SWOT platform stability challenges to maximize KaRIn performance

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Introduction

SWOT satellite (Surface Water and Ocean Topography) is born from a cooperation between CNES and NASA, with a platform developed by Thales Alenia Space and a payload under Jet Propulsion Laboratory responsibility. Launched on December 2022, it began the first global survey of Earth's surface water. Thanks to its wide-swath Ka-band Radar Interferometer (KaRIn), combined with a nadir altimeter as well as support instruments, it offers a new opportunity for measuring the height of lakes, river and flood zones, and for seeing mesoscale and sub-mesoscale circulation patterns of oceans.

Preliminary science data show excellent results (Figure 1), opening new perspectives in hydrology and oceanography fields.

KaRIn interferograms are very sensitive to flight hardware geometry, and especially the relative positions of the reflectors and the sources. Biases or long term variations can be calibrated, but components whose frequency is higher than the orbital pulsation have a negative impact in the performances.

Consequently, platform design has taken special care of the mechanical disturbances injected by the attitude control and transmitted to the payload structure. This poster presents the stability challenges overcome at platform level to minimize its impact on science data.

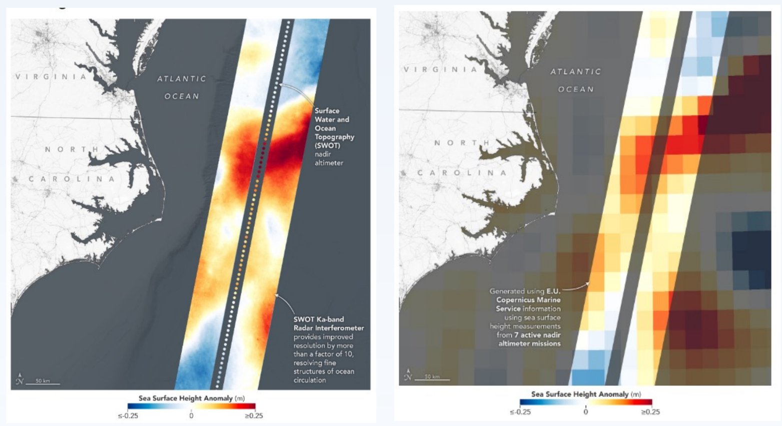


Fig.1: Sea level data gathered by SWOT (left), which has 10 times the spatial resolution taken by altimeters on seven other satellites (right). Credit: NASA, swot.jpl.nasa.gov

SWOT specific stability context

Radar interferometry induces stringent constraints on mechanical stability over frequency range of several decades. Indeed, the resulting height measurement is impacted by the geometrical distortion of the system through three components :

- ΔR, the elastic mast roll
- ΔP, the impact of the geometrical displacement of the sources and antenna, defined for Horizontal & Vertical polarizations
- ΔB, the variation of the baseline length.

A stability criterion combining these 3 components with their relative weight is defined and bounded to a maximum acceptable value with low impact on science performance.

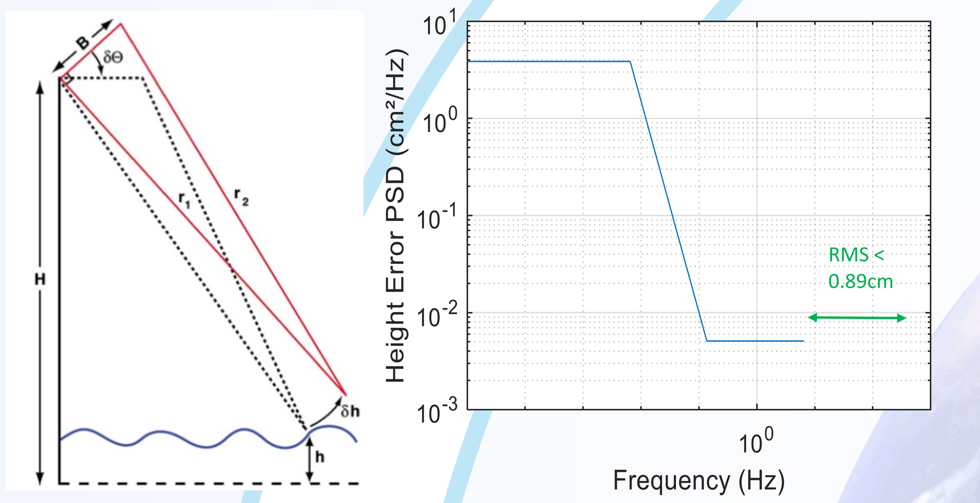


Fig.2: Left : illustration of roll error impact on height measurement – Right : Platform stability criterion requirement over 8 frequency decades

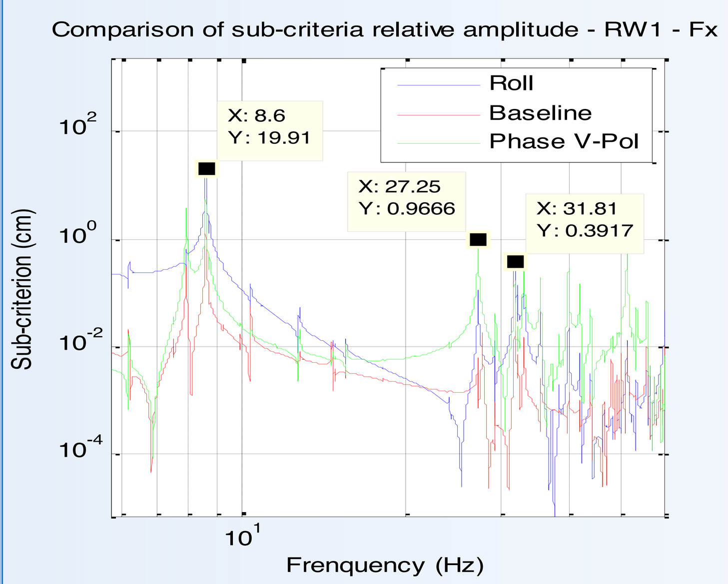


Fig.4: Transfer function to each criterion component illustrates sharp resonances

SWOT satellite features large solar arrays sized to supply power to a demanding payload on a low Earth drifting orbit, and KaRIn instrument accommodates two 5m-large reflect-arrays separated by a 10m baseline (Figure 3).

These large structures have low frequencies and low damping flexible modes, leading to sharp resonances (Figure 4) and long transient in the system mechanical behavior when excited.

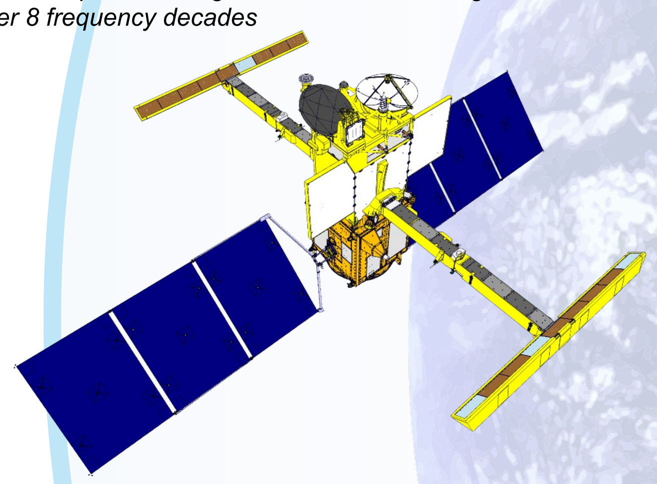
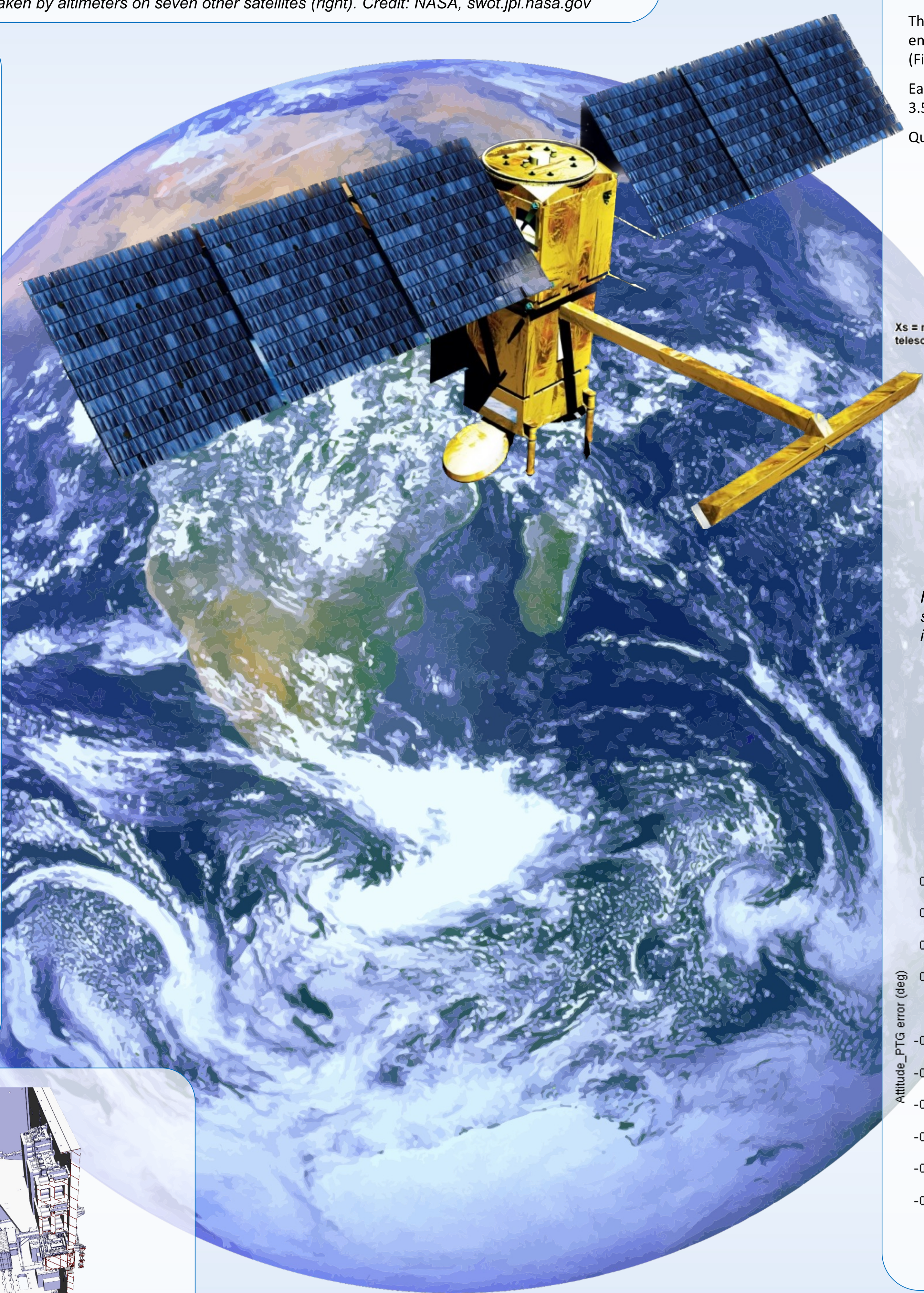


Fig.3: SWOT satellite features large appendices

Science needs, coupled with sensitive appendices led to account for the stability challenges early in the design phases. However, usual micro-vibration strategies were not applicable for SWOT context :

- Reaction wheels isolators are specifically designed to absorb high frequencies loads, which are above SWOT most critical bandwidths. They could even add uncertainties in the 5 to 30 Hz bandwidth which jeopardizes the science mission performances
- Typical analytical approach relying on successive steady-state harmonic solicitation is only valid outside of resonances. While this can be justified out of critical bandwidths, it neglects the transient effects and shall be applied with careful timescales assessment to ensure capturing worst cases.

Consequently, stability issues on SWOT have been addressed with a tailored approach, both in terms of design optimization at platform level and for analytical demonstration of performances.



Platform design optimizations

Satellite flexible behavior can be decomposed into a rigid body composed of platform and payload modules, on which are mounted the solar arrays and the KaRIn masts with their dedicated bending modes. Thus, load transfers from platform to KaRIn are dominated by torques at center of mass.

Solar arrays oscillating frequencies can be reconstructed from flight telemetry, so not exciting the KaRIn mast flexible modes is the biggest challenge on the platform design. Major disturbance sources over KaRIn sensitive bandwidth are the reaction wheels used for attitude control. They generate harmonic axial and radial loads, whose frequencies and amplitudes depend on the reaction wheel actuation rates.

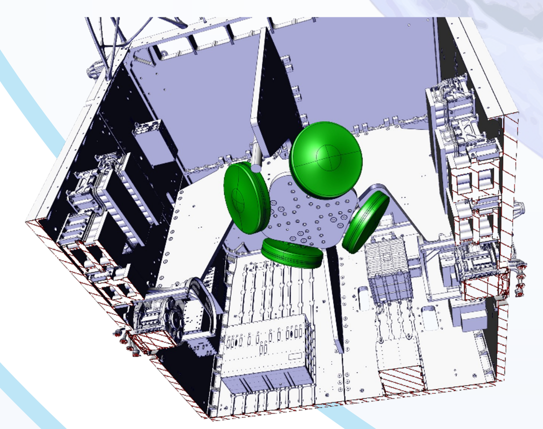


Fig.5: Reaction wheels are gathered in the heart of the platform to minimize loads lever arms

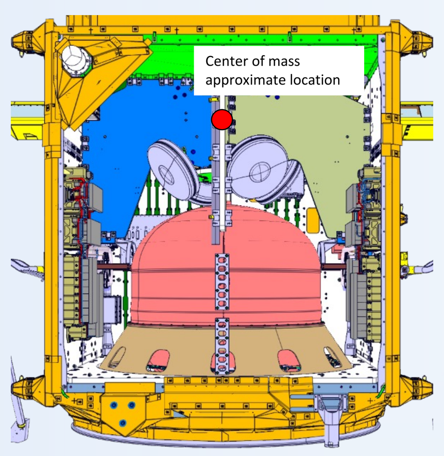


Fig.6: Reaction wheels axes convergence to satellite center of mass

Mechanically, impacts of reaction wheels loads can be limited by minimizing the lever arms of the radial and axial forces. The reaction wheels are accommodated close to the satellite center of mass (Figure 5), with their rotation axis aligned to it (Figure 6).

Frequencially, the wheels generate a disturbance spectrum looking like a ray comb, whose rays frequencies depend on the reaction wheels rates (Figure 7).

The principle to minimize disturbances is to avoid phasing reaction wheels harmonics to transfer function main resonances. This is made possible by using the 4 to 3 wheels redundancy and a continuous momentum unloading of magnetotorquers to manage the wheels rates kernel, in order to limit the rates excursion within the 19 to 23 Hz range.

This approach guarantees that no PL mode reacts to the wheels harmonic disturbances, minimizing science performance impact and transient issues.

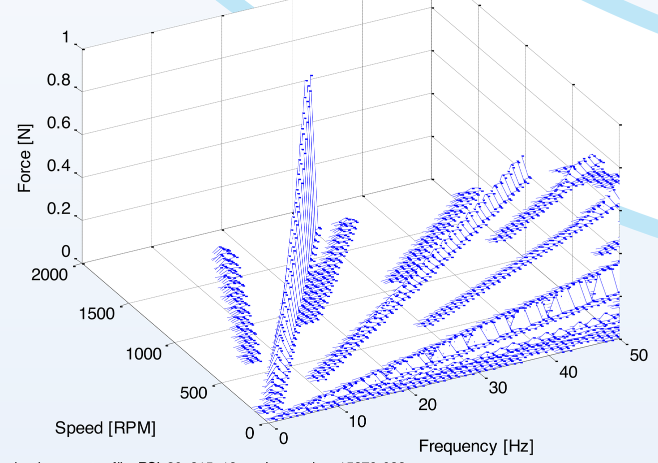


Fig.7: Waterfall diagram of exported radial force (Fx) for SWOT wheels

Conclusion

SWOT science mission requires high stability performances from the satellite, made challenging by the solar arrays wings and the KaRIn masts large dimensions. It requested a dedicated approach, different from typical micro-vibration reduction strategies, and relying on minimization of lever arms, wheels frequencies control in non-sensitive bandwidths. Specific analytical principles have also been applied to demonstrate the satellite capability to provide the payload with adequate mechanical conditions in steady-state mission operations.

Local phenomena also play a role in the overall picture. Among them, the thermo-elastic effect leading to attitude disturbances at eclipse entry / exit is enhanced on SWOT satellite due to solar arrays to body relative dimensions. Analytical approach has been correlated with a dedicated flight experiment on CoRoT satellite before extrapolation to SWOT satellite.

Overall, preliminary flight feed-back demonstrates good stability performances, contributing to the very positive return on the quality of the science data provided by the mission. Further processing of KaRIn data over ocean will help refining the approaches derived for SWOT.

Thermal snap

Thermal snap is the thermo-elastic effect due to sudden illumination change on a satellite large appendices at eclipse entry / exit. On SWOT, large solar arrays, and illumination of their low thermal inertia back side at eclipse entry / exit (Figure 11) make the expected effect more critical than for other satellites.

Early identification led to allocate 120s unavailability for eclipse transients during the eclipse season. This results in a 3.5% of mission data a-priori unavailability.

Quantifying thermal snap impact and duration needed to damp its effects has requested a dedicated unusual approach.

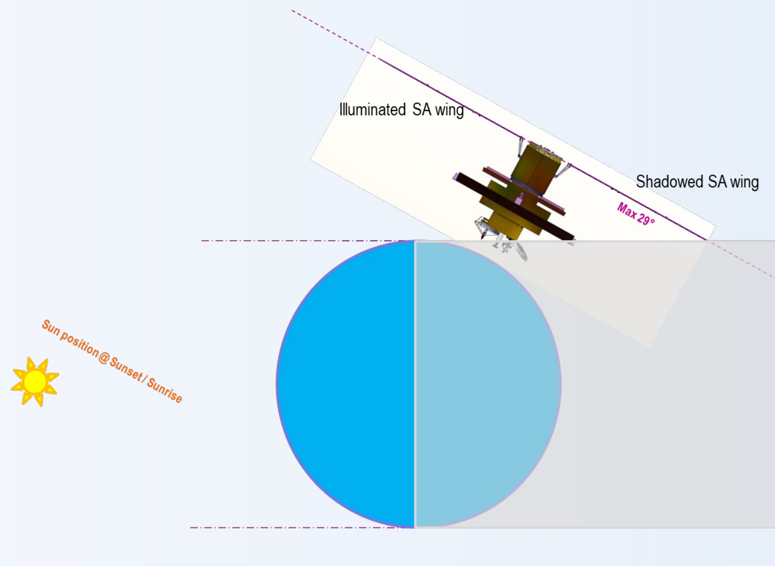


Fig.11: SWOT satellite at eclipse entry. Totality of forward wing is in the satellite shadow.

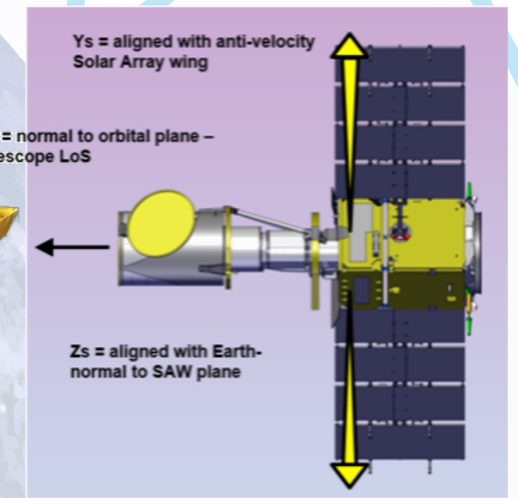


Fig.12: CoRoT satellite at eclipse entry as seen from the Sun. Only the forward yoke is in the satellite body shadow.

To investigate on this atypical phenomenon, a flight experiment has been set in place by CNES on CoRoT satellite as part of its end of life activities (Figure 12).

- An attitude representative of SWOT flight configuration has been reproduced for eclipse entry / exit.
- Flight temperature on solar arrays and attitude control errors have been recorded, highlighting a satellite transient mispointing with no oscillations.

By analysis, the orbital effects have been reproduced, and orders of magnitude have been successfully compared (Figure 13), with a succession of thermal, thermo-elastical, mechanical then attitude control simulations.

Experiment concluded on 3 main aspects :

- No oscillations were generated by thermal snap events, there is no shocks
- Analytical approach of the whole process is valid and can be extrapolated to SWOT scales
- Mispointing on CoRoT was generated by asymmetrical yoke thermo-elastic distortion only, while on SWOT, the complete wing behavior would be asymmetrical

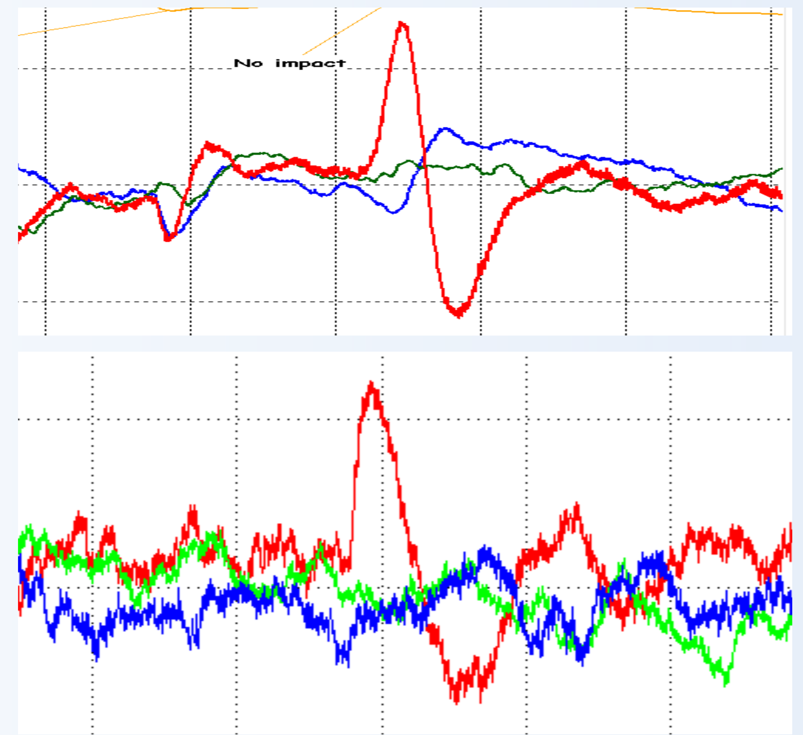


Fig.13: CoRoT satellite flight attitude control error (top) and AOCS simulations results (bottom) show consistent behavior and order of magnitude of perturbation

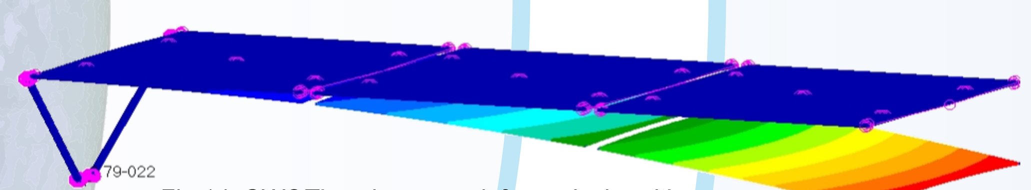


Fig.14: SWOT's solar array deformed when it's loaded by a thermal gradient across wing.

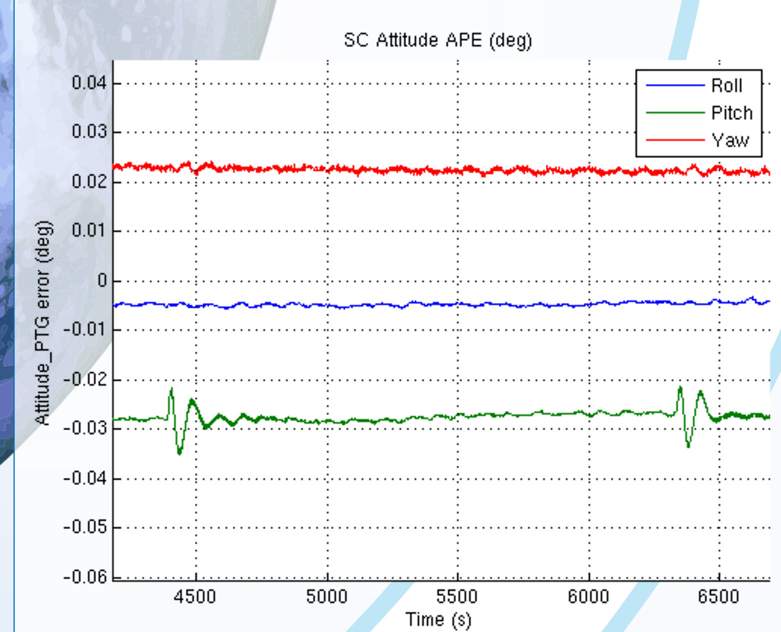


Fig.15: SWOT predicted attitude control error due to eclipse entry / exit

Reproduction of method on SWOT enabled to derive the torques at the solar wing root. Injected in the attitude control simulator, it provides prediction of attitude control error and impact on low frequency stability PSD.

- Attitude impact # +/-5mdeg is damped in about 20s (Figure 15)
- No significant residual impact is visible on PSD after 120s

First level of flight feed-back confirms presence of attitude control error impact, with order of magnitude of the order of the simulation results #+/-3mdeg, hardly visible in the control-related noise.

At first release, science data during eclipse entry / exit had not been distributed. However, in order to better assess the actual impact on measurement performance, the flagging of these 120 seconds period as been relaxed to a warning, thus, these periods will be made available in products. This will allow additional feed-back on this very specific effect.

Analytical performances demonstration

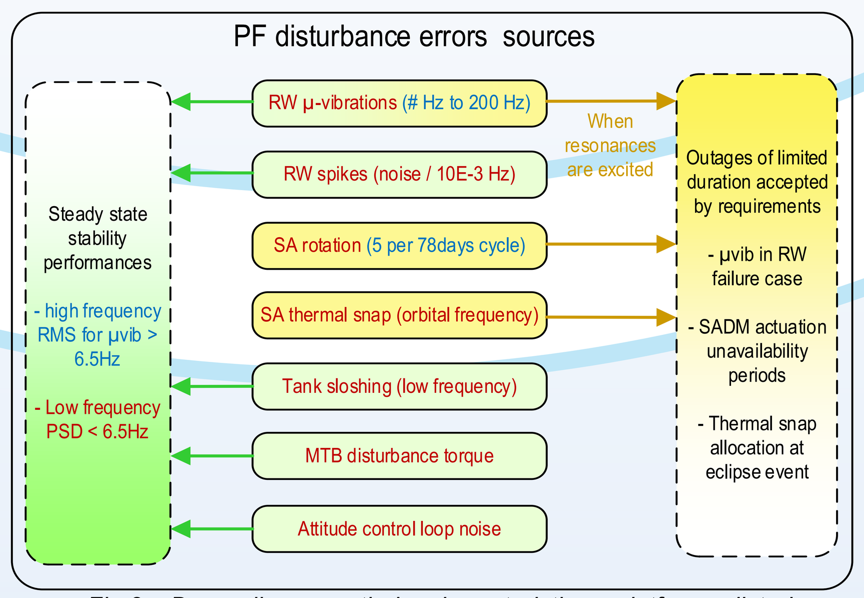


Fig.8: Depending on their characteristics, platform disturbance sources are accounted for in the steady state stability performances, or as outages

For SWOT, all platform disturbances are accounted for within one of the following performances demonstration methods (Figure 8), all showing performances better than requested:

- High frequencies RMS performance is demonstrated with solicitation of Finite Element Model with reaction wheels harmonic disturbances. Wheels rate management, coupled with fine temporal sampling ensures validity of successive steady-state assumption (Figure 9)
- Low frequency PSD performance is demonstrated with integration of solar arrays and payload first 10 flexible modes in the attitude control simulator (Figure 10)
- Unavailability tolerances covering tranquilization time are sized :
  - By solar arrays flexible mode damping after rotation (#700s) or eclipse entry / exit (#120s, see thermal snap discussion above)
  - By KaRIn resonance tranquilization after local excitation in failure cases (<5% of the orbit, dedicated transient modeling)

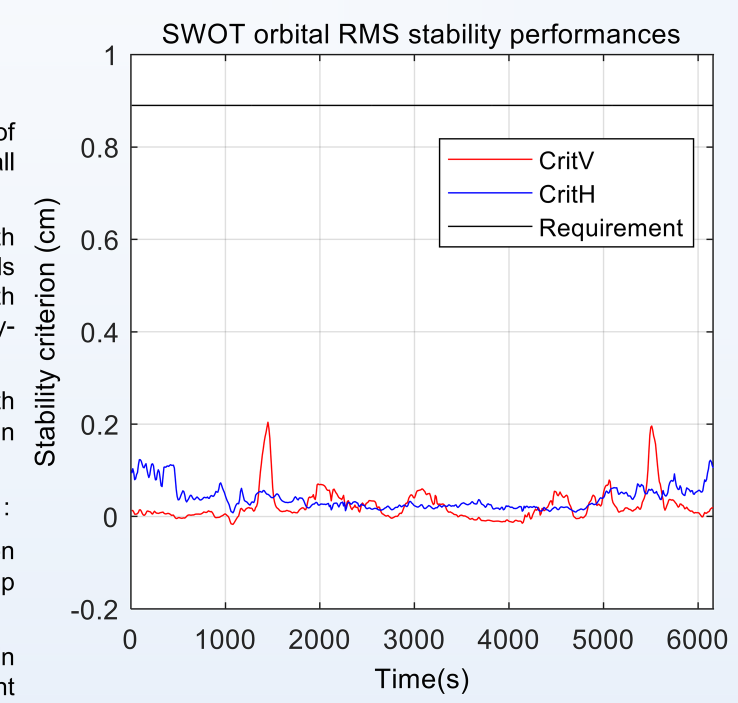


Fig.9: High frequency stability performance is better than requirement

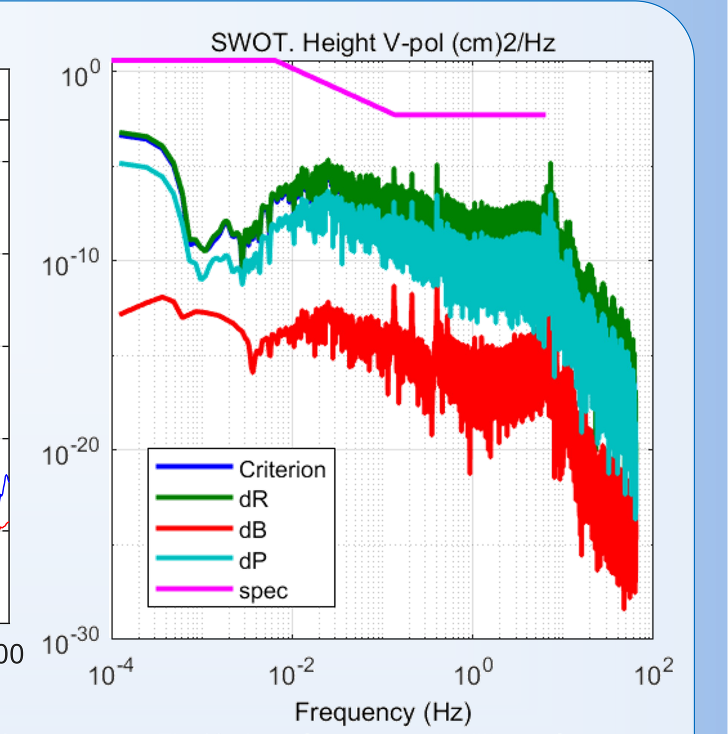


Fig.10: Low frequency stability performance is well within allocation

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