e.Deorbit Phase B1 GNC & Combined Control Simulation Results

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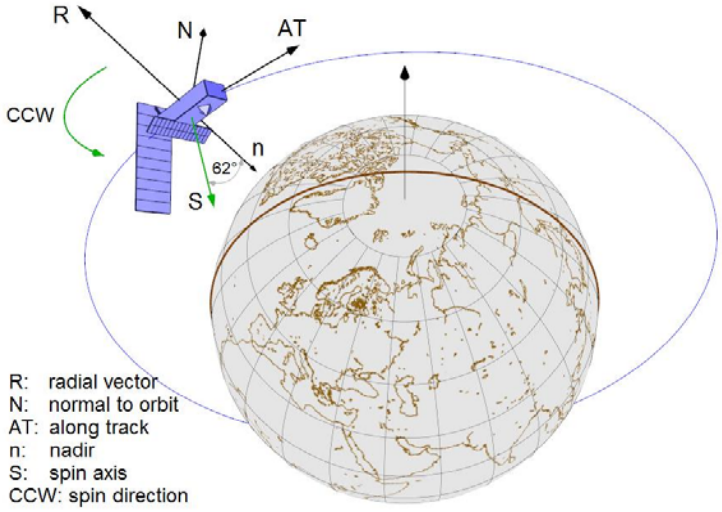
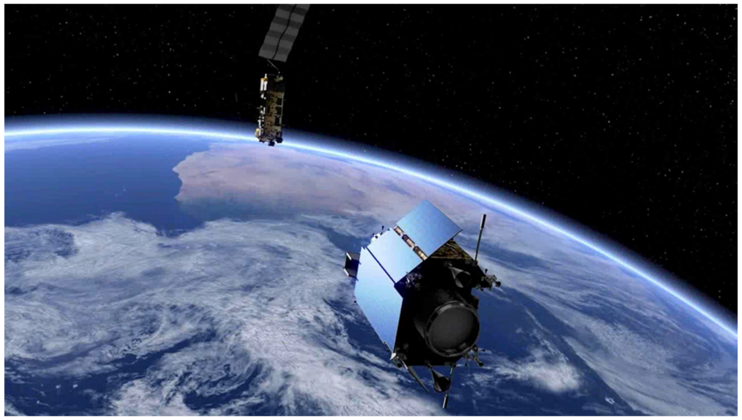
Outline

- e.Deorbit mission overview
- Chaser configuration
- Vision based navigation
- Close range GNC, motion synchronisation
- Coupled control, chaser platform and robotic arm for capture
- Target stabilisation

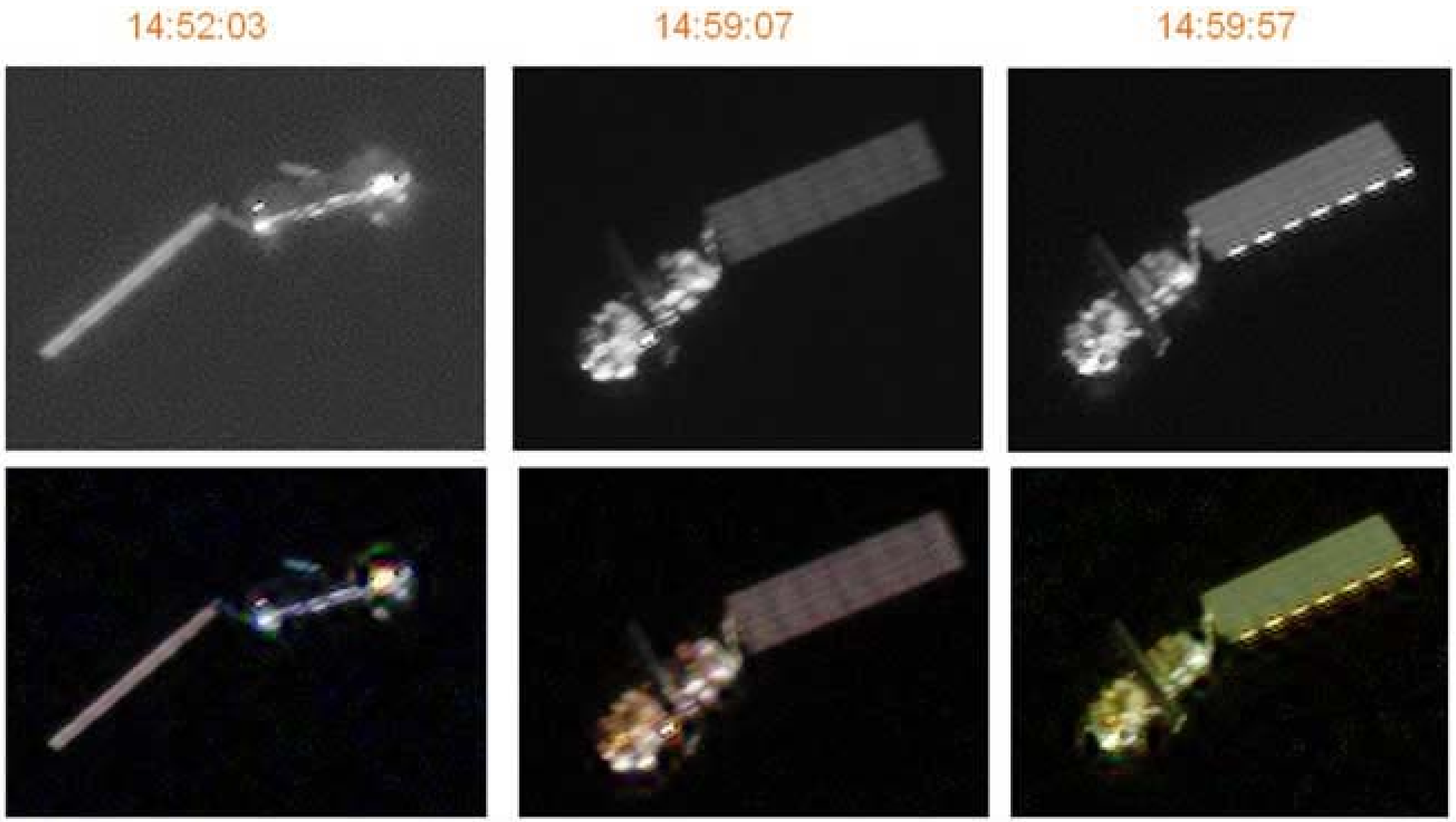
Design Reference Mission



- Tumbling target with large appendices in LEO
- Approach concept
  - o Far range
    - – Camera as line of sight sensor
    - – e/i-separated relative orbit with adjustable drift
  - o Mid range
    - – LIDAR measuring line of sight and range
    - – e/i-separated relative orbit with adjustable drift
  - o Close range
    - – Target pose estimation
    - – Forced motion



Envisat – Status after Loss of Contact



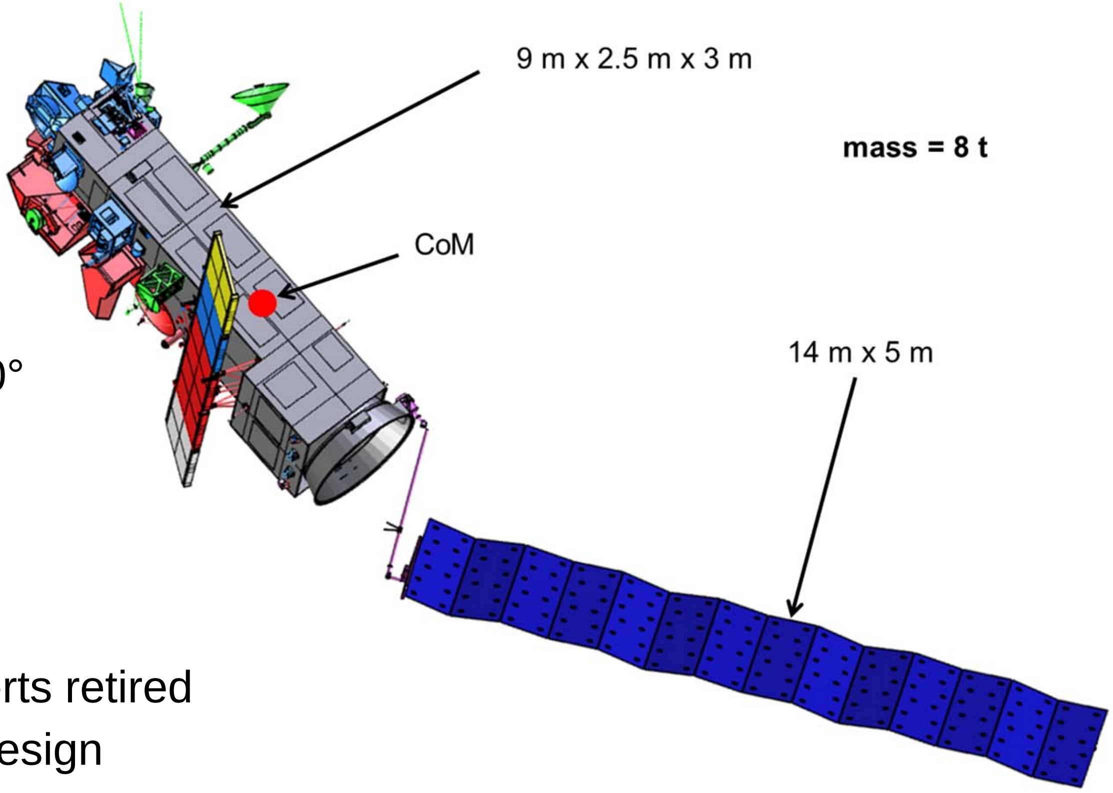
Envisat in orbit shortly after loss of contact in April 2012, photographed by Pléiades 1A during fly-by at 100 km distance.
Credit: CNES

Envisat – Status on Envisat attitude and design

Attitude

- Unexpected increase of Envisat rotation rate was observed in 2013 (3.5°/s)
- New baseline: 5°/s, nutation up to 90°

→ Tumbling motion



Design

- Many old documents deleted + Experts retired
- Different versions of “final” Envisat design

→ Airbus DS defined Envisat structure baseline supported by available CAD, documents, experts and photos

Mission scenarios

Three rotational scenarios shall be considered for the ENVISAT rotational state

Scenario 1

Spin axis in body frame is aligned with the +Ys axis.

Spin axis in LVLH frame is aligned with the +H-bar axis.

Spin rate is 5 deg/s.

Scenario 2

Spin axis in body frame is along a direction contained in the YsZs plane at 45 degrees w.r.t. +Ys and +Zs.

Spin axis in LVLH frame is aligned with the +H-bar axis.

Spin rate is 5 deg/s.

Scenario 3

Spin axis in body frame is aligned with the +Zs axis.

Spin axis in LVLH frame is at an angle of 45 degrees with respect to the +H-bar axis and is contained in the H-bar/R-bar plane.

Spin rate is 5 deg/s.

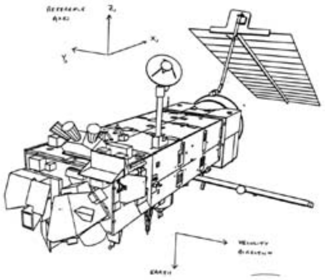


Figure 10-1. ENVISAT body reference frame

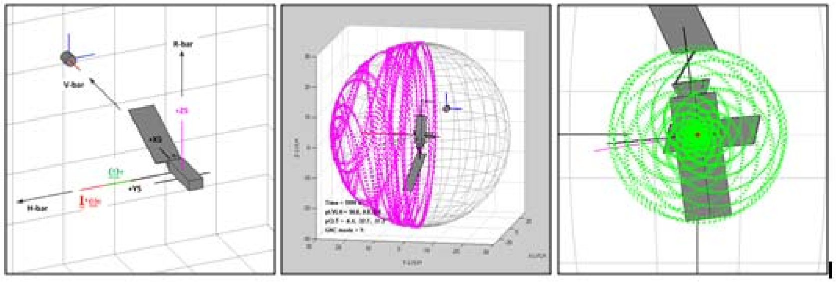


Figure 8-8: Scenario 1 results in a +/-90° cone containing the ZS figure axis motion (middle) w.r.t. LVLH and a +/-25° cone for the spin vector (right). The angular momentum vector stays very close to the H-bar

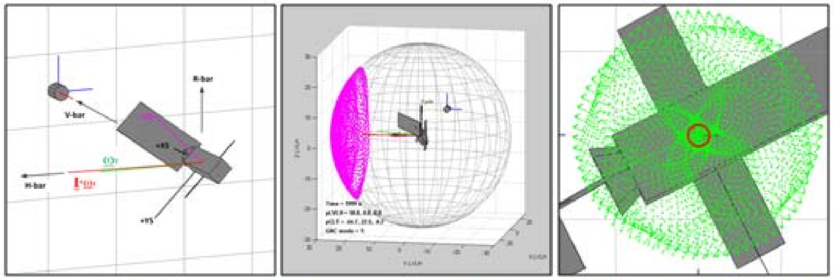


Figure 8-9: Scenario 2 results in a +/-45° cone containing the ZS figure axis motion w.r.t. LVLH and a +/-18° cone for the spin vector. The angular momentum vector stays very close to the H-bar

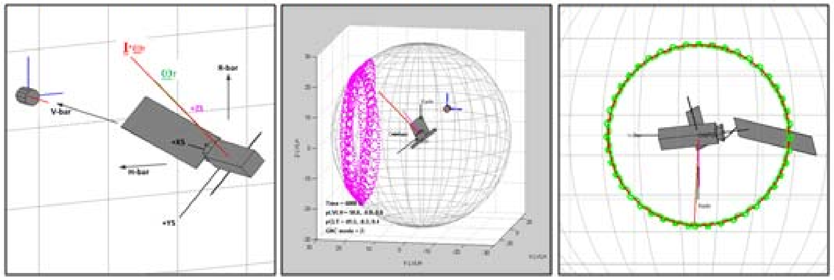
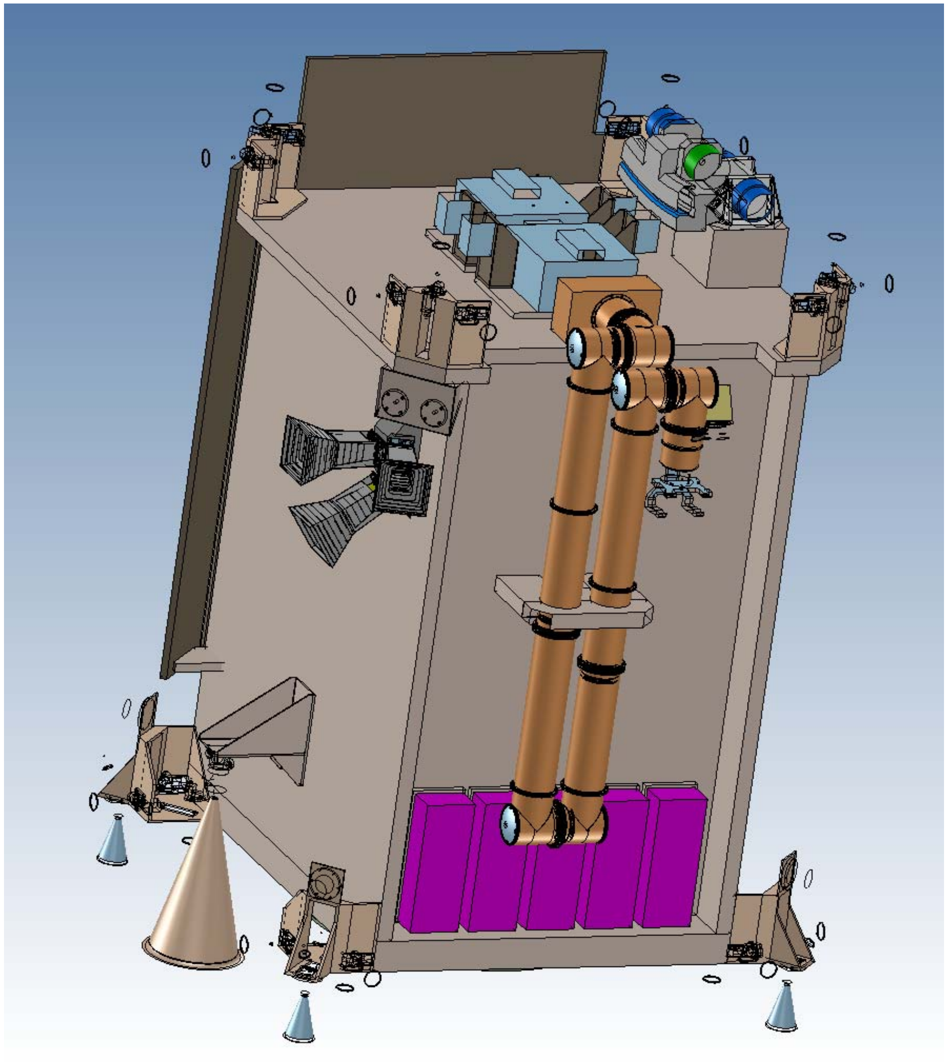


Figure 8-10: Scenario 3 results in a +/-45° virtual precession cone for the angular momentum vector (right, red). Superimposed, a small nutation of both the ZS figure axis (middle) and the spin axis (right, green) is seen

Chaser configuration

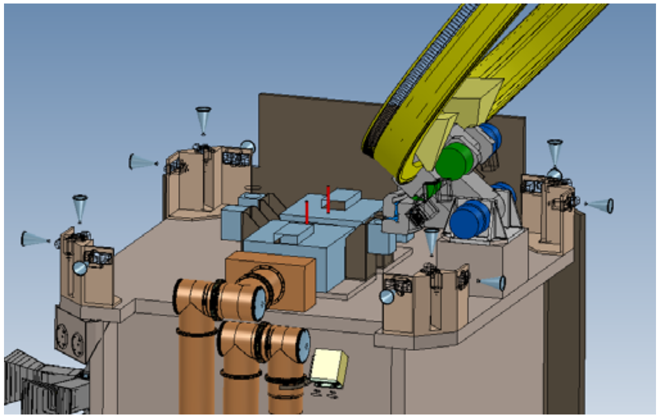


AOCS sensors
- IMU, STS, CSS, GPSR

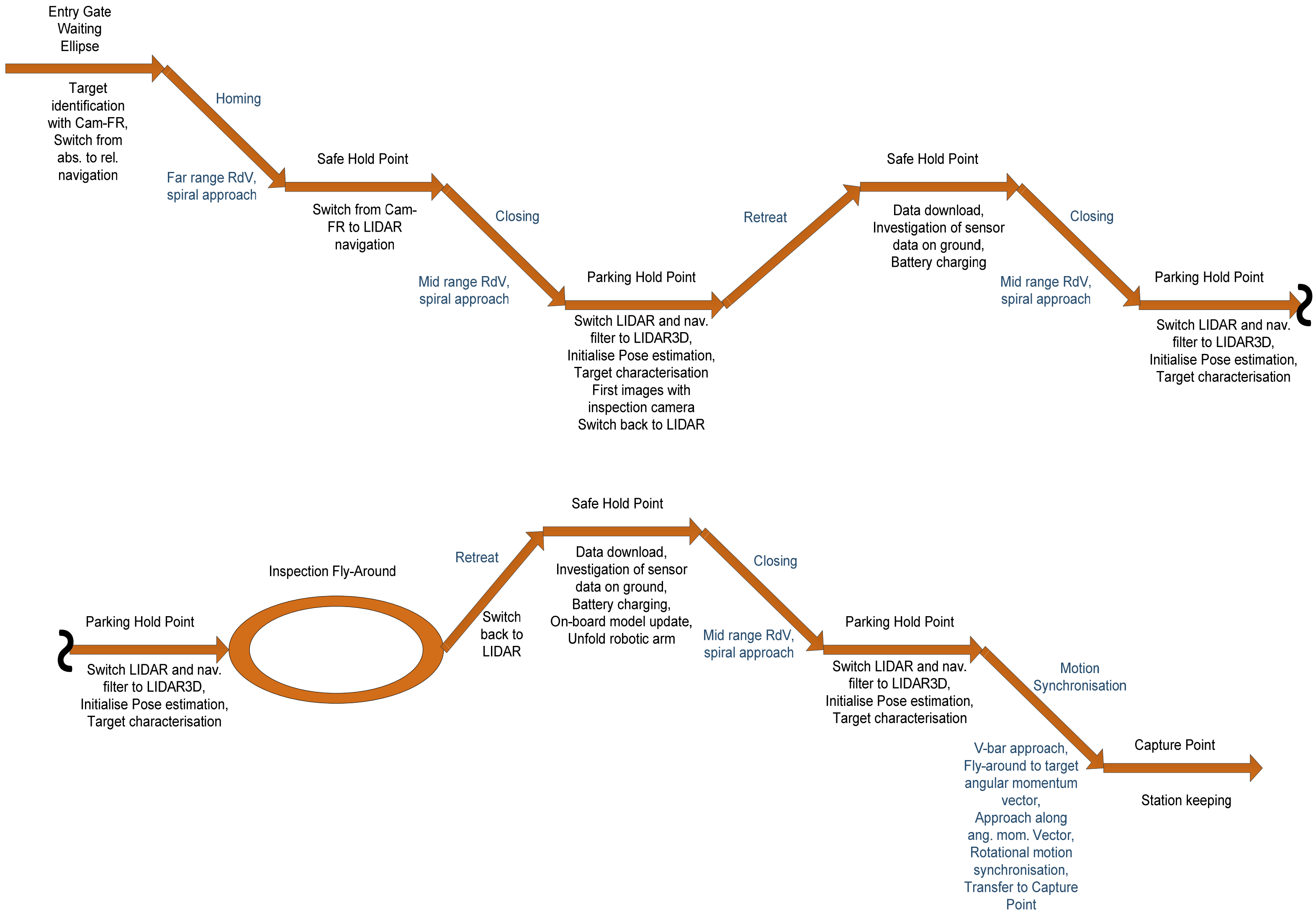
Rendezvous sensors
- Narrow and wide angle cameras
- LIDAR

Robotic arm sensors
- Camera and illumination system at gripper
- Sensors for joint states and joint torques

Thruster system
- ACS: 24x 22 N
- OCS: 2x 425 N
- Assist AOCS: 4x 220 N



Guidance and Control Design



Entry Gate
Waiting
Ellipse

Target
identification
with Cam-FR,
Switch from
abs. to rel.
navigation

Homing

Far range RdV,
spiral approach

Safe Hold Point

Switch from Cam-FR to LIDAR navigation

Closing

Mid range RdV,
spiral approach

Parking Hold Point

Switch LIDAR and nav. filter to LIDAR3D,
Initialise Pose estimation,
Target characterisation
First images with inspection camera
Switch back to LIDAR

Retreat

Safe Hold Point

Data download,
Investigation of sensor data on ground,
Battery charging

Closing

Mid range RdV,
spiral approach

Parking Hold Point

Switch LIDAR and nav. filter to LIDAR3D,
Initialise Pose estimation,
Target characterisation

Parking Hold Point

Switch LIDAR and nav. filter to LIDAR3D,
Initialise Pose estimation,
Target characterisation

Inspection Fly-Around

Retreat

Switch back to LIDAR

Safe Hold Point

Data download,
Investigation of sensor data on ground,
Battery charging,
On-board model update,
Unfold robotic arm

Closing

Mid range RdV,
spiral approach

Parking Hold Point

Switch LIDAR and nav. filter to LIDAR3D,
Initialise Pose estimation,
Target characterisation

Motion
Synchronisation

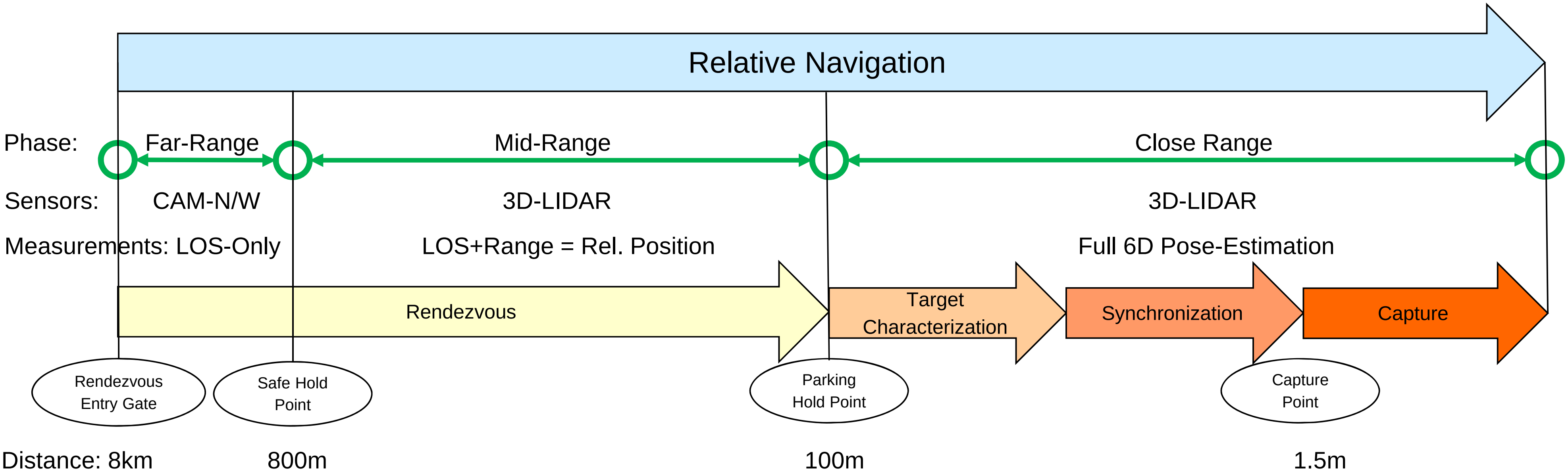
V-bar approach,
Fly-around to target angular momentum vector,
Approach along ang. mom. Vector,
Rotational motion synchronisation,
Transfer to Capture Point

Capture Point

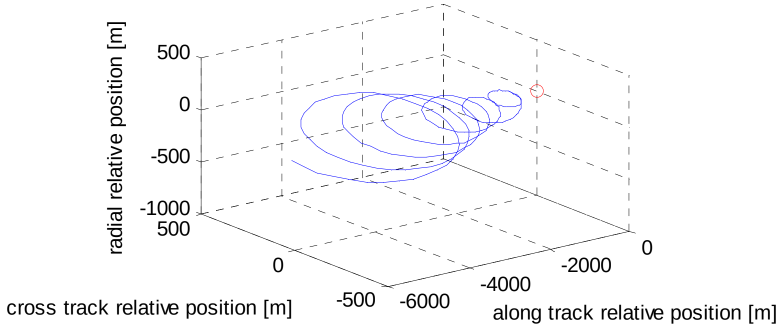
Station keeping

Vision Based Navigation

- Timeline of Main VBN Functions



- Far-Range:
  - Only line-of-sight measurements are possible, range is not available
  - Potential sensors: Monocular camera, either LWIR or visible spectrum
- Mid-Range:
  - Line-of-sight measurements and range measurements
  - Potential sensors: 3D-LIDAR, Flash-LIDAR, Stereo camera (either LWIR or visible spectrum)
- Close-Range:
  - Full 6D pose-estimations are required



Vision-Based-Navigation – LWIR vs. Visible Spectrum

Trade-Off-Analysis:

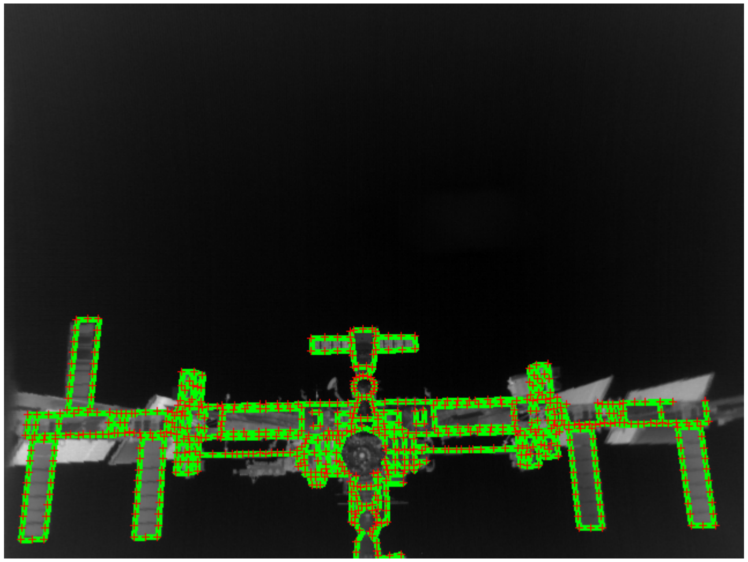
- Trade mainly selected usage of monocular camera for far-range and for monitoring
- Decision between visible and LWIR camera is not so clear.

Advantages of LWIR:

- Visibility of target even during eclipse or difficult illumination conditions (target between sun and camera) (refer to LIRIS-1 experiment).

Disadvantages of LWIR:

- Less sensitive: Target detection up to 6.7km for LWIR, >8km for visible spectrum
- Lower resolution: 640x480 vs. 2048x2048/1024x1024
- Less mature, larger development costs expected, would bring an additional sensor since VIS camera is required for inspection.
- Verification concept on ground still not solved.



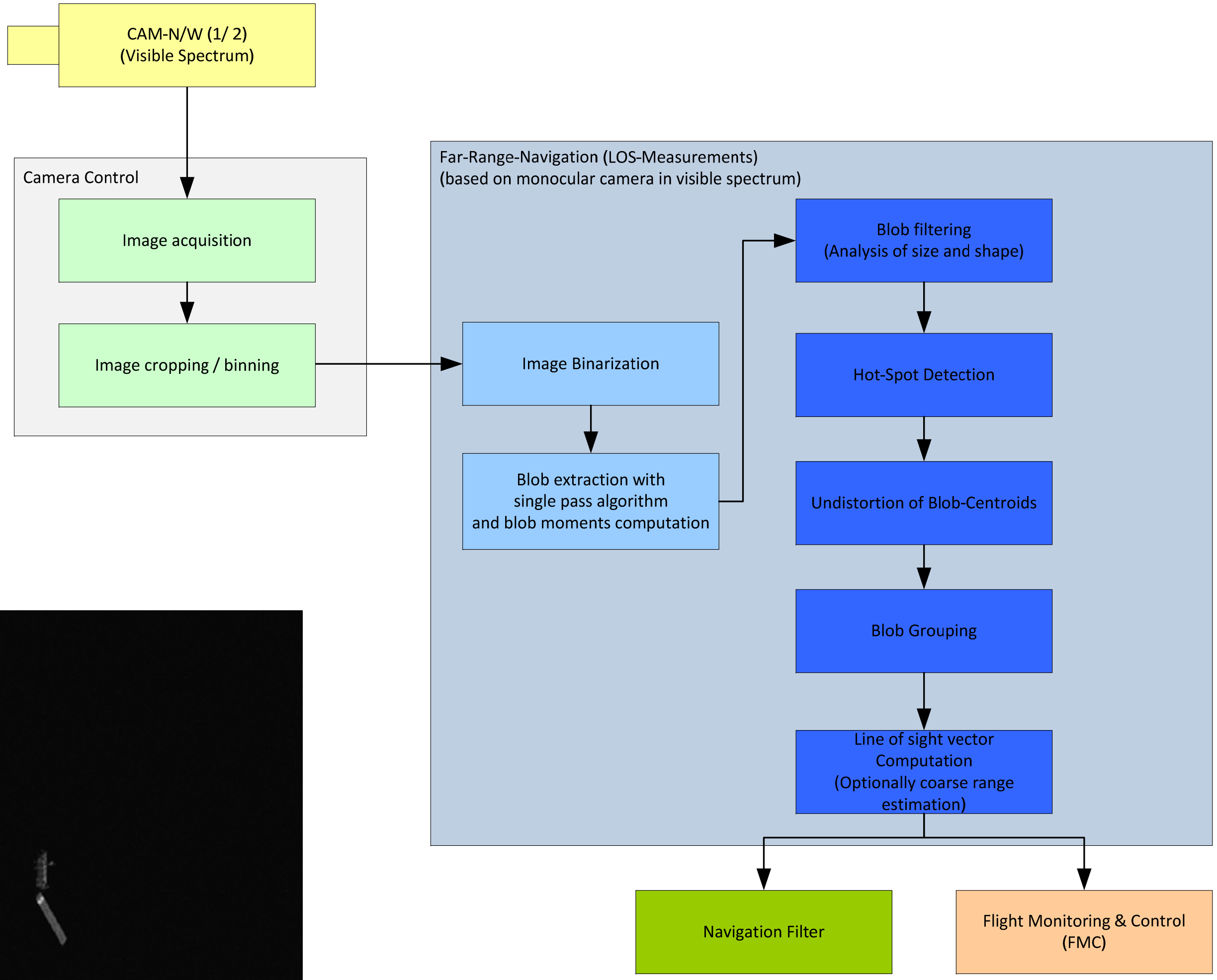
Example of LWIR-images: Target tracking on LWIR-images of ISS acquired during LIRIS-1 experiment on ATV-5.

Further observations/ open questions:

- In any case, inspection shall be performed in visible spectrum (ref. to AI#54).
- The visibility during far-range in eclipse not necessary! Navigation filter converges anyway.
- Critical capture operations will be performed during illuminated periods (not during eclipse).
- Is periodic blinding acceptable for *monitoring* sensors?
- If not, LWIR camera is needed at least for monitoring at close ranges.
- Recommendations from **IRPN study**: Usage of LIDAR+LWIR camera for navigation.

Vision-Based-Navigation: Far-Range

- Visibility of stars will be switched off during navigation.
- Visibility of stars will be switched on only for navigation purposes
- No confusion with stars is expected.
- Visibility of larger celestial bodies (e.g. Moon, Earth) can be predicted and masked out.
- Simple centroid computation then enables line-of-sight measurements.



CAM-N/W (1/ 2)
(Visible Spectrum)

Camera Control

Image acquisition

Image cropping / binning

Far-Range-Navigation (LOS-Measurements)
(based on monocular camera in visible spectrum)

Image Binarization

Blob extraction with
single pass algorithm
and blob moments computation

Blob filtering
(Analysis of size and shape)

Hot-Spot Detection

Undistortion of Blob-Centroids

Blob Grouping

Line of sight vector
Computation
(Optionally coarse range
estimation)

Navigation Filter

Flight Monitoring & Control
(FMC)

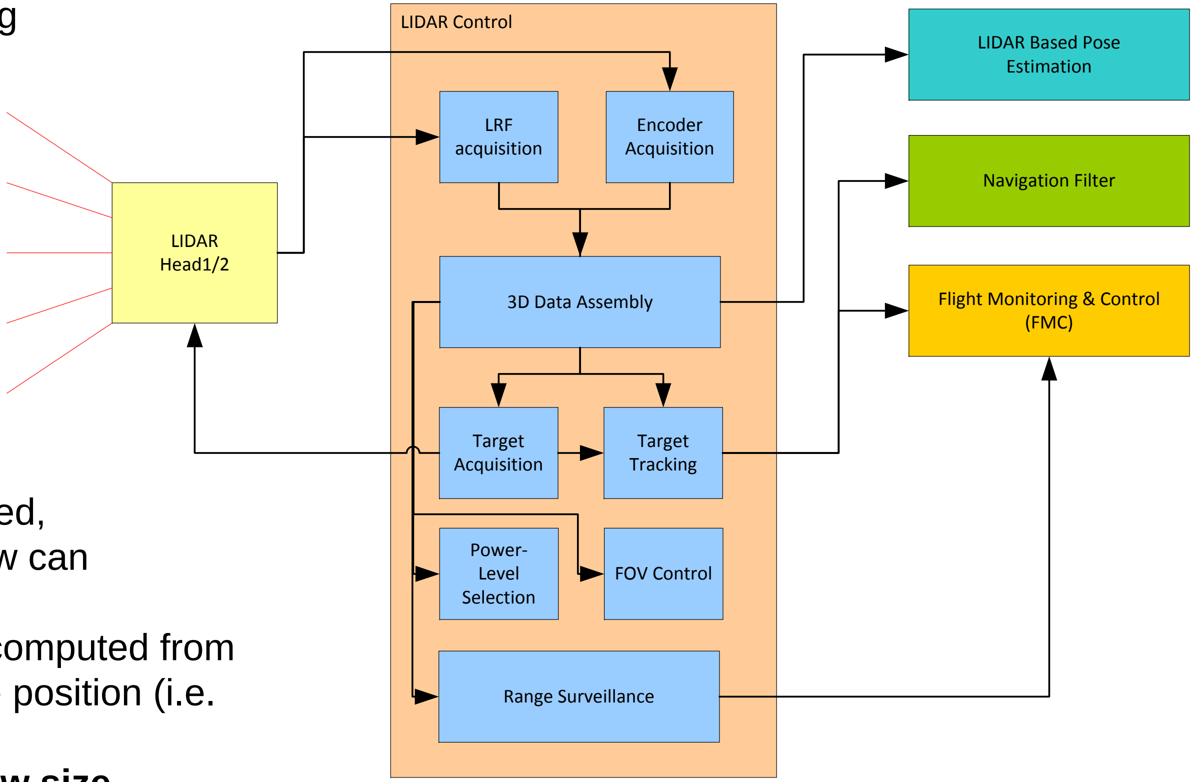
Simulated images for far-range-navigation with ASTOS simulator

Vision-Based-Navigation: Mid-Range

- Mid-range navigation will be based on simple centroid computation of the scanning LIDAR.

- **Target Acquisition:**
  - **Slow scanning** with high density and overlapping laser beam divergence.
  - Relatively **large field of view** that ensures visibility of target (e.g. 12°x12°).

- **Target Tracking:**
  - Once sufficient hits have been collected, the target is found and the field of view can be **narrowed**.
  - During tracking, the **centroid** will be computed from all hits. The centroid gives the relative position (i.e. Line-of-sight plus range).
  - The range determines the **field of view size.**

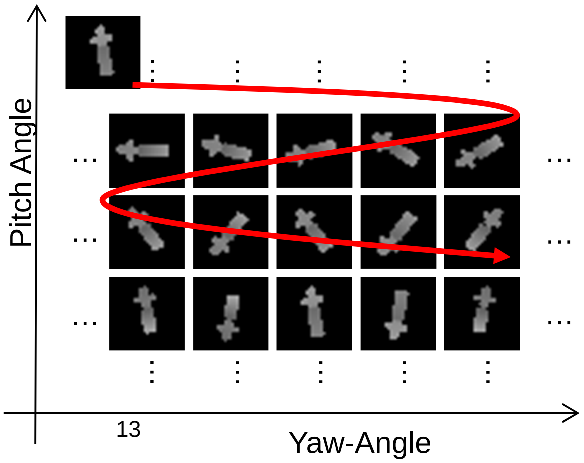


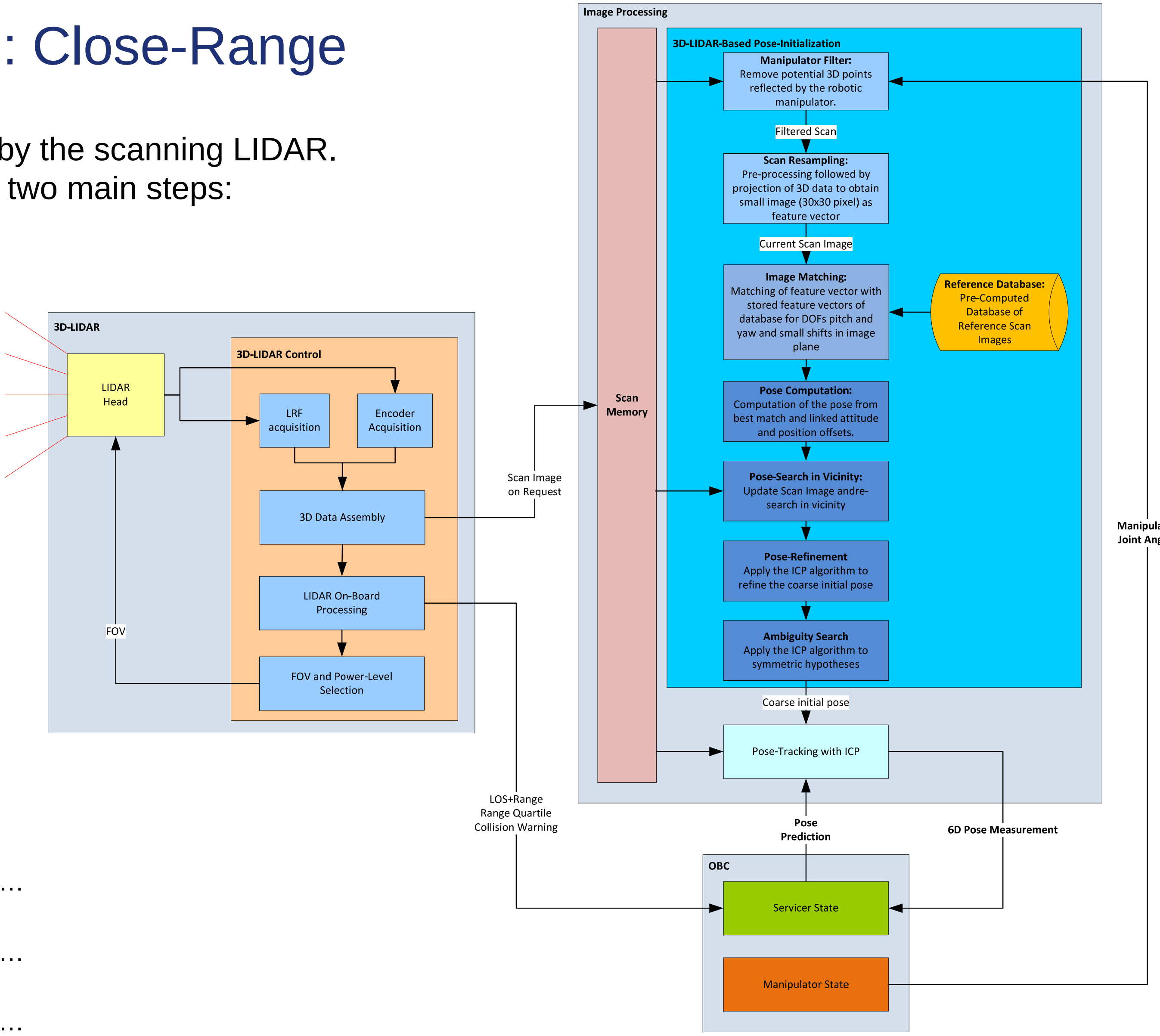
- Measurements will show **significant bias** due to the tumbling and the simple centroiding instead of considering the shape of the target.

Vision-Based-Navigation: Close-Range

- Based on 3D point-clouds provided by the scanning LIDAR.
- Close-Range-Navigation consists of two main steps:
  - Pose-initialization
  - Pose-tracking

- Pose-Initialization:
  - Raw scan is transformed into small range image
  - Range image is compared to reference images stored in a database.
  - Best match gives coarse viewing direction and thus an initial guess of target attitude.





3D-LIDAR

LIDAR Head

FOV

3D-LIDAR Control

LRF acquisition

Encoder Acquisition

3D Data Assembly

LIDAR On-Board Processing

FOV and Power-Level Selection

Scan Image on Request

LOS+Range
Range Quartile
Collision Warning

Image Processing

Scan Memory

3D-LIDAR-Based Pose-Initialization

Manipulator Filter: Remove potential 3D points reflected by the robotic manipulator.

Filtered Scan

Scan Resampling: Pre-processing followed by projection of 3D data to obtain small image (30x30 pixel) as feature vector

Current Scan Image

Image Matching: Matching of feature vector with stored feature vectors of database for DOFs pitch and yaw and small shifts in image plane

Reference Database: Pre-Computed Database of Reference Scan Images

Pose Computation: Computation of the pose from best match and linked attitude and position offsets.

Pose-Search in Vicinity: Update Scan Image andre-search in vicinity

Pose-Refinement Apply the ICP algorithm to refine the coarse initial pose

Ambiguity Search Apply the ICP algorithm to symmetric hypotheses

Coarse initial pose

Pose-Tracking with ICP

Pose Prediction

6D Pose Measurement

Manipula
Joint Ang

OBC

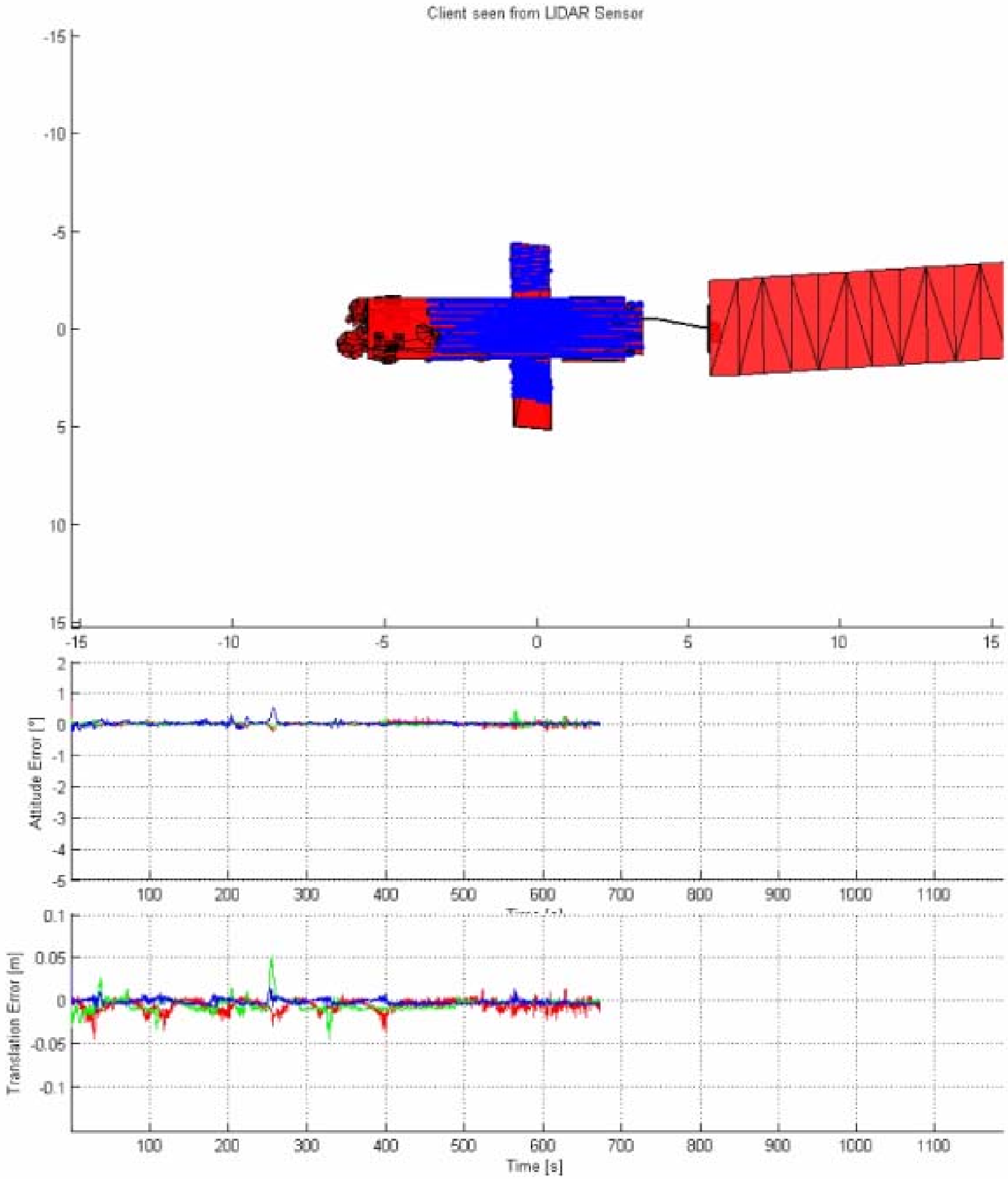
Servicer State

Manipulator State

GNC, Dynamics Analyses – Visual Navigation Performance Models

Example of LIDAR-based Pose-Estimation:

- Raw measurements without filtering!



Vision-Based-Navigation: Motion Estimation

Objectives:

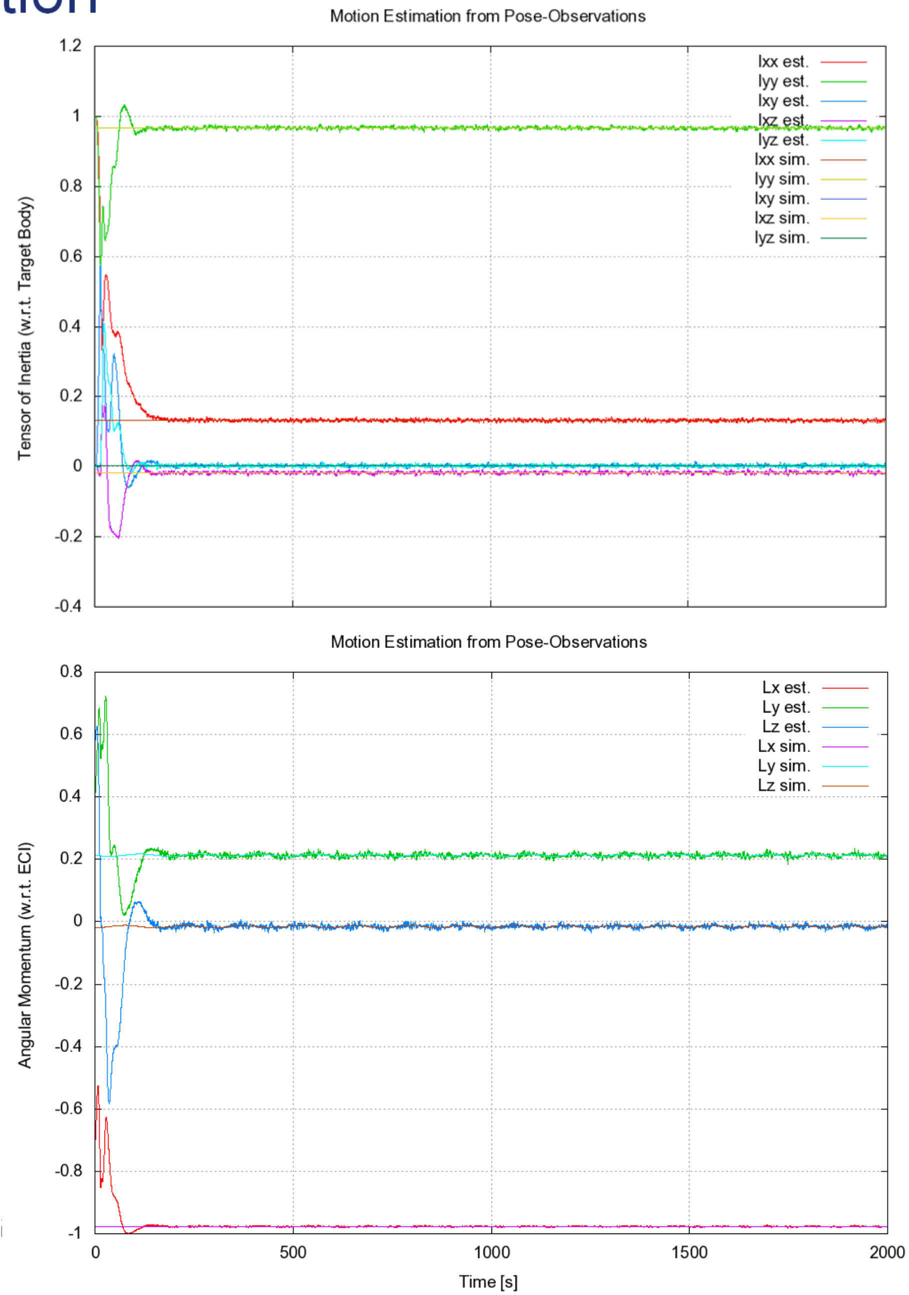
- Estimate the dynamic motion parameters from LIDAR-based pose-estimations:
  - Current attitude (transform ECI → body system),
  - Angular rates $\omega = \left(\omega_x, \omega_y, \omega_z\right)^T$
  - Tensor of inertia $I = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{pmatrix} / I_{zz}$,
  - Angular momentum $L = I \cdot \omega$ (w.r.t. ECI)

  - Stabilizing the pose-estimation (tracking)
  - Estimate the tensor of inertia.
  - Estimate the angular momentum for planning the synchronized motion trajectory.

Background:

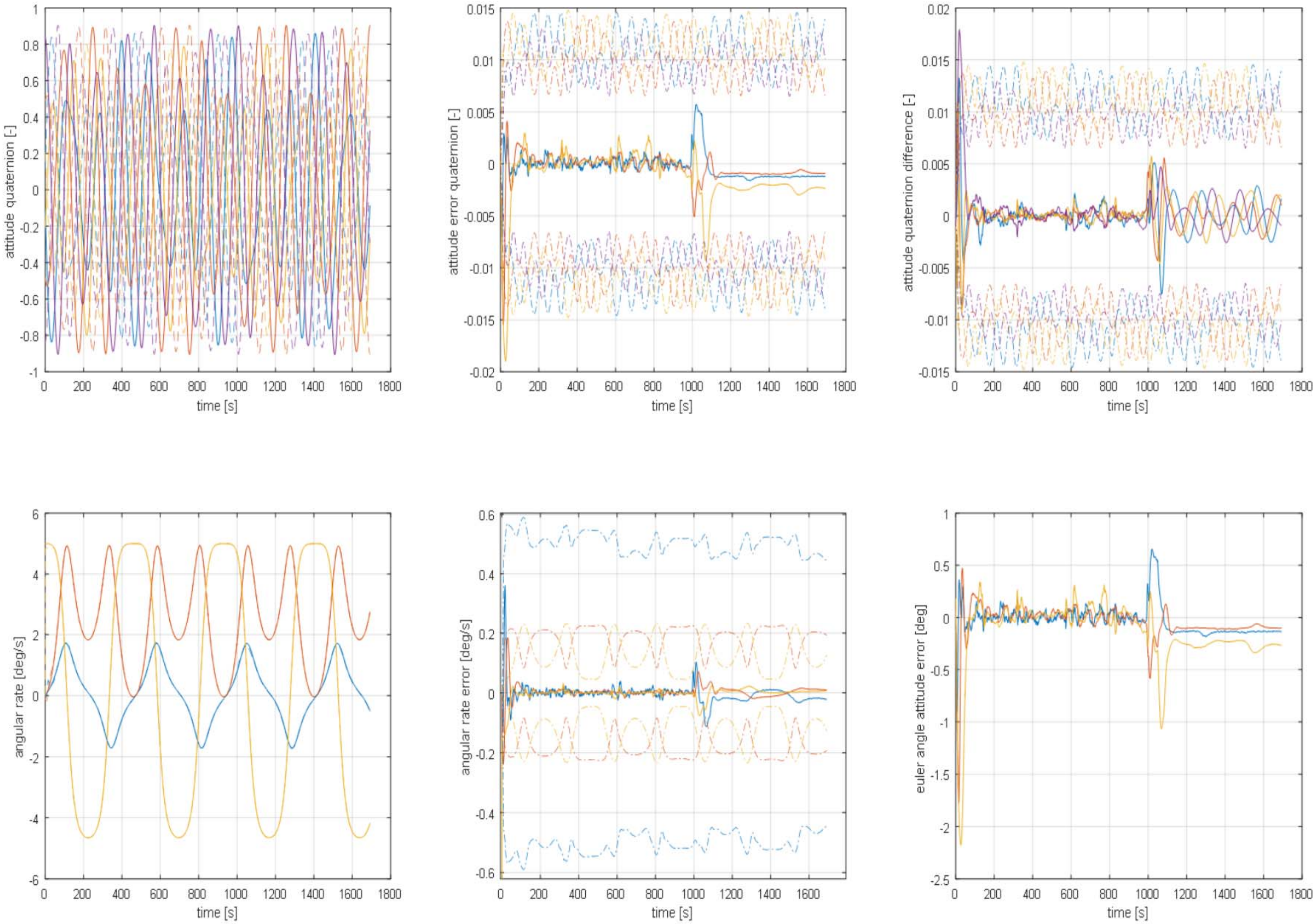
- Target motion is described by Euler's equations for rigid body motion: $M = I \cdot \dot{\omega} + \omega \times (I \cdot \omega)$
- In combination of the derivative of unit quaternions, the following system of differential equations gives the system equations of a Kalman filter:

$$\dot{q} = \frac{1}{2} q \cdot \overline{\omega}$$
$$\dot{\omega} = I^{-1} \cdot \left(-\omega \times (I \cdot \omega)\right)$$



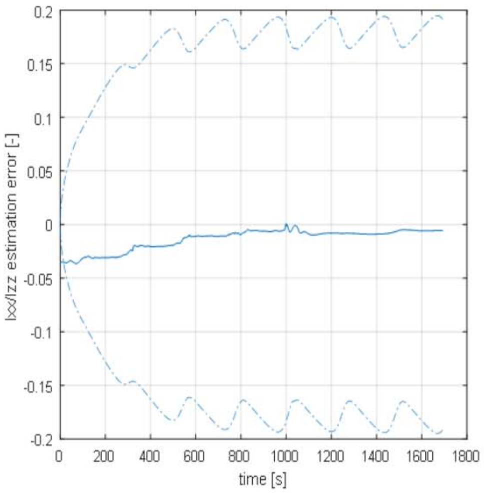
Vision-Based-Navigation: Simulation of Motion Estimation

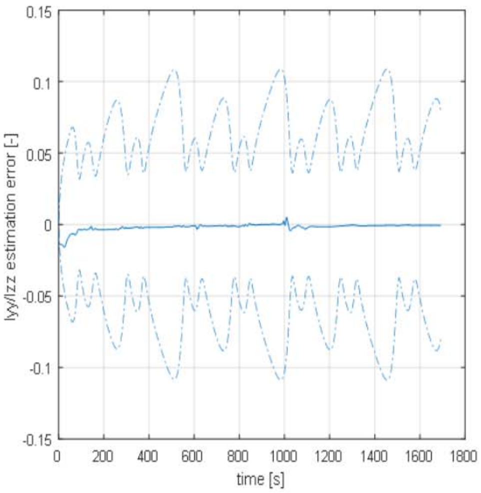
- Following diagrams show the simulation results of close-range performance model and navigation filter for estimation of attitude and angular rates.

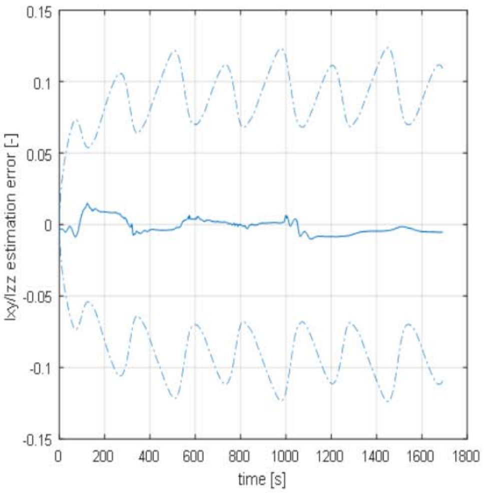


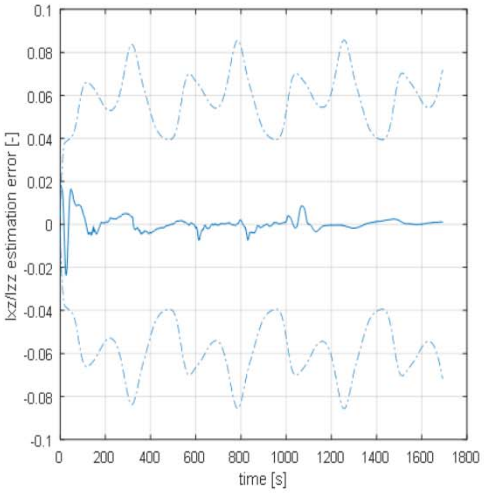
Vision-Based-Navigation: Simulation of Motion Estimation

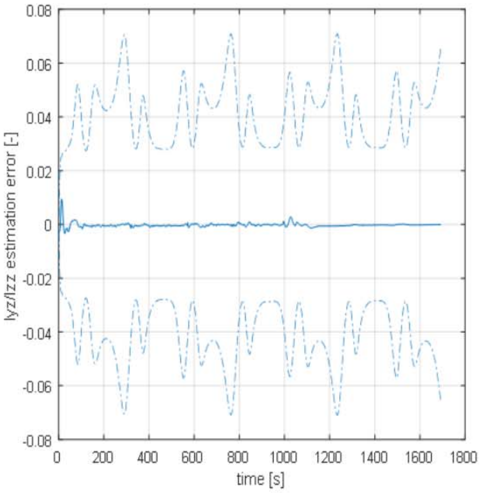
- Following diagrams show the simulation results of close-range performance model and navigation filter for estimation of tensor of inertia.

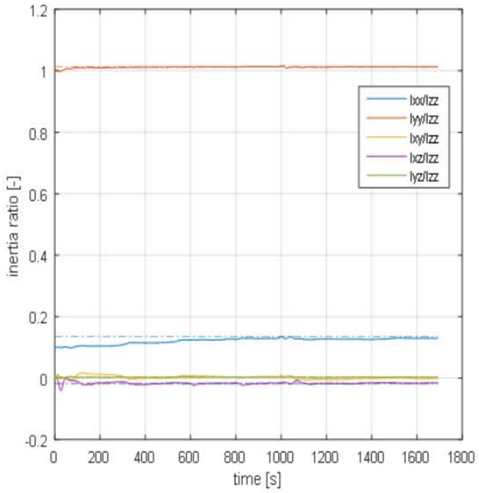












Extended Kalman Filter Design for Relative Orbital Elements

Prediction

$$\Phi = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1.5 n_\omega dt & 1 & 0 & 0 & -10.5\gamma \sin(2i) n_\omega dt & 0 \\ 0 & 0 & 1 & -\dot{\varphi} dt & 0 & 0 \\ 0 & 0 & \dot{\varphi} dt & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 3\gamma \sin^2(i) n_\omega dt & 1 \end{bmatrix}$$

$$\gamma = 0.5 J_2 \frac{R_{eq}^2}{a^2}$$

$$\dot{\varphi} = 1.5 \gamma n_\omega \left(5\cos^2(i) - 1\right)$$

Thruster commands

$$a\delta\delta\alpha_{F_{RTN}} = \frac{dt}{m n_\omega} \begin{pmatrix} 2F_T \\ -2F_R \\ F_R \sin u + 2F_T \cos u \\ -F_R \cos u + 2F_T \sin u \\ F_N \cos u \\ F_N \sin u \end{pmatrix}$$

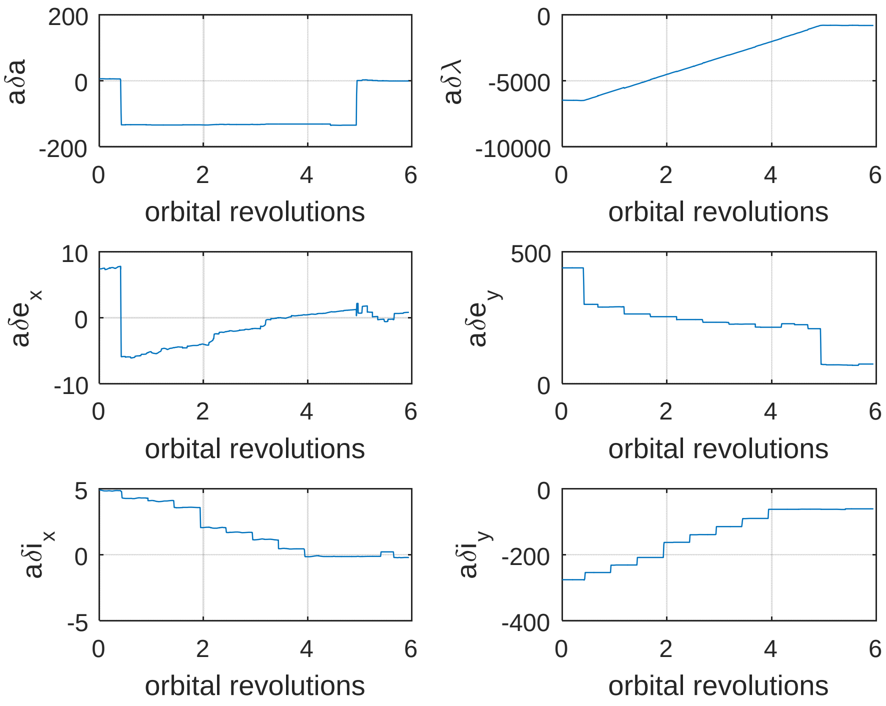
Low computational effort!

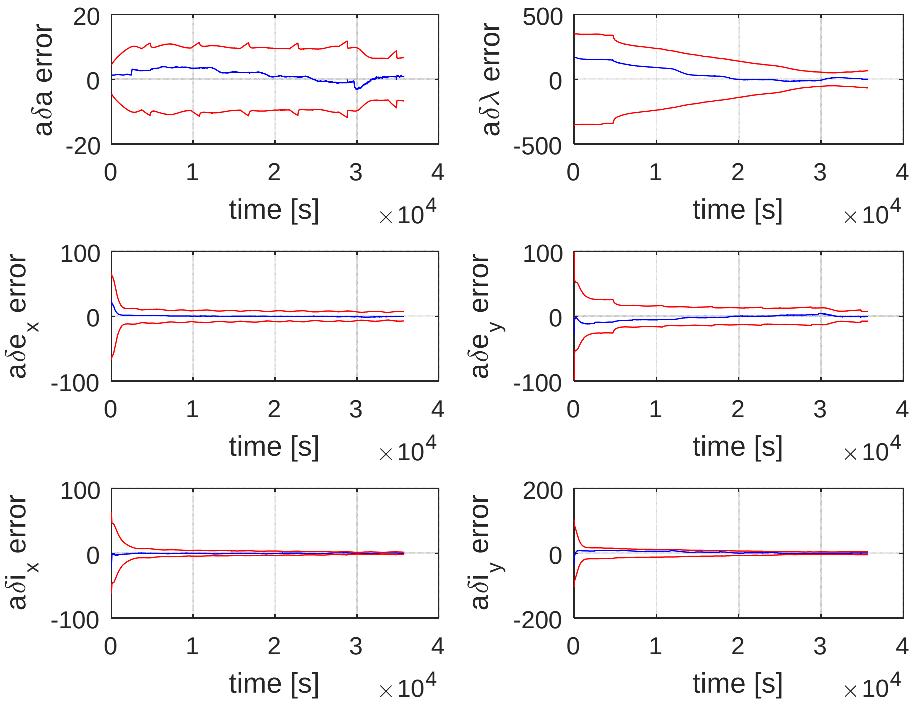
Measurements

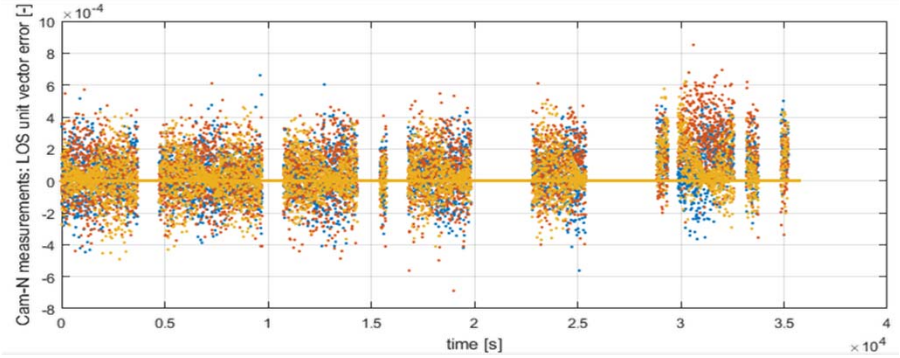
$$LOS_{predicted} = z_1 = \begin{pmatrix} -r_N / r_T \\ -r_R / r_T \end{pmatrix}$$

$$H = \begin{bmatrix} \frac{\partial z_1}{\partial r_{RTN}} & \frac{\partial z_1}{\partial v_{RTN}} \end{bmatrix} \cdot \frac{\partial \begin{pmatrix} r_{RTN} \\ v_{RTN} \end{pmatrix}}{\partial ROE} = \begin{bmatrix} 0 & \frac{r_N}{r_T} & 2\frac{r_N}{r_T}\sin u & -2\frac{r_N}{r_T}\cos u & -\sin u & \cos u \\ -1 & \frac{r_R}{r_T} & \cos u + 2\frac{r_R}{r_T}\sin u & \sin u - 2\frac{r_R}{r_T}\cos u & 0 & 0 \end{bmatrix} \cdot \frac{1}{r_T}$$

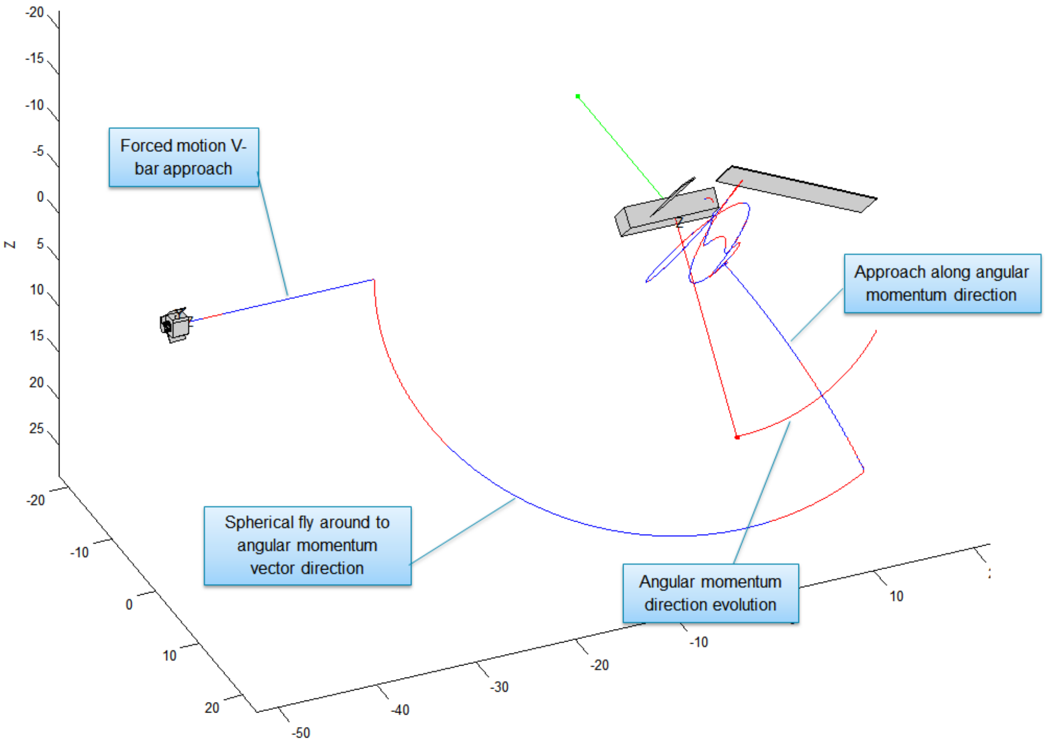
Navigation Filter Performance: Far Range







Guidance trajectory: Motion synchronisation

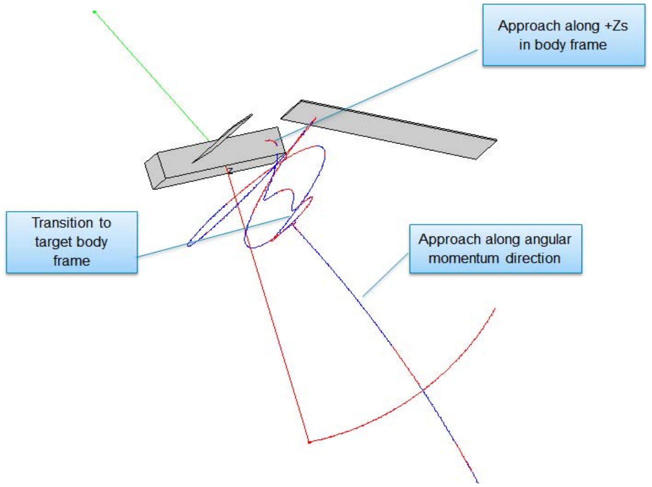


Forced motion V-bar approach

Approach along angular momentum direction

Spherical fly around to angular momentum vector direction

Angular momentum direction evolution



Approach along +Zs in body frame

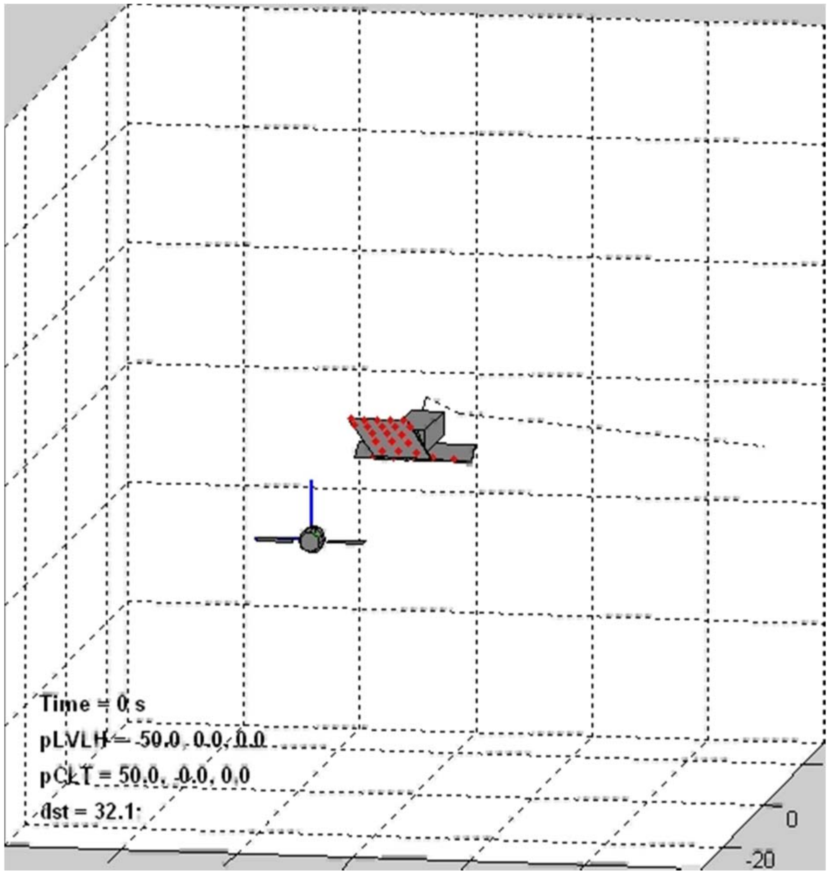
Transition to target body frame

Approach along angular momentum direction

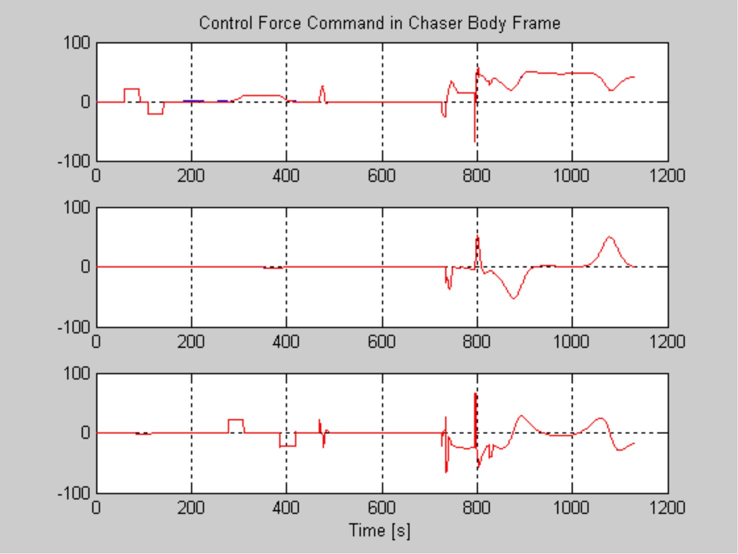
Synchronized flight to the target

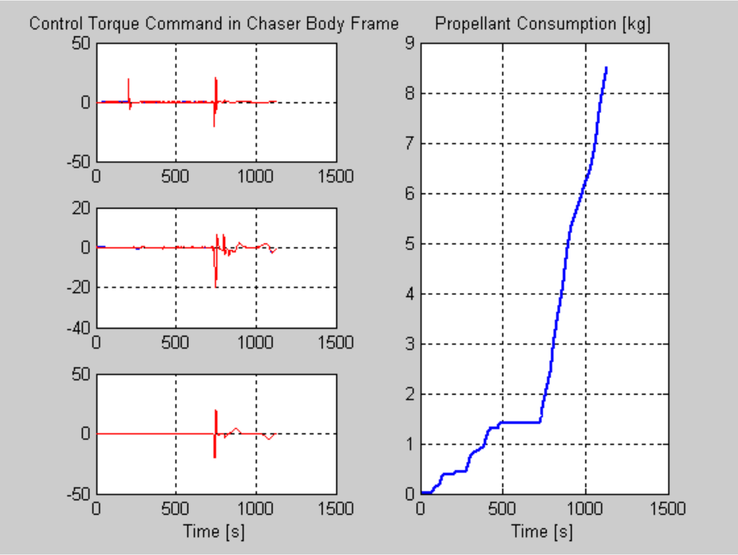
Guidance solutions to reach and sync with the rotating target

Attitude dynamics based on Phase A results



„90 deg nutation“ case





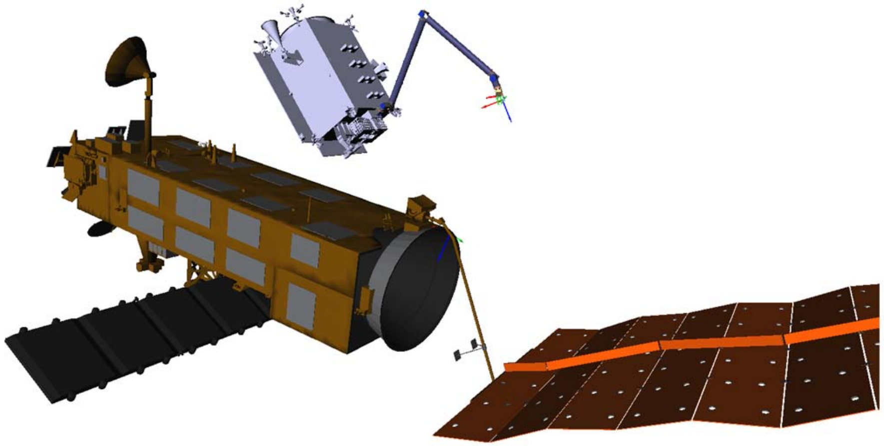
Coupled Control: Station keeping at Capture Point

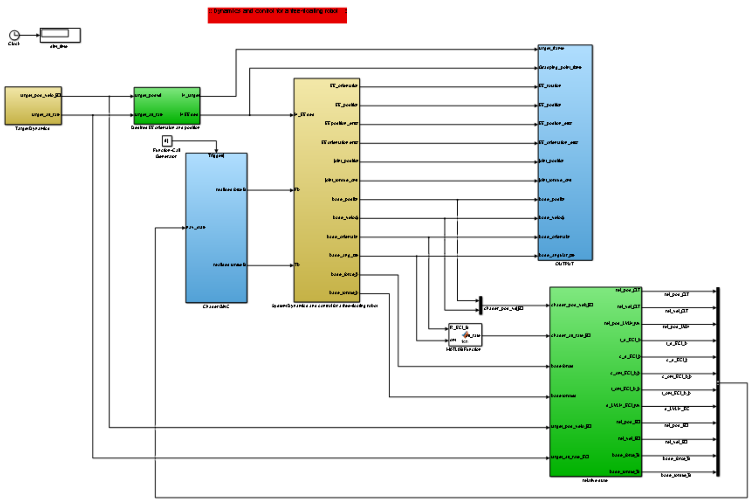
Control design

- GNC control frequency: 1 Hz
- GNC control bandwidth: 0.2 Hz
- Feedforward terms for translational and angular acceleration
- Feedforward term for robotic arm forces and torques
- Joint control frequency: ~ 1 kHz

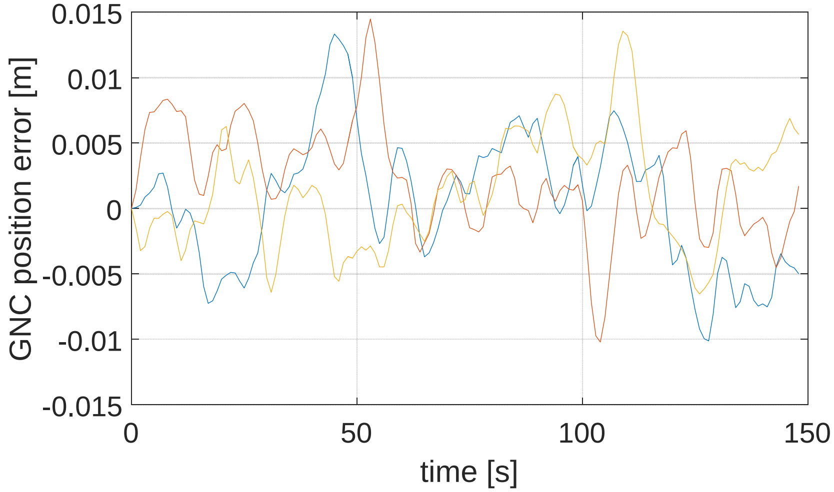
Simulator setup:

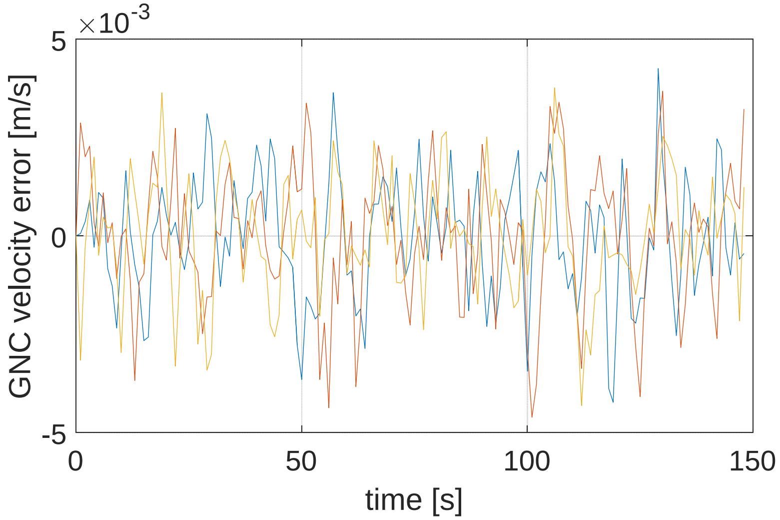
- Coupled chaser and robotic arm dynamics
- Thruster and relative navigation models
- Chaser controller for motion synchronisation
- Robotic arm joint controller for capture
- Target dynamics

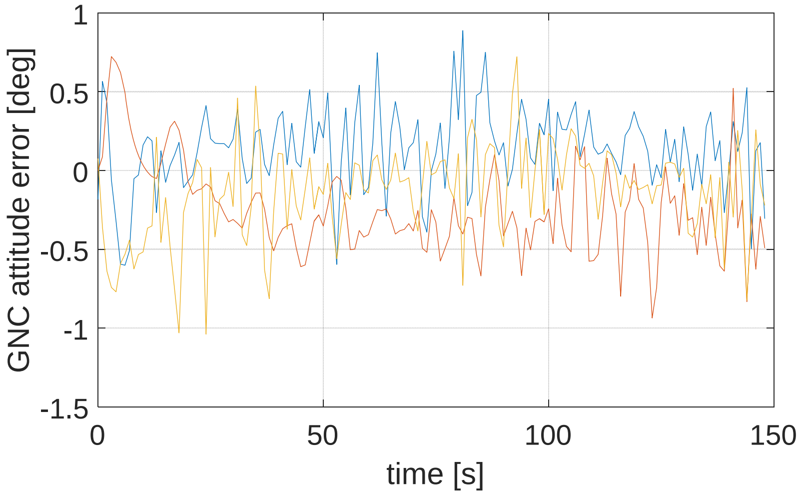


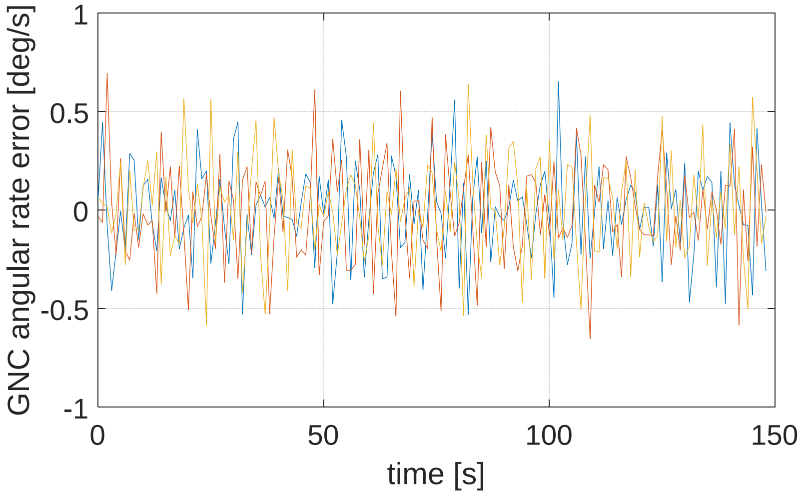


Coupled Control: Station keeping at Capture Point, Target Rotational Scenario 1

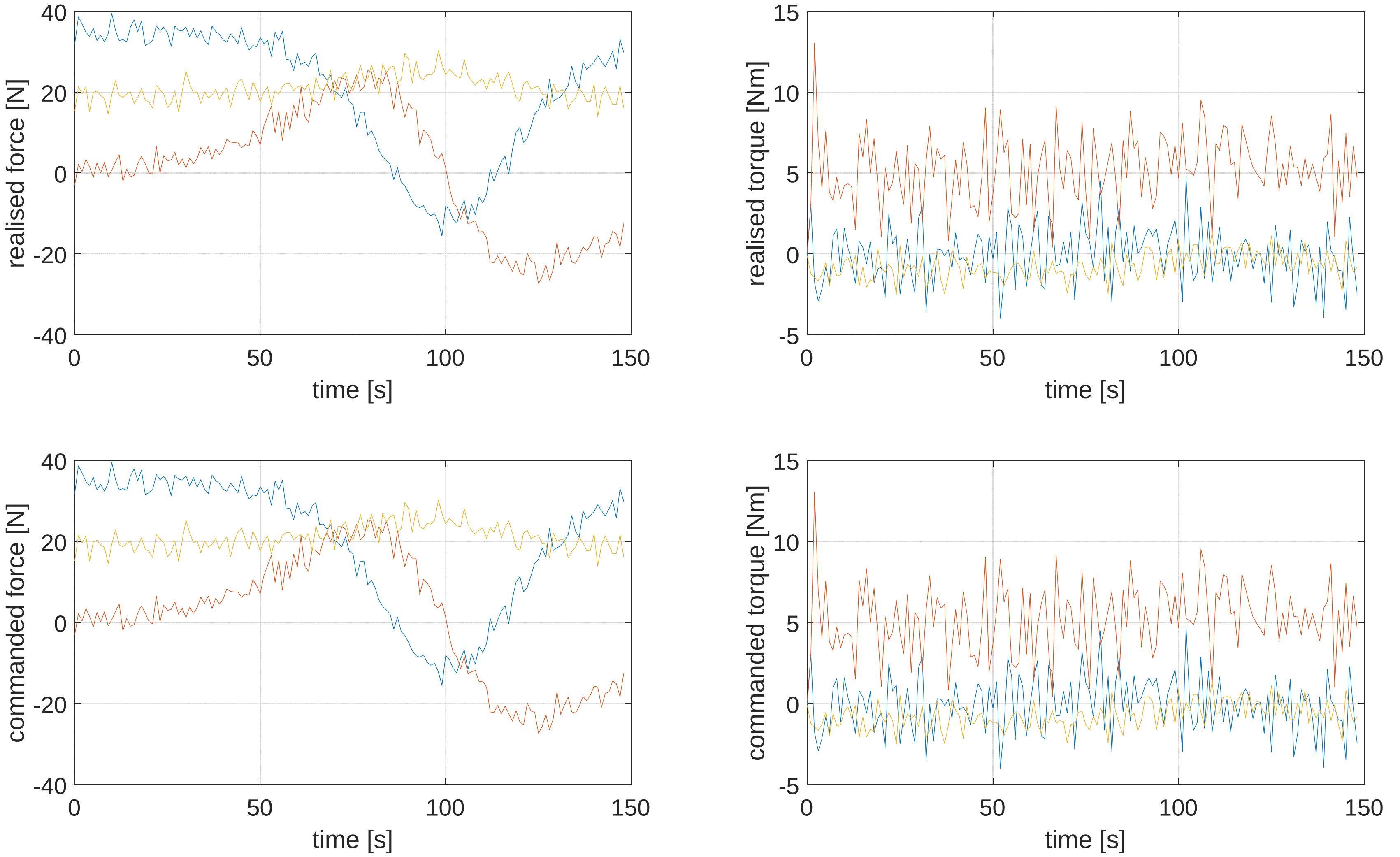




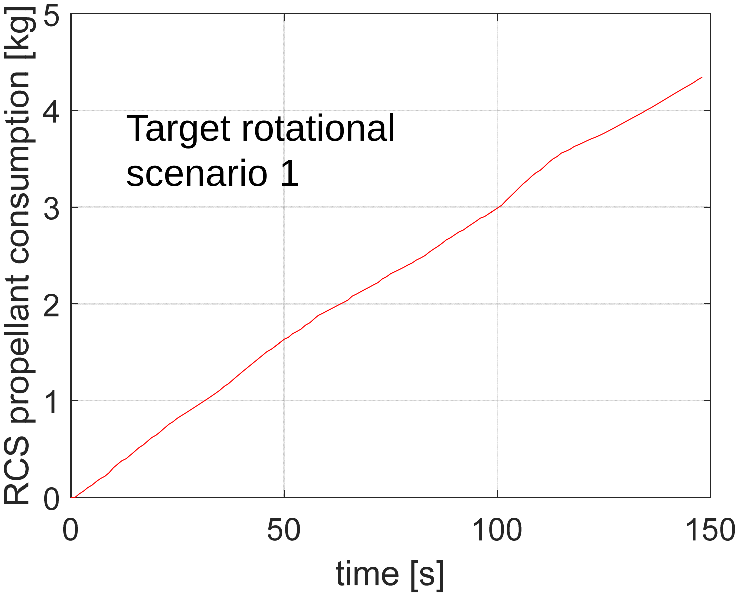


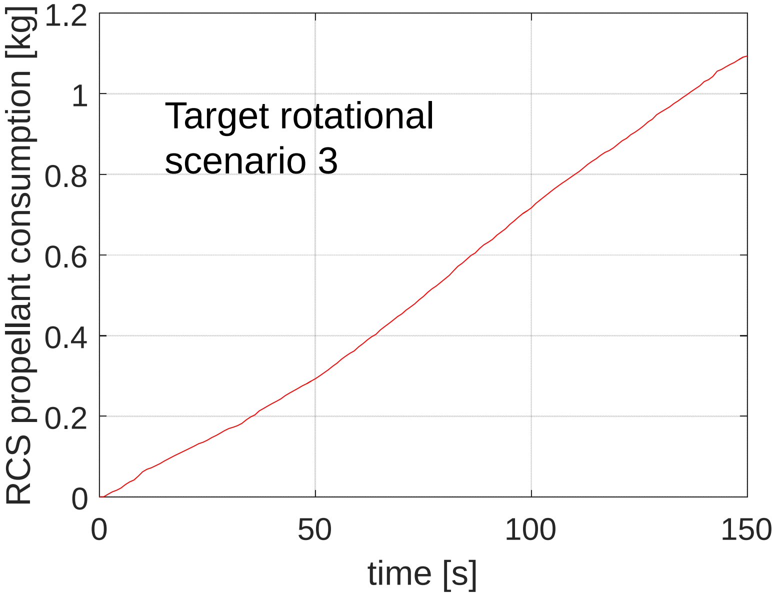


Coupled Control: Station keeping at Capture Point, Target Rotational Scenario 1



Coupled Control: Station keeping at Capture Point, RCS consumption





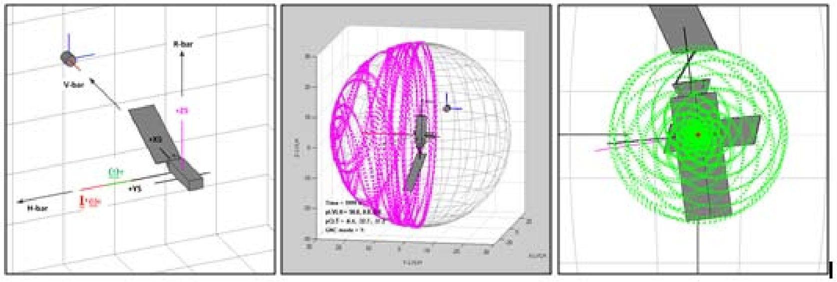


Figure 8-8: Scenario 1 results in a +/-90° cone containing the ZS figure axis motion (middle) w.r.t. LVLH and a +/-25° cone for the spin vector (right). The angular momentum vector stays very close to the H-bar

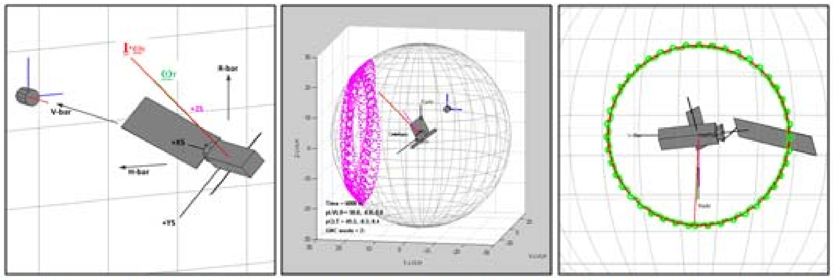
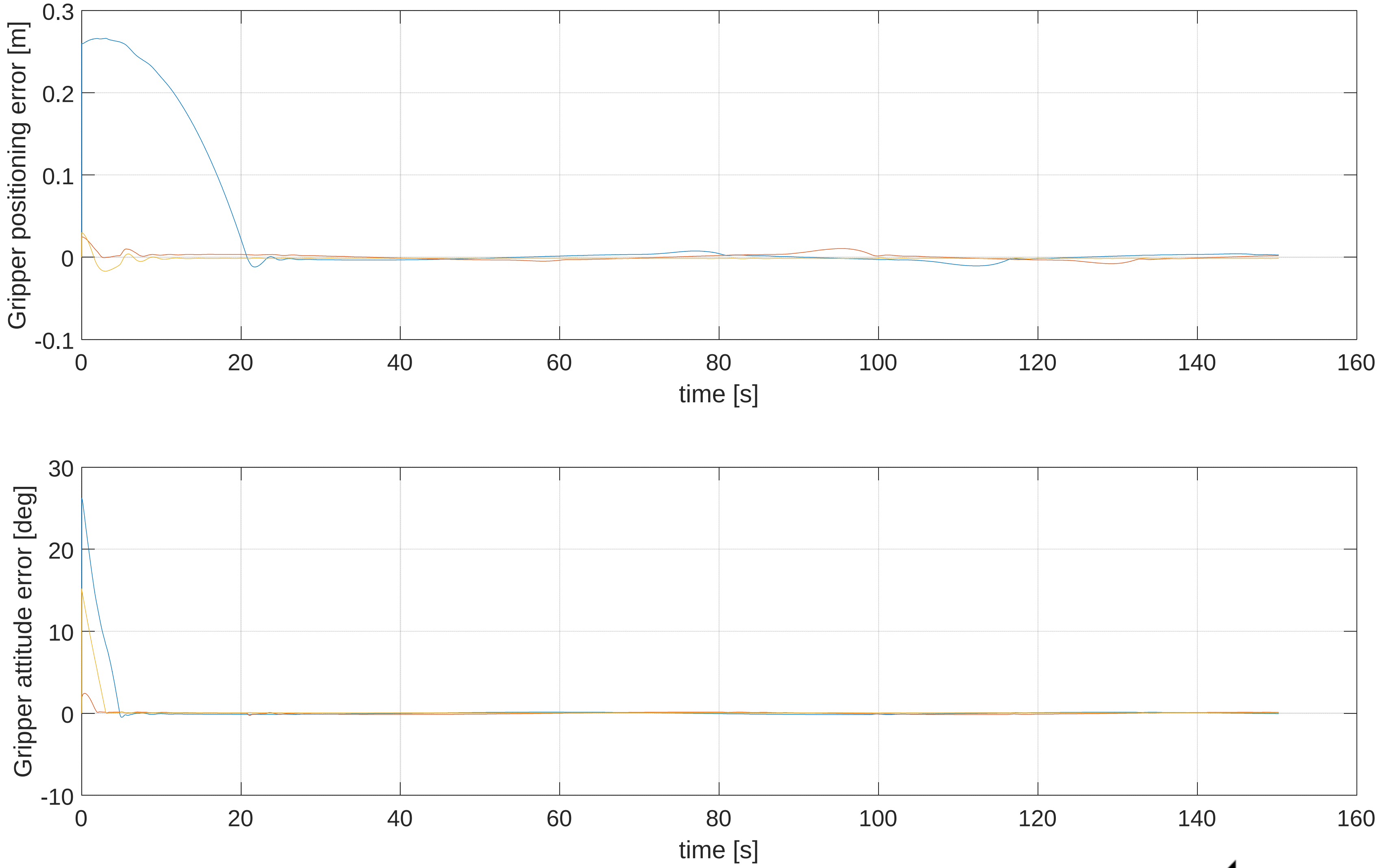


Figure 8-10: Scenario 3 results in a +/-45° virtual precession cone for the angular momentum vector (right, red). Superimposed, a small nutation of both the ZS figure axis (middle) and the spin axis (right, green) is seen

Coupled Control: Station keeping at Capture Point, Target Rotational Scenario 3



Coupled Control: Station keeping at Capture Point

Main Chaser GNC results

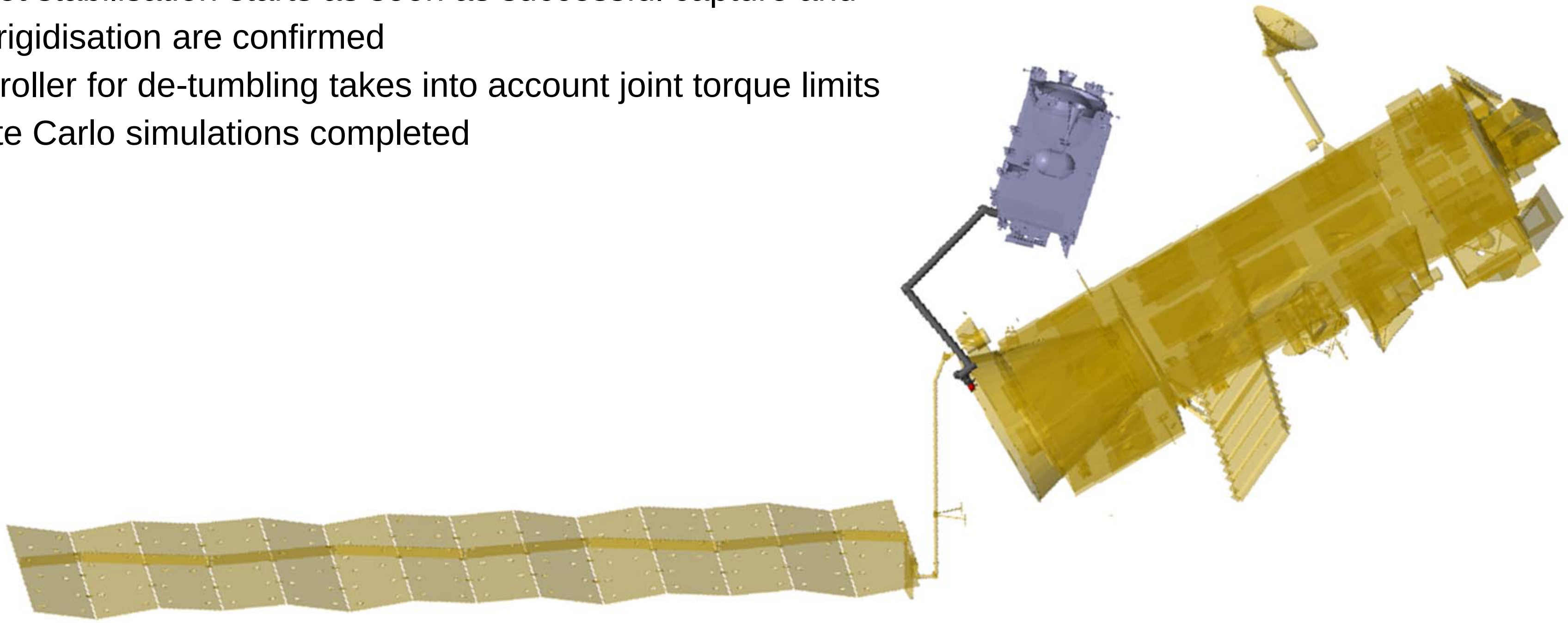
- Relative position control accuracy < 5 cm
- Relative velocity control accuracy < 5 mm/s
- Relative attitude control accuracy < 1°
- Relative angular rate control accuracy < 0.5°/s

Robotic arm performance (without visual servoing)

- Gripper positioning error < 5 mm
- Gripper orientation error < 0.5°

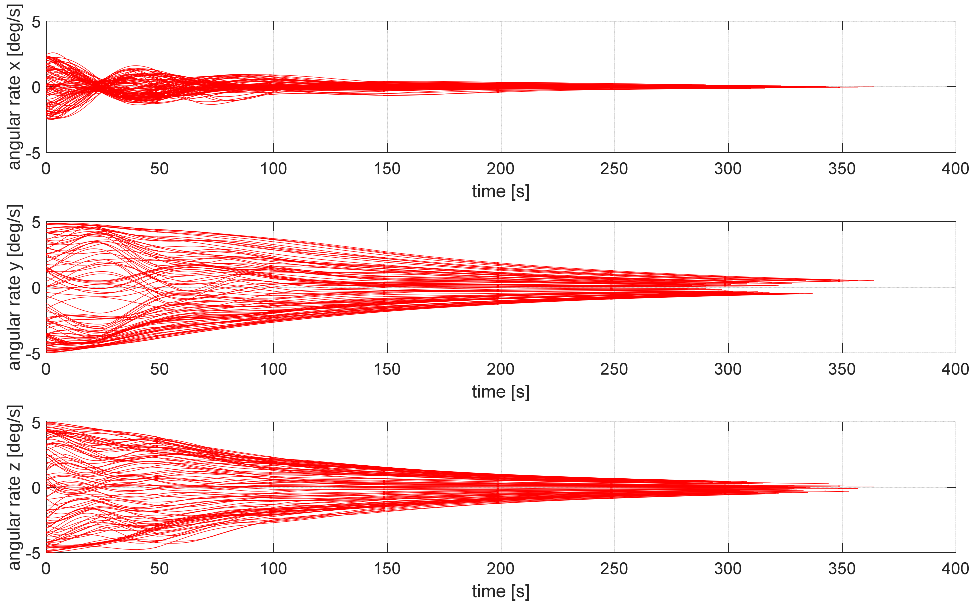
Coupled Control: Target Stabilisation

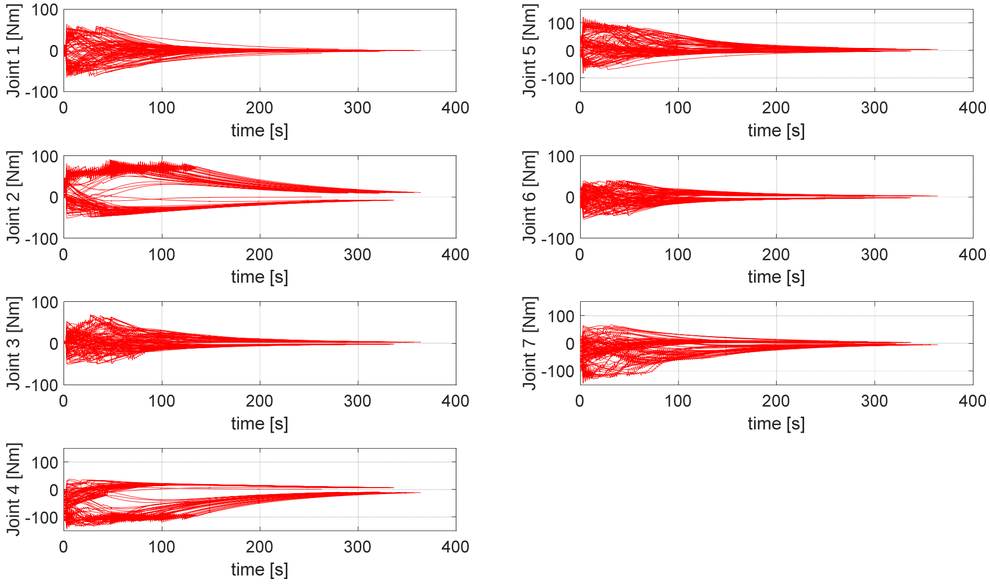
- Target stabilisation starts as soon as successful capture and arm rigidisation are confirmed
- Controller for de-tumbling takes into account joint torque limits
- Monte Carlo simulations completed



Coupled Control: Target Stabilisation

MC simulation results for target rotational scenario with 5°/s around random axis, limited to 30° w.r.t. target y/z plane





Coupled Control: Target Stabilisation

Nominal joint torque limit: 176 Nm, i.e. operational joint torque limit: **88 Nm** + 100% margin

Main simulation results

- Maximal joint torque due to free tumbling motion at 5°/s: 150 Nm
- Maximal joint torque during target stabilisation: 150 Nm (not higher than free motion!)
- Maximal angular rate for 88 Nm joint torque: 3.8°/s (Envisat is currently tumbling at less than 3.5°/s)
- Worst case duration until joint torques remain below 88 Nm: 150 s

Conclusions and way forward

- Current margin on joint torques is below 20% for 5°/s
  - Note: 5°/s is 43% above currently estimated angular rate
  - Centrifugal forces and rotational energy scale with ω^2

    ➔ 5°/s instead of 3.5°/s means factor 2 in consumption for motion synchronisation and stabilisation
- Options to increase the margin for 5°/s design case
  - Support tumbling motion by Chaser GNC (compensation of centrifugal forces)
    - Feed Forward term could be sufficient
    - Drawback: Large torques in Chaser contingency case
  - Increase joint torque limit
    - Option 1: Delta qualification for current design
    - Option 2: Design modification (joint with 372 Nm nominal torque limit is available)