

The background of the slide is a deep blue space scene. In the upper left, a small Earth is visible. In the upper right, a bright sun or star is shining, creating a lens flare effect. At the bottom, a large, grey, cratered asteroid or moon surface is shown in the foreground. The text is overlaid on this scene.

Vision-based navigation for approach and landing on small bodies

Workshop on GNC for Small Body missions

14th / 15th January – ESTEC

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Astrium Satellites

Contents

1. Reference mission and environment

The Marco Polo mission

2. Far range guidance & navigation

Trade between ground involvement / autonomy

Optical navigation for interplanetary cruise

Vision-based GNC for Rendez-Vous

3. Vision-based navigation for landing on small bodies

Vision-based navigation for planetary landing

LiDAR-based navigation for landing and hazard mapping & avoidance

Optical solution for absolute navigation

4. Conclusions

1. Reference mission and environment

- Marco Polo : M-class candidate mission for Cosmic Vision 2015-2025.
- Objective : NEO sample return
 - Far range (~500,000 km) NEO detection and tracking
 - Landing operations
 - Earth return
- Major specificity with respect to classical planetary landing : very low gravity environment, low relative velocity.



2. Far range guidance & navigation

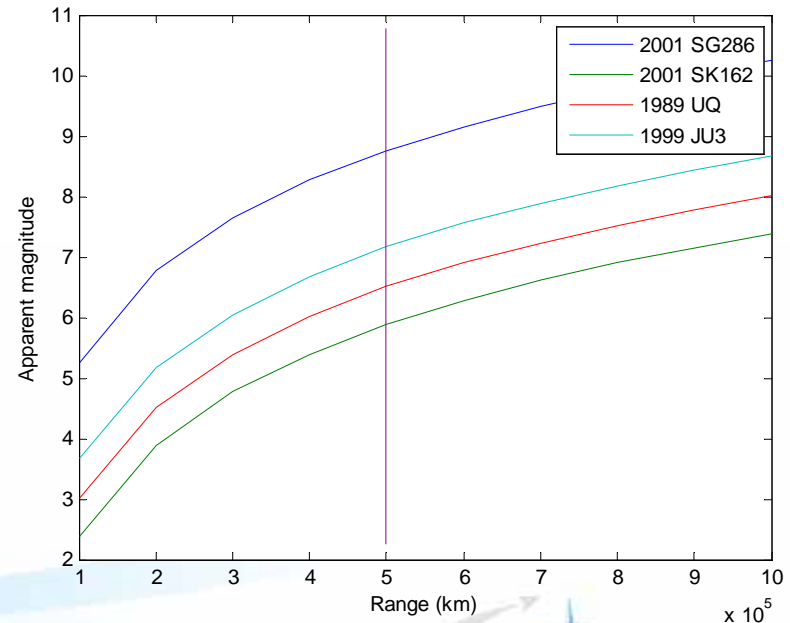
- R-SS.ACS-4: The spacecraft navigation system shall be able to acquire the target from 500 000 km distance.
- Initial uncertainty on NEO localisation is a few hundreds of km, radius of NEO sphere of influence < 20 km.



Vision-based navigation is required at some point.

- Active techniques (LIDAR) are prohibited due to the long range. A camera is required.

- Detection magnitude is a key parameter : not an issue for the candidate targets.



2. Far range guidance & navigation

- Main trade for far range guidance & navigation : time when autonomous closed-loop guidance & navigation takes control over ground.
- The major driver comes from mission analysis. Depending on the relative velocity to the target (impact / landing mission), the time when autonomous navigation takes control over ground is more or less close to the encounter time.
- For Marco Polo the relative velocity is quickly reduced ($< 1\text{km/s}$ @ 500,000 km). Therefore the correction of transverse velocity is not an issue, and the time detection is not critical. Autonomous navigation can be engaged at closer range to relax navigation camera design constraints.

2. Far range guidance & navigation

- The needs for Marco Polo are therefore :
 - A vision-based autonomous navigation function to cover the last part of the interplanetary cruise towards the NEO (target detection and tracking).
 - A full optical GNC system for autonomous Rendez-vous (functionally the last part of the cruise trajectory is a Rendez-vous : the objective is to insert the spacecraft at a given position with a given velocity to initiate the orbiting phase).
- Astrium has developed two solutions for each of these needs :
 - Autonomous On-Board Navigation for Interplanetary Missions (AutoNav)
 - Integrated Multi-Range Rendez-vous Control System & Autonomous Rendez-vous and Capture GNC Test Facility (HARVD)

2. Autonomous On-Board Navigation for Planetary Missions (AutoNav)

- ESA Technological Research Program, led by Astrium since 2001 to 2005.
- Develop and mature a complete solution for the navigation of interplanetary vehicles (ObNav):
 - Navigation on asteroids in cruise
 - Navigation with extended bodies in approach
 - Multi-purpose solution (at hardware and software levels)
- Validate through a complete sequence of tests on simulated, real, ground and flight images (Earth telescope, AMIE camera on-board SMART1). Reference missions : Rosetta and SMART1.
- Design the optimised dedicated camera.



**Asteroid Expertise
astronomy**



**Navigation Filters
Guidance**



Image Processing



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2. Autonomous On-Board Navigation for Planetary Missions (AutoNav)

- Image processing software includes several modules to cope multiple observation conditions.
 - MTI (Multiple Time Integration) for accurate LOS measurement of faint asteroids with background stars.
 - Multiple frame observation mode to enable measurement of bright objects with faint background stars.
 - Extended object measurement mode to enable Center Of Mass and Center Of Brightness measurement in the last part of the encounter trajectory.
 - Limb measurement mode to enable navigation in the very last part of the encounter trajectory (when the target is larger than the FOV).

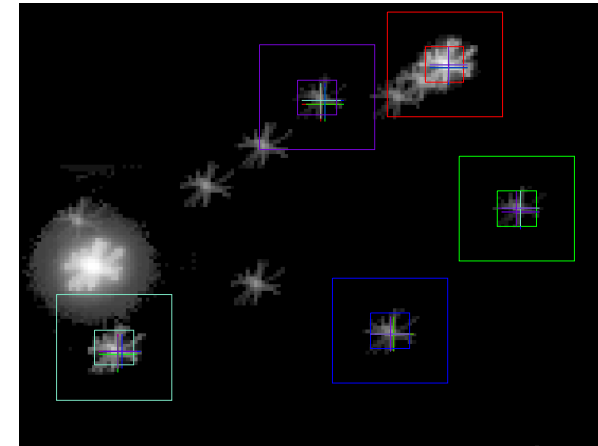
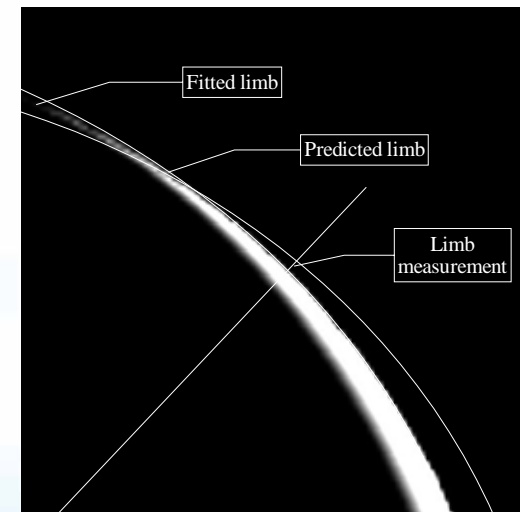


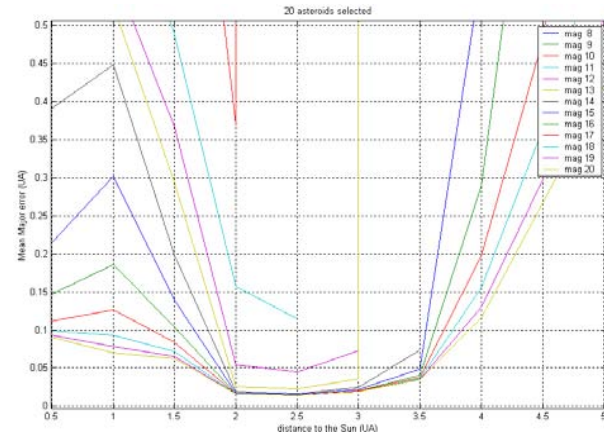
Image processing for faint object detection and subpixel restitution



2. Autonomous On-Board Navigation for Planetary Missions (AutoNav)

- Performances are validated with three levels of representativity:
 - Simplified camera model
 - Representative camera model with synthetic images.
 - Real images from ground or space missions.

- Expected performances demonstrated.



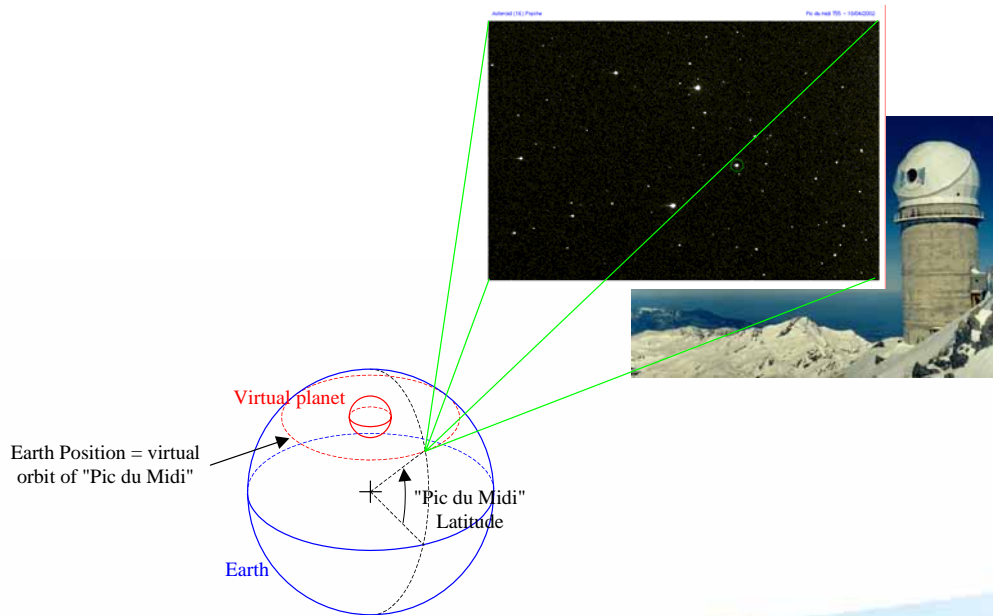
Statistical analysis on asteroid databases

Mission Phase	Expected Accuracy
Cruise	<500km between 1 and 3.5 AU
Encounter with asteroid	< 1 km 3 hours before encounter.
Encounter with planet	<[5-10] km 3 hrs before encounter
Navigation in orbiting electrical transfer	<40km



2. Autonomous On-Board Navigation for Planetary Missions (AutoNav)

- Validation has been performed using Asteroid images from “pic-du-midi” Observatory (reconstruction of “pic-du-midi” trajectory), and Earth and Moon images from AMIE camera on-board SMART1. Performances proved good (500 km position accuracy) and coherent with the requirements.



2. Autonomous On-Board Navigation for Planetary Missions (AutoNav)

- In the frame of the AURORA missions, optical navigation is now a valuable alternative to classical radiometric navigation, providing autonomy and accuracy for:
 - cruise navigation (especially appropriate for low thrust navigation).
 - Planetary fly-by, aerocapture and aerobreaking.
 - planetary rendez-vous with passive targets.
- Validation with real images show very good performances.
- This technology is applicable for the target acquisition and tracking of Marco Polo.

2. Vision-based GNC for Rendez-vous (HARVD)

- The approach phase of Marco Polo is functionally similar to a Rendez-Vous, making the HARVD study of interest for Marco Polo.
- HARVD : ESA study (2006-2009) led by Astrium, still on-going.

- Develop an autonomous and generic vision-based GNC for rendez-vous with cooperative and non-cooperative targets (reference missions : MSR, Cone Express)



**Guidance, Control
and TMS**



Simulator and Guidance expert



**Object
recognition**



Scene generator



2. Vision-based GNC for Rendez-vous (HARVD)

- Navigation for non-resolved target
 - Based on LOS measurement
 - Valid throughout the mission
 - Target size in the FOV smaller than a few pixels
 - No image processing necessary for navigation
- Navigation for resolved target
 - Based on feature tracking
 - Valid at close ranges only
 - Target size larger than 10% of the FOV
 - Image processing
- Vision navigation => v/d ambiguity, solved using different solution depending on the mission phase.
- Next step : real-time demonstrator, dynamic demonstrator (robotic bench)

3. Vision-based navigation for landing

- Mission requirements define landing requirements relatively to the terrain (horizontal and vertical velocity, attitude with respect to the ground, position with respect to hazards)
- Communication time is too long to control the last part of the descent from ground.



An autonomous navigation function relative to the terrain is required. Vision-based solutions are natural candidates.

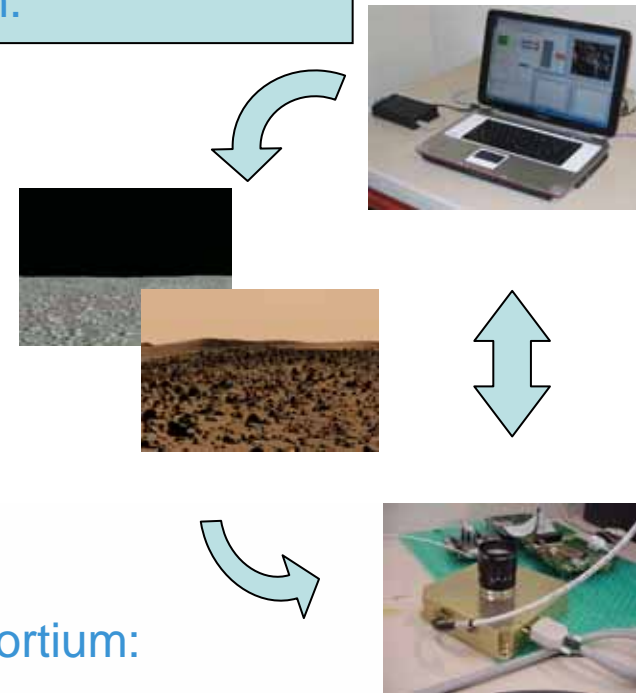
- Vision is an « intuitive » solution to support a safe landing in an unknown environment:
 - Automatic detection of obstacles and hazards, trigger avoidance manoeuvres,
 - Natural motion estimation, by tracking « visual clues » on successive images.

3. Vision-based navigation for landing

- Major questions for vision-based navigation :
 - Is the vehicle state completely observable ?
 - Is the image processing feasible in real time ?
 - Validation strategy is a major issue.
- Different needs are identified for Marco Polo :
 - Guidance need : the GNC system shall ensure that the lander will reach the selected landing site. An absolute navigation capacity is required for that purpose.
 - Navigation & Control need : the final relative state of the lander is fully specified in the requirements. Relative navigation to the terrain will allow meeting these requirements.
- Astrium has studied different solutions to cover these needs :
 - Vision-based (camera, LIDAR) relative navigation functions,
 - Optical flow based navigation function for absolute navigation.

3. Navigation for Planetary Approach and Landing (NPAL)

- ESA-Science Critical Technology Program (2001-2006).
- Full state reconstruction based on vision / IMU hybridisation with tracking of unknown features, under high acceleration.
- Design of key technology components:
 - A smart « image compressor » for extracting observables from image flow : the FEIC.
 - A compact, high resolution large FoV camera for landers : the VBNC.
 - A validation test bench based on virtual scenes : the VBNAT.
 - A navigation system for real time implementation on-board processing.
- EADS Astrium prime contractor, with industrial consortium:



The NPAL camera



The FEIC FPGA PANGU



Image Processing



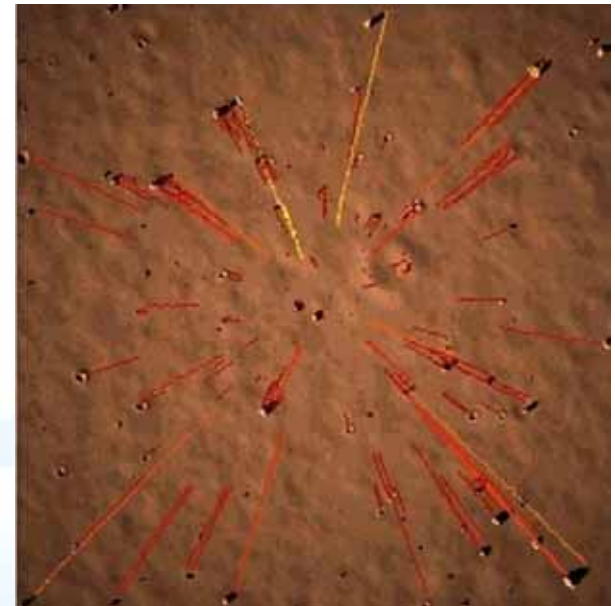
Simulation: the VBNAT



3. Navigation for Planetary Approach and Landing (NPAL)

- Principle : extract more than 200 “feature points” from a 70° FoV picture, and track them through a 10Hz frame rate.
 - The point distribution serves to optimise navigation observability and terrain reconstruction in candidate landing areas.
- Harris detector for features extraction, features correlation for optimising the track length and robustness to distortion.
- Hardware implementation : ***The Feature Extraction Integrated Circuit (FEIC)***

Frame Rate	10 Hz
Image size	1024 x 1024
Maximum rotation (2 successive frames)	8 deg
Maximum zooming (2 successive frames)	20 %
Noise : Minimum SNR	70



3. Navigation for Planetary Approach and Landing (NPAL)

- Camera design
 - Small, compact, rugged design
 - APS detectors with fast, snapshot capacity and large resolution
 - Low distortion optics, for a 70° Field of View
- “Elegant Breadboard” for laboratory tests

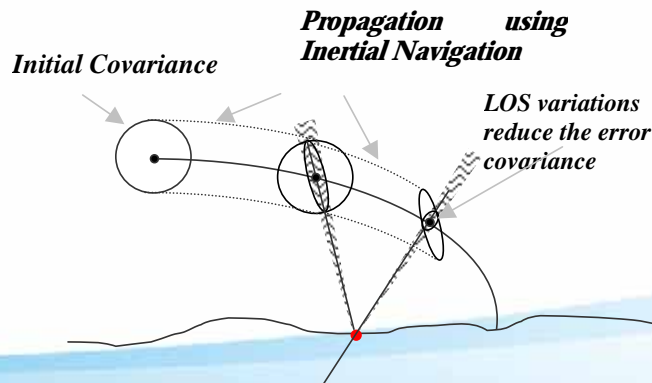
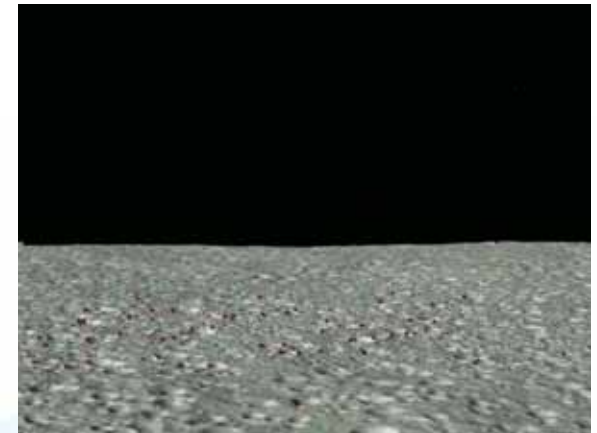
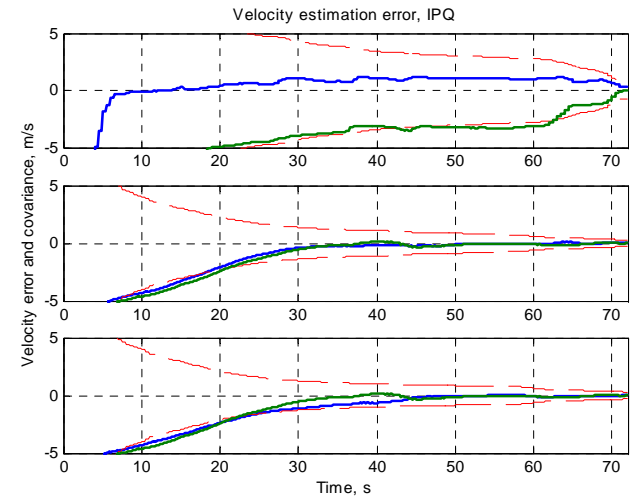
Camera Size	13 cm x 13 cm x 8 cm (baffle incl.)
Camera mass budget	500 grs
Camera Power	2 W
Communication link	SpaceWire 100 Mbit/sec
Memory capacity	Up to 200 FPs and textures for tracking



- Next Step : VisNav (multi-purpose navigation camera). Architecture study on-going under new ESA contract, EM in 2010.

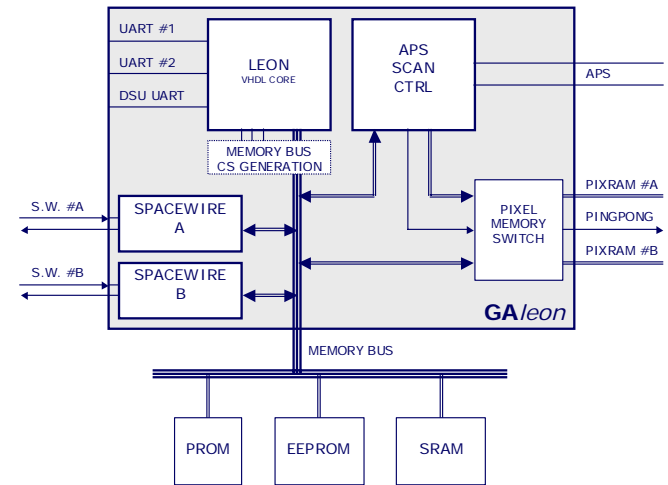
3. Navigation for Planetary Approach and Landing (NPAL)

- **Convergency demonstrated in stand-alone configuration**
 - For unknown terrains, a metric accuracy is demonstrated. Final velocity estimation error is a few 10 cm/s.
- **Validation with statistical runs on virtual scenes**
 - Pangu adapted for fast generation, high resolution, large scenes: 12 hierarchical levels, presence of boulders, accelerated rendering...



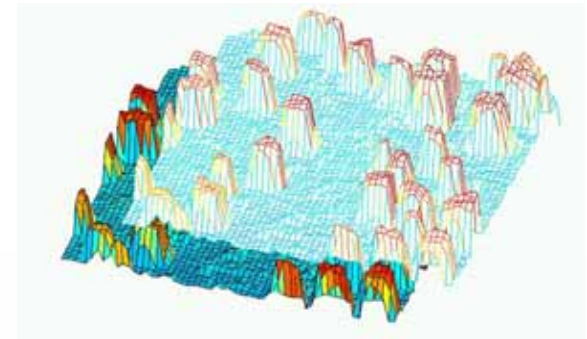
3. Navigation for Planetary Approach and Landing (NPAL)

- A dedicated real time architecture is designed to support the real time constraints:
 - APS detector for 10Hz, 1024x1024 images
 - LEON processor for camera control
 - The FEIC as a « smart compressor » for navigation observable production in line
 - Up to 200 points tracked, vignettes stored in memory
 - Two redunded SpaceWire communication links for OBC interface.
- Next step : flight experimentation on PLGTF (2009).



3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

- ESA – Aurora Program for planetary exploration (2003-2005).
 - Dedicated to the design and simulation of a complete GNC chain based on LIDAR for a safe landing on Mars and rendezvous in orbit, for supporting the MSR mission.
-
- Lidar-based GNC design for soft landers.
 - Lidar-based GNC design for rendezvous with non cooperative targets.
 - Lidar technology assessment.
 - Lidar behaviour modelling in the Mars environment.



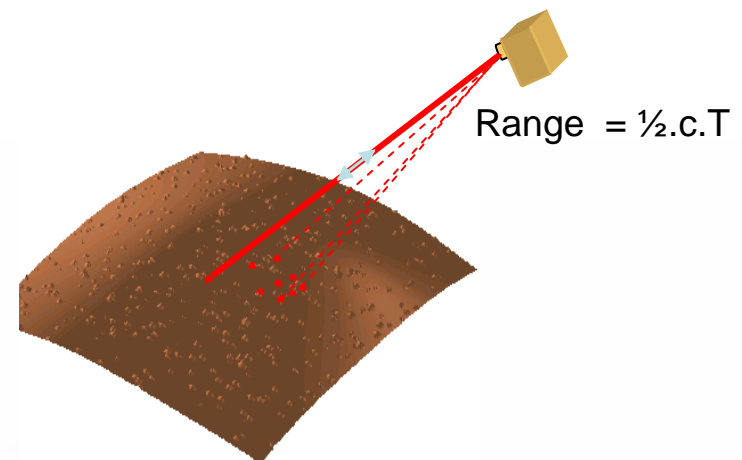
Solscientia Lda



3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

- A LIDAR is an active vision system
 - Laser pulses are emitted in predefined directions (mirrors)
 - Measure of laser Time of flight translates into a range measurement
 - Scan over 20deg x 20 deg to constitute a full 3-D map of the observed terrain
 - Typically 200 x 200 points 3D map at 1 Hz

- Advantages
 - robust to light conditions
 - cm accuracy range measurement
 - 3D maps with a single scan of the terrain
- Limitations
 - Complex sensor: emission & reception optics, scanning mirrors and mechanisms, accomodation (LOS direction close to nadir)
 - Mass and power budgets



3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

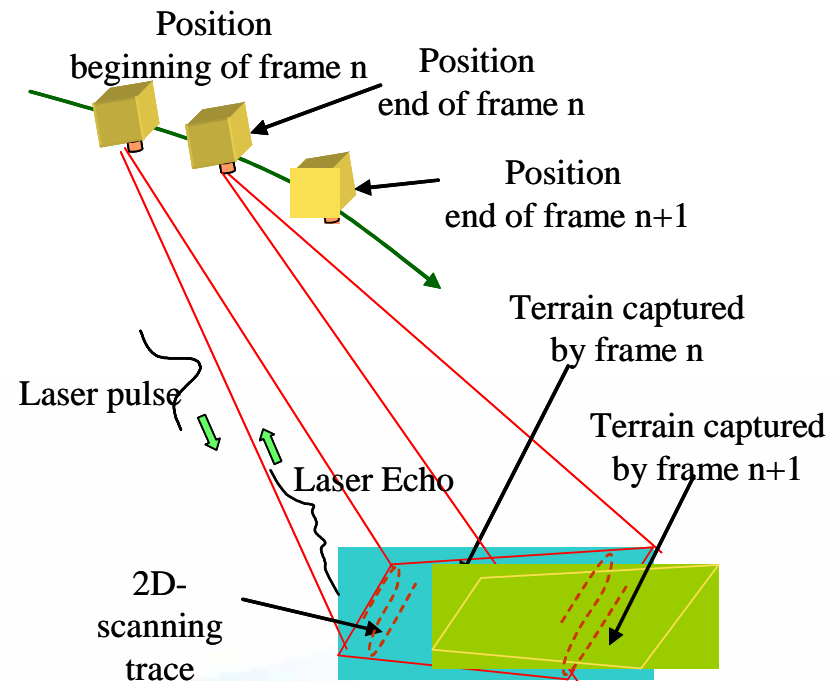
■ Lidar use

- Successive LIDAR maps are used for Navigation function (velocity vector estimation)
- LIDAR maps are used for Hazard detection and designation of a safe landing site.

■ Main challenges for the GN&C

- The motion of the spacecraft during the scan (1 second) introduces distortion in the image
- Successive terrain maps must be aligned

■ Calls for innovative solutions at navigation and image processing levels



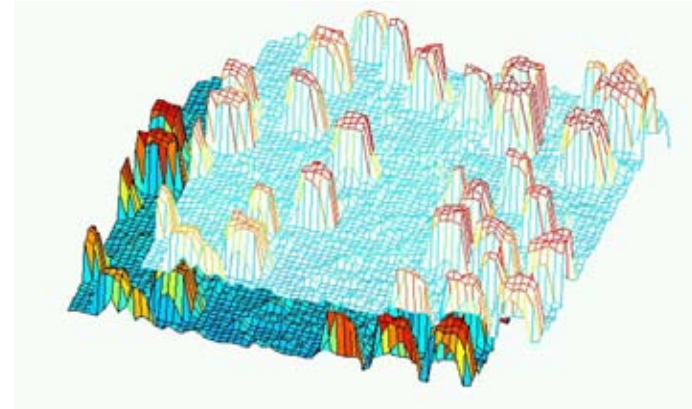
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3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

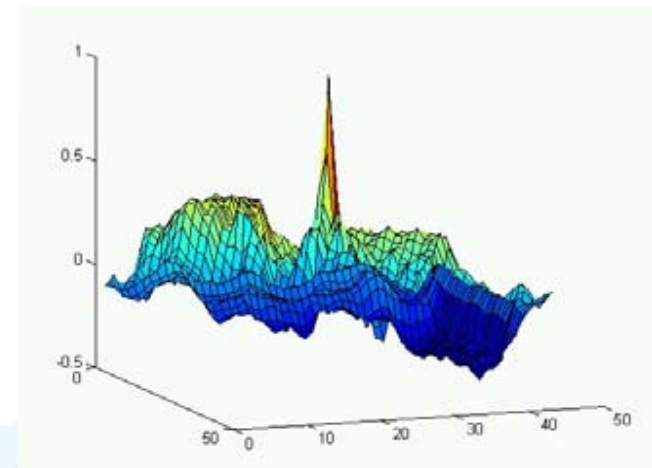
The image processing module estimates the motion between frames and perform the hazard mapping.

1. Use of the navigation aiding information to compensate the Lander motion and to generate accurate Elevation maps.
2. Resampling on a regular grid
3. Estimate motion (velocity) between successive images.
 - This information is provided to the navigation filter
4. Compute hazard maps
 - Roughness
 - Slope
5. Design a Landing site
 - Guidance information are provided to the LS designation module.

Alignment of successive 3D terrain maps



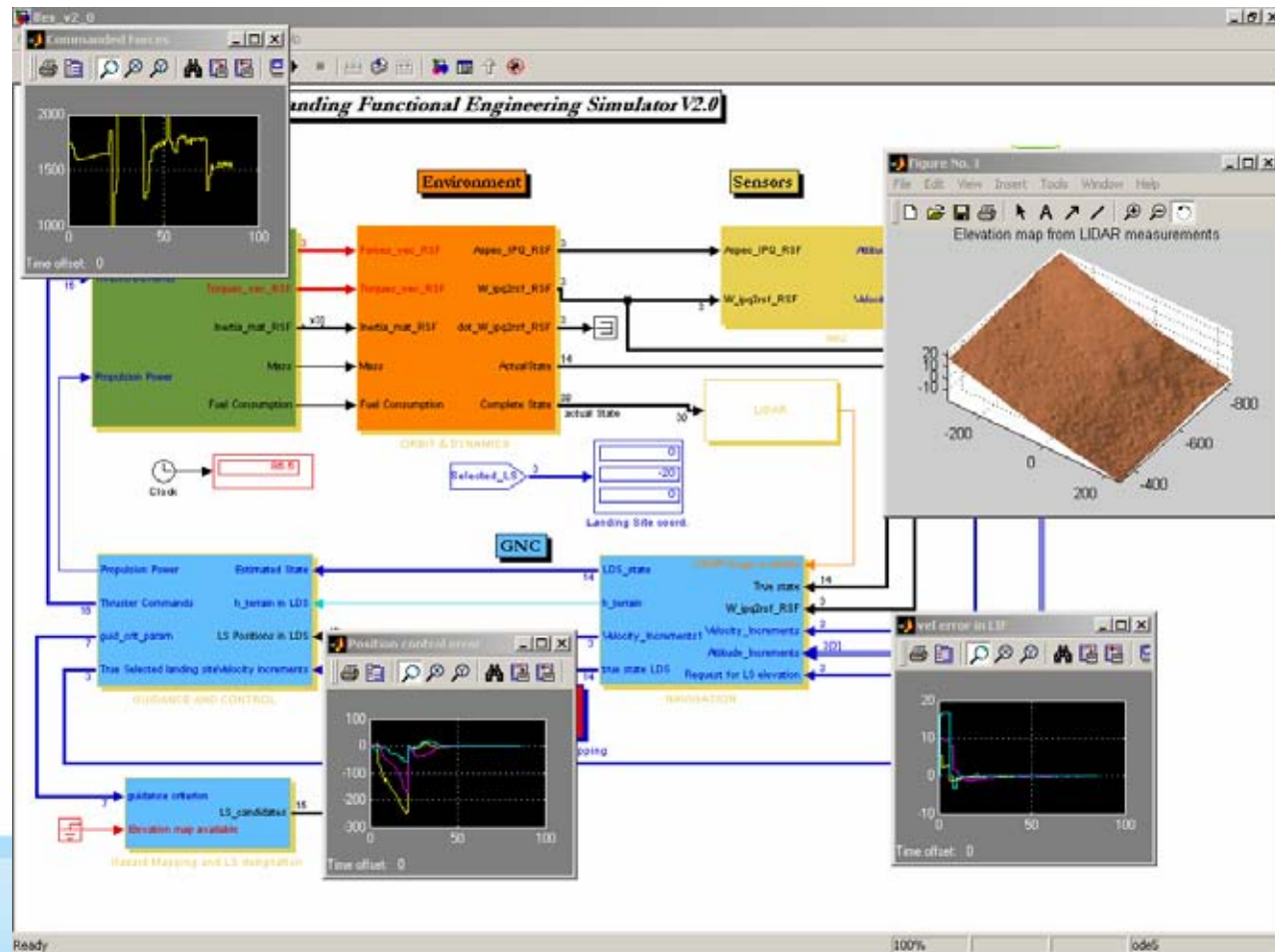
Correlation function for alignment



3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

- The LIDAR chain was completely modelled : The LBNAT
 - LIDAR image generation (PANGU)
 - LIDAR model
 - LIDAR image processing

- The LBNAT has proved to be able to undertake Monte-Carlo campaigns with hundreds of cases



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3. LIDAR-based GNC for Rendez-Vous & Landing (LiGNC)

- Landing GN&C design is very challenging:
 - About 1 minute to estimate vehicle states, designate a landing site, and control the vehicle in a large domain of dynamic conditions.
 - Technology limitations: LIDAR scan time (typ. 1 s) and propulsion on-off modulation frequency (10 Hz max).
- The proposed GNC design fulfills those challenges:
 - An innovative guidance law turned out to be very well adapted to retargetings : the Modified Bi-Linear Tangent Law (MBTL).
 - Navigation design based on LIDAR image correlation: robust convergence has been demonstrated.
 - Metric accuracy of the control, with a full tolerance to wind gusts (up to 15 m/s).
 - Autonomous Landing site designation was demonstrated, with multiple criteria (simplified guidance criterion, surface roughness, minimum slope).
- Next step : ILT (LIDAR breadboard development, Jena Optronik for Rendez-Vous, ABSL for landing), LAPS (flight experimentation on PLGTF, Astrium), both on-going.



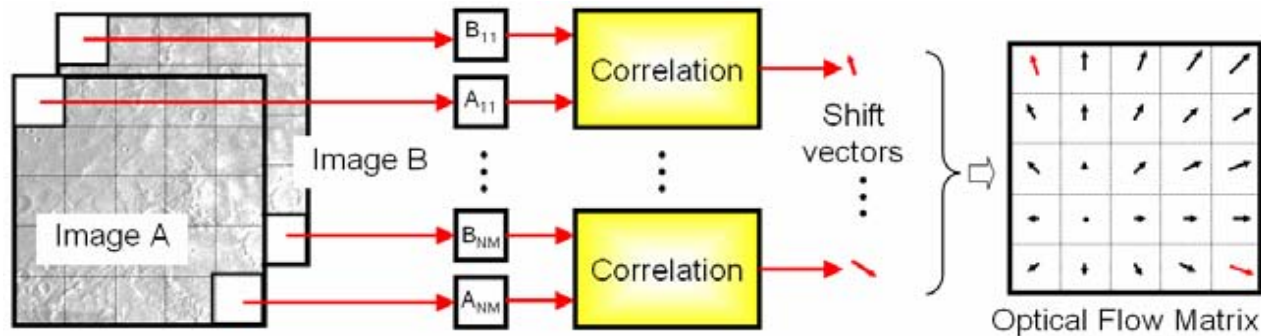
3. Optical Flow Navigation System for Landing (OFNSL)

- ESA on-going study (2007-2009), dedicated to the design, implementation and validation of an optical flow based navigation chain for soft and precise landing in the frame of AURORA program.
- In collaboration with University of Dresden (TUD) for the optical correlator technology, following two previous activities.
- Complementary to the feature points tracking approach (NPAL), but makes possible absolute navigation with respect to a reference DEM.
- Preliminary assessment of a flight experimentation on-board the PLGTF.



3. Optical Flow Navigation System for Landing (OFNSL)

- Principle: observe the motion of elementary images fragments between two successive images (= optical flow determination).

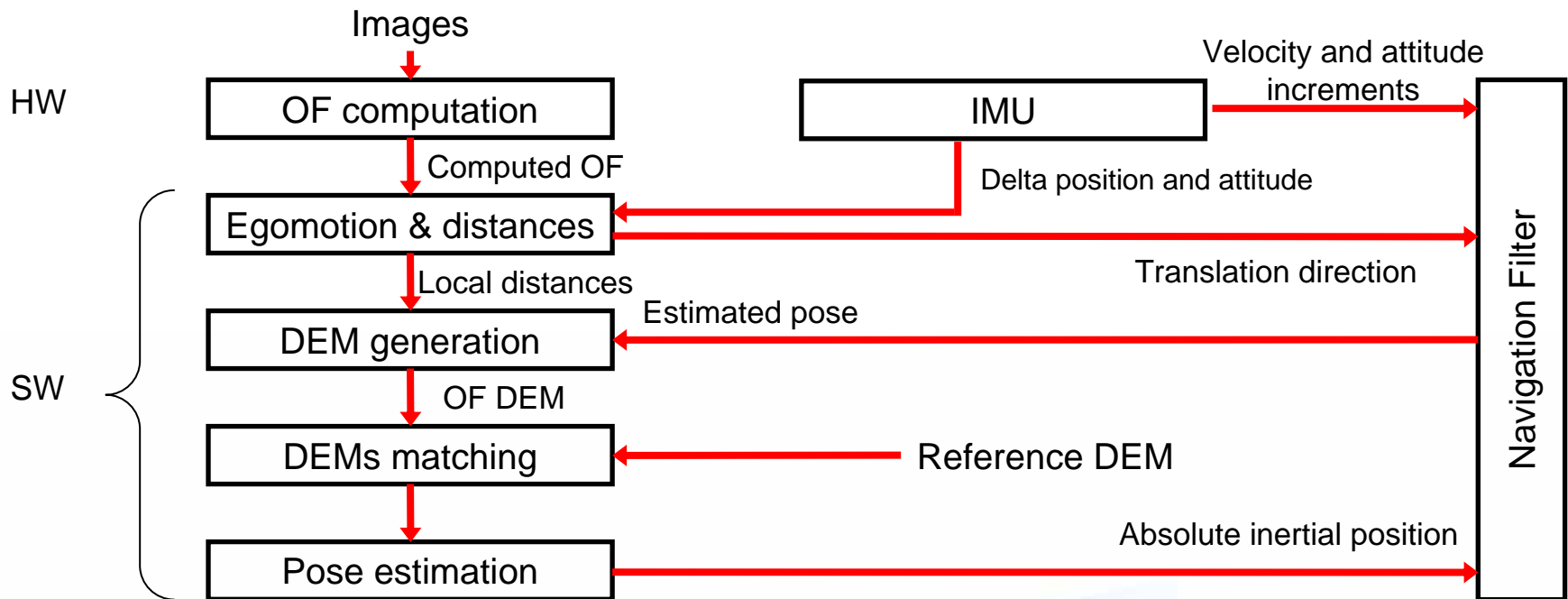


Direct observation of velocity direction.

- Major Innovation : optical implementation of part of the image processing function (not possible in CPU), with the Optical Correlator HW (TUD).

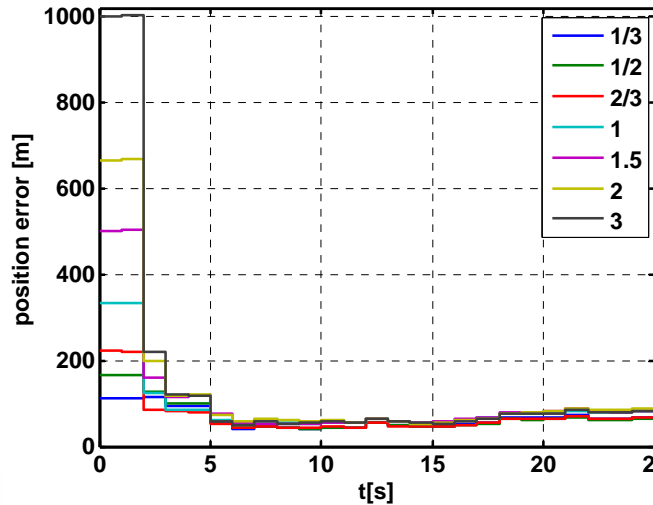
3. Optical Flow Navigation System for Landing (OFNSL)

- Measurements provided to the filter : translation direction and absolute inertial position (+ IMU measurements). Navigation or IMU aidings are required.
- Time between two images is not constant and is optimised by the Optical Correlator itself.

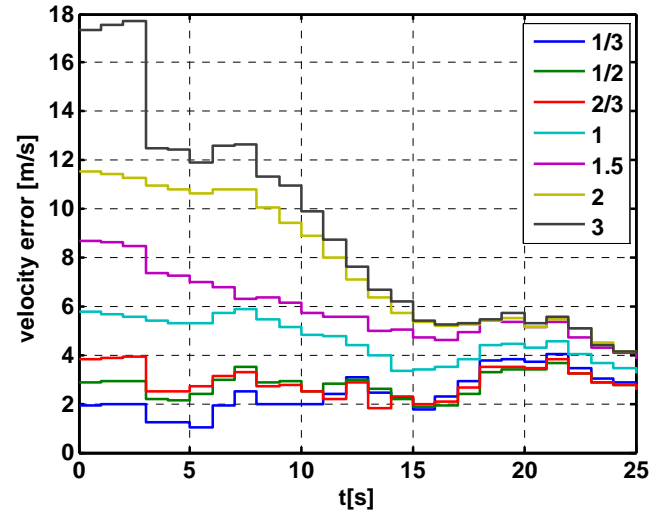


3. Optical Flow Navigation System for Landing (OFNSL)

- Open-loop tests have been completed and show good results.



Position convergence

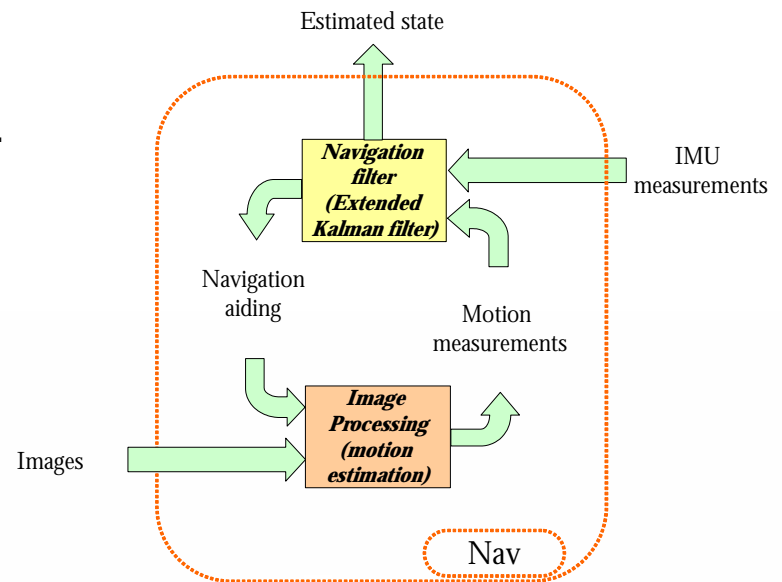


Velocity convergence

- Closed-loop tests to be performed.
- Next step : preparation of a flight experimentation on-board the PLGTF.

3. Generic Hybrid Navigation Filter

- All these navigation solutions rely on a generic navigation filter, hybridising the specific sensor measurements and the IMU outputs.
- NPAL :
 - The feature points are dynamically integrated in the state vector.
 - V/d ambiguity solved in the presence of acceleration.
- LiGNC :
 - Velocity vector measurement.
- Optical Flow :
 - Translation direction and absolute position.
- Sparsity accounted for (optimal real time implementation)
 - Parallel implementation for feature point estimation, possibility to demultiply the number of FP



4. Conclusions

- Vision-based navigation offer various relevant solutions for both target approach and landing.
- Landing on small bodies is less constrained than classical planetary landing as the gravity is very weak and the velocity is low, allowing landing rehearsals. In particular, autonomous hazard mapping & avoidance function is not required.
- Therefore, visual solutions (NPAL-like, or optical flow determination) are preferred to the LIDAR-based solution (heavier and costlier).
- VisNav multi-mission navigation camera is a key technology for Marco Polo (reference missions : interplanetary cruise, rendez-vous, landing, rover). The architecture definition study will end in 2009, the EM development study will then take place until 2010.

4. Conclusions

Technique	Marco Polo mission phase		Comment
	Approach	Landing	
AutoNav	☑		<ul style="list-style-type: none"> ▪ Faint object detection ▪ For cruise navigation if autonomous
HARVD	☑		<ul style="list-style-type: none"> ▪ Vision-based Rendez-Vous
NPAL		☑	<ul style="list-style-type: none"> ▪ Possible complement to absolute navigation ▪ Weak acceleration : altimeter needed to solve V/d ambiguity ▪ Only a few images are required
LiGNC		(☑)	<ul style="list-style-type: none"> ▪ Heavier and more consuming, vision is preferred
Optical Flow		☑	<ul style="list-style-type: none"> ▪ Absolute navigation is possible, to reach the designated landing site