LEO SATELLITE IMAGING WITH ADAPTIVE OPTICS

COAT 2019

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Context

- **Space :**

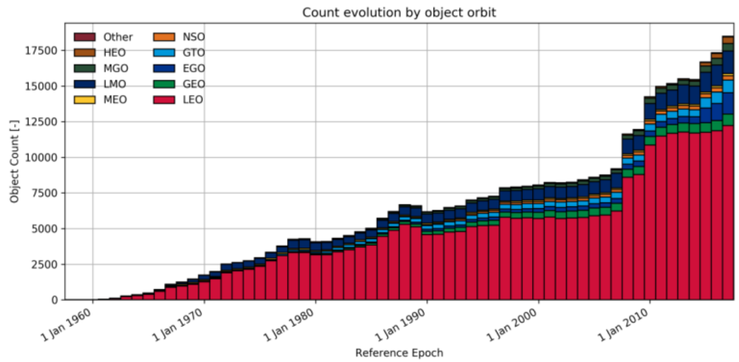
- Acceleration of scientific, defense and economical activities (new space)

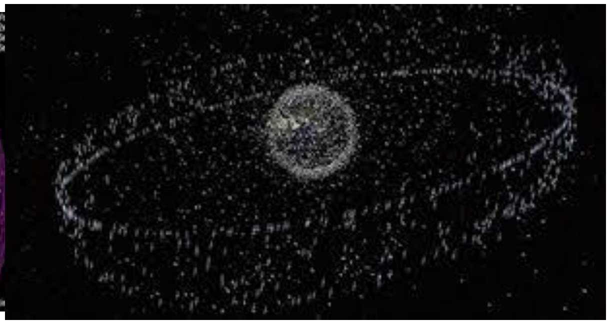
2000 satellites in operation

Next constellations: SpaceX (Starlink) 1600 sat. (goal 12000), Blue Origin: 3200 sat.

Millions of debris larger than 1mm

Credit ESA





Credit ESA

- A new field to survey and protect: a national defense issue (USA, France …)
- Focus here on LEO satellites

Space Situational Awareness (SSA)

Definition: detection, tracking, characterization, identification, follow-up of (LEO) satellites/debris state and their surroundings, from post-launch till deorbiting (collision, impact of space weather …)

→ Defense and Civil applications

Example: follow-up of ENVISAT

>> ESA satellite dedicated to earth observation

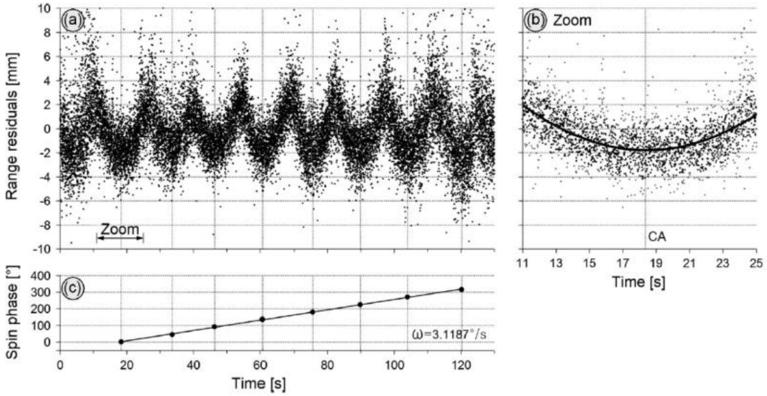
>> out of control (end of life 2012)

>> one of the biggest debris on LEO orbit.

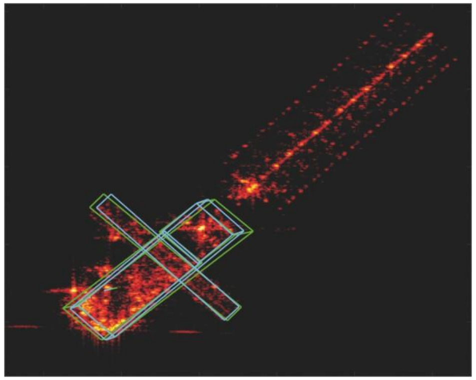
>> regular observation to assess tumbling

>> objective: regular observation of tumbling to assess factors influencing attitude changes (break-off, gas/fuel leaks, impacts of debris, atmospheric drag) and evolution along time

Spinning estimation by Satellite Laser Ranging, Kucharski et al.



Spinning estimation by TIRA ISAR images, credit Fraunhofer Inst. (website), Lemmens et al.



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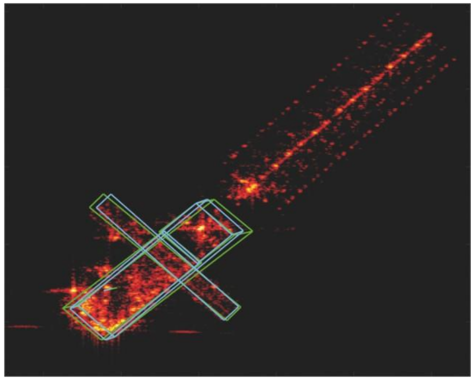
Satellite Imaging

→ Focus on characterization and identification based on direct imaging.

Means:

- Radar imaging (ISAR): historical, high energy, with limited resolution and hard-to-interpret images, though all-weather (or almost)



credit Fraunhofer Inst.

- Optical imaging

→ correction of the atmospheric turbulence-induced effects on the wavefront

⇒ **Adaptive Optics (AO)**

Strong relation with optical space-to-ground telecommunication

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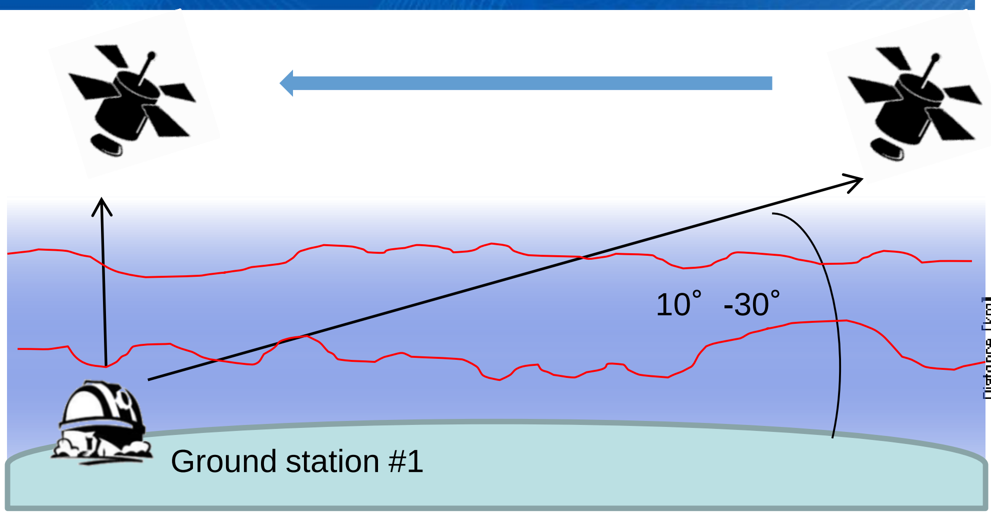
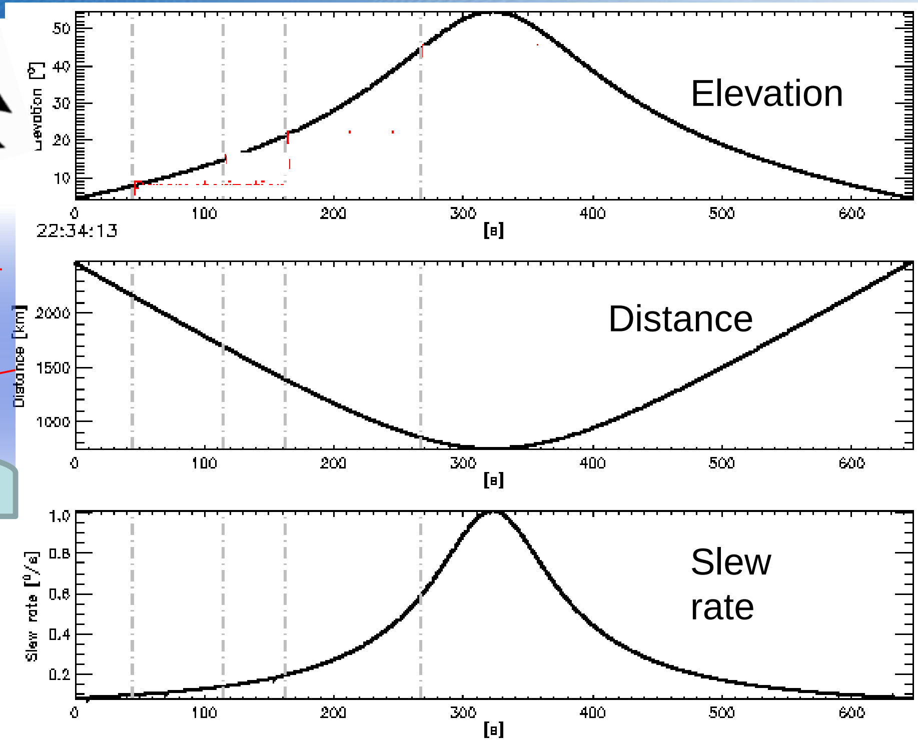
Satellite Imaging with AO: the challenge





	Astronomy	Telecom	LEO observation
Source distance	∞, fixed	800km, x3 (run = 3-10’)	800km, x3 (run = 3 -10’)
Source illumination	Faint, Fixed	Brilliant, up to /10	Faint, up to /10
Angular position	stellar	1°/s, x5	1°/s, x5
Wind speed	# 10-20m/s, slow evolution	200m/s @ (10km, 60°), x5	200m/s @ (10km, 60°),x5
Turbulence strength	<1”, slow evolution	Poor seeing, fast evolution	Poor seeing, fast evolution
Scintillation	No scint.	At low elevation	disregarded

Satellite Imaging with AO: the challenge

- **Constraints** :

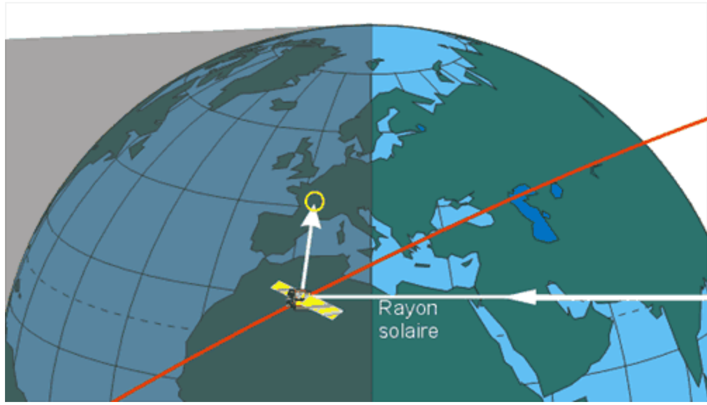
- strong and fast variations of conditions (SNR, turbulence), strong apparent wind speed,

→ need for real-time optimization of AO

→ temporal error in AO budget ?

→ impact on post-processing.

- Target illumination

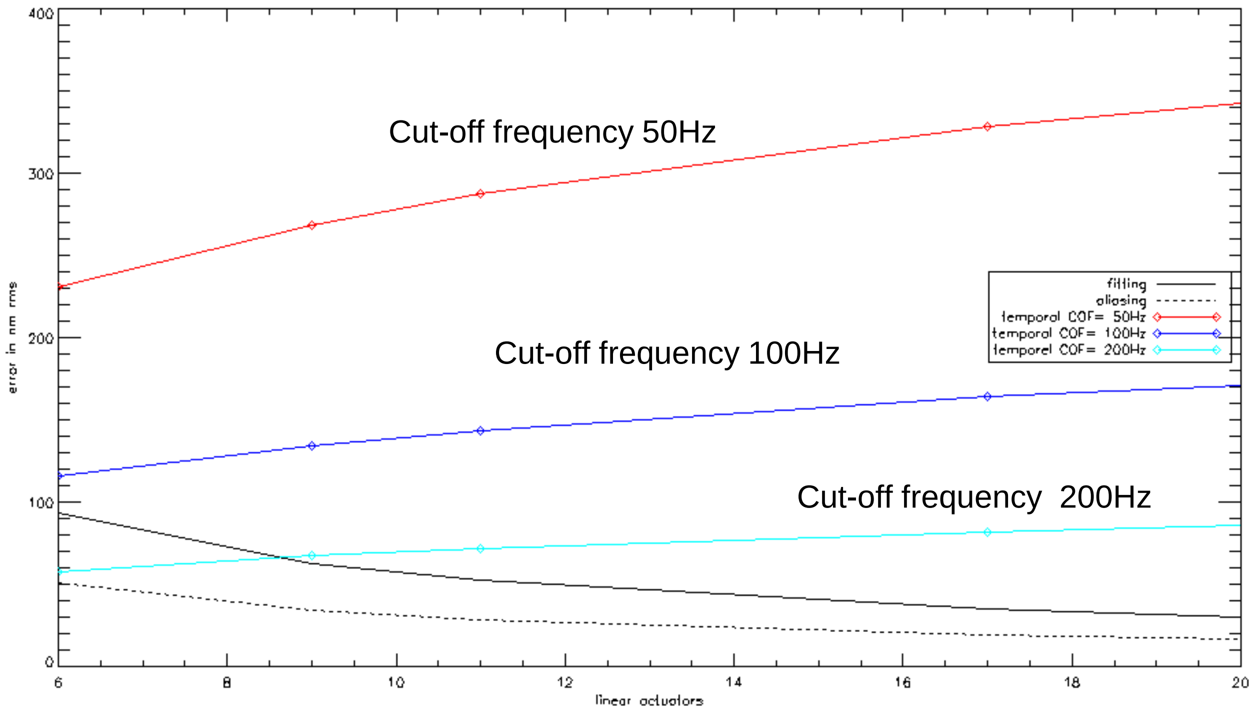


- **Goal: explorate AO assisted assets for SSA**

- Improve performance of an existing asset
- Generalize and optimise system design and performance, using technologies developed in astronomy
- Develop smart and robust automatic post-processing
- Strong synergy with LEO to ground optical telecommunication

Temporal error and system design with LEO satellites: rough error budget

AO for telecommunication
D=0.5 m
r_0 # 4cm@500nm
λ=1550nm
Elev = 70°
Wind profile dominated by apparent wind
Satellite : 800km, 7km/s



- ➢ **Performance driven first by temporal error**
- ➢ **Increase Cut-Off Frequency before number of actuators !**
- ➢ **You may gain wrt vibrations !**
- ➢ **In particular if increase of number of degrees of freedom slow down the system …**

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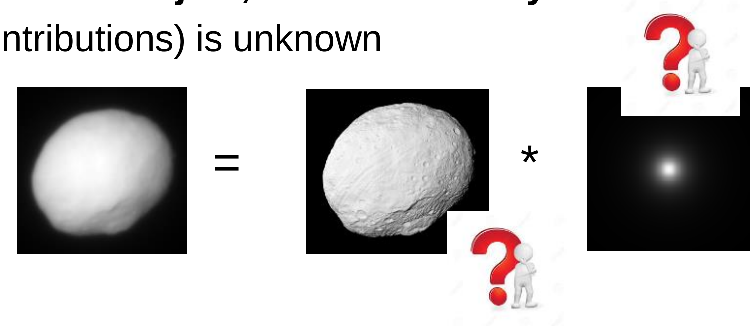
Image post-processing

Whatever the AO performance, deconvolution is required to restore object, as in astronomy

Problem: PSF (including instrumental and residual turbulence contributions) is unknown

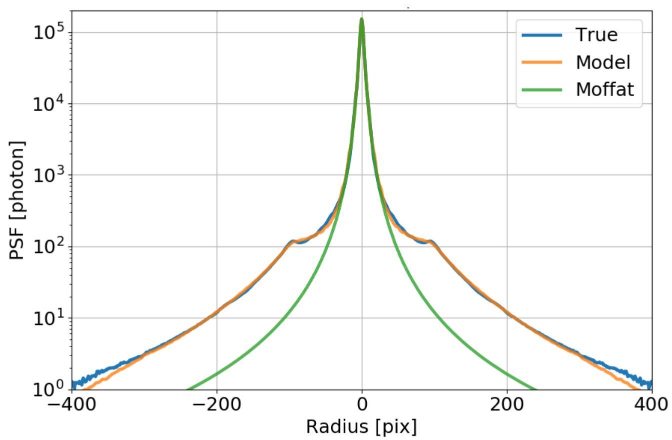


How to optimize deconvolution ?

- Use of stars temporally and spatially close to LEO observation ill-adapted (conditions strongly differ between satellite and star (scrolling ….), turbulence conditions evolve in time and with elevation …)
- Blind (myopic) deconvolution degenerated without strong constraints (positivity, support) with quadratic criterion due to too little data for too many parameters

Strategy:

- Use of parsimonious PSF model in partial AO correction, based on physical considerations (r_0, residual phase variance …) based on Fetick et al*. approach.
- Use parsimonious model for object and noise through acceptable PSDs
- Identify PSF only, on all possible objects = marginalisation wrt object
- Deconvolve with identified PSF



→ Marginal blind deconvolution

**Physics-based model of the adaptive-optics-corrected point spread function. Applications to the SPHERE/ZIMPOL and MUSE instruments*, R. JL. Fétick et al. Astrophys., 628:A99, 2019.

Going to the sky : experimental validation

Experimental validations: Onera's prototype

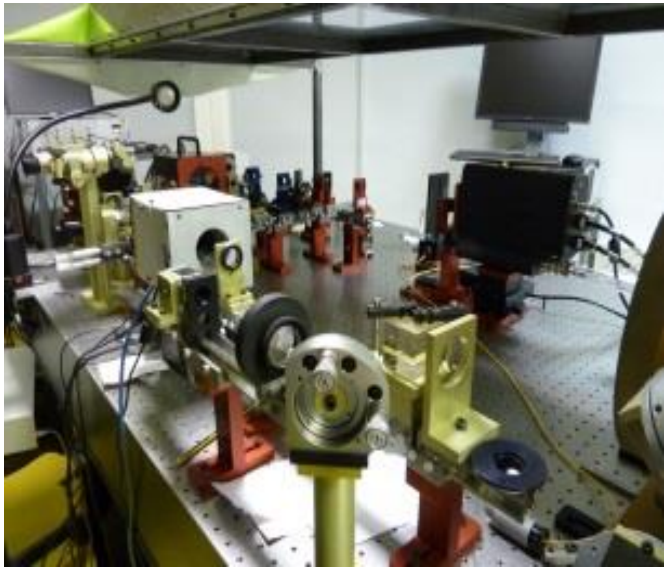
Location : on MeO telescope (1.5m) @ OCA (south of France, close to Nice)

- Telescope, with LEO tracking ability

1m50, 20 T, 5°/s, 1°/s²

- AO bench : ODISSEE

Limited performance,
OCAM² EMCCD based 8x8 sub-aperture Shack-Hartmann,
88 actuators (SAM)
1500Hz, with previously 3.3 frame delay (50Hz Cut-off Freq.)



AO system analysis & optimisation

- **Real-time acceleration with Shakti company**
  - Reduction of overall loop delay → critical due to satellite scrolling

→ GPU based architecture (WFSing), coupled to CPU, on simple PC RTC

→ 2.15 frames global delay @ 1.5kHz (GPU pure delay 70 µs)

→ reduces impact of vibrations (mainly <Fc=100Hz)

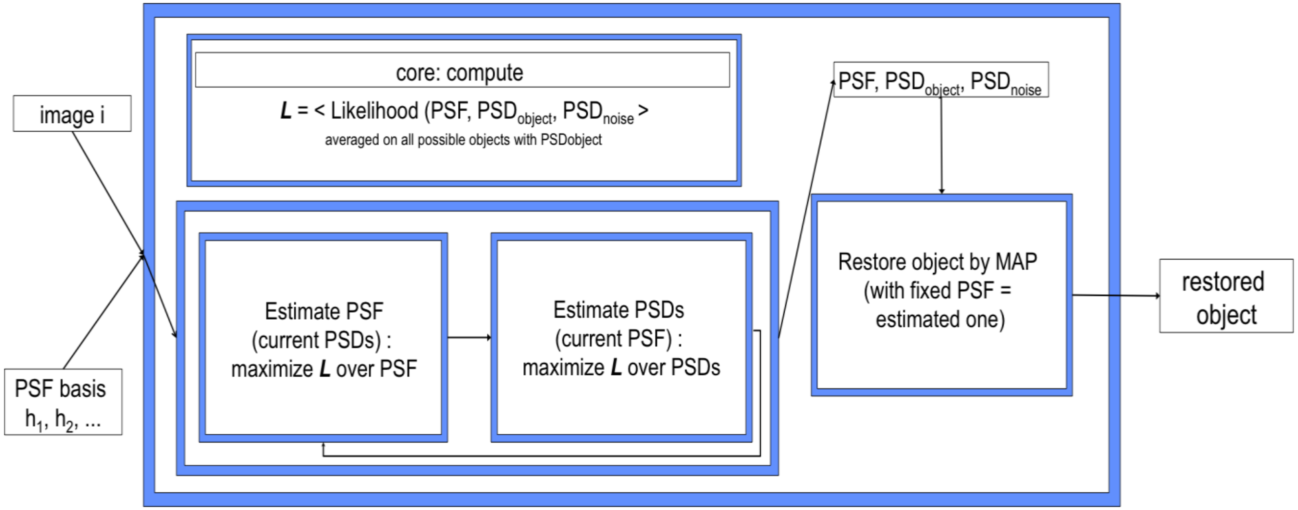
→ Allows on-line optimisation (automatic EMCCD gain adjustment, refined WFSing) and further control law improvements

→ System scalable to 16x16 sub apert. typ. without loss of performance

- **On-line optimisation/automatisation of AO: virtually fully automated**

Image processing

→ **Effective process:**



→ Per image approach

→ Parsimonious model of PSF based on physical parameters

Allows adjutement of PSF all along the observation

→ few parameters: fast processing

→ strong robustness demonstrated on large set of images

Results: ENVISAT

>> Tests on ENVISAT, 800km
>> Comparison to 3D model

Seeing conditions >1’’
Resolution on target: classified

Open-loop | AO, brute images | AO + post-processing | 3D model

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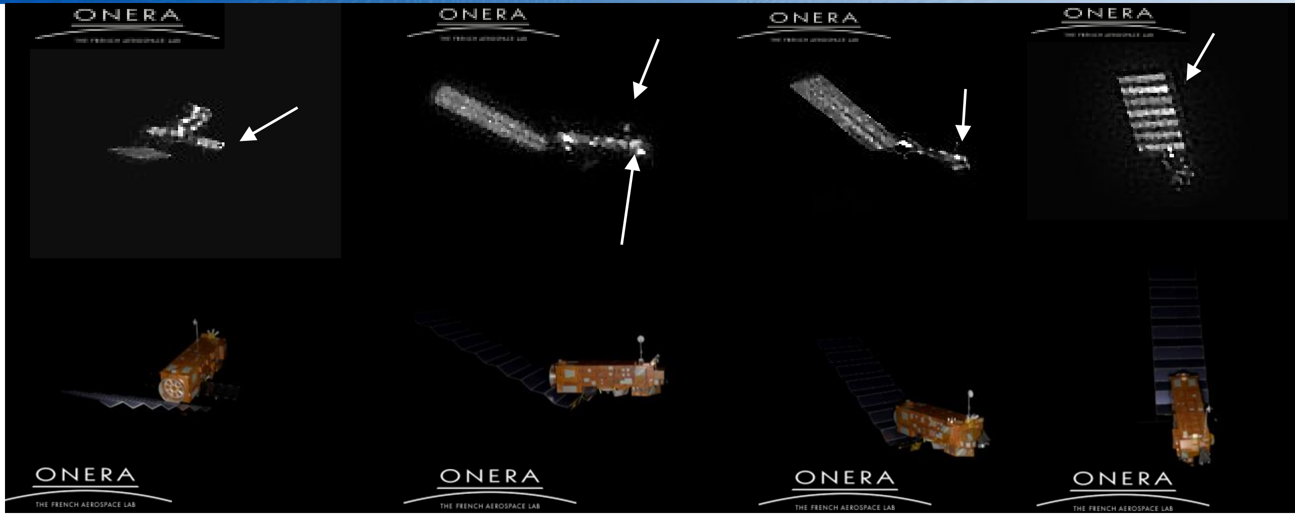
Results: ENVISAT



Data:

- Interesting features accessible, gain brought by image sequence
- Estimation of rotation speed: should account for change of attitude/shape due to tracking, distance …

Rough evaluation from images leads to 202s tumbling period. Laser range estimation was 134,7s in 2013, with an increase of 36.7ms/day (Kucharski et al), leading to estimated period during acquisition of 206,9s.

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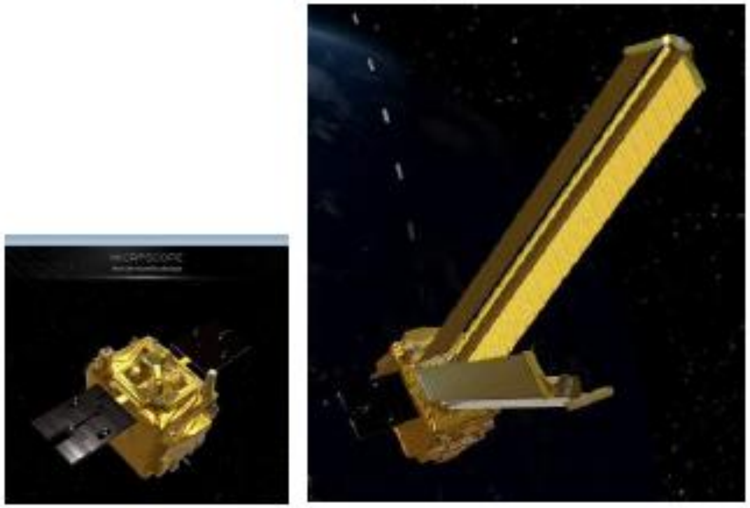
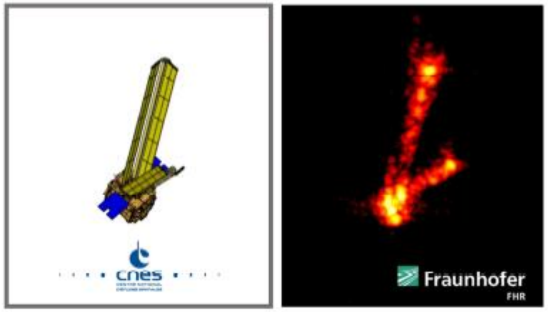
Control of deorbiting system: the Microscope mission

Microscope mission (Cnes/onera): scientific mission to validate the equivalence principle

Mission : 2016- oct 2018. acceleration of deorbitation by use of inflatable wings (4m long)





Conclusion & perspectives

Conclusions:

- AO system improvement, though AO system still ill-adapted wrt seeing conditions
- Far from american systems
- Allows investigation/optimisation of AO on-line optimisation, control and post-processing

Perspectives:

- Further work on low latency RTC (GPU / FPGA), though mainly driven by telecommunication needs
- Can we improve AO performance along the observation ?
  - Estimation/follow-up of turbulence conditions
  - Predictive evolution of turbulence conditions, with strong apparent wind effect
- Can we improve post-processing strategy ?, based on:
  - Recent work by Fetick et al. (PSF parsimonious model)
  - Use of real-time turbulence conditions estimation as well as AO information for refined post-processing
  - Considering overall images sequence
- Can we optimize system design based on multi parameter optimisation (site, turbulence, targets …) ?

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