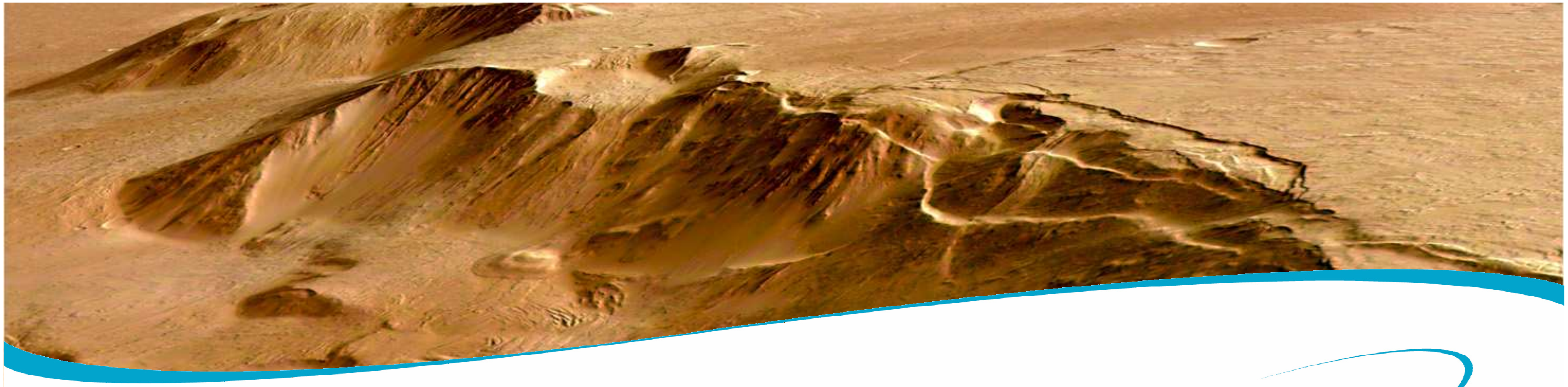


Crater Detection and Identification for Autonomous Navigation of Interplanetary Vehicles

**S. Clerc (TAS Cannes), M. Spigai (TAS Toulouse),
P. Lanza (TAS Turin)**

Observation & Science

Date BT UAV, ENSAM

Outline

- Problem statement: precision landing
- TAS activities in vision-based navigation
- A vision-based navigation chain
- Focus on crater detection for reckoning
- Perspectives

Mission to Mars

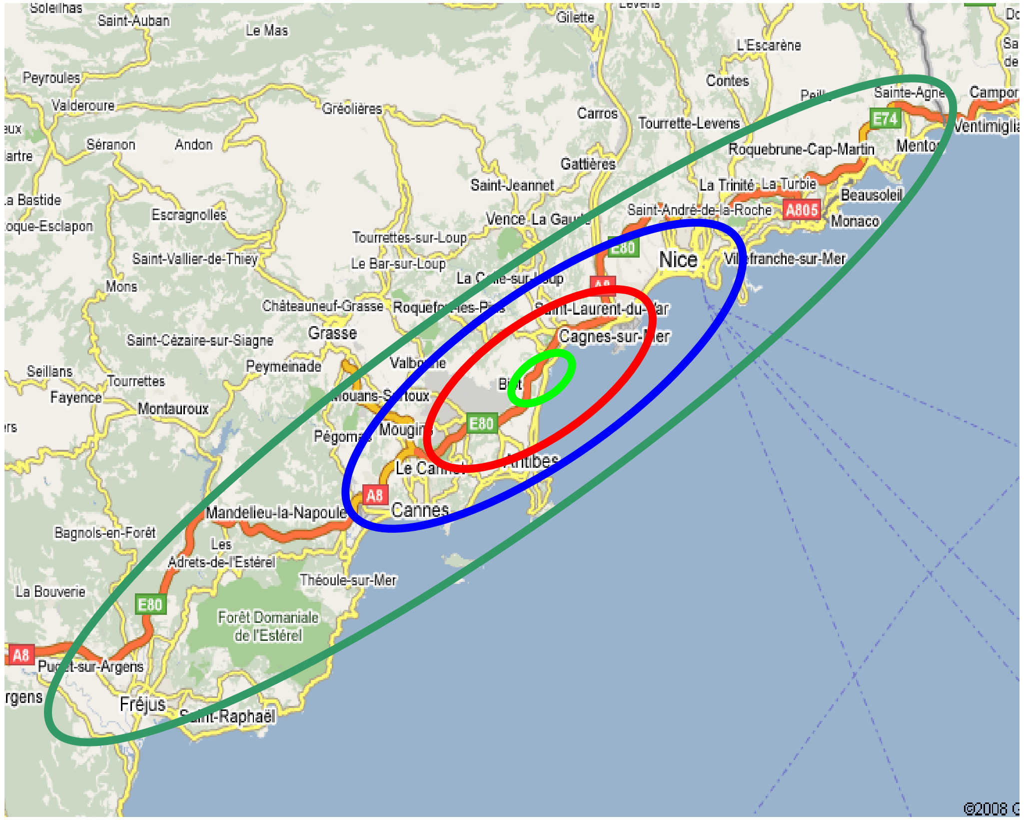
- We want to reach points of scientific interests on Mars
  - Methane sources
  - Exposed ancient terrain
  - Other…

🟩 **MER (~ 150 x 25 km) 2004**

🟦 **Phoenix (~ 70 x 20 km) 2008**

🟥 **MSL (~ 20 x 10 km) launch 2011**

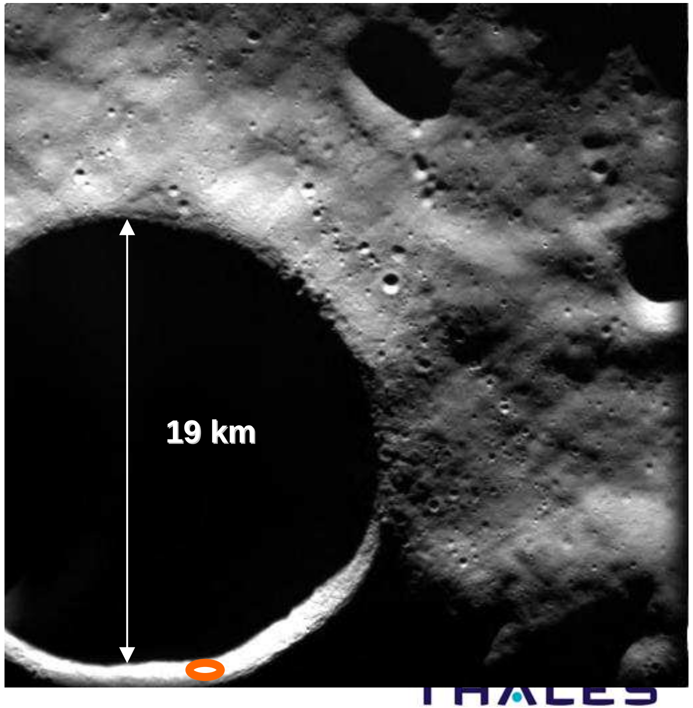
🟩 **target (~ 5 km) > 2011**



Mission to the Moon

- Operational points of interest
  - Near the lunar poles, the Sun always low on the horizon
  - High altitude points (crater rims) are nearly always in the Sun
    - A good place to land
  - Low altitude points (crater bottoms) are always in the shade
    - A possible place to find water ice
  - Enabling capability for human base on the Moon
- Typical need: 100 m – 200 m

Shackleton crater



© ESA

“Standard” lander navigation

- Position knowledge initialized from “ground tracking”
- On-board knowledge of gravity field
- Measurement of non-gravitational acceleration by IMU
- Propagation by inertial navigation

Error sources

- Initial position error (typically 1 km)
- On-board gravity model errors (up to 500 m on the Moon)
- IMU integration error (typically 600 m – 10 km)

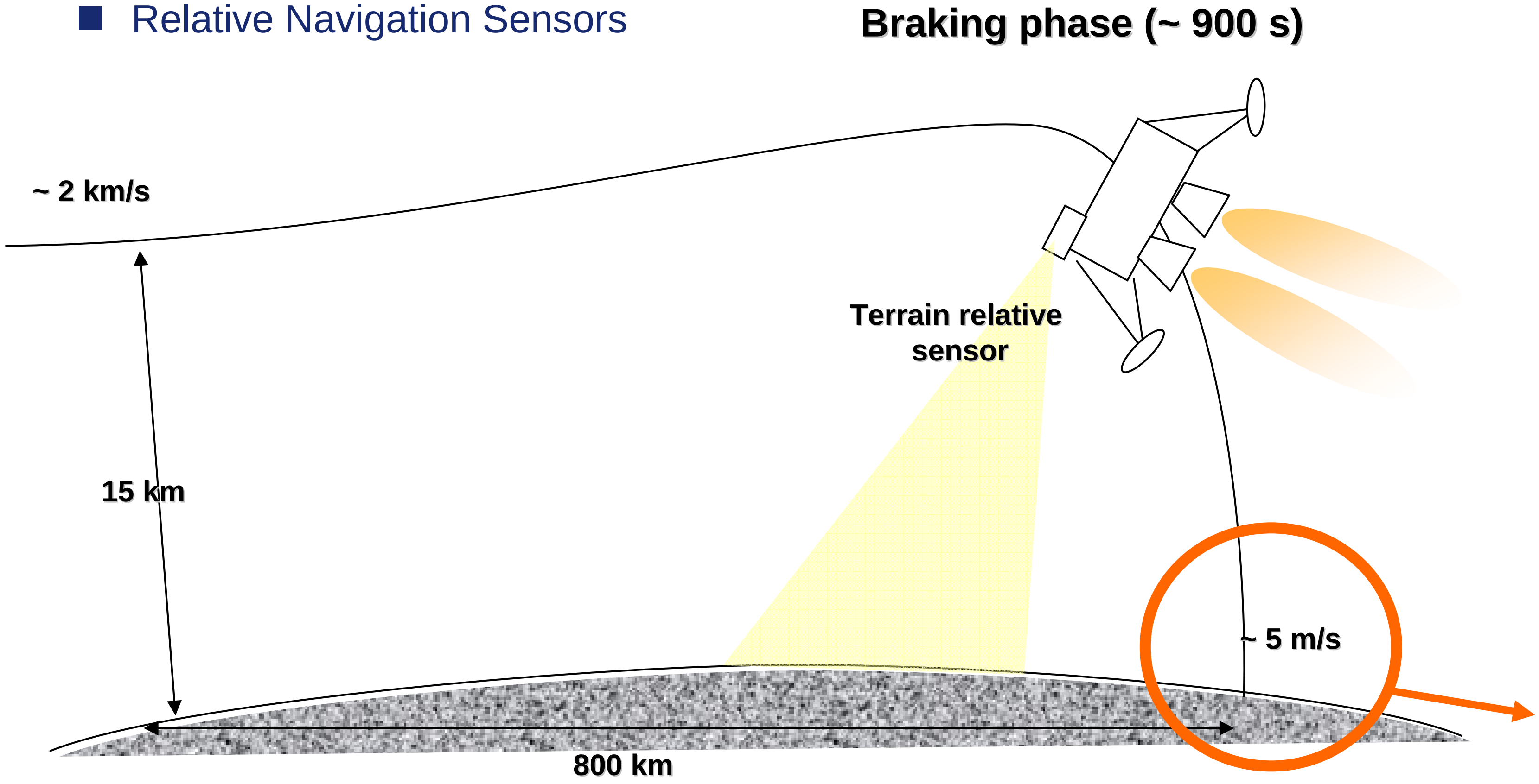
Conclusions

- Need terrain-relative sensors to reduce navigation error (altimeter, lidar and/or camera)
- NB: terrain-relative sensors are also needed for other purposes:
  - Fine control of terminal velocity
  - Hazard detection and avoidance

Lunar Lander Scenario

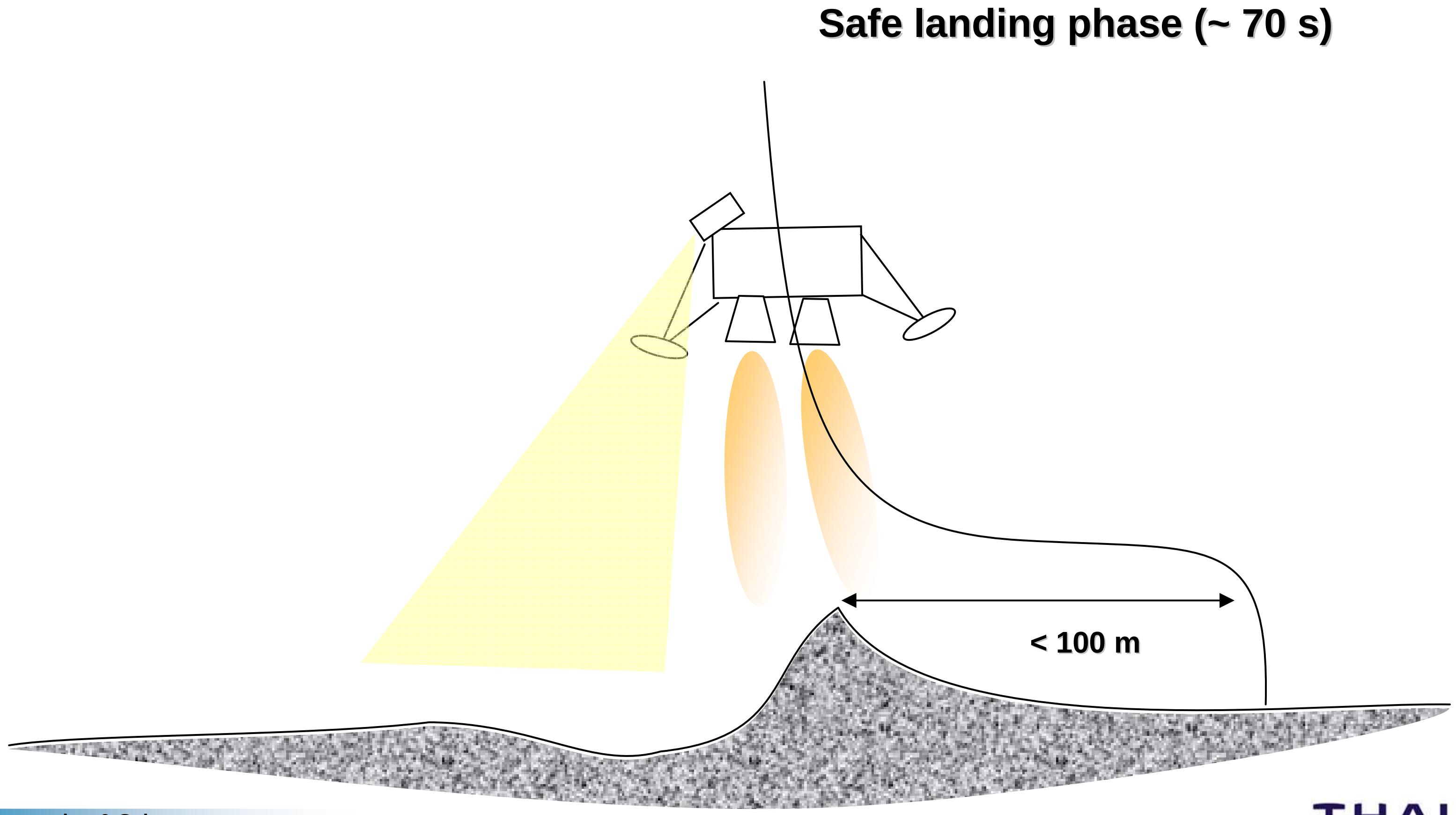
Powered landing

- High-thrust rocket engine to reduce velocity
- Attitude Control Thrusters
- Relative Navigation Sensors



Powered landing

- Hazard avoidance (last 100 meters)

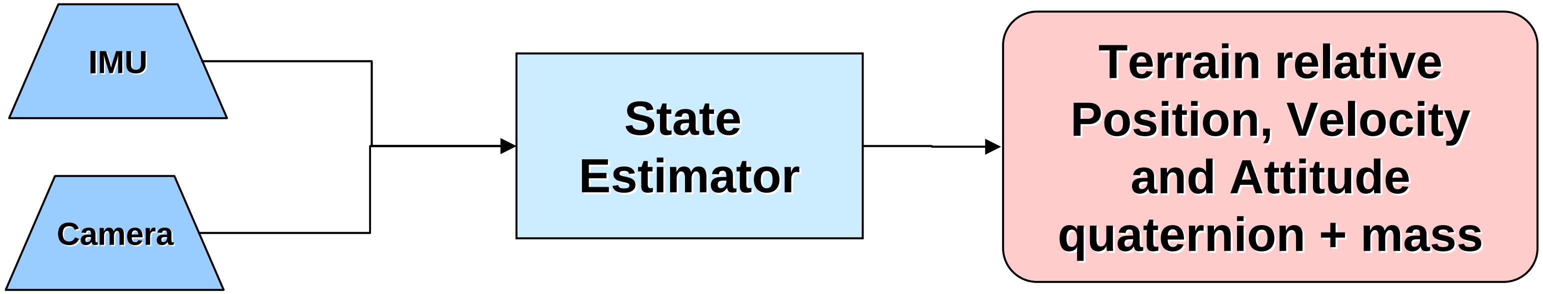


On-going research at Thales Alenia Space

- STEPS project in Turin
  - Design of an end-to-end autonomous safe landing system
  - With optical navigation and hazard avoidance
- Collaboration with ESA and NGC (Canadian SME)
  - Navigation system focused on precision landing using visual landmarks
  - PhD thesis of V. Simard Bilodeau
- Present work
  - A new method for crater detection
  - To be used for both projects

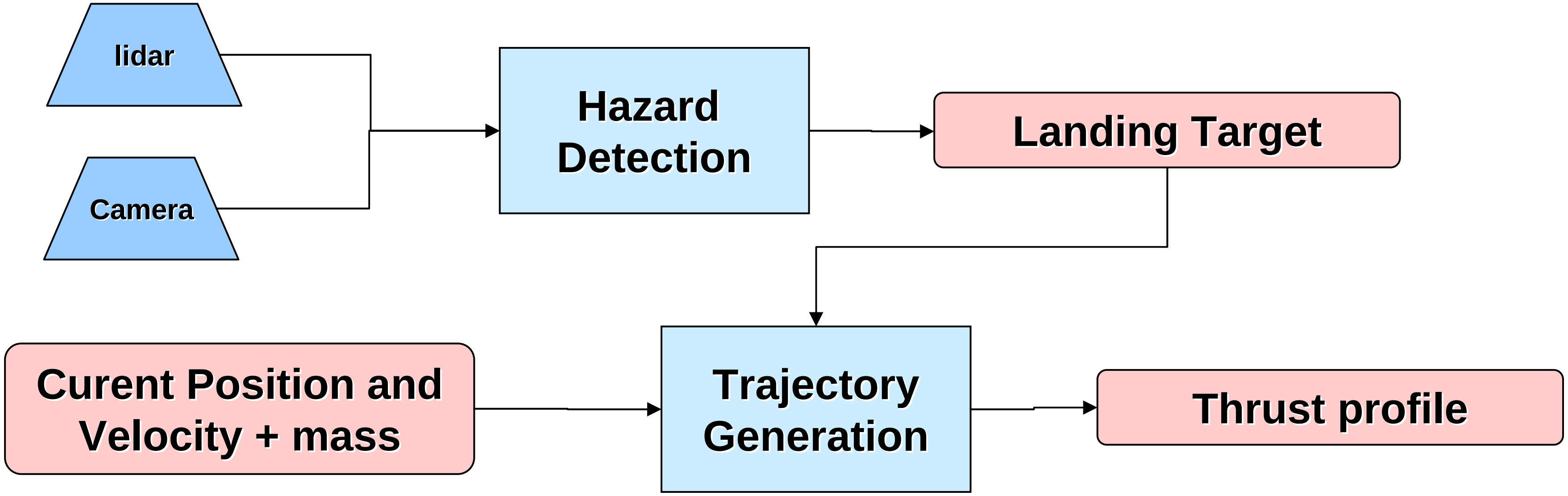
A possible Guidance, Navigation and Control scheme for Lunar Landing

Navigation Function



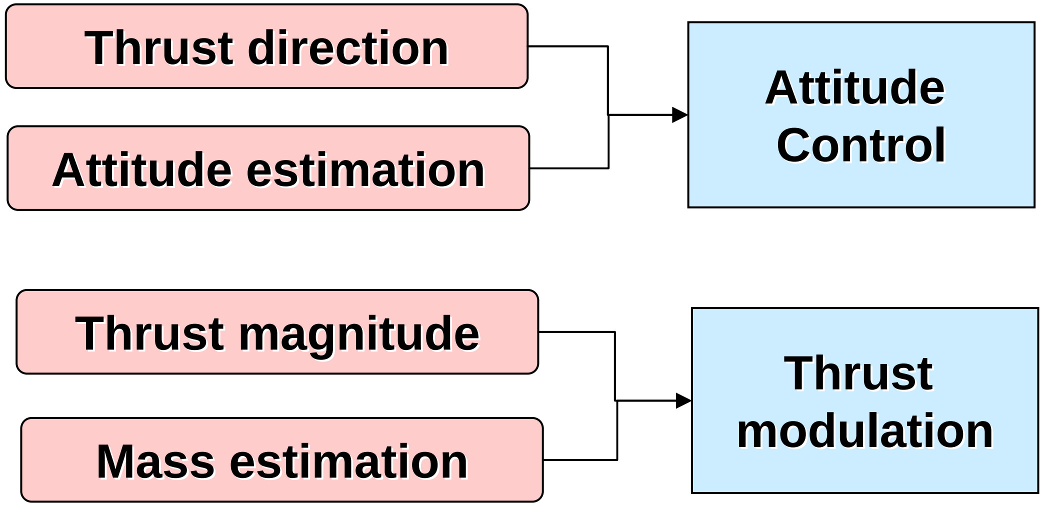
Guidance, Navigation and Control scheme

Guidance Function



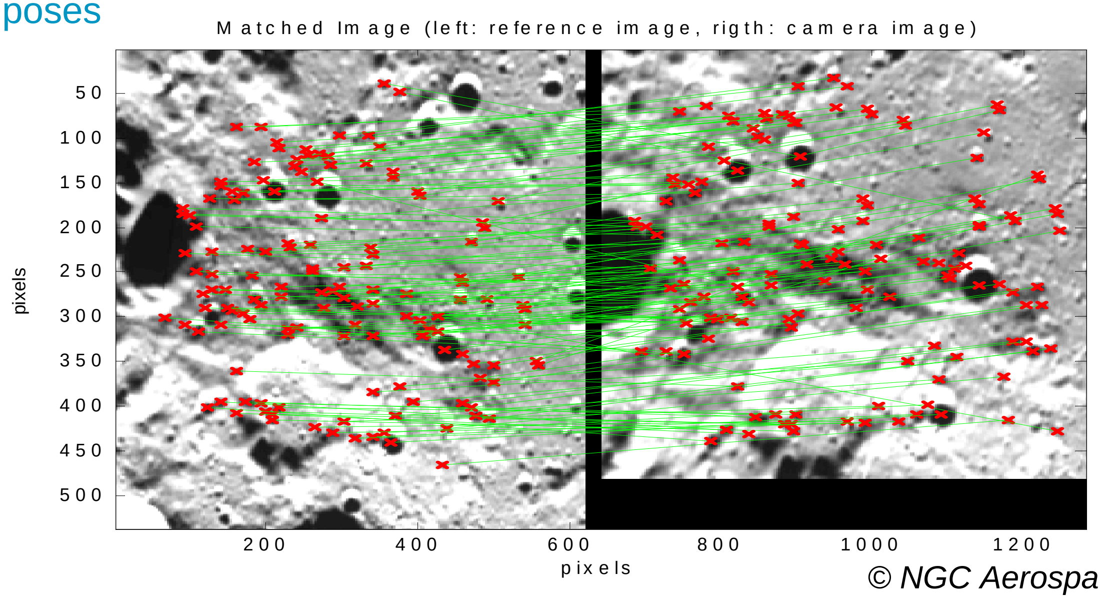
Guidance, Navigation and Control scheme

Control / Actuator management Function



Optical Navigation

- Two types of measurements
  - Tracking of image features between successive frame
    - Provides information on rotation and translation direction between two spacecraft poses



© NGC Aerospace

  - Detection and identification of referenced features or landmarks: reckoning
    - Using on-board landmark map
    - Provides information on the spacecraft position and attitude

Vision-based navigation

Navigation Filter

- Based on a classical Extended Kalman Filter, typically at 1 Hz
- Spacecraft states
  - Attitude quaternion
  - Spacecraft position and velocity
  - Gyro and accelerometer bias
- Propagation
  - Linear (non-gravitational) and angular accelerations are provided by the IMU
  - On-board gravity model
- Modeled process noises
  - Gyro and accelerometer white noise
  - Gyro and accelerometer bias drift (also accounts for gravity field uncertainty)
- Measurements noises
  - Camera localization noise (in pixels)
  - Landmark map position error

Handling measurement delay to due to processing time

- Tracking
    - FPGA implementation assumed
    - negligible delay assumed
- Reckoning
    - uses full frame images
    - Complex algorithms
    - We assume 5 s (5 cycles) of delay
- Several ways to deal with measurement delay, we chose to augment the states with the time-lagged state (position, velocity and attitude)
    - Time-lagged state is linked to current state by cross-covariance
    - Although measurement bears on time-lagged state, the current state is also updated
- Augmenting states is also useful for feature tracking measurement model

Measurement model

- Reckoning
  - Straightforward measurement model: line of sight to reference points
  - Noise: contributions from camera measurement noise + landmark position error
- Tracking
  - Feature position is not known
  - Classical approaches use variants of SLAM
  - Proposed approach: the same feature tracked between two images provides one epipolar constraint on the movement of the camera
  - Treat essential matrix $Q_{1,2}$ as a function of states 1 and 2
  - Noise: measurement error in image 2 of feature extracted in image 1
- To appear in V. Simard Bilodeau et al, AAS GNC Conf., Breckenridge, 2010

Reckoning

Using one or several images + on-board map, determine the position & attitude of the camera

- Reference map has been constructed previously (former mission or former phases of the same mission)
- Reference map acquired with a different resolution, with different viewing conditions (illumination and pose)

The reckoning algorithm should

- Be robust to changes of pose, resolution and illumination
- Minimize CPU time
- Minimize memory requirements

Assumptions

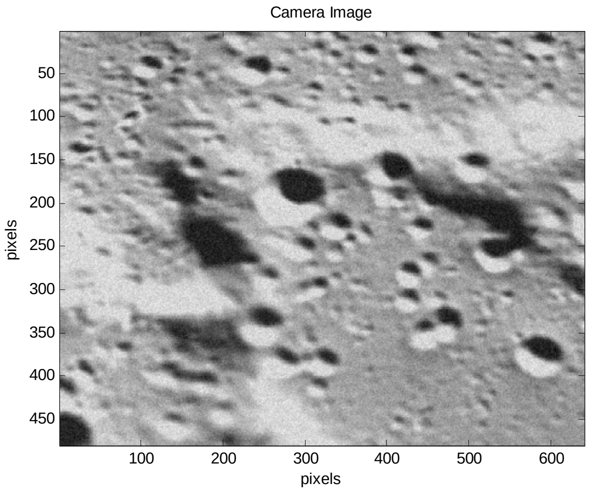
- A priori knowledge of attitude is already quite good
- Current Sun direction is also quite well known
- On bodies without atmosphere: very sharp shadows (no diffuse light)

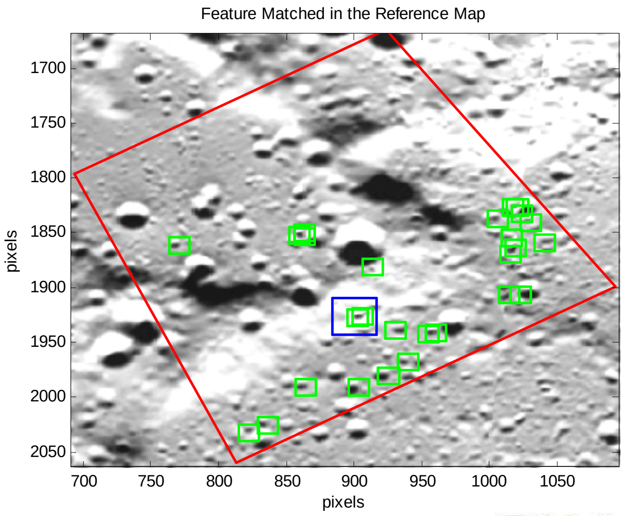
Type of cues that can be used for global reckoning

- Structure
  - Matching of Digital Elevation Map
  - Complex
  - Requires specific sensor (scanning lidar) or large baseline (structure from motion)
  - Robust to pose/lighting conditions

Type of cues that can be used for global reckoning

- Local low-level features
  - Texture elements from the image
  - Matching based on
    - Correlation (Mourikis et al)
    - Feature descriptor (SURF)
    - geometry of the feature pattern (Landstel, Pham et al)
  - Very slow to very fast algorithms
  - Limited robustness to pose/scale/lighting conditions


Camera Image


Feature Matched in the Reference Map

© NGC Aerospace

Type of cues that can be used for global reckoning

- Global features or landmarks
  - High-level surface features
    - Boulders
    - Ridges
    - Craters
  - Complex algorithms for detection and matching
  - Robust to pose/lighting conditions

Why craters ?

- Impact craters are ubiquitous in the Solar System
  - except on bodies with a dense atmosphere (Venus, Earth, Titan)
  - And except on small asteroids
- Created by impacts of asteroid and comets
- Craters are present at every scale
- Simple craters (below 100 km) have a very distinctive shape
  - Does not depend on impactor size, velocity
  - Shape creates a distinctive visual signature
  - Erosion on Mars: old vs. new craters

© ESA

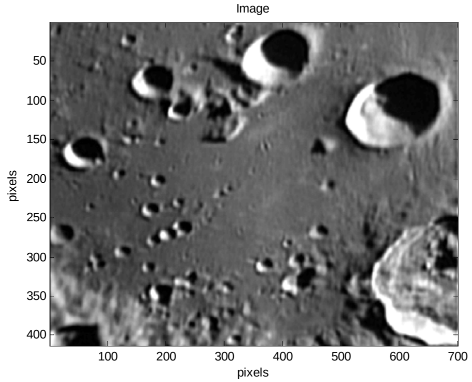
Crater detection: state of the art

- **Hough-transform based :**
  - Exemple of previous work :Yong Sang Chia 2 Yong 2007, Ballard 1979.
  - Principle
    - Edges or pixel based
    - Finds ellipses by building accumulators on ellipse parameter space
    - Methods to reduce the parameter space
  - Pros
    - Robust against edge discontinuity.
  - Cons
    - Requires high computation power
    - Sensitive to noise.

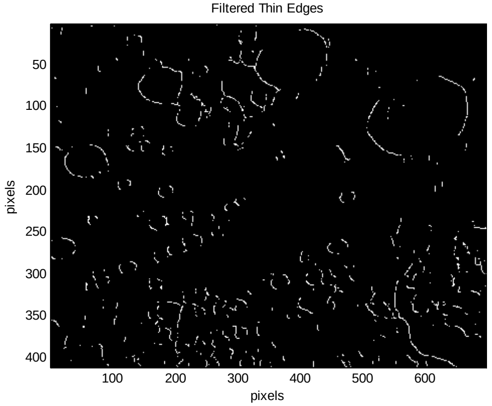
Crater detection: state of the art

Edge-based :

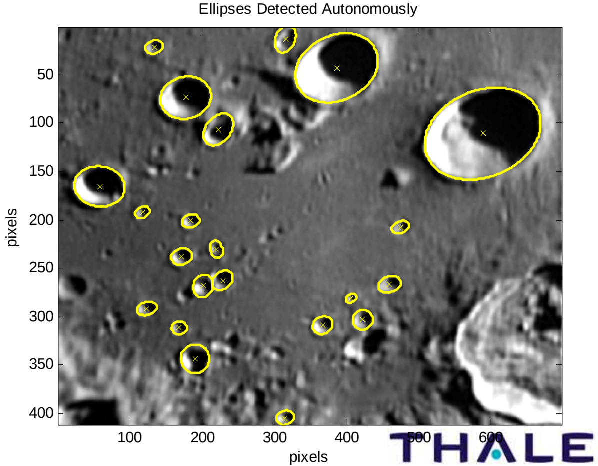
- Exemple of previous work : Cheng and al. (2005)
- Edge detection and continuation
- Light-consistency filtering, dark/bright arc pairing
- Pros
  - The algorithm false detection rate is low and accuracy of the crater localisation in pixel is good.
- Cons
  - Not robust to noisy edges of old craters (but more robust than the majority of Hough-based algorithm)
  - Requires high computation power.



Image



Filtered Thin Edges

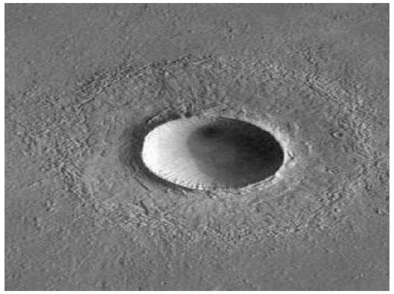


Ellipses Detected Autonomously

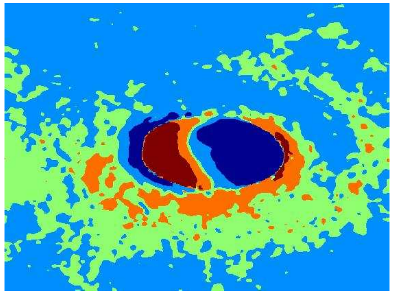
© NGC Aerospace

Segmentation-based Crater Detection

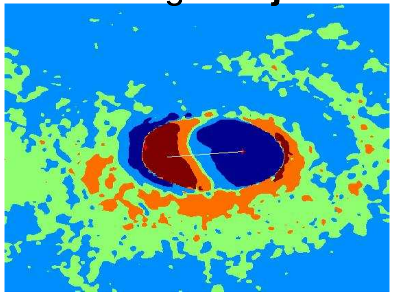
Initial Image



Unsupervised segmentation
Example : K-means with N classes

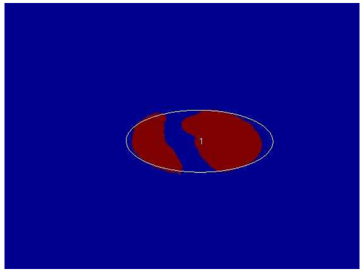


Selection of potential
Dark/Bright **objects**

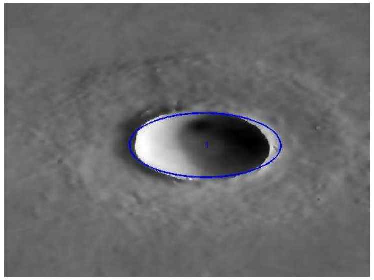


Prior information :

Sunlight « rough » angle and elevation,
Min/Max size of objects of interest



Geometrical check



Ellipse
characterization

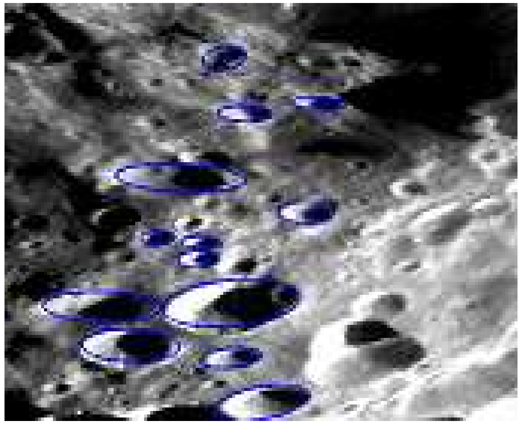
Visual results on real images

Tests on real images

- Same algorithm performs correctly on very different images
- Very low level of false alarm
- Detection is more difficult on highly eroded martian craters

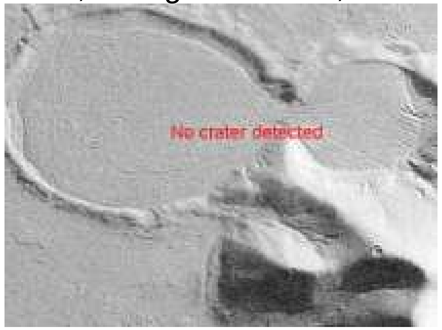
Moon, Billy Crater, ©ESA

Asteroid, Phoebe, ©ESA

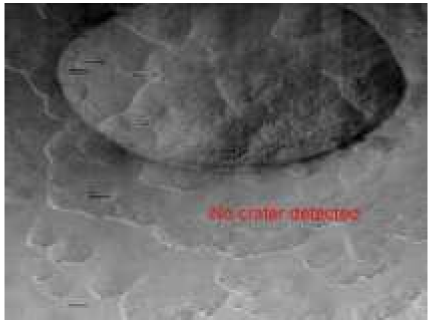


But the algorithm is
not always adapted :

Mars, Hourglass Crater, ©ESA



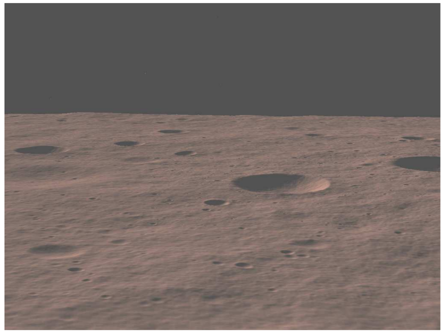
Mars, Crater ice, ©NASE HiRISE

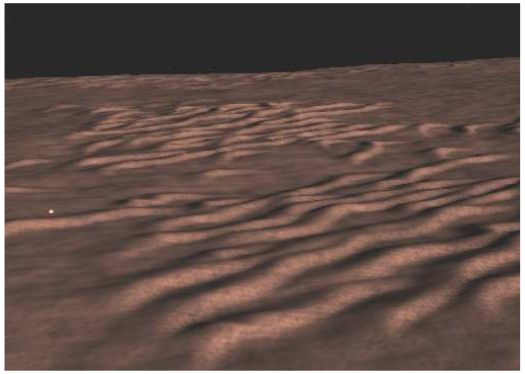


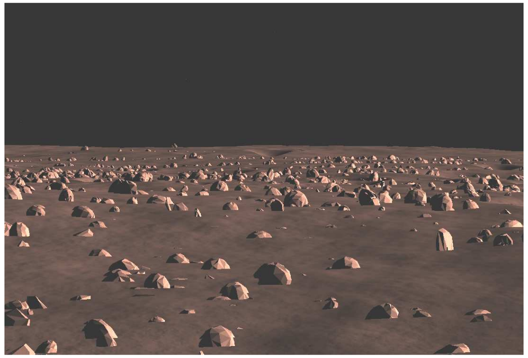
Shadow-Bright objects couple very difficult to detect

Tests on synthetic images

- **PANGU (Planetary Graphical Utility)**
  - Scene generator developed by U. Dundee under ESA contract
  - Generates multi-resolution planetary terrain
    - User-provided DEM
    - Fractal refinement
    - Impact crater, boulder, dunes generation
  - Pre-computed shadow map allows real-time scene generation
  - Viewer
  - Client/server mode for closed-loop simulations
  - Available upon request from ESA







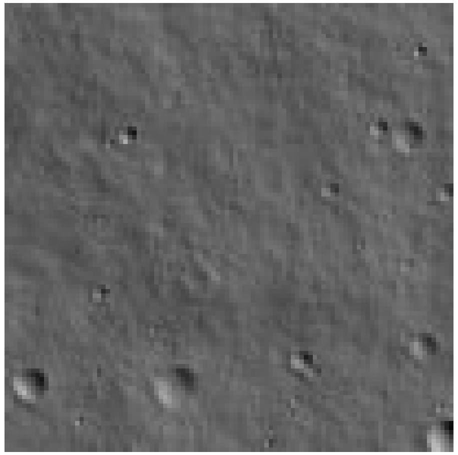
Tests on synthetic images

- **Test images generated with PANGU**
  - Images and associated « ground truth » of crater locations and sizes
  - Three Sun elevations: 77.5°, 22.5° and 2.5° (~ Moon pole case)
  - 2 different views: nadir and slant

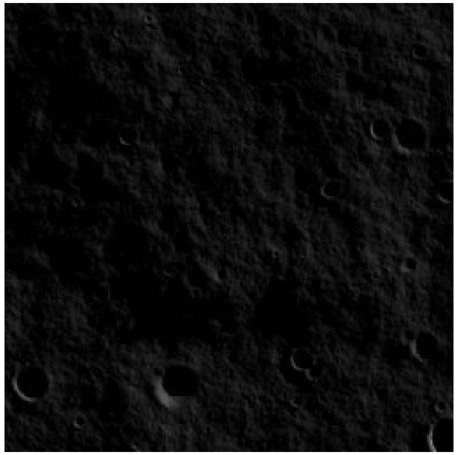
Raw images

Nadir view, Sun high

Nadir view, Sun low



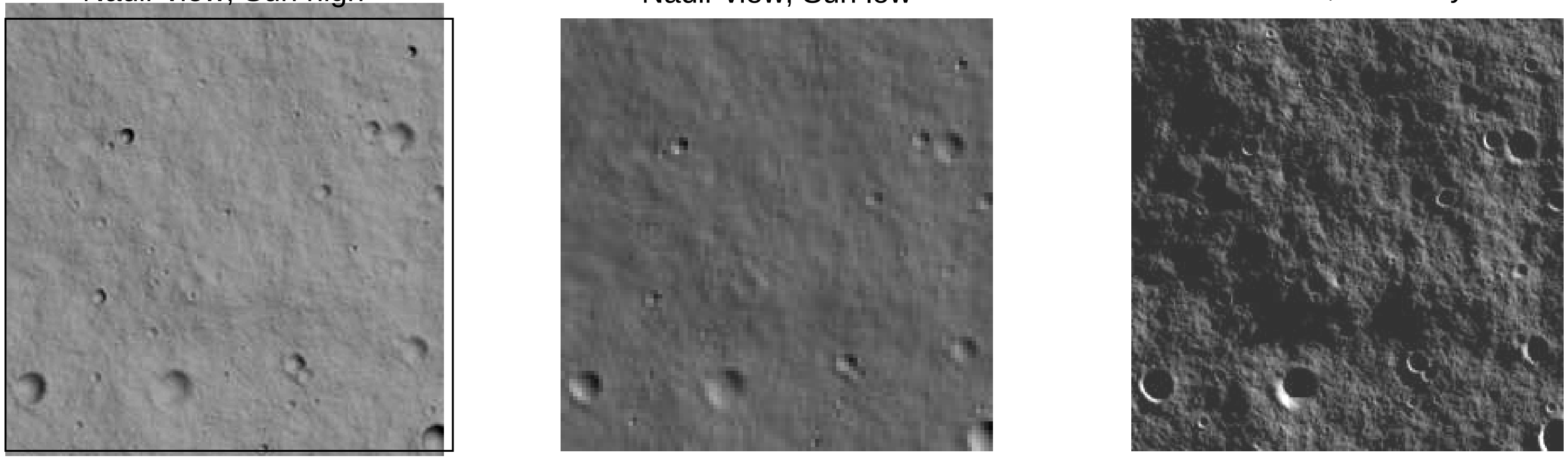
Nadir view, Sun very low



Tests on synthetic images

- **Test images generated with PANGU**
  - Images and associated « ground truth » of crater locations and sizes
  - Three Sun elevations: 77.5°, 22.5° and 2.5° (~ Moon pole case)
  - 2 different views: nadir and slant

Enhanced images

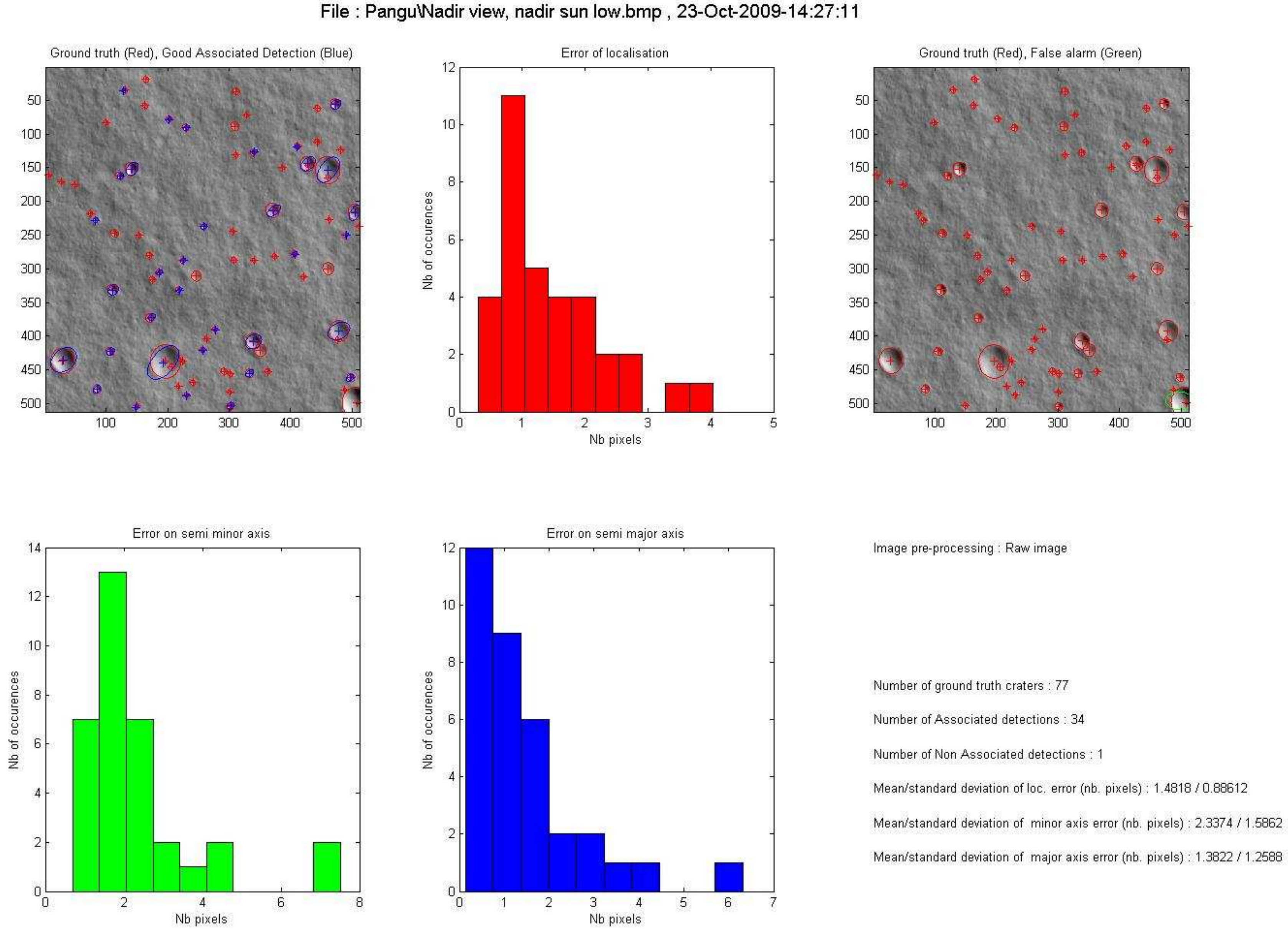


Nadir view, Sun high

Nadir view, Sun low

Nadir view, Sun very low

Quantitative results (synthetic images)



File : Pangu\Nadir view, nadir sun low.bmp , 23-Oct-2009-14:27:11

Image pre-processing : Raw image

Number of ground truth craters : 77

Number of Associated detections : 34

Number of Non Associated detections : 1

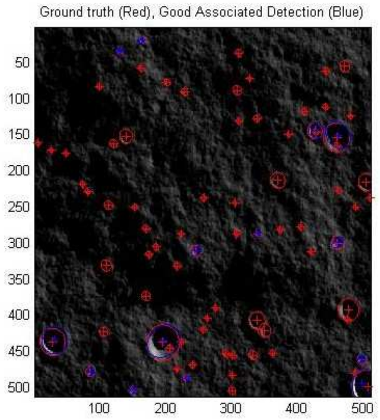
Mean/standard deviation of loc. error (nb. pixels) : 1.4818 / 0.88612

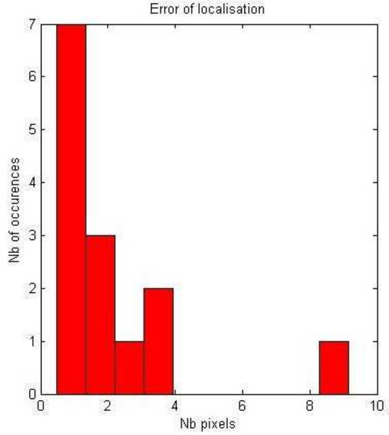
Mean/standard deviation of minor axis error (nb. pixels) : 2.3374 / 1.5862

Mean/standard deviation of major axis error (nb. pixels) : 1.3822 / 1.2588

Quantitative results (synthetic images)

Pangu Simulation : Nadir view/very low sun elevation angle





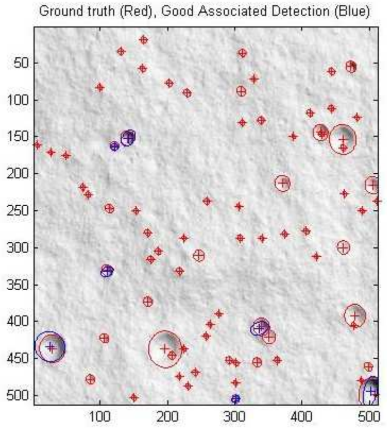
Pd : 14/77

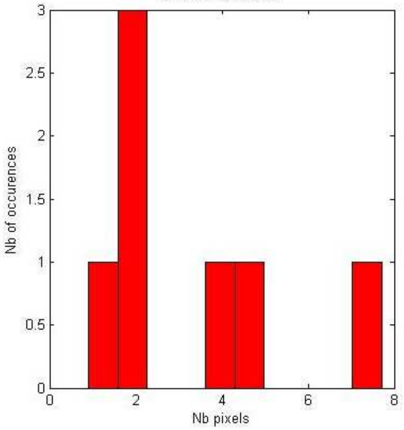
Pfa low : 0/77

Loc. error: mean ≈ 2.2 pixels, σ ≈ 2.3 pixels
=> to be slightly enhanced

NB : Slant view simulations give the same kind of results

Pangu Simulation : Nadir view/high sun elevation angle





Pd : 7/77
=> to be slightly enhanced

Pfa low : 0/77

Loc. error: mean ≈ 3 pixels, σ ≈ 2 pixels
=> to be enhanced

Segmentation-Based Crater Detection

Conclusions

- Good points
  - Very simple and fast algorithm
  - Robust and not very sensitive to parameters
  - Very low rate of false alarm (side effects only)
  - Good quantitative performance (localization < 3 pixels and size), could probably be enhanced
  - Robust to change of pose (slant view)
- To be improved
  - Large craters with non classical shape not detected on real images
  - Performance drops at high and very low Sun elevation
- So far, no use of a priori information

Navigation Filter simulation results (not presented here)

- Assumptions: 15 meter error on crater map position + 3 pixels camera localization
- Performance < 50 m at touch-down

Perspectives

Once crater have been detected, they must be identified

- Assuming that the attitude of the camera is known with good accuracy, one must first rectify the crater positions in the reference frame

Identification algorithms: state of the art

- Simple minimum distance approach
  - Not robust to large uncertainties
- Distance between pairs of craters
  - Not robust to uncertainty on scale
  - Leads to large database (list of all crater pairs)
- Projective invariants
  - Robust to large uncertainties on viewing conditions
  - Applicable to non-flat terrain
  - Very complex and costly

Perspectives

Possible algorithms

- "Pole Star" signature
  - Identifier based on number of neighbours in successive distance bins
  - Very simple matching, small database
  - Not robust to large uncertainty on scale
- "Scale invariant" Pole Star
  - Using crater size as the reference distance for bins
- Use azimuth bins instead of distance bins