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Reverse Engineering of Juno Mission
Final report

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Group 5

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Notation

MAG	Magnetometer
HGA	High Gain Antenna
ΔV	Velocity budget
DSN	Deep Space Network
LEOP	Launch and early orbit phase
SECO	Second engine cut off
L+	Time after launch
PJ	Perijove number
MWR	Microwave Radiometer
JEDI	Jupiter Energetic-particle Detector Instrument
JADE	Jovian Auroral Distribution Experiment
UVS	Ultraviolet Spectrograph
JIRAM	Juno Infra-Red Auroral Mapper
EGA	Earth Gravity Assist
JOI	Jupiter Orbit Insertion
DSM	Deep Space Manoeuvre
PRM	Period Reduction Maneuver
GSO	Gravity Science Orbit

1.1 Introduction

Juno is a NASA spacecraft orbiting Jupiter. Built by Lockheed Martin and operated by NASA, it was launched by an Atlas V551 on the 5^{th} of August 2011. After 5 years, during which many maneuvers occurred, including an Earth flyby, Juno entered a polar orbit around Jupiter and started its observation, which lasts to this day. Its aim is to study the planet to understand its composition and evolution, analyzing its gravitational and magnetic fields and its atmosphere dynamics. The mission should have ended in 2017, but it is still ongoing[1] and it will end with a de-orbit that will destroy the spacecraft into the planet's atmosphere to avoid contaminating the environment.

1.2 High level goals

Through an analysis of the mission and payload, the main goals of the mission can be highlighted.

1. **How did Jupiter form and influence the solar system?**[2][3]
   Since Jupiter is the biggest planet of the solar system, it has influenced the formation of all other planets. Its composition has remained unchanged ever since, making it like a time capsule: understanding how and where it formed could give knowledge on Earth and the whole solar system's origin, evolution and characteristics.
2. **What's Jupiter's deep structure?**[3][4]
   One important aspect of the mission is the analysis of Jupiter's deep structure through the measurement of radiations, magnetic and gravitational fields. This allows to comprehend whether or not the planet has a solid nucleus, if so how large it is, and to analyze the supposed layer of metallic hydrogen, compressed so much that it loses its electrons creating a conducting layer. Moreover, Juno will possibly reveal if Jupiter is rotating as a solid body or if the rotating interior is made up of concentric cylinders.
3. **What's the structure of Jupiter's atmosphere?**[3][5]
   One of the mission's goals is to study the composition and dynamics of Jupiter's atmosphere, composed by stripes and dots made of different gasses and vapors, including water, whose percentage has to be defined. A significant aspect of the analysis is the great red spot, a swirling mass of gas bigger than Earth, which resembles a hurricane but is very different in the way it works. The movement of stripes and dots is dictated by the weather, characterized by lighting an thunderstorms, which are observed by Juno.
4. **What do auroras look like and what are the physical processes generating them?**[3][5]
   Juno's orbit is designed to be polar, to allow the observation of Jupiter's poles and the analysis of its auroras, representative of the interaction between charged particles and the atmosphere. Studying this phenomenon allows a better understanding of the atmospheric composition and the magnetic field's structure and extension.
5. **What do the poles look like?**[3]
   One of Juno's side goals is the observation of Jupiter's poles, which had never been possible before because of the absence of a polar orbiting spacecraft. This also increments the public's involvement in the mission.

1.3 Mission drivers

Being Juno an interplanetary mission starting from a distance of around 1 AU, with a final nominal distance from the Sun of 5.2 AU, and operating in an highly radiation intense environment, the following drivers have been identified:

1. **Using proven technologies**[6]
   The total program is financed with 1.1 Billion \$ for 74 months from the launch date and includes development of the spacecraft, science instruments, launch services, mission operations, science processing and relay support. The simplicity and the need of proven technologies was thus fundamental. The spacecraft is mainly maintained stable during the manuevers thanks to its spin, raised to 5 RPM from 2, nominal condition during science operations, reducing the need of active stabilization methods.
2. **Providing enough electricity during the duration of the mission**[3][6][7][8][9]
   The journey of Juno is long and passes through different regions of the solar system. Solar panels were chosen to provide electric energy across the mission over a nuclear source, since it has been decided that it was better to advance technology of solar cells rather than developing a new reactor. It is the first spacecraft to operate with solar panels at such distance from the Sun. The system needed is thus oversized at 1 AU: the solar radiation on Jupiter is in fact up to 96% lower than on Earth. Furthermore the operations are scheduled to begin around 5 years into the mission, so degradation of the solar cells must be taken into account. The final design consists in 11 solar panels, eight are 9 by 2.65 m each, meanwhile the inner three are only 2 m wide, resulting in a surface of about 60 m^2 and granting a maximum power of 14 kW around Earth and up to 500 W around Jupiter. The solar panels are mounted in three arrays on the side of hexagonal body of the spacecraft at 120° one by the other, three arrays are composed by 4 panels, one by 3. This configuration is needed to mount the MAG faraway from the electronics and store everything correctly inside the fairing. Before separation from the upper stage, the spacecraft is spinning at around 1.4 RPM and the deployment of the solar arrays slows it down to 1 RPM. Moreover, since the fly-by around Earth is done to gain ΔV, the spacecraft will be in an eclipse for around 20

minutes: attention must be paid to size the battery. Two lithium-ions battery of 55 Ah each are present to make sure power is always provided. The nominal polar orbit around Jupiter allows Sun pointing during the majority of nominal Science Operation phase.

3. **Shielding the instruments from the harsh environment of Jupiter**[1][2][10][11]
   To accomplish its goals, Juno will need to cross the Jupiter radiation belts: a heavy shielding structure is needed. The magnetosphere represents a great challenge for Juno: the value of the magnetic field measured at its perijove is 776 μT, 50% higher than expected. The main issue with Juno is represented by the ionizing particles present in the belt around Jupiter: with measured value up to of tens and hundreds of MeV ions located between 2 and 4 R_J, order of GeV were expected under 2 R_J, where Juno should pass through to reach a lower altitude, thanks to its highly elliptical orbit, where radiations are lower, to perform science. The vault in which all the electronics is preserved is cubed shaped and it is made of 1 cm thick titanium alloy, 144 kg in total. The top deck of Juno is planned to receive a radiation dose of 22 Mrad. Moreover, star trackers are also heavily shielded.
4. **Maintaining communication during the journey and the science operations**[6]
   The attitude of the spacecraft is defined in a way to point Earth during most of the cruise and science operations. This configuration, given the distance from the Sun and the Earth, grants also a sufficient inclinations of the solar panels with respect to the Sun to provide enough electric power. The ground equipment used by Juno is NASA's DSN.

1.4 Functional analysis

Functional analysis is performed in order to identify the functionalities that the spacecraft must perform during the mission. The identified functionalities are schematized in Figure 1.1.

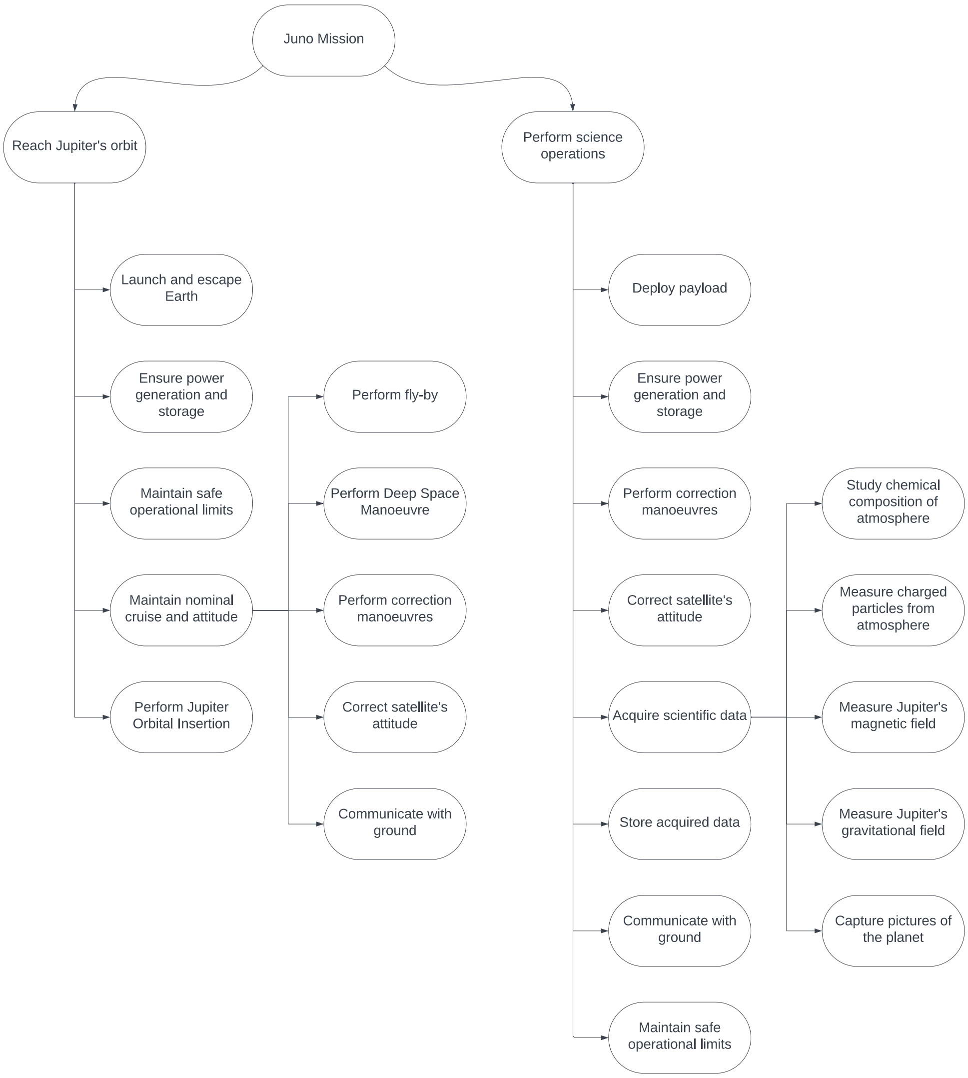

Figure 1.1: Functional analysis for Juno mission

1.5 Main mission phases

The Juno mission was divided into five phases: LEOP, Cruise, Jupiter approach and insertion, Science Operations and De-orbit.

1. **LEOP**
   Following the launch from Cape Canaveral, the spacecraft entered a low Earth parking orbit.[6] Afterwards Juno was injected in an interplanetary trajectory and was separated from its upper stage after SECO-2 at time L+54 min. The solar panels deployment was performed about five minutes after the spacecraft separation, and it took approximately five minutes.
2. **Cruise**
   The cruise had a duration of about five years, during which two deep space manoeuvres, multiple minor corrections and an Earth fly-by were performed. All manoeuvres will be better described in section 1.8. This phase also included instruments testing and verification, to ensure they were functioning properly and ready for the usage during the mission.
3. **Jupiter approach and insertion**
   This phase began four days before the start of orbit insertion manoeuvre and ended one hour after the start of the orbit insertion manoeuvre. The latter occurred at closest approach to Jupiter and slowed the spacecraft down enough to let it be captured by Jupiter in a 53-days period orbit. The Jupiter orbit insertion burn was performed by the Leros 1-b main engine, and it lasted 30 minutes. After the burn, the spacecraft was in a polar orbit around Jupiter. The 53-days orbit provided substantial propellant savings with respect to the direct insertion in the operational orbit.
4. **Science operations**
   The Juno polar and highly eccentric orbit was designed to facilitate the close-in measurements and to minimize the time spent in the Jupiter radiation belts. During this phase all the science operations, in different attitudes, are being performed.
5. **De-orbit**
   The de-orbit phase will occur during the final orbit of the mission. The latter was designed to satisfy NASA's planetary protection requirements and ensure that Juno doesn't impact any of Jupiter's moons. A de-orbit burn will be performed, placing the spacecraft on a trajectory towards Jupiter inner and denser layer of the atmosphere where it will burn up.

1.6 ConOps

The mission's Conceptual Operations are summarized in Figure 1.2.

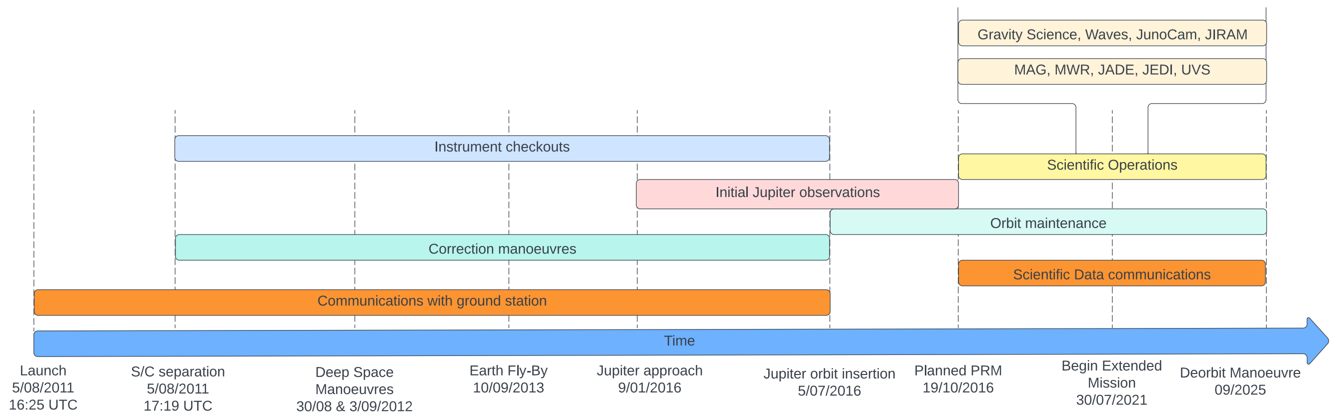

Figure 1.2: Conceptual Operations, time not in scale[6][12][13][14]

1.7 Payload analysis

1.7.1 Instruments overview

As previously described in section 1.2 the mission scientific goals are quite numerous and diverse. Thus, to achieve all of them, the payload consists of several instruments, nine to be precise, covering a wide spectrum of experimentation. In its entirety the payload has a mass of around 174 kg and consumes approximately 125 W of power excluding the Gravity science experiment.[7] Here we have a brief overview of all the singular instruments where, unless otherwise specified, only the sensors are mounted on the exterior of the spacecraft, while all the relevant electronics are located inside the radiation vault.

- **Magnetometer (MAG):** As the name implies its objective is to accurately measure Jupiter's magnetic field, achieved by employing two flux-gate magnetometers, a scalar helium magnetometer and two star cameras. All the sensors are mounted on the magnetometer boom, located at the end of one of the solar array wings to reduce the interference from the spacecraft itself. Even then the presence of two magnetometers allows to subtract this contribution from the measurement.
- **Microwave Radiometer (MWR):** It consists of six antennas which measure six different frequencies (600 MHz, 1.2 GHz, 2.4 GHz, 4.8 GHz, 9.6 GHz and 22 GHz) in order to investigate the Jovian atmosphere below the visible external layer. A key objective of this analysis is also the determination of the abundance of water inside the planet. The antennas are mounted on two sides of the hexagonal prism that constitutes the main body of the spacecraft, relying on its spin to survey Jupiter.
- **Gravity science:** It's quite a unique instrument as it's composed both by a space and a ground elements, which mainly consists with the telecommunication systems of both the spacecraft and ground stations. This is because this experiment is based on measuring the doppler shift in the returning signal from Juno which, allows to characterize Jupiter's gravitational field. Thus the instrument can't really be separated from the telecommunication hardware, which is the reason why its weight and power requirement were omitted in the previously shown totals.
- **Jupiter Energetic-particle Detector Instrument (JEDI):** It detects high energy electrons and ions present in the Jovian magnetosphere, which are discriminated by composition. Each sensor is characterized by six electron and six ion viewing directions that together cover a $160° \times 12°$ field of view. In total three sensors are present on Juno, two arranged to obtain an almost compete 360° view perpendicular to the spacecraft spin axis, while the third one is instead aligned with it to achieve a full scan of the sky over one spin period. As the JEDI sensors are self-contained units no electronic hardware is present within the radiation vault.
- **Jovian Auroral Distribution Experiment (JADE):** It detects low energy electrons and ions with the same goal of characterizing the magnetosphere as JEDI. The instrument comprises of three identical electron energy per charge analyzers (JADE-E) and a single ion mass spectrometer (JADE-I). The electron sensors are located on the three sides of the spacecraft that do not house the solar arrays pointing outwards, to again obtain a complete view normal to the spin axis. The spectrometer field of view, instead, contains the spin axis and like the third JEDI sensor it scans all the sky over a full rotation.
- **Ultraviolet Spectrograph (UVS):** This instrument images and measures the spectrum of the Jovian aurora in order to understand its morphology and source. The chosen ultraviolet range of $68 \div 210$ nm covers all of the most important UV emissions form the aurora, mainly the H Lyman series and longer wavelengths from hydrocarbons. The sensor is mounted on the side of Juno, relying once more on the spinning of the spacecraft to achieve a full sweep of the planet.
- **Radio and Plasma Waves (Waves):** Its objective is to study both components of the electromagnetic field generated by plasma and radio waves inside the polar regions of Jupiter's magnetosphere to understand its interaction with the atmosphere and magnetic field. To detect the electric component a V-shaped dipole antenna is used, while for the magnetic component a much smaller magnetic search coil is employed. Both sensors cover a vast range of frequencies, namely from 50 Hz up to 40 MHz.
- **Visible-spectrum Camera (JunoCam):** It's designed to provide highly detailed color images of Jupiter to help and support public engagement of the mission without any real scientific purpose. The instrument is thus only comprised of the camera itself, mounted on the side of the spacecraft, and all the necessary electronics which, given the less critical objective and relaxed radiation tolerance requirements, aren't housed in the radiation vault.
- **Juno Infra-Red Auroral Mapper (JIRAM):** It's an infrared imager and spectrometer that studies the Jovian atmosphere in the $2 \div 5$ μm range complementing both the atmospheric and magnetospheric experiments. This instrument is also completely housed outside of the radiation vault since it is a late addition after mission selection, reason for both the relaxed radiation requirements and less than ideal positioning of the sensor on the aft deck of the spacecraft.

All the instruments and their positions can be seen in Figure 1.3.

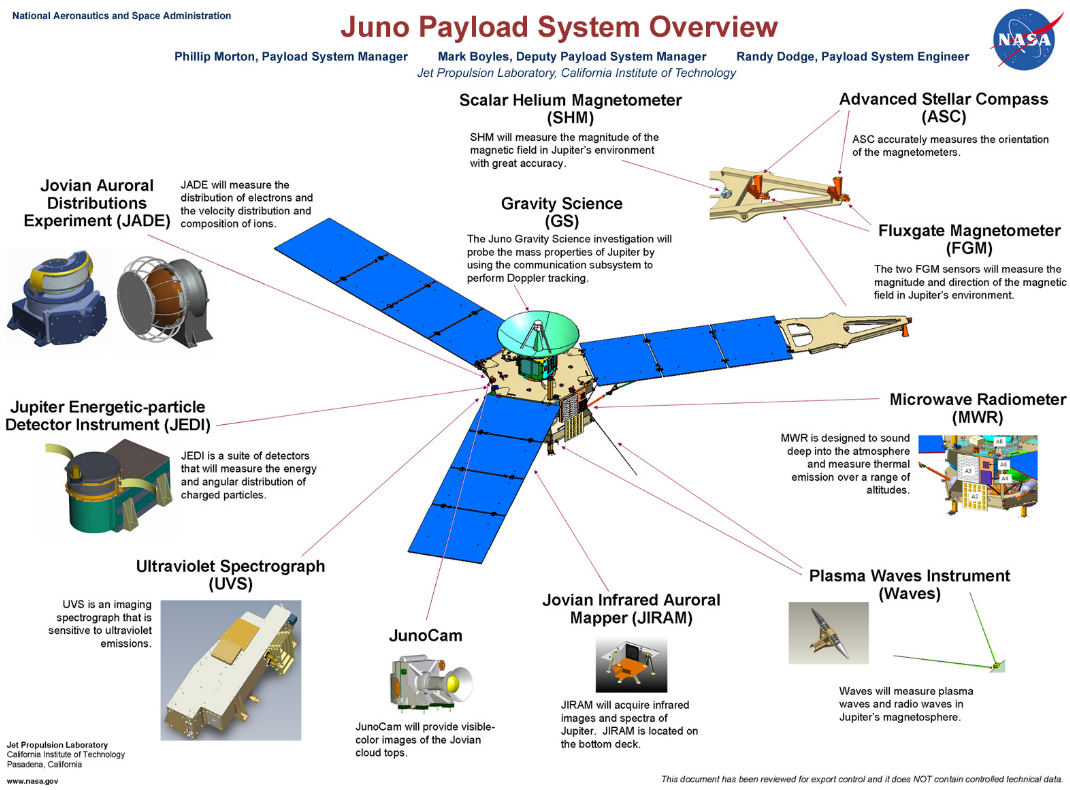

Figure 1.3: Positioning of the instruments on the spacecraft

1.7.2 Payload and Goals correlation

There is a notable overlap in the main objectives of the payload instruments, both in the sense that multiple ones collaborate towards a single scientific goal, but also in the sense that a single instrument can address multiple goals. All of these relations are exemplified in Table 1.1.

Guiding questions	**Science objectives**	**Measurements objectives**
How did Jupiter form and influence the solar system?	Determine Jupiter's inner composition	Composition analysis: MWR
What's Jupiter's deep structure?	Analyze gravitational and magnetic field, measure water abundance in the planet	Gravitational field analysis: Gravity science Magnetic field analysis: MAG Water abundance measurements: MWR
What's the structure of Jupiter's atmosphere?	Analyze atmospheric composition and dynamics	Atmospheric composition determination: MWR Atmospheric dynamics study: JIRAM
What do auroras look like and what are the physical processes generating them?	Image auroras, study interactions between atmosphere and magnetic field, characterize the magnetosphere in the polar regions	Imaging auroras: UVS, JIRAM Atmosphere-magnetic field interaction: JIRAM Characterize the magnetosphere: Waves, JADE, JEDI

Table 1.1: Mission goals and instrument objectives correlation

It can be noted that the JunoCam instrument doesn't appear in the table since it's not part of the scientific goals of the mission, as previously mentioned in its description.

1.7.3 Payload and Phases/ConOps correlation

Another high-level correlation can be highlighted between the mission phases/ConOps and the activities of the payload as shown in Table 1.2.[6]

Mission phases	**Payload activities**
LEOP	Mag boom is deployed together with solar arrays
Cruise	Instruments checks are performed regularly and the high gain antenna (used for Gravity science) is calibrated and aligned
Jupiter approach and insertion	Final instruments checks are carried out together with some initial scientific observations of Jupiter
Science operations	Complete nominal operation of the payload with observations divided between Gravity science passes (Earth pointing) and MWR passes (Nadir pointing)
De-orbit	No planned payload operations

Table 1.2: Mission phases/ConOps and Payload activities correlation

1.8 Mission analysis

1.8.1 Launch and cruise

The spacecraft was launched into orbit with an Atlas V 551 Rocket from Cape Canaveral. The actual launch date belonged to a 21-day time window limited by a number of events and their timings such as the Deep Space Maneuvers, the Earth Flyby, the Jupiter Insertion and the science orbits. The adopted transfer strategy allowed for significant reduction in ΔV with respect to a direct transfer between Earth and Jupiter.

Following the launch, after booster separation, Juno was put in a low Earth parking orbit thanks to a first burn of the Centaur upper stage. Afterwards, at time L+645 s, via a second burn given by the same stage, Juno entered an heliocentric trajectory. Solar arrays were deployed and initial checks on the instruments were performed at this time. This procedure is fundamental in order to provide enough electrical power to the spacecraft to perform initial check on its health. The specific trajectory followed by Juno is called "2 + dV-EGA", which means that the spacecraft will perform an Earth gravity assist at around two years after launch. During the initial cruise various correction maneuvers were performed: the main ones being the two DSMs needed to place Juno on the correct path to achieve the planned fly-by. DSMs were performed near the apocentre, located farther away from the Sun than Mars' orbit, causing the spacecraft to pass as close as 0.88 AU before approaching Earth. During the approach to perform the fly-by, attitude corrections were performed to protect the spacecraft by the incoming radiation from the Sun. The fly-by around Earth occurred on the 10^{th} of September 2013 and puts the spacecraft on its final trajectory to Jupiter. Particularly, the fly-by gave the spacecraft 7.3 km/s, avoiding a fire-up of the Leros 1-b main engine of Juno. A last correction maneuver was performed to refine Juno's trajectory.[4][6][9][15][16]

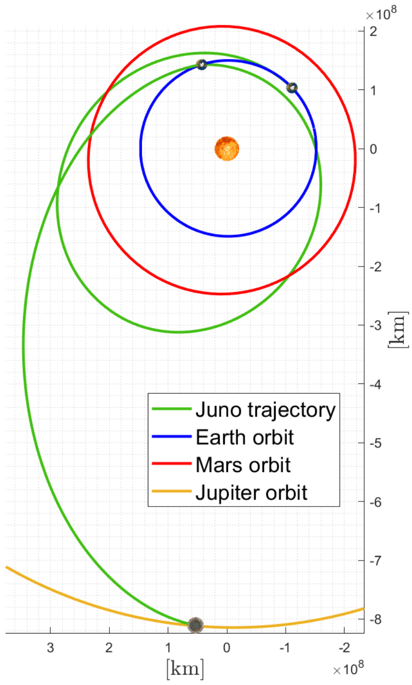

Figure 1.4: Juno's trajectory from ecliptic north pole

1.8.2 Jupiter approach and insertion

After the flyby, Juno spent 791 days on its last interplanetary leg in which no significant manuevers nor scientific operations were conducted. Jupiter approach lasted a further 178 days, during which calibration, validation of the on board instruments and telecommunications checks were accomplished. Initial science observations of Jupiter's distant environment were also performed.

JOI burn was made at the closest approach to Jupiter: this moment is called PJ-0, indicating the first passage at the perijove of Juno. The targeted point for this maneuver is at an altitude of 4200 km, calculated above the 1-bar level of Jupiter. The spacecraft is left on a highly elliptical 53-days period around Jupiter with and inclination of 90° (±10°). Additional clean-up manuevers were planned to correct the trajectory. The attitude during JOI phase, as the spacecraft was slowing down, was such that the HGA was not pointing Earth, constraining communications to low tones, only meant to send information about the completion or failure of the events. After 50 hours from PJ0 all instruments were successfully powered up and started to perform nominal science operations.

1.8.3 Science operations and extended mission

The nominal science orbit, with a period of 14-days, had to be achieved via a PRM at PJ-02. This orbit had been chosen for many reasons:

- it allowed to avoid Jupiter's strongest radiation belts
- enabled near Sun pointing to generate enough electrical power and granted Earth communications via HGA
- it provided the closest possible approach of the instruments to Jupiter's clouds
- it allowed, thanks to Jupiter's oblateness, to scan the whole planet with only 32 orbits obtaining a resolution of 11.25°.

During science operations, two types of orbits should have been performed, differing in terms of spacecraft orientation: MWR passes, which required nadir pointing of Juno's spin plane in order to let the radiometers scan directly the planet, and GSOs, designed to align HGA with Earth.
However, due to a malfunctioning of an helium tank valve, Juno entered Safe Mode for 13.5 hours and PRW was discarded. This change showed the robustness of the designed capture orbit. It was in fact possible to conduct science operations on this longer path with only minor changes: the disposal of the spacecraft had to be moved from 2017 to 2021 to allow the completion of the 35 orbits. Moreover, the 53-days orbit required a slight plane change (from 90° to 105°) between PJ-22 and PJ-23 to avoid a solar eclipse since the batteries are only suited for the 19 minutes eclipse during the Earth fly-by.
The so conducted mission was scheduled to end on July 2021 but the conditions of the spacecraft and the remaining fuel on board allowed to extend the mission by other 42 orbits for 5 more years of mission. During the nominal phases, the PJ had been shifted northwards, so during the extended phase a series of close passes of Jupiter's north polar cyclones occurred. Furthermore, flybys of Ganymede, Io and Europa are performed in addition to an analysis of the faint rings of the observed planet.[1]

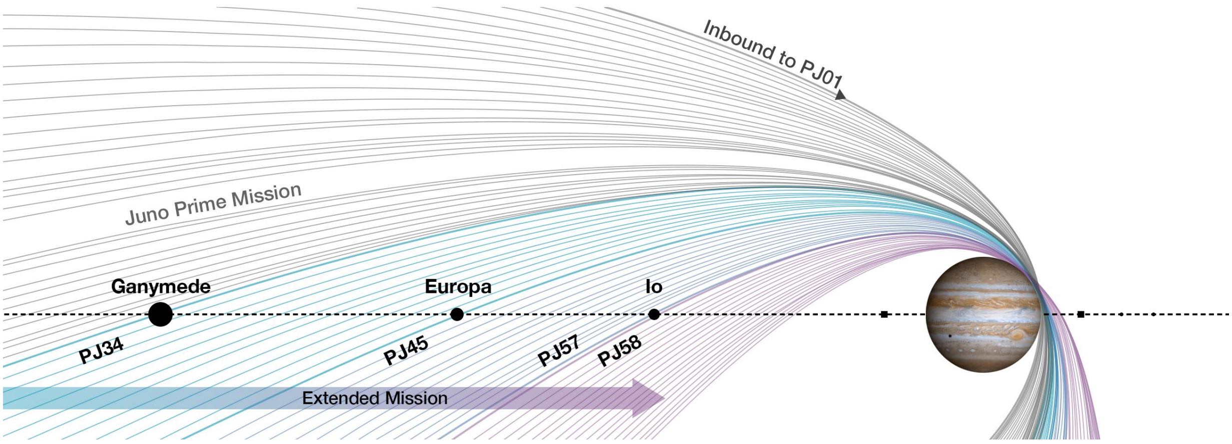

Figure 1.5: Orbits around Jupiter

1.8.4 Mission disposal

Under the planetary protection requirements, Juno is designed to de-orbit itself after the extended mission succeeds. The dose of radiations absorbed during the lifetime of the spacecraft won't allow for safe operations. The de-orbit manuever is supposed to begin with an apocentre burn, slowing down Juno by 75 m/s, enough to lower its perijove in the atmosphere of Jupiter. The dense gas layers will cause the spacecraft to disintegrate.
De-orbiting the spacecraft, now planned in 2025, will eliminate the possibility of contamination of Jupiter and its Moons' environment, especially to avoid unreliable results from the planned ESA Juice mission, expected to enter Jupiter's orbit in 2031.[13][14]

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Homework 2

Notation

ΔV	Velocity budget
ME	Main Engine
RCS	Reaction Control System
NTO	Nitrogen Tetroxide
O/F	Oxidizer to Fuel ratio
M_{dry}	Total dry mass of satellite [kg]
M_{launch}	Total mass of satellite at launch [kg]
M	Total mass of satellite [kg]
M_p	Total mass of propellants [kg]
M_f	Total mass of fuel [kg]
M_{ox}	Total mass of oxidizer [kg]
M_{He}	Total mass of helium [kg]
V_{He}	Total volume of helium [m^3]
I_s	Specific impulse [s]
g_0	Standard gravitational acceleration [m/s^2]
r_{tank}	Radius of spherical propellants tanks [m]
p_{tank}	Pressure of propellants tanks [Pa]
T_{tank}	Temperature of propellants tanks [K]
t_{tank}	Thickness of propellants tanks [m]
V_{tank}	Volume of one empty propellants tank [m^3]
M_{tank}	Mass of one empty propellants tank [kg]
$r_{tank,He}$	Radius of cylindrical helium tanks [m]
$h_{tank,He}$	Height of cylindrical helium tanks [m]
$t_{tank,He}$	Thickness of helium tanks [m]
$M_{tank,He}$	Mass of one empty helium tank [kg]

2.1 Mission analysis and ΔV budget

2.2 Propulsion system architecture

2.3 Reverse engineering of propulsion system

As described in (REFERENCE), the propulsion system counts four tanks for storing hydrazine, two tanks for storing NTO and two tanks for storing helium. To better understand the reasoning behind this choice, a reverse sizing for both the propellants and the pressurizer has been conducted given the data on the engine, the ΔV highlighted in TABLE REF and the total dry mass M_{dry} CITE of the spacecraft. All the process has taken into account the standardized margins from ESA.[1] Since the actual mission has greatly deviated from its initial design, a second propellant sizing was also performed on the real manoeuvres up to 7th June 2021 CITE plus the required de-orbit to check the compliance with the design masses.

2.3.1 Fuel and oxidizer tanks sizing

1. To estimate the masses of the propellants, Tsiolkovsky rocket equation has been applied iteratively on the ΔV of the first column of TABLE REF. This process needs the dry mass $M_{dry} = M^{(0)}$ of the spacecraft as first input and starts from the last ΔV (the de-orbit burn) incrementing the computed total mass $M^{(i)}$ and the propellant mass $M_{p,me}^{(i)}$ or $M_{p,rcs}^{(i)}$ after each iteration.

$$M_{p,me}^{(i+1)} = M^{(i)} \cdot \left[\exp\left(\frac{1.05 \cdot \Delta V^{(i)}}{I_{s,me} \cdot g_0}\right) - 1\right] + M_{p,me}^{(i)} \tag{2.1}$$

$$M_{p,rcs}^{(i+1)} = M^{(i)} \cdot \left[\exp\left(\frac{2 \cdot \Delta V^{(i)}}{I_{s,rcs} \cdot g_0}\right) - 1\right] + M_{p,rcs}^{(i)} \tag{2.2}$$

$$M^{(i+1)} = M^{(i)} + M_{p,me}^{(i)} \qquad \text{or} \qquad M^{(i+1)} = M^{(i)} + M_{p,rcs}^{(i)} \tag{2.3}$$

   where the respective formula is applied based on which engine type performs the i-th manoeuvre.

2. From the final $M_{p,me}$ and $M_{p,rcs}$, the masses of fuel and oxidizer are then computed. This is done by knowing the nominal O/F ratio of the ME[2] and that the RCS only uses hydrazine as propellant. Exploiting the density of the propellants, the total volumes for fuel and oxidizer are retrieved.

$$M_f = \frac{1}{O/F + 1} \cdot M_{p,me} + M_{p,rcs} \tag{2.4}$$

$$M_{ox} = \frac{O/F}{O/F + 1} \cdot M_{p,me} \tag{2.5}$$

   The estimated masses are rather similar to the real ones, as it can be seen in Table 2.4.

	Estimated masses [kg]	**Real masses [kg] CITE**	**Relative error [%]**
M_f	1310.5	1280	2.38
M_{ox}	752.6	752	0.08

Table 2.3: Comparison between estimated and real masses

3. Having the total volumes of propellants, they have been split among the number of spherical tanks. Since the radius r_{tank} obtained for the two types of tanks are very similar and having two different tanks is inconvenient, the larger one was selected.

4. The pressure of the tanks p_{tank} is kept constant (as described in (REFERENCE)). From the pressure and the volume of one tank, the required thickness t_{tank} can be computed by choosing the material, characterized by its density ρ and its tensile strength σ.

$$t_{tank} = \frac{r_{tank} p_{tank}}{2\sigma} \tag{2.6}$$

5. The dry mass of one tank is then computed to select the material:

$$M_{tank} = \frac{4}{3}\pi\rho\left[(r_{tank} + t_{tank})^3 - r_{tank}^3\right] \tag{2.7}$$

Three different materials have been taken into consideration, and the lighter configuration has been selected.

	Ti6Al4V	**Al7075**	**Stainless steel**
σ **[MPa]**	950	510	1400
ρ **[kg/m^3]**	4500	2810	8100
t_{tank} **[mm]**	0.50	0.93	0.34
M_{tank} **[kg]**	5.55	6.46	6.77

Table 2.4: Properties of the materials tested for the sizing of the tanks

2.3.2 Pressurizer tanks sizing

1. As a first approximation, the pressure for the helium tanks is supposed to be ten times the pressure for the propellant tanks p_{tank}, and helium is considered to be a perfect gas (actually it is in a supercritical state). The temperature T_{tank} for the tanks is assumed to be 20 °C. Starting from these assumptions, the mass and the volume of the total required helium is computed as follows:

$$M_{He} = 1.2 \cdot \frac{p_{tank} \cdot 6V_{tank} \cdot \gamma_{He}}{(1 - 1/10)\, R_{He} T_{tank}} \tag{2.8}$$

$$V_{He} = \frac{M_{He} R_{He} T_{tank}}{10 p_{tank}} \tag{2.9}$$

2. Since the two tanks are cylindrical (REFERENCE), the geometry is undefined given only the volume of one tank. To add the missing constraint, a minimization of the total surface is assumed, which can minimize the internal stress due to pressure and the heat transfer through the walls (REFERENCE?).

$$r_{tank,He} = \left(\frac{1/2 V_{He}}{2\pi} \right)^{1/3} \tag{2.10}$$

$$h_{tank,He} = \frac{1/2 V_{He}}{r_{tank,He}^2 \pi} \tag{2.11}$$

3. As already done in subsection 2.3.1, the thickness $t_{tank,He}$ is computed for the materials in Table 2.4 as:

$$t_{tank,He} = \frac{r_{tank,He} \cdot 10 p_{tank}}{2\sigma} \tag{2.12}$$

4. The dry mass of one tank is then computed to select the material:

$$M_{tank,He} = \rho\, h_{tank,He}\, \pi \left[(r_{tank,He} + t_{tank,He})^2 - r_{tank,He}^2 \right] + 2\rho\, t_{tank,He}\, r_{tank,He}^2\, \pi \tag{2.13}$$

As for the propellants tanks, titanium alloy appears to be the lightest solution (Table 2.5). This is the material most likely used for the tanks on the real satellite, and it is the most widely used in space due to its high strength to mass ratio and corrosion resistance.

	Ti6Al4V	**Al7075**	**Stainless steel**
$t_{tank,He}$ **[mm]**	3.60	6.71	2.45
$M_{tank,He}$ **[kg]**	31.14	36.34	37.99

Table 2.5: Thickness and mass of helium tanks for different materials

2.3.3 Computation of actual propellants usage

The second sizing relies on the same procedure highlighted in subsection 2.3.1 with the difference that it starts from the launch mass $M_{launch} = M^{(0)}$ CITE and considers the ΔV from the second column of TABLE REF in chronological order. Equation 2.1 and Equation 2.2 are thus modified as follows:

$$M_{p,me}^{(i+1)} = M^{(i)} \cdot \left[1 - \exp\left(\frac{-\Delta V^{(i)}}{I_{s,me} \cdot g_0} \right) \right] + M_{p,me}^{(i)} \tag{2.14}$$

$$M_{p,rcs}^{(i+1)} = M^{(i)} \cdot \left[1 - \exp\left(\frac{-\Delta V^{(i)}}{I_{s,rcs} \cdot g_0} \right) \right] + M_{p,rcs}^{(i)} \tag{2.15}$$

where the ESA margins[1] were not applied since the actually performed manoeuvres were utilized. The real and consumed masses are reported in Table 2.6.

	Real masses [kg]	Consumed masses [kg]	Remaining masses [kg]
M_f	1280	986	294
M_{ox}	752	560	192

Table 2.6: Real and consumed propellants masses

The *remaining masses* column denotes the propellants masses still present in the spacecraft as of 7th June 2021, which are obtained by subtracting the calculated masses from the real ones. Since the de-orbit is mandatory its ΔV has been considered as a final real manoeuvre even though it hasn't happened yet.

Bibliography

[1] European Space Agency. “Margin philosophy for science assessment studies”. In: (2012).

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