Rosetta Optical Navigation

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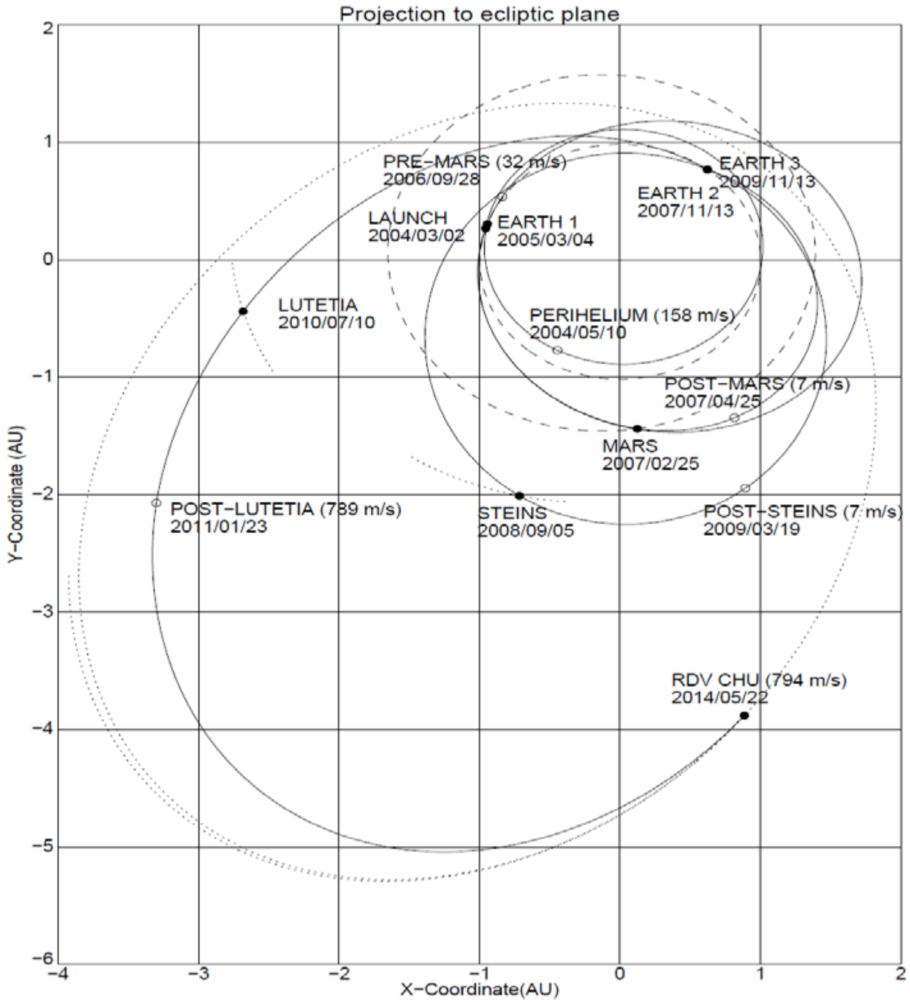
Overview

Rosetta: Mission and Spacecraft

Asteroid Flybys (Steins):
- Scenario
- Navigation Strategy
- Image Processing
- Autonomous Attitude Steering

Near Comet Navigation:
- Landmark Detection
- Image Processing

Rosetta Orbit / Ecliptic Projection



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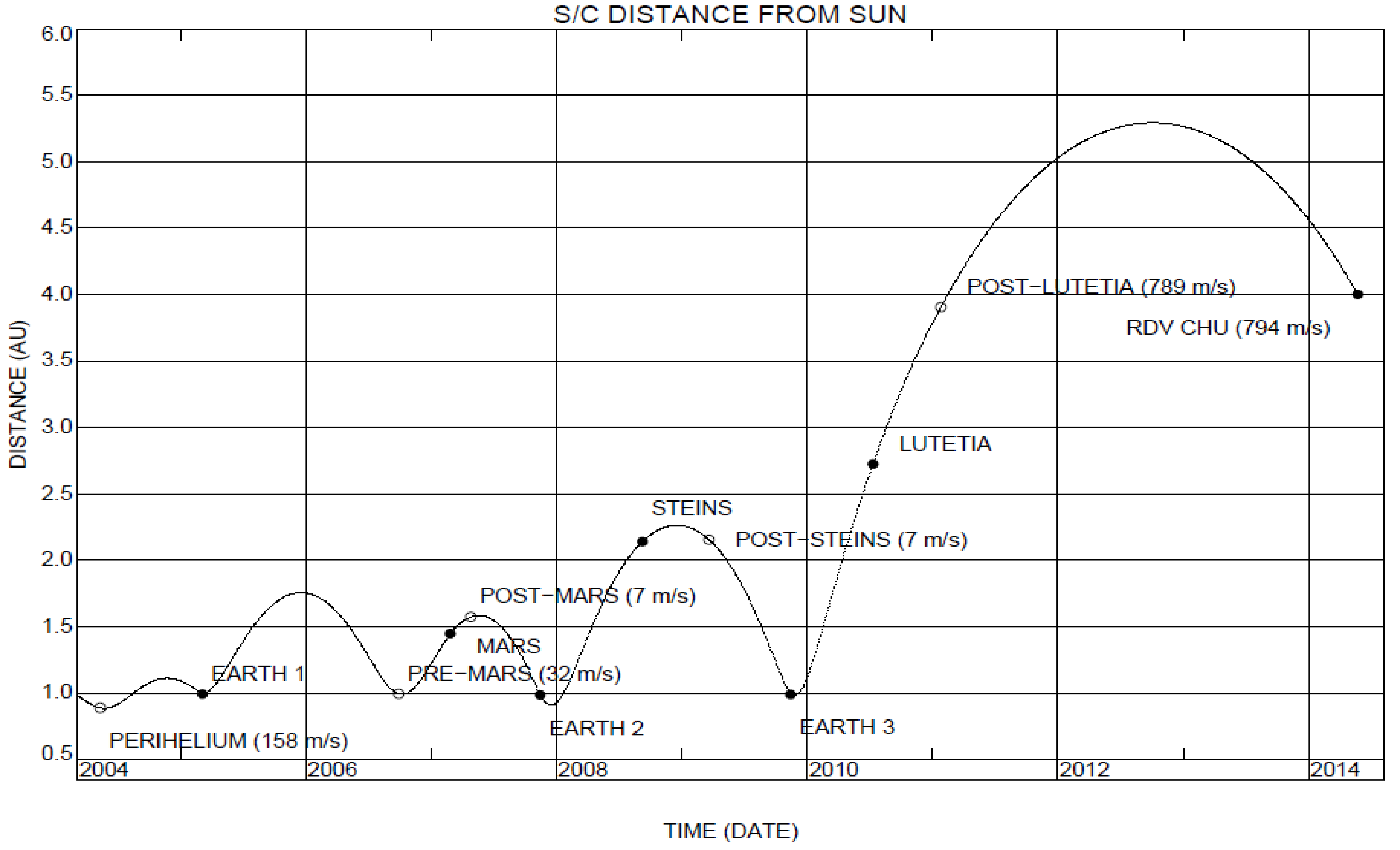
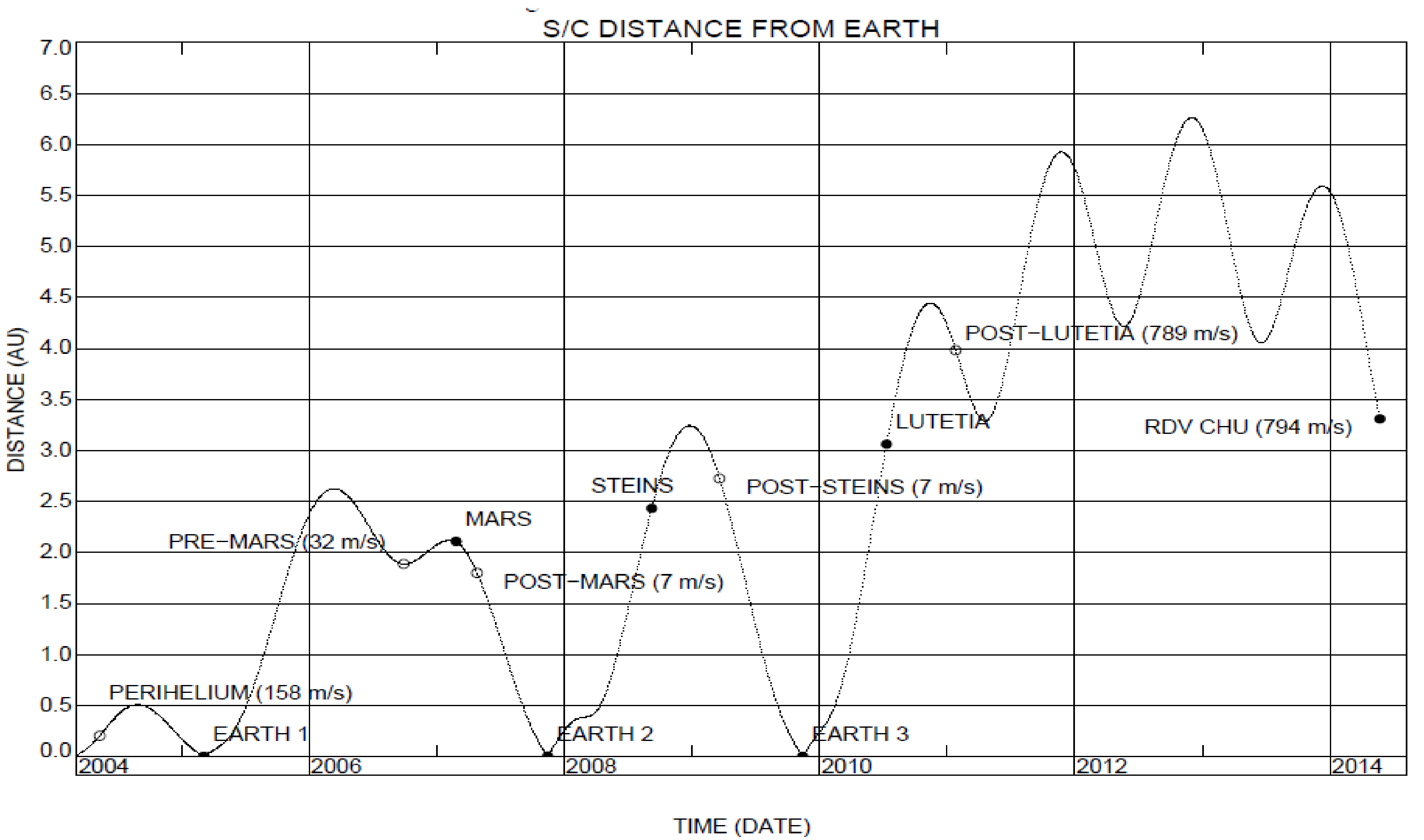
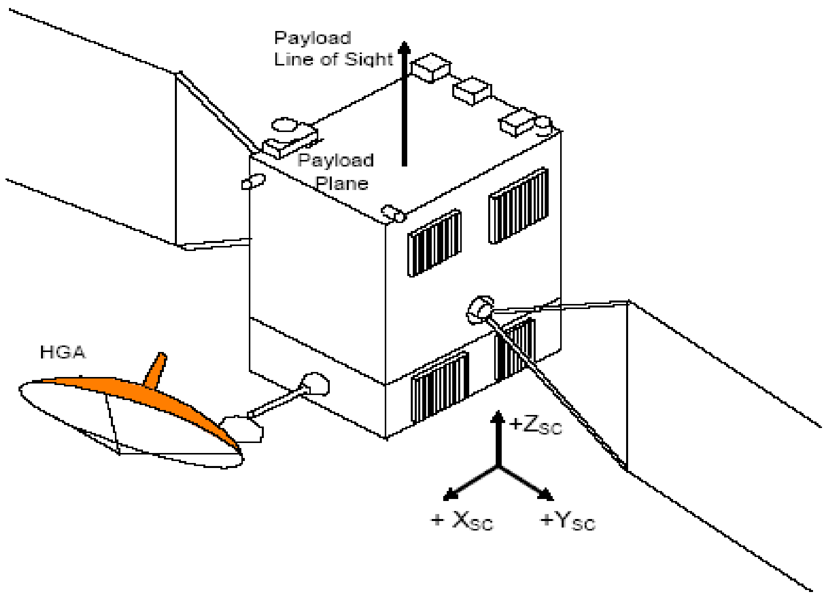
Rosetta Orbit / Sun Distance



Rosetta Orbit / Earth Distance



Rosetta Spacecraft



Geometry:

Box 2.0 m x 2.1 m x 2.6

2 Solar arrays 2.3 m x 14.4 m

Mass: 1343 kg dry and 1725 kg propellant at launch

RCS: 2x8 10N thrusters for attitude control (OCM / WOL / safe mode)

2x4 10N thrusters for orbit manoeuvres

Attitude control: 4 RW

Attitude sensors: 2 STR, 3 IMU (3 gyros & 3 acceleros), 4 SAS

Communication: articulated HGA (1.1 m radius dish), MGA, 2 LGA's

Navigation: 2 cameras (Navcam)

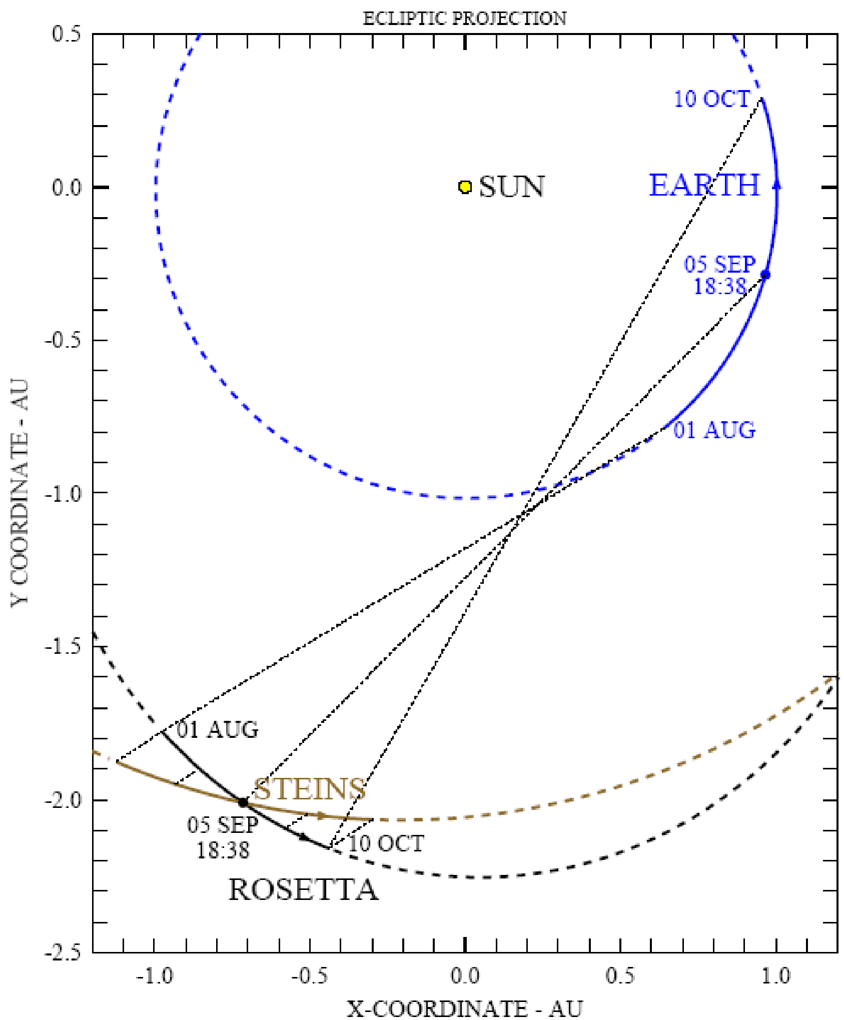
Payload: OSIRIS NAC & WAC cameras, …

Rosetta / Cameras

The relevant properties of the on-board cameras are:

	CAM	Osiris/NAC	Osiris/WAC
Optics Type	7 lenses	3 mirrors	3 mirrors
Filters	3 filters	dual filter wheels	dual filter wheels
Sensitivity	11 mag	> 15 mag	n/a
Field of View (deg)	5 x 5	2.2 x 2.2	11 x 11
Pixels	1024x1024	2048x2048	2048x2048
Resolution (angle per pixel)	5 mdeg	1 mdeg	1 mdeg
Pixel capacity	70,000 el	100,000 el	100,000 el
Resolution (bit/pixel)	12	16	16
CCD temperature	-10 +/- 10 degC	160K-300K	160K-300K
Data vol/image (bit)	13 M	67 M	67 M
Data vol/coverage (bit/deg^2)	0.50 M	13.9 M	0.55 M

Rosetta Trajectory at Steins Flyby



Nominal date of closest approach (CA): 2008/09/05 18:38:16 UTC

Sun distance: 2.1 AU

Earth distance: 2.4 AU

Signal delay: 20 minutes

Flyby speed: 8.616 km/s

Phase angle at approach: 38 deg

Asteroid Navigation Principle

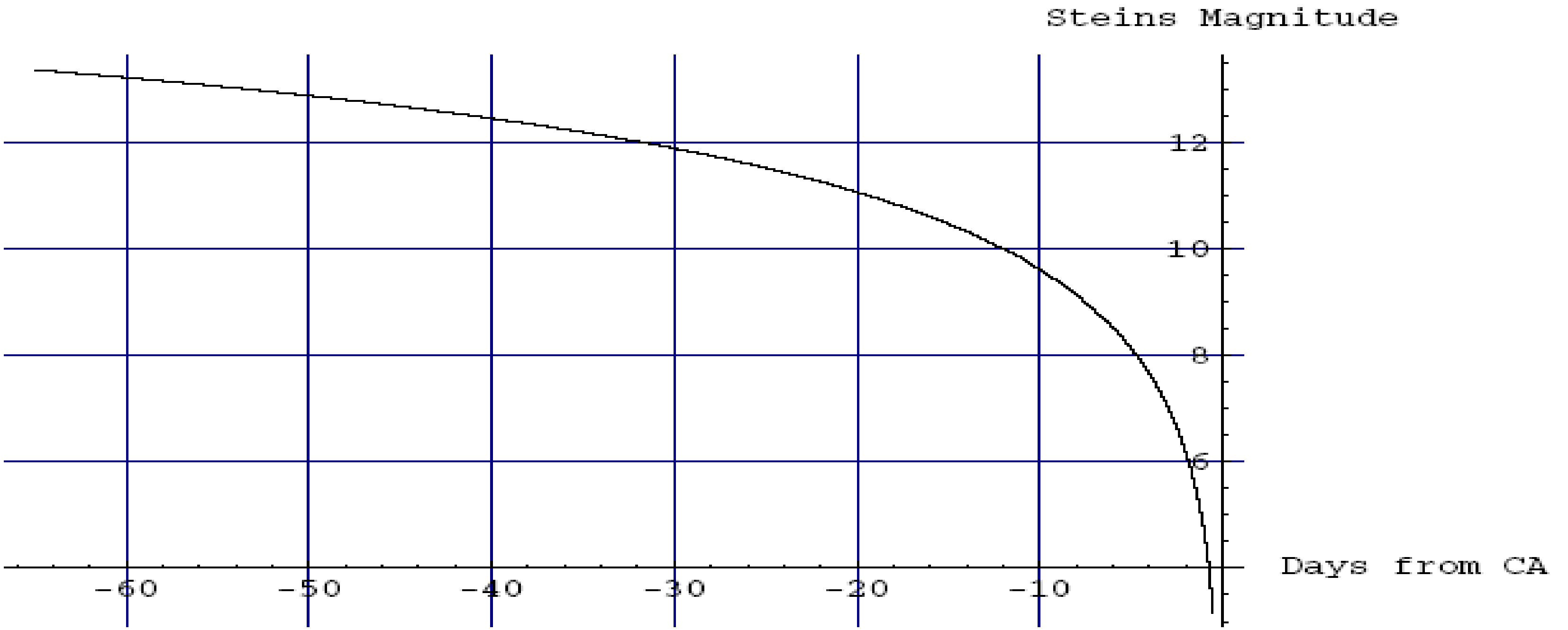
Initial knowledge of absolute asteroid position:
- orbit determination from ground based observations
- accuracy in the order of 100 km (1σ), in each component

Navigation cycle:
- acquire images with on-board cameras and reduce to optical measurements: inertial line-of-sight from S/C to asteroid
- improve knowledge of relative asteroid position in target plane (knowledge of relative position perpendicular to target plane, i.e. equivalent to flyby time, can not be improved from optical measurements)
- determine and execute orbit manoeuvre to guide the S/C towards target (i.e. 800 km flyby distance and 0 deg minimum phase angle)

5 Navigation cycles were allocated for Steins navigation

Asteroid Steins / Brightness

Brightness (logarithmic scale) depends on distances (asteroid -> Sun and asteroid -> S/C) and phase (angle Sun-asteroid-S/C).
Standard IAU phase function for asteroids depends on slope parameter.
Brightness parameters were calibrated by Osiris
Light curve: +/- 0.2 mag over 6.1 hrs period
Predicted diameter: ca. 5 km



Steins in Plane of Sky

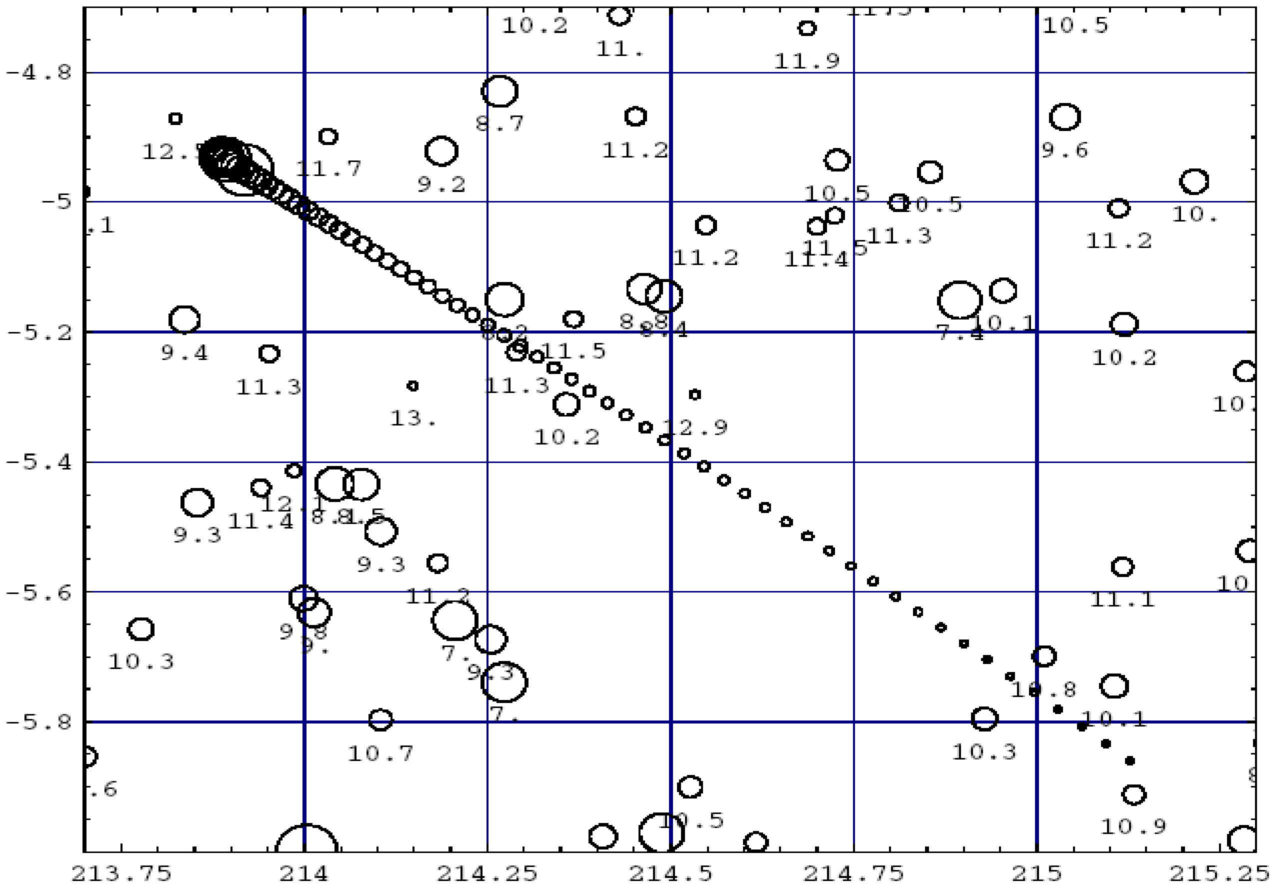


Figure 2: Steins apparent motion from CA - 65 days to CA - 1 day
horizontal axis: right ascension (deg) / vertical axis: declination (deg)

The figure shows Steins in the plane of sky as seen by Rosetta.

The position is shown once per day.
The size indicates brightness.

The stellar background is taken from Hipparcos/Tycho catalogue (complete up to magnitude 11).

Relative motion: 40mdeg/day, slowing down until CA – 4 days.

Image Processing / Image Acquisition

1) Storage of images on-board in mass memory

2) Download to ground during passes
   (ca. 3 hrs required for 1 obs. slot)

3) Conversion from raw TM to image format
   For Navcam:
   - raw TM is retrieved from the MCS/TM archive to the FDS and converted into FITS format
   For Osiris/NAC:
   - raw TM is retrieved by the Osiris team from the DDS, converted to PDS format and published on dedicated web server
   - the images are downloaded by HSO-GFS from the web server to the FDS/devlan, transferred to the opslan and converted into FITS format

Image Processing / Objects on CCD

Pre-processing:

Determination of mean background level and background noise

Object Detection:

Mode 1: - Identification of all pixels with significant signal on CCD
- Grouping of adjacent pixels with significant signal to objects

Mode 2: - Prediction of star and target positions on CCD based on predicted attitude
- Identification of all pixels with local maximum close to predicted positions

Image Processing / Centroiding

Centroiding:

Determination of object centre position from matrix of pixel values

201	220	230	213	203
209	290	561	272	208
216	341	1343	308	222
210	242	301	237	202
202	205	210	201	200

Several methods were implemented:
- 1 dimensional, 2 dimensional
- barycentre, parabola fit, gaussian fit
- symmetric window around maximum, all pixels above background

All methods show similar performance

Image Processing / Object Directions

Object directions in camera frame:

Ideal Projection (from direction to pixel position):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} \rightarrow \begin{bmatrix} x/z \\ y/z \end{bmatrix} * \, focalLength \Big/ pixelSize$$

Optical distortion is deviation from ideal projection:

fit of 5^{th} order polynomial for Navcam (GAL)
fit of 3^{rd} order polynomial Osiris/NAC (Osiris)
deviation increases up to several pixels towards the edge of the FoV

Object positions on CCD are converted into directions in camera frame using a transformation (inverted projection) including optical distortion.

Image Processing / Star Matching

Object directions in inertial frame:

A first camera attitude refinement is computed by matching only the brightest stars in the field of view using predicted attitude and camera alignment.

Based on the refined attitude, object directions are predicted in inertial frame for matching against the Hipparcos/Tycho star catalogue

Star and target matching:

Objects are matched against a star in the star catalogue if there is a unique star within a match radius around the object direction, and if there is no other star within a wider search radius (to avoid close neighbours).

Star directions, used for matching, are corrected for proper motion, parallax and stellar aberration.

Image Processing / Target Direction

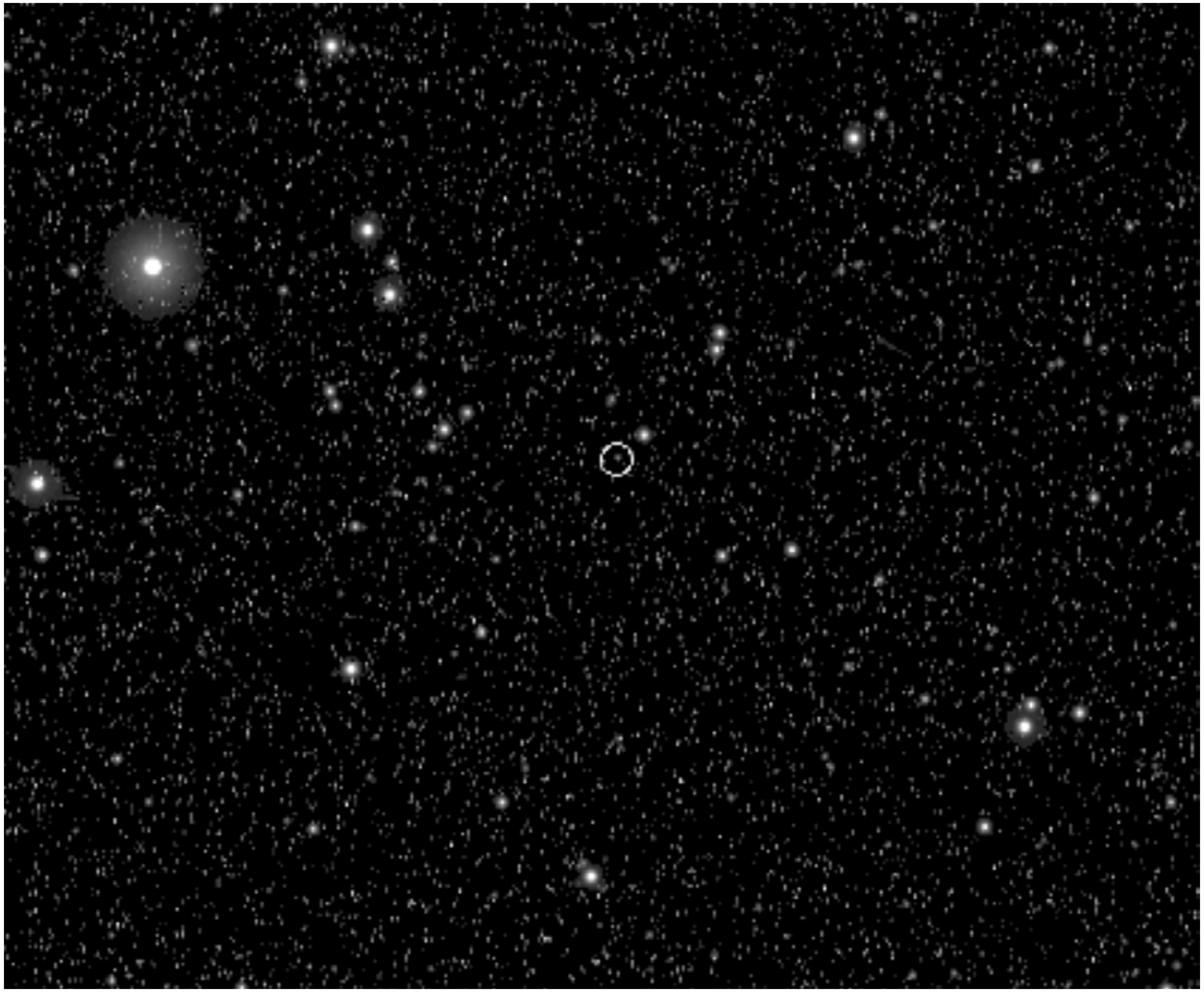
Target direction determination:

Input:
- List of star direction pairs (for each star, its direction in camera frame and in inertial frame)
- Target direction in camera frame

Method:
Using a batch least squares method, the optimum attitude of the camera is determined which minimizes the residuals of the measured against the predicted directions of all matched stars. (During optimisation, stars with high residuals are rejected)
Based on the optimum attitude, the target direction in camera frame is converted into apparent direction in inertial frame.

Output:
The apparent target direction is corrected for stellar aberration to find the true target direction.

First Steins Observation from Navcam A



-Date: 2008/08/04,
CA - 32 days

- Image size:
  ca. 3 deg x 3 deg
  (205 pix/deg)

- Distance to Steins:
  24.5 Mio km

- Magnitude: 12

- Exposure time: 30 s

- ‘small’ dots are white pixels

Navigation Schedule (1)

Observation Slots:

In total 17 observation slots:
- Weeks CA - 5 to CA - 3 prior to CA: 2 observation slots per week
- Last 2 weeks prior to CA: daily observation slots until CA – 1 day

In each observation slot: 5 Osiris/NAC images + 1 Navcam obs. slot

Timeline of Navcam observation slot:

+ 5 min:	5 images with Navcam A
+ 20 min:	5 images with Navcam B
+ 30 min:	Navcam A&B tracking mode for 25 minutes
+ 60 min:	Navcam A&B tracking mode for 25 minutes
+ 95 min:	5 images with Navcam B
+ 110 min:	5 images with Navcam A

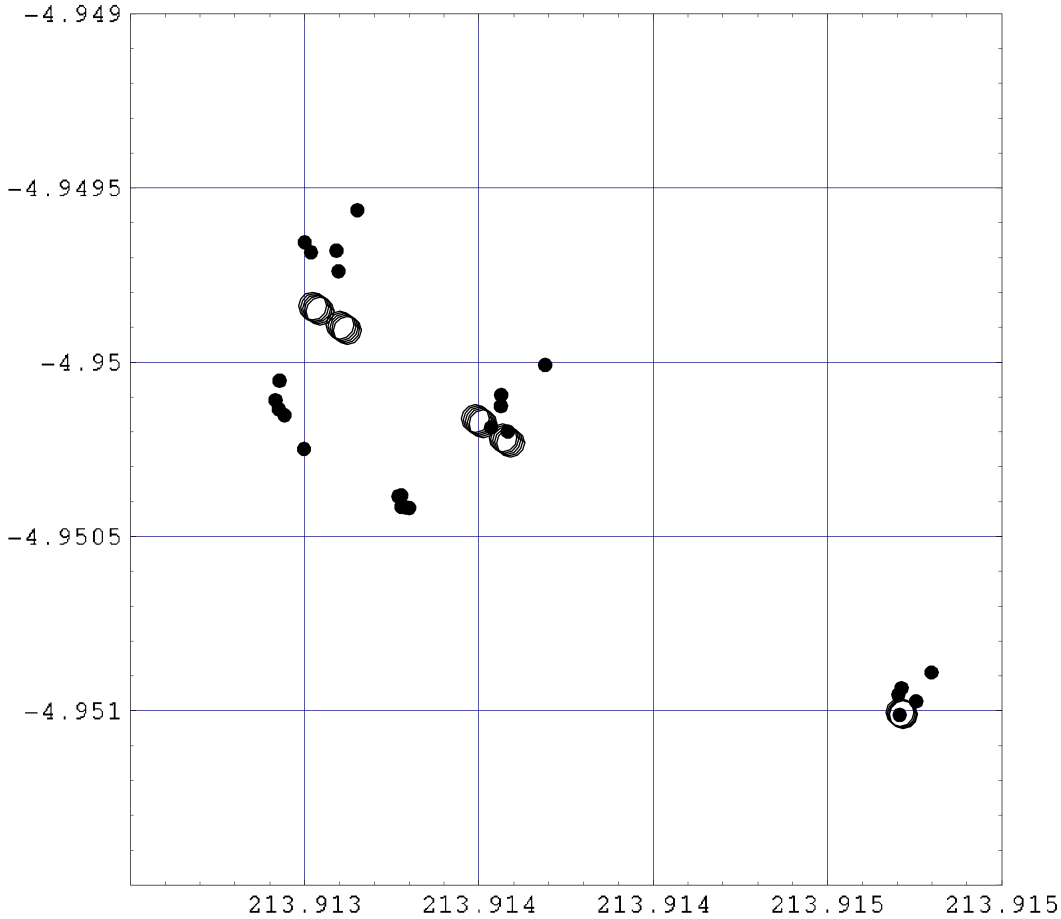
Navigation Schedule (2)

Orbit Correction Manoeuvre (OCM) Slots:

Flight Rule: error in target plane > 2 * knowledge, and magnitude > 2 cm/s

Date	Before CA	Optical data cut-off prior to OCM	Delta-V
2008/08/14	-3 weeks	- 3 days	12.8 cm/s
2008/08/18	-8 days	- 3 days	not used
2008/09/02 15:30	-3 days	- 32 hours	not used
2008/09/04 04:00	-36 hours	- 20 hours	11.8 cm/s
2008/09/05 06:00	-12 hours	- 13 hours	not used

Typical Observation Slot Results



Optical Measurements from observation slot on 25/8 (CA – 11 days)

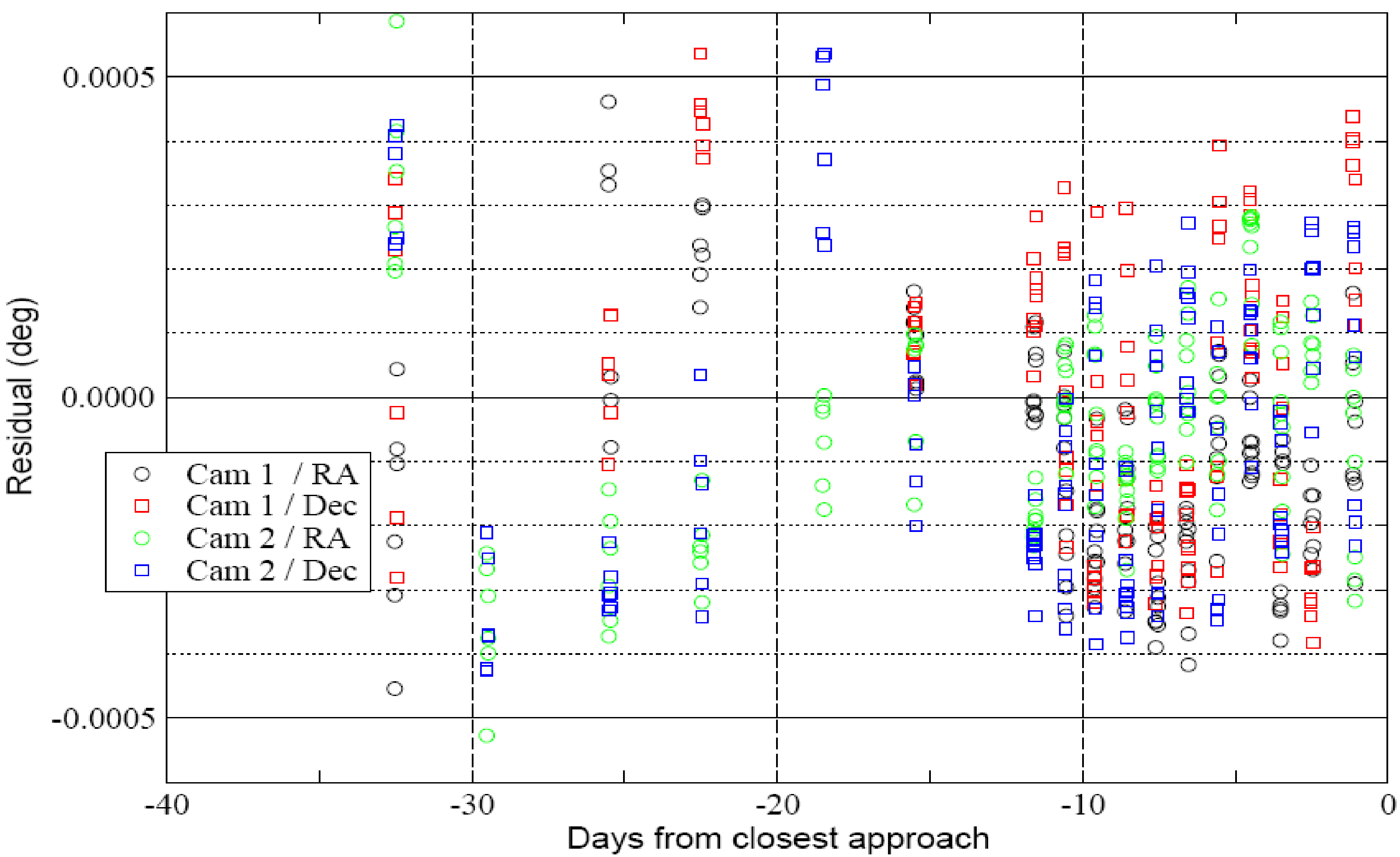
Horizontal: Right Asc. (deg)
Vertical: Declination (deg)
Grid lines every 0.5 mdeg (~1/10 Cam pixel)

Steins moves from down right to upper left.

Open circles: Steins from final orbit determination

Black dots: Measurements

Optical Measurement Residuals (Navcam)



Optical Measurement Residual Statistics

Based on final orbit determination result (S/C and asteroid orbit):

Camera	1 Pixel (mdeg)	Right Ascension (mdeg)		Declination (mdeg)	
		Mean	Std. Dev.	Mean	Std. Dev.
Navcam 1	5	-0.107	0.177	0.014	0.231
Navcam 2	5	-0.040	0.178	-0.064	0.230
Osiris/NAC	1	0.002	0.054	0.024	0.047

The target flyby distance was 800 km with 0 deg minimum phase angle. The finally achieved flyby distance was 802.6 km with 0.27deg minimum phase angle

Steins

Osiris/WAC image at 18:38:18 UTC

Steins distance: 803 km

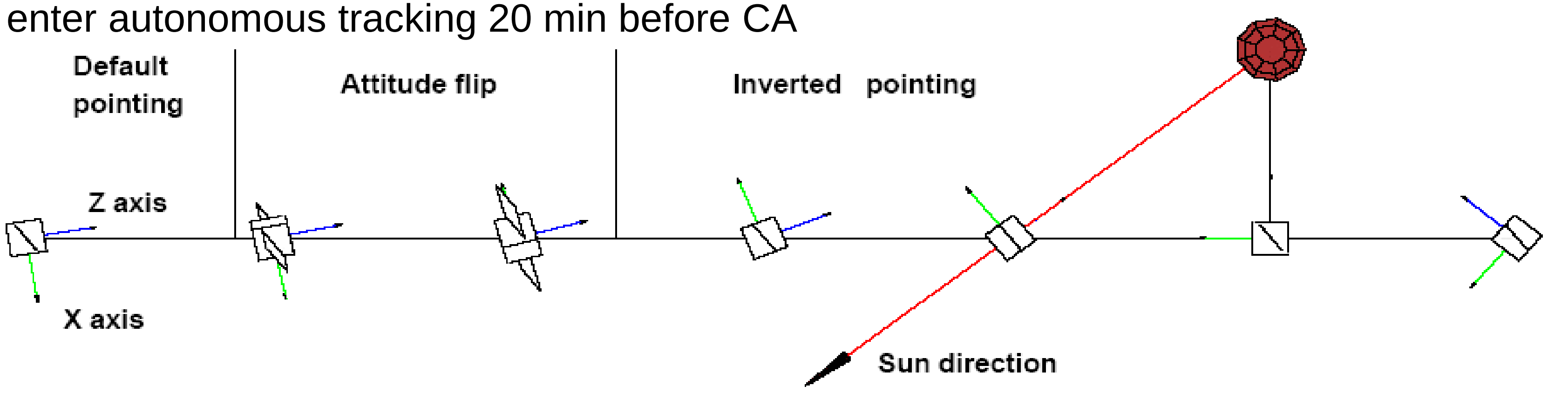
Earth distance: 360,448,350 km

Steins Flyby Strategy

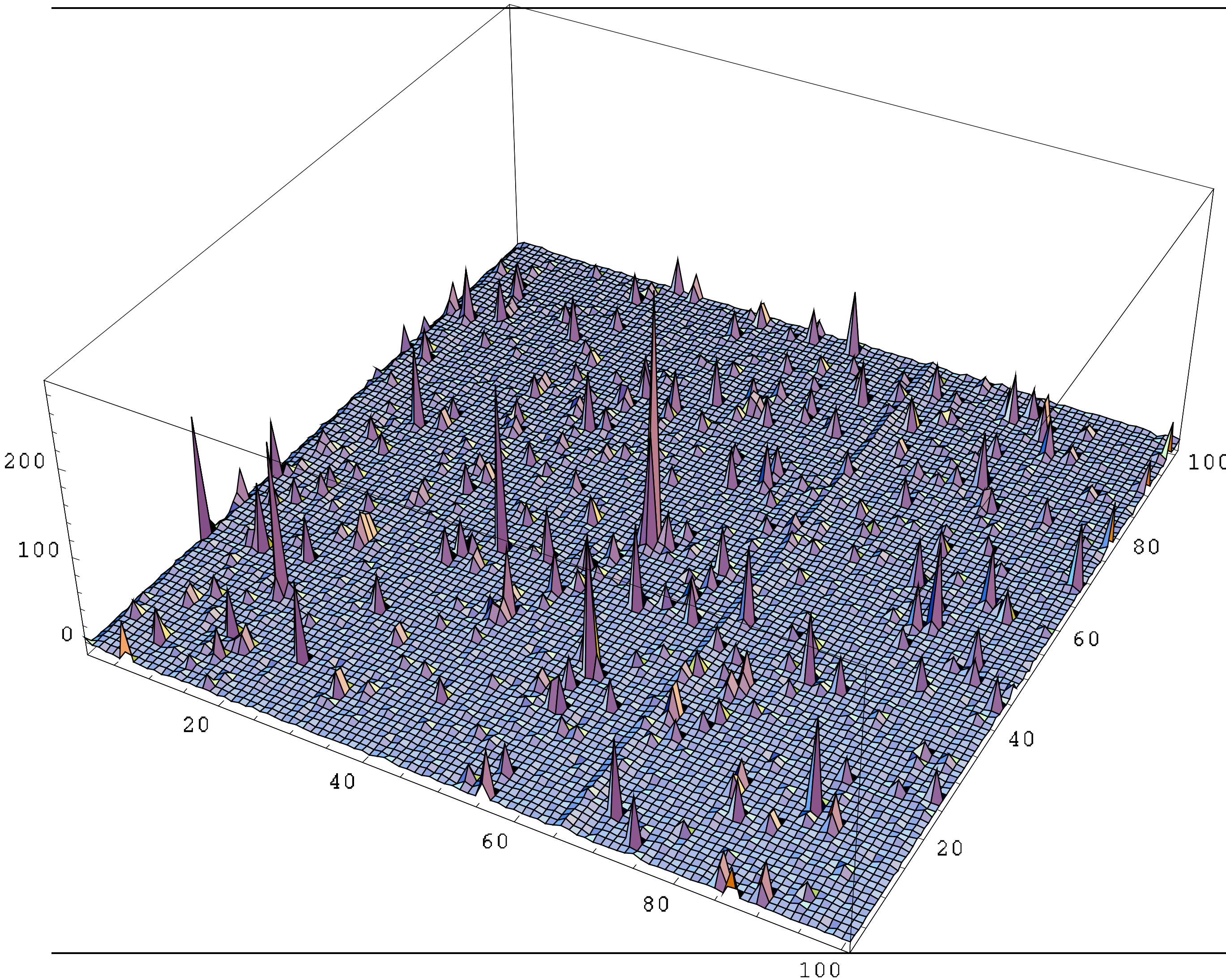
Scientific requirement: 800 km minimum flyby distance, minimum phase angle 0 deg

Operational constraints:
- solar arrays pointing to Sun
- no extended exposure of cold face (-X) to Sun
- maximum rates and torques compliant with unit performance (STR, wheels)

Resulting pointing strategy:
- point payload boresight (+Z) always towards Steins
- flip attitude before flyby, CA – 40 min to CA – 20 min
- enter autonomous tracking 20 min before CA



Steins Flyby: Navigation Camera Tracking Performance



Camera image at 08:41:43 while in tracking mode.

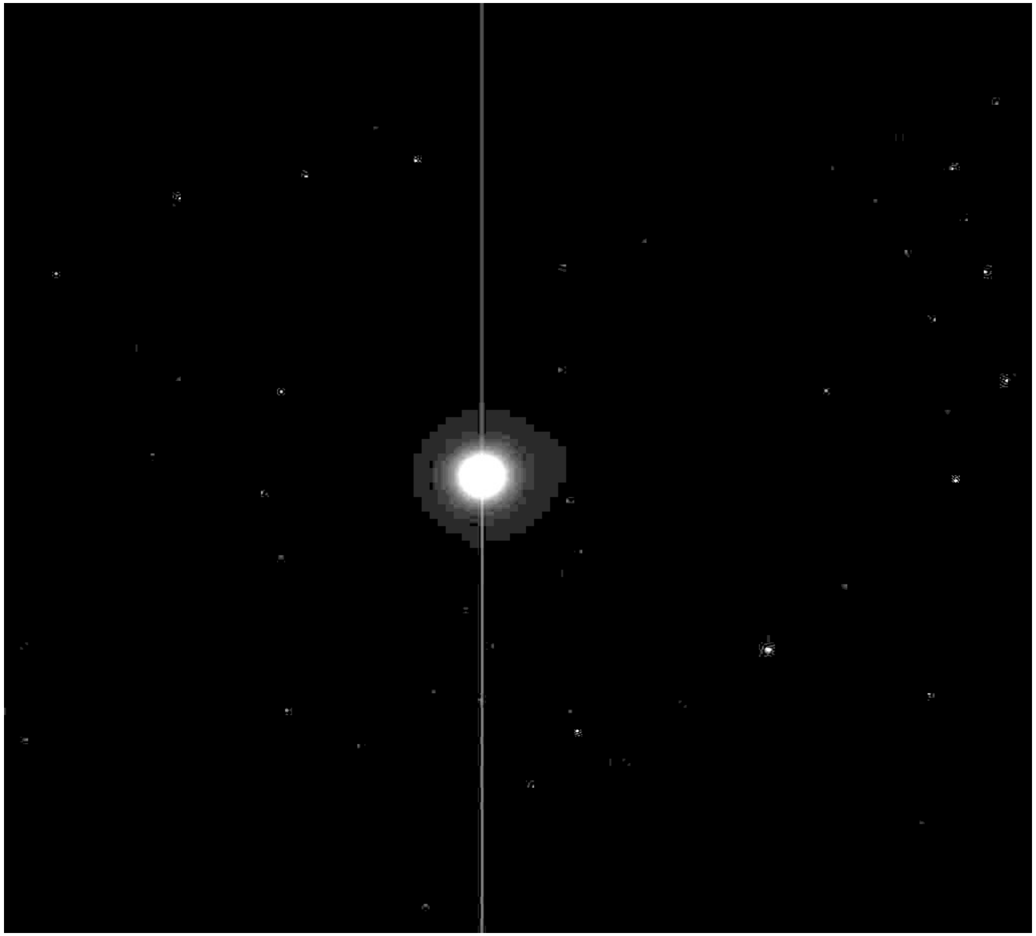
Central peak is Steins.

Object detection failed due to presence of warm pixels.

Performance did not improve until GO/NOGO for AFM

=> Cover was modified from attenuated to not-attenuated

Steins Navcam Tracking Anomaly



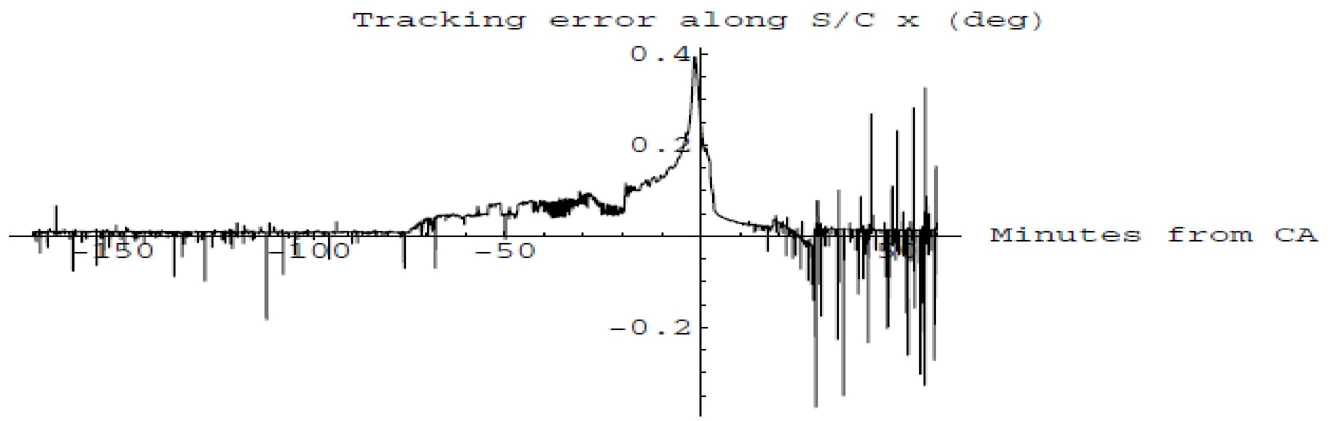
Steins tracking by Navcam was disturbed due to:
- warm pixels
- full CCD columns over detection threshold with not-attenuated cover

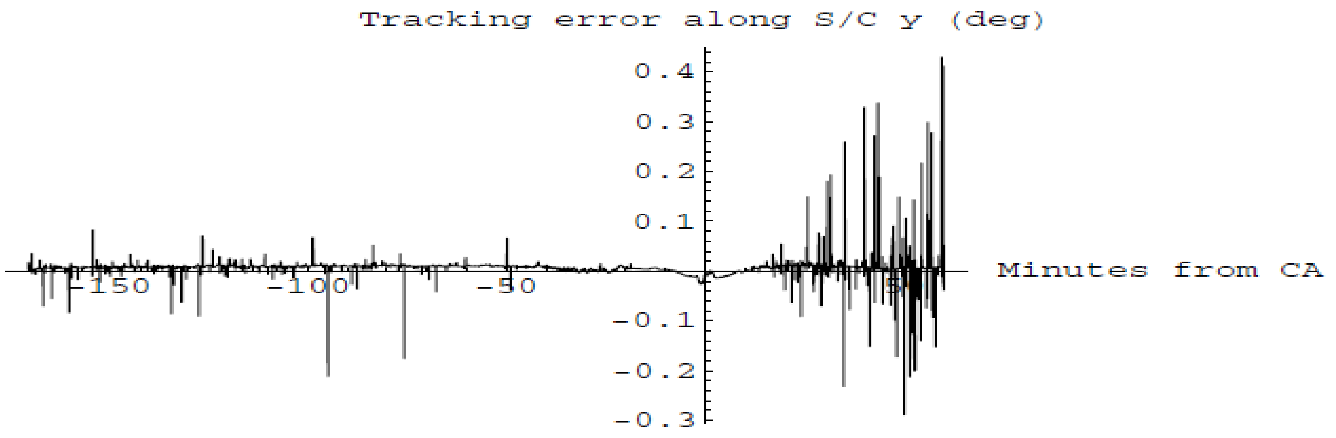
in combination with Navcam s/w algorithms

Second effect can be seen also in image of Earth/Moon system during commissioning (see image on the left side)

Signal from bright object is transferred to pixels below during CCD reset, and to pixels above during CCD readout.

Navcam Tracking Error





Near Comet Navigation

For Rosetta navigation near the comet and lander delivery operations the comet had to be modeled as extended body:

- Gravitational field, not only point mass
- Landing site definition (shape), not only centre of mass
- Attitude dynamics (moments of inertia, torques)

For the estimation of related parameters, a new observation type was needed:
Observation of landmarks (features) on the comet surface in images.

Due to the irregular surface of the comet and the high variation in observing conditions (illumination angle, viewing angle), a pure feature matching (direct correlation between raw images) is not sufficient.

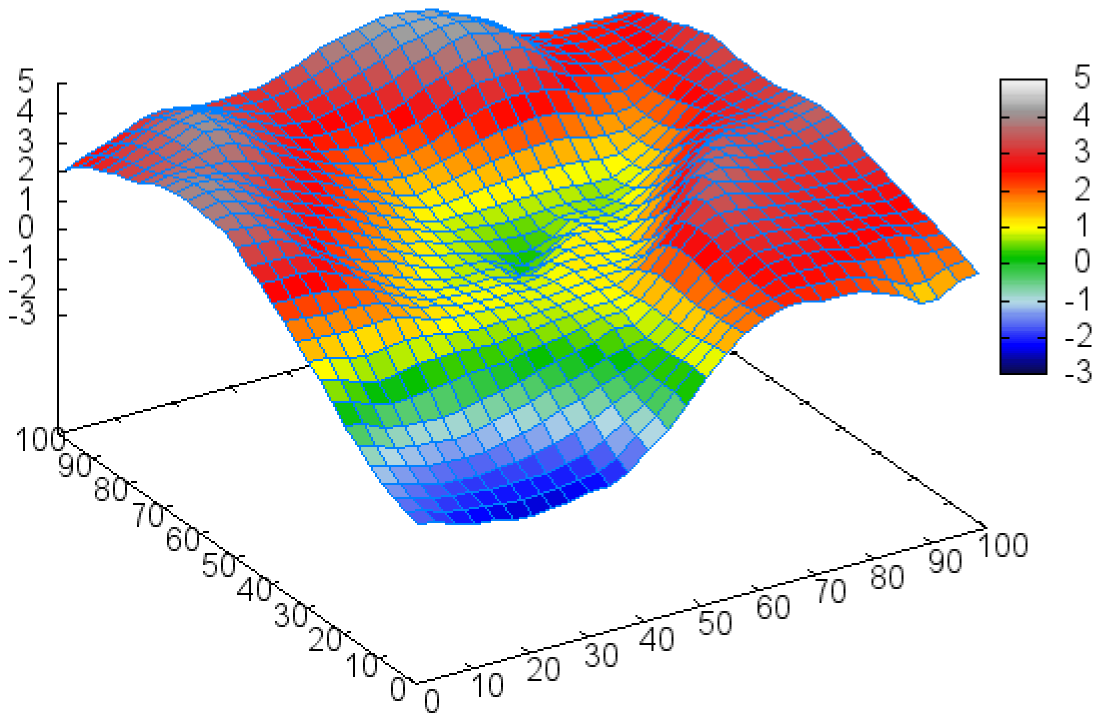
Instead, for robust and accurate landmark observation a local model of the surface and its appearance in the image is needed => “maplet”

Maplet

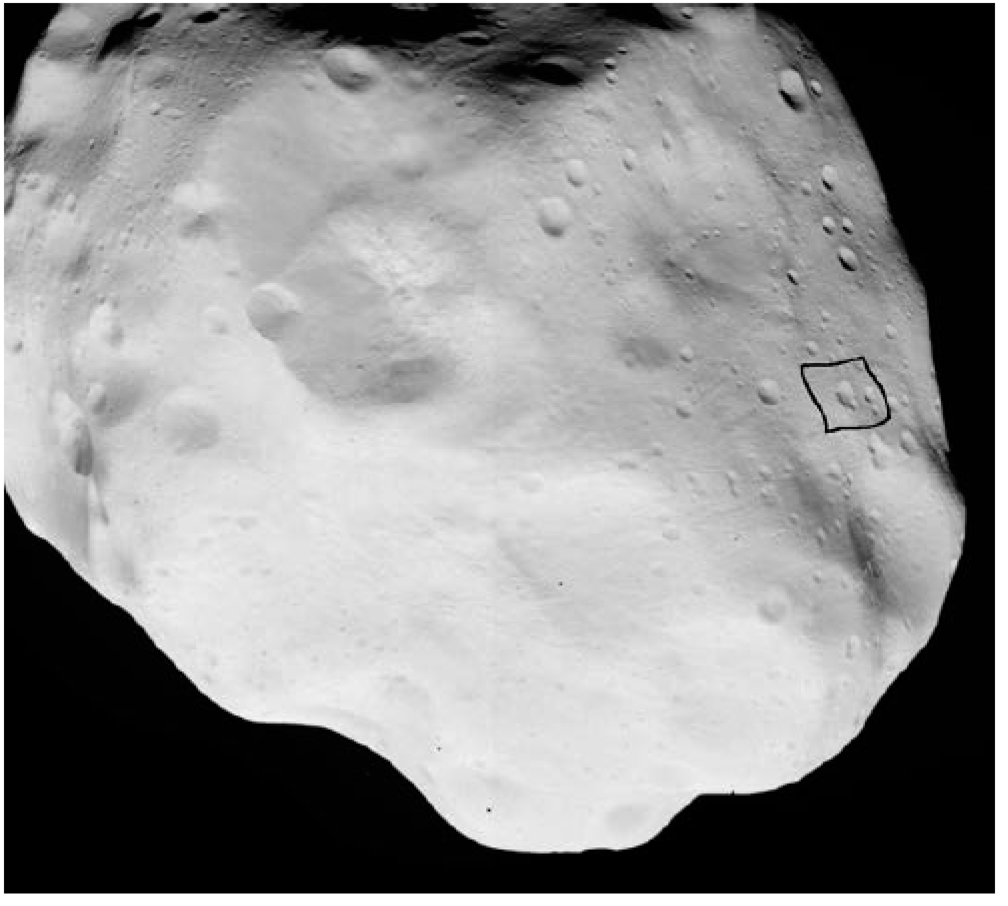
A maplet is defined by

- landmark position,
- reference frame
- cell number, size
- height map.

The cells are aligned with the X and Y axes with a height associated to them representing surface points along the Z axis and over the XY plane



Maplet Rectification



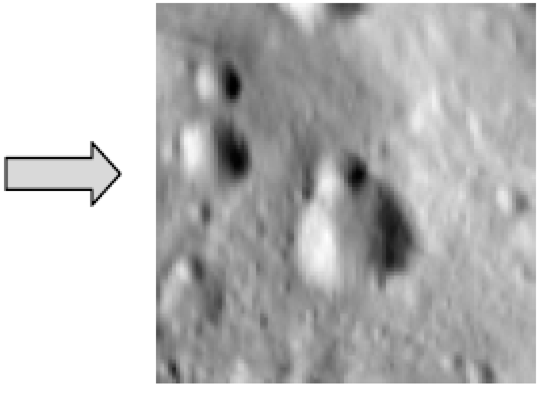
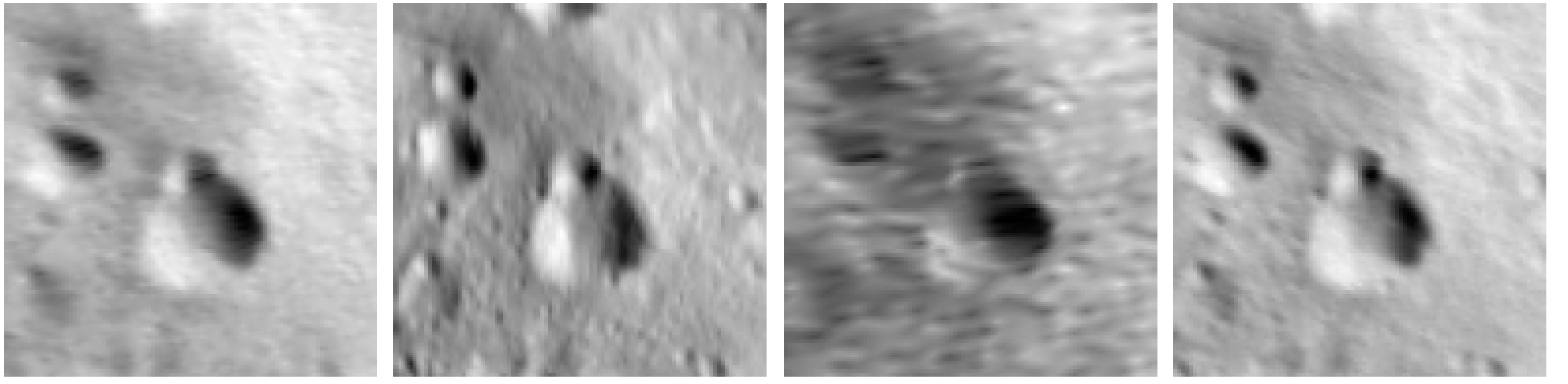


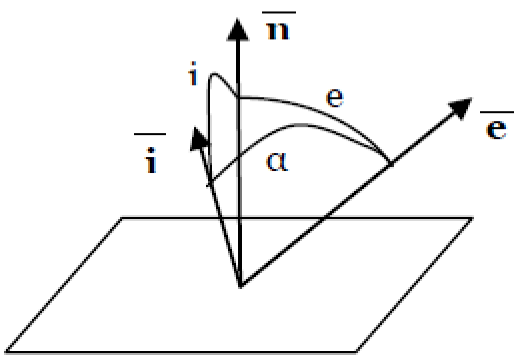
Image rectification example from Lutetia using camera position and attitude

Maplet Rectification



Same maplet around a landmark of Lutetia in four rectified images.

Maplet Photometry



- i: incidence angle. Angle between incidencen and surface normal.
- e: emission angle. Angle between emission and surface normal.
- α: phase angle. Angle between emission and incidence .

$$S = \Lambda(t_I, K_{CAM}, d_S) \cdot a \cdot R(\alpha, i, e) + \Phi$$

$$\Lambda = K_0 \cdot \frac{t_I \cdot K_{CAM}}{d_S{}^2}$$

$$R(\alpha,i,e) = P(\alpha)\cdot\left[(1 - L(\alpha))\cdot R_L(i) + L(\alpha)\cdot R_{LS}(i,e)\right]$$

$$R_L(i) = Cos(i) = \overline{n}\cdot\overline{i}$$

$$R_{LS}(i,e) = \frac{Cos(i)}{Cos(i)+Cos(e)} = \frac{\overline{n}\cdot\overline{i}}{\overline{n}\cdot(\overline{i}+\overline{e})}$$

$$L(\alpha) = e^{-\frac{\alpha}{\alpha_0}}$$

$$P(\alpha) = e^{-\frac{\alpha}{\beta_0}}$$

Maplet Construction

1) Slope Estimation:

Expression of local normal from local slopes:

$$\bar{n} = \frac{(-t_1, -t_2, 1)}{\sqrt{t_1^{\,2} + t_2^{\,2} + 1}}$$

Each rectified image provides one measurement per cell to estimate the local slopes.

2) Height Integration:

$$\frac{t1_{i,j}}{\sigma^{t1}{}_{i,j}} = \frac{h_{i-2,j} - 4 \cdot h_{i-1,j} + 3 \cdot h_{i,j}}{2 \cdot dl \cdot \sigma^{t1}{}_{i,j}}$$

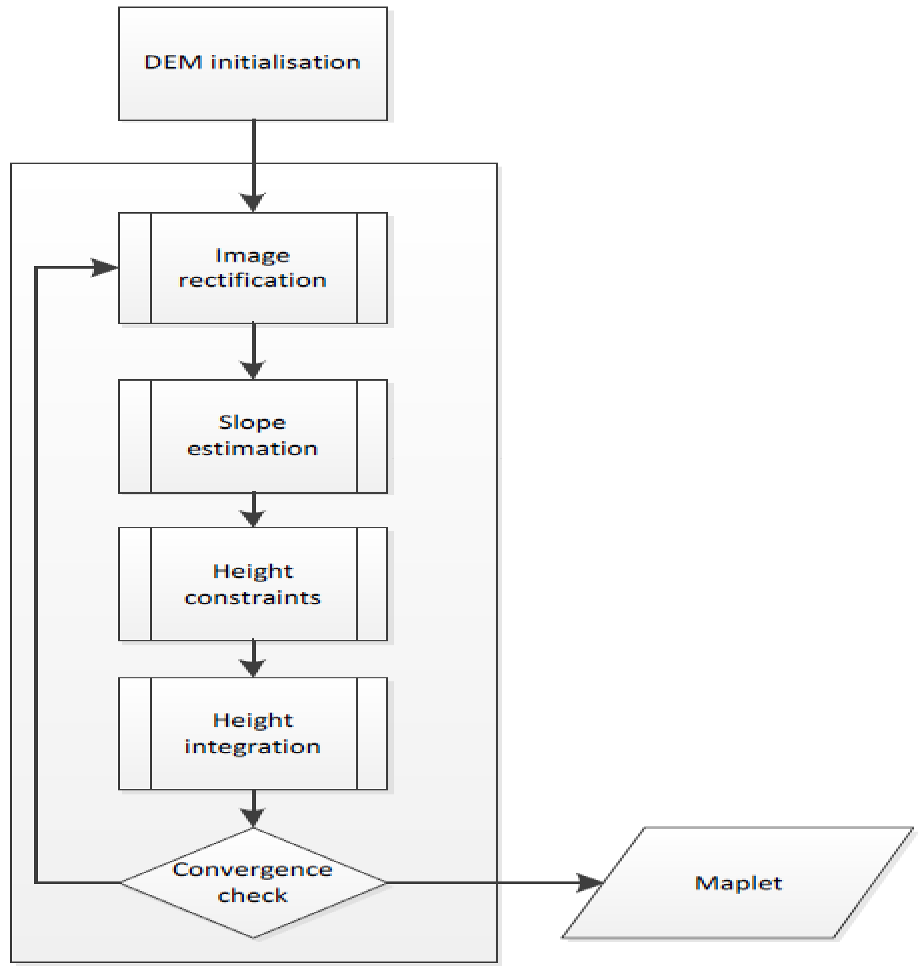
$$\frac{t2_{i,j}}{\sigma^{t2}{}_{i,j}} = \frac{h_{i,j-2} - 4 \cdot h_{i,j-1} + 3 \cdot h_{i,j}}{2 \cdot dl \cdot \sigma^{t2}{}_{i,j}}$$

Finite difference approximation leads to linear system of equations (~ #cells^2) which is solved by a direct method.

Additional constraints are applied: landmark position …

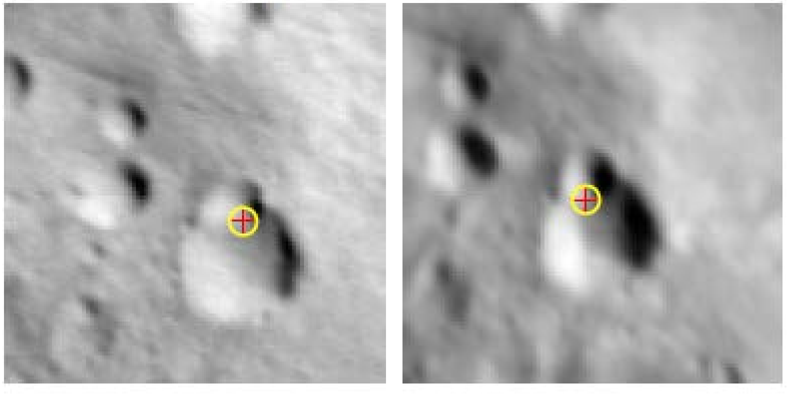
Maplet Construction

- A maplet is needed to rectify images
- Rectified images are used to integrate heights, i.e. to generate a maplet
- Therefore, an iterative process is needed to converge to a consistent solution.
- The initial maplet is derived, e.g. from simple initial shape model, or just as a flat surface



Landmark Observations

For any landmark in a new image, a rectified maplet image is generated and compared to a simulated image:



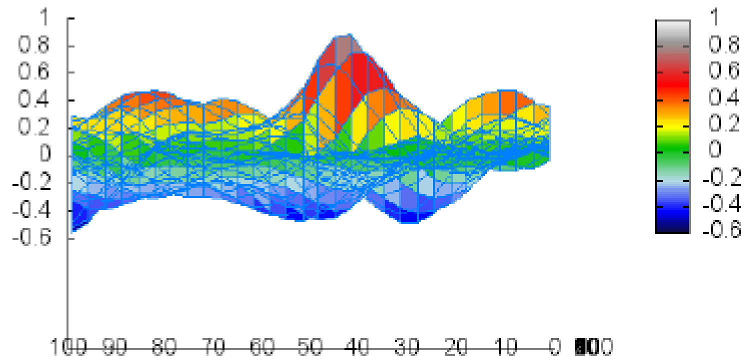
Due to imperfect knowledge of camera position, both appear shifted w.r.t. each other

Landmark observation

The shift between rectified and simulated image is determined by autocorrelation:

$$Correlation = \frac{\sum_i \sum_j \left[\left(x_{ij} - \bar{x} \right) \cdot G(r) \right]}{\sqrt{\sum_i \sum_j \left[\left(x_{ij} - \bar{x} \right)^2 \cdot G(r) \right]}} \cdot \frac{\sum_i \sum_j \left[\left(y_{ij} - \bar{y} \right) \cdot G(r) \right]}{\sqrt{\sum_i \sum_j \left[\left(y_{ij} - \bar{y} \right)^2 \cdot G(r) \right]}}$$

$$G(r) = e^{-\frac{r^2}{2 \cdot \sigma^2}}$$



Based on the determined shift, the observed landmark position in the image is computed.

Overall Navigation Process

- Images are acquired regularly (ca. once every 5 hours) on-board the S/C.
- In each processing cycle (e.g. twice per week), landmark observations are generated for all images (from a few up to several hundred observations per image)
- The landmark observations are converted from pixel positions into inertial directions from camera to landmark based on S/C attitude and camera alignment data.
- The landmark observations are processed together with radiometric data to estimate a full set of parameters:
  S/C position, comet position and attitude, landmark positions, comet physical parameters (gravity field, moments of inertia, disturbance torques)

Typical Results

The accuracy of the landmark observations is usually better than one pixel.

For example, an orbit determination performed last week of May has used 24,539 observations of 1,079 landmarks in the period April 30 to May 27.

·The RMS of the landmark residuals were 3.3 mdeg (~0.7 pixels) in camera X and 3.9 mdeg (~ 0.8 pixels) in camera Y direction.

The accuracy of the estimated landmark positions is usually better than 1 m.

The determined comet rotational parameters are as follows:
Rotational period on 2015/05/27 19:00 UTC [hh:mm:ss.s]: 12:25:50.1

Summary

Optical navigation is used for Rosetta in two major areas:

1) For the approach to, or rendezvous with a small body (asteroid or comet), images of the target against the star background are used to determine the inertial direction from the S/C to the centre of the body with high accurcy (1/10 of a pixel). These measurements are used to navigate towards the target.

2) Near the comet, images are processed to derive landmark measurements, i.e. inertial directions from the S/C to features on the surface of the comet. These measurements are used to navigate at close distances from the body and to deliver the lander. Landmark measurements are generated automatically using a technique based on local area maps (maplets) by correlating rectified images with their predictions.

The images are processed on ground. Only the attitude steering around the asteroid flybys was implemented as an autonomous process on board the S/C, which however required a considerable amount of preparation and tuning.

Acknowledgements

ESOC / Flight Dynamics / Science Mission Support Section:

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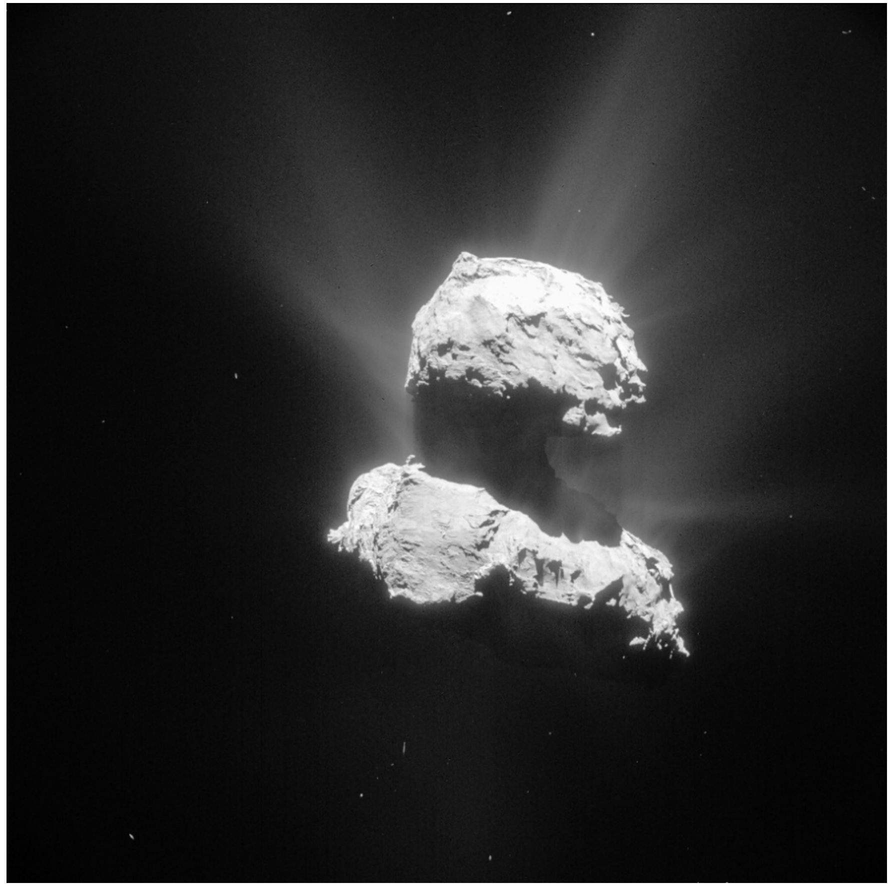
Image Processing:	U. Herfort, S. Kielbassa, R. Pardo, D. Wokes

Churyumov-Gerasimenko



Navcam image of the comet from April 26, 2015