End-to-end simulations for the LISA Technology Package

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- Models & control laws
  - Space environment and noise models
  - Test-mass actuation
  - Drag-free control
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- Outlook

Introduction (1/2)

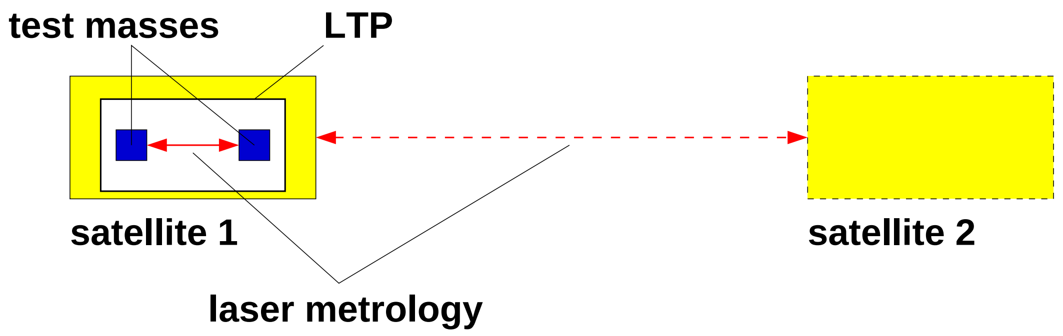
SRON's involvement:

- Relevant expertise:
  - E2E performance simulations of the GOCE mission
  - Expertise in dev. of capacitive readout & actuation electronics
- Involvement in the LTP program:
  - Construct E2E simulator
  - Integrate existing models and control laws
  - Execution and analysis of test runs, refinement of models
  - Trade-off study of different hardware & control concepts

ZARM's involvement:

- Relevant expertise:
  - Attitude Control System (ACS) algorithms for BREM-SAT, ABRIXAS and DIVA
  - Drag-Free and Attitude Control System (DFACS) and E2E simulator for STEP
  - Development of Generic Drag-Free Simulator (GDFS)
- Involvement in the LTP program:
  - Delivery of S/C and TM dynamics open-loop integrator
  - Development of DFACS algorithms

SMART-2 setup:



Either an orbit around L1 or a geostationary orbit will be considered.

Test of technological key concepts for LISA:

- Test of inertial sensor technology
- Test of micro-thruster technology
- Test of S/C Drag-Free-Control at nm level
- Test of various aspects of laser metrology

E2E simulator concept (1/2)

LTP top science requirement:

Acceleration noise on the geodetic motion of one test mass

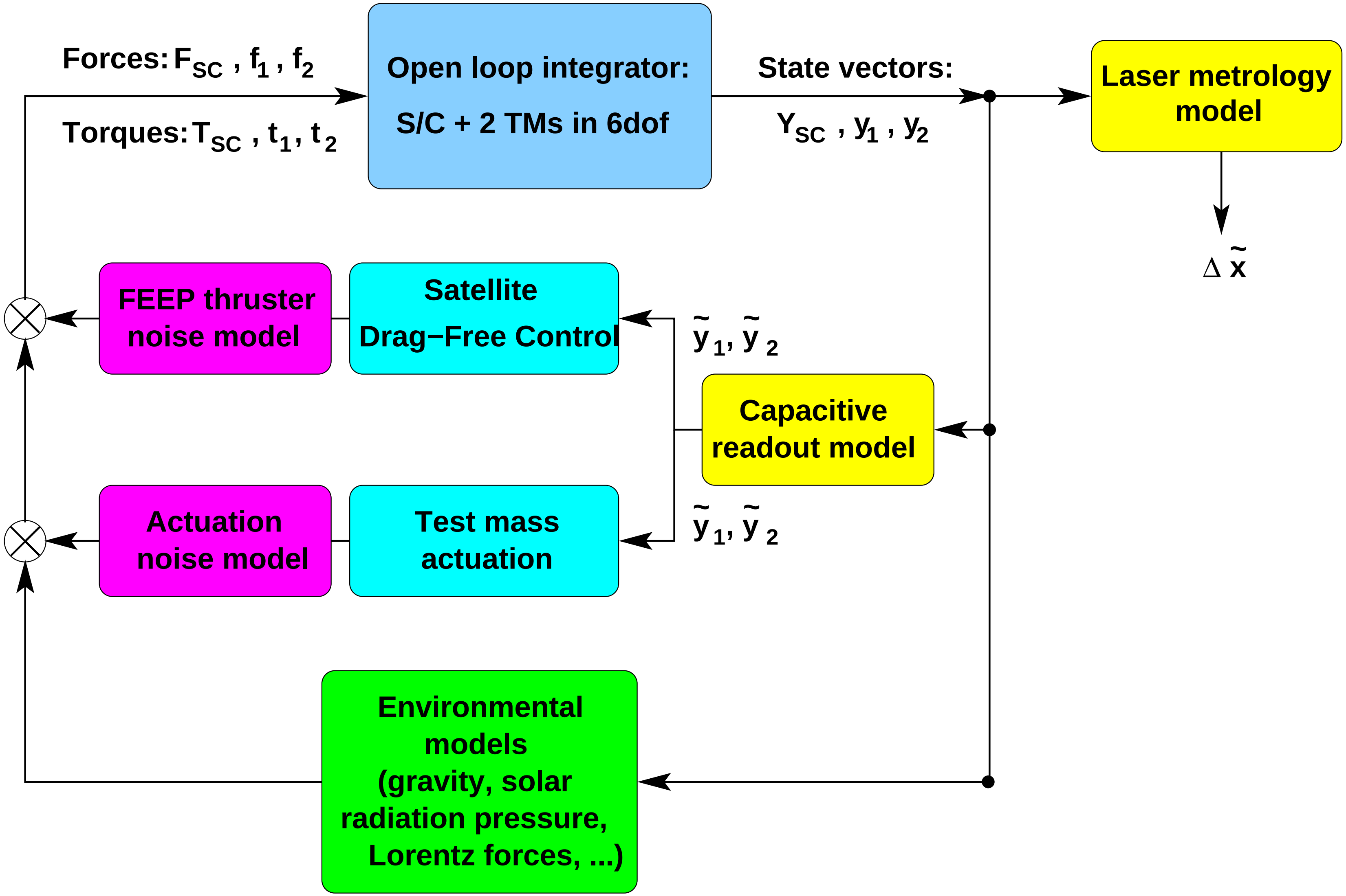
$$S_a^{1/2} \leq 3 \cdot 10^{-14} \left[1 + \left(\frac{f}{3\ \mathrm{mHz}} \right)^2 \right] \frac{\mathrm{m}}{\mathrm{s}^2} \frac{1}{\sqrt{\mathrm{Hz}}}$$

in the range $1\ \mathrm{mHz} \leq f \leq 30\ \mathrm{mHz}$

Objectives of **E2E** simulations:

- Verification of mission performance requirements
- Assessment of error budgets of the various subsystems
- Hardware and control algorithms trade-off studies
- Support LTP test definitions
- Possibly in the future: Hardware in the loop tests

E2E simulator concept (2/2)



Space environment (1/3)

Gravity field:

- For a geostationary orbit a spherical harmonics expansion of the earth gravity field (EGM96 or JGM-3) is used and sun and planets are assumed to be point masses.
- In case of an orbit at L1, all objects may be treated as point masses.

Solar wind pressure:

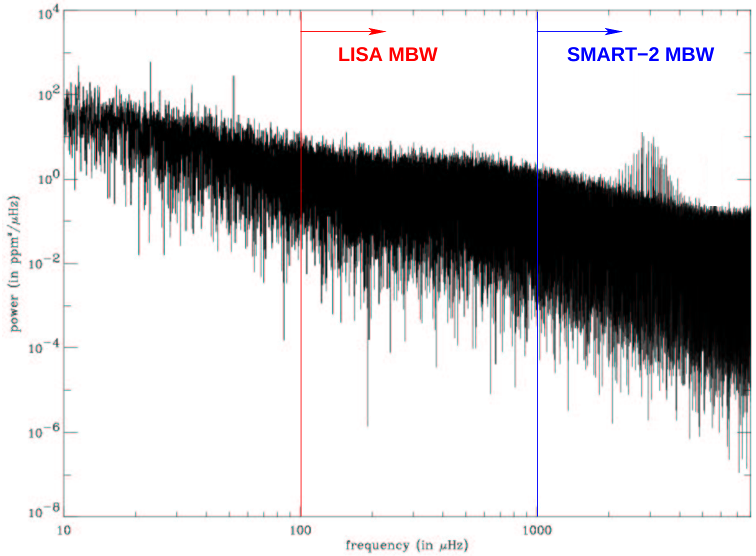
- For a maximum estimate a number density of $N \approx 10/\text{cm}^3$ and velocity of $v \approx 700$ km/s is assumed

  $\Rightarrow$ Solar wind pressure: $P \leq 10^{-8}\ \text{N/m}^2$
- Shot noise: $(A_{SC} = 2\text{m}^2,\ \text{M} = 200\ \text{kg})$:

  $\Rightarrow S_a^{1/2} \leq 2 \cdot 10^{-17}\ \text{ms}^{-2}/\sqrt{\text{Hz}}$

Solar radiation pressure:

- Constant part: $F = 1.36$ kW/m$^2 \Rightarrow P = 4.54 \cdot 10^{-6}$ N/m^2
- Orbit eccentricity: $\delta F/F \approx 0.03$, $\tau \approx 1$ yr
- Sunspot dips: $\delta F/F \approx 10^{-3}$, $\tau \approx 15$ days
- Continuum noise: superposition of $[1 + (\omega\tau)^2]^{-1}$ spectra due to switching on and off of granulation cells and supergranulation cells
  $\delta F/F \approx 0.7 \cdot 10^{-6}$, $\nu \geq 1$ mHz
- Solar oscillation modes, discrete line spectrum:
  $\delta F/F \approx 3 \cdot 10^{-5}$, $\nu_0 \approx 3$ mHz
- Estimate of acceleration noise at 1 mHz ($A_{SC} = 2$m^2, M $= 200$ kg):
  $a_n \approx 5 \cdot 10^{-11}ms^{-2}/\sqrt{\text{Hz}}$



Space environment (3/3)

Magnetic field:

- Field at L1

  Average field strength: $\langle B \rangle \approx 5$ nT

  Field variations: $S_B^{1/2} \approx 2 \cdot 10^{-2} \, \nu^{-0.85}$ nT$/\sqrt{\text{Hz}}$

  Estimated acceleration noise at 1 mHz (without shielding): $a_n \approx 4 \cdot 10^{-16}ms^{-2}/\sqrt{\text{Hz}}$

- Field for geostationary orbit

  The geomagnetic field is represented by a spherical harmonics expansion (IGRF2000). Average field strength (geostationary orbit): $\langle B \rangle \approx 100$ nT Fluctuations of the field have to be investigated.

Test mass charging:

Charging of the test masses occurs mainly through interaction with energetic protons ($E_p \geq 100$ MeV) and obeys (cumulative) poisson statistics.

The present estimate of the mean charge rate is $\approx 15 \; e/$s

Noise models

Besides noise resulting from the space environment, there are a number of noise sources within SMART-2 / LTP, for example:

Noise source	Requirement in the MBW
Electrostatic sensor noise	$S_{x,y}^{1/2} \leq 1.8 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$ $S_{z}^{1/2} \leq 18 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$
Electrostatic actuation noise	$S_{x,y}^{1/2} \leq 2 \cdot 10^{-15}$ N/$\sqrt{\text{Hz}}$ $S_{z}^{1/2} \leq 2.7 \cdot 10^{-15}$ N/$\sqrt{\text{Hz}}$
FEEP noise	$S_{F}^{1/2} \leq 0.1 \cdot 10^{-6}$ N/$\sqrt{\text{Hz}}$

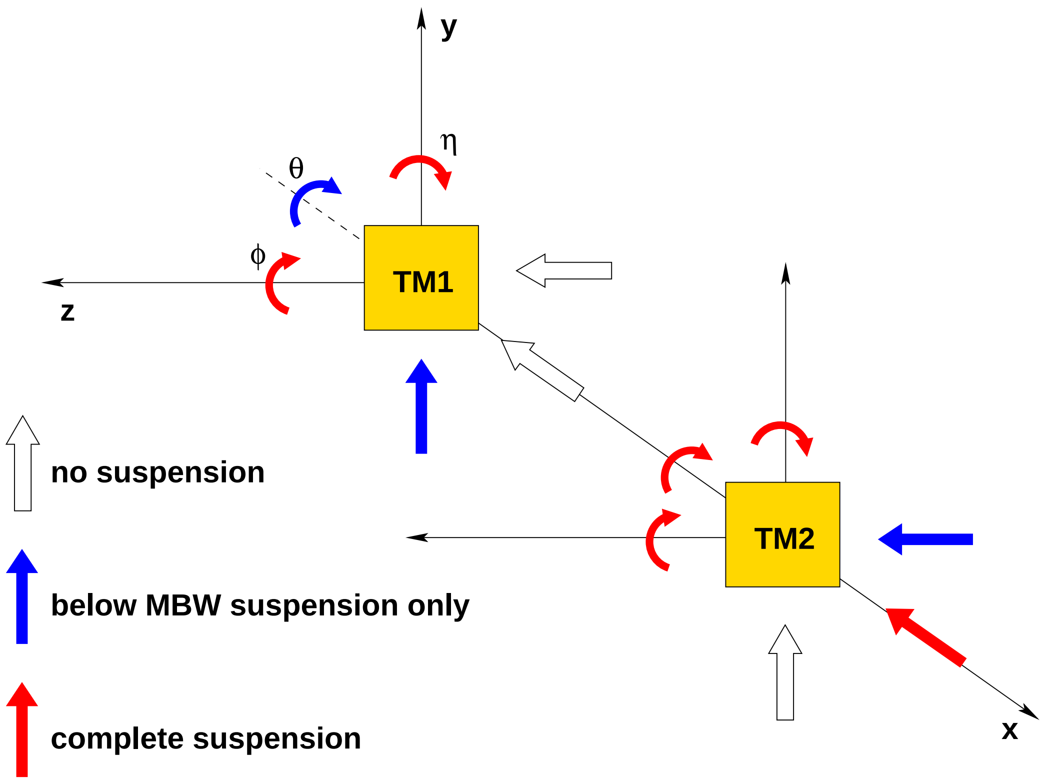
Initially, noise sources will be implemented in the E2E simulator using white / colored noise models meeting the requirements in the MBW.

In the course of simulator development, these will be replaced by realistic models of the underlying hardware.

Test mass actuation

The basic science operating mode M1 can be characterized by the control exercised on each degree of freedom of the two test masses:

- Unsuspended DOFs:
  x_1, z_1, y_2
- Below MBW suspension:
  y_1, θ_1, z_2
- Complete suspension:
  η_1, ϕ_1, x_2, θ_2, η_2, ϕ_2



Control laws implementing the outlined suspension scheme were provided by Uni Trento and have been implemented in the E2E simulator.

Drag-free control (1/3)

Purpose of drag-free control (**DFC**):

Reduction of residual acceleration from non-gravitational sources on the test masses in order to meet the top science requirement.

DFC in translation and rotation (operation mode M1):

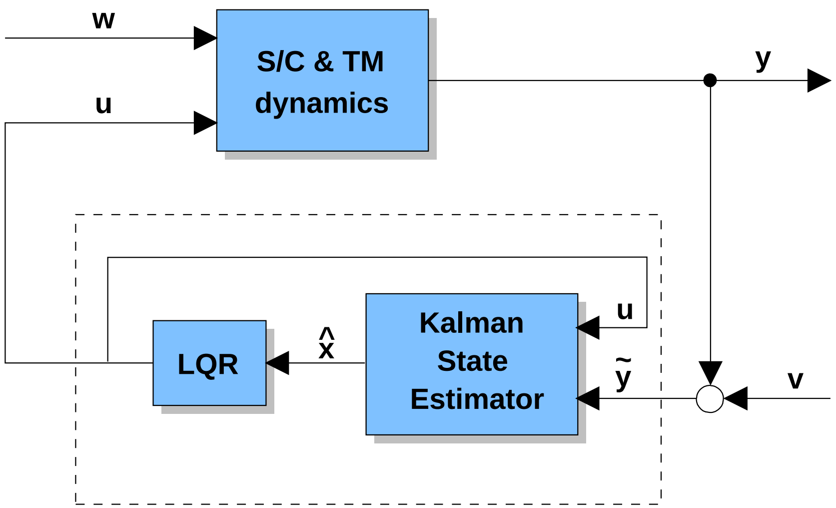
S/C d.o.f.	DFC based on measurement of	required performance
x	x_1	$5 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$
y	y_2	$5 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$
z	z_1	$19 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$
θ	θ_1	$201 \cdot 10^{-9}$ rad/$\sqrt{\text{Hz}}$
η	$(z_2 - z_1)/l$	$97 \cdot 10^{-9}$ rad/$\sqrt{\text{Hz}}$
ϕ	$(y_2 - y_1)/l$	$37 \cdot 10^{-9}$ rad/$\sqrt{\text{Hz}}$

S/C attitude control outside the LTP measurement bandwidth is based on star tracker data.

Drag-free control (2/3)

DFC baseline concept: Modified Linear Quadratic Gaussian Regulator (LQG)

- Modern state-space technique for designing optimal state regulators
- Process noise w and sensor noise v can be taken into account
- Consists of optimal Linear Quadratic Regulator (LQR) with full state feedback and Kalman Filter for state estimation



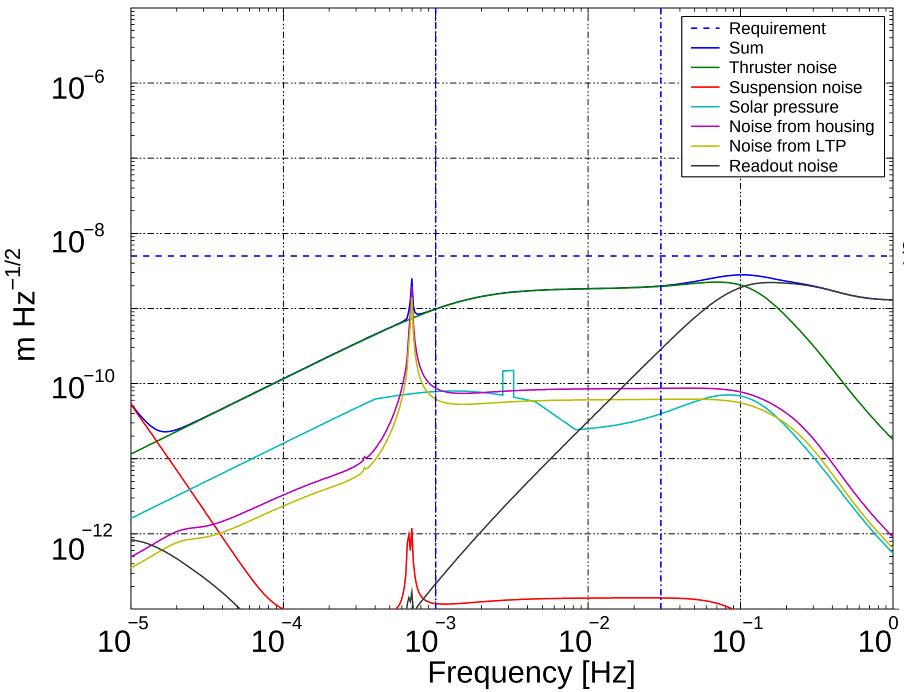
- Standard LQG regulator has been modified to include integral control action needed to reject constant disturbances (e.g. solar pressure)
- Model of the disturbance is included in Kalman state estimator and the estimated disturbance is used in a feed-forward control, i.e.

$$u = -K_{LQR} \cdot \hat{x} - d_{estim}$$

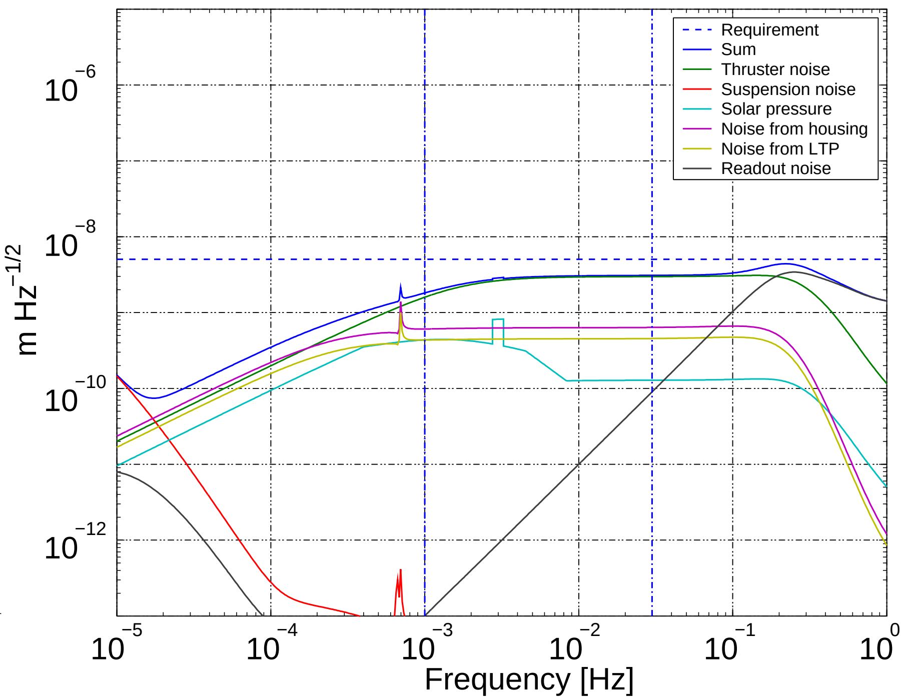
Drag-free control (3/3)

DFC performance analysis through closed-loop transfer function analysis:

The analysis of the current controller design indicates that all the requirements can be met. Two examples are given below:



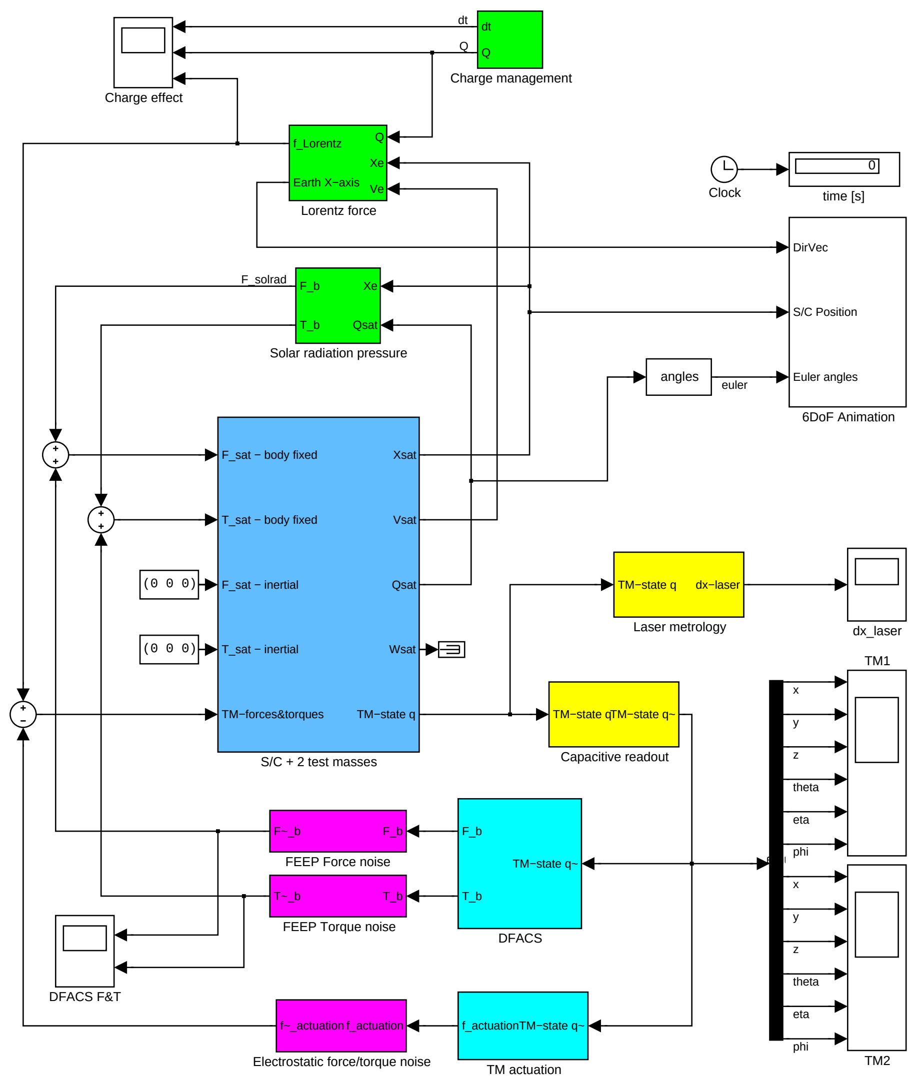
DFC performance for x_1



DFC performance for y_2

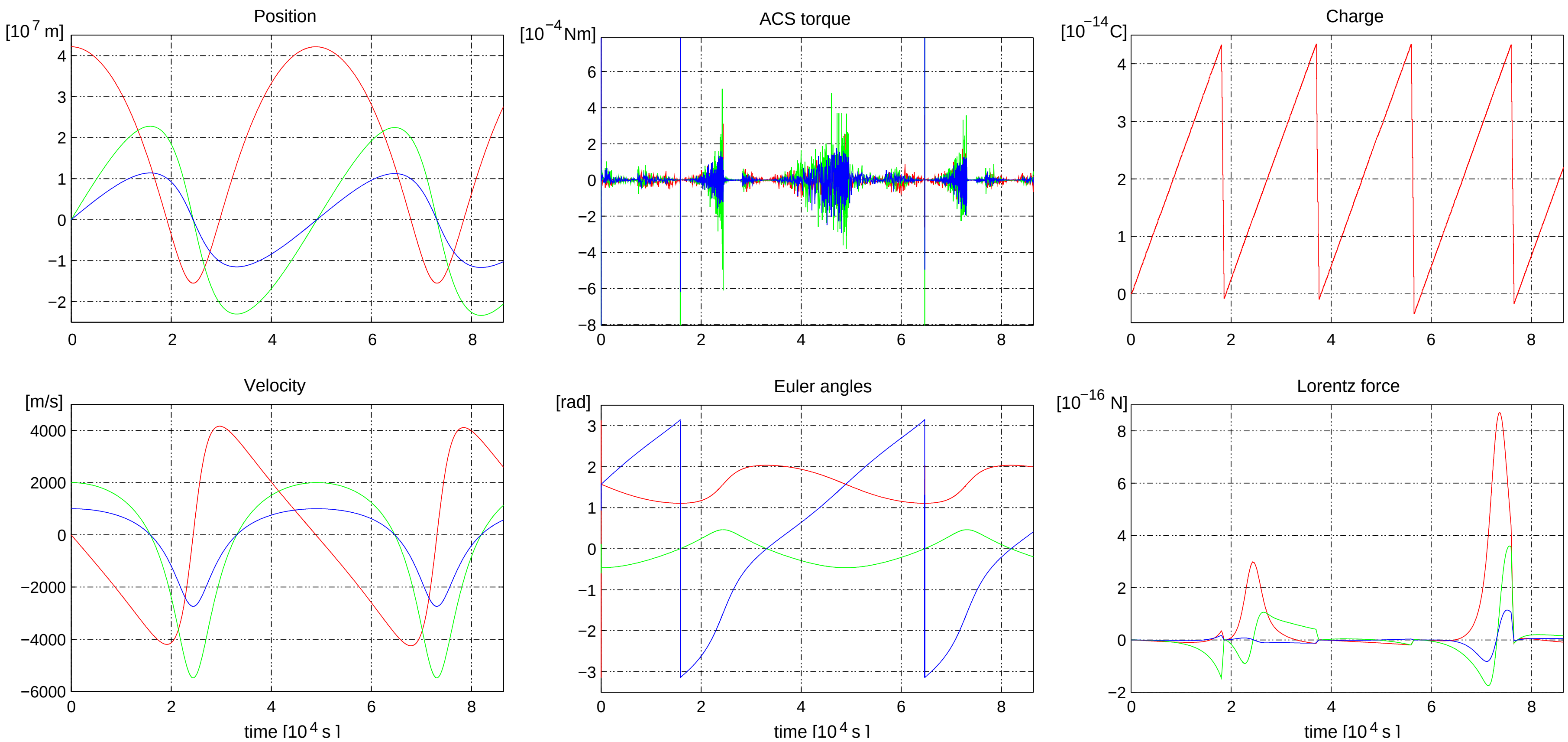
Simulator implementation

- The E2E simulator is realized using the MathWorks Simulink package
- To avoid performance problems computational intensive modules are written in compiler languages (C, C++, FORTRAN) and included as S-functions
- The open-loop integrator for S/C and test mass dynamics is based on a module developed by ZARM for the STEP mission
- To verify results obtained with this module a linearized version of the S/C and test mass dynamics will be implemented



Closed loop test

Test of the E2E simulation environment, using a S/C model in a geocentric orbit and a simple attitude control which keeps the satellite earth pointing:



Outlook

- Implement noise models for the various hardware components
- In the long term replace noise models by realistic models of the underlying hardware
- Implement drag-free and attitude control laws into the E2E simulator
- Execute and analyse simulator test runs
- As a means of validation of the results obtained with the ZARM open-loop integrator, implement a linearized LTP dynamics model