fly-by while last column after the JOI and before and after the PRM.

	1 RPM ↔ 5 RPM	1 RPM ↔ 2 RPM	2 RPM ↔ 5 RPM	Total
Fuel Consumption [kg]	4.27	1.07	3.21	33.14
# of occurrences	5	2	3	10

Table 7: Spin manoeuvres

- **Slew manoeuvre**: this specific manoeuvre is performed eight times to align the ME with the required direction to perform a burn subsection 2.5, twice for each DSM while spinning at 1 RPM, twice for the JOI once spinning at 1 RPM and once spinning at 2 RPM and twice for the PRM while spinning at 2 RPM. A worst case scenario is always considered with a 90° realignment.[15] All the slew manoeuvres are performed with a maximum velocity of 0.1 °/s as stated in subsection 4.1. Given the considerable moment of inertia along the Z-axis, higher rotational speed imply a significant augment in fuel consumption. Results are of 2.7 kg for each slew at 1 RPM and 6.28 kg for each slew at 2 RPM. Total consumption for these manoeuvres is 32.34 kg.
- **Interplanetary Phase corrections**: in this control mode only the SRP is considered as perturbation SRP affects both angular speed and the attitude of the spacecraft. Corrections of the angular velocity are continuously performed to ensure stability in pointing without correcting the attitude directly. However, after a 20-day period corrections are needed to align the HGA to its nominal pointing requirements.[15]. All constraints cited in subsection 2.9 are respected. The consumption of hydrazine in these phases is reported in Table 8.

	IC 1	IC 2	IC 3	Total
Fuel Consumption [kg]	4.82	3.00	13.94	21.76

Table 8: IC consumption

- **Jovian planetary Phase**: while around Jupiter, Juno performs science while spinning at 2 RPM, ensuring natively an higher robustness to disturbances. Major correction must be performed near the pericentre of the orbit, as it speed approaches 58 km/s. Requirements in pointing could be satisfied in this phase as the maximum error achieved during the simulation was lower than 0.025°. Consumption of hydrazine is estimated at 1.01 kg per orbit, 33.24 kg for the whole nominal mission. An important note shall be made in regards of the planetary phase: propellant consumption is based on the 11-day orbit around Jupiter, planned but never actually performed. Consumption during the real 53-day orbit is actually lower, as both gravity gradient and magnetic disturbances diminish with distance, allowing for a longer life mission.

A total of 142.24 kg of fuel were found to be consumed. If margins are considered as in Homework 2, the computed value is shy of the real on-board mass.

5 Appendix

5.1 Simulink model description

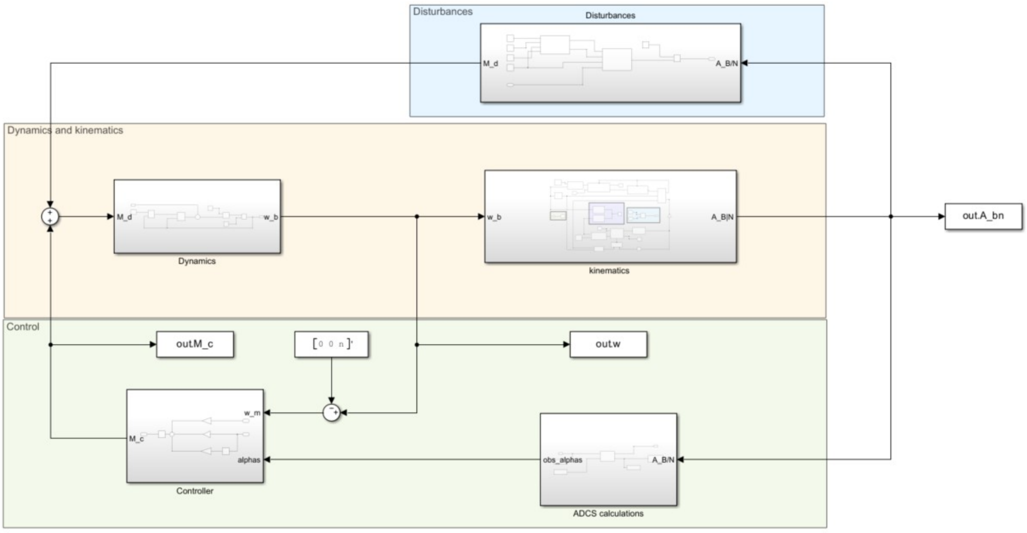

Figure 7: Simulink model of the dynamics

The model used to mimic the dynamics of Juno is reported in Figure 7. Here three main blocks can be distinguished:

- **Dynamics and kinematics**: the behavior of the spacecraft is described by the Euler equations and the attitude kinematics is continuously updated via Euler angles.
- **Disturbances**: all the disturbances affecting Juno's attitude are here implemented. Based on the different requirements of the phase, only some are considered. For the planetary part, the highly elliptical orbit has been modelled as restricted two body problem.
- **Control**: this part is responsible of calculating the target attitude and its errors at each time-step, allowing the controller to satisfy the pointing requirements of the current phase.

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