Space Optical Navigation Techniques - an overview

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ABSTRACT

Optical or vision-based navigation is an enabling technology for satellite autonomous navigation associated to different navigation approaches such as cruising, fly-by, terrain relative navigation, landing, rendezvous and docking between spacecrafts, rigidity of multi-satellite constellations. Since 2001, in many different ESA projects, the author and his team (at INETI and currently at FCUL) have been associated to most of the developments of the optical components of autonomous navigation, in cooperation with space primes or GNC subsystems suppliers.

A unique experience related to seemingly simple photonic concepts associated to computational vision, photonic noises, camera tradeoffs and system concepts has emerged, and deserves a synthesis especially because some of these concepts are being implemented in the ESA Proba 3 mission and ESA is currently updating the technology in view of forthcoming planetary missions to Jupiter, Jupiter moons and asteroids. It is important to note that the US have already flown several missions relying on autonomous navigation and that NASA experience is at least one decade old.

System approaches, sources of difficulty, some tradeoffs in both (and between) hardware and software, critical interface issues between the imaging and GNC (Guidance, Navigation and Control) subsystems, image processing techniques, utilization of *apriori* or to be estimated information, uncertainties, simulation of the imaging chain and non-cooperative environments will be addressed synthetically for both passive (optical) and active (lidar) systems.

Keywords: Space instrumentation (OCIS 120.6085), Space optics (OCIS 350.6090), Optical navigation, Autonomous navigation, Image processing (OCIS 100.0100), GNC.

1. INTRODUCTION

Autonomous Navigation (AN) is one of the key technologies for the European Space Agency (ESA) and, in fact, for all space agencies. AN is mandatory whenever there is no time to validate navigation decisions in the Earth, which is too far away. AN is required for deep space navigation, rendezvous between spacecrafts (S/C), terrain-relative navigation, autonomous landing in planets and asteroids planet flyby and S/C relative navigation to ensure strict relative positions and orientations between S/C in a constellation. Aerocapture - one technology being considered to reduce mass constrains for Mars missions - relies on AN for several of its mission phases.

Optical or vision-based (to be used with the same meaning) navigation (ON) is one enabling technology for AN. Using ON, objects with known and reliable ephemerides are used as beacons, enabling the navigation system to accurately locate the S/C in inertial space and plan subsequent maneuvers to accomplish the mission. In this context, beacons are stars, planets, asteroids, comets or other spacecrafts.

ON is not alone. Other technologies such as IMU (Inertial Measurement Units) or DDOR (Delta Differential One-way Ranging) [1] compete and may be used in different phases, either alone or redundantly. All technologies are routinely compared and tradeoff against each other during mission design. While IMU accurately measures accelerations and

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reconstructs an accurate trajectory of the S/C, the DDOR technique uses two widely separated antennas to simultaneously track the location of a transmitter in space in order to measure the time delay between signals arriving at the two stations. Theoretically, the delay depends only on the positions of the two antennas and the spacecraft. In reality, it is affected by several sources of error: for example, the radio waves travelling through the troposphere, ionosphere and solar plasma, and clock instabilities at the ground station. Typically, DDOR is used to improve a planet's ephemerides using accurately determined orbiting S/C positions in time.

ON can be active or passive. Passive ON is based on passive imagers, active ON requires light sources, for example, LEDs, lasers or LIDARs. Image-based ON is based on 2D camera (V or NIR), which became space qualified and can be purchased as OEM subsystems, endowed with their own computing capability. There is no short supply of lenses. Sensor (CCD or CMOS) number of elements and dimensions, together with optical focal lens determine key operational parameters, such as FOV, angular resolution and sensitivities. Cameras typically provide Line-Of-Sight (LOS) estimates to the Guidance, Navigation and Control (GNC) system, which combines such estimates with the output of other sensors, implements filters and generates the best possible estimation for the actual orientation and position of the S/C.

LIDARs are very good candidates for autonomous landing and may be irreplaceable whenever the surface topography is not accurately known; contrary to passive cameras, ESA is still in short supply of space qualified LIDARs for navigation, which must be small, fast and should not demand too much power. LIDARs also require large computing capabilities, because the position and orientation of the S/C cannot be considered stable during the acquisition of one complete LIDAR frame; therefore, linear and angular velocities and accelerations must be recomputed several times to update kinematics parameters of previous frames in order to improve terrain knowledge. LIDARs have variable resolution and variable SNR, and power is obviously one big concern. New configurations are under development to overcome drawbacks for landing missions.

There are other important active configurations. For example, in S/C formation flying, some S/C may carry light beacons (either LEDs or lasers) which facilitate their detection by cameras located on chaser S/C's – which usually navigate in order to perform rendezvous with the target mires-carrying S/C’s. Alternatively, target S/C may carry rectro-reflectors, the active source being located in the chaser. Active sources improve SNR and system sensitivity, although they cannot overcome one key problem in rendezvous: direct solar illumination which strongly degrades system performances. Rendezvous in eclipse is the apparent solution but too many missions cannot comply with eclipse conditions, even for small periods. Direct solar illumination is, anyhow, a serious problem for any type of ON: it reduces contrasts, creates stray-light problems, constrains exposures through saturation effects, generates spectral diversity issues, creates a multiple reflections on the insulator layers of the S/C, etc.

ON always requires image processing (IP) with its peculiar computer power needs - in principle, boundless. IP design is far from trivial for ON because there are many IP modes (not necessarily synchronized with navigation modes) associated with different geometric configurations between the camera and the beacons. Most important, there are transition modes, in which IP performances are unstable. In order to understand mode definitions, it must be taken into account that, in general, beacons can be point-like or extended. For point-like beacons, IP extracts LOS to the beacon’s center of brightness (COB), which is the an estimator of the center of mass (COM). Very faint beacons require large exposures - and their image can therefore by blurred – or many independent images to be superimposed using time-integration methods which require intensive IP but allow detection, say, of magnitude 13 beacons.

Limb is extracted from extended beacons images; the limb is the line separating illuminated area from deep space. There is a second important line, the terminator, which separates the illuminated and shadowed areas; it is unfortunate that both limb and terminator cannot be used: in fact, although both require apriori knowledge of the 3D shape of the beacon, the image contrast around the terminator is poor and therefore estimations have large errors. In any case, the estimated limb location and the known beacon shape do enable COM’s estimation, mandatory for relative navigation. Unfortunately few bodies are accurately known in 3D; 3D mapping requires previous missions, or a number of orbits, mappers and intensive computing power – which typically space agencies are not willing to make available easily. In most of the envisaged cases, mission-accepted beacons are therefore constrained to be quasi-spherical. Extended beacons have their own set of problems. As range decreases and beacon size increases: 1. exposures must be smaller and therefore background stars are no longer visible simultaneously, inhibiting attitude determination; 2. the angular size of the beacon exceeds camera FOV, therefore splitting the limb into pieces – its radius of curvature increases and COM estimation becomes problematic. In the transition between point-like and extended beacon modes, IP has a problem: angular resolution is not sufficient to analyze the limb and solar illumination phase degrades the use of COB as a good COM estimator. Alternatives do exist, always quite demanding in terms of (un)available on-board computer resources or needs of additional information.

IP is therefore the subject of demanding system tradeoffs which have somehow restricted ON in the past. Nevertheless, there are no really alternatives to ON for deep space missions, and technology will inevitably make tradeoffs more sympathetic to ON. What is typically requested by the ON engineer to the system?

- Two co-aligned cameras to cope with very different beacons angular size – technically feasible but creating problems in terms of volume, mass and computer requirements;
- Zoom lenses to cope with dramatically different situations: zoom technology is not yet available for space;
- Plenty of computer resources to use state-of-the art IP methods: the evolution of space qualified computers is slow and very often computers are shared between different S/C subsystems;
- Optimal location of camera in the S/C: heat shields and communication antennas may create unexpected limitations;
- Redundant attitude determination instruments in order to reduce the number of problems to solve by the ON camera: not always an option for system engineers;
- A priori accurate information on beacon ephemerides, space bodies 3D shape and surface topography (in case of landing); while the ephemerides are continuously being improved with longer and longer time series, space bodies volume and surface geometry requires dedicated missions, which are rare and costly.

This paper will try to explain some of concepts of autonomous and optical navigation to the photonics community. Its past in the US and in Europe, the main features and difficulties of passive ON, some examples of active ON. It is based on the experience accumulated in the last 12 years in the context of ESA technological programs and in close collaboration with the industry, especially in the area of GNC: participating in systems design, simulating optical systems, computing performance models, creating laboratory prototypes and, in some cases, interfacing to replicas of space processors. Experience has shown that image-derived modes or phases are not aligned with mission or GNC phases, which has created complex situations in the past. Some effort is therefore dedicated to clarify this issue, as well as the strong *bidirectional* interface that should exist between the client and the ON server. Recently I had to review AutoNav technology, trying to analyze critically past experiences and providing recommendations - this paper is strongly supported by such review.

2. MISSIONS AND METHODS

2.1 Autonomous Navigation

Autonomous navigation (AN) has long been considered a critical technology for long missions to be conducted far from the Earth. In this section I will closely follow the background provided by ESA when launching a new initiative in this area [2].

Interplanetary probes rely heavily on Earth ground tracking stations to perform mission critical manoeuvres such as gravity assisted, fly-by or orbit insertion manoeuvres. This puts some operational constraints on the mission design such as the need for a long duration arc for accurate Delta-DOR measurements or a last correction manoeuvre very early with respect to actual encounter. These constraints could be partly overcome by an increased use of on-board sensors (e.g., using ON techniques) coupled with an improved on-board autonomy. For missions where precision navigation is required (e.g. Mars Precision Landing), or where the target ephemeris are not known with a sufficient accuracy (e.g. missions to Saturn or Jupiter systems), use of onboard navigation capability is a mission-enabling technology while autonomy allows to achieve more accurate manoeuvres by relaxing the operational timeline (e.g. by allowing for more accurate manoeuvres closer to the encounter).

US missions into the solar system have made the case for vision-based navigation as primary sensor for such a purpose. Optical measurements have been used in numerous missions, primarily as an additional navigation measurement processed and used by ground operators to improve the orbit determination and the target-versus-spacecraft knowledge (Mariner 9, Viking, Galileo, Cassini, Voyager). In the Galileo case [2], due to antenna deployment failure, some autonomy has become mandatory for the vision based navigation to limit the data to be transmitted to Earth for each picture, and most of the IP tasks were performed on-board. On MRO (Mars Reconnaissance Orbiter), a navigation camera was embarked as passenger experiment, and took pictures of Mars' Moons Phobos and Deimos on stars background between 30 days and 2 days before orbit insertion [4]. The aim was to demonstrate that such technique could be used for future Mars missions to ensure accurate delivery manoeuvres. Other missions have gone a step further by implementing a fully autonomous vision-based navigation system based on well-established ON techniques previously implemented. This generic technology, known as AutoNav, has been successfully tested for the first time in flight on Deep Space 1 mission (2001), and matured on subsequent missions NEAR [5] in 2005, StarDust and Deep Impact [6] and now on the DAWN mission (2007-) [7].

In Europe, vision-based navigation has been implemented for the first time in-flight on the ROSETTA mission with the NAVCAM camera, with in particular a vision-based autonomous attitude control to "track" the asteroid during the flyby [8]. Vision-based support of navigation is also currently the baseline for the JUICE L-CLASS mission to Jupiter System [9], which includes 14 flybys of the different Moons and an insertion into Ganymede orbit.

Autonomous navigation techniques, more specifically ON, are enabling technologies for interplanetary missions that include challenging features like an autonomous beacon detection and insertion, high accuracy insertion, (possibly multiple) gravity assist or fly-by manoeuvres. Effective autonomous navigation strategies can also significantly decrease the operations cost and delta-V required for interplanetary missions and possibly for low thrust orbital transfer (Earth, L2,...). Significant work has been validated by ESA, performing major steps towards autonomous navigation for interplanetary "cruise" parts, "early" and "late" planetary encounters (using either Multiple-Time Integration techniques, limb or Center-of-brightness measurements over background of stars).

2.2 Optical Navigation modes

Optical navigation provides 3D position of a S/C from known positions in 3D space. Optical cameras estimate Line Of Sight (LOS) to beacons or to specific locations at the surface of the beacons. The number of estimated LOSs drives the positional uncertainty of the S/C, which can be further filtered by repeating measurements in time.

Optical navigation can be used in a variety of missions including several phases: cruise (towards) a body of interest, fly-by (planets or asteroids), rendezvous (& docking), orbiting and landing. They are not completely independent. For the sake of analysis, comments will be provided to cruise, relative navigation and landing phases of missions.

Cruise modes are in-between phases with a very small number of orbital maneuvers - which take place at very well defined mission points. Accuracy is not critical and conditions are reasonably stable during cruise phase. Detection of targets can take place during the cruise mode in order to begin tracking as soon as possible, therefore launching a new navigation mode of relative navigation. Far target detection is a strong drive for ON specification. In the cruise phase, reference stars are previously selected and available on the on-board star catalogue; non-resolved visible planets can also be used to update trajectory or perform calibrations of some sort.

Once a *relative navigation* mode is launched, accurate LOS towards the targets becomes mandatory:

- in aerocapture missions, LOS criticality is high because the width of the entrance corridor is small to ensure that planet atmosphere will successfully perform aerobreaking and will enable the entrance of S/C without fuel consumption.
- in fly-by missions, the goal is to perform visits to successive space bodies (ESA JUICE mission, for example); in such missions, there is a need to perform accurate manoeuvres close to the swing-by points;
- for two S/C systems, one typically must navigate towards the other, the chaser needs to perform rendezvous and physically capture the target; LOS is critical as well as relative attitude, for there are no energy resources to make a second trial - this is the concept behind missions such as ESA MRS (Mars Return Sampler), where (in the conceptual design driving technology developments) a very simple sampler S/C (most probably a spherical canister short after launch) is ballistically launched from Mars surface and a chaser orbiting S/C must navigate and perform rendezvous.
- finally, orbiting S/C can navigate with respect to a planet terrain, recognizing landmarks and using them to

improve their own trajectory determination; this kind of navigation is based upon IP of extended surface images, either using visible or IR cameras, or even LIDAR. In a way, it is a multiple LOS analysis. To some extent, recognition missions may trigger relative navigation modes if gravitational potential is not accurately known.

In relative navigation, there is no shortage of complex problems to overcome and systems tradeoffs for limited variety of ON sensors are scary. Probably the biggest issues are related to:

- sensitivity: detect as soon as possible;
- flexibility: deal with resolved bright and non-resolved faint objects at the same time, or ensuring small LOS uncertainty and large FOV;

Landing is quite a peculiar mode: it is irreversible once started, inadequate navigation will destroy the S/C, the last landing phase (vertically dominant) takes place during a very short period and may be subjected to unexpected turbulence and visibility degradation. Landing can be mechanically assisted (parachutes) or protected (using airbags) and can be assisted by ON continuous hazard determination which provides GNC with the right inputs to control descent (Figure 1) until the so called low gate, beyond which no more navigation corrections can be applied. Landing must not take place where surface slope is high, or where lots of boulders or craters exist (Figure 2). [As a lateral comment, Beagle 2, carried by Mars Express (MEX) did not land successfully, most probably because it could not actively select its own landing site, and may have become immobilized in a rather tilted configuration where antennas could not establish communication links with MEX]. ON role is therefore to keep constantly updated slope maps and "texture" maps, encompassing all surface irregularities which will de-stabilize the S/C at the very moment of landing. Obviously, shadows are also to be avoided and updating the shadow map is also ON responsibility when updating the overall hazard map (HM). All the approaches using light can also be easily jeopardized by turbulent dust induced by S/C engines, in addition to normal dust storms which are well documented in Mars atmosphere.

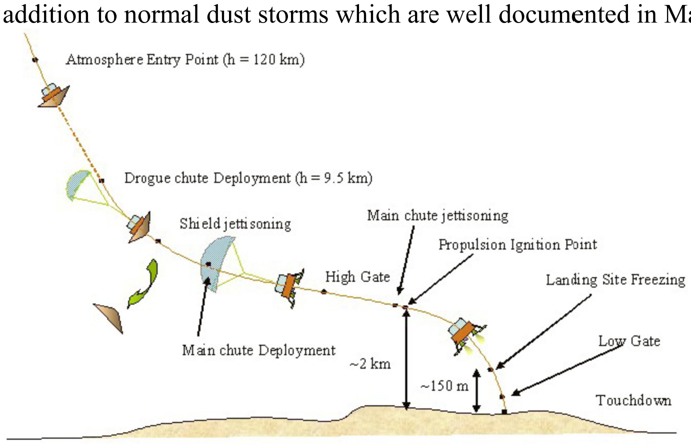


Figure 1 – Typical landing profile

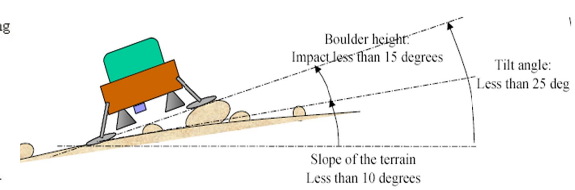


Figure 2 – Safe landing requirements

ON can assist landing with passive or active systems:

- Passive systems are vision-based cameras, visible or infrared, acquiring images and analyzing them on-board using IP, continuously updating the landing area HM (GNC decides how to navigate based on the last HM's); extremely complex problems are related to slope estimation and atmospheric effects (eventually induced by landing engines in the very last phase).
- Active systems use LIDAR to continuously update the digital elevation model (DEM) of the surface within the FOV of the instrument (where the landing site is supposed to be). The biggest issue - beyond lidar availability - is related to the computational burden because 1. S/C dynamics must be recomputed several times to account for the fact that the S/C is not stable during the time required to integrate one complete frame and 2. the sampling on the ground is not uniform.

2.3 Optical Navigation Methods

ON can be absolute if coordinates are estimated in the inertial space, or relative.

Camera characteristics determine resolutions, sensitivities and uncertainties. Distance to the beacon (range) is a scaling parameter. In time, a small faint unresolved body evolves toward a bright, resolved and endowed with detailed surface landmarks. IP modes are therefore strongly determined by the scale of the object in the focal plane, by its SNR, as well as its shape and diversity of illumination sources. As a reminder, it must be stressed that IP modes are not, in principle, determined by navigation modes, although IP performances at each mode are affected by navigation mode (e.g., in modes where thrusters are active, any IP mode can be launched but attitude instability will affect image quality and, therefore, uncertainties).

ON in practice typically deals with the following objectives:

- Accurately compute (forecast) a space body position in the observing camera reference system, knowing everything about S/C dynamics and camera position and orientation in the S/C frame;
- The inverse problem: how to derive target location in space from its location in the image(s); this problem is purely an image-processing (IP) problem when the target is to be known at the camera observation system, but requires time series and filtering when the actual location and orientation of the S/C are not accurately known in the inertial space.

Although both objectives are related and require simple 3D analytical geometry and the imaging equations, the latter is a component of the orbit and attitude determination processes and may be influenced by other independent sensors with greatly different accuracies. It is typically considered a GNC component.

ON methods are a collection of well known techniques in the photonics and computer vision community - see [13] for a good overview. The difficulty of ON are the tradeoffs at system level which requires full scale simulation and performance models, taking into account all physical parameters and too many environmental conditions. A very wide set of resources and skills are needed, such as, for example:

- From *photonics:* geometrical optics, PSF, MTF's (optics, sensor, blurring), sensor technology and related optoelectronic parameters, noises [photonic, dark signal (DS) and DS non uniformity (DSNU), photo-response non-uniformity (PRNU) and their thermal dependences], scattering, straylight, atmospheric effects, diffusion models (single or multiple), attitude representation using different representations (quaternions, Euler angles and their different conventions in the different space communities), geometric and radiometric accurate calibrations, variety of environments with large dynamics (eclipse, non-eclipse, one or several illuminating bodies), radiation effects on sensors, lasers, LED's, spectral filters, astrometry, astronomical reference systems.

- From *computer vision (image processing):* signal and image processing, 1D and 2D filters, computational geometry, 2D and 3D shape handling, ray tracing, physically-based light diffusion models, optimization, interpolation, 2D sampling issues, compact yet accurate algorithms for ASIC's, numerical analysis.

ON has basically a server to one S/C client: the GNC (Guidance, Navigation and Control) system. GNC also receives (and sends) data from the AODCS (Attitude and Orbit Determination and Control System) which manages S/C trajectory according to mission profile. In previous ON experiments, ON is not supposed to request services to GNC. Nevertheless, in my view, some intrinsic ON difficulties will only be overcome by performing specific attitude manouevres which should challenge the traditional S/C architecture and hierarchy between subsystems.

3. IMAGE-BASED NAVIGATION ISSUES

In this section key issues of ON using vision-based systems will be highlighted. Technicalities on many of them are well understood by the optical community and can be found in many references. Emphasis will therefore be on system-related issues.

3.1 Camera characteristics

Main geometric requirements are on FOV and the angular resolution. These are determined by focal length, pixel dimension and number of pixels. They should be derived by navigation specifications and mission objectives (dimensions and visibility range for objects of interest) as well as transverse velocity for a given approach.

Main radiometric requirements are on objects magnitude. This is determined by all types of optoelectronic and photonic noises, including, in particular, DSNU and black and white spots (also called warm spots in the US). These may potentially change in time (due to cosmic particles, radiation, …) and should be regularly monitored (with IP calibration modes). This is particularly critical when ON is handling non-resolved objects (pixel-like), white spots should not be misunderstood as stars or targets of interest. Black spots, on the contrary, are not welcome if the target is angularly very close to such locations, because its centre of brightness (COB) - the best possible estimation of the center of mass (COM) - relies upon interpolations around the brighter pixel and such neighborhoods should not therefore include dark pixels.

Sensor technology is critical and selection of CCD or CMOS / APS (Active Pixel Technology) technology is of utmost importance. CCD has lower noise, but APS may provide multiple regions of interest (ROI) and different process parameterization for different areas of the focal plane, which may be important to deal with large planets stray light, areas around defective pixels, non-uniform noise, etc. The trend is clear, favoring CMOS technology.

An important decision must always be taken concerning the number of cameras. When AutoNav was originally used in the initial US mission, the navigation camera was also the science camera. The strong interplay between IP and GNC should ensure a stand-alone camera. In addition, due to the wide variety of missions considered, it makes sense to have independent cameras for narrow angle (NAC) and for wide angle (WAC) – in the future, zooming lens technology will be robust enough for space applications! Both should share the same IP modes and should be used by the camera manager according to the tasks received from the GNC manager and mission details.

3.2 Inter-relations between IP and AODCS

IP requires knowledge of S/C attitude in several composite modes to reduce search space in images when superimposing them, for example, in the MTI composite mode. Absolute (and not only relative) attitude is needed because MTI strives to increase the SNR for very faint beacons expected to become visible in known positions in the inertial space. Attitude knowledge is not required, for example, in the bright beacon composite mode, because the instantaneous quaternion for the beacon image can be interpolated from the before / after star field images.

In the cruise mode, IP is basically a star mapper for the brightest stars and generates camera quaternion, for example in J2000 reference system (using a processed working version of the Tycho star catalogue). From two independent attitude estimations (ADCS system and IP), thermo-elastic deformation of the cameras mechanicalsupport should be estimated - this is, usually a strong requirement from space agencies.

Many IP modes may be complex and computer intensive. Restricting image analysis to small ROI's within specific locations (star, beacons, etc) is obviously welcome - sensor architecture and camera electronics allowing - and may be feasible if the adequate dialogue can be setup between the GNC and the IP executive.

3.3 ON impact on System architecture

Optical navigation requires:

- A system-level decision on the number of navigation cameras
- An IP executive to handle *composite* IP modes, requesting work to IP sub-executives, integrating results and generating observables
- An P2M executive to track coherently recent silhouette data for large objects
- An Calibration executive to handle all calibration modes
- One IP sub-executive to handle each *primary* IP mode, by:

  - requesting images to be generated (by simulation, emulating the camera(s) response)
  - receiving auxiliary data from ADCS
  - interacting with the Calibration executive
  - launching IP modes to be executed on such images
  - finalizing observables and releasing them to other systems
- An image simulator (IS) executive, to build images upon request, fully emulating the camera(s) response, especially noises and functional directly in relation to local programmability of the sensor
- An on-board star catalogue
  - Processed, taking into account navigation camera(s) characteristics
  - Cut into sky sectors, according to the mission profile

3.4 IP modes and sub-modes

Composite modes require launching several primary modes under control of a Camera Executive and/or the Navigation Executive (in charge of specific attitude manoeuvres):

1. **Primary modes**
   a. Calibration (on-board)
      i. Geometric distortion
      ii. Flat field
      iii. Black & white pixels / warm pixels
      iv. Thermo-elastic effects affecting cameras
      v. Fine tuning operational parameters
   b. Spot mode
      i. No beacons
      ii. Bright beacons
      iii. Faint beacons
   c. Extended (bright) object mode
      i. Object fully within the FOV
         1. Too small object, limb is useless; phase compensation may apply
         2. Object contour is large and limb can be manipulated
            a. Spherical object
            b. Non-spherical object
               i. Known shape and dynamics
               ii. Unknown shape and dynamics
      ii. Object partially within the FOV
         1. Landmark analysis
         2. Limb analysis for spherical objects only
2. ***Composite modes***
   a. Calibration strategies
   b. Multiple Time Integration (MTI) for very faint beacons
   c. Too bright beacons inhibiting stars observation

3.5 Qualitative discussion on some IP modes

Calibration modes: Specific data taken sequences should be acquired requiring attitude manoeuvres of small magnitude, with different goals, for example: 1. detecting degraded pixels; 2. anticipate variation of optoelectronic characteristics of the sensor (noise non-uniformities) and stray light effects near large and bright planets, in order to setup minimum and maximum integration time and processing thresholds; 3. regular optical distortion calibration using known fields of stars to account for launch effects or long term degradation of the optics; 4. regular cross checking between attitude estimations by the satellite ADCS and the navigation camera working as a star mapper, to update camera orientation in S/C reference frame and therefore account for thermo-elastic deformation.

Spot modes: depending on integration time, star images are modeled by the PSF of the instrument, degraded by motion of the object in the camera reference frame. The glyph is, in fact, the convolution of the trajectory of the star in the focal plane and the instrument PSF (Figure 3). We cannot take for granted that there is no motion degradation either due to target motion or to satellite attitude instability. Identification of stars and therefore of their LOS is therefore more complex than analyzing, say, a Gaussian distribution of irradiance in order to locate the maximum to sub-pixel accuracy.

a) b) c)

Figure 3 – a) PSF, b) glyph (or LOS trace) (exagerated), c) convolution between PSF and glyph

AutoNav technology used Multiple Cross Correlation (MCC) (Figure 4), an appropriate technique to locate star centroids, because the glyph is the same for all objects in the same image (although it can change from image to image).

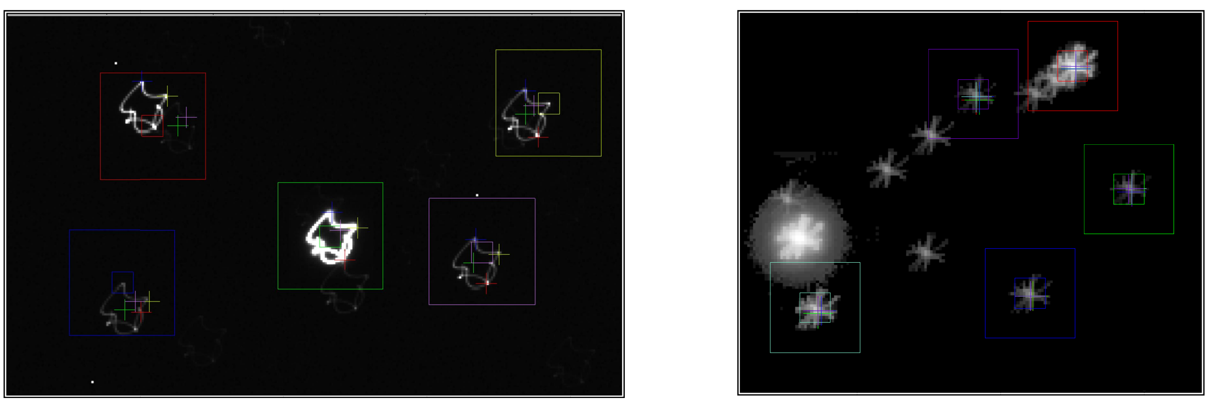


Figure 4 – Using MCC to accurately locate star centers when the gliph width is non-negligible

A non-resolved beacon may be handled similarly to stars, but its glyph is different because of proper motion. It is therefore important to use a priori information on their location and direction of motion (taking beacon ephemerides and attitude uncertainties into account) in order to restrict analysis and fine tune detection algorithms. *Bright* beacons and very faint beacons should be analyzed differently. Bright beacons images should be acquired without sensor saturation in order to estimate COM accurately. *Faint* beacons will require Multiple Time Integration (MTI) (Figure 5), in which several images are acquired in sequence, reference stars are identified and used to geo-register the images within the region of the image we expect to locate the beacon. Geo-registration should be restricted to a small area, but a priori knowledge of the beacon direction and relative velocity is required in order to setup individual exposure and number of images to acquire. If images are correctly superimposed and the asteroid is not moving too fast, the SNR increases dramatically and a very faint asteroid can be detected easily. In a past ESA activity, AutoNav, it has been possible to reach magnitude 13 beacons with 30 images, one of the most important results of the activity.

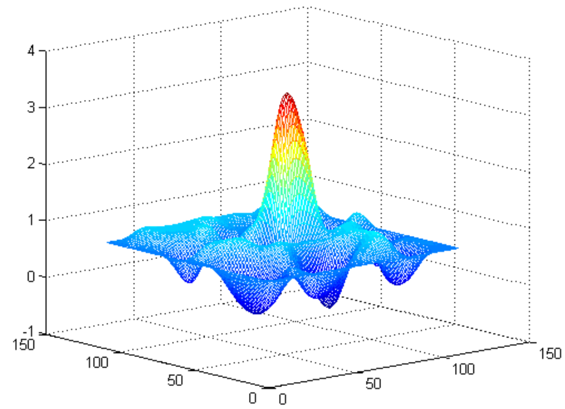


Figure 5 – MTI final result for a simulated magnitude 13 asteroid, after filtering

Extended (bright) object / Object fully within the FOV modes: for small (~20 pixels) and objects known to spherical, illumination phase compensation may apply, provided it is realistic to assume that objects are lambertian. For larger objects, information must be found using limb information, lit terminator not being reliable in most of the cases. There are several strategies to discriminate limb and analyze its shape, the centre of the best fitting ellipse (taking into account the correct projection of the ellipsoid shape) being the centre of the beacon that is communicated to GNC to drive navigation. Previous experience with the ESA GNCOMAT activity also takes into account limb irregularities.

For non-spherical bodies for which the true shape is unknown there is not much we can do except estimate a "centre" using several ad-hoc algorithms, which must differ in the situations of full "moon" configuration (full visible surface well lit) and the others. It must be always discussed within a specific mission design if we can assume a minimum *apriori* information on such beacons, in order to drive IP. When the shape of the non-spherical beacon is known from previous missions or from previous phases of the same mission, the really important issue is the speed of rotation of the beacon around its spinning axis and the extent of knowledge that can be assumed about such rotation. In the (unrealistic) limit - especially for bodies which are not too symmetric - it should be possible to cross correlate the visible contour with the known shape and derive a measure of the body centre – a concept which also requires careful definition. Past US missions have managed to derive the shape of strongly irregular asteroids by stereophotoclinometry, a technique which is far too complex and computer-intensive to be handled on-board, but that can provide a very accurate description of irregular bodies for navigation purposes - see [10] for a good summary of such approaches and further references, and Figure 6 for a photograph of the truly non-spherical Lutecia asteroid [11].

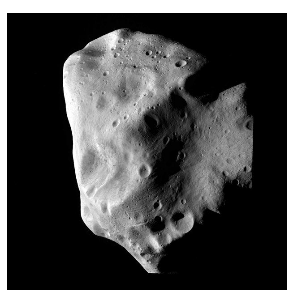


Figure 6 – Asteroid Lutecia following Rosetta fly-by [11]

When resolved, Lutecia is a good example of the difficulties related to ON. Fly-bys do not require relative navigation (if they can rely upon background stars) and can setup comfortable security margins to accommodate large LOS uncertainty of the COM. Nevertheless, a landing mission should always require a previous preparatory mission to build an accurate 3D shape of the asteroid and a sufficient number of landmarks to guide the approach and the landing. The limb of Lutecia is virtually useless without landmarks to define correctly the orientation of the natural reference frame and orientate the ON camera properly.

Object partially within the FOV modes: limb information is no longer useful unless the beacon is perfectly spherical.

When beacon contours approach image borders, several IP modes should be executed in parallel: on the one hand, limb analysis, similarly to AutoNav, with an attitude manoeuvre, but only when the target is known to be spherical; in addition, landmarks analysis, considering that they are already visible and can be useful. Running both IP modes in parallel ensures a smooth transition between IP-derived uncertainties in two different regimes. When image borders are about to be intersected, we believe that attitude manoeuvres might re-centre the beacon enabling limb analysis for some additional time.

3.6 Relevant Algorithms per IP mode

3.6.1 Calibration modes

Geometric distortion - This is a critical issue because LOS uncertainty depends upon it. It is normally performed before launch but there are reasons to repeat it during the mission, in case there are strong variations of the thermal environment or to account for launch vibrations. It therefore must rely upon sets of reference bright stars within the FOV. Several images might be required to ensure no saturation or motion blurring. Due to the small FOV, radial distortion might eventually be sufficient. Nevertheless, good correction must be ensured far from the optical axis, because the camera is not necessarily aligned with the S/C velocity.

Geometric calibration must be based on known angles and angular distances between many pairs of stars (Figure 7), and previous camera accurate calibration of intrinsic parameters (pixel size and focal length). The correction may in principle be executed on the ground because of insufficient on-board resources and of the availability of a more reduced catalogue, while this calibration may require a considerable number of stars well distributed within the FOV. The merit function is, for example:

$$\Delta^2(C_1, C_3, P_3, P_5; x_c, y_c) = \sum_{i=1}^{n}\left\{w_i\left[\alpha_i(P)-\beta_i\right]^2 + \Omega_i\left[d_i(P)-D_i\right]^2\right\}$$

Angular distances between two stars are represented by d_i and configuration angles (between three stars) are represented by α_i. The C's and the P's are coefficients of the distortion model (radial and shear, respectively), (x_c, y_c) are offset parameters for the optical axis of the lens with respect to the centre of the sensor, and the *w*'s and Ω's are weights.

Optical distortion was a real concern for the JPL team of the Deep Space-1 mission: on the one hand, the error affecting distortion parameters might had been too high for operations; on the other hand, post-launch effects may have created decentring of the optical axis or the displacement of the plane of best focus.

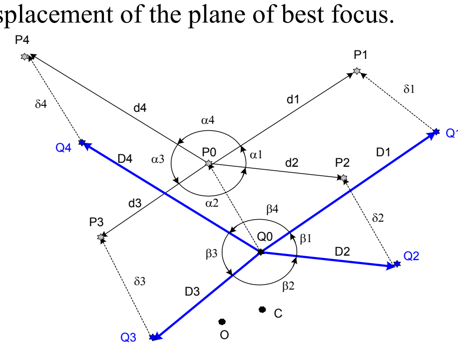


Figure 7 - Reference (distortion free) star pattern (Qi's) and the distorted and translated measured star pattern (Pi's).

The following problems are still relevant today:

- for large focal lengths, optimization algorithms are trapped to local minima far from optimum location; this is well known when calibrating cameras using the standard chessboard target [12];
- calibration methods for zoom lenses are still unstable;
- impact of using irregular pattern of stars with eventual gaps of uniformity within the FOV is difficult to assess.

Identification of defective pixels (warm, black, white) - A list of these pixels should be updated regularly because defects may increase with accumulated radiation dose. Noise is basically "salt-and-pepper" and makes detection tricky.
Defective pixels will not generate glyphs in the image (Figure 3). Strategy is different for defective pixels with different

characteristics and for sensors with different technologies (CCD / CMOS). “Whiter” pixels have many trapped electrons and will be easily identified, provided they do not coincide exactly with one star. Black pixels will generate stable minima, irrespectively of the attitude motion. While the S/C is performing an attitude manouevre, images with different integration times should be acquired and analyzed by multiple cross-correlation to locate actual stars. A systematic local analysis will then proceed to locate defective pixels and update their list. This process requires previously obtained noise statistics, should be repeated several times with decreasing integration times and may trigger fine-tuning of local thresholds in case of CMOS sensors.

Flat field - The concept applies to noise non-uniformities (DSNU and PRNU) and to stray-light monitoring. The former should be reasonably stable, the latter depends on the orientation of the camera with respect to the brightest sources within and around the FOV of the camera(s). Flat field calibration is performed for a given baseline direction. It requires a set of images (~3-5) synchronized with attitude motion – which should be a function of the known orientation of the potentially disturbing bright object. Algorithms are simple, most probably an analysis of minima, and should generate (for example) fine tuning of pixel offset or gain coefficients (in case of CMOS sensors).

Thermo-elastic effects - Once ON camera(s) are calibrated, this mode amounts to observing the same pattern of stars simultaneously with the ADCS sensor, in case their FOV intersect partially (as they should) and should be repeated regularly during the mission. A reasonable a priori knowledge of the actual orientation of the S/C and of the ON camera in the satellite reference frame should facilitate star detection and recognition. Many algorithms can be used to estimate the relative quaternion between both reference systems. A high level executive module should accumulate and filter this data to generate compensation quaternions for navigation LOS estimations.

3.6.2 – Spot modes

A - No beacons - In this mode the ON camera(s) act as star mappers. An on-board star catalogue (e.g., Tycho 2) is required, previously processed in order to contain visible stars and cut into sections according to mission profile.

The photo-elastic effect should be “continuously” monitored. Attitude uncertainty might be computed by using one set of stars for attitude estimation and another independent set for assessment – this should be feasible only for certain regions in the sky, with larger density of stars. This study must be performed simultaneously with camera(s) design because it must be strictly ensured that a minimum number of stars are always visible. It therefore affects ON camera specification and performances.

The IP algorithm is based on spot detection within several regions of interest (ROI), validation against the list of defective pixels, and either multiple cross-correlation (in case there is an extended glyph) or maxima location with 2D (Gaussian or parabolic) fits, to accurately locate stars. Charge integration around maxima should help validate star identification (at least in relative terms; the processed working catalogue should store a measure of integrated charge for each star, taking into account its magnitude, spectral class and camera sensor sensitivity and spectral response); nevertheless, if attitude is available from ADCS, charge information is probably not needed. An adequate interface between ADCS and IP would be welcome to eliminate the “lost-in-the-space” problem.

IP must perform several function in this mode: removing defective pixels and sensor noise, finding candidate points to be identified as stars (using MCC or simple centroiding), and performing star identification by mapping images into the star catalogue. Attitude may be estimated by algorithms such as the QUEST. Star mapping is a complex exercise of computational geometry, which amounts to finding a pattern within a background (Figure 8), whatever the relative orientation - which is the very goal of the mapping. Apriori knowledge of the S/C orientation helps in order to restrict the search. Use of star magnitudes (provided IP builds such estimations) helps reducing false positives and should be required in case of smaller number of stars with larger magnitudes within the FOV (which will inevitably happen when LOS specifications are more demanding and the FOV is smaller).

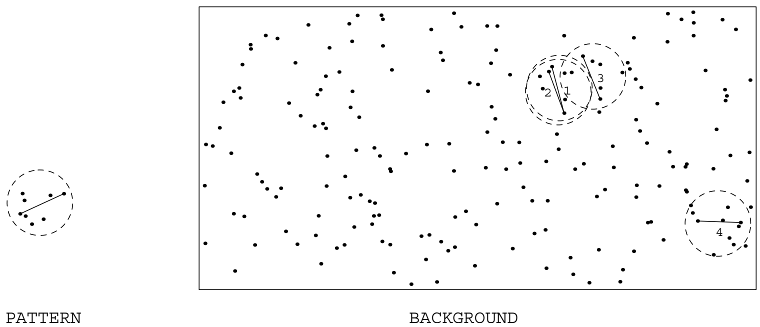


Figure 8 – Star matching - intermediate phase of the algorithm, with still 4 best cases to process

B - Bright spot beacons - In this mode, the beacon may be much brighter than stars and therefore saturate the image or may have a magnitude of the same order of magnitude of the background stars. Very faint beacons are handled next. If the beacon and stars can be imaged simultaneously (without saturation) the only difference between the beacon and stars is, eventually, beacon transverse displacement during the integration time, which would blur the image. As the expected magnitude, location and velocity of the beacon are known, the image analysis has to take place only within a small ROI, requiring the detection of small lines. Care must be taken if the ROI contains defective pixels, in case a small attitude manoeuvre may eventually be needed. As an alternative, if the beacon is bright enough, the integration time may be reduced (in a sequence of images) in order to locate the beacon more accurately, while not jeopardizing the visibility of a pattern of stars enabling attitude determination.

If beacons are too bright we may have two options: 1. in case of CCD sensors, a fast sequence of 3 images may be acquired: the reference star pattern is identified in images 1 and 3, while the beacon saturates; 2. alternatively, for CMOS sensors, one image may be acquired, the beacon can be coarsely located, local offset / gain parameters within the ROI adjusted, and a second image acquired, therefore enabling stars and beacon in the same image at the same time.

For the first option, the 1st and 3rd images are used to estimate attitude, and attitude is interpolated for the 2nd image containing information on the bright beacon. The time interval between t_1 and t_3 is short and for relatively stable spacecrafts, interpolation should be accurate enough. Again, the ADCS system might provide reliable information for t_2; in such case, interpolation should be replaced by sensed attitude.

C - Faint spot beacons - This requires the multiple time integration (MTI) mode which was tested successfully with Cremona asteroid from a ground telescope in the ESA AutoNav project. A sequence of N images is acquired; in the 1st image, 3 reference stars are located accurately; these stars will be tracked in all the remaining images, allowing to register all the images over the first one; if lens distortion is completely under control, image registration accounts for translations and small rotations; the expected location of the faint beacon is known and a ROI is setup around that location, as small as possible but complying with estimation uncertainty; image registration must be performed only within the ROI, which reduces computational burden; when all N ROI's are geometrically corrected, they can be integrated, therefore increasing the SNR within the ROI, and making visible beacons up to magnitude 13 or even fainter. For CMOS sensors, N can be made smaller (in AutoNav 30 images were used) because gain can be locally controlled; nevertheless this also increases noise and trade-offs must be performed with realistic CMOS sensor noise levels. A typical result was presented in Figure 5.

The MTI process must be repeated (at least) three times, with an adequate temporal separation. A list of candidates is generated each time MTI is run, comprising the beacon, eventual noise spikes and faint images which are made visible by the same process. In order to find the beacon, all possible triples of candidates are analyzed from the point of view of the actual trajectory in time, and the one complying with the dynamics of the beacon is retained. The process may be simplified if anticipated beacon position is trustful, by reducing the ROI and therefore the number of candidate sequences.

The MTI process is sketched in Figure 9. The first image in every MTI sequence is used to determine attitude. The upper-right box must ensure that image data is integrated within the ROI (where the beacon is likely to be), for several images; the ROI should be as small as possible, not only to reduce computational burden but also to reduce the number of detected maxima. Data should be prepared by using the most adequate set of reference stars (upper left box), taking into account that reference stars should be visible in all frames, coping with spacecraft attitude instability. Finally, the lower box generates candidate locations of the beacons. This is a critical phase because for very faint beacons, the searched object has the same structure of noise. A trade-off must be setup between the number of accepted candidates and the complexity of the algorithm of validation by propagation.

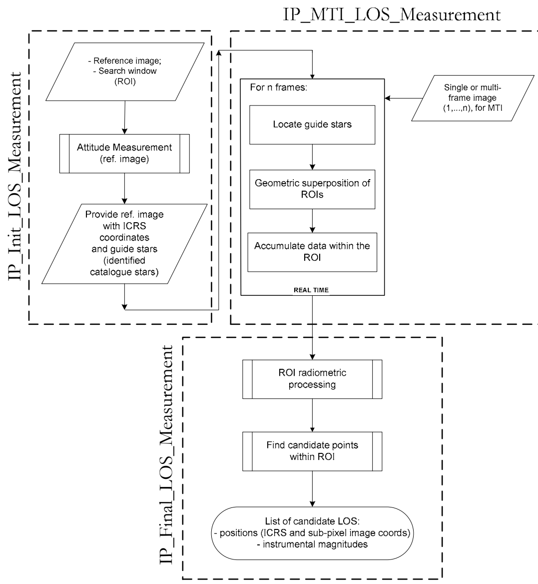


Figure 9 - Architecture of MTI

Only the sequences showing adequate relative positions of the candidate beacon (in the validation by propagation, positions should be compatible with a line segment in focal plane) and radiometric consistency (radiometric validation) should be accepted, ideally, only one. Propagation validation is potentially time consuming if too many candidates are generated but should not be discarded.

MTI request an adequate dialogue with ADCS to speed up the identification of the reference stars to be used for image registration. Tradeoffs between CMOS processing and MTI should be assessed for each ON camera, by playing CMOS gain (and derived noise levels) against the number of images.

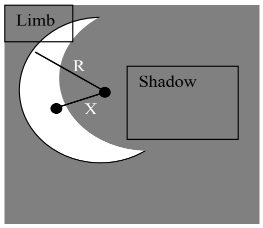
3.6.3 Extended object modes

Extended objects are classified as *small* or *large*, according to the possibility to use limb information. In practice, the difference between large and small is set around ~20 pixels. For smaller sizes, it is meaningless to expect to have well defined limb arcs we may fit ellipses to. In addition, IP modes are different for objects fully within the FOV or only partially within the FOV. There are, therefore, several sub-modes.

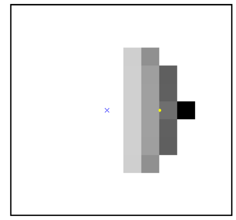
A - Too small bright bodies fully within the FOV - Again, sub-modes may be necessary in case beacon is too bright and forbids simultaneous visibility of the star pattern to enable attitude estimation. Options have been discussed above requiring 3 or 2 images. Once the beacon is well identified within its own ROI, the issue of beacon phase must be addressed. Phase refers to the relative geometric configuration between the beacon illuminating body (the sun, a large planet), the beacon itself and camera. Zero phase means a "full moon (spherical)" configuration, 180º phase means a "new moon" configuration. As phase increases, body magnitude is reduced accordingly. When the image size of the beacon is less than 10-20 pixels, contours cannot be resolved properly. IP can estimate only the COB and use the COB as an estimator for the COM – which is the relevant navigation parameter. Now, for spherical and lambertian objects, a COB→COM correction exists which can improve COM estimation from COB. When the beacon is small and spherical (with known radius, R), phase compensation may apply, if the direction of the illumination source is known and the object can be considered as lambertian. IP methods easily determine the COB, the correction towards COM is applied along the illumination direction (projected on the focal plane) and is given by:

$$X = \frac{3\pi}{16} \frac{\sin\alpha\left(1+\cos\alpha\right)}{(\pi-\alpha)\cos\alpha+\sin\alpha} R$$

α is the angle between the illumination and viewing directions (Figure 10). For non-lambertian, non-spherical objects or for objects illuminates simultaneously by two sources (sun and planet) no such correction exists.



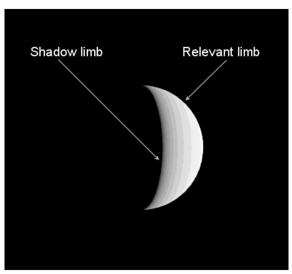
Relation between the COB and COM
for spherical beacons



Small planet with 10 pixel diameter and 90 degrees phase.
COB: Yellow marker. COM: Blue cross.

Figure 10 – Phase compensation for small extended objects

Large objects fully or partially within the FOV - Composite modes are necessary when the object is too bright and disturbs visibility of the star pattern to enable attitude estimation. These modes are illustrated in Figure 11:



a)

b)

Figure 11 – Difference between a) Full Object within the FOV and b) Large object partially within the FOV. a) Illustrates the difference between the limb and the terminator (shadow limb)

Once the body is well identified within its own ROI - as small as possible, although providing enough background to apply detection techniques by thresholding, for example - contours must be carefully estimated. There are, in general two contours, the *limb* (lit-to-space border) and the *terminator* (lit-to-non-lit transition). The former is generally useless, because the transition is smooth (although it might be conceivable to use the terminator for shape estimation in case of irregular and unknown asteroids).

Although limb and terminator are relatively easy to extract globally, it is more difficult to discriminate limb from terminator. Contrast around transitions and known illumination direction help, but in case of strongly irregular asteroids, the lit area may be split into different pieces and the analysis becomes much more complex – especially because it must be computed on-board and without knowing the actual 3D shape of the object. In such cases – unknown 3D shape and instantaneous relative geometry – an ellipse can be found to integrate all lit "pieces" in its interior, but no use can be made of limb arcs. A particularly critical case is the "full moon" configuration (zero phase angle) because there is no terminator and the limb is closed (in some cases, circular or elliptical); robust IP methods to deal with this case are still under development.

When there is only one visible lit piece, limb identification is a seemingly simple process, although it must be implemented as an iteratively because the normal to the contour is not known initially and must also be estimated by radial profile analysis from "current central" points. Once limb pixels are located (and the criteria may be space-variant especially when phase is large – an ellipse can be found to fit to such points. For spherical objects we can therefore get a very reasonable estimation of the centre of the sphere, which is not necessarily the COM. For non-spherical objects either the centre of the ellipse is taken as COM or further analysis must be pursued with shape information. When the object is known to be an ellipsoid, it is conceivable to try to match the observed limb with borders of ellipsoid perspectives, although the spinning axis and angle of the asteroid are not known; nevertheless, for ellipsoids, this method should not lead to unique solutions if no additional data (landmarks) is available.

These models were further improved in the context of the ESA Mars Return Sampler preparatory technology development, where a spherical canister approaches an orbiting spacecraft carrying an ON camera to drive GNC. Camera specifications are driven by the need to detect the 20 cm canister at 5 km in normal sun illumination, at the orbit of Mars. Mars diffusion must be considered. It is necessary to estimate the LOS to the centre of the canister and estimate range from the measured radius of the canister, which carries a set of 12 retro-reflectors (RR), in an icosahedron configuration, that are imaged as dark blobs when resolved. In the worst case, these dark spots cause interruptions in the, otherwise, circular shape of the limb. Sun phase and azimuth are assumed to be known. The strategy was to proceed in stages, improving the circular fit of the limb in each stage, as represented in Figure 12 and Figure 13.

The image is thresholded to obtain a crude initial segmentation of the canister, a blob. An elliptical fit to the blob provides the initial estimate (Figure 12). The ellipse larger axis is a good approximation of the canister radius and the ellipse centre, shifted by a phase compensation (computed from the Sun phase and azimuth), provides a good estimate of the centre of the canister. This initial circle estimate if further improved by limb analysis. The limb is scanned along radial profiles to pinpoint, with sub-pixel accuracy, the dark to bright transition. A robust circle estimate is computed from these limb points (following the RANSAC algorithm, Figure 13) to cope with limb imperfections due to the RR's. The process is iterated a few times to cope with limb imperfections, due to the (possible) presence of RR's near the limb which may mimic visible limb irregularities in an (almost) spherical planet.

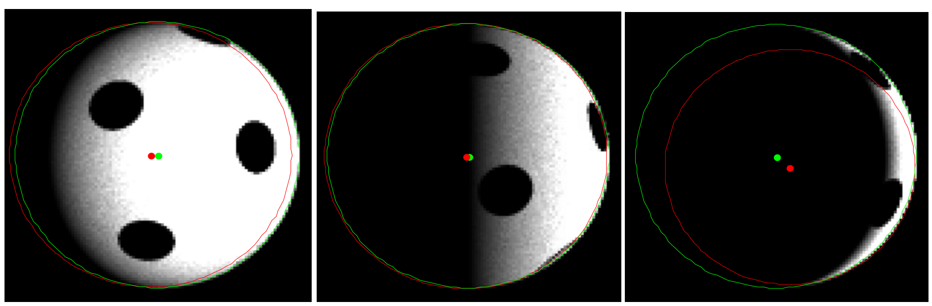


Figure 12 – Fitting circles to limb. Red: initial estimate, fitting an ellipse to an initial blob (phase compensation). Green: true circle.

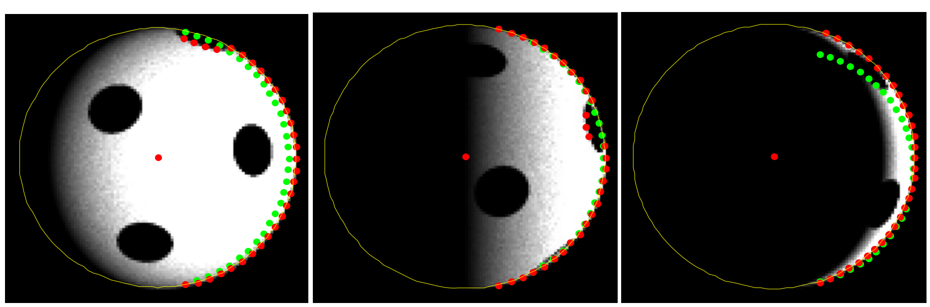


Figure 13 – Further improvement of the circle fit to the limb

When the target is partially within the FOV problems may be mitigated by either 1. switching to a larger FOV camera or 2. implementing a *tracking* procedure from the previous IP mode. The first option may solve the problem (although with smaller accuracies) or just delay it, because the object will actually overfill the FOV again, although for a smaller range. The second option assumes that a reasonable management of the complete geometric situation is active, a function that is not yet considered by space agencies. We called it P2M or Projects 2D Model.

When objects are partially within the FOV, limb and terminator arcs are intersected (and split into several arcs) by image borders and the same arc may reappear elsewhere in the image. This mode is typically run in a “snapshot” mode, with complete independence between frames. It is therefore necessary to ensure continuity and arcs tracking (both limb and terminator arcs) from the "full within FOV" phase. The position of the ON camera is dynamic and silhouettes do not correspond to the same perspectives (scales are also different due to different ranges); this is part of P2M task: accumulate and ensure consistent geometric representation of the target within the ON FOV, both when approaching or leaving the target, as mission proceeds.

In addition – even for perfectly spherical objects - the radius of curvature R of the limb increases (when approaching) which will increase COM uncertainty. Worse: when R increases the number of limb pixels decreases (the limb is intersected by image borders) and COM uncertainty increases even faster.

3.6.4 Conclusions

Most of the reported problems and limitations require optical flexibility: number of cameras or zoom lenses. Several missions have flown two ON cameras (in addition to star mappers) but these are exceptions. Several cameras also increase the thermo-elastic problems. Flexibility also requires more elaborated and performing IP models which requires larger computer resources - still scarce in space. The most challenging and interesting alternative are zoom lenses, bringing two very large sets of problems still pending: new technologies to ensure robust mechanisms within the lens and accurate calibration methods to be executed on board using available resources: patterns of irregularly distributed stars.

4. ACTIVE OPTICAL NAVIGATION - SOME EXAMPLES

Active ON relies on lasers or LED's and can fulfill different roles. LIDAR's can be used to estimate surface topography during autonomous landing, and therefore generate range and hazard maps (slope, boulders and craters) during descent. Lasers can also be used to illuminate passive rectro-reflectors (RR) on other S/C in multi-element constellations; in a lidar mode, range can be estimated, otherwise accurate LOS to RR's becomes available and range can still be estimated indirectly from the image acquired by a camera collocated with the source. Finally, LED's can be used to create a pattern of light spots on the target S/C that can be imaged by the chaser S/C and all observables are extracted by IP. In general, active ON makes navigation independent of environment / illumination conditions

Active ON also encompasses optical systems in charge of the internal metrology of constellations of free-flyers satellites. Frequency sweeping interferometers to measure distances to within 1µm @ 100 m have been demonstrated, as well as trains of ps laser pulses in Michelson interferometers, simple lateral interferometers for transverse displacements or multi-wavelength interferometers for longitudinal metrology. In this wider sense, ON can comprise all optical systems delivering accurate information on relative distances and attitudes between different S/C's. Traditional ON deals usually with one S/C, extended ON also includes these new tasks for configuration management of constellations.

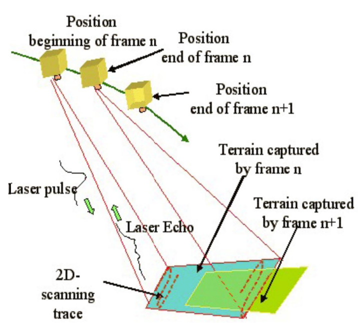


Figure 14 – Lidar assisted autonomous landing

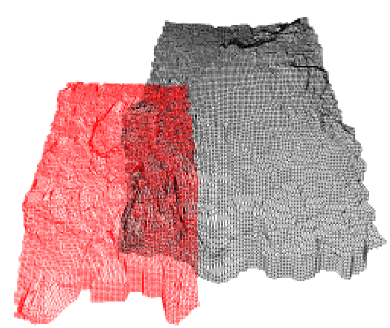


Figure 15 – Consecutive lidar frames

Lidar's to build surface topography in case of landing must overcame several challenges. As shown in Figure 14, the S/C falls while one lidar frame is being acquired, therefore the sampling of the surface and the SNR are not uniform within each frame. In addition consecutive frames (projected on the surface) partially intersect (Figure 15) and the $(n-1)^{th}$ frame must be re-processed within the area in common with the n^{th} frame to improve estimations of linear and angular velocities and accelerations. From the analysis, both the actual trajectory and the surface topography (therefore the slope and roughness maps) are derived. This huge computational burden can be minimized by reducing the fall of the S/C within the frame duration, and this means a new generation of lidar's, with strip-based illumination and parallel detection. This is an on-going activity in ESA, aiming at more than 1 million of pixels per second, 1 Hz operation, from 5 Km down to 10 m above the surface (cm-level resolution).

As a final example, ON is baselined for a rendezvous (RdV) experiment in ESA Proba 3 mission [14] following ON activity led by INETI / FCUL and Deimos Engenharia in this field for the last 10 years (Figure 16). This RdV experiment will test sensors and algorithms for Rendezvous (cooperative and uncooperative) in elliptical orbit. This technology could be used for a future Mars Sample return mission and for de-orbiting satellites from low-Earth orbit. Proba 3 implements a solar coronograph using two small S/C, but is essentially a technology demonstration mission for formation flying technologies. The RdV experiment includes a pattern of light spots (LED's) (Figure 17), a visible camera supplied by DTU (Denmark Technical University), the IP software to estimate range and relative attitude between the two S/C's and the GNC system (Figure 18) that will take the control of the Proba 3 configuration for four complete orbits. Proba 3 is scheduled for launch in 2017. The experiment will take place in a wide variety of conditions in terms of range and solar illumination (no eclipse conditions are currently considered).

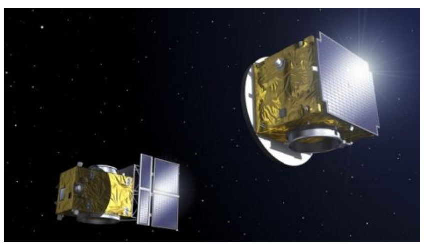


Figure 16 – Proba 3

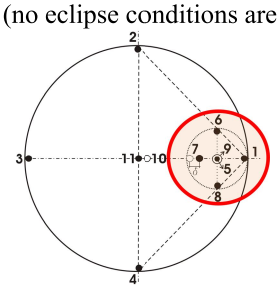


Figure 17 – Active light pattern

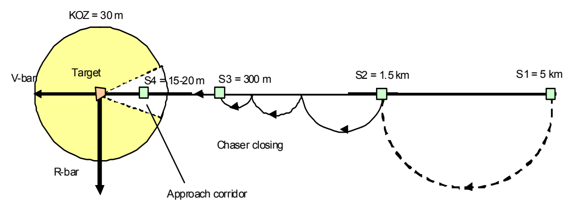


Figure 18 – GNC concept

The geometrical transformation between object and image being a general affine transformation (angles, areas and distances are not invariant, but images of collinear points are collinear and when lines intersect, their images also intersect), the light pattern contains: 1. two independent and scaled patterns (to be used in the far and in the low range), 2. several linear alignments between spots such that their intersections contain meaningful information, 3. slight geometric and radiometric asymmetries to remove rotation ambiguities and 4. an out-of-plane light spot to enable attitude determination in the short range. Several IP modes must be considered: in the far range no spots are resolved; then the outer pattern is resolved, and subsequently, the small pattern is also resolved; finally the outer pattern is no longer within the FOV and for the minimum specified range (either docking or, in case of Proba 3, 10 m) the smaller pattern no longer fits within the FOV. Due to geometrical optics laws, the transitions between modes are too smooth and too slow. This is the main challenge to IP, tasked to estimate LOS, attitude and range: to recover information from such extended transition ranges.

5. CONCLUSIONS

ON systems need to be extended to mature further the developed IP and navigation algorithms while adding new online functionalities such as recognition and tracking of known surface landmarks, hybridization with other measurements such as star tracker and ground-based radiometry, and offline functionalities such as shape model and landmark database generation.

In general, there is a need to increase further the TRL of optical, autonomous, interplanetary navigation in order to develop a robust design of a vision-based autonomous GNC and autonomous mission-planner, including autonomous guidance. Efforts should target the improvement of the end-to-end accuracy performance e.g. through the optimization of the navigation strategy based on optical beacons and planetary limbs, on multi-head sensors to reduce thermo-elastic distortion, on the possibility of multiple windowing with APS star-trackers.

This paper is by no means a treatise on space optical navigation techniques. It condensates part of the experience of the last 12 years in the field in ESA projects and in close interaction with the industry, for which optical navigation is a black box that provides measurements required by GNC: line of sight, range, attitude angles. The photonic and the computer vision perspectives are not independent and, very often, signal processing and statistics do enable compliance with specifications. The dialogue between ON and the other spacecraft subsystems is tough and system engineers handling space missions and systems are not yet ready to accept limitations or specific requests from ON. I therefore tried to highlight areas where there should be the opportunity to reconsider some details of space systems architecture. Personally, I strongly believe that once programmable zoom lenses can be space qualified - but the technology does not exist, yet - the potential of optics and photonics in space will revamp considerably.

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GLOSSARY

ADCS	Attitude Determination and Control System
AN	Autonomous Navigation
AODCS	Attitude and Orbit Determination and Control System
APS	Active Pixel Sensor
CCD	Charge Coupled Device
CMOS	Complementary Metal-Oxide-Semiconductor
COB	Center of Brightness
COM	Center of Mass
DDOR	Delta Differential One-way Ranging
DS	Dark Signal
DSNU	Dark Signal Non Uniformity
ESA	European Space Agency
FCUL	Faculty of Sciences of the University of Lisbon
FOV	Field Of View
GNC	Guidance, Navigation and Control
HM	Hazard Map
IMU	Inertial Measurement Unit
LIDAR	LIght Detection and Ranging
LOS	Line Of Sight
MCC	Multiple Cross Correlation
MEX	Mars EXpress
MRS	Mars Return Sampler
MTF	Modulation Transfer Function
MTI	Multiple Time Integration
ON	Optical Navigation
PRNU	Photo-Response Non Uniformity
PSF	Point Spread Function
QUEST	QUaternion ESTimator
RANSAC	RANdom SAmple Consensus
RDV	RenDezVous
ROI	Region of Interest
S/C	SpaceCraft
SNR	Signal to Noise Ratio
TRL	Technological Readiness Level