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Reverse Engineering of Juno Mission

Homework 5

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Group 5

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Notation

EGA	Earth Gravity Assist	EPM	Earth Pointing Mode
TCS	Thermal Control System	HGA	High Gain Antenna
TP	Thermal Phase	LILT	Low Intensity and Low Temperature
LEOP	Launch and Early Orbit Phase	SOI	Sphere Of Influence
IC	Inner Cruise	JOI	Jupiter Orbit Insertion
OC	Outer Cruise	BOL	Beginning of the Mission
DS	Deep Space	EOM	End of the Mission
S/C	SpaceCraft	IR	InfraRed
SPM	Sun Pointing Mode		

1 Introduction of TCS

The Thermal Control System of Juno adopts various strategies in order to maintain the instrumentation within operative ranges of temperature. This is done through both active and passive systems, which will be analyzed in [section 3](#). First thing first, an analysis of the mission will be conducted to enlighten the thermal conditions the satellite is exposed to, which range from really hot environment nearby the Sun to extremely cold environment nearby Jupiter. A selection of the two most extreme situations will be done through a preliminary evaluation of the heat fluxes in these phases. In the light of this, the architecture of the Juno's TCS will be studied and justified through a brief rationale analysis. Finally, a reverse sizing will be carried out imposing some simplifying assumptions in order to find the temperatures on Juno and to verify the compliance with its mission.

2 Analysis of thermal conditions along the mission

In this section, the mission will be analyzed and divided in perspective of thermal environment encountered. During this study, the internal heat flux generated by instrumentation won't enter the reasoning. This is done because its maximum value and its variability are both contained during the mission, so it won't affect the sectioning of the TPs and the selection of the hot and the cold cases. The architecture of the S/C won't affect the reasoning and only the heat fluxes from the external environment (Sun flux, planets' albedo and IR emission) will enter this preliminary analysis. A deeper study will be conducted during the reverse sizing in [section 4](#).

2.1 Thermal phases analysis

Different thermal conditions have been encountered by Juno during its cruise. In previous chapters, the mission was divided into phases by different attitude and communication constraints. These phases will be now grouped by the means of thermal constraints to better analyze their evolution during the mission time.

- **TP-1:** in this first phase, which comprehends both LEOP and IC-1, the S/C is in SPM due to thermal and power requirements. In particular, since the trajectory is relatively close to the Sun, Juno has to protect the vault with the HGA (as already explained in the previous chapters). Even if TP-1 is considered a hot phase, it is not the most critical as other phases have more stringent requirements, facing longer periods closer to external heat sources (i.e. Sun and Earth).
- **TP-2:** this second phase corresponds to IC-2. Among the ICs it is the longest and the only one featuring EPM. It does not call for any particular thermal requirement, being Juno farther from both Sun and Earth. No specific attitude is required to thermally control the S/C during the different manoeuvres performed during IC-2. Neither hot nor cold phase is considered along TP-2.
- **TP-3:** the third thermal phase consists of IC-3 till the EGA, performed in SPM to protect the electronics inside the vault as the S/C passes through the perihelion of the orbit (at 0.88 AU). During TP-3, Juno was found to face the most relevant hot environment, occurring at the closest approach to the Sun. As a consequence, this condition was selected to be the hot case.
- **TP-4:** the fourth phase analyzed consists only of the EGA, from the entrance till the exit of Juno from Earth's SOI. This phase contains both a possible hot case and a possible cold case, the first due to the proximity to the planet, the latter due to the eclipse. As a consequence, this is the phase when Juno faces the highest flux excursion of the entire mission. It was found that both of the two conditions are the most extreme in terms of heat flux as the obtained results are linked with the simplified model used. As explained in [subsection 2.2](#), these conditions won't be selected as hot or cold case.
- **TP-5:** this phase is the continuation of the TP-3, except that the S/C does not encounter such high flux environment as at perihelion. It goes from the end of EGA till the end of IC-3.
- **TP-6:** this phase only includes the OC up to JOI. The S/C encounters a progressively colder environment as it is going away from the Sun. However, knowing its trajectory, Juno will face colder contexts along its mission. The transition between TP-6 and TP-7 can be seen in [Figure 2](#).
- **TP-7:** the last phase goes from the JOI till the end of the mission, including all the science orbits around Jupiter. During this period of time, the spacecraft is subject to the harsh environment of Jupiter, where it faces oscillating flux from the planet: higher nearby the perijoves and lower at the apojoves. Overall, the environment stays cold during the whole phase with a minimum when both Jupiter and Juno are around the apocentre of their respective orbits. This condition is elected as the coldest case of the entire mission.

2.2 External heat flux analysis

In order to find the hot and the cold cases, a simplified model of the main external heat fluxes has been carried out. All the formulas for this analysis are reported in [section 4](#). To facilitate the computation, some assumptions have been adopted:

- as previously mentioned, only the external heat fluxes have been modeled discarding the internal contribution,

which is better treated in [section 4](#);

- the only contribution considered during the interplanetary phases is the Sun flux, while in proximity of the planets also albedo and IR emissions are added;
- for the hot case only TP-3 and TP-4 have been analyzed, since the other phases do not have critical condition in this sense;
- for the cold case TP-4, TP-6 and TP-7 have been analyzed, the first because of the criticality of the eclipse condition, the second because of the increasingly farther position of the spacecraft with respect to the Sun in an interplanetary environment, the third because Juno is orbiting Jupiter at its farthest points from the Sun;
- the analysis has been carried out from the ephemeris of the real mission instead of taking the nominal cruise;
- the $\cos\theta$ factor in the albedo formula is assumed to be always equal to 1 as a conservative simplification, so only the distances are taken into account during the calculations.

The external heat fluxes computed by this simplified model for TP-3 ([Figure 1](#)), transition between TP-6 and TP-7 ([Figure 2](#)) and TP-4 ([Figure 3](#)) are shown in the plots below.

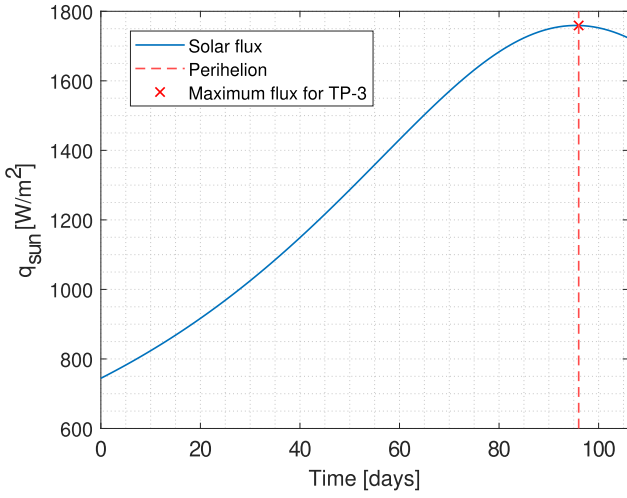


Figure 1: Flux analysis of TP-3

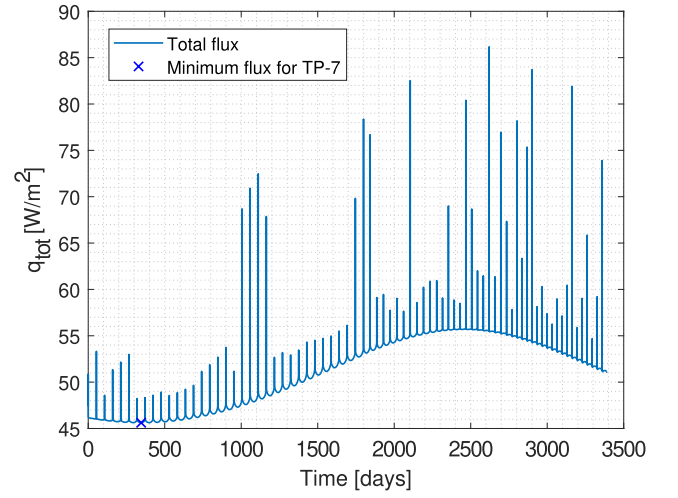


Figure 2: Flux analysis of TP-7

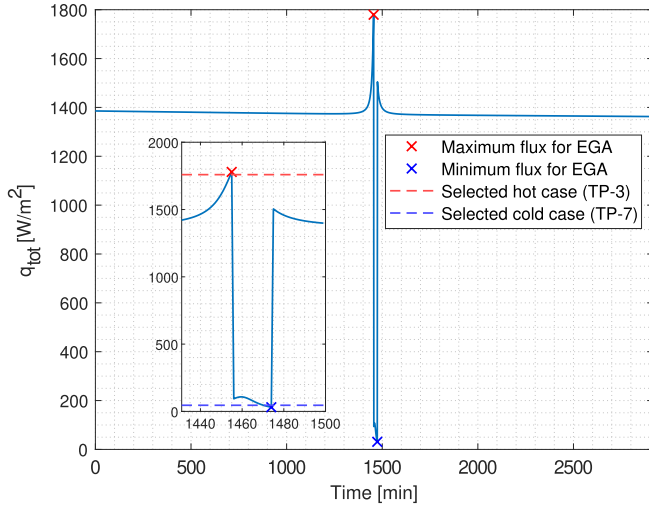


Figure 3: Flux analysis of TP-4 (EGA phase)

Phase	Total heat flux [W/m^2]
TP-4 hot case	1779.32
TP-3 hot case	1759.23
TP-4 cold case	31.13
TP-7 cold case	45.62

Table 1: Summary of considered hot and cold cases

It is worth noting that the flux derived from both planets' albedo contribution is greatly overestimated due to the simplification discussed before. Despite TP-4 presents both the hottest and the coldest points of the whole mission, the time spent by Juno in these regions is limited. As can be noticed in [Figure 3](#), the S/C spends only around half a minute in an environment characterized by a heat flux above the one of the hot case (TP-3) and spends around four minutes in an environment where the heat flux is below the one of the cold case (TP-7). Moreover, as can be also seen in [Table 1](#), the cases are very close to each other. For this reason, the choice is to not consider EGA's peaks as hot and cold cases, also because in reality Juno has to overcome a transient before reaching extreme temperatures. The passage from perihelion during TP-3 is hence selected to be the most significant hot environment. On the other side, the most relevant cold case was found to be a few orbits after JOI, around the farthest position of Juno

from both Sun and Jupiter, where both solar flux and the planet's contribution are at their lowest. Particularly, in [Figure 2](#) oscillations with two different frequencies can be observed: the long period one is related to Jupiter's lightly elliptical orbit around the Sun, the short term oscillation, with its peaks, is related to Juno's highly elliptical orbit around Jupiter. The chosen resolution for the ephemeris determines the non uniform high of the observed peaks.

3 Architecture and rationale of TCS

The TCS of Juno must tackle a wide range of thermal environments, as discussed in [REFERENCE](#). The cold case however is the most critical condition for the S/C, so TCS is mainly designed on this situation: the vault, the main body and the external hardware are all thermally insulated and decoupled. Heaters are also present on each individual section/sensor. This guarantees flexibility in order to ensure the operating temperature for each component. Despite the insulation, more than half of the power generated at Jupiter is demanded by the TCS just to heat up the S/C.

Four main zones were identified for the following analysis:

- **Vault:** all the main electronic hardware is contained here. The size of this box is $0.8\text{ m} \times 0.8\text{ m} \times 0.7\text{ m}$. The lower surface is attached to the main body while the top surface is linked to the HGA, lateral surfaces points outwards and mainly to deep space. The walls are made of 1 cm thick titanium walls. This metal has a low conductivity value ($\approx 6.7 \div 7.4\text{ W/mK}$) which is a positive feature for the cold case at Jupiter. Also, major heat generation happens during science orbits since all the instrument electronics is powered on. In addition, the low external thermal flux during science imposes additional requirements in relation to the optical properties of the lateral vault surfaces. Tantalum MLI blankets were used in order to ensure both low emissivity and absorptivity ($\epsilon \approx 0.01 \div 0.035$ [REFERENCE](#)). However, during the phases in which the thermal flux is at its highest (TP3), the vault shall be able to dissipate enough power. This is in contrast with the above mentioned design choices. To ensure compatible thermal environment in the vault, three louvers were applied on its external lateral surfaces in order to point deep space and have an efficient IR emission. The dimension of a single louvre is $0.53\text{ m} \times 0.40\text{ m}$, two of them are placed vertically while one of them is placed horizontally. The motivation for this choice is relative to the internal configuration of the electronics. The opening of the louvre's shutters raises the emissivity value from 0.14 to 0.74 ([REFERENCE](#) produttore), enabling higher out-going radiative heat flux. The justification for this passive and low complexity solution was mainly due to the fact that the hot case scenario was encountered only during a restricted time of the overall mission. Moreover, the louvre technology effectiveness was tested and ensured by previous interplanetary mission such as Rosetta and New Horizons. However, most of the radiation coming from the sun was shielded by the HGA which protected the vault. The Germanium coated Kapton used to cover the antenna dish has an operating range temperature of $-200^\circ\text{C} \div +200^\circ\text{C}$, while its absorptivity and emissivity values are $\alpha = 0.568$ and $\epsilon = 0.72$ respectively [REFERENCE](#). The HGA will heat up and exchange radiative heat with the lower vault, hence the necessity to dissipate heat also from the electronic vault with louvres. The electronics contained in the vault are tightly packed to reduce the effects of internal reflection of high energy particles that can still penetrate the walls. From a thermal viewpoint this means that the generated heat is better retained and the internal temperature of the hardware is fairly uniform.
- **Main body:** it is the hexagonal prism that contains most of the propulsion subsystem hardware (propellant and pressurizer tanks, feeding lines and ME). Two payload sensors are also present inside, namely UVS and JunoCam. All of these elements require separated strategies to manage the temperatures. The six propellant spherical tanks (two of oxidizer and four of fuel) are arranged into six bays that corresponds to the equally distributed volumes of the the hexagonal prism. Hence, each compartment contains just one tank and it is thermally uncoupled from the others in order to guarantee a better independent and redundant thermal management. To ensure this uncoupling, high reflectance blankets are used over the tank surface. Nominally, aluminized polyester film is used ($\alpha/\epsilon \approx 3.5$) this material minimizes heat flow to and from the S/C, it is generally used for temperature ranges from -250°C to $+120^\circ\text{C}$ and has been successfully used on previous mission ([link bibliografia](#)). The tanks are made of titanium which has low thermal conductivity. The honeycomb composite lateral walls of each bay are also covered with high reflectance coating to ensure radiative insulation. In addition, heaters are present into the propellant tanks, helium tanks ([reference paolo](#)) and also feeding lines. [REFERENCE](#) Other thermal considerations on the internal main body refers to the operations of the main engine which is mainly inside the central body. In that moments high thermal flux must be handled by the internal structure which must be thermally decoupled both radiatively and conductively. (manca materiale facce laterali main body)
- **External hardware:** which comprehend all the remaining payload sensors ()
- **Solar panels:** three solar arrays are present on the spacecraft to provide electricity throughout the different phases of the mission. They are connected to the main body through hinges and struts. To guarantee the correct pointing towards the Sun, stiffness was required to avoid deformation during the spin. The configuration allows each panel to have a clear view of both Sun and DS: dissipation of heat occurs from both front and back faces as the view factor between panels and Juno's main body is close to 0. To ensure the proper functioning in drastically

diverse environments, solar panels were designed to withstand a wide range of temperatures, going from the predicted +100 °C of the perihelium to the -140 °C around Jupiter^[1]. Moreover, the whole spacecraft has to survive to radiations up to 10^{15} MeV so a custom made CMG coverglass with coating was employed. Every cell of the panels is thus covered on the front side with a 304 μm , 14.3 mil fused silica equivalent^[1], anti-reflective coating and Indium Tin Oxide, the first to improve performance in a LILT environment, the second to mitigate surface charge buildup^[1]. The rear side shielding of each panel's substrate is shielded with a 30 mils fused silica equivalent of Kapton and Germanium. In order to guarantee the correct amount of electricity during science operations, around 440 W at JOI and 400 W EOM, the arrays are drastically oversized at any distance below 5.4 AU: at 1 AU 14 KW are produced. During the ICs and OC, more electricity than needed is generated but left on the panels in the form of heat that must be dissipated from both front and back faces. To do so, different kinds of coatings are used: values of absorptivity vary from 0.7 to 0.92 for Kapton, placed on the front side, while values for emissivity vary from 0.84 to 0.88 for Black Kapton on the back side. Coverglass on the front side is transparent to the incoming radiation, but it is able to emit towards the DS with an emissivity ranging from 0.73 to 0.82. All the intervals for the reported coefficients are related to hot and cold case.

4 Reverse sizing of TCS

Bibliography

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