AGADiR
Advanced GNC for Active Debris Removal

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I. Introduction

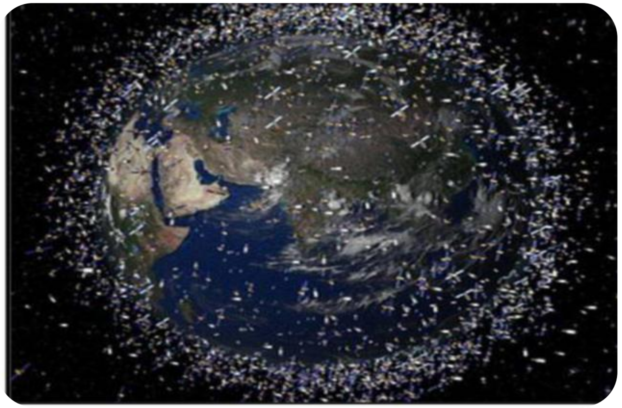
II. GNC architecture & control Design

III. Simulation analysis

IV. Conclusion

Top Level Objective – Clean Space Program

- Remove uncontrolled, decommissioned spacecraft and orbital stages of launch vehicles from regions populated by operational spacecraft
- Inhibit Kessler syndrome effect which predicts an exponential and un-controllable growth of debris density in space
- Tethered Space System (TSS) judged as credible option to capture devices (e.g., harpoon, net)
- Multi-disciplinary technical issues to be investigated (TSS modeling, guidance, navigation and control for uncooperative target)



Main study objective

- Develop & validate an advanced GNC concept for active debris removal of space objects
- Develop a GNC solution focusing on tether-based deorbiting strategy
- GNC solutions suitable to handle multi-burns deorbiting strategy
- Application to Large satellite evolving in SSO orbit (**ENVISAT**)

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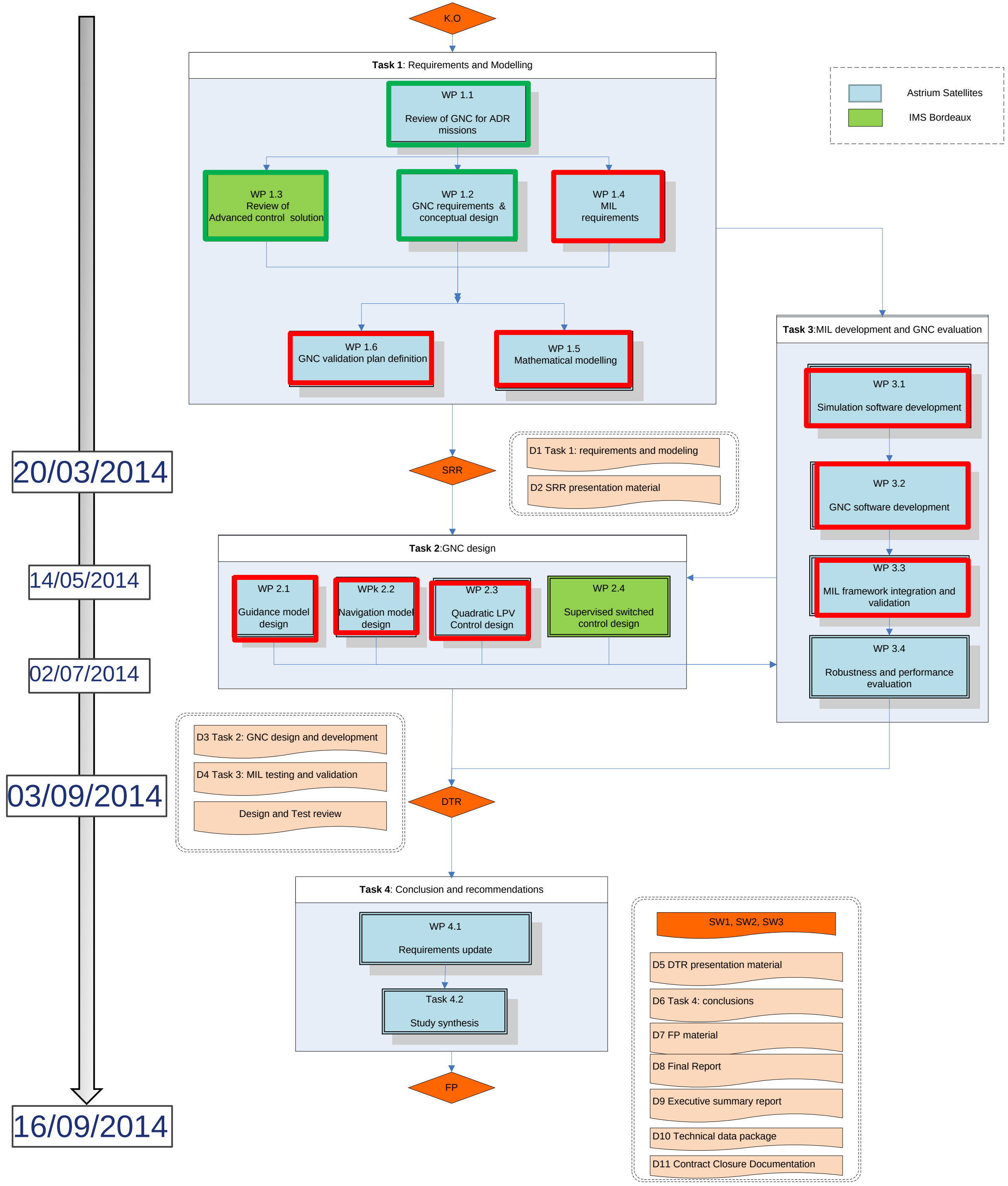
Overview of AGADiR project study logic



Progress status of activity

WP	Resp.	Title	Completion
1.1	Airbus DS	Review of GNC for ADR missions	100%
1.2	Airbus DS	GNC requirements and conceptual design	100%
1.3	IMS	Review of advanced control techniques	100%
1.4	Airbus DS	MIL requirements	100%
1.5	Airbus DS	Mathematical modelling	100%
1.6	Airbus DS	GNC validation plan	50%
2.1	Airbus DS	Guidance model	100%
2.2	Airbus DS	Navigation model	100%
2.3	Airbus DS	Quadratic LPV control design	90 %
2.4	IMS / Airbus DS	Supervised switched control design	20%

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Objective: Perform a safe & accurate controlled re-entry of the flight formation

- South areas uniformly distributed in Longitude
- **Area 1**: (Safer) -70° <Latitude < -40° - (SPOUA for South Pacific Ocean Uninhabited Area): (area classically used for ATV)
- **Area 2**: -30° < Latitude < +30° : West of America (Commpton Gamma Ray Obervatory – 2000)
- **Area 3**: +30° < Latitude < +50° : (Express AM4 in 2012)

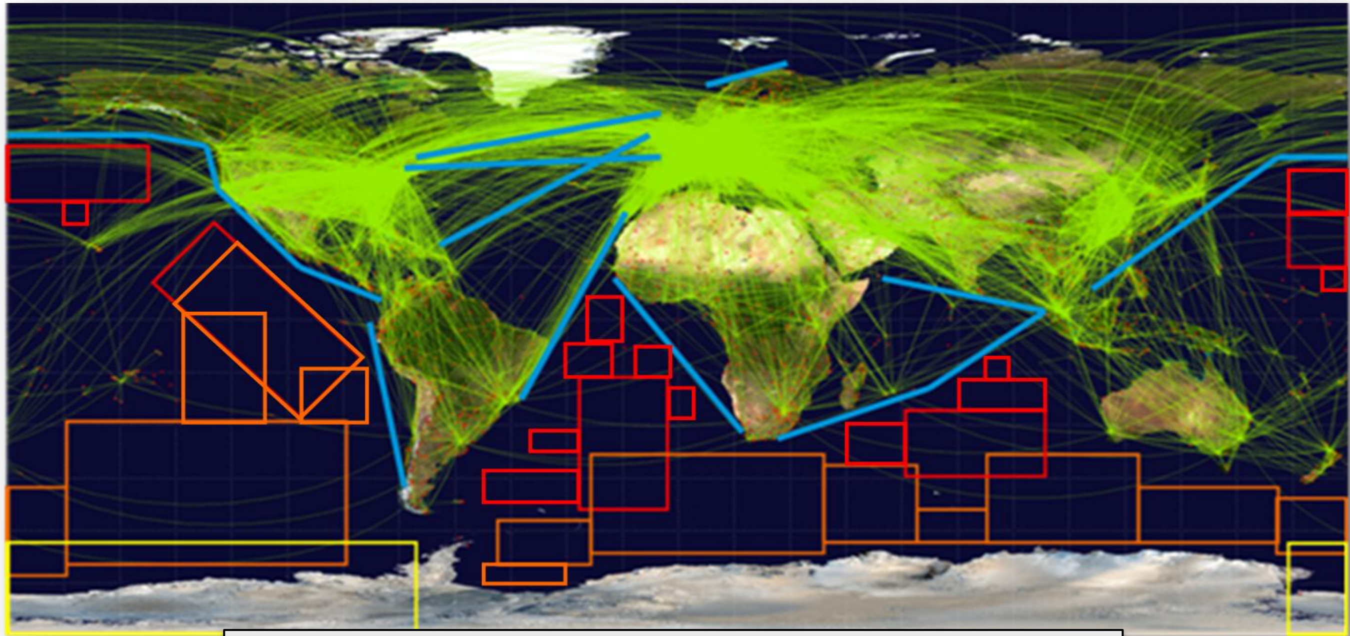


Fig.1: Synthesis of the more secured deorbiting areas

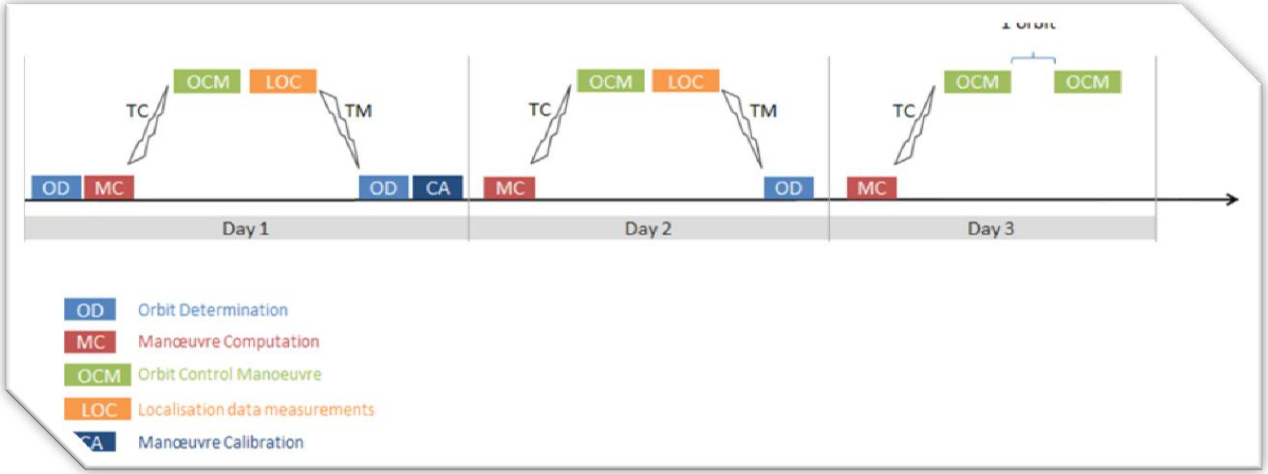
- Main maritime areas
- Re-entry area with low impact on maritime & aerial traffics – areas to be prioritized
- Re-entry area with acceptable disturbances on maritime & aerial traffics
- Uninhabited areas

Controlled re-entry – Classical assumptions for reentry trajectory computation

- Atmospheric dispersions (+/- 50% on the atmospheric density)
- Fragmentation model (ballistic coefficient, fitness)
- Initial orbit position (depend to the orbit restitution)
- Nominal deorbiting plan execution – realization of DeltaV
  - Thrust magnitude error and efficiency (depend to the distance of Apogee and maximum allowed duration of thrust linked to mechanical constraints)

Deorbiting scenario for ADR (500 N case)

- 4 burns with duration lower than 20 minutes
- Duration at low Perigee is minimized to avoid high dispersion on orbit due to the atmospheric drag
- Mission duration of 3 days



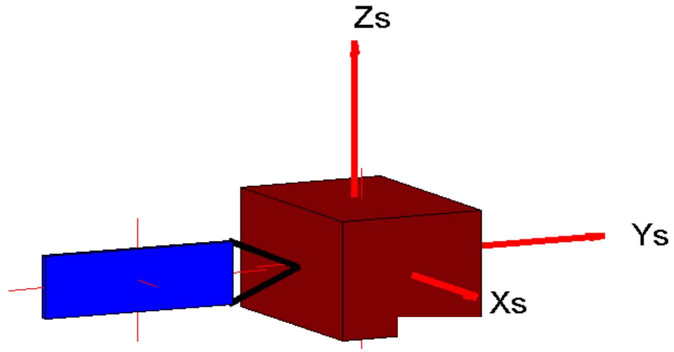
OCM #1: 52,3 m/s	Perigee: 793 Km
OCM #2: 52,3 m/s	Perigee: 595 Km
OCM #3: 52,3 m/s	Perigee: 219 Km
OCM #4: 52,3 m/s	Perigee: 40 Km

Chaser model parameters

$$I_{sat} = \begin{bmatrix} 2040 & 130 & 25 \\ 130 & 1673 & -54 \\ 25 & -54 & 2574 \end{bmatrix} kg \cdot m^2$$
$$m = 1500kg$$

➢Proposition for Chaser: use of Eurostar3000-based platform

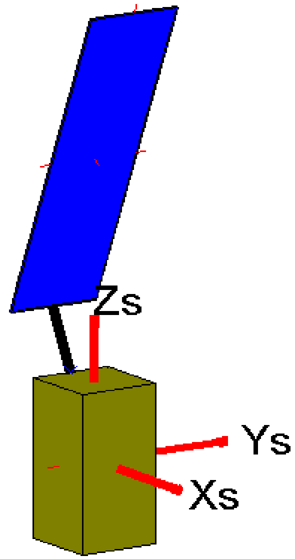
- Strong interest of cost-reduction through the use of a widely adopted and flight-proven platform
- Avoid full on the shelf design
- SA surface adapted to CDF study data (~2.8m2)
- Common LAE ~450N



Target model parameters

- Target model refined from Airbus's internal Envisat data Important add-on of the 80m2 SA panel: realistic disturbance torques estimation

- Flexible modes Effective masses up to 0,5Hz have an impact, with first two in-plane and out-of plane flexible modes dominating



$$I_{sat} = \begin{bmatrix} 124900 & -350 & 2060 \\ -350 & 120600 & 400 \\ 2060 & 400 & 17000 \end{bmatrix} kg \cdot m^2$$
$$m = 7500kg$$

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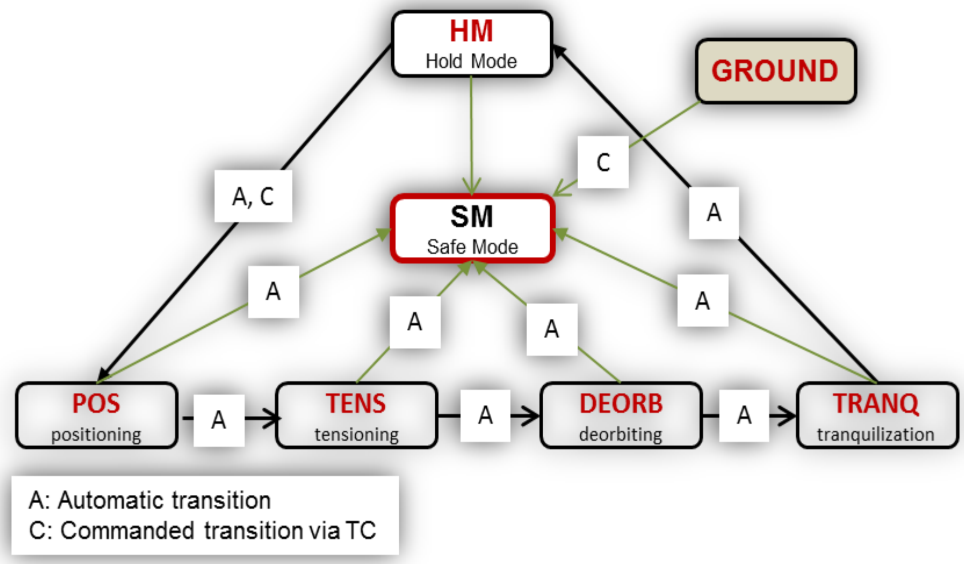
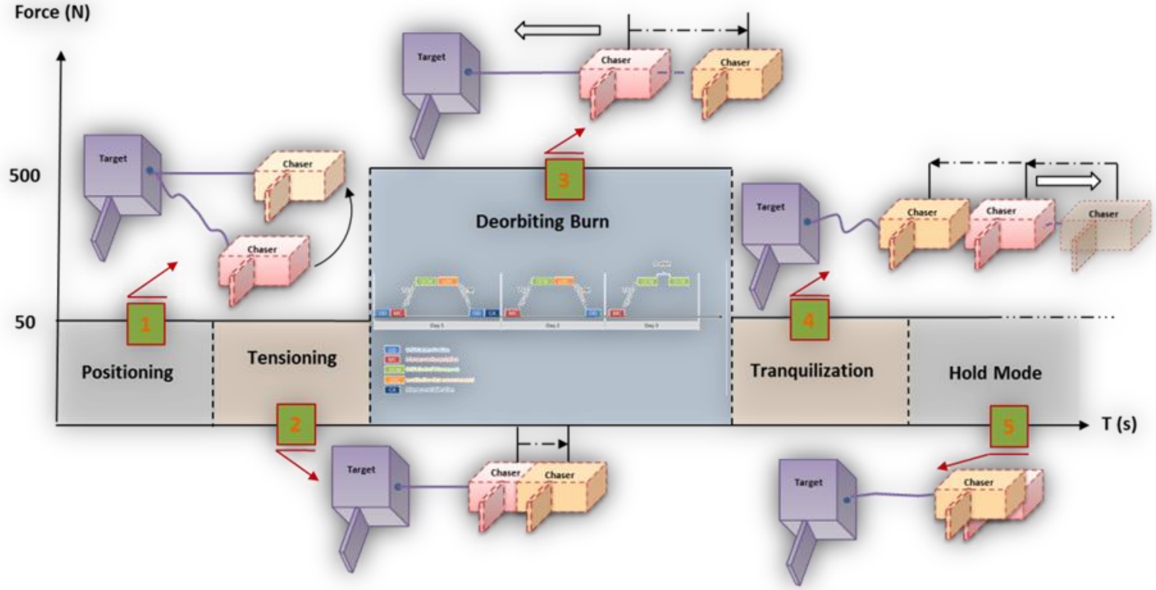
❑ Different tether/sensors configurations to be analysed

❖ 6 Tether x 4 Lidar → 24 cases

ID	E [N/m2]	A0 [m2]	Ls [m]	m_TOT [kg]	N_masses [-]	M [elements]	m [kg]	B [Ns/m]	L_el [m]	k_el [N/m]	K estimate [N/m]	Tether type
1	1,0E+08	0,0	200,0	5,0	2	3	2,5	0,3	66,7	30,0	10,0	Nominal
2	1,0E+08	0,0	200,0	5,0	0	1	0,0	0,3	200,0	10,0	10,0	Massless
3	1,0E+08	0,0	800,0	5,0	2	3	2,5	0,3	266,7	7,5	2,5	Long tether
4	1,0E+09	0,0	200,0	5,0	2	3	2,5	0,3	66,7	300,0	100,0	Stiff tether
5	1,0E+08	0,0	200,0	5,0	2	3	2,5	0,0	66,7	30,0	10,0	Very low damping
6	1,0E+08	0,0	200,0	5,0	4	5	1,3	0,3	40,0	50,0	10,0	More masses

Parameter	Units	Lidar type			
		Nominal	Slow	Low Accuracy	Low Performance
FOV	[deg]	40x40	30x30	30x30	20x20
Range	[km]	3	1,5	1,5	1,5
Range Error, 3σ	[-]	1%	1%	2%	3%
Range Bias	[-]	±0,5%	±0,5%	±1,0%	±1,5%
LoS Error	[deg]	0,5 per axis	0,5 per axis	1 per axis	2 per axis
LoS Bias	[deg]	±0,3 per axis	±0,3 per axis	±1 per axis	±1,5 per axis
Attitude Error, 3σ	[deg]	5 per axis	5 per axis	10 per axis	15 per axis
Meas. Rate	[Hz]	1	0,5	1	0,25
Meas. Delay	[s]	1	3	1	3
Meas. Outrages	[-]	1%	2%	1%	5%





❑ Positioning (POS)

- Chaser positioning for deorbiting sequence execution
- From any offset position from the target negative along-track direction

❑ Tensioning (TENS)

- Low-thrust pre-tensioning phase to stiff the TSS formation
- Target damping and smooth management of the discontinuities effects induced by slack/taut configurations change

❑ Deorbiting (DEORB)

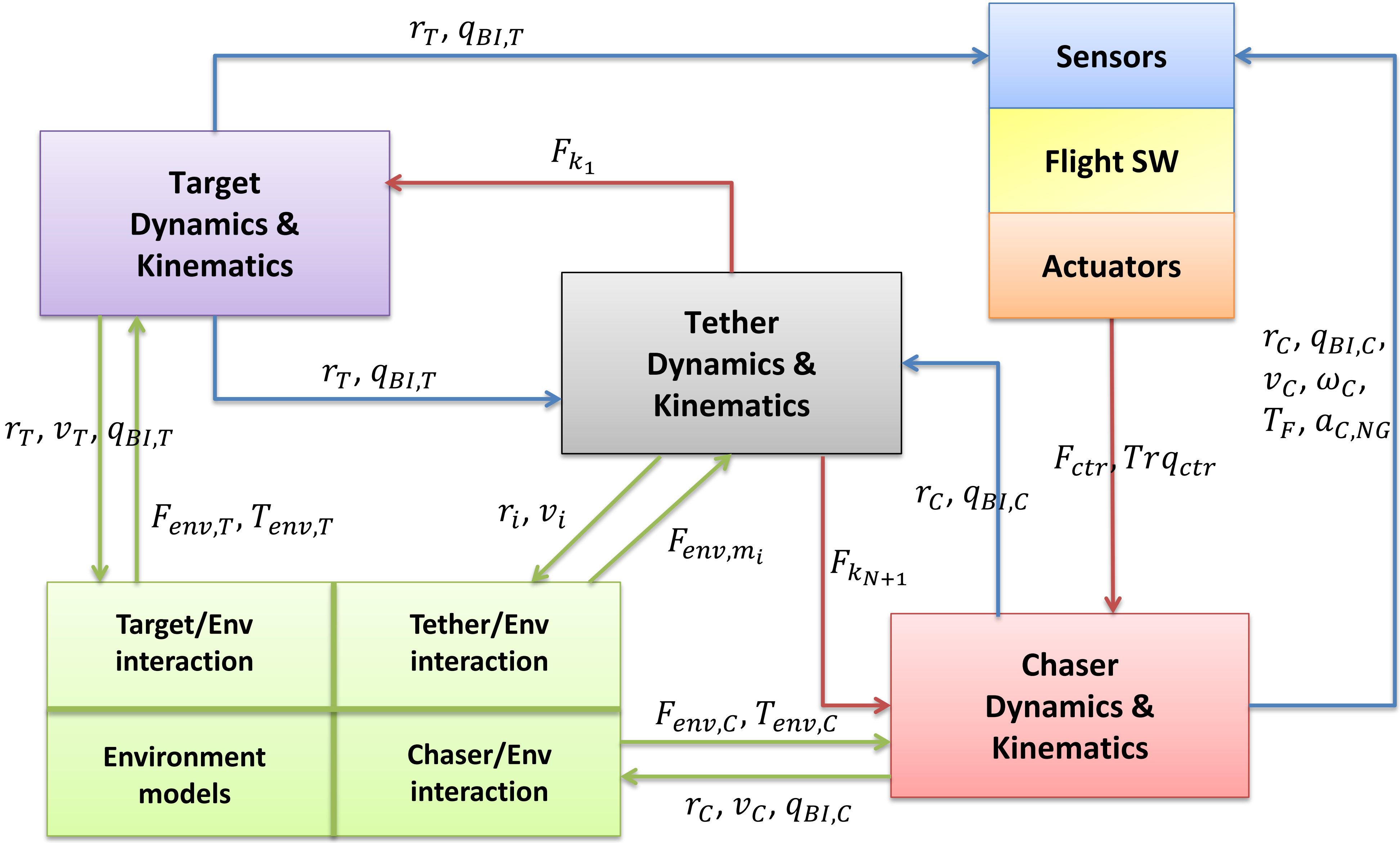
- Reference deorbiting sequences execution
- Most stringent phase in terms of control specification (alignment of thrust vector))

❑ Tranquilization (TRANQ)

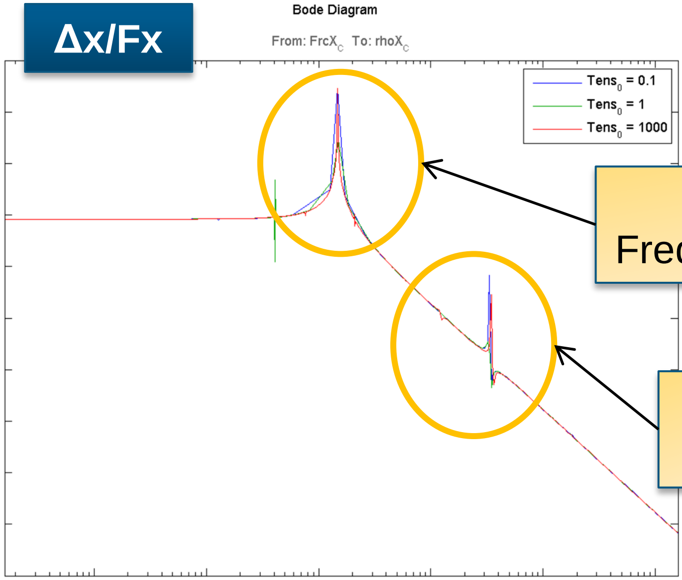
- Post-burn braking phase to reduce the formation relative velocity
- Loss of target controllability during this phase (target winding will depend to braking duration depending to the thrust authority)

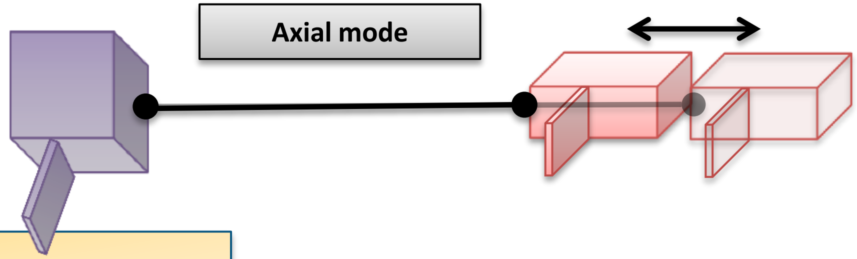
❑ Hold Mode (HM)

- Take away the chaser to the target once the Tranq phase achieved
- Keep the flight formation in an acceptable holding position


$r_T, q_{BI,T}$
Sensors
Flight SW
Actuators
Target Dynamics & Kinematics
F_{k_1}
Tether Dynamics & Kinematics
$r_T, q_{BI,T}$
$r_C, q_{BI,C},$
$v_C, \omega_C,$
$T_F, a_{C,NG}$
$r_T, v_T, q_{BI,T}$
F_{ctr}, Trq_{ctr}
$r_C, q_{BI,C}$
$F_{env,T}, T_{env,T}$
r_i, v_i
F_{env,m_i}
$F_{k_{N+1}}$
Target/Env interaction
Tether/Env interaction
Chaser Dynamics & Kinematics
$F_{env,C}, T_{env,C}$
Environment models
Chaser/Env interaction
$r_C, v_C, q_{BI,C}$

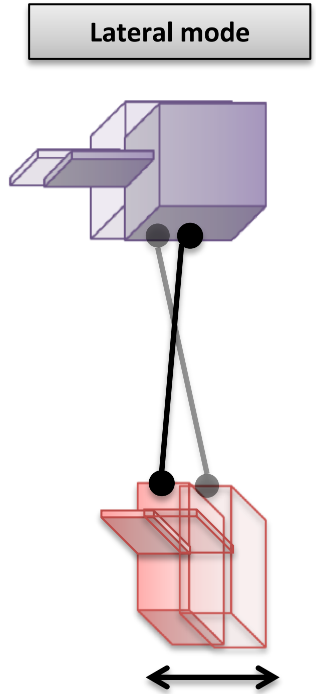
❑ Dynamics analysis

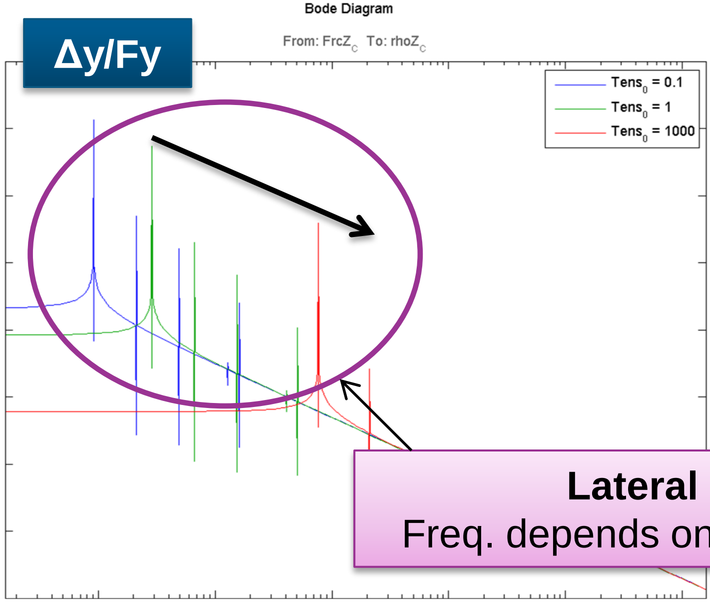


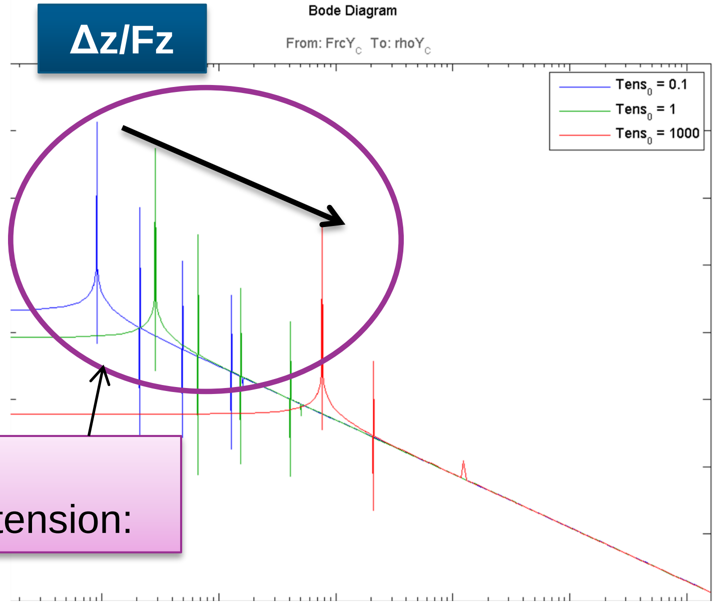


Axial mode
Freq. independent of tether tension:

Flexible mode (appendage)



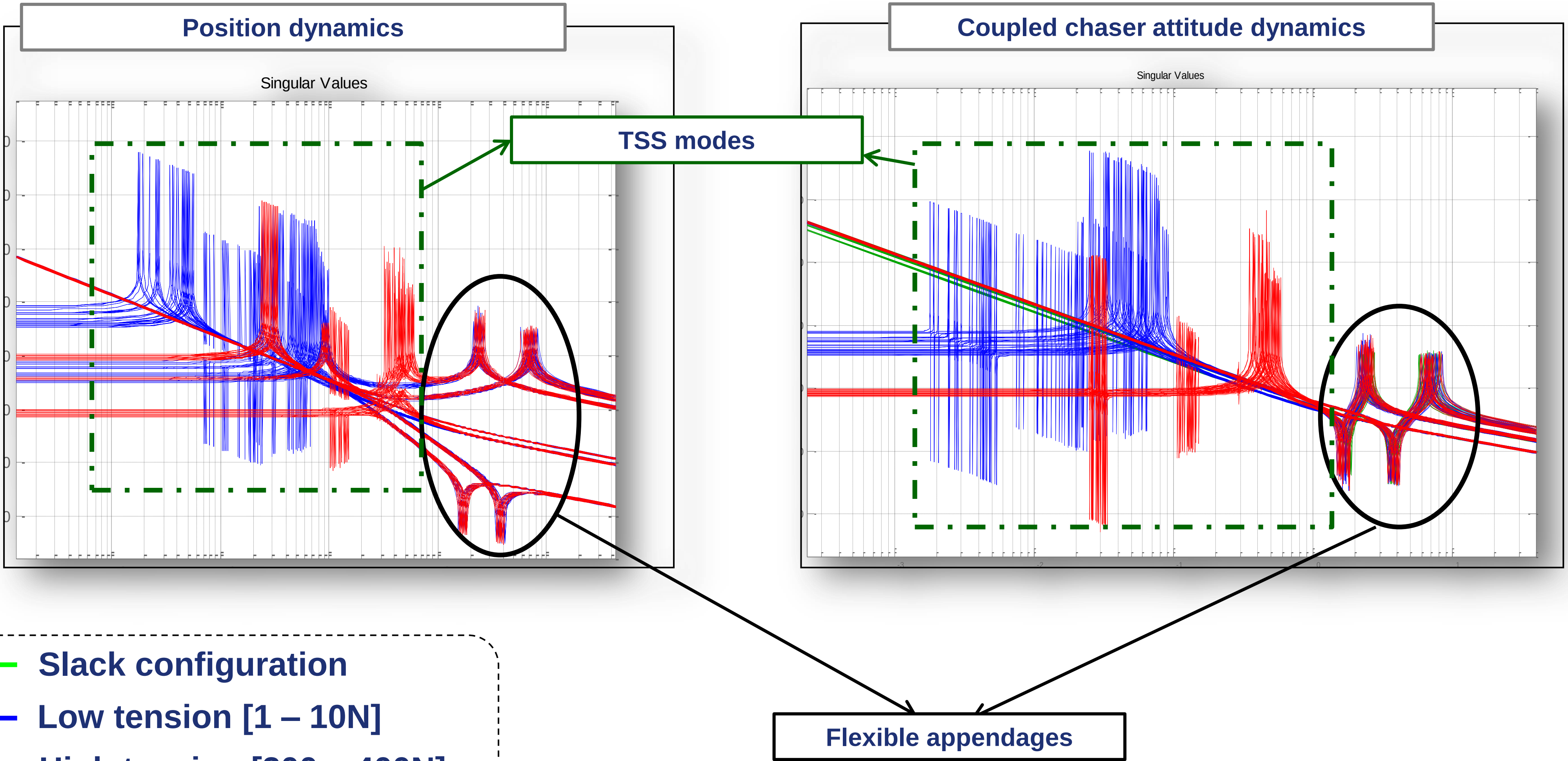




Lateral mode
Freq. depends on tether tension:

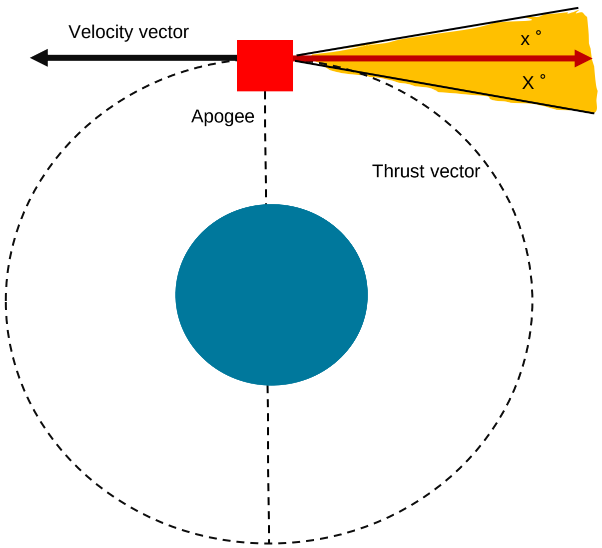
❑ Position & attitude dynamics

- ✓ Flexible modes spread over a large frequency range (expanded Modal density)
- ✓ Lead to a complex control design problem – high dimension and highly flexible !
  - ➢ **Design**: assumptions should be retained – judicious selection of synthesis model
  - ➢ **Analysis**: considered on the overall coupled dynamics & fine LFT model



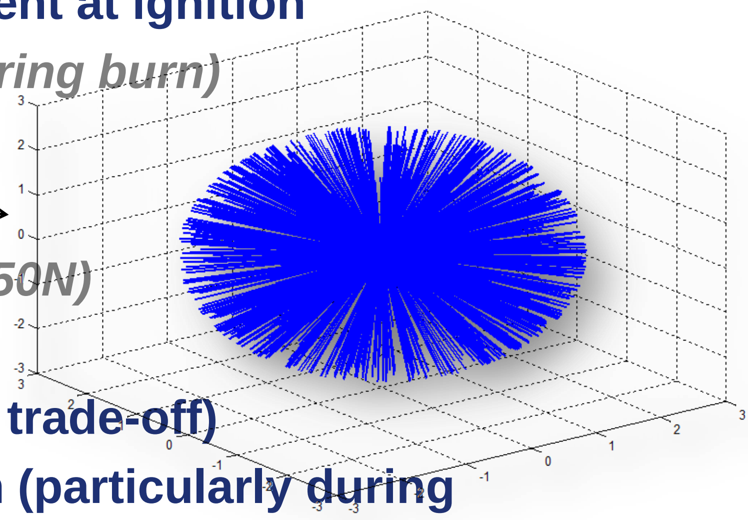
- Slack configuration
- Low tension [1 – 10N]
- High tension [200 – 400N]

❑ Control design – problem overview



- ❖ **Control design objectives:**
  - ✓ **MPE requirement for chaser pointing: 1deg**
    (mission analysis for safe/accurate deorbiting)
  - ✓ **Input/Output stability margins: 6dB**

- ❖ **CDO shall be fulfilled considering the following constraints**
  - ❖ **Disturbances induced by Apogee thruster misalignment at ignition**
  - ❖ **Worst case environmental disturbance at apogee** *(during burn)*
  - ❖ **Initial conditions of target** *(spin-rate, attitude)*
  - ❖ **Gradual LIDAR performances**
  - ❖ **Actuator saturation** *(Maximum torque/force of 20Nm/50N)*
  - ❖ **Great variety of tether materials (stiff, long,…)**
  - ❖ **Consumption minimization (performance/robustness trade-off)**
  - ❖ **System commutation from/to slack/taut configuration (particularly during tensioning/hold phases with possible switches induced to actuation period)**
  - ❖ **Phase-dependent target controllability**

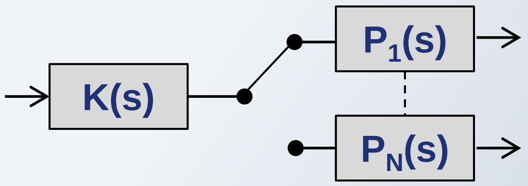


❑ Control design – problem overview

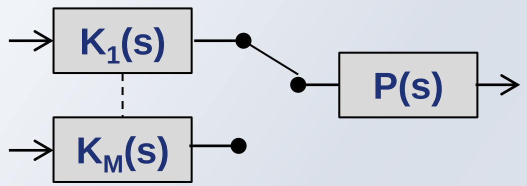
Control Objective: Design a multi-controllers structure with stability certificate during switching sequences while satisfying the robust performances requirements (modulus margin, pointing specification, limitation of consumption)

Switching possibilities….

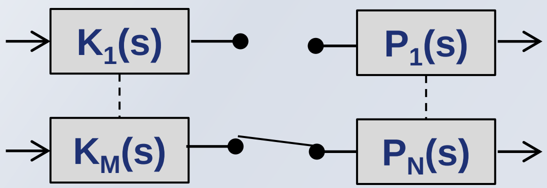
1 controller for N models



M controllers for 1 model



M controllers for N models

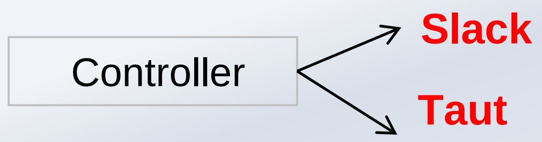


How to compute the stability certificate during switching sequences?

Lyapunov theory

Find a common Lyapunov function that satisfies the conditions of the Lyapunov theory simultaneously for all constituent systems

Arbitrary switching sequence



Dwell-time theory

Compute the optimal time to switch from one configuration to another one to ensure stability & performances

Supervised switching sequence

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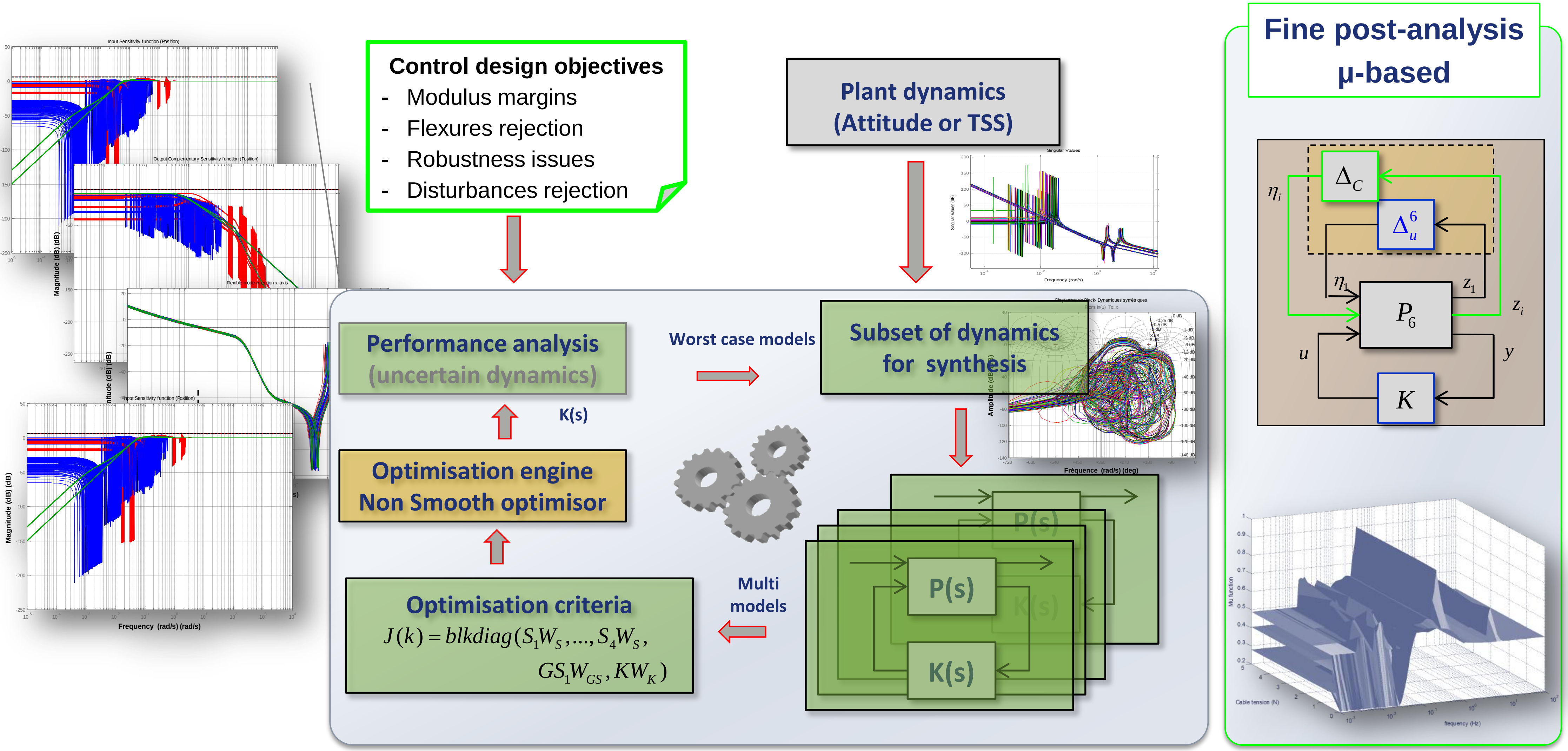
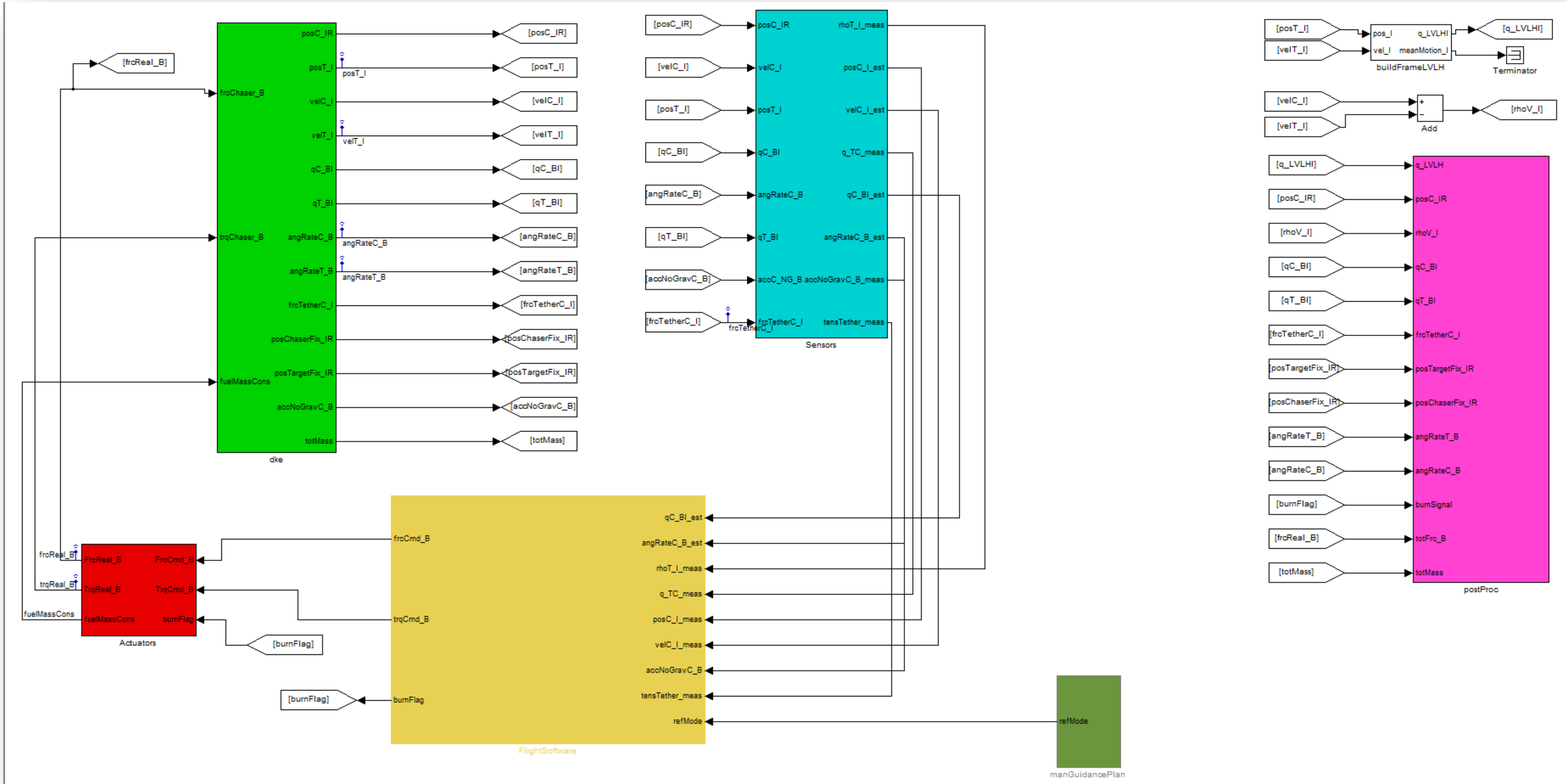
❑ Controller design – iterative synthesis & analysis process

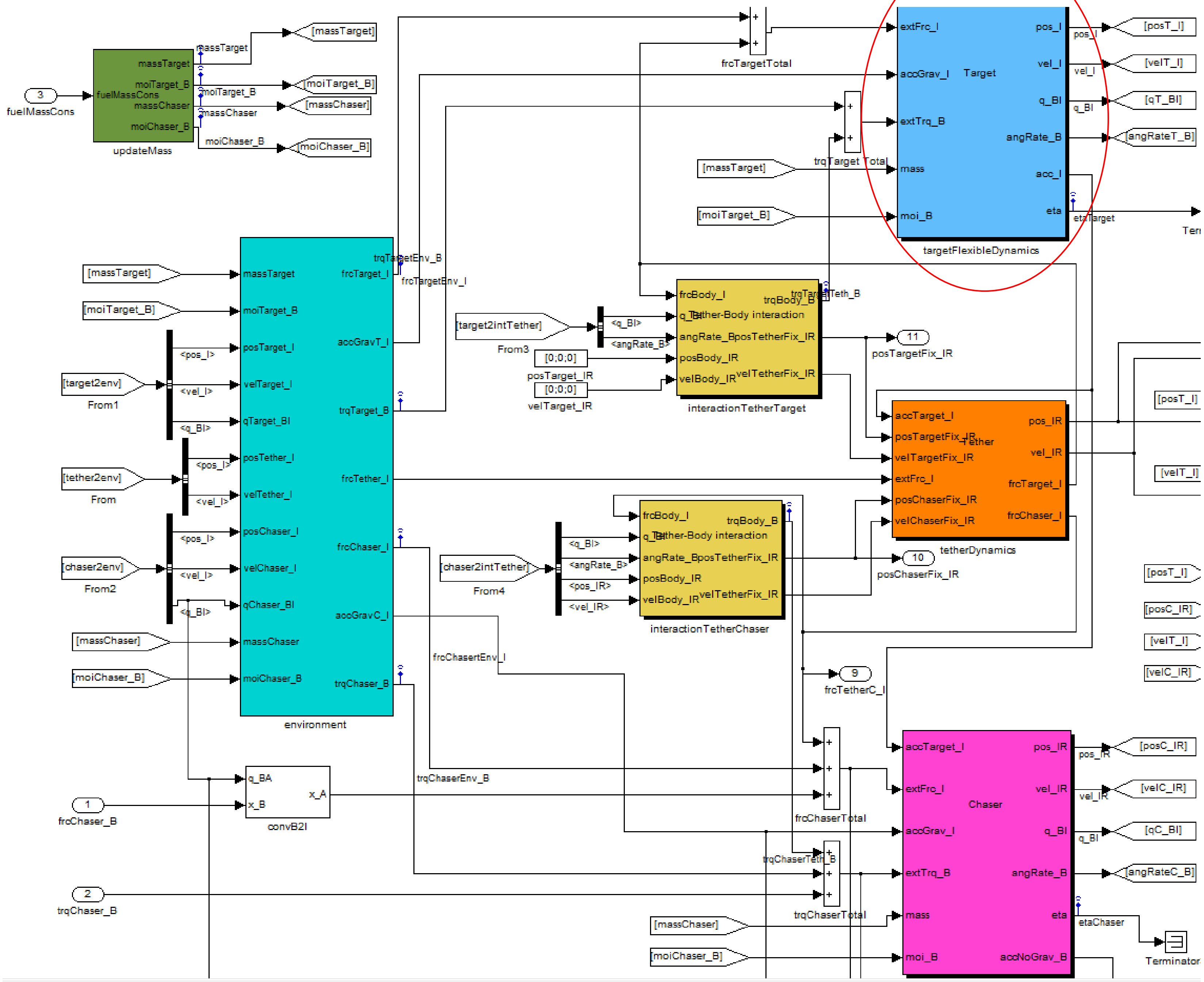


- **Iterative update of WC model in the structured H∞ multi-models synthesis**
- **Controller structure directly imposed to respect implementation constraints**
- **Robust performances assessment a-posteriori check based on fine µ-analysis**

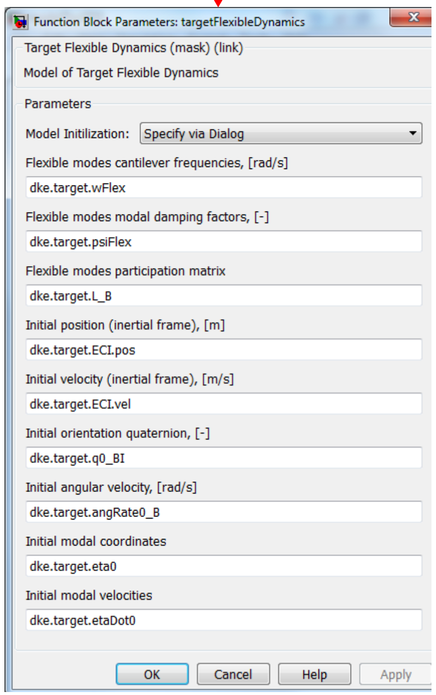
❑ Simulator overview



❑ Simulation envrironment



SpaceLAB template



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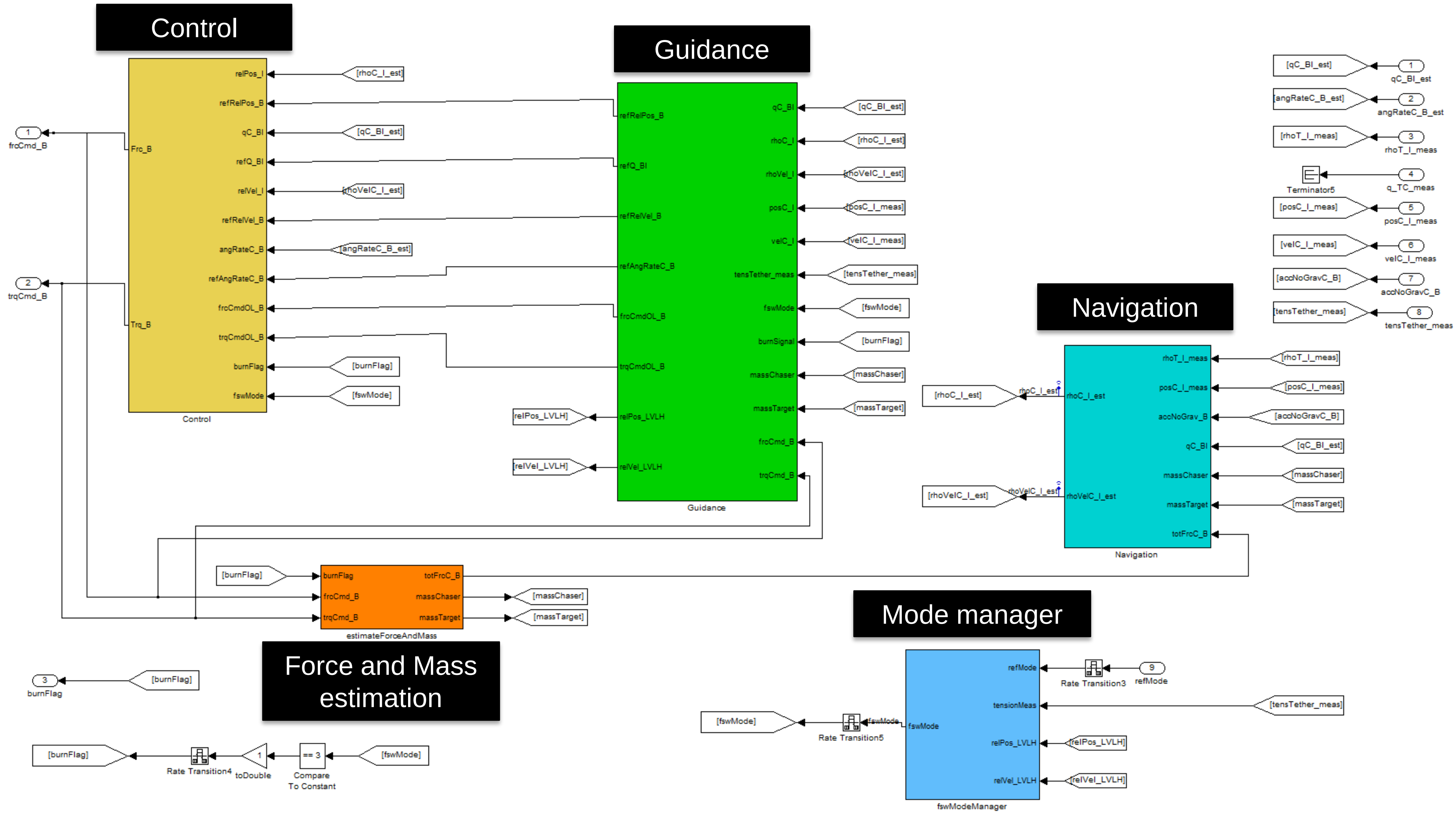
❑ Flight Software



❑ Tether and Lidar types for analysis

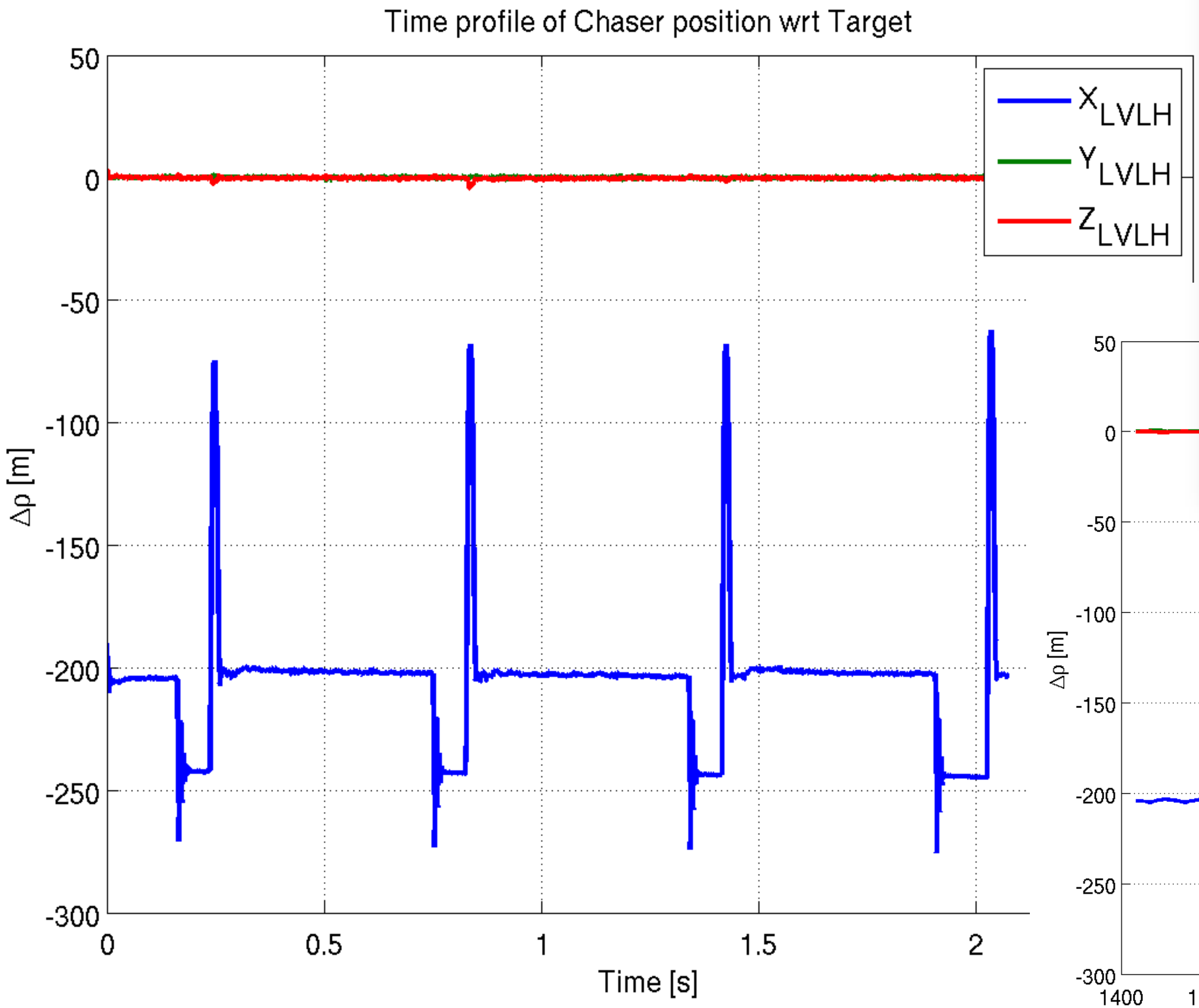
❖ 6 Tether x 4 Lidar ➔ 24 cases

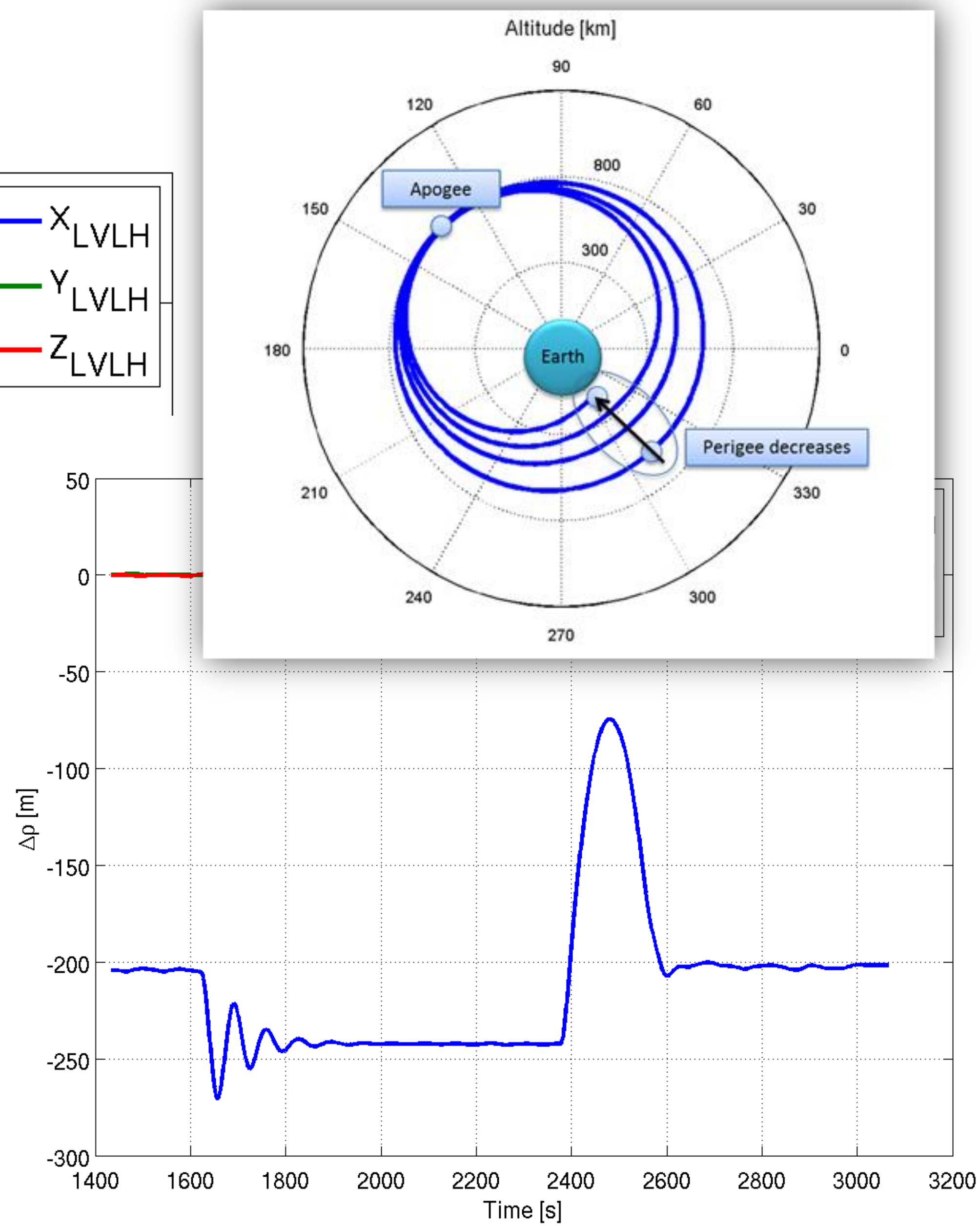
ID	E [N/m2]	A0 [m2]	Ls [m]	m_TOT [kg]	N_masses [-]	M [elements]	m [kg]	B [Ns/m]	L_el [m]	k_el [N/m]	K estimate [N/m]	Tether type
1	1,0E+08	0,0	200,0	5,0	2	3	2,5	0,3	66,7	30,0	10,0	Nominal
2	1,0E+08	0,0	200,0	5,0	0	1	0,0	0,3	200,0	10,0	10,0	Massless
3	1,0E+08	0,0	800,0	5,0	2	3	2,5	0,3	266,7	7,5	2,5	Long tether
4	1,0E+09	0,0	200,0	5,0	2	3	2,5	0,3	66,7	300,0	100,0	Stiff tether
5	1,0E+08	0,0	200,0	5,0	2	3	2,5	0,0	66,7	30,0	10,0	Very low damping
6	1,0E+08	0,0	200,0	5,0	4	5	1,3	0,3	40,0	50,0	10,0	More masses

Parameter	Units	Lidar type			
		Nominal	Slow	Low Accuracy	Low Performance
FOV	[deg]	40x40	30x30	30x30	20x20
Range	[km]	3	1,5	1,5	1,5
Range Error, 3σ	[-]	1%	1%	2%	3%
Range Bias	[-]	±0,5%	±0,5%	±1,0%	±1,5%
LoS Error	[deg]	0,5 per axis	0,5 per axis	1 per axis	2 per axis
LoS Bias	[deg]	±0,3 per axis	±0,3 per axis	±1 per axis	±1,5 per axis
Attitude Error, 3σ	[deg]	5 per axis	5 per axis	10 per axis	15 per axis
Meas. Rate	[Hz]	1	0,5	1	0,25
Meas. Delay	[s]	1	3	1	3
Meas. Outrages	[-]	1%	2%	1%	5%

❑ Simulation examples: Relative position

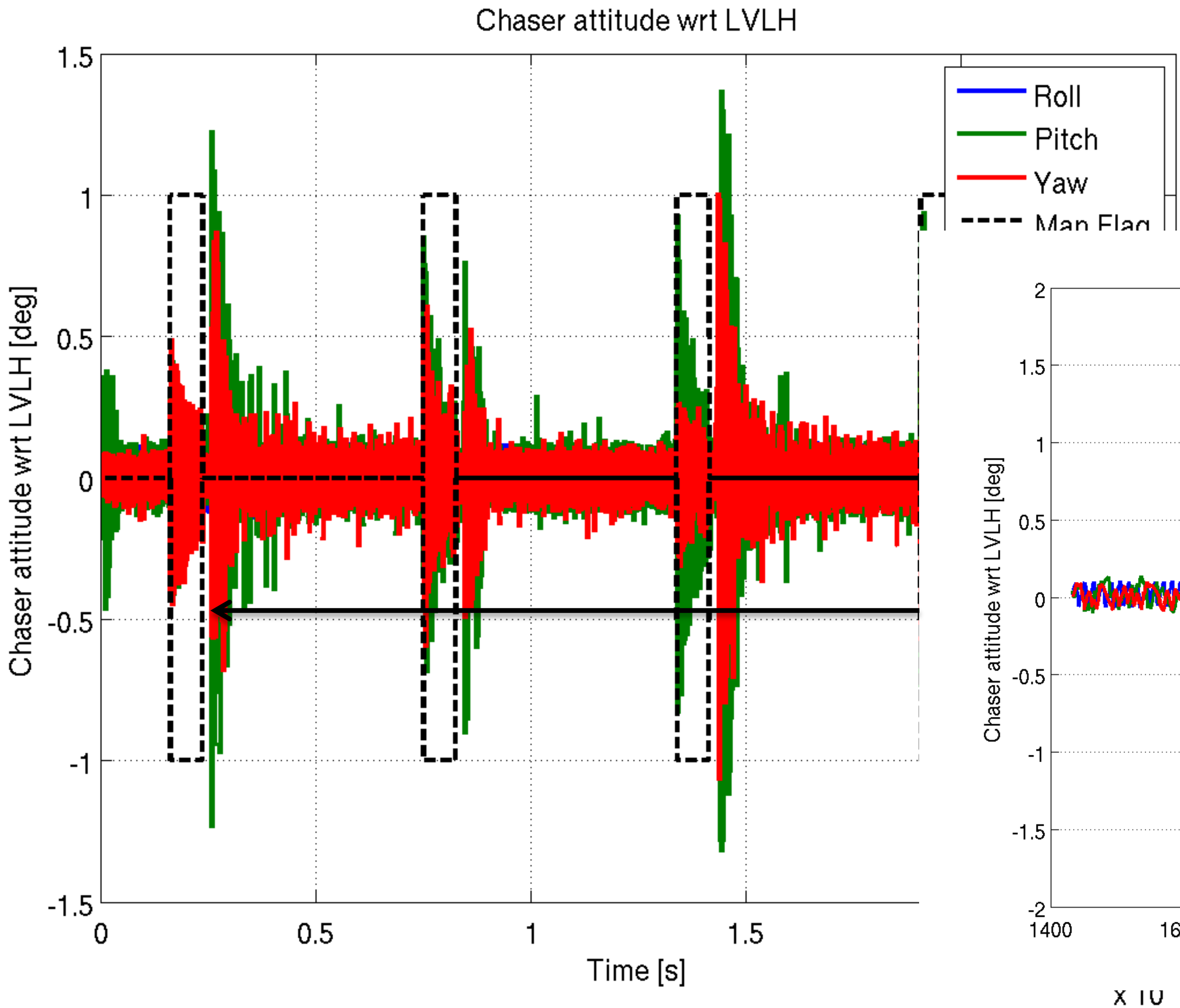
- Demonstration on a complete scenario -

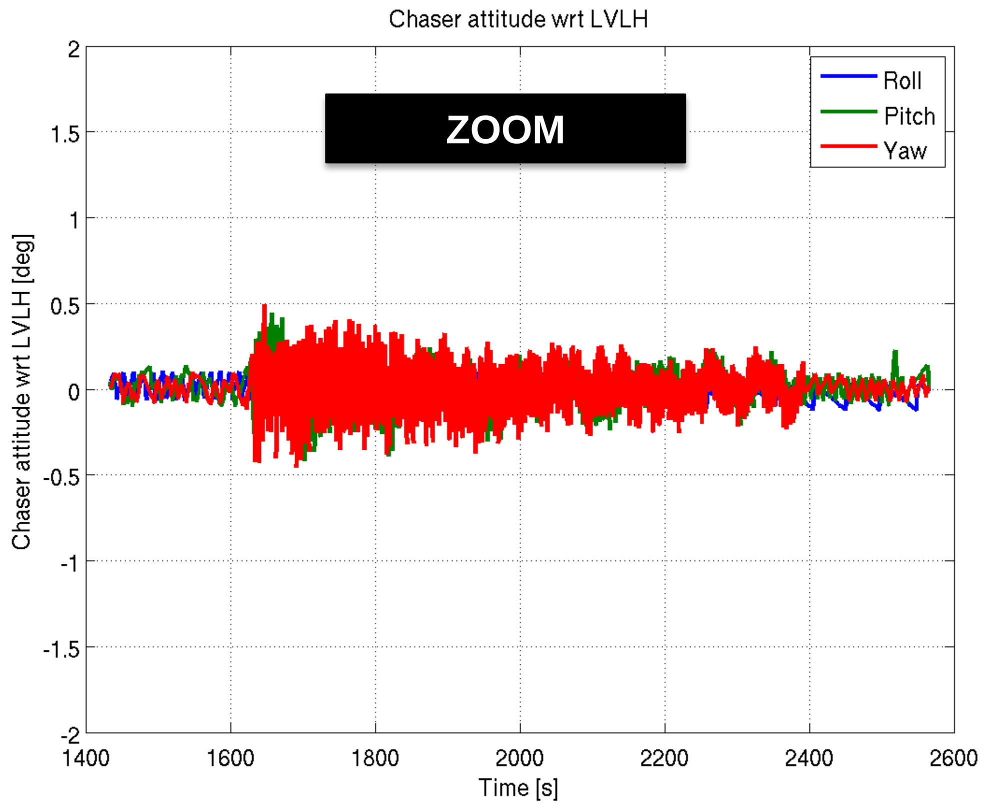




❑ Simulation examples: Chaser Attitude

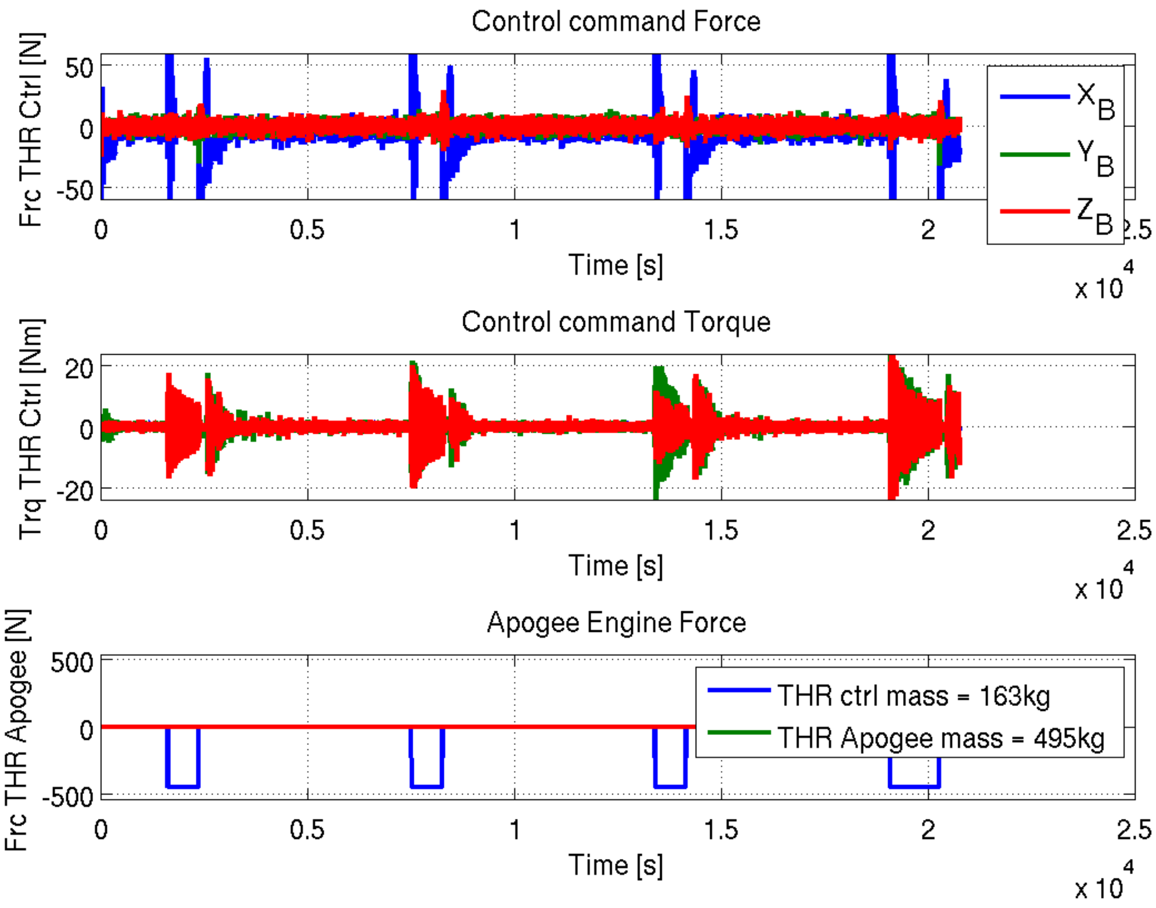
- Pointing specification verification-

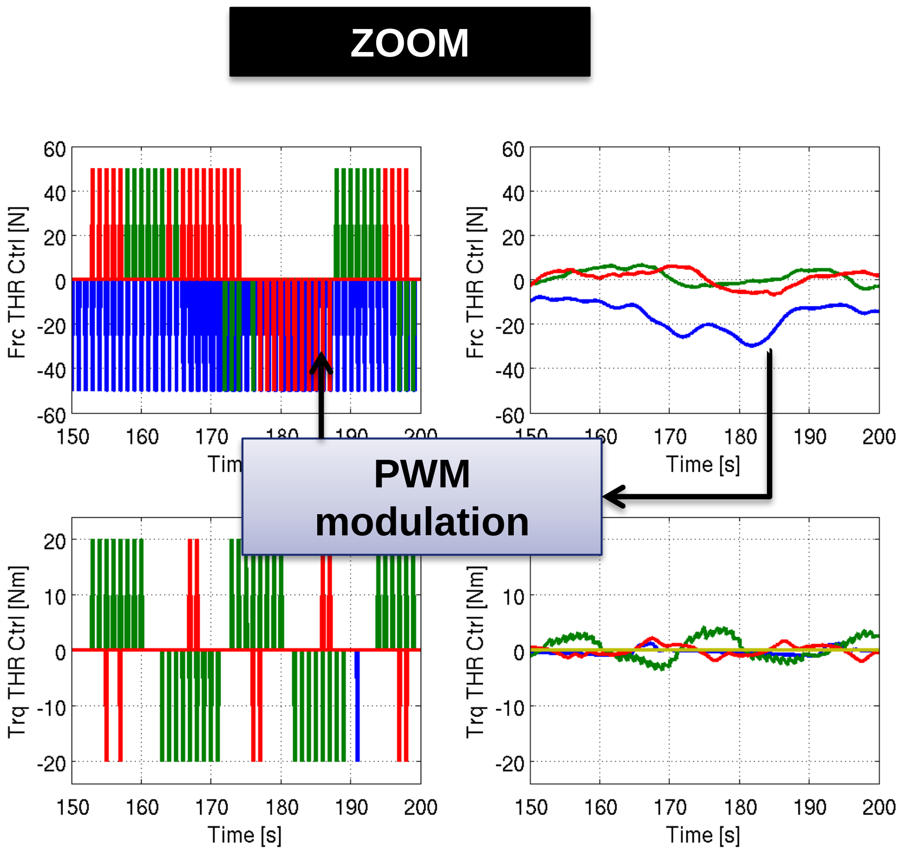




❑ Simulation examples: Actuators

- Fuel consumption analysis -





Conclusions

❑ Performed tasks

- ✓ Fine analytical modelling of tether, chaser, target, environment and coupled TSS dynamics
- ✓ Analysis & understanding of drivers for GNC design
- ✓ Development of a multi-controllers architecture to handle slack/taut configurations
- ✓ First analysis of the solution on a complete deorbiting scenario including the overall GNC functionalities , environment, and sensors/actuators models
- ✓ Feasibility certificate of the proposed GNC architecture

❑ Integration & Analysis

- ✓ Sensitivity analysis considering different LIDAR & Tether materials (under finalization)
- ✓ Extensive Monte Carlo campaign
- ✓ GNC requirements refinement/update