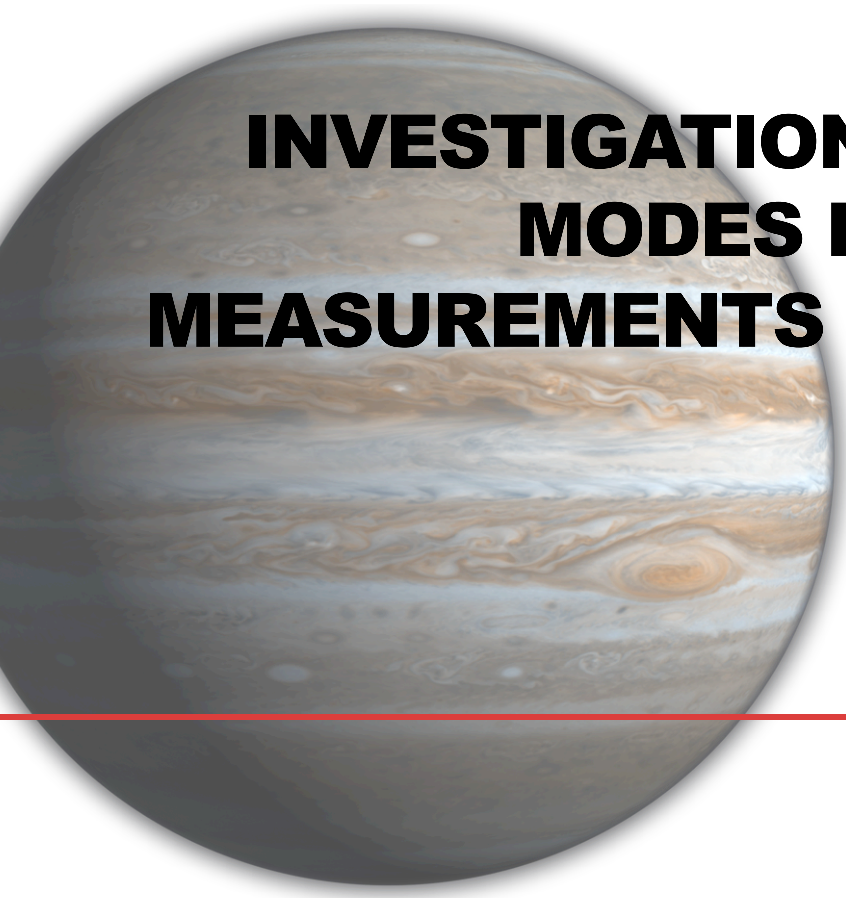

INVESTIGATION ON JUPITER NORMAL MODES BY MEANS OF GRAVITY MEASUREMENTS OF THE MISSION JUNO

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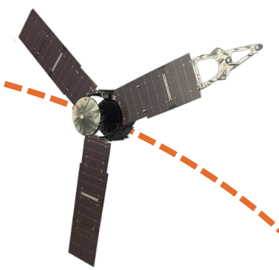
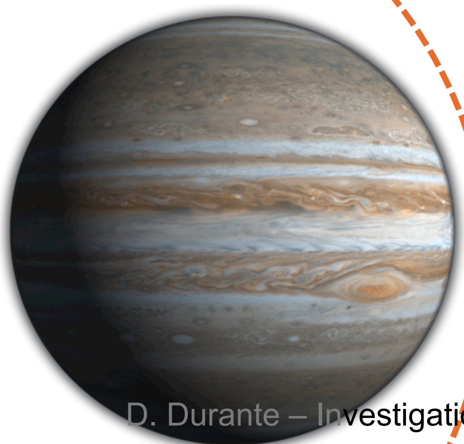
JUNO MISSION OVERVIEW

- Jupiter is the largest planet of the solar system, visited only eight times since 1973 by a robotic probe.
- Juno spacecraft: launched on August 2011, will reach Jupiter on July 2016 (in three months!).



- NASA Juno mission will investigate:
  - ➢ The origins of the giant planet, to constrain the process of giant planet formation;
  - ➢ His interior structure by means of gravity field and magnetic field mapping;
  - ➢ Jupiter's magnetosphere and atmosphere (to depth greater than 100 bars).



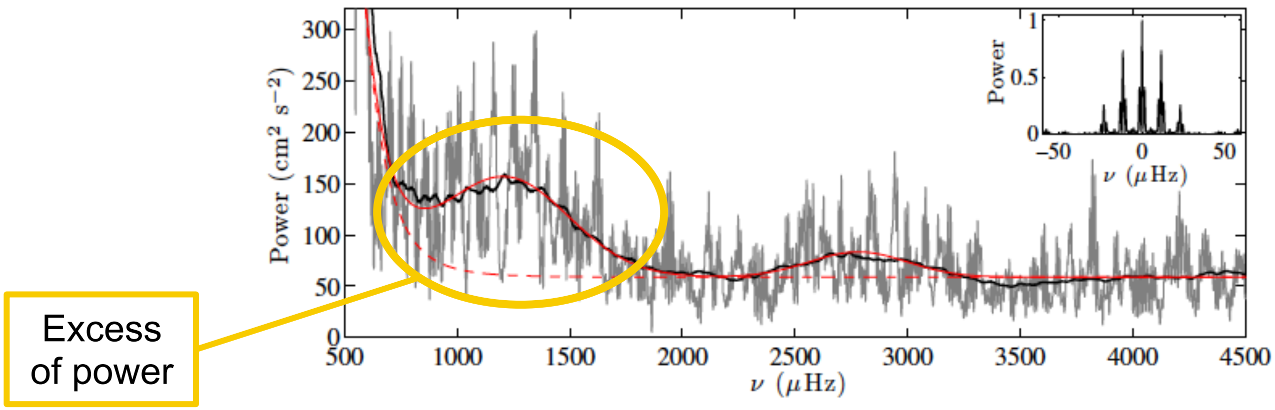
- Juno gravity field experiment is essential to additionally constrain the internal structure of the planet. In particular, it will help to characterize the extension in depth of the atmospheric zonal flows.

JUPITER OSCILLATION MODES

- Recent detection of Jupiter global modes suggests that pressure waves cause a significant redistribution of Jupiter's internal masses:
  - Jupiter acoustic modes (p-modes).
- The energy source sustaining the acoustic modes is unknown, but internal dissipation must be small (very high *Q*).
- These modes may displace a large amount of mass, causing time-variable perturbations in the gravitational field, to levels that may be detectable by Juno's high accuracy radio tracking system.
- Jupiter normal modes are both an unique opportunity to probe Jupiter's interior, and a source of noise that may threaten Juno gravity experiment.
- <u>Juno's radio science experiment</u> may in principle be used to probe Jupiter's acoustic modes. We address the following questions:
  - ☐ Are normal modes detectable by Juno?
  - ☐ How do normal modes affect the determination of the static gravity field and Love numbers?

AMPLITUDE OF ACOUSTIC MODES

- Recently, Gaulme, *et al.* (2011) analyzed a data set of radial velocity maps of Jupiter surface (as seen from Earth), retrieved with their instrumentation. They founded an excess of power between 800 and 2100 μHz, evidence of **Jupiter global modes**. The maximum radial velocity is about 50 cm/s, peaking at about 1200 μHz.



- Results by SYMPA instrument.

- However, the velocity maps are not associated to a specific harmonic (degree and order), thus we cannot predict each mode's amplitude, neither we know which modes dominate.

MATHEMATICAL MODEL

- Static harmonic coefficients of gravitational field are perturbed by Jupiter's oscillations:

$$U_{l,m} = U_{l,m}^{STATIC} + \sum_{n \geq 0} \widetilde{U}_{l,m,n} \cos(\omega_{l,m,n} t + \varphi_{l,m,n})$$

- The perturbation on harmonic coefficients is computed as:

$$\widetilde{U}_{l,m,n} = \frac{\iiint_V r'^l \, Y_{l,m}(\vartheta', \varphi') \, \widetilde{\Delta\rho}_{l,m,n}(P') \, dV}{(2l+1) \, M \, R^l}$$

- The associated density perturbation is:

$$\widetilde{\Delta\rho}_{l,m,n}(r', \vartheta', \varphi') = \left(\frac{\partial \rho}{\partial r'}\right)\bigg|_{r'} \left[A_0 \, f_{l,m,n}(r')\right] Y_{l,m}(\vartheta', \varphi')$$

Density gradient — Surface displacement (unknown) — Radial eigenfunctions

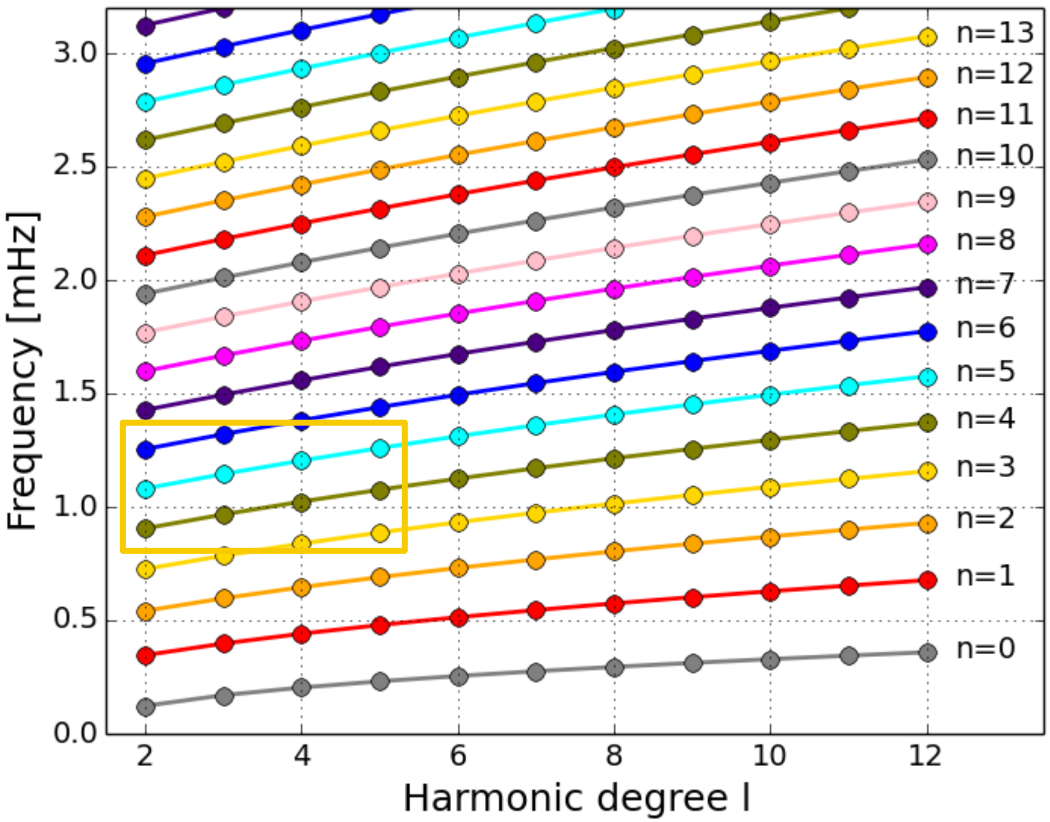
- It depends on Jupiter's interior (modeled as a polytrope with *n=1*).
- Oscillation spectrum has been computed with GYRE software.

JUPITER OSCILLATION SPECTRUM

- Jupiter (polytrope, n=1) oscillation spectrum for first lower degree is:

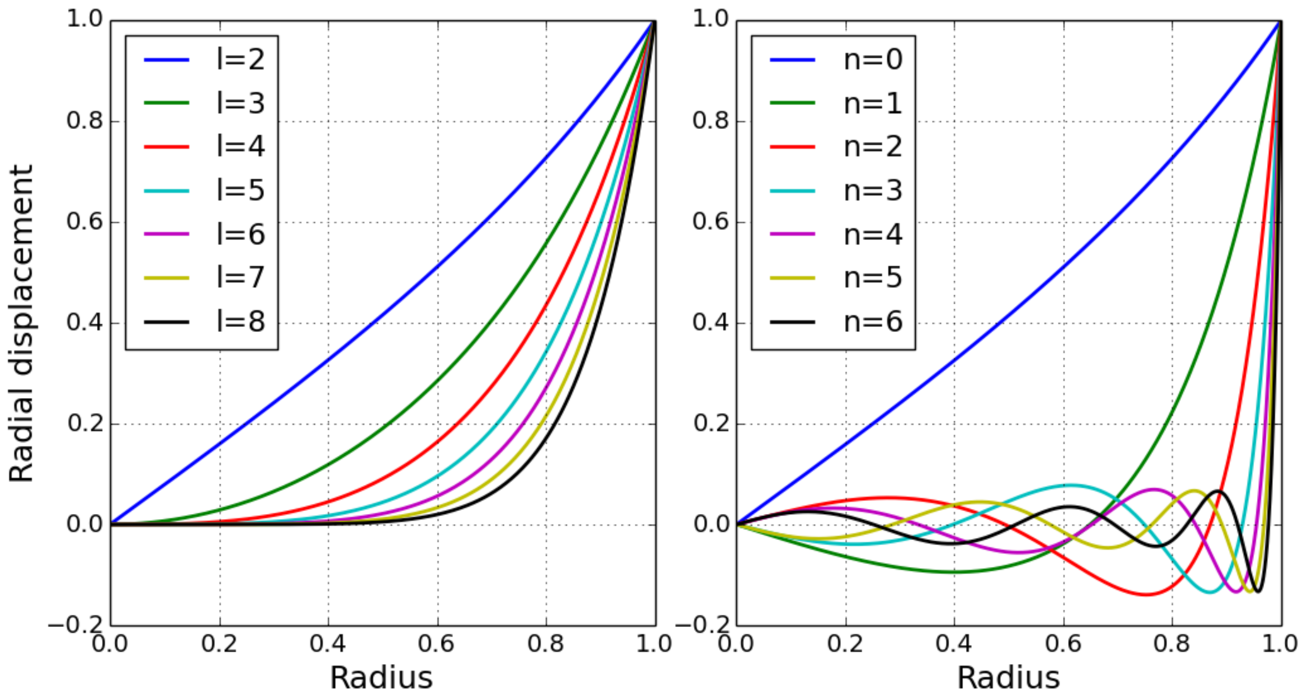
- Jupiter cut-off frequency is about 3 mHz.

- The frequency range of excess of power seen by Gaulme, *et al.* corresponds, for low degree modes, to radial order n=5≈7.



MODES EIGENFUNCTIONS

- Radial eigenfunctions for the Jupiter model adopted are:



- As the radial order increase, eigenfunctions move toward the surface. High radial-order modes influence Jupiter upper layers, whereas low radial-order modes penetrate deeper in the planet.

AMPLITUDES OF THE MODES

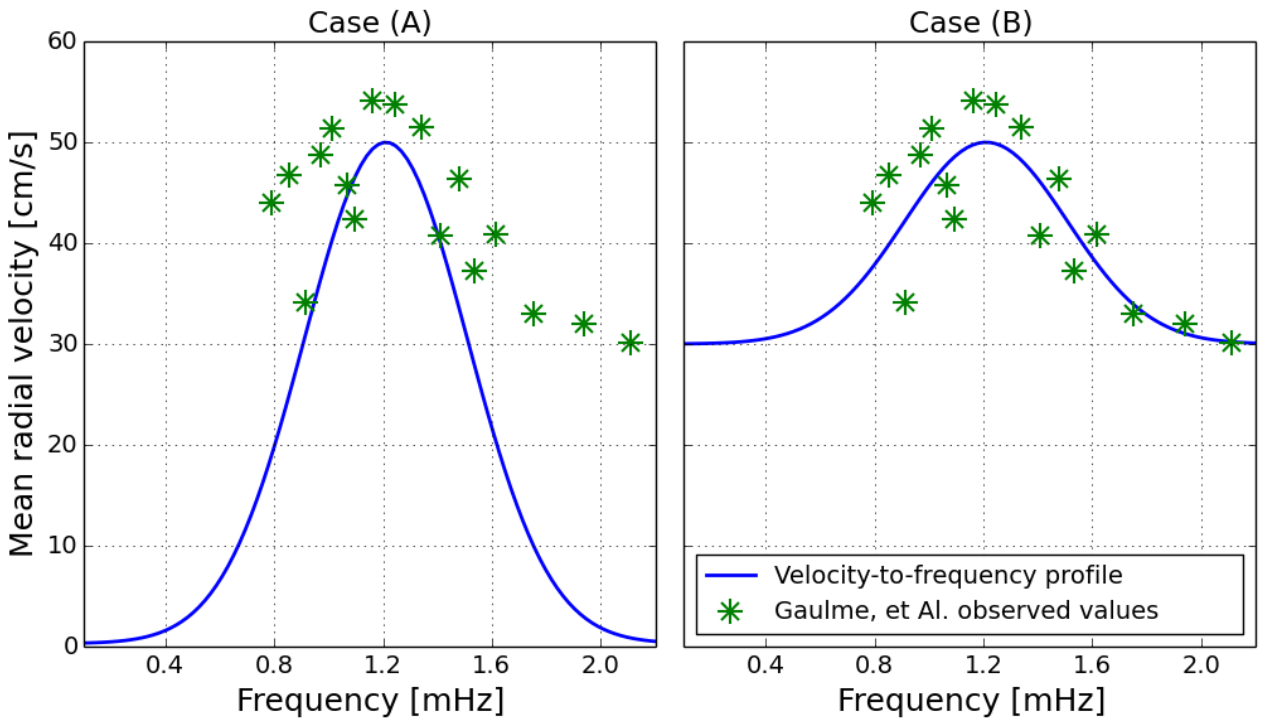
- The results provided by SYMPA instrument does not provide information on how the energy of the modes is distributed among the different degrees and orders.
- An empiric function has been implemented to estimate the radial velocity of a given mode, according to its oscillation frequency:

$$v(f) = v_{bias} + (v_{max} - v_{bias}) \exp\left[-\frac{1}{2}\left(\frac{f - f_{max}}{\sigma_f}\right)^2\right]$$

- The selected velocity-to-frequency mapping can be tweaked to approximate the radial velocity points extracted with SYMPA in the frequency window of maximum amplitudes:
  - $v_{max} \approx 50$ cm/sec, $f_{max} \approx 1200$ μHz, $\sigma_f \approx 300$ μHz, v_{bias} = (?)
- Note that also in the solar case the modes radial velocity seems to be well characterisable by only its frequency, and not by its degree or order.

TWO DIFFERENT CASES

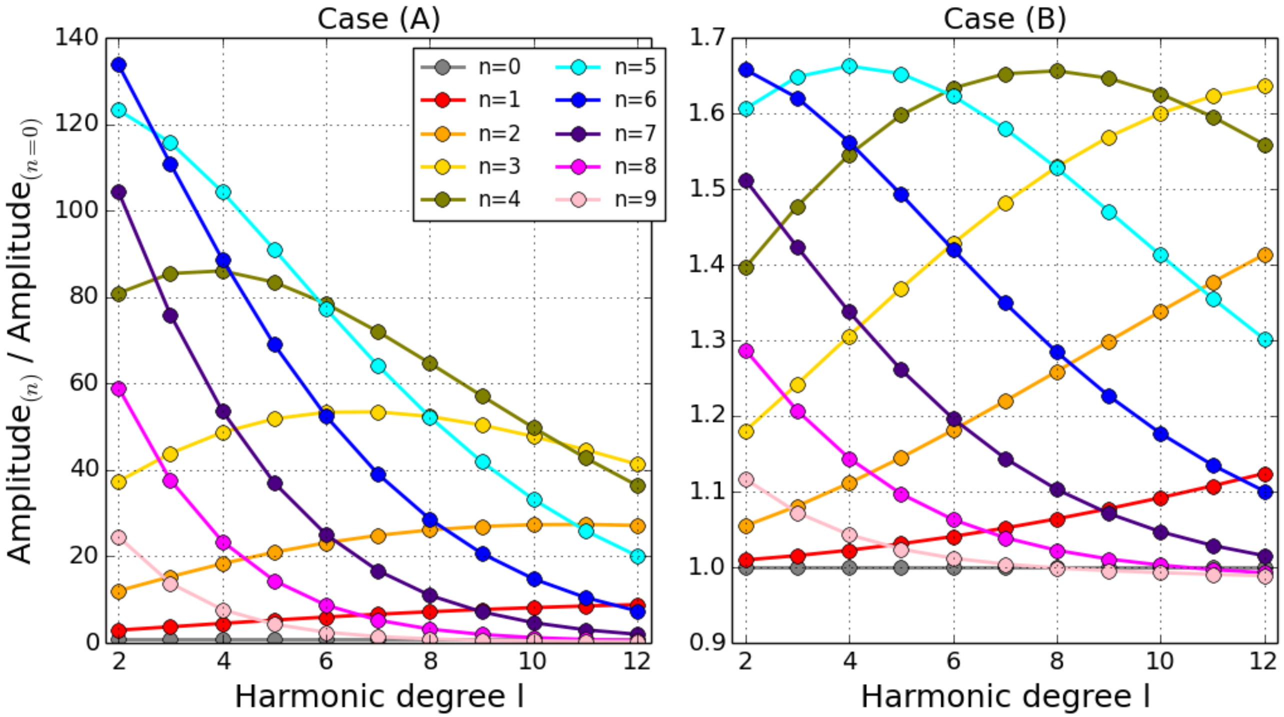
- Two different cases has been selected, which both fit the results provided by Gaulme, *et al.* within the maximum peak and differ elsewhere.



- Case (A) is a less energetic scenario (low freq. modes << n=5-7 modes) whereas case (B) depicts a very energetic scenario.

NOTE ON THE TWO CASES

- An interesting quantity is the ratio between the n-th mode amplitude and the corresponding fundamental mode amplitude.



- Case (A) has been constructed such to have this ratio to approximately equal those that can be found on the Sun (~100).

GRAVITY COEFFICIENTS COMPUTATION

- Given the velocity-to-frequency mapping function for the two cases, one can compute the amplitude of the surface displacement for a given mode:

$$A \sim \frac{v}{2\,\pi f}$$

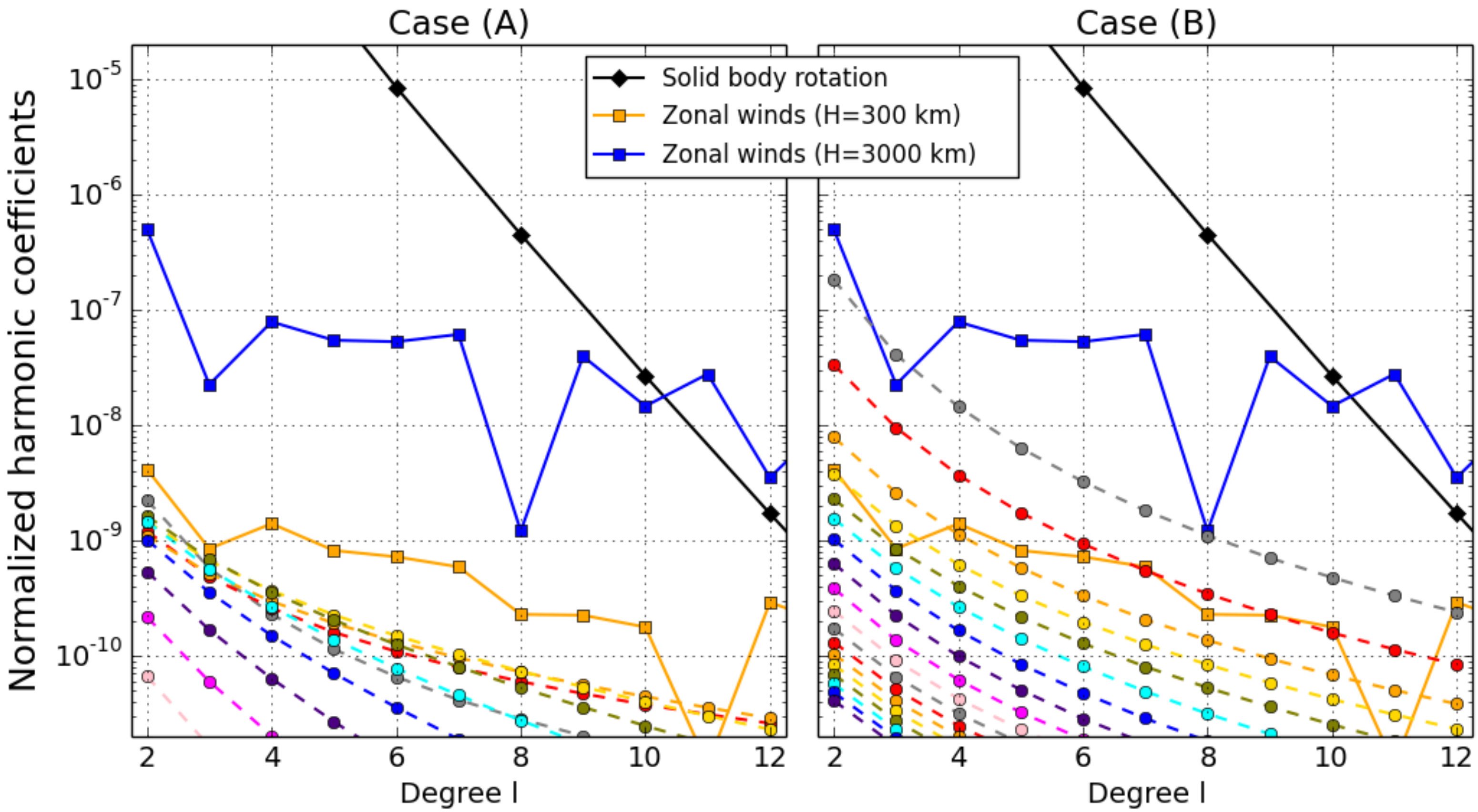
- The computation of surface displacement for each mode allows to integrate the equation for the dynamical gravity coefficients:

$$\widetilde{U}_{l,m,n} = \frac{\iiint_V \; r'^{l}\, Y_{l,m}(\vartheta', \varphi')\; \widetilde{\Delta\rho}_{l,m,n}(P')\, dV}{(2l+1)\, M\, R^{l}}$$

- You can compute the gravitational moment amplitudes given by the acoustic modes.

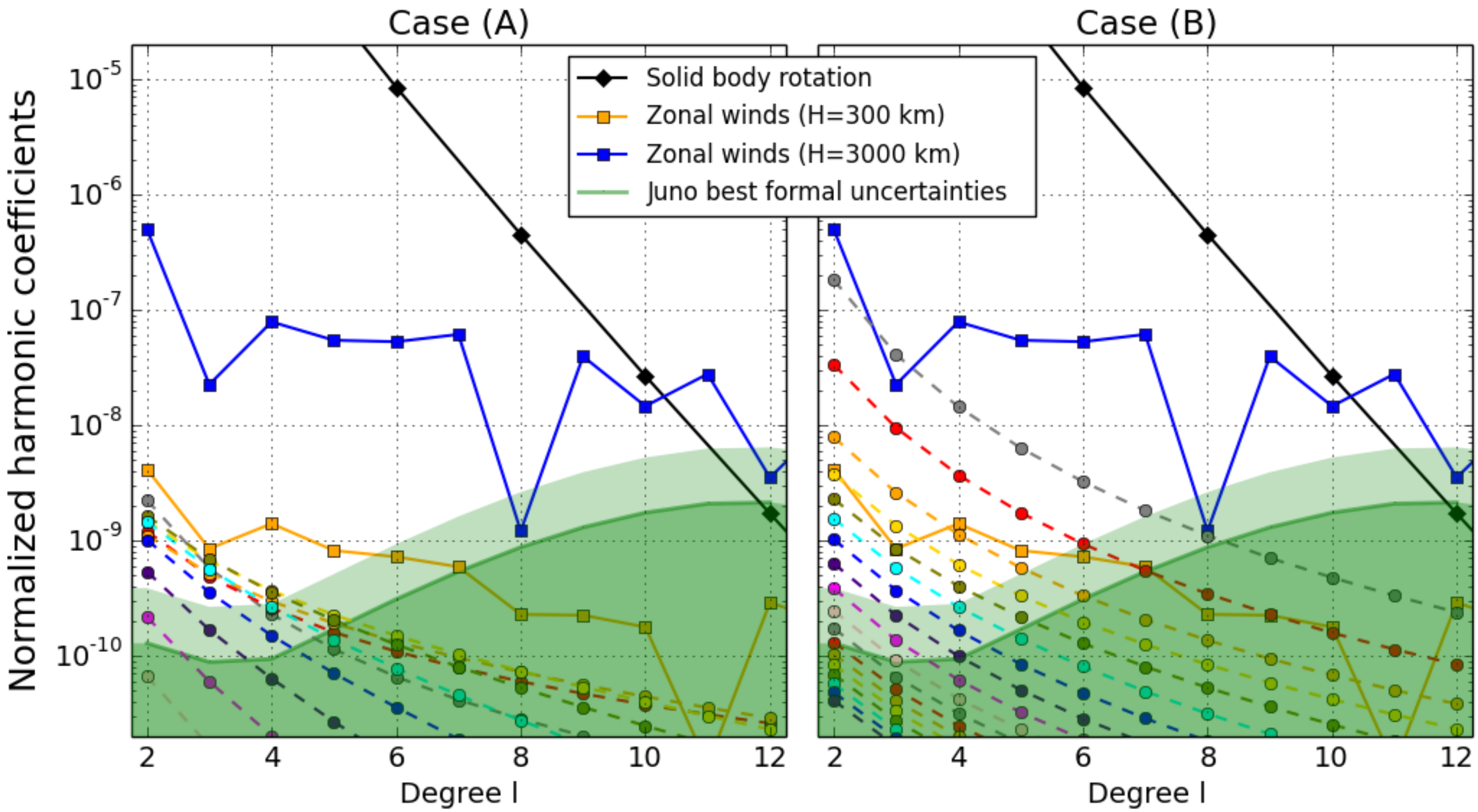
GRAVITY FIELD PERTURBATION

- The gravity field perturbation can be computed for each mode, and compared to a possible contribution from zonal winds (Kaspi *et al*, 2010).



GRAVITY FIELD UNCERTAINTIES

- Juno performance in terms of spherical harmonics uncertainties is reported, to be not confused with real performance if modes are relevant!



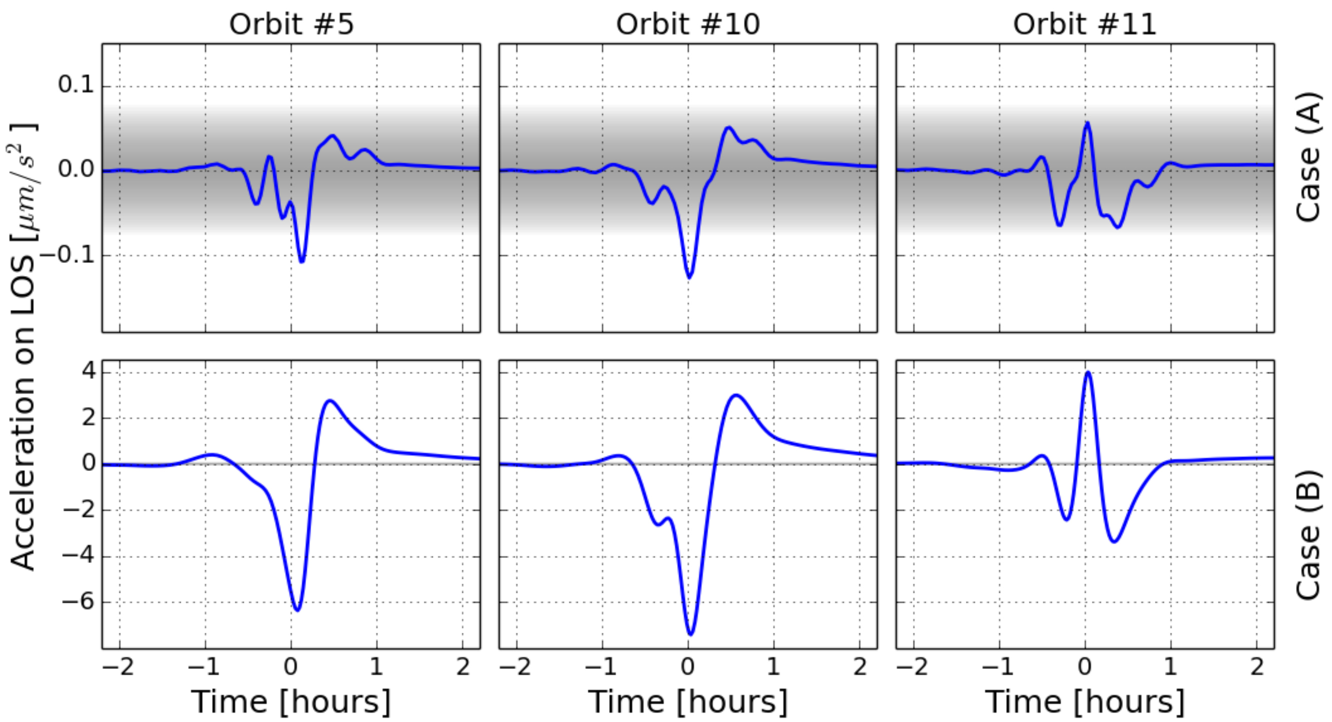
JUNO SIMULATIONS SETUP

- The simulations aim to *assess the effect of oscillations on static gravity field estimation*, i.e. to evaluate at what level the acoustic modes begin affecting the estimation of the static part of Jupiter's gravitational field.
- In the estimation process, acoustic modes are not estimated, but only the static gravity coefficients are.

- Juno simulations are performed using JPL's latest orbit determination code (Monte). Simulated dynamical model for Juno spacecraft includes:
  - Gravity (also relativity) from all the solar system bodies;
  - Jupiter's gravitational moments (shallow winds case);
  - Effects of tides raised by Galilean satellites;
  - Solar pressure;
  - Gravity perturbations due to the acoustic modes.

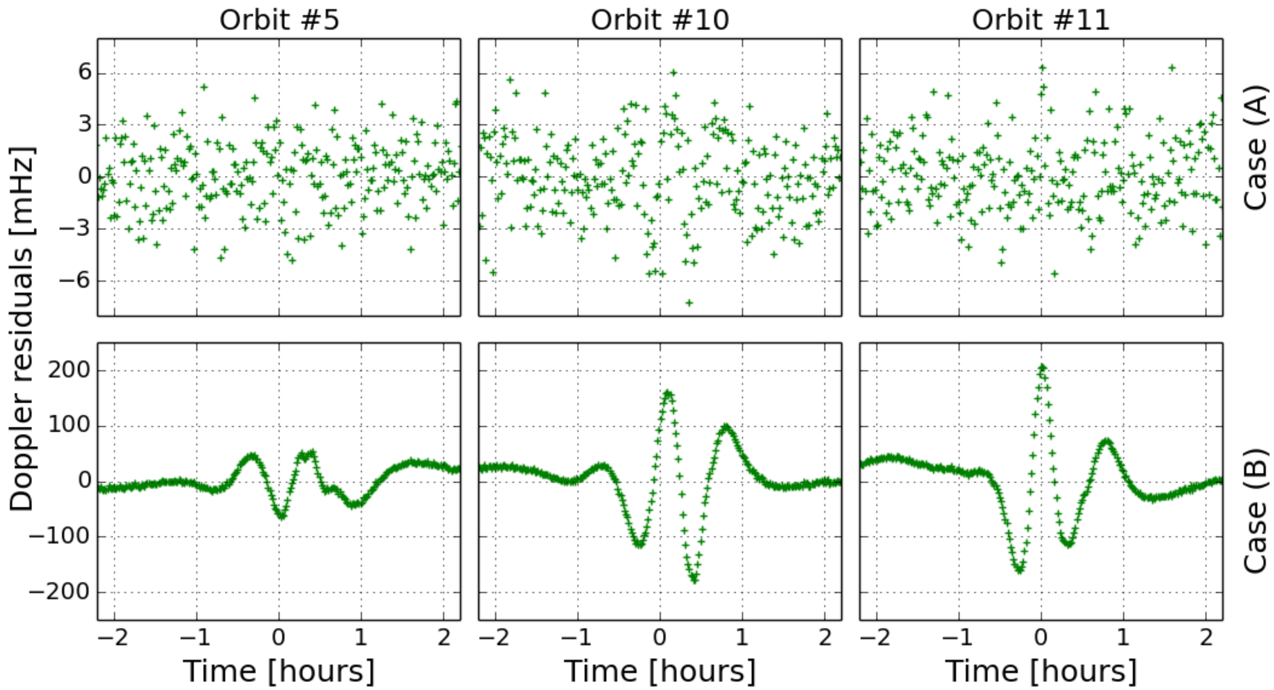
ACCELERATION PROBED BY JUNO

- For both the scenario, the perturbing acceleration caused by the modes has been evaluated and projected on Earth-Juno line of sight to be compared with Juno radio tracking system accuracy (~0.08 μm/s^2).



DOPPLER RESIDUALS

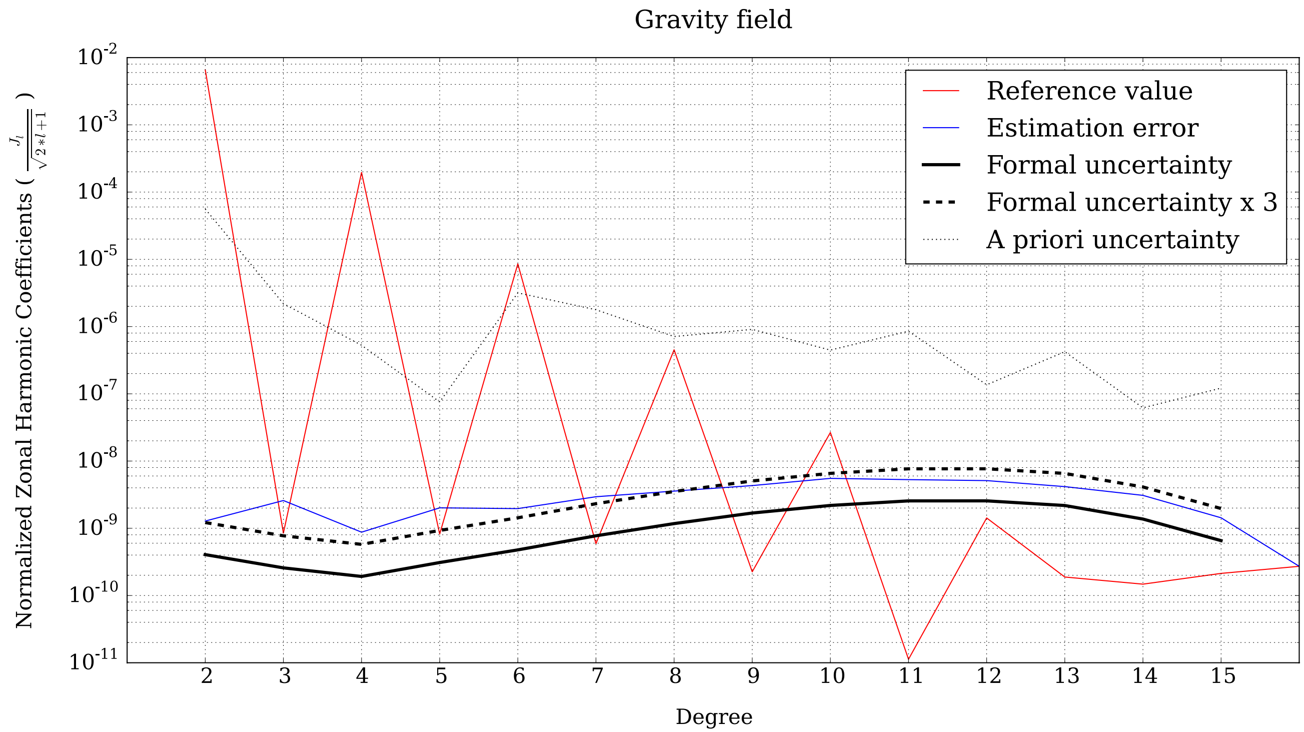
- After a filtering attempt solving only for static gravity field coefficients (plus state vector, etc.), the residuals appear:



- In case (B) signatures appears: the static gravity field cannot absorb the signal coming from the acoustic modes, which emerge from the noise.

GRAVITY COEFFICIENTS, CASE (A)

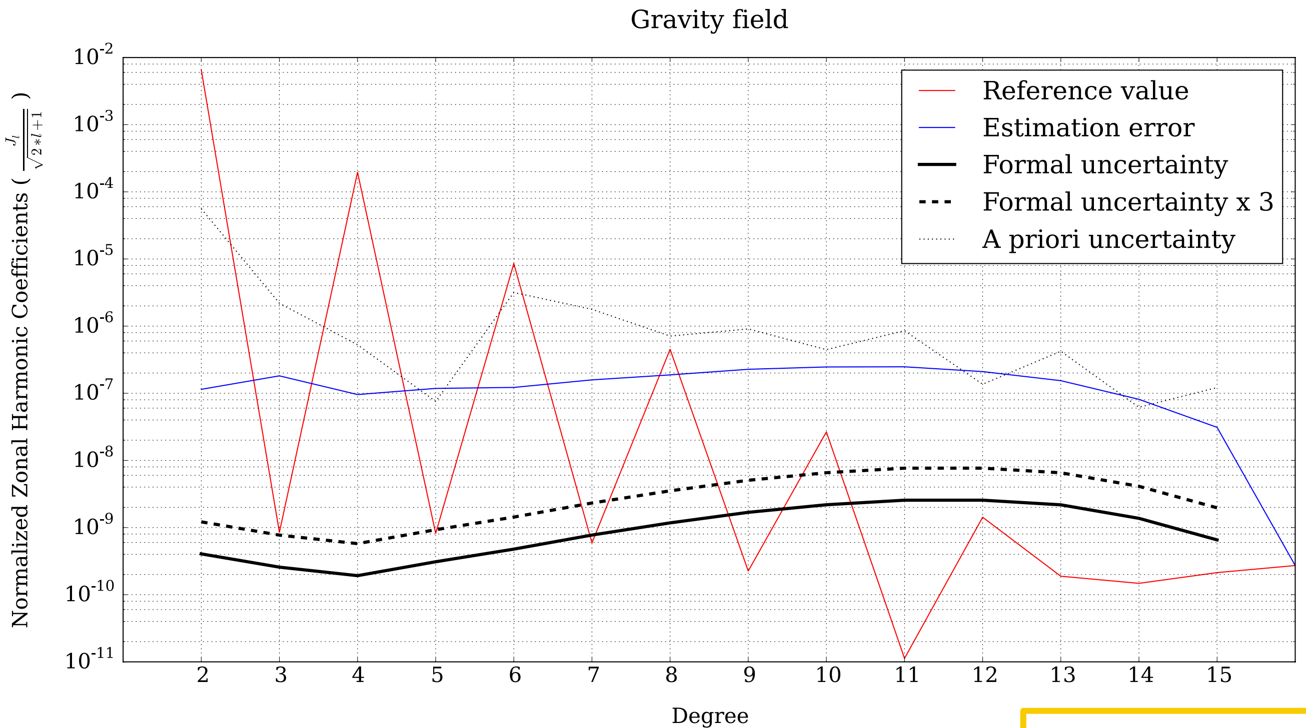
- The error on spherical harmonic coefficients and its uncertainty are reported:



- Neglecting the modes lead to an error slightly higher than 3-sigma.

GRAVITY COEFFICIENTS, CASE (B)

- The error on spherical harmonic coefficients and its uncertainty are reported:



- Neglecting the modes leads to consistent errors:

Gravity field not recovered!

CONCLUSIONS (1)

- The aim of this work was to evaluate the impact of acoustic modes to the Juno gravity experiment.
- Although SYMPA instrument allowed to glimpse Jupiter's acoustic behaviour, it was unable to discriminate the different modes amplitude, reporting only low degree modes with n~5 to 7.
- The two scenario analysed lead to very different conclusions:
  - The less energetic *case (A)* does not shows an immediate signature of acoustic modes, although small traces are present in some of the passages, depending on whether the modes interact constructively;
  - In *case (B)* the signatures are mainly produced by the fundamental modes, which produces the highest perturbation, invalidating the success of the experiment.

- Thus, the results depend strongly on the amplitudes of the modes and, to a lesser extent, on the dominating modes.

CONCLUSIONS (2)

- Juno can potentially provide useful information on low degree, low radial order acoustic oscillations modes, if their amplitudes are large enough (above ~1 cm/s for n=0 modes).
- However, the discrimination of dominating modes and the estimation of modes frequencies will certainly be challenging. A dedicated approach must be developed to analyze the modes characteristics.
- In the case of modes with relevant amplitude, an external contribution in term of modes discrimination and estimation is certainly useful both to fulfil Juno gravity experiment requirements, both to extract additional information from Juno Doppler data, expanding our knowledge about Jupiter modes.
- If the modes are weak, Juno data will not show any dynamical perturbation associated with Jupiter global modes; if this is the case, it will be possible to derive an upper limit on Jupiter acoustic mode amplitudes.