Innovative Visual Navigation Solutions for ESA's Lunar Lander Mission

Dr. E. Zaunick, D. Fischer, Dr. I. Ahrns, G. Orlando, B. Polle, E. Kervendal

9th International Planetary Probe Workshop, Toulouse, June 21th , 2012

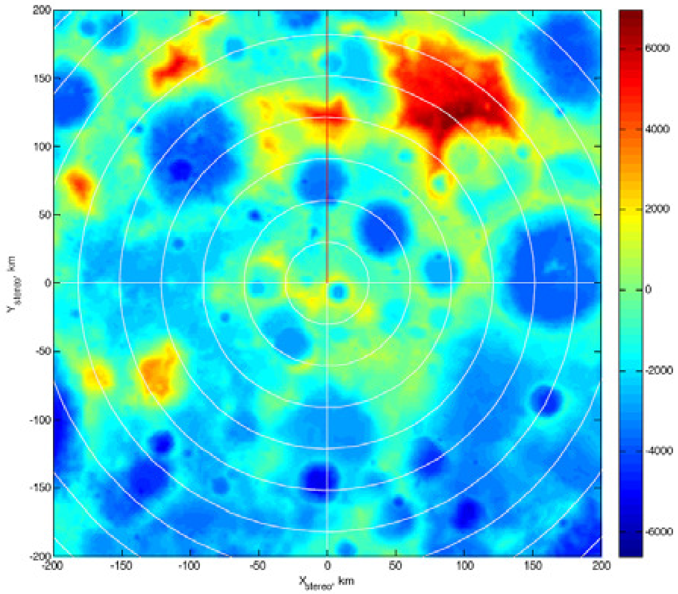
Outline

- Mission Overview
  - Mission Scenario
  - Navigation Requirements
  - Vehicle
- Navigation Overview
- Visual Navigation
  - Feature Point Matching
  - Feature Point Tracking
- Navigation Performance (Open Loop)
- Summary

Mission Overview

Landing Site:

- Lunar South pole region
  - Unique spot to find water-ice (might shelter clues of Earth and solar system)
  - Permanently, illuminated areas ➔ allows continuous operations
- Challenging, since:
  - Chaotic region, made up of many craters, ridges and shadows ➔ only limited area is favourable to autonomous landing in permanently illuminated areas



Mission Overview

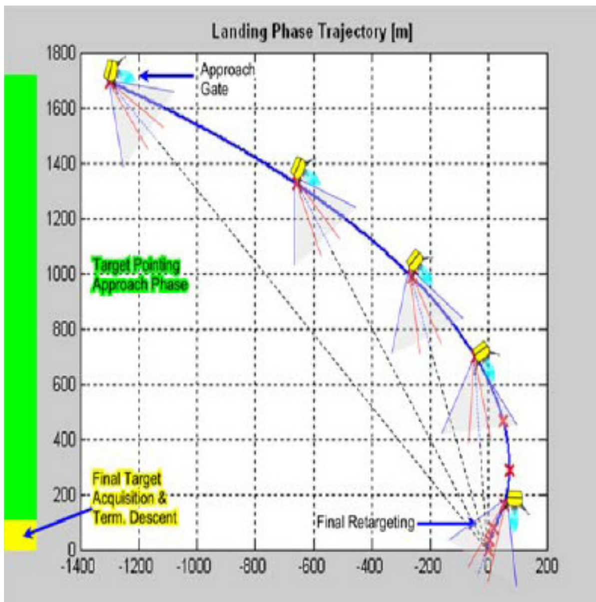
Navigation Requirements at Touch Down

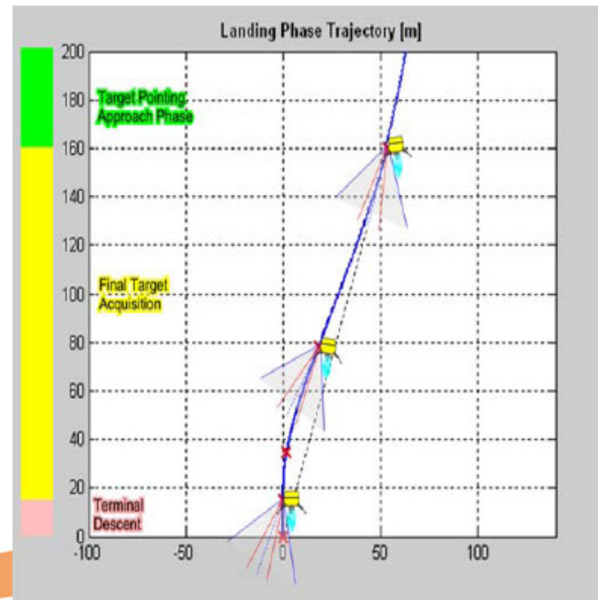
- Soft landing
  - Attitude angles: < 2 deg
  - Velocity: < 1 m/s
- Safe landing
  - Landing site slope: < 12 deg
  - Landing site roughness: < 0.5 m
  - Permanent illumination
- Precision landing
  - Position uncertainty: < 200 m (3 sigma)

Mission Overview

Trajectory:

- Descent Orbit (Hohmann transfer from 100 km to 12 km)
- Braking Phase (powered descent from 12 km to 1.7 km)
- Landing Phase (1.7 km to TD, about 500 sec):
  - HDA including two retargeting manoeuvres
  - Target pointing

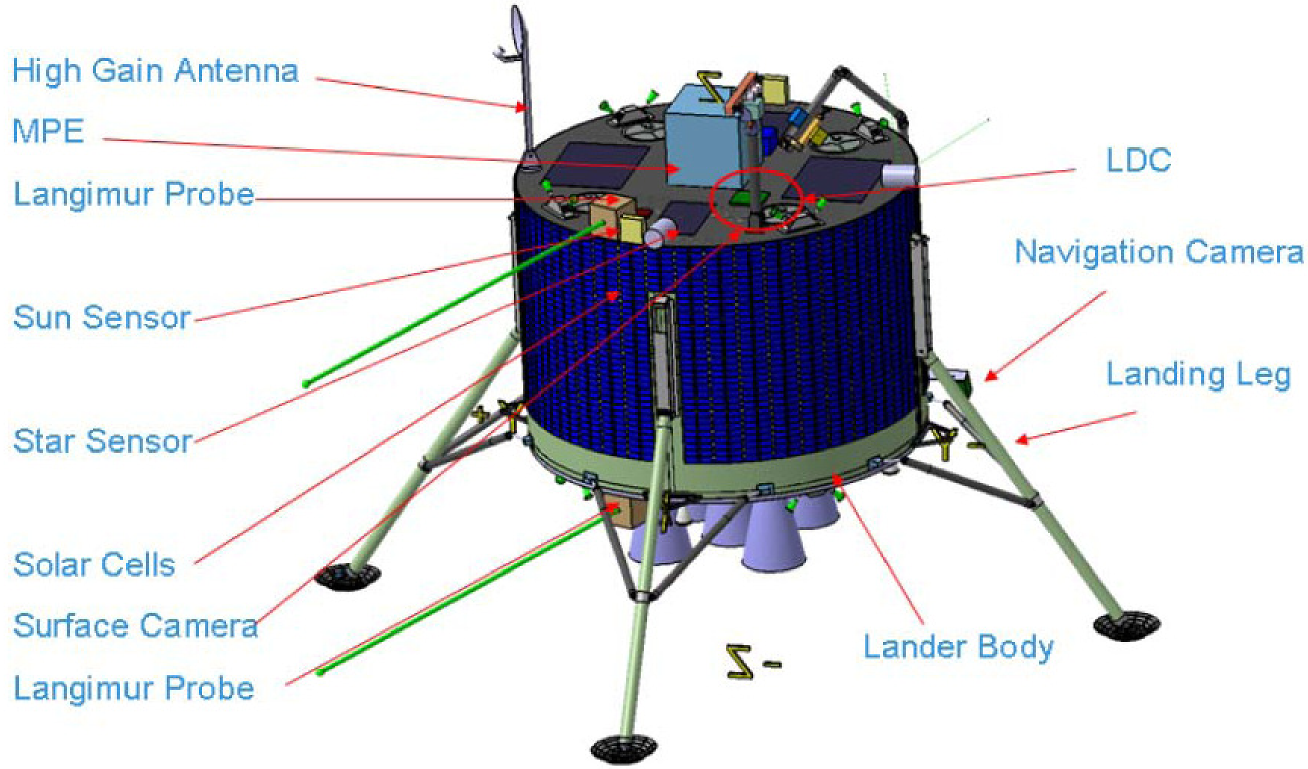




Mission Overview

Vehicle:

- Design: legged lunar lander

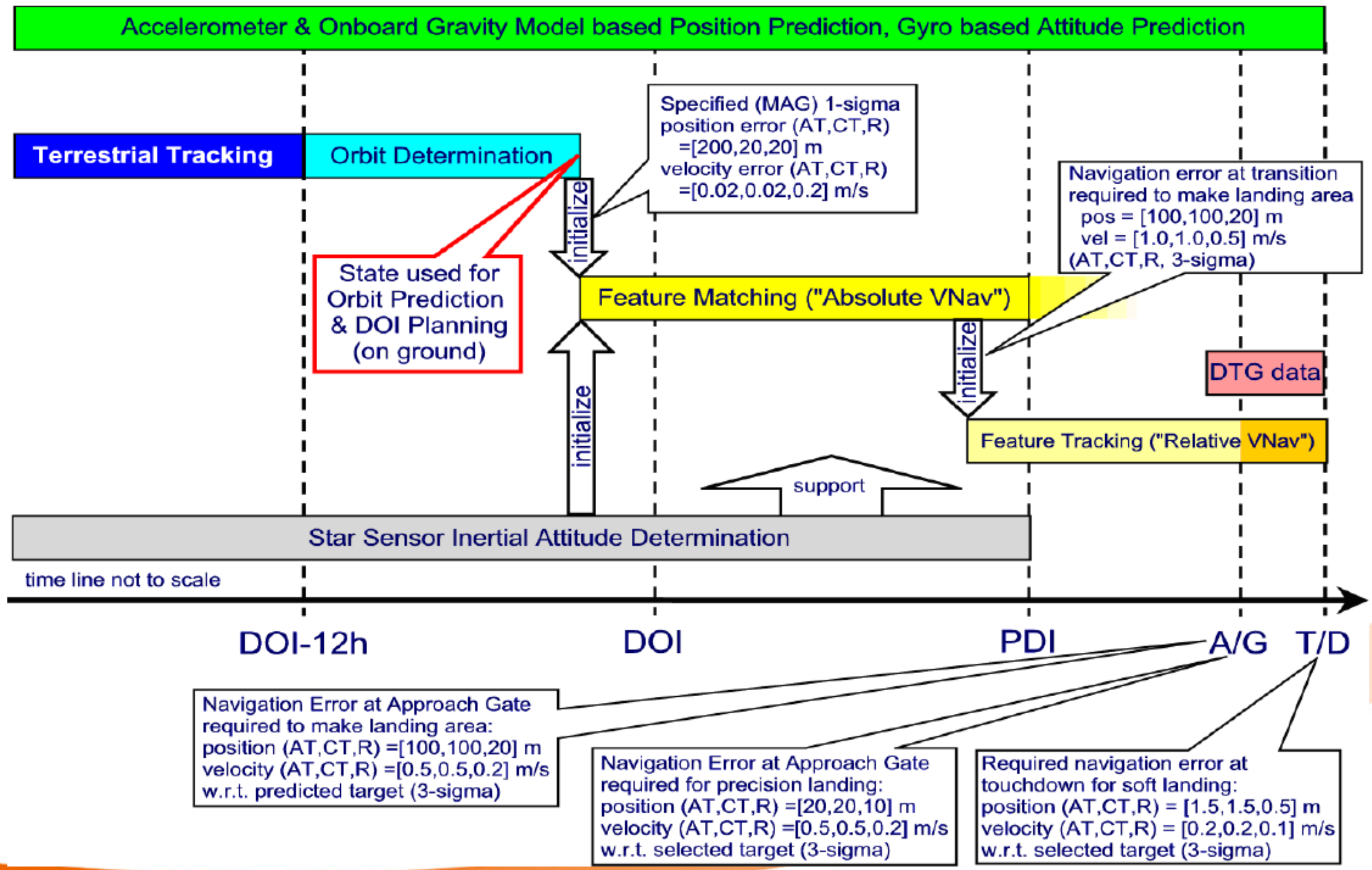


Navigation Overview

Sensor Suite:

- Navigation camera (NPAL camera) used for:
  - Feature matching
  - Feature tracking
- IMU
- Star tracker
- Distance to ground sensor (DTG)
- Navigation is filter used for sensor fusion and state estimation, e. g.
  - position, velocity, attitude
  - IMU accelerometer bias

Navigation Overview



Feature Point Matching

Introduction:

- During the last half elliptical orbit from DOI (descent orbit initiation) down to the braking phase PD (powered descent) precise navigation is required to achieve the accuracy at the landing in the range of 200m (3σ accuracy).
- Approach:
  - Use available digital elevation map data (from LRO and Kaguya) of the lunar surface to extract visual features (landmarks) and their corresponding 3D coordinates in PCPF.
  - Apply image processing to extract visual features from camera images
  - Perform matching of visual features to solve for the correspondence between camera features and features
  - Matched features are used to feed the navigation filter
- Challenge
  - Feature matching has to be precise and robust under all illumination conditions scheduled for the mission phase
  - Available map data only shows limited number of illumination conditions
- Main Idea to achieve Robustness and Illumination Independence:
  - Generate reference database of visual features from virtual images that reflect the scheduled illumination conditions.

Feature Point Matching

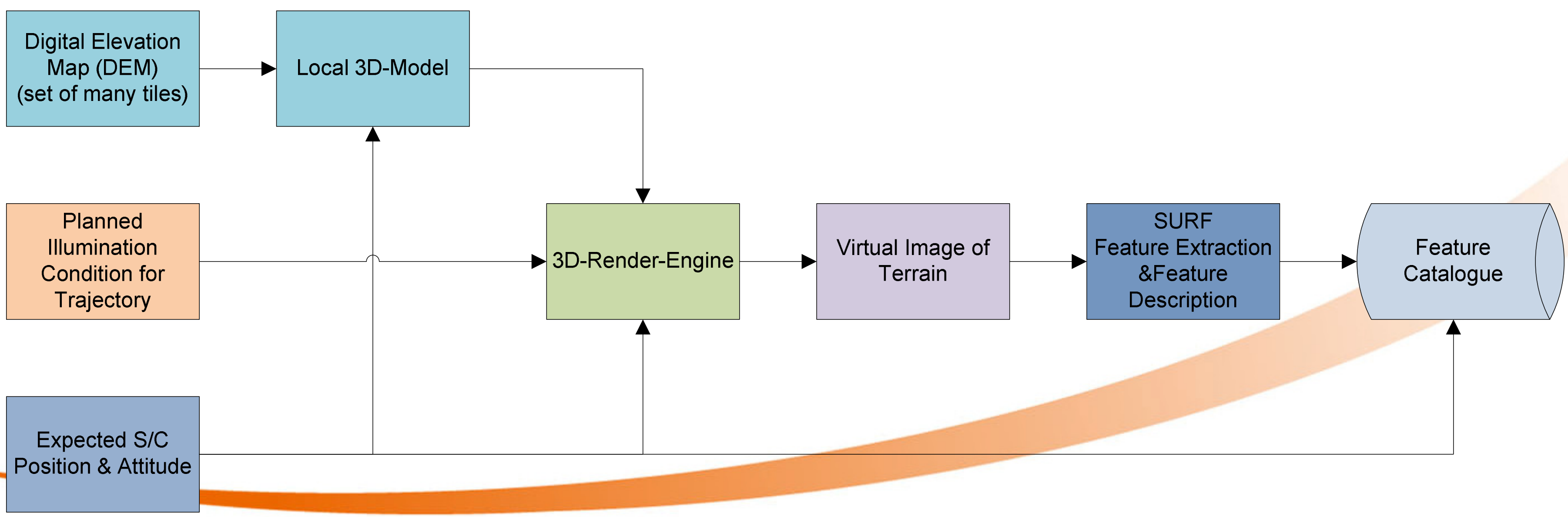
Separation of the approach into two different stages:

- Offline-Processing:
  - Preparation of available map data (interpolating gaps, noise reduction, etc.)
  - Rendering of virtual camera images reflecting the expected views during scheduled mission time
  - Extraction of visual features and storage in reference database
- Online-Processing:
  - Feature Detection
  - Feature Description
  - Feature Matching
  - Pose Estimation of Filtering

Feature Point Matching

Offline-Stage

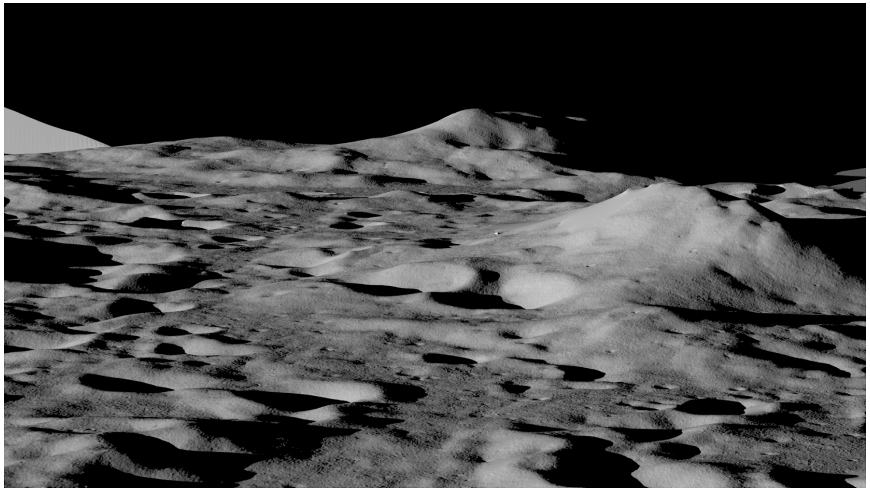
- DEMs from Kaguya and LRO (for polar regions) are taken as lunar surface model
- Scheduled illumination and camera position and local terrain model are fed into a ray-tracing tool.
- Virtual image is fed into feature detector and feature descriptor (U-SURF)
- Visual features and their 3D-location in PCPF is stored in feature catalogue
- Feature catalogue is stored on board.



Feature Point Matching

Comparison btw. Real and Virtual Images

- Virtual Image Approach shows good accordance



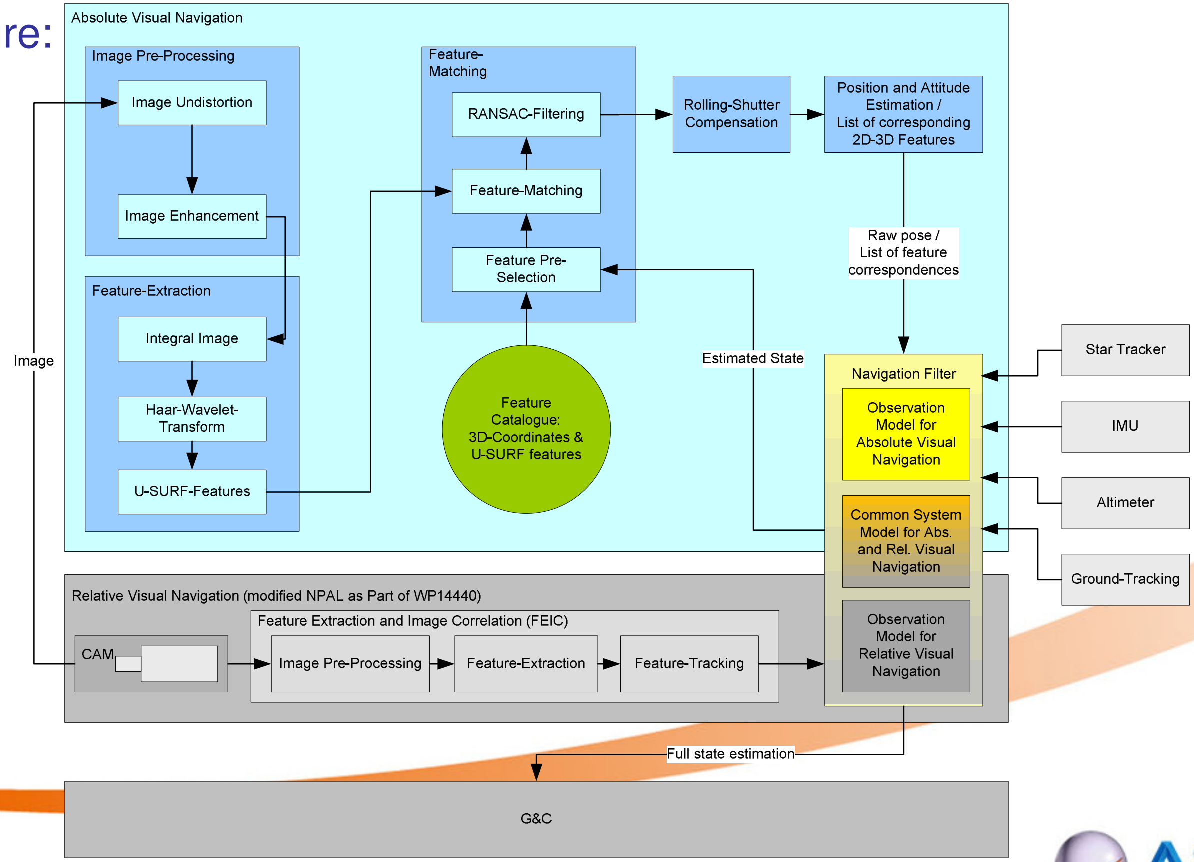
Virtual Image

Kaguya's image of HDTV camera

Feature Point Matching

On-Board Stage

- Feature Detection and Feature Description based on upright version of the SURF detectore (speed-up robust features).
- Matching is performed on nearest neighbor matching based on Euclidean distances between 64-dimensional SURF features
- Architecture:



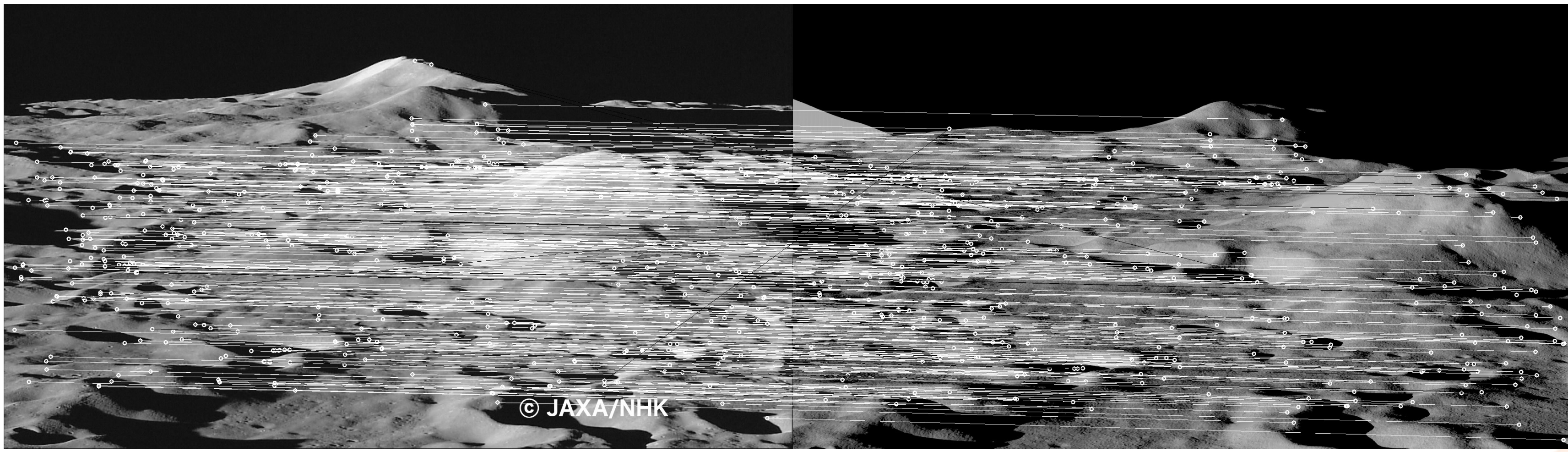
All the space you need

ASTRIUM
AN EADS COMPANY

Feature Point Matching

Evaluation of On-Board-Processing

- Image Processing based on U-SURF operator for feature matching between features of real camera images and features stored in database

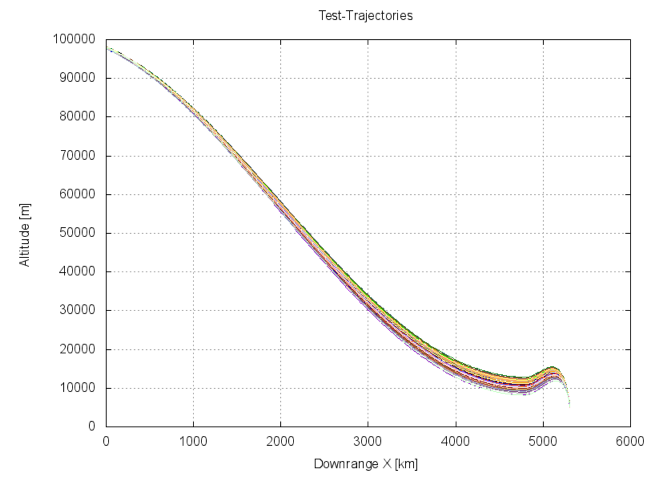


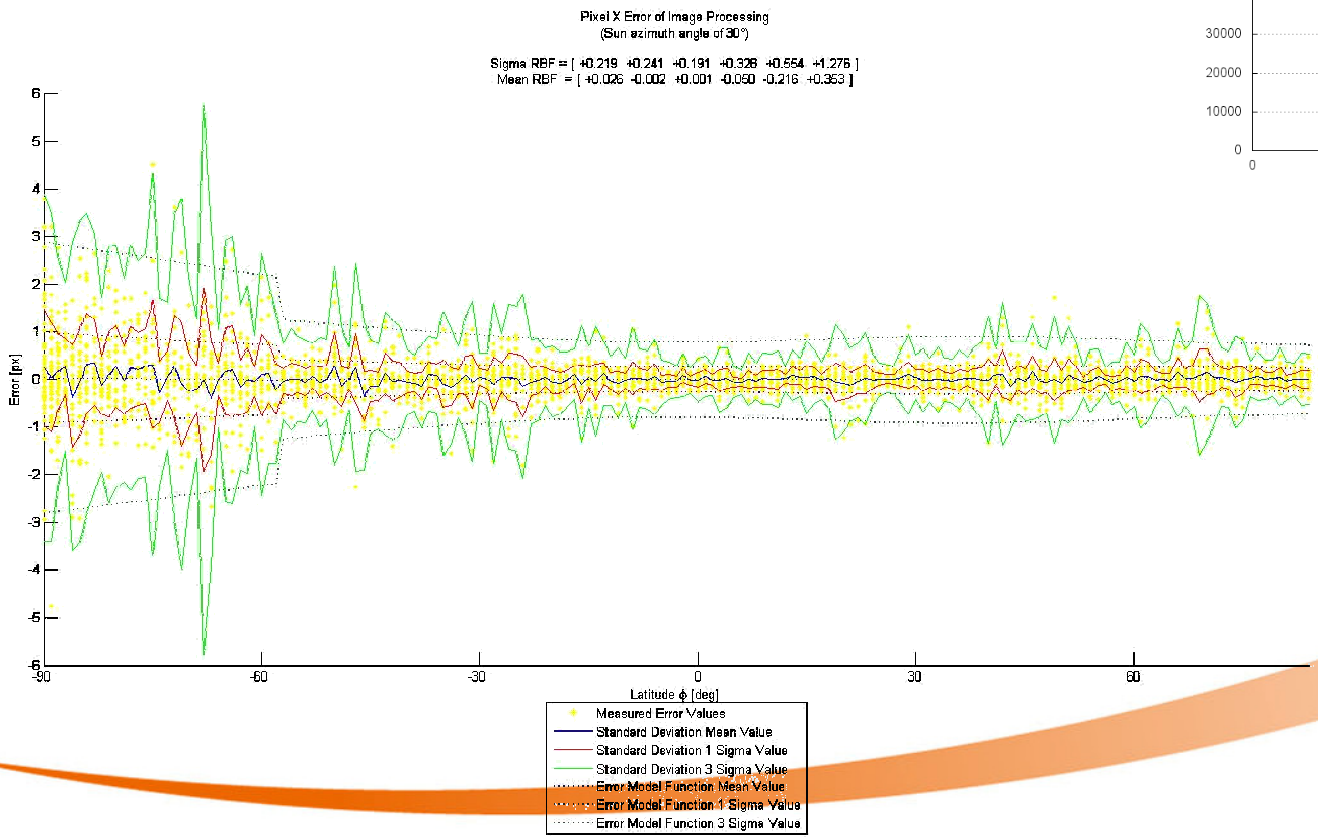
- Tests have been performed on virtual image sequences for full coasting arcs
- Virtual images have been computed from Kaguya and LRO DEMs
- A total number of 57 trajectories has been analyzed with different start conditions
- An error model has been derived from statistical analysis of these results

Feature Point Matching

Error Model

- Large set of test trajectories
- Error model for the image processing of corresponding feature sets.

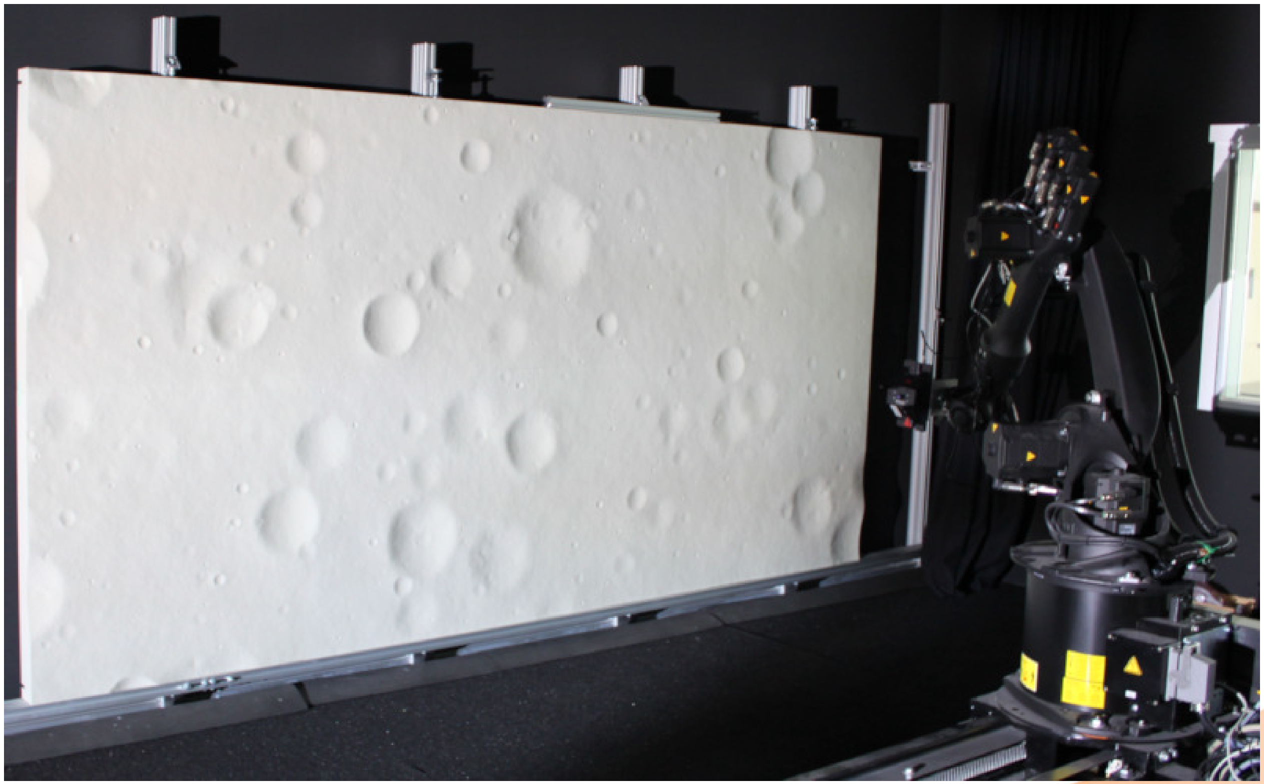




Feature Point Matching

Next Steps

- Evaluations in Robotic Test Facility TRON (part of institute DLR RY)



- Breadboarding of the proposed approach using a FPGA hardware architecture

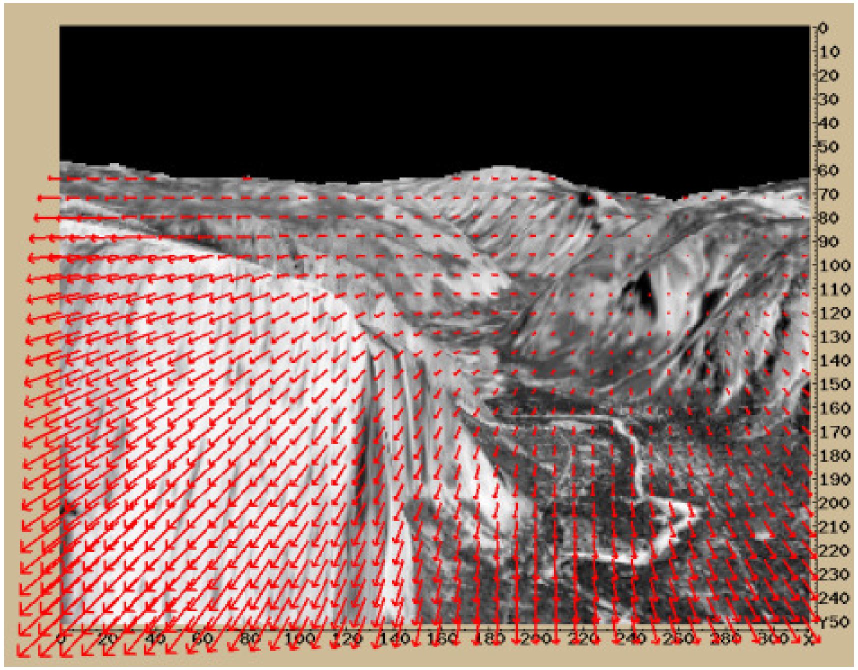
Feature Point Tracking

Introduction:

- As the spacecraft moves towards the ground, map errors become significant and feature point matching is no longer reasonable. It is required to apply a visual navigation approach which does not depend on the terrain.
- Approach:
  - Use successively acquired images to match feature points between these two images.
  - Displacement of feature points (Optical Flow) gives a conclusion of the s/c translational and rotational motion and of the terrain.
  - Apply evaluation of optical flow in order to extract information about s/c motion ➔ translation direction.
  - Translation direction is used to feed the navigation filter.
- Challenge
  - Terrain ambiguity.
- Main Idea to achieve Terrain independency:
  - Remove rotational influence from optical flow field ➔ focus of expansion directly gives the translation direction, which can be derived from the state vector.

Feature Point Tracking

- Yosemite sequence:



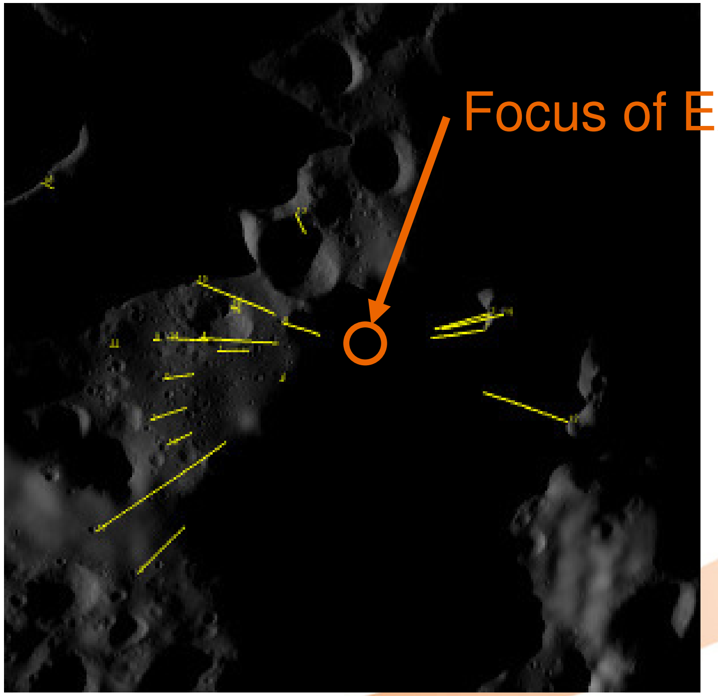
- Optical flow ego-motion equation:

$$\mathrm{d}\boldsymbol{u}(\boldsymbol{x}) = \boldsymbol{A}(\boldsymbol{x})\,\mathrm{d}\boldsymbol{\Psi} + \frac{1}{\rho}\boldsymbol{B}(\boldsymbol{x})\,\mathrm{d}\boldsymbol{p}$$

  - $\mathrm{d}\boldsymbol{u}$ … optical flow vector field
  - $\mathrm{d}\boldsymbol{p}$ … translational motion
  - $\mathrm{d}\boldsymbol{\Psi}$ … rotational motion
  - ρ … scene depth
  - $\boldsymbol{A}, \boldsymbol{B}$ … Projection function
  - $\boldsymbol{x}$ … Image coordinates
- Idea:
  - Extract a measurement, which is independent of the (unknown) terrain
  - Estimation of translation direction via Focus of Expansion (FoE) ➔ only applicable when no rotation is present
- Approach:
  - Remove effect caused by rotational motion ➔ IMU
  - Still ambiguity between translational motion and scene depth ➔ estimate FoE

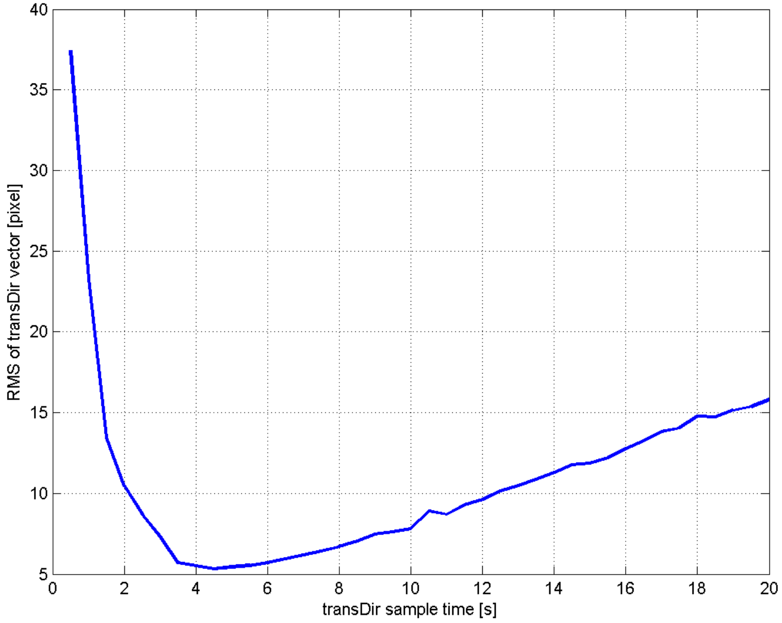
Feature Point Tracking

- Computation of translation direction
  - All optical flow vectors intersect in one point ➔ Focus of Expansion
  - Applying a least squares optimisation to estimate the intersection point
- Result: Translation Direction vecotor w.r.t. the camera frame
- Input to the navigation filter ➔ depending on particular motion, it helps to let the filter converge

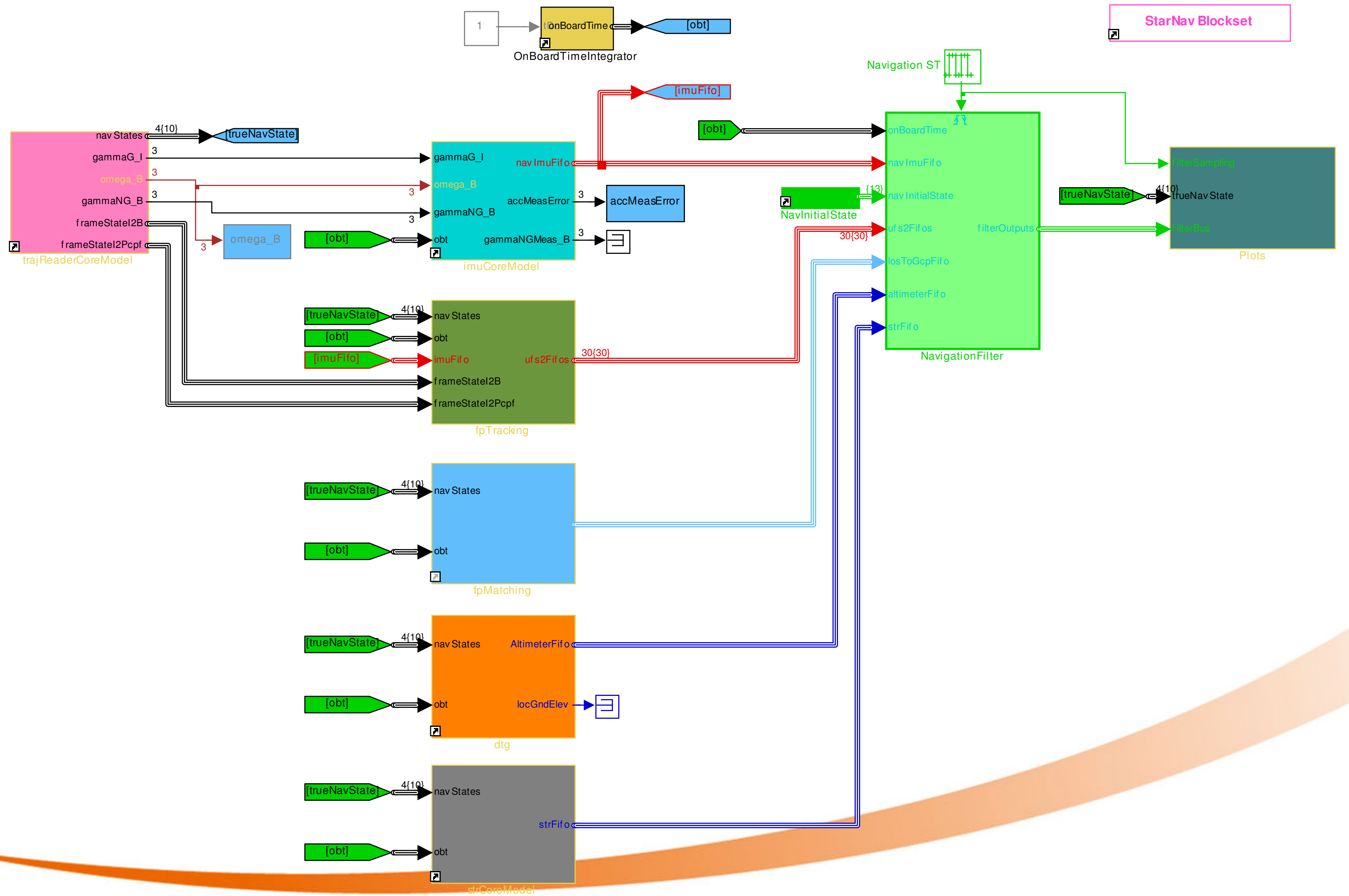


Sample Rate of Trans. Dir. Measurements

- In case of small optical flow vectors ➔ noise becomes significant and translation direction measurement unreliable
- Key frame selection to improve robustness:
  - Not every image is used
  - Significant change of image content is needed
  - Frame selection depending on current motion and scene depth ➔ dynamic key frame selection
  - States of both images are “latched” in order to be applicable in the navigation filter

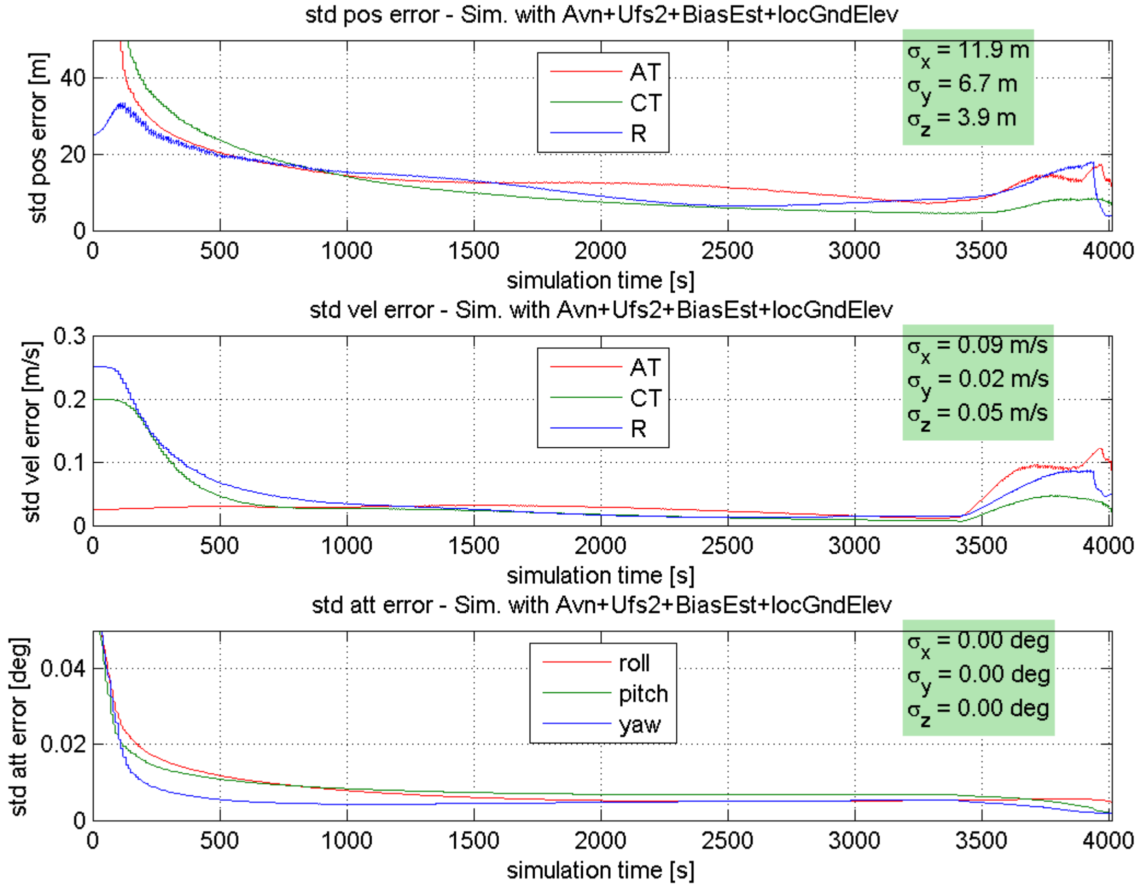


Navigation Performance



Navigation Performance

- Current navigation performance from DOI to TD
- Setup: FP matching + tracking, DTG (radar altimeter), STR, bias estimation



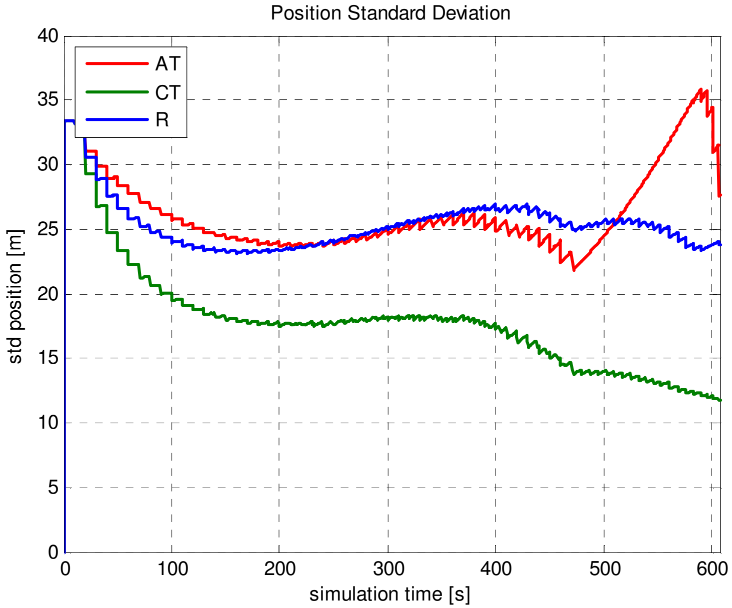
→ Std. position error

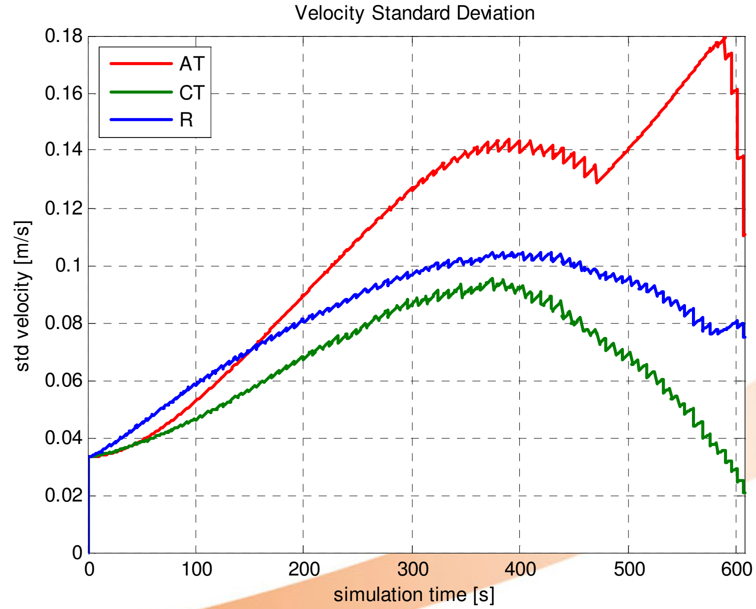
→ Std. velocity error

→ Std. attitude error

Navigation Performance

- Braking and landing phase **w/o distance to ground sensor ➔** end phase: IMU + Translation Direction
  - Along track component is not observable from t=470s.
  - When the s/c moves and rotates towards the ground at t=580s along track component becomes observable.





Summary

- Overview of ESA's Lunar Lander Mission
- Navigation solution proposed by Astrium (Bremen, Toulouse, Friedrichshafen)
- Key technologies:
  - Feature Point Matching during descent orbit and partly braking phase
  - Feature Point Tracking during braking and landing phase
- Open loop performance ➔ stringent requirements are met

Thank you for your Attention