APPLICATION OF THE AADDTool IN EUMETSAT'S STUDY ON THRUSTER'S ALLOCATION AND MOMENTUM MANAGEMENT FOR METEOROLOGICAL SPACECRAFTS

AADDTool features

OVERVIEW

To support both mission analyses of the future programs and the in-flight analyses for the currently flying satellites, EUMETSAT implemented a dedicated study with the objectives of modeling the dynamic loads induced by the space environment : genesis of AADDTool

The AADDTool implements accurate models of space environment torques, in line with ECSS standard, as relevant for LEO (solar radiation, gravity gradient, magnetic, air drag) and GEO

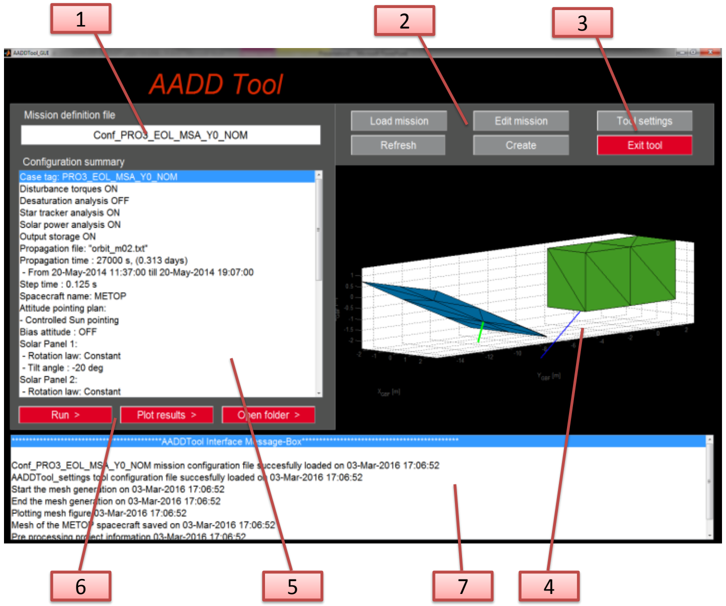
- It has been used in the past in the EUMAAD project context, to analyse the disturbances impacts on attitude of the spacecraft, start tracker blinding, momentum unloading schemes, and solar power supply.
- Since the initial development, it has suffered also extensions to its features to attitude propagation, attitude guidance schemes, and spinning spacecraft, and closed loop analysis
- It is kept flexible and modular to integrate new libraries and its development is continuous

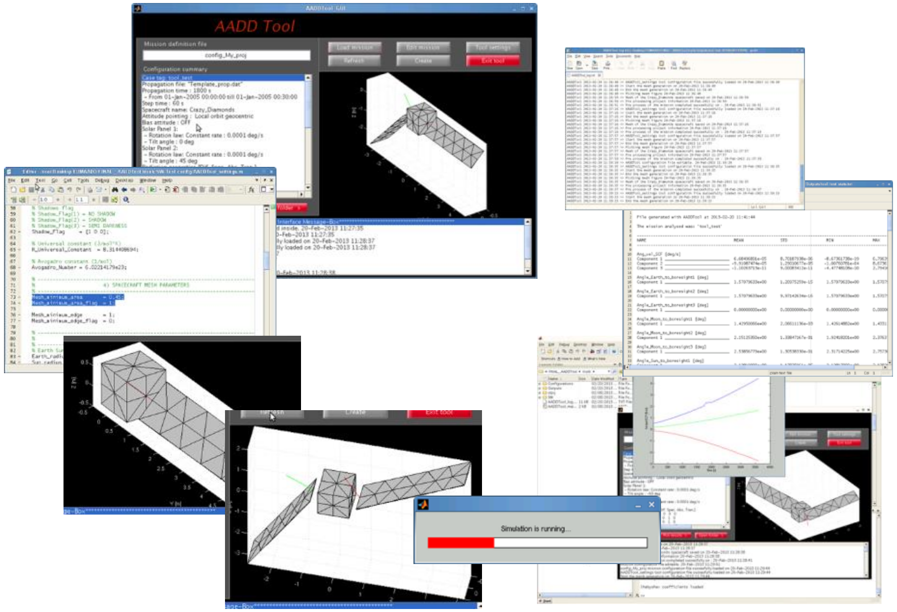
INTERFACE

Configuration and management through a GUI

Seamless management of simulation

- Loading a configuration file
- Editing a configuration file
- Creating a configuration file
- Refreshing and inspecting the configuration
- Running the mission
- Generate the output results
- Modifying the tool settings

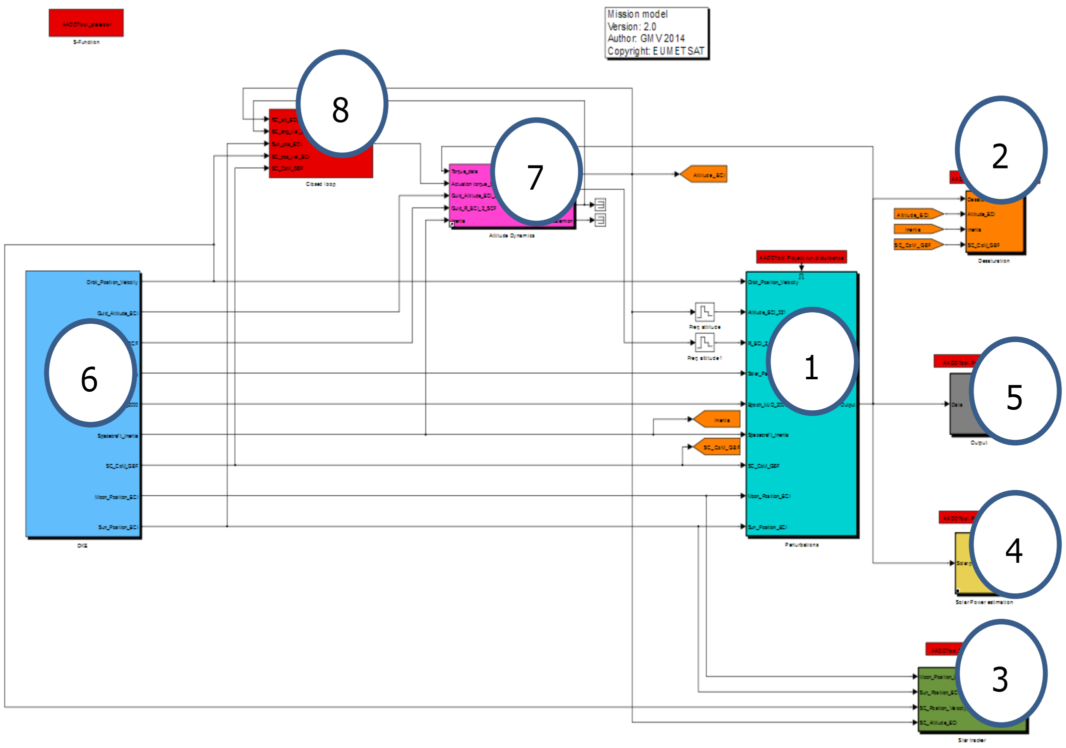




FEATURES AVAILABLE IN AADDTOOL

Components of AADDTool:

1. Environment disturbance torques (gravity gradient, magnetic torque, aerodynamic drag, solar pressure)
2. Reaction wheels offloading analysis
3. Star tracker blinding analysis
4. Solar power estimation analysis
5. Data storage
6. Top level block that contains:
   - Attitude guidance law
   - Solar array rotation angle law
   - Ephemerid determination
   - Orbit history
   - Maneuver history
   - Inertia update
7. Free dynamics computation
8. Metop closed loop control



Running over Matlab/Simulink (Win/SUSE)

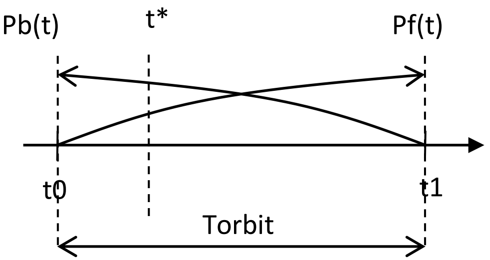
PROPAGATION AND DYNAMICS

Orbit history can be set:

- Through an history file
- Setting intermediate points and perform interpolation:
  The values corresponding to unindexed points in time are propagated from the previous samples in the orbit history file through an analytical Keplerian propagation model

- **DATE:** In calendar OR MJD2000 time formats.
  (NOTE: the file must keep the same date format all through the file.)
- **STATE VECTOR:** X, Y, Z, Vx, Vy, Vz in J2000 coordinates

```
2010/01/01-00:04:00 2519.22697167 6337.12998667 1770.39136875 0.3108172148 -2.1475422721 7.2035987813
2010/01/01-00:05:00 2532.69191532 6195.35771772 2198.66710743 0.1378593982 -2.5765855579 7.0673593594
2010/01/01-00:06:00 2535.75869507 6028.15111524 2617.89252296 -0.0356685716 -2.9950605853 6.9020255775
2010/01/01-00:07:00 2528.41465364 5836.19650163 3026.34193188 -0.2090482355 -3.4012346728 6.7082835256
```



Attitude history can be:

- Supplied through an attitude history file
- Propagated taken into account dynamics

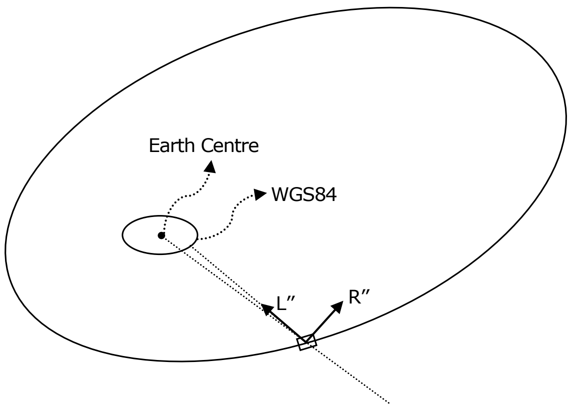
$$\mathbf{I}\dot{\boldsymbol{\omega}} = \mathbf{N}_{\mathbf{GG}} + \mathbf{N}_{\mathbf{D}} + \mathbf{N}_{MAG} + \mathbf{N}_{S} - \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega} - \dot{\mathbf{I}}\boldsymbol{\omega}$$

- Set perfect, and accordingly to a guidance law

ATTITUDE

Available attitude guidance (perfect control) for EUMETSAT missions:

- Local orbital geocentric frame attitude
- Local orbital geocentric frame attitude with yaw steering law
- Local orbital geodetic frame attitude
- Local orbital geodetic frame attitude with yaw steering law
- Earth target pointing attitude
- Spun Inertial pointing (spinning spacrafts, e.g., MSG)
- Spun Sun pointing (spinning spacrafts, e.g., MSG)
- Bias can be applied on top of any of the above



Free dynamics: Attitude propagation without control or guidance

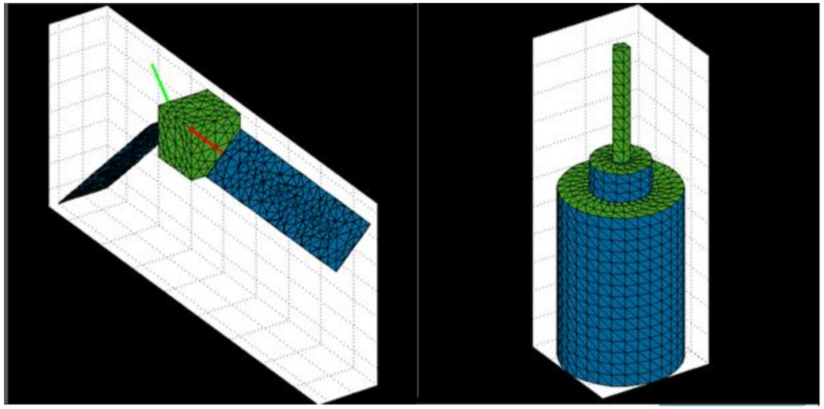
Attitude guidance can be supplied as reference for attitude control

Possibility of an attitude guidance timetable for mode switching

```
% History of attitude guidance transitions, where each line contains:
% [initial time the scheme, coding integer for the scheme]
%                               t               scheme
Attitude_guidance_queue = [     0*24*3600         0;
                                180*24*3600       2;
                                360*24*3600       8;
                                540*24*3600       6];
```


DISTURBANCES MODELING

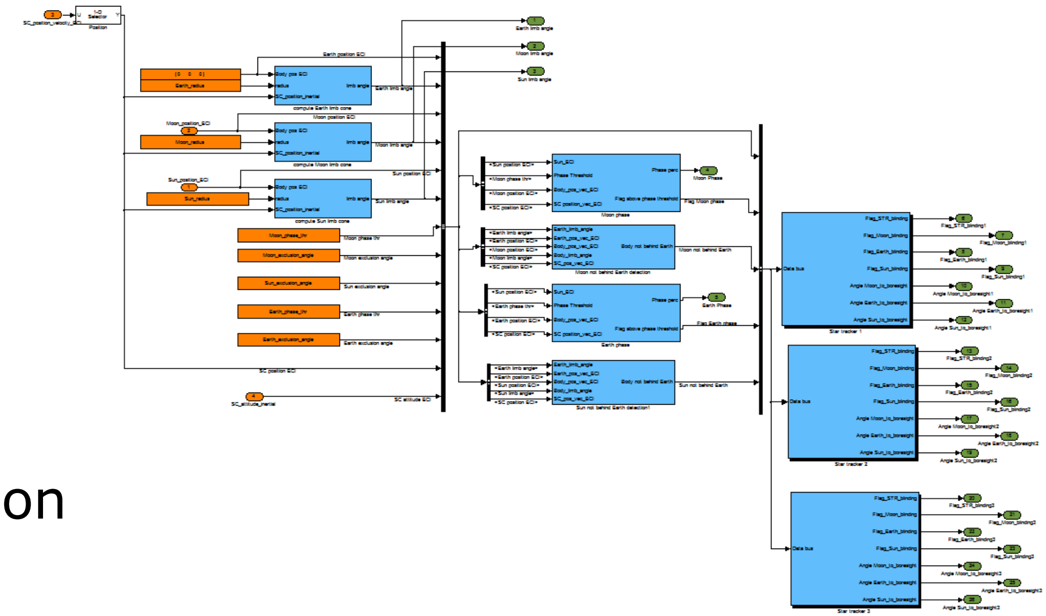
Effect	ECSS [3]	ACTION
Solar radiation model	Compliant with standard	-
Atmosphere model	Compliant with standard	NRLMSISE -00 model implemented (loading MSFC bulletins). JB2006 not required
Magnetic field model	Compliant with standard	IGRF-10 model implemented.
Gravity gradient torque	Not addressed in ECSS	Implemented accordingly to literature [4], without geopotential effects (Earth as point mass)
Magnetic torque	Not addressed in ECSS	Model implemented in the tool compliant with literature, see [4], and spacecraft as a single dipole.
Solar radiation pressure	Not addressed in ECSS	Model implemented in the tool compliant with literature, see [4], using 3D mesh model
Aerodynamic	Not addressed in ECSS	Model implemented in the tool compliant with literature, see [4], using 3D mesh model
Wind model	Not compliant with the standard	Not required. Simple model implemented. Atmosphere fixed with the Earth.
Shadowing	Not addressed in ECSS	Model inherited from previously implemented libraries
Shear stress	Not addressed in ECSS	Model inherited from previously implemented libraries
Planet Ephemerid	Compliant with standard	DE405 JPL ephemerid implemented.



Tile by tile analysis:
- to compute drag and solar radiation resulting torques
- to remove contributions from shadowed areas of the spacecraft

Availability of 3D meshing of the spacecraft:
- MTG type (body + solar panels)
- MSG type (cylindrical)

STAR TRACKER ANALYSIS

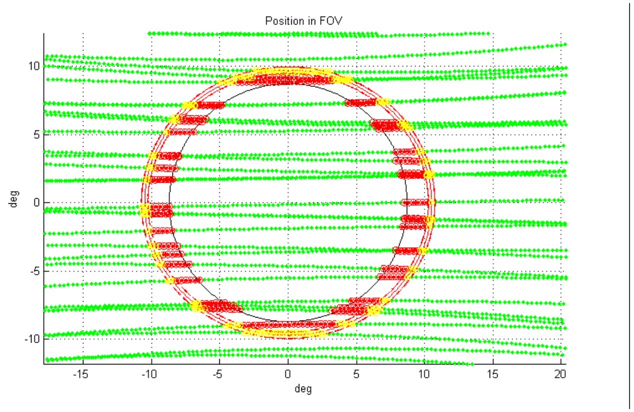


Sensor analysis:

- Up to 3 Star trackers (or "equivalent" sensors)
- Conical FOV
- Individual parameterisation for Sun, Earth and Moon
- Blinding conditions and intrusions

$$\left.\begin{array}{l} u_{ST}^{SCF} \bullet \dfrac{r_{rel}^{SCF}}{\left\| r_{rel}^{SCF} \right\|} > 0 \wedge \\ \alpha_{Pos} < \varepsilon_{Moon} + \alpha_{Limb} \wedge \\ P_{Moon} > P_{Thr_{Moon}} \wedge \\ a\cos\left(\dfrac{e_{Ear} \bullet e_{Moon}}{\left\| e_{Ear} \right\| \left\| e_{Moon} \right\|} \right) > \alpha_{Limb}^{Earth} - \alpha_{Limb}^{Moon} \end{array} \right\} \Rightarrow Moon\ blinding$$

$$Moon\ blinding \vee Earth\ blinding \vee Sun\ blinding \Rightarrow ST blinding$$



Analysis on Moon intrusion into a sensor's elliptical FOV pointing towards Earth (in center): yellow are parital intrusions, and red are full intrusions

SOLAR POWER ESTIMATION

The solar panels rotation can be set with 3 laws:

- Constant angle

$$\alpha_1(t) = \alpha_1(0)$$
$$\alpha_2(t) = \alpha_2(0)$$

- Constant rate rotation

$$\alpha_1(t) = \alpha_1(0) + \delta_1 T_s$$
$$\alpha_2(t) = \alpha_2(0) + \delta_2 T_s$$

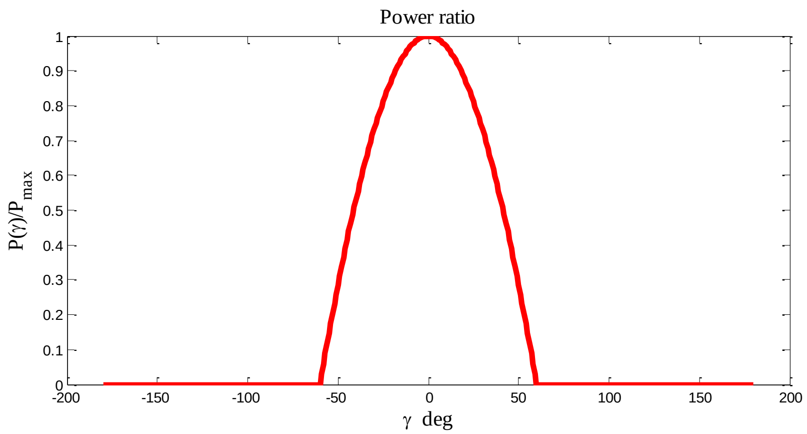
- Maximum exposure: rotation angles of the solar panels are chosen to maximize the direction to the Sun

- Inertia and Centre of mass are updated at each time step to account for rotation of panels

- Exposure area of solar panel takes into account partial shadowing, by checking how many tiles are exposed

$$\frac{P_{available}}{P_{\max}} = area * power_{ratio}$$

$$power_{ratio} = \begin{cases} 0, & if\ \ eclipse \\ 0, & if\ \ \gamma < -\frac{\pi}{3} \quad \vee \gamma > \frac{\pi}{3} \\ \cos(1.5\gamma) & otherwise \end{cases}$$



REACTION WHEELS MOMENTUM MANAGEMENT

With Magnetorquers:

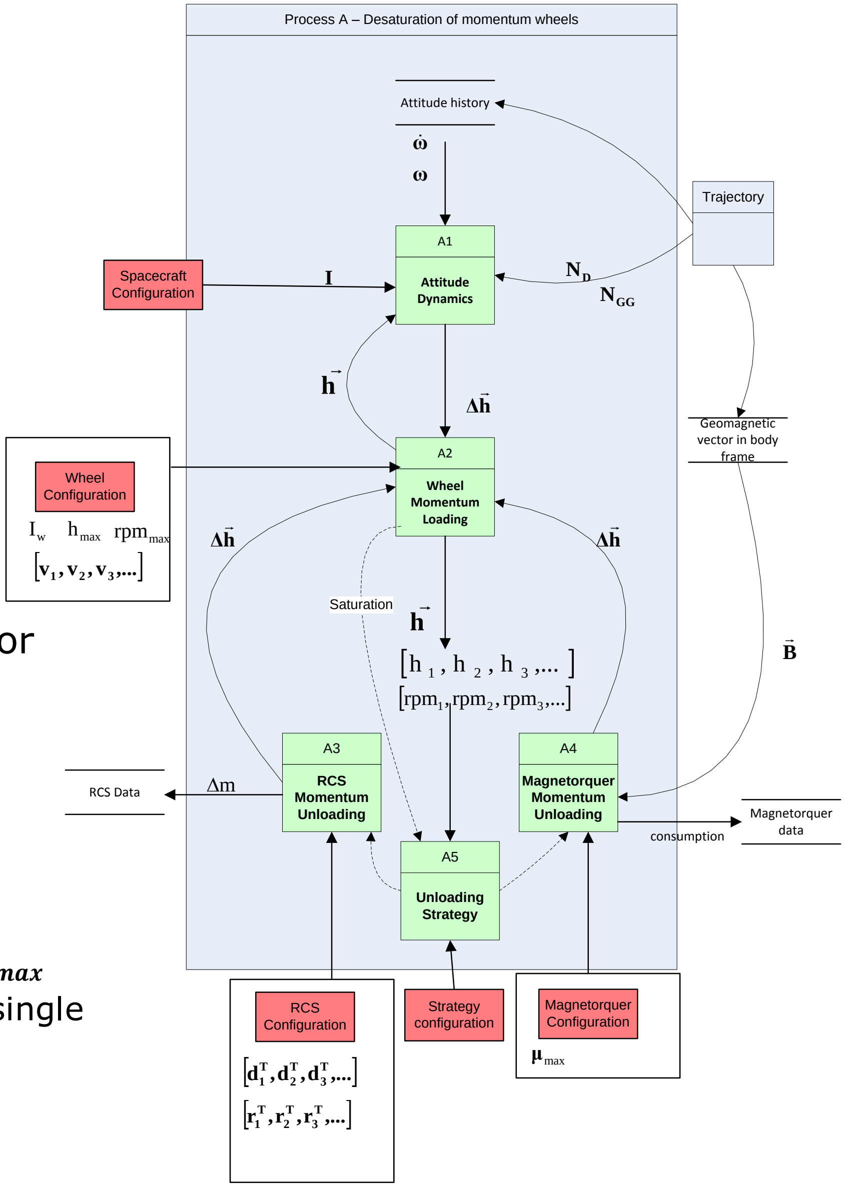
- Continuous
- Threshold, if μ is above a minimum $|\mu| \geq \mu_{min}$
- Triggering threshold rpm_{max}

With Reaction Thrusters

- Periodically
- Time table and individual momentum targets for each wheel

```
% Queue for time tabled desaturation [Nms]
%                t              hi_ref
desat_table = [  0*24*3600     5  -5  -5  5  5;
               180*24*3600     5  -5  -5  5  5;
               360*24*3600     5  -5  -5  5  5;
               540*24*3600     5  -5  -5  5  5];
```

- Threshold triggering:
  - maximum accumulated momentum threshold $|\mathbf{h}| \geq \mathbf{h}_{max}$
  - maximum accumulated momentum or speed in any single wheel i:
    $\mathbf{rpm_i} \geq \mathbf{rpm_{max_i}}$ or $\mathbf{h_i} \geq \mathbf{h_{max_i}}$



TOOL VALIDATION

Unitary verification of all individual modules and libraries

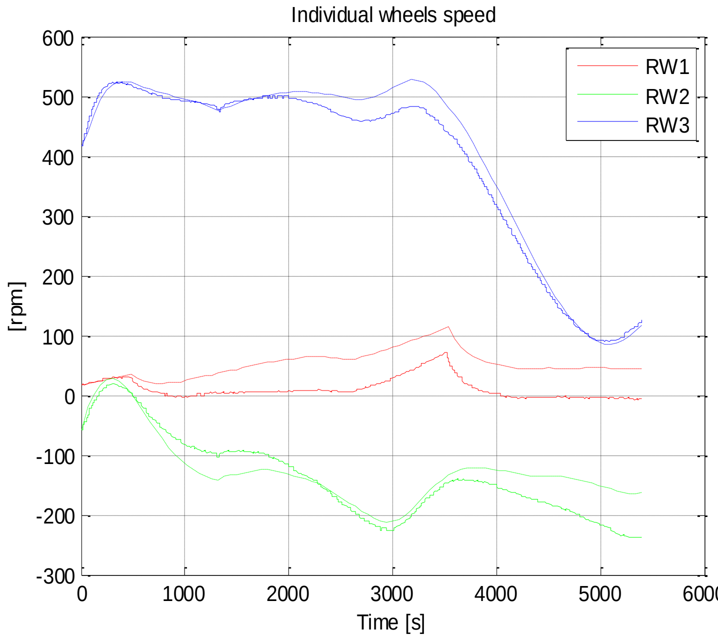
Validation against independent tools and data

Extensive campaign with:

- 58 unit test (verification of single functionalities of the tool)
- and 17 system tests, combining sub-sets or the entire modules of the simulation

Higher level system validation. E.g.:

- Validation of attitude guidance (geodetic with yaw steering), the disturbance models (all considered),
- Wheel loading algorithm
- the de-saturation scheme with continuous off-loading using exclusively magnetorquers
- Against reference data directly from MetOp's metrology



Validation of simulated reaction wheels speed vs. Metop telemetry flight data

AADDTool ICATT16

MetOp Scenario

STUDY ACTIVITIES

Specific features for the MetOp study were to be implemented in the AADDTool, and added to its libraries, to accommodate the activities:

a) Implement a 3D model of MetOp with rotating solar array and thrusters, and numerical integration of free attitude dynamics

b) Model simplified Earth and Sun sensors (geometric model only), computation of torque requests, based on Earth/Sun de-pointing; conversion to thrusters' modulation signals

c) Analysis of specific test cases, tuning the default thrusters grouping according to mission phases or scenarios , for improvement of propellant consumption

METOP

MetOp scenario:

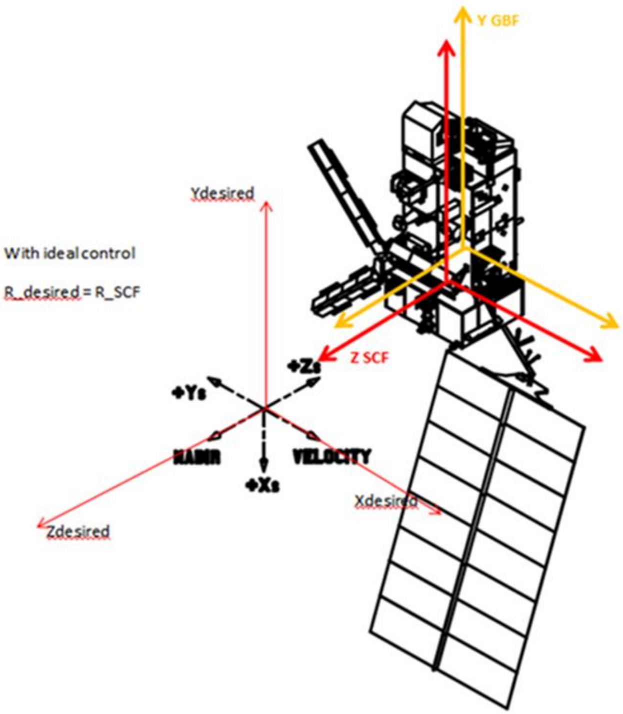
- LEO orbit
- Large central body with rotating large Solar panel
- ~90 minute orbit

Two operating modes:

- FAM2 : Earth pointing
- PRO: Sun pointing

Parameterization:

- Roll bias angle and guiding rates null for Sun pointing
- No lag filter for Sun pointing
- Fixed solar panel in Sun pointing, and solar array pointing with maximization law during Earth pointing
- In Sun pointing, Z_S is not estimated (or controlled)
- Coefficients for thruster's parameterization taken from METOP2
- Lifecycle BOL, MOL, EOL vary in:
  - mass, inertia, com,
  - thruster pressure
  - parameterization of the control



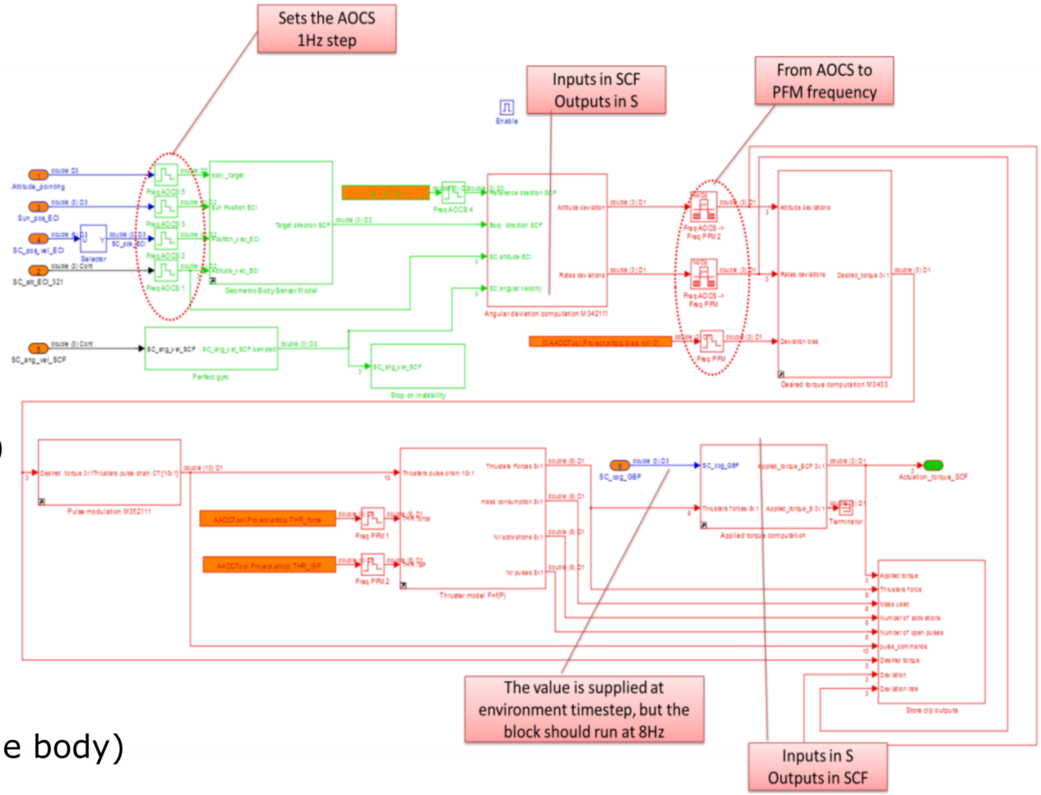
Working frames:

- SCF frame (defined in AADDTool)
- GBF frame (defined in AADDTool)
- S frame specific to the METOP spacecraft (most of the closed loop parameters are set in this frame)

ADDITIONAL LIBRARY: METOP'S CONTROL

This library implements:

- Geometric body sensor
  (supplies the Sun or Earth in sensor frame)
- Perfect gyro
  (supplies angular velocity)
- Deviations computation
  (computes the error for control)
- Desired torque computation
  (computes the desired torque to be applied)
- Pulse modulation
  (creates the pulses issued to the thrusters)
- Thruster model
  (performance model of the thruster)
- Applied torque
  (computes the effective torque applied to the body)



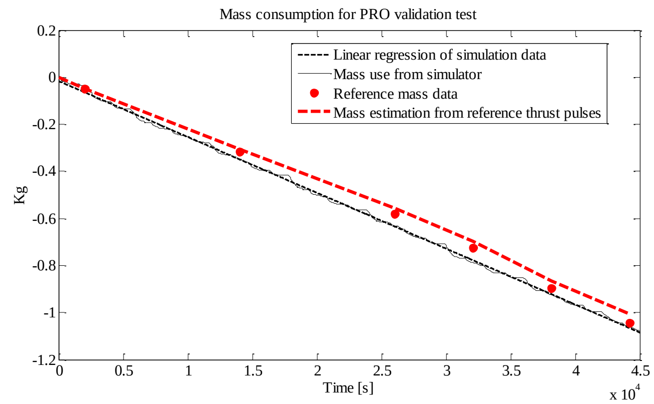
These run at different frequencies to emulate the on-board discrete implementation:

- time step used for discrete attitude modes (no free dynamics). When using free dynamics, some simulation blocks run with this frequency (inertia, orbit, CoM, solar panel rotation)
- Freq_AOCS – Frequency set for the attitude closed loop control
- Freq_PFM – frequency for pulse modulation

CLOSED LOOP MODULE VALIDATION MASS CONSUMPTION RATE

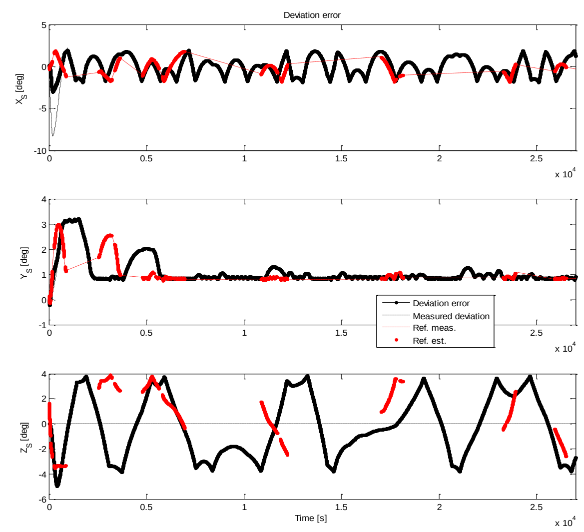
PRO(Sun pointing)

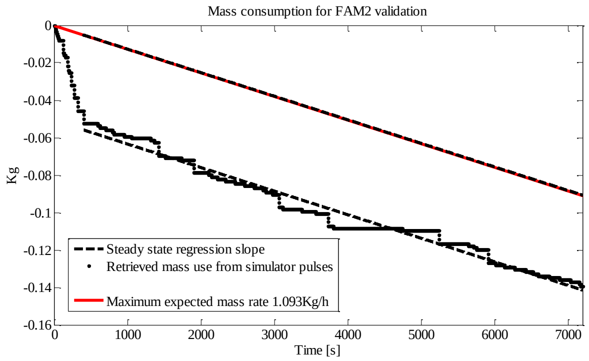
- Reference thruster pulse history was used to estimate a reference mass use
- The simulated closed loop kept the control requirements, stability and
- Simulated mass rate and estimated rate were in agreement



FAM2 (Earth Pointing)

- The initial attitude for the simulation needed an initial correction
- After reaching the error steady state (t>400 s), the regression on simulated mass consumption agrees with the expected reference rate
- The deviation pointing errors present a very similar behavior to the reference data, demonstrating a close representation of the controlled dynamics and environment influence





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FAM2 Study results (Earth pointing)

INNOVATING SOLUTIONS

FAM2 CASE DEFINITION

Case Tag	Mode	Lifecycle (mass)	Solar activty	Roll bias [deg]	Pulse grouping	Nr. Sim. orbits
FAM2-1	FAM2	BOL	Medium	2.0	Nominal_BOL	5
FAM2-2	FAM2	MOL	Medium	2.0	Nominal_MOL	5
FAM2-3	FAM2	EOL	Medium	2.0	Nominal_EOL	5
FAM2-4	FAM2	BOL	Medium	2.0	Nominal_BOL +1 (in Y)	5
FAM2-5	FAM2	MOL	Medium	2.0	Nominal_MOL +2 (in Y)	5
FAM2-6	FAM2	BOL	Medium	3.0	Nominal_BOL	5
FAM2-7	FAM2	MOL	Medium	3.0	Nominal_MOL	5
FAM2-8	FAM2	BOL	Medium	3.0	Nominal_BOL +1 (in Y)	5
FAM2-9	FAM2	MOL	Medium	3.0	Nominal_MOL +2 (in Y)	5

- Case FAM2-1 is to be used for comparison in analysis all below for BOL
- Case FAM2-2 is to be used for comparison in analysis all below for MOL
- Sensitivity analysis on mass (1 vs 2 vs 3), bias (1 vs 6 and 2 vs 7), and grouping number in Y (1 vs 4 vs 8, 2 vs 5 vs 9)

The outputs/criteria to be analyzed are:

- Stability (with the implementation of a stop condition based on SC angular rates)
- Mass consumption (based on ISP)

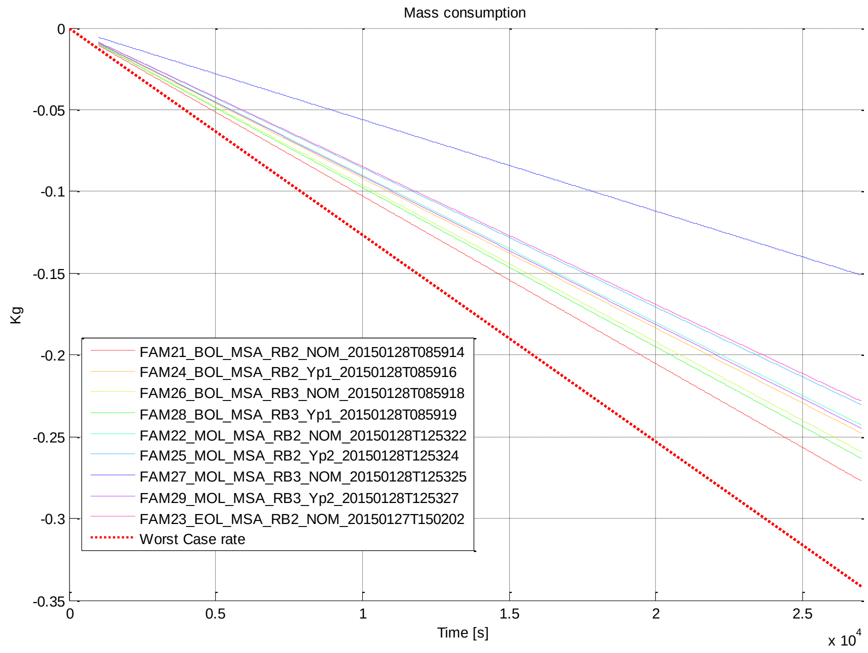
MASS VARIATION

Comparing the consumptions rates for BOL, and comparing them with the nominal setup FAM22, increasing the grouping number Y+1 decreases the consumption in about 10%, if the bias is not modified.

Comparing the consumption rates for MOL and comparing them w.r.t. to the nominal setup, by far the best consumption rate is to increase the roll bias angle to 3 deg (a 37.76% reduction).

This is in discord with the results for BOL, showing that in different life cycles, the best strategy modifications can be different.

Comparing the nominal setup consumption rates, it is clear that the mass consumption decreases with time, despite a higher thrust use. The difference is more significant from BOL to the other life cycles.



Case	Kg/day	% w.r.t. FAM21
'FAM21_BOL_MSA_RB2_NOM_20150128T085914'	-0.8859	100.0000
'FAM24_BOL_MSA_RB2_Yp1_20150128T085916'	-0.7922	89.4200
'FAM26_BOL_MSA_RB3_NOM_20150128T085918'	-0.8286	93.5388
'FAM28_BOL_MSA_RB3_Yp1_20150128T085919'	-0.8415	94.9918
Case	**Kg/day**	**% w.r.t. FAM22**
'FAM22_MOL_MSA_RB2_NOM_20150128T125322'	-0.7766	100.0000
'FAM25_MOL_MSA_RB2_Yp2_20150128T125324'	-0.7368	94.8779
'FAM27_MOL_MSA_RB3_NOM_20150128T125325'	-0.4833	62.2352
'FAM29_MOL_MSA_RB3_Yp2_20150128T125327'	-0.7826	100.7833
Case	**Kg/day**	**% w.r.t. FAM21**
'FAM21_BOL_MSA_RB2_NOM_20150128T085914'	-0.8859	100.0000
'FAM22_MOL_MSA_RB2_NOM_20150128T125322'	-0.7766	87.6589
'FAM23_EOL_MSA_RB2_NOM_20150127T150202'	-0.7298	82.3794

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PRO Study results (Sun pointing)

PRO CASE DEFINITION

Case Tag	Mode	Lifecycle (mass)	Solar activty	Yaw rotation [deg]	Pulse grouping	Nr. Sim. orbits
PRO-1	PRO	BOL	Medium	0	Nominal	5
PRO-2	PRO	MOL	Medium	0	Nominal	5
PRO-3	PRO	EOL	Medium	0	Nominal	5
PRO-4	PRO	MOL	High	0	Nominal	5
PRO-5	PRO	MOL	Medium	0	Nom.+1 (Y only)	5
PRO-6	PRO	MOL	Medium	0	Nom.-1 (Y only)	5
PRO-7	PRO	MOL	Medium	90	Nominal	5
PRO-8	PRO	MOL	Medium	-90	Nominal	5
PRO-9	PRO	MOL	Medium	180	Nominal	5

- Case PRO-2 is to be used for comparison in analysis all below
- Case PRO-2, 1, 3 are for sensitivity analysis to mass changes
- Case PRO-2, 4 are for sensitivity analysis to solar activity
- Case PRO-2, 5, 6 are for sensitivity analysis to pulse grouping for Y only
- Case PRO-2, 7,8,9 are for sensitivity analysis to initial attitude (to be rotated around sun direction at 90 deg step)

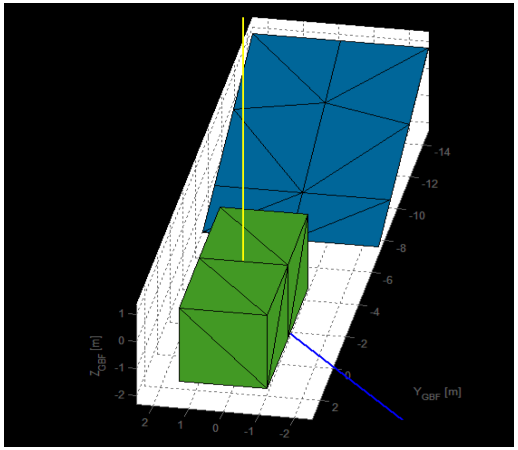
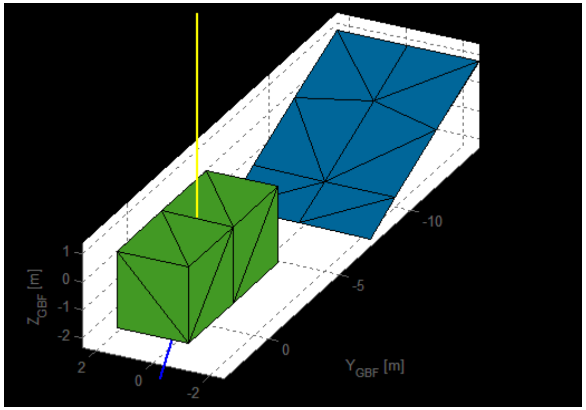
The outputs/criteria to be analyzed are:

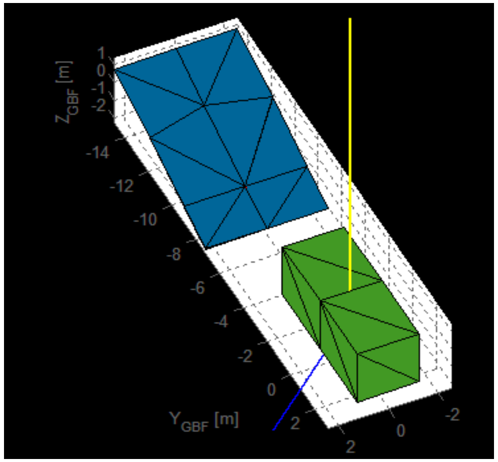
- Stability (with the implementation of a stop condition based on SC angular rates)
- Mass consumption (based on ISP)

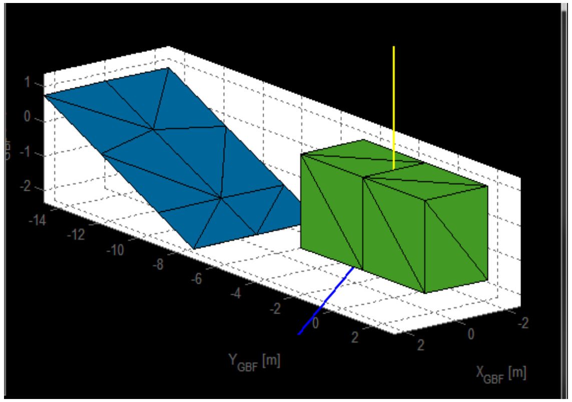
INITIAL ORIENTATION

Initial orientations for PRO cases PRO1-6, PRO-7,PRO-8 and PRO-9

Sun direction in yellow and Earth direction in blue, revealing the offsets multiple of 90 deg offsets)



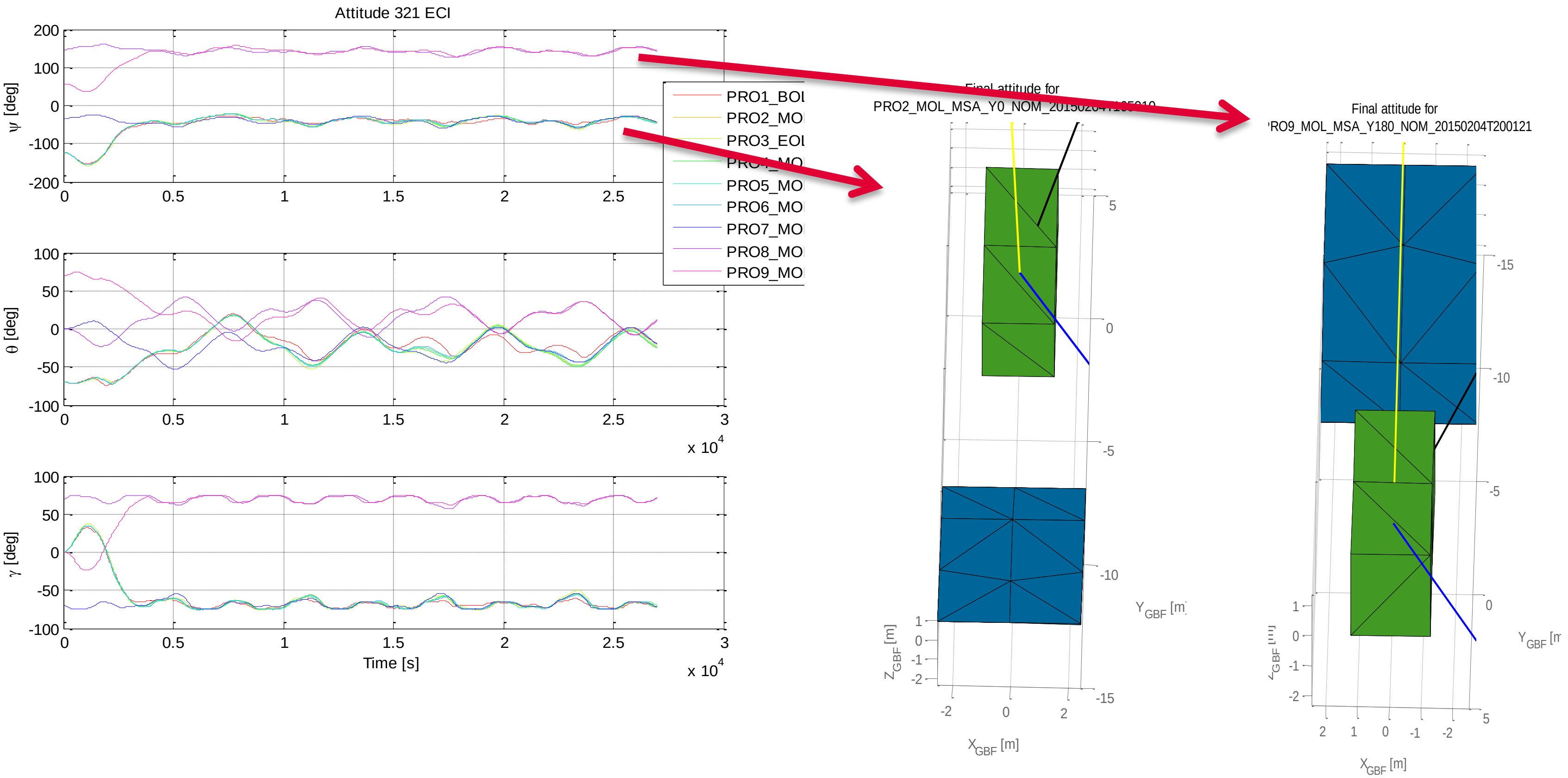


ATTITUDE

The main conclusion from the attitude history is that there are two possible attitude profiles, where the attitude converges after a 4000 second transitory period, varying in θ symmetrically.

This comes from the fact that the angle about the pointing direction is not controlled. The tendency for each profile seems to be defined by the initial attitude. All cases apart PRO8 and PRO9 converge to the same approximate attitude history.

These two profiles seem to be close to initial configuration of PRO8 and PRO7, given that these two cases don't vary much.



Final relative directions for the Sun and Earth for cases PRO2 and PRO9. Axis Z_{SCF} point towards the Sun in both cases, but w.r.t. to Earth's direction, there is approximately a 180 deg offset.

MASS VARIATION

Effects of the different setups are visible in the resulting consumption rates, with the setups from PRO8 and PRO9 to appear more beneficial than the rest.

Generally the rates decrease if the initial points are disregarded. Exceptions to this are PRO8 and PRO7 which are the setups that with a very slight re-orientation (and the difference in the rates for full or partial simulation are small).

Regarding the lifecycle, MOL (PRO2) has a consumption marginally higher EOL, but almost 4% more than BOL (PRO1).

The presence of a higher solar activity increases the consumption rate in less than 1% (PRO2 vs PRO4). The impact of drag is less than other disturbances such as gravity gradient.

Modifying the grouping number has a slight impact on the consumption rate. Increasing Y+1 increases the rate in less the 0.2% (PRO5 vs PRO2). Decreasing the grouping number decreases the consumption in more than 2% (PRO6 vs PRO2), but has it was seen previously, a slight performance is lost in the correction of the deviations.

The initial orientation of the spacecraft has the most impact on the consumption. There seems to be a reorientation at the beginning of all simulations towards 2 stable orientations $\{\psi \approx 140, \gamma \approx 70\}$ deg (PRO8-9) vs $vs\,\{\psi \approx -40, \gamma \approx -70\}$ deg (PRO2-7), where the former is beneficial in terms of consumption reducing the mass rate in 10 to 15 %.

There seems to be a preferred rotation about Z_S for which the consumption can be minimized.

Case	Kg/day after 0 sec	% w.r.t. PRO2 after 0 sec	Kg/day after 4000 sec	% w.r.t. PRO2 after 4000 sec
'PRO1_BOL_MSA_Y0_NOM_20150204T165001'	-2.1861	98.9001	-2.0756	96.0863
'PRO2_MOL_MSA_Y0_NOM_20150204T165010'	-2.2104	100.0000	-2.1601	100.0000
'PRO3_EOL_MSA_Y0_NOM_20150204T165021'	-2.1773	98.5012	-2.1593	99.9611
'PRO4_MOL_HSA_Y0_NOM_20150204T165030'	-2.2251	100.6621	-2.1794	100.8894
'PRO5_MOL_MSA_Y0_Yp1_20150204T174448'	-2.2013	99.5866	-2.1643	100.1918
'PRO6_MOL_MSA_Y0_Ym1_20150204T174454'	-2.1587	97.6580	-2.1090	97.6341
'PRO7_MOL_MSA_Y90_NOM_20150204T174458'	-2.1586	97.6543	-2.1712	100.5119
'PRO8_MOL_MSA_Y270_NOM_20150204T174502'	-1.9454	88.0117	-1.9466	90.1162
'PRO9_MOL_MSA_Y180_NOM_20150204T200121'	-1.9002	85.9660	-1.8236	84.4207

AADDTool ICATT16

Conclusions

CONCLUSIONS

1. AADDTool v2.1 has been released and has been used for studies on on-going and future missions

2. The features in the tool have been thoroughly verified at unitary level and validated at system level with flight data

3. The validation of the closed loop with telemetry flight data consolidated the confidence in the tool representativeness

4. The latest study concerning the OBSW of MetOp entailed the integration of two modes:
   - Closed loop Earth pointing (FAM2)
   - Closed loop Sun pointing (PRO)

5. Studies were carried for the two configurations, varying the lifecycle, solar activity, initial conditions, and closed loop settings; impact on thruster use and mass consumption were analyzed

Thank you

Thomas Peters

GMV SA, SPS-GNC

Email: tvpp@gmv.es

www.gmv.com

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