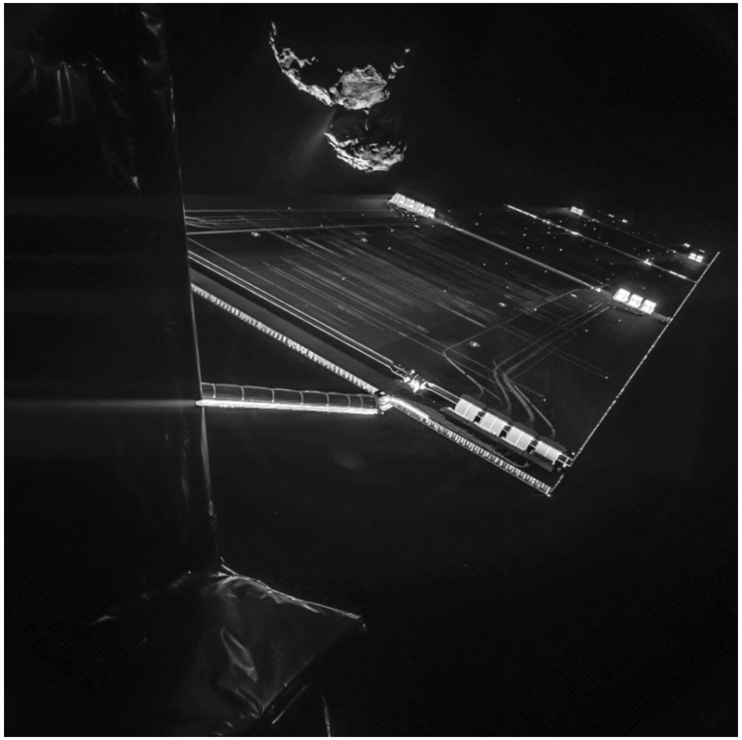
International Conference on Astrodynamics Tools & Techniques



Rosetta: Optical Navigation and Trajectory design around Churyumov-Gerasimenko

Pablo Muñoz

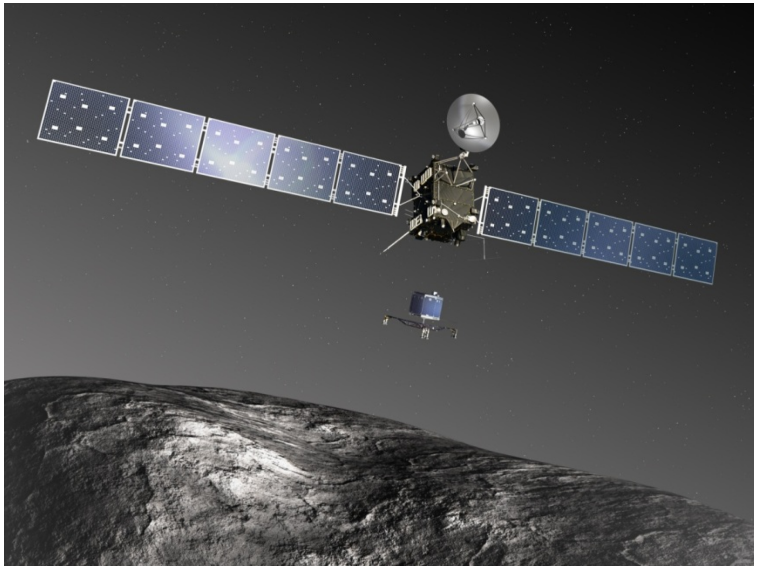
ICATT - 2016/03/14 - Darmstadt

European Space Agency

Contents

Mission Overview

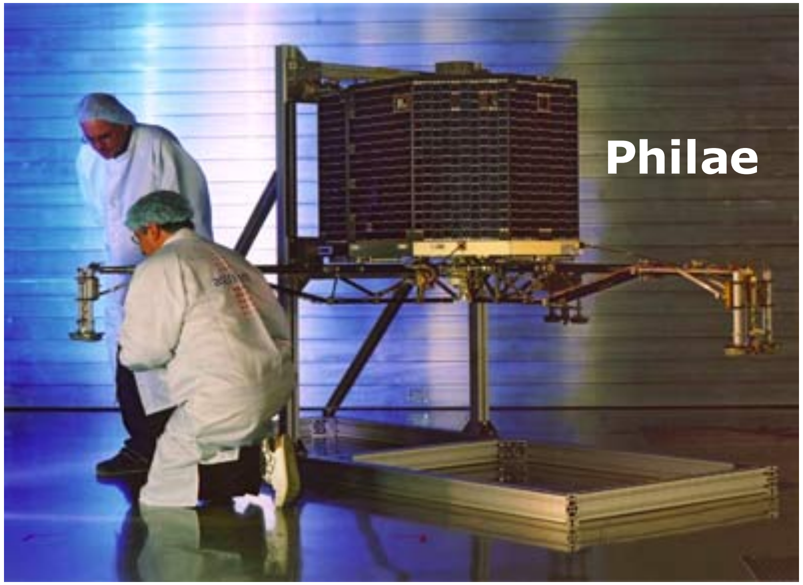
- Mission objectives:
  - Rendezvous the comet 67P/Churyumov-Gerasimenko (CG)
  - Fly around the comet to study its characteristics
  - Deliver the lander module, Philae, to touch down comet's surface
  - Escort the comet in its perihelion passage, monitoring its evolution
- Mission milestones:
  - Launched in 2004
  - Performed 4 planetary swing-bys
  - Flyby of asteroids Steins and Lutetia
  - S/C hibernation: Jun 2011 - Jan 2014
  - Comet arrival in August 2014
  - Landing in November 2014
  - Comet perihelion in August 2015



	Perihelion distance	Aphelion distance	Orbital period	Nucleus diameter	Rotation period
Comet CG	1.2 AU	5.7 AU	6.5 years	3-5 km	12.4 h

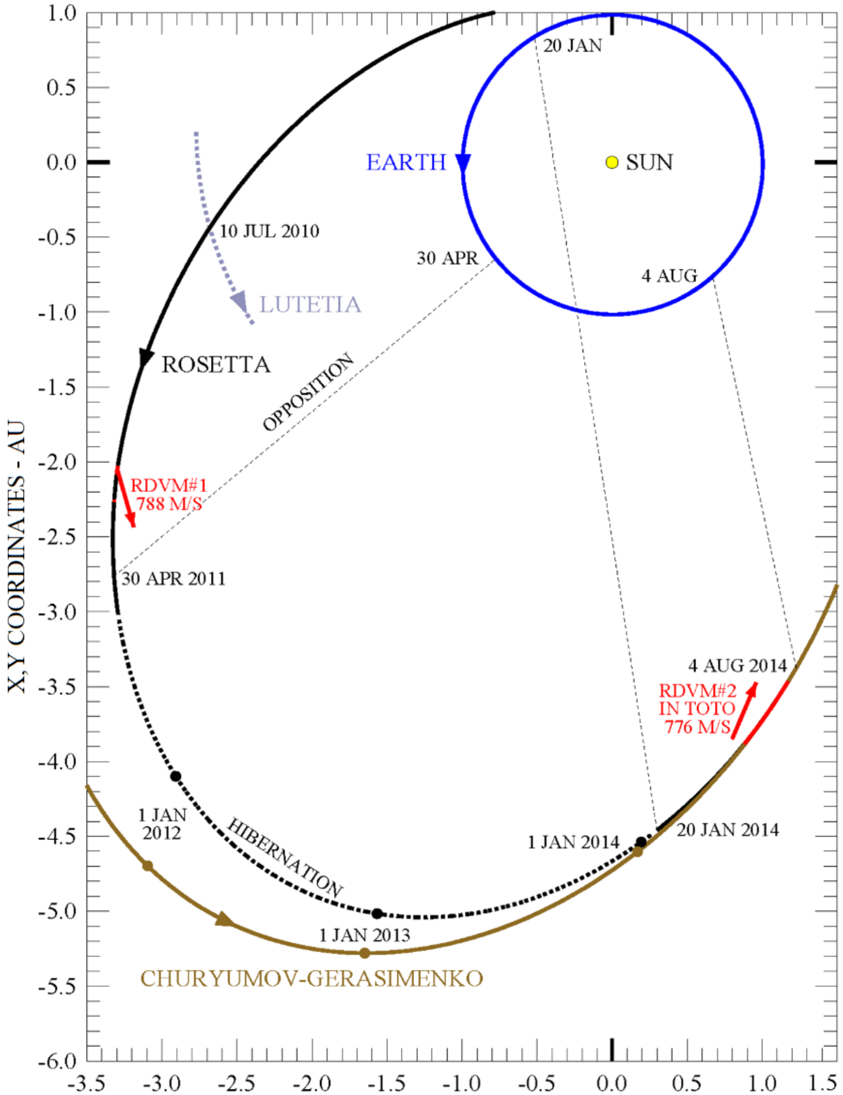
Spacecraft Overview

- Rosetta:
  - Body: 2.8 x 2.1 x 2.1 m
  - Mass: 1580 kg dry + 1490 kg fuel
  - 64 m^2 solar arrays
  - 2.2 m steerable antenna
  - 2 navigation cameras
  - 11 scientific instruments (165 kg)
  - Philae lander (100 kg)

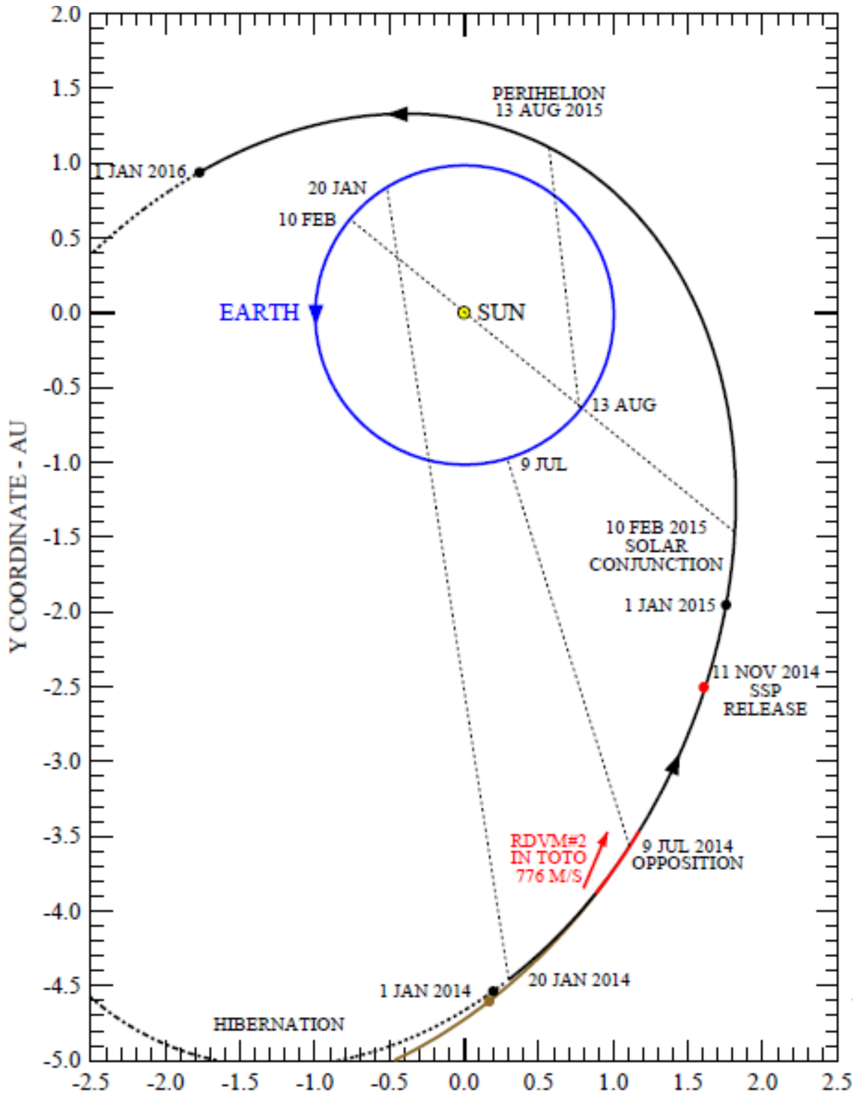


Rosetta & Comet Orbits around the Sun

2010 - 2014



2014 - 2015



Rosetta Navigation Challenges

- Rosetta is a very challenging mission in terms of navigation
- Limited a priori knowledge on comet properties (orbit, attitude, mass, gravity field, shape, centre of mass, coma properties, …)
- Active comet: space & time-varying coma (density, velocity), dust, jets
- Small gravity => possible bound orbits have very small relative velocity:

  (-) Orbit is more sensitive to perturbations

  (+) Trajectory changes are cheap in delta-V
- Very tight mission timeline. In only 3 months (2014):
  1. August: arrival to the comet and initial characterization
  2. September: global mapping and selection of landing site
  3. November: lander delivery
- Next challenge: end of mission operations!

Rosetta Navigation Concepts

- Main tasks:
  - Design the trajectories around the comet
  - Orbit determination (OD) and trajectory reconstruction
  - Prediction of future trajectory
  - Optimization of next manoeuvres
  - Calibration of executed manoeuvres

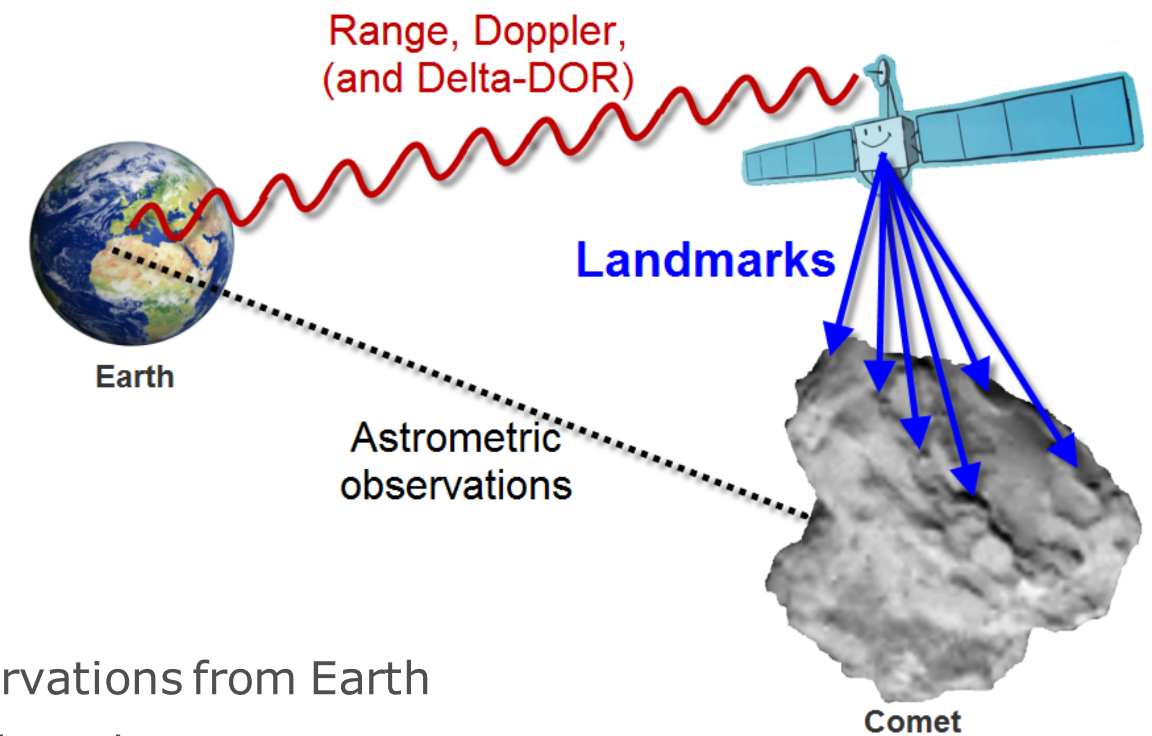
- Relative navigation around the comet:
  - Image processing for comet detection and landmark identification
  - Determination and prediction of comet orbit and attitude
  - Estimation of additional comet parameters:
    - Mass, gravity field
    - Coma density => nebulae of gas and dust around the nucleus
    - Centre of mass position
    - Landmark coordinates
    - Shape model

Rosetta Navigation Concepts (I)

- Main tasks:
  - Design the trajectories around the comet
  - Orbit determination (OD) and trajectory reconstruction
  - Prediction of future trajectory
  - Optimization of next manoeuvres
  - Calibration of executed manoeuvres

- Relative navigation around the comet:
  - Image processing for comet detection and landmark identification
  - Determination and prediction of comet orbit and attitude
  - Estimation of additional comet parameters:
    - Mass, gravity field
    - Coma density => nebulae of gas and dust around the nucleus
    - Centre of mass position
    - Landmark coordinates
    - Shape model

Measuring where is Rosetta



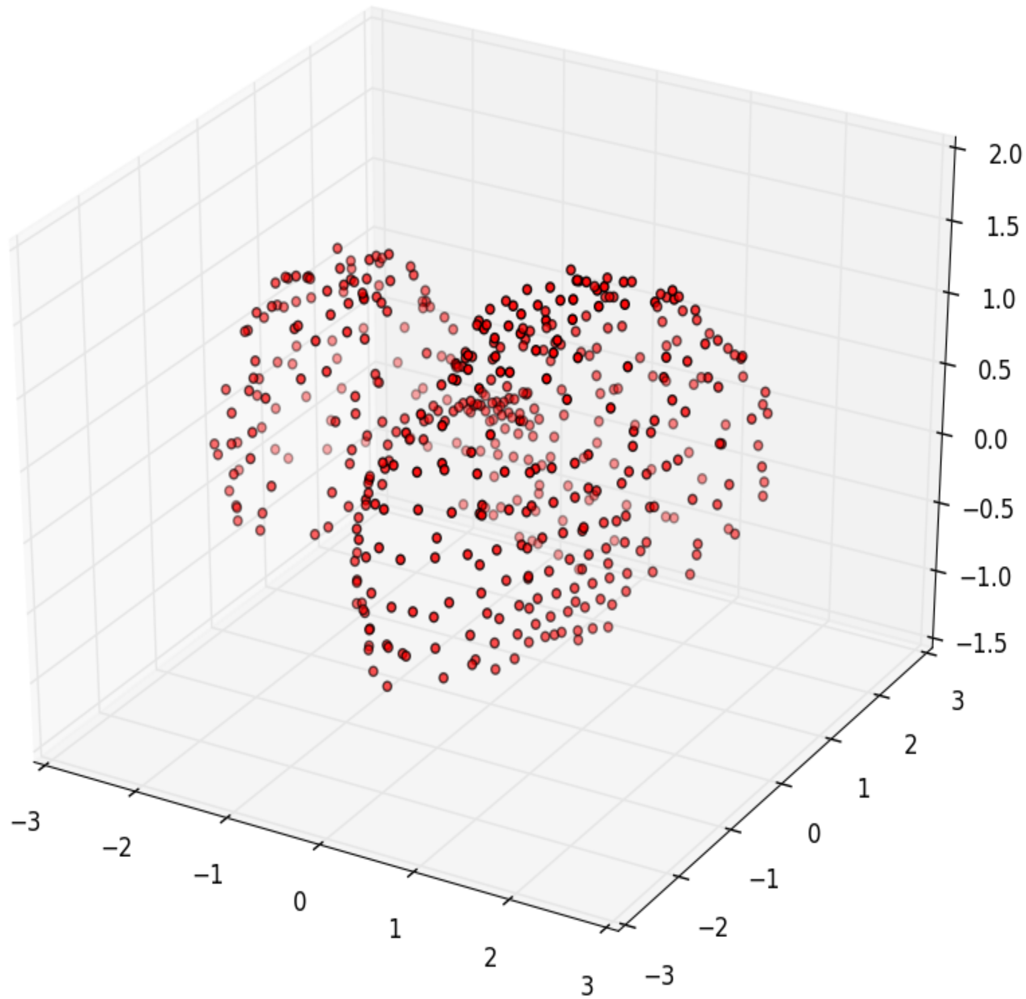
- Radiometric observations:
  1. 2-way range
  2. 2-way Doppler
  3. Delta-DOR
- Optical observations:
  1. Comet astrometric observations from Earth
  2. Comet images from on-board cameras:
     - Direction from S/C to comet centre
     - Directions from S/C to landmarks on comet surface

Comet Detection from Rosetta on-board cameras on March 24th 2014

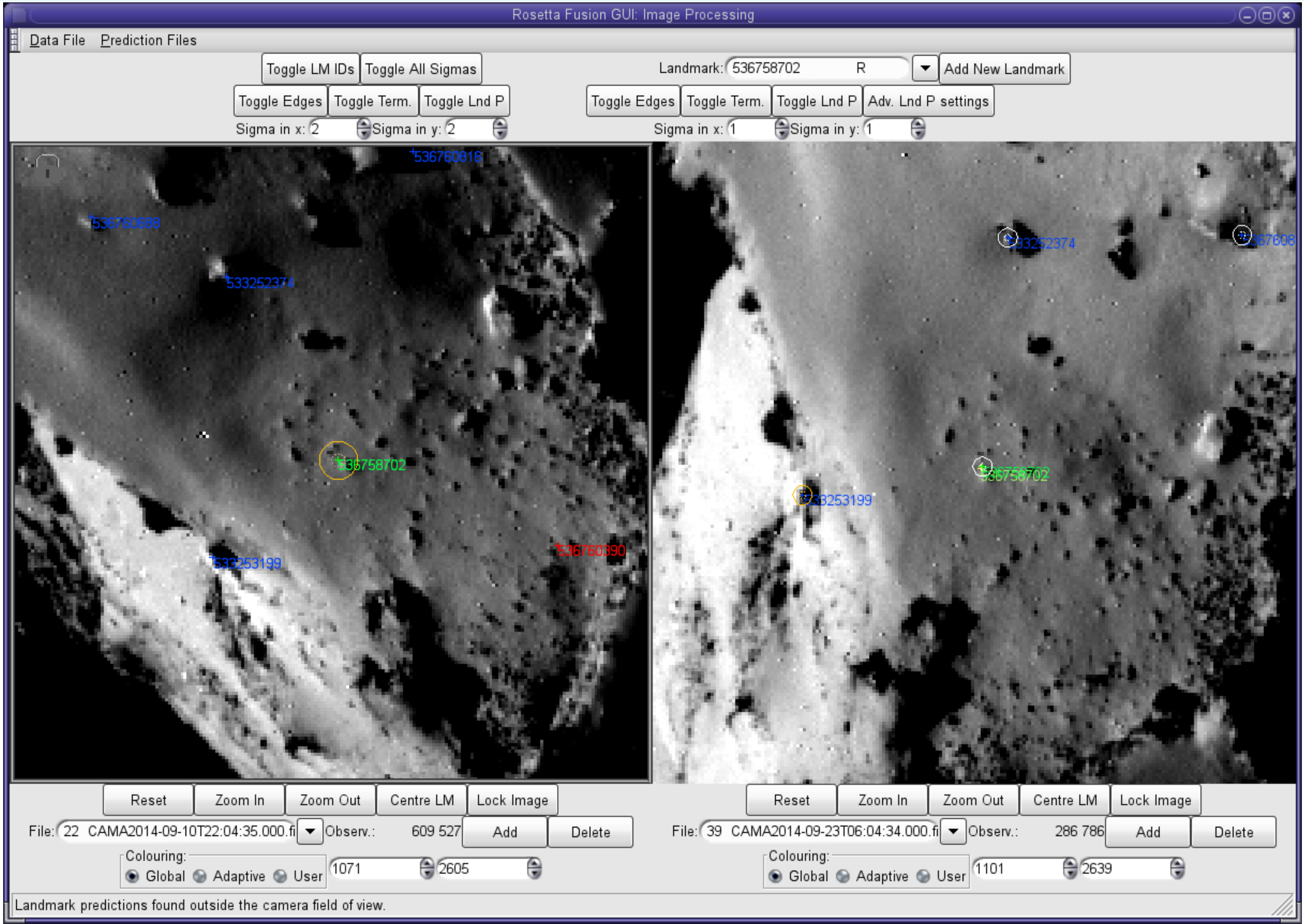
OSIRIS-NAC view of comet 67P/CG (globular cluster M107 also in view)
Credits: ESA © 2014 MPS for OSIRIS-Team

Optical Navigation with Landmarks

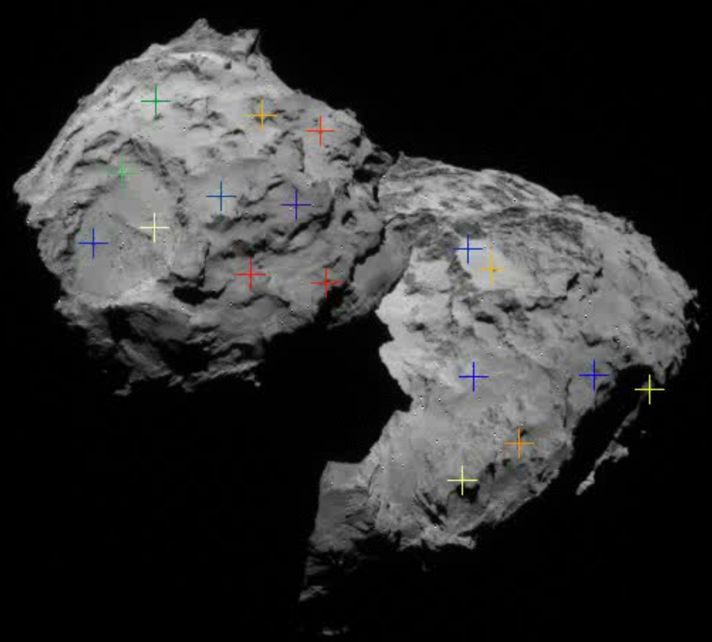
- Main observation type for navigation around the comet
- Rosetta is the first ESA mission navigated with landmarks
- Images are processed on ground to identify the landmarks
- The input to OD is the directions from S/C to the landmarks in each image
- Comet attitude must be modeled and estimated in the OD



Manual Landmark Identification



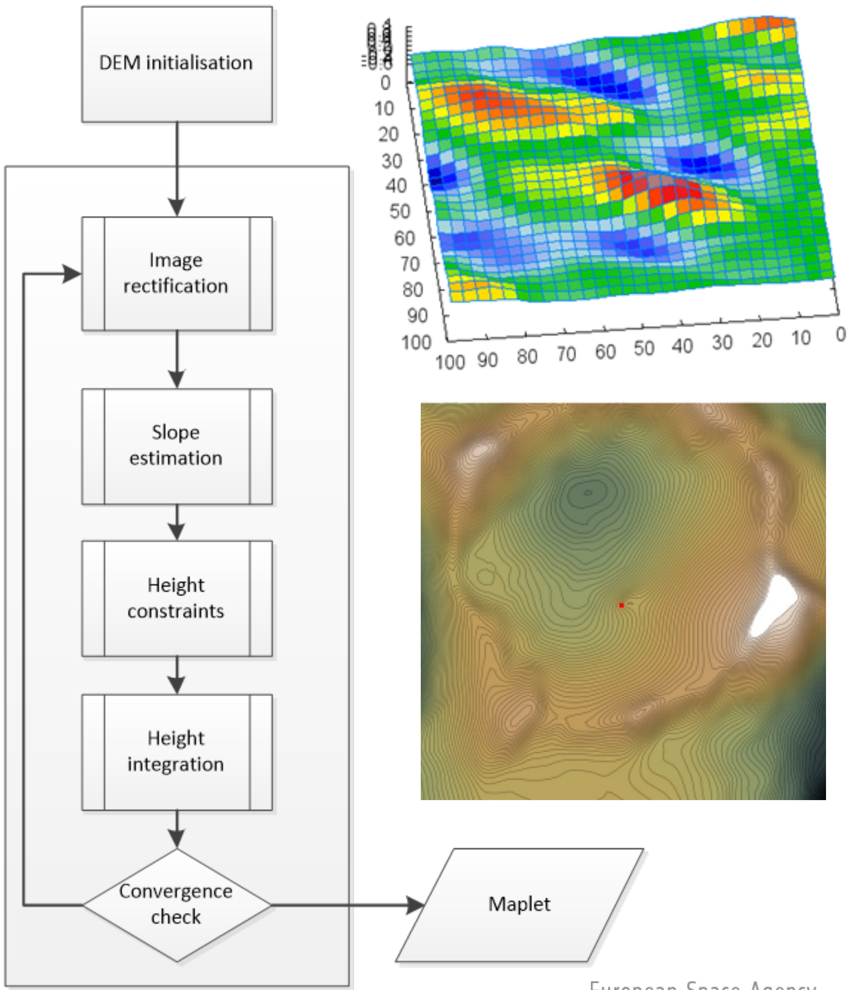
NAVCAM Movie: Identified Landmarks



European Space Agency

Automatic Landmark Identification

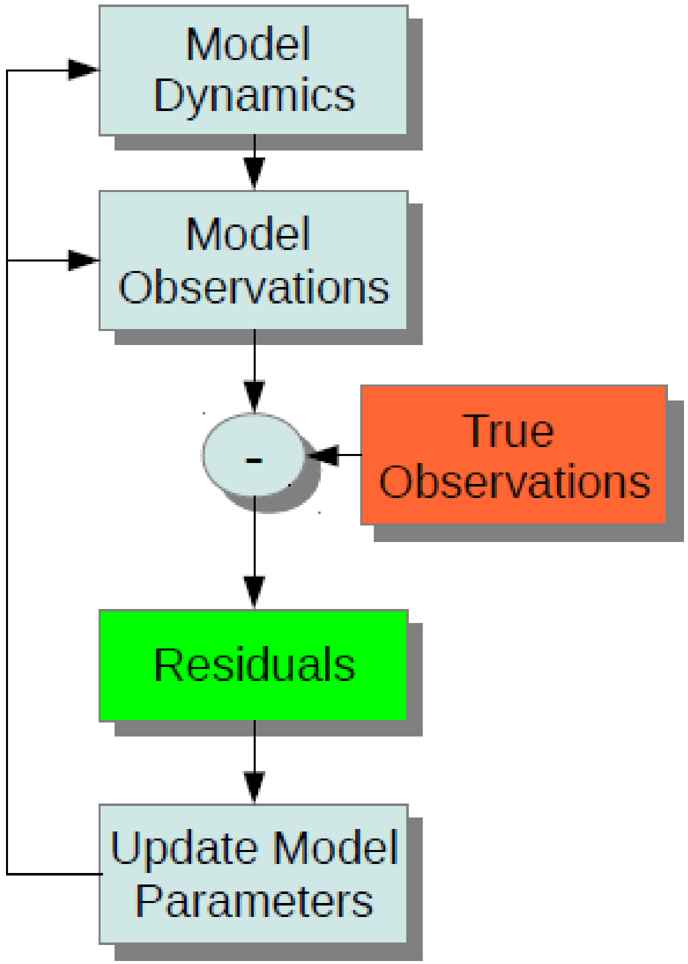
- Based on L-map (or maplets) technique
- An L-map is an elevation and albedo map of a portion of the comet surface
- The centre of the grid is the "landmark"
- The L-map does not have to be centred in a specific surface feature, although for convenience it was done that way
- Once a new image is processed it can be correlated with the L-map database in order to identify the landmarks in the image, generating the landmark observations
- An initial guess of the S/C position is required
- L-map observations have sub-pixel accuracy



European Space Agency

L-map reconstruction process diagram

Rosetta Orbit Determination



Estimated parameters (~3600) in a typical long arc OD:

- Rosetta orbital state (6)
- Comet orbital state (6)
- Comet attitude & rot. rate (4)
- Torque on comet attitude (1+)
- Comet mass (1)
- Comet 3x3 gravity field (10)
- SRP calibration (1)
- Coma drag calibration (1+)
- Manoeuvre & WOL calibrations (~360)
- Landmark positions (~3000)
- Camera orientation calib. (6)
- Range biases (~200)

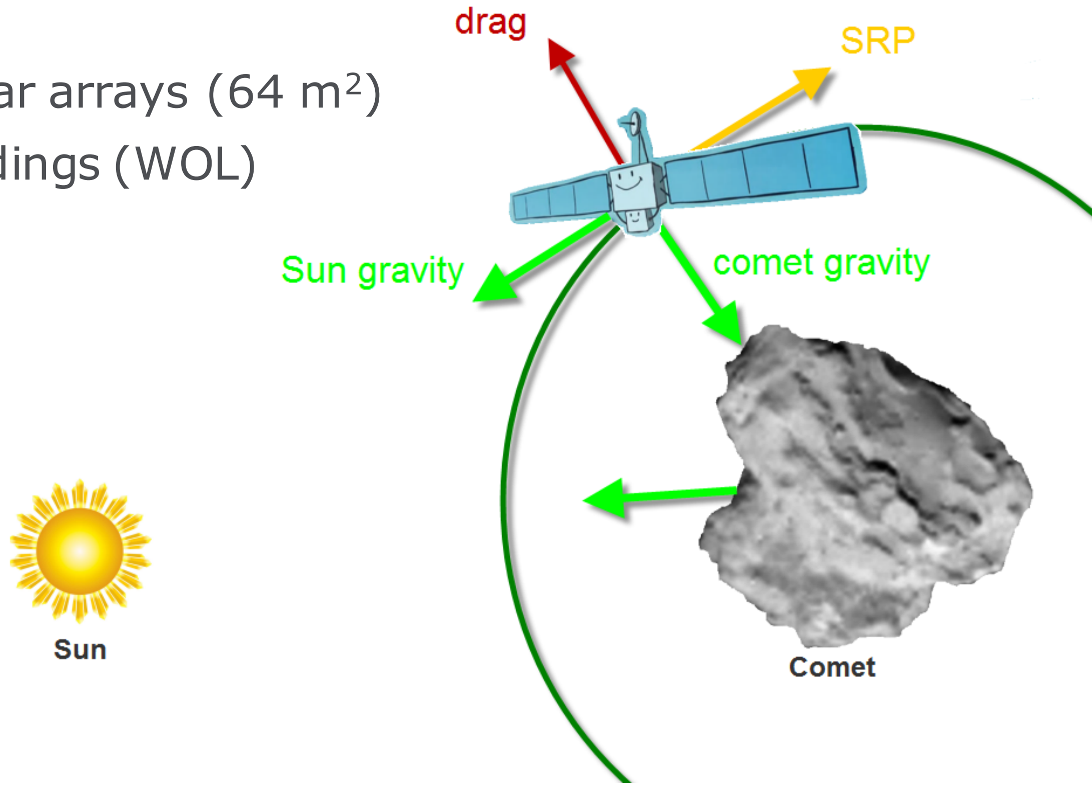
Long/short Arc ODs

- Initially, all cometary parameters were estimated in the short term planning orbit determination => increasing computation time
- To simplify the operations during planning days, OD split in 2:
  - Long arc OD (2-3 months): run offline, estimating all cometary parameters:
    - Comet orbit
    - Comet attitude (spin axis, rotation rate, torque)
    - Comet mass and gravitational field harmonics
    - Landmark coordinates
    - Centre of mass location
  - Short arc OD (~2 weeks): fixing all previous parameters and estimating:
    - Rosetta orbit
    - Rosetta dynamic parameters (manoeuvres, WOLs, coma drag scale)
    - Coordinates of new landmarks
- Typical execution: 10 hours for long arc, 10 min for short arc

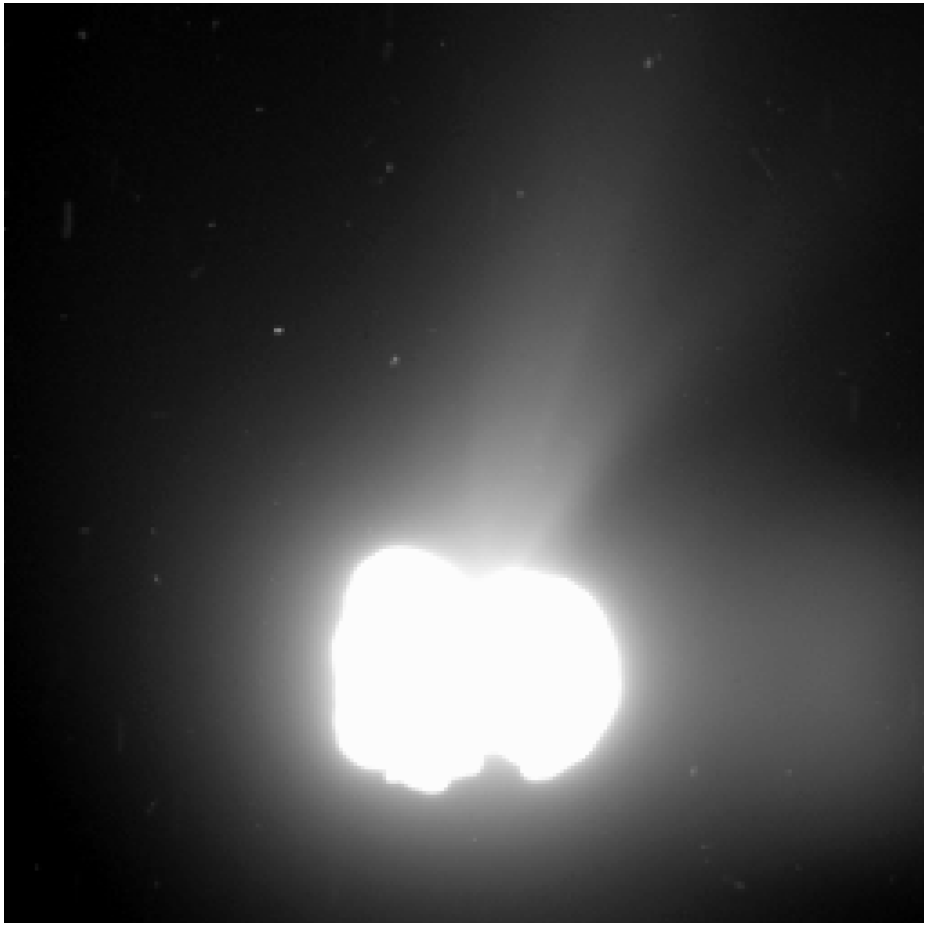
Rosetta Acceleration Models

1. Gravity from biggest Solar System bodies
2. Comet gravitational field
3. Solar radiation pressure (SRP)
4. Thermal radiation
5. Coma drag <= very big solar arrays (64 m^2)
6. Manoeuvres & wheel-off-loadings (WOL)
7. Anomalous accelerations

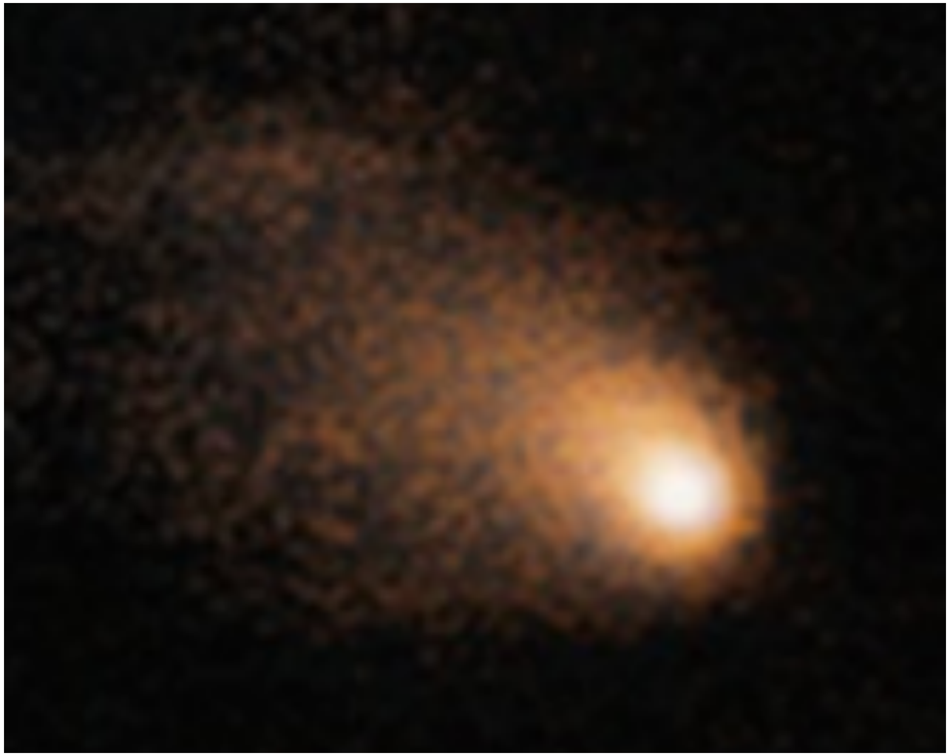
   => spacecraft outgassing



Comet Activity at Arrival (Aug 2014)



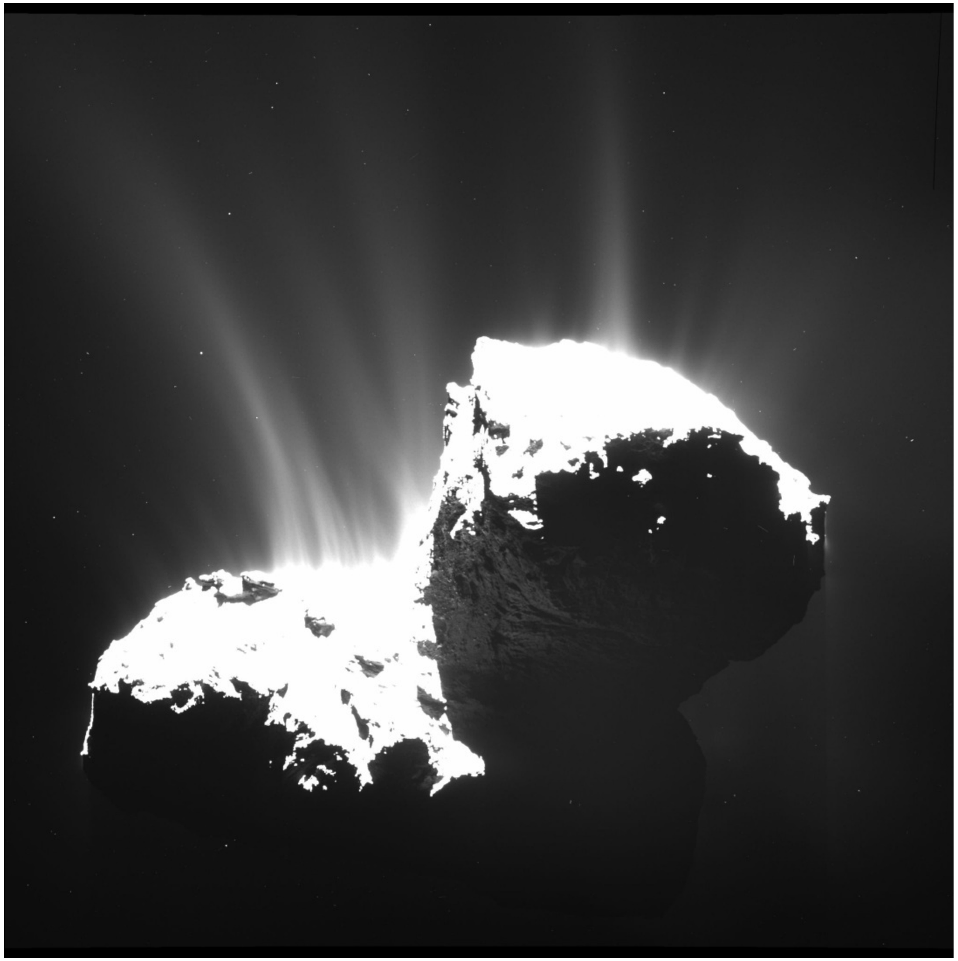
OSIRIS-WAC – Aug 2nd 2014



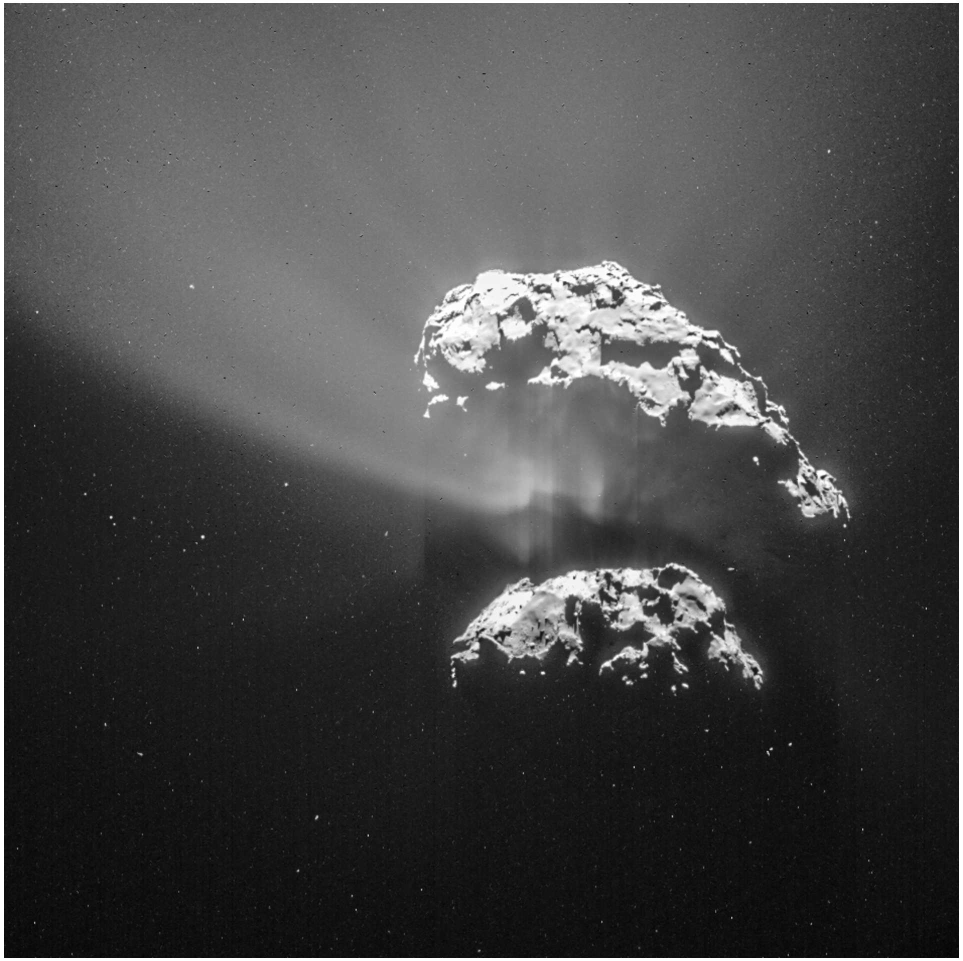
Comet tail as seen from Earth

ESO VLT (Chile) – Aug 11th 2014

Coma Jets as seen from Rosetta

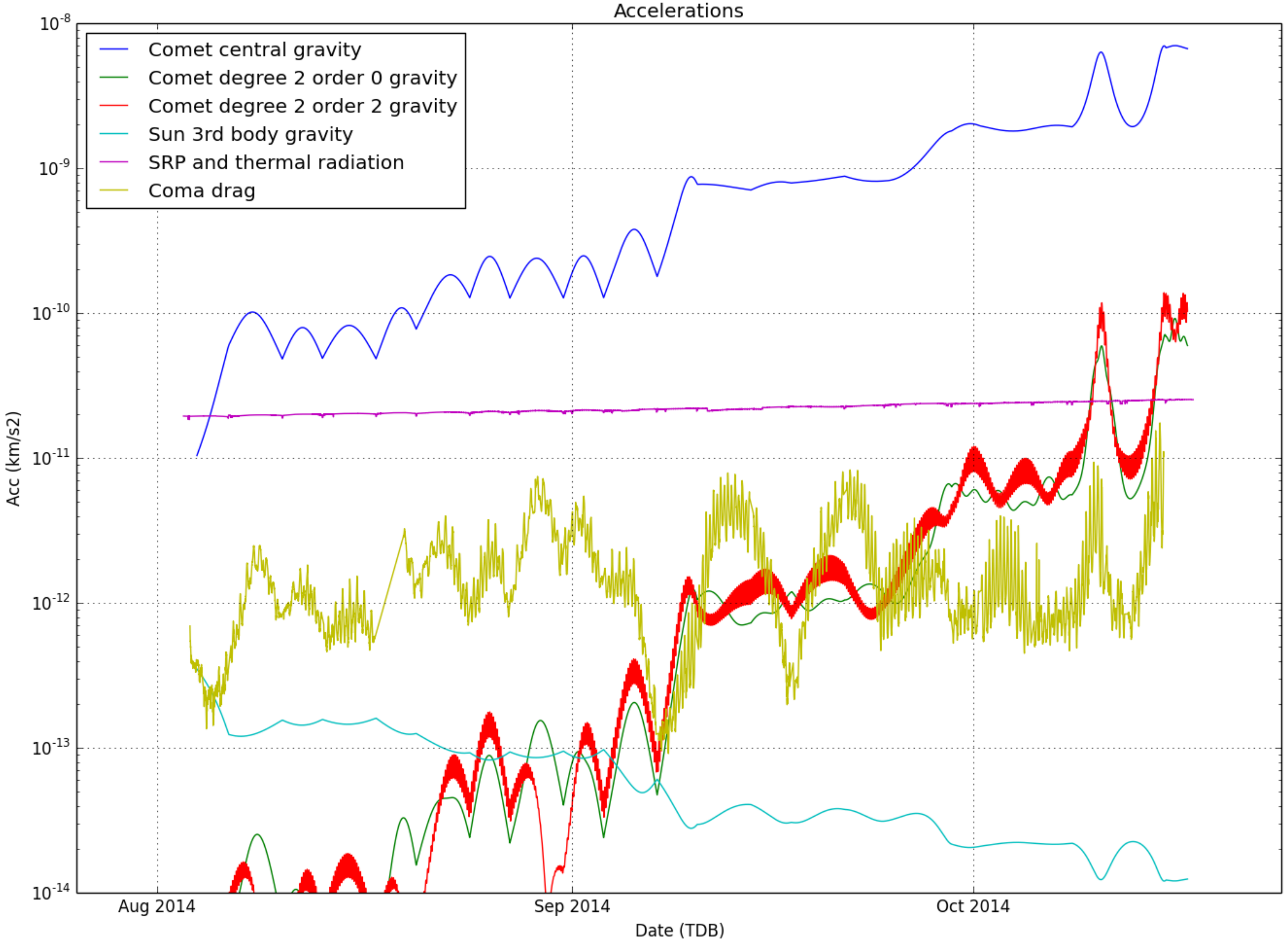


OSIRIS-WAC – Nov 22nd 2014



NAVCAM – Feb 9th 2015

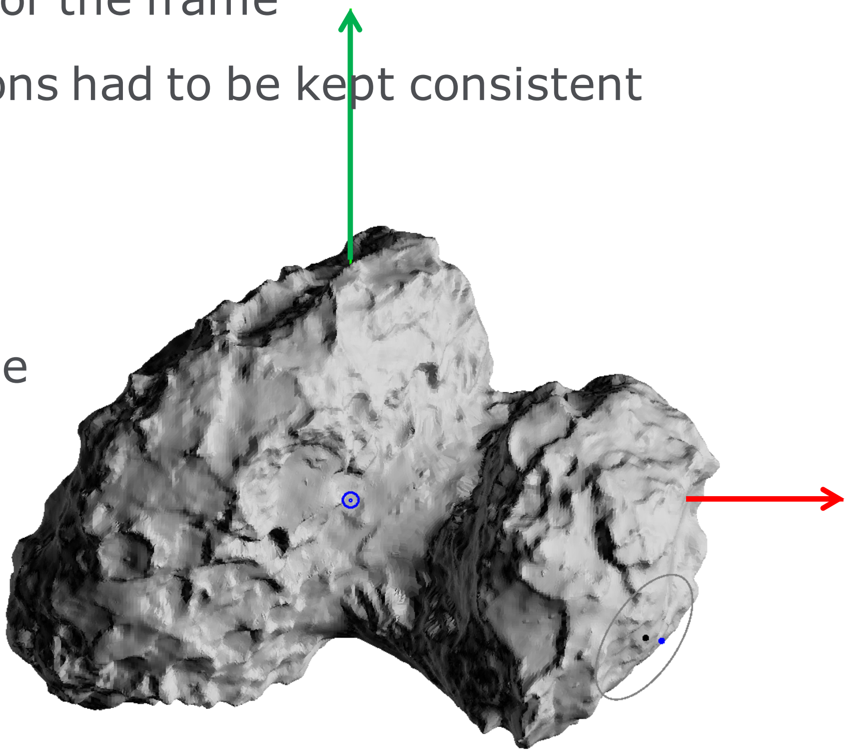
Rosetta Accelerations (2014 Aug – Oct)



Comet Frame Definition

- Comet fixed frame was defined to have the angular velocity vector in +Z
- One degree of freedom is still undefined: prime meridian (+X direction)
- Just after comet arrival an arbitrary selection of the prime meridian was done trying to align X, and Y to the principal axes of inertia
- Initially, there was a significant uncertainty in the centre of mass location which was defined to be the origin of the frame
- Once the frame was defined, all OD solutions had to be kept consistent to that frame
- This could be set-up in different ways:
  - Fixing the coordinates of 1 landmark
  - Fixing the comet attitude at certain time
  - Let comet frame and landmarks free and convert later to the original frame
- 2 updates to the frame definition were

done to update the centre of mass location



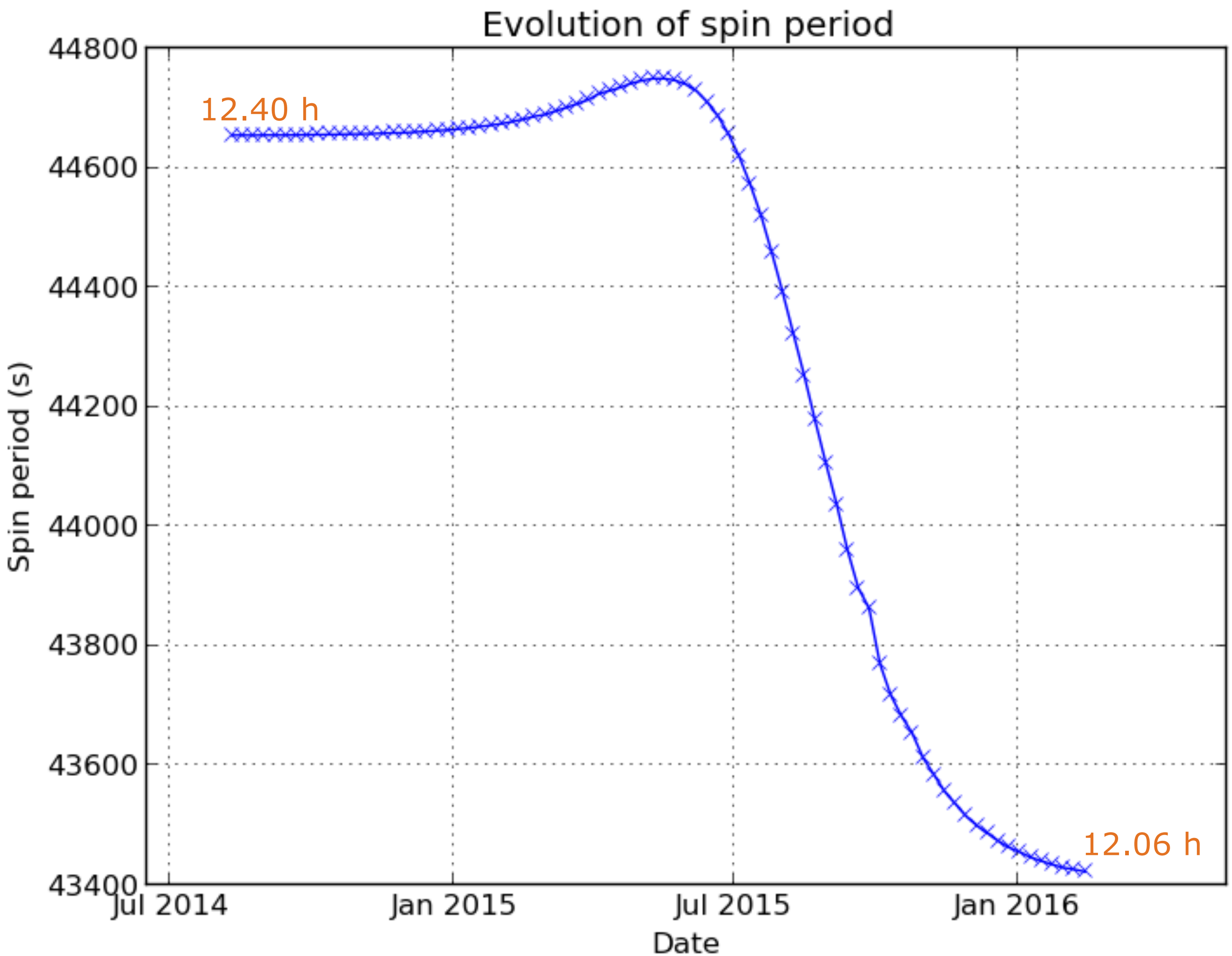
Evolution of Comet Rotation

- Outgassing of cometary material induces a force and a torque on the comet:
  - Acceleration in comet's trajectory
  - Change in the rotation period and spin axis orientation (difficult to model)

- Currently, the orbit of the comet is re-estimated in each short arc OD, mitigating the impact of the mis-modeled acceleration
- The rotation phase, rotation rate and rate-rate are re-estimated in each OD
- Spin axis orientation is only re-estimated in long arc OD
- To monitor the evolution of the comet rotation, overlapping 2-week arcs are periodically run, estimating the comet rotational parameters

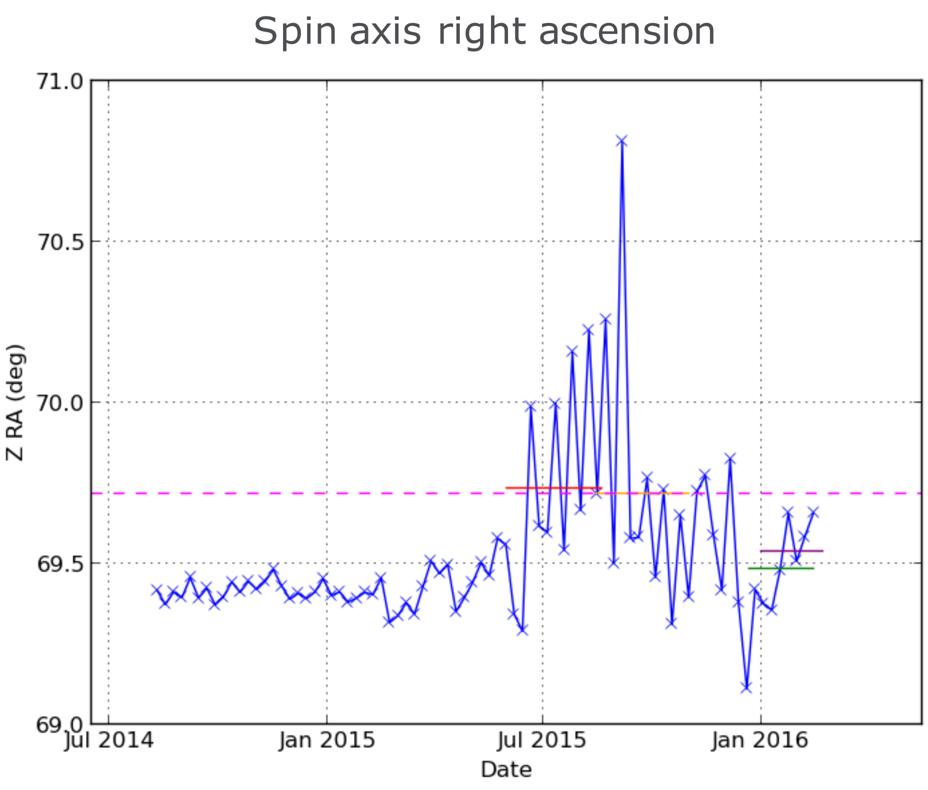
- Comet season and distance to the Sun are the main drivers of the evolution of these parameters

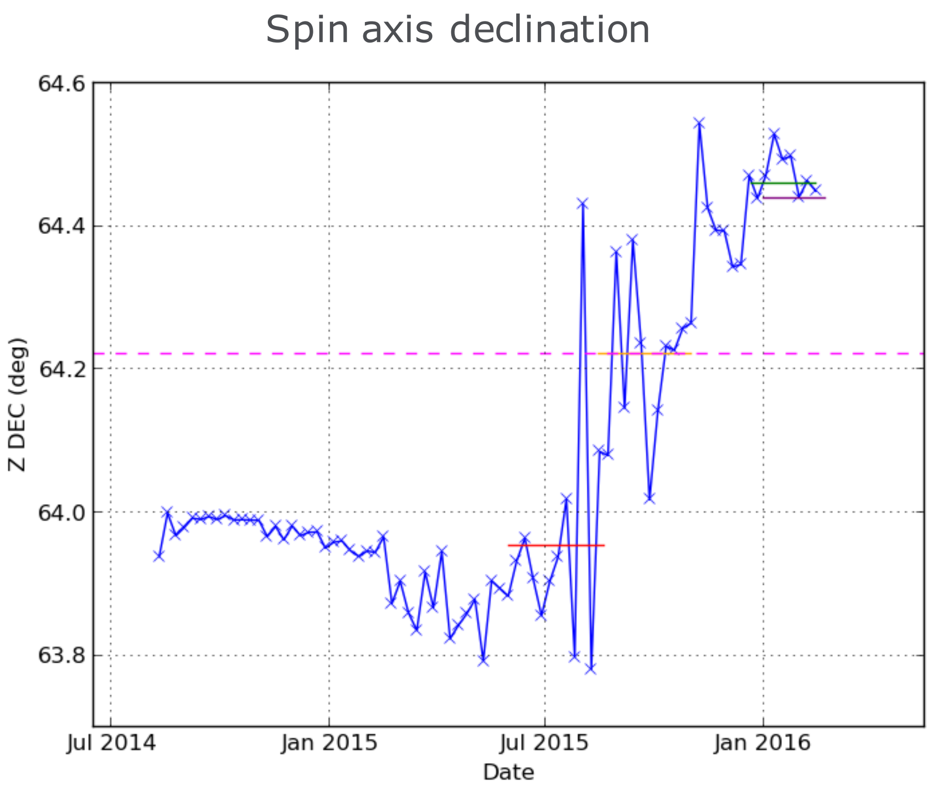
Evolution of Rotational Period



European Space Agency

Evolution of Spin Axis Orientation





Rosetta Navigation Concepts (II)

- Main tasks:
  - **Design the trajectories around the comet**
  - Orbit determination (OD) and trajectory reconstruction
  - Prediction of future trajectory
  - **Optimization of next manoeuvres**
  - Calibration of executed manoeuvres

- Relative navigation around the comet:
  - Image processing for comet detection and landmark identification
  - Determination and prediction of comet orbit and attitude
  - Estimation of additional comet parameters:
    - Mass, gravity field
    - Coma density => nebulae of gas and dust around the nucleus
    - Centre of mass position
    - Landmark coordinates
    - Shape model

Trajectory Design

- Define the trajectories for each mission phase satisfying:
  - Mission constraints
  - Phase specific objectives

- Navigation analysis to estimate the navigation accuracy that would be achieved in each trajectory. Two methods:
  - Covariance analysis
  - Montecarlo simulations:
    1. “Real-world” initial orbit generation
    2. Tracking data simulation
    3. Orbit determination
    4. Manouevre optimization & orbit prediction
    5. “Real-world” orbit propagation
    6. Evaluation of reconstruction and prediction errors

Mission Constraints

- Spacecraft safety:
  - Avoid collision trajectories to the comet (small pericentre)
  - Avoid small relative velocities w.r.t. the comet
  - Avoid Sun eclipses
  - Avoid all previous conditions even in the case of aborting a manoeuvre, or being interrupted during its execution
- Navigation accuracy:
  - Reconstruction and prediction of S/C relative trajectory with sufficient accuracy in a range of possible comet environments
  - Pointing error to the comet, up to next OD data cut-off, should be less than half the FOV of the NAVCAMs
- Aim to have planning cycles in normal working hours. Weekly regular pattern:
  - Planning cycles on Mondays and Thursdays
  - Manoeuvres on Wednesdays and Sundays (/Saturdays)

Planning Cycles

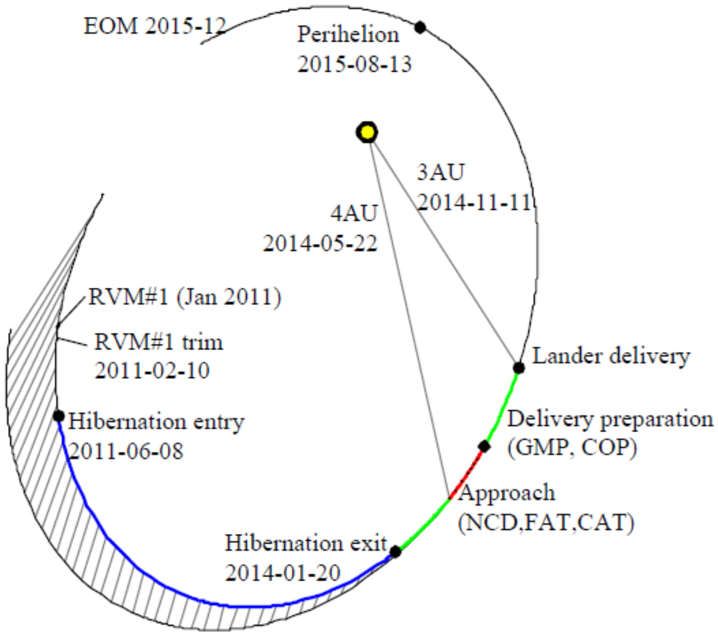
- Long Term Planning (LTP):
  - Months in advance, the reference trajectory is generated
  - It is delivered to the scientific community so that the observations can be planned
  - The actual trajectory flown must be close enough to the reference trajectory (within certain error box)

- Medium Term Planning (MTP):
  - Based on the LTP trajectory the Science Ground Segment produces the pointing requests
  - S/C attitude constraints are checked accounting for the error box, in order to accept the pointing requests

- (Very) Short Term Planning (VSTP):
  - Planning cycles on Mondays and Thursdays
  - Actual trajectory is determined and manoeuvres are commanded to follow the reference trajectory

Mission Phases

Phase	Time interval	Relative distance	Sun distance
Comet Approach (CAP)	May to August 2014	1 million to 100 km	4 au
Initial Characterization (ICP)	August 2014	120 to 60 km	
Global Mapping (GMP)	September 2014	30 to 20 km	3.5 au
Close Observation (COP)	October 2014	20 to 10 km	
Lander Delivery (SDP)	November 2014	30 to 15 km	3 au
Relay (RP)	November 2014	15 to 50 km	
Extended Monitoring (EMP)	Dec 2014 to end of 2015+	>100 km to 8 km	3 to 1.2 au



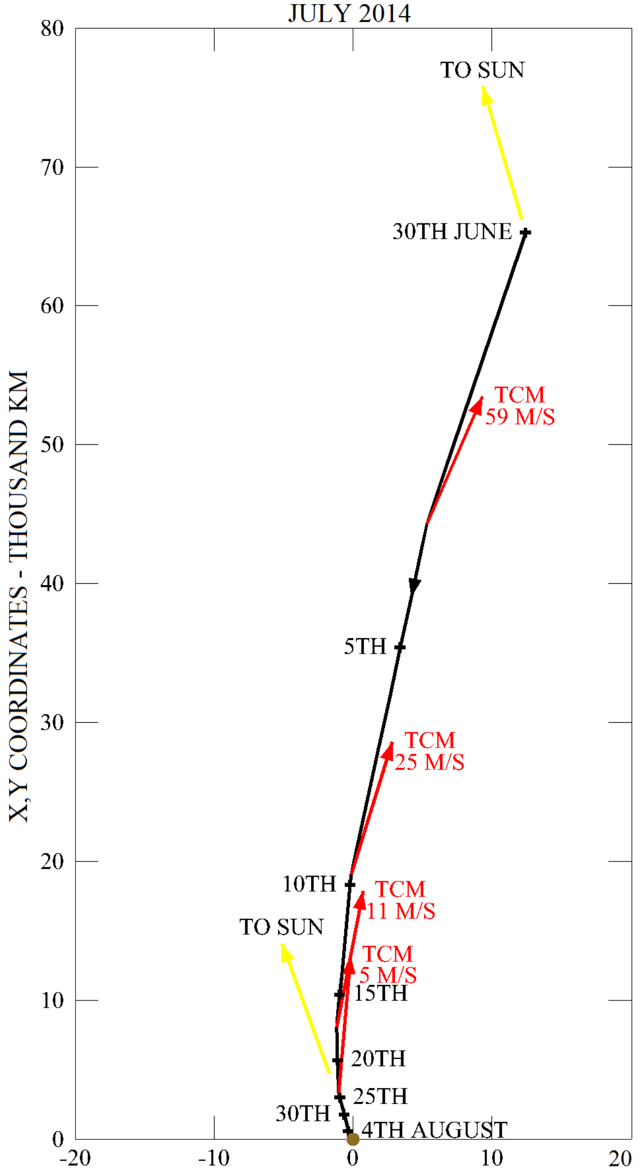
CAP - Comet Approach Phase

- Objectives:
  - Reduce relative velocity from 780 m/s to 1 m/s
  - Progressively bend the trajectory towards the comet
  - Improve estimation of comet ephemeris

- Comet detection with on-board cameras is required to determine relative trajectory
- Total ΔV is divided in manoeuvres of decreasing size
- ΔV of each manoeuvre is selected such that if next manoeuvre is missed, there is enough time margin to the closest approach so that the spacecraft can be recovered and a new manoeuvre can be commanded
- The miss-distance is progressively reduced from 50000 km to 100 km => improve observability of the relative distance

CAP - Comet Approach Phase

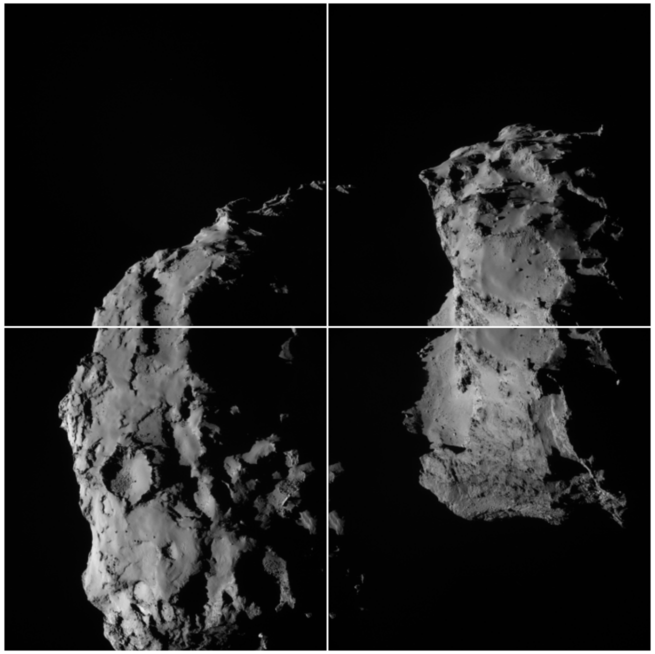
Manoeuvre	Date	ΔV [m/s]	Comet distance [km]
RDVM#2_test	May 7th	20	1,870,000
RDVM#2_1	May 21st	291	954,000
RDVM#2_2	June 4th	271	396,000
RDVM#2_3	June 18th	91	166,000
RDVM#2_4	July 2nd	59	45,000
RDVM#2_5	July 9th	25	19,000
RDVM#2_6	July 16th	11	8,200
RDVM#2_7	July 23rd	5	3,500
ICP pre-insertion	August 5th	2	400
ICP insertion	August 8th	1	100



ICP – Comet Initial Characterization Phase

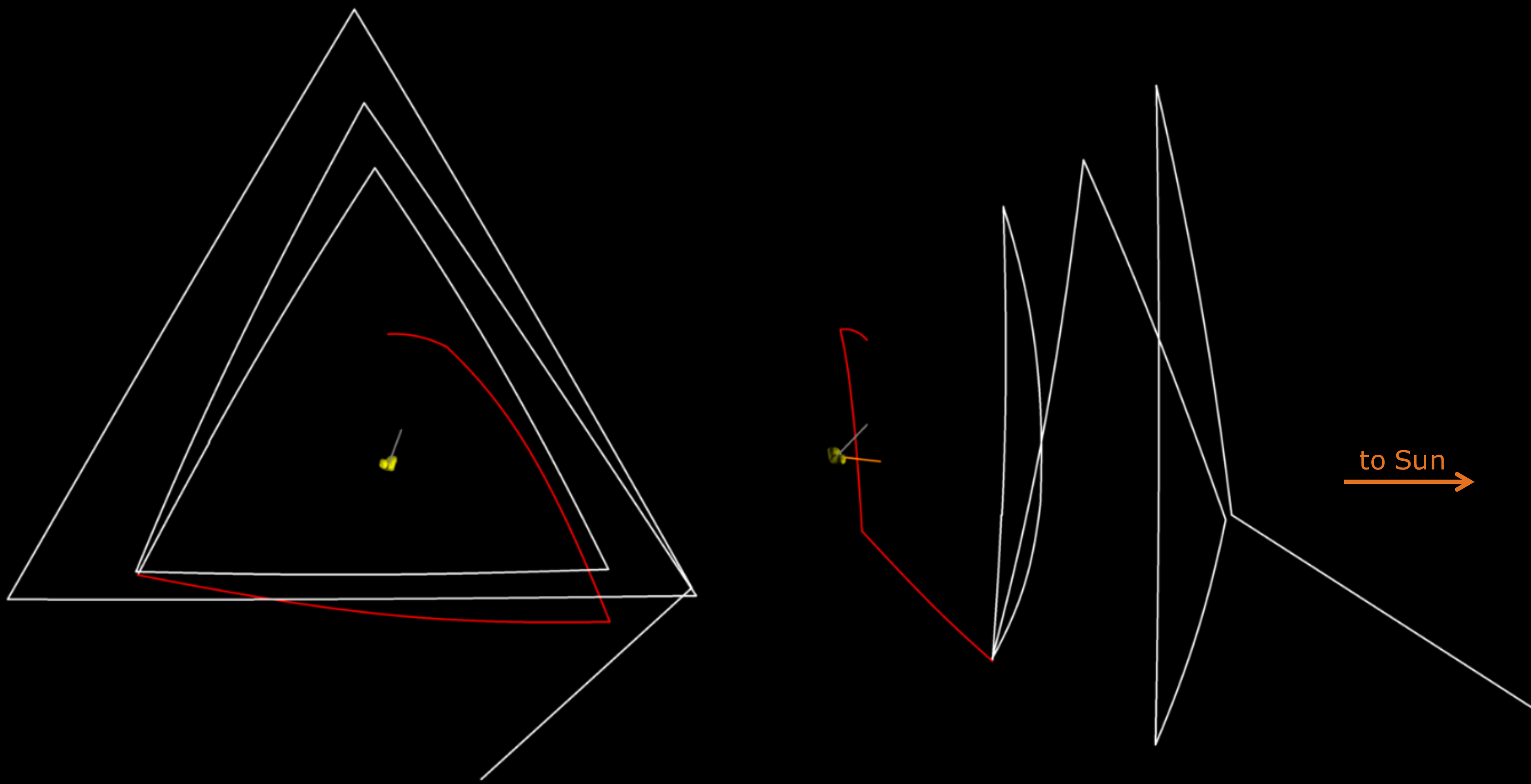
- Objectives:
  - Initial estimation of comet characteristics (rotational state, mass)
  - First landmarks identification
  - Taking images of the full comet nucleus varying Solar phase angle

- Trajectory:
  - 8 hyperbolic arcs of 3-4 days
  - 2 triangles: first ~100, then ~60 km
  - Relative Velocity: ~ 0.5 m/s
  - Manoeuvre at the end of each arc: 0.8 m/s
  - Orbital plane tilted 30 degrees w.r.t. Sun direction



- Starting at 70 km, rasters of 2x2 NAVCAM images, so that the whole comet nucleus is captured in the mosaic

ICP – Comet Initial Characterization Phase



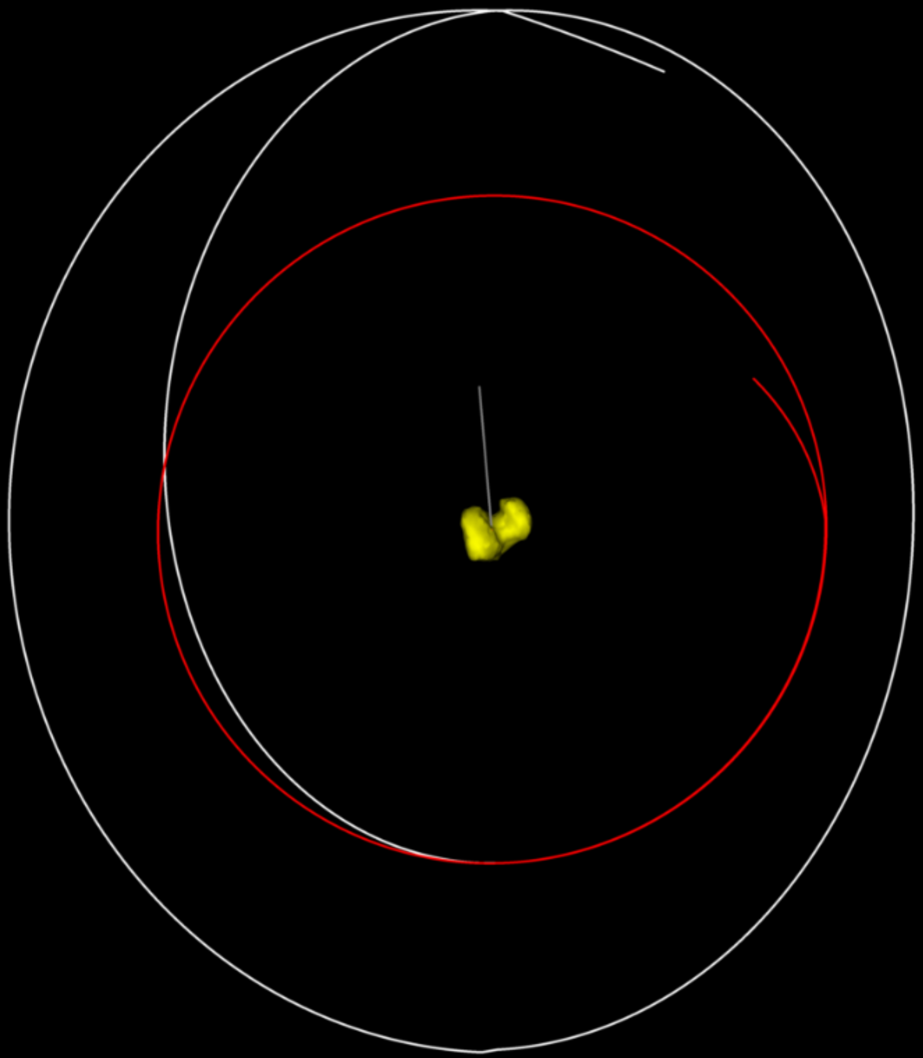
View from Sun

View from ~terminator

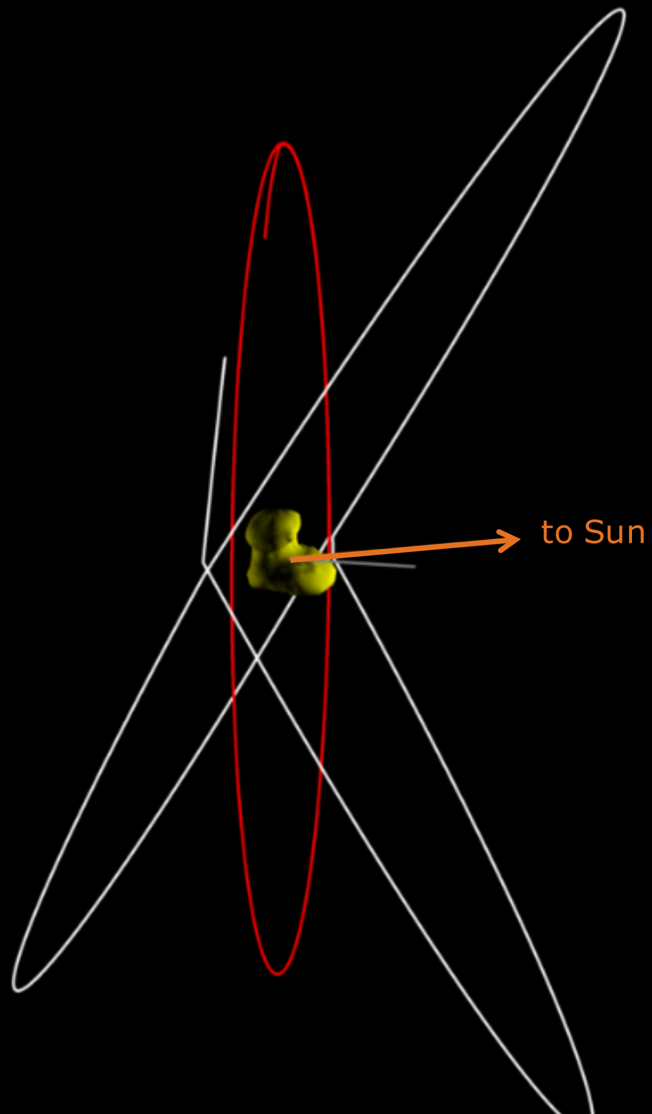
GMP - Global Mapping Phase

- Objectives:
  - Map 80% of comet's surface with a resolution of ~1.5 m.
  - Gain enough navigation knowledge to fly closer trajectories.
- Trajectory at 30 km:
  - 3 semi-circular arcs of ~30x30 km quasi-polar orbits
  - Orbital period: 14 days
  - 2 orbital planes tilted 30 deg w.r.t. terminator plane
  - Manoeuvres to invert velocity and switch plane, keeping the S/C in the day side
  - Night side excursion going down to 20 km
- Trajectory at 20 km:
  - ~20x20 km orbit in the daylight terminator plane (to reduce cross-sectional area opposed to the coma flow)
  - Orbital period: 7 days

GMP - Global Mapping Phase



View from Sun



View from ~terminator

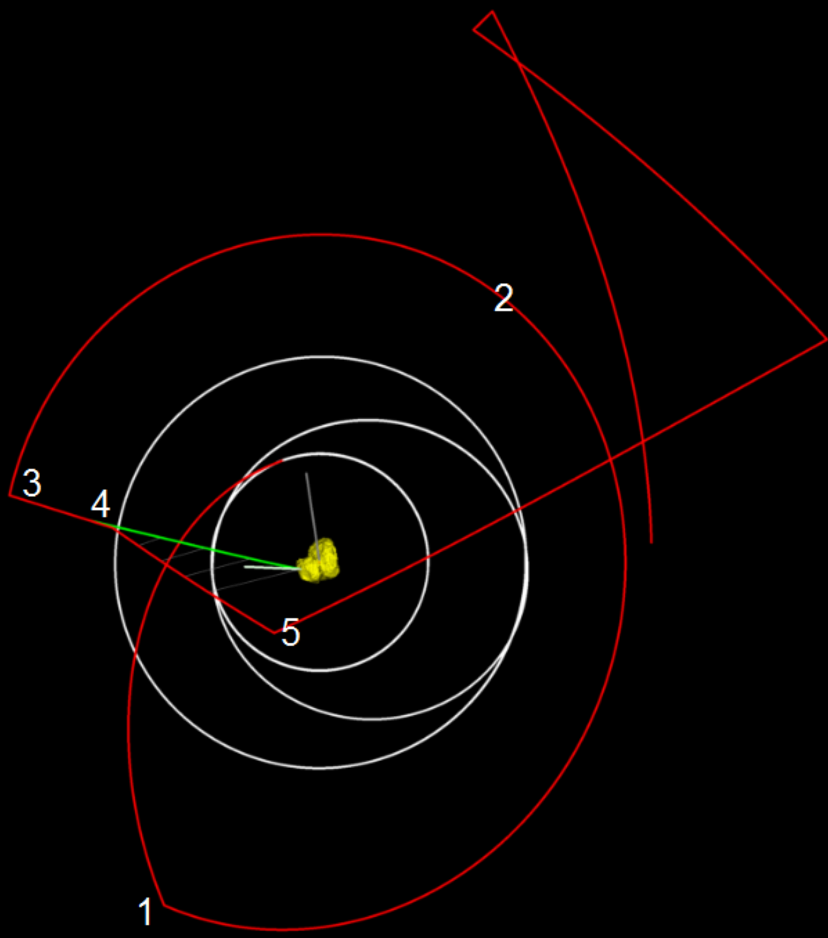
COP - Close Observation Phase

- Objectives:
  - Detailed observation of prime and backup landing sites, to confirm suitability for landing
  - Refine estimation of comet parameters so that navigation accuracy is further improved:
    - Landmark coordinates
    - Gravity field
    - Centre of mass position
    - Rotational state and outgassing torque
    - Coma drag models
- Trajectory:
  - 20x10 and 10x10 km orbit in the terminator plane
  - Orbital period of 20x10 such that one week corresponds to 1.5 revolutions
  - Very small manoeuvres are needed in this phase

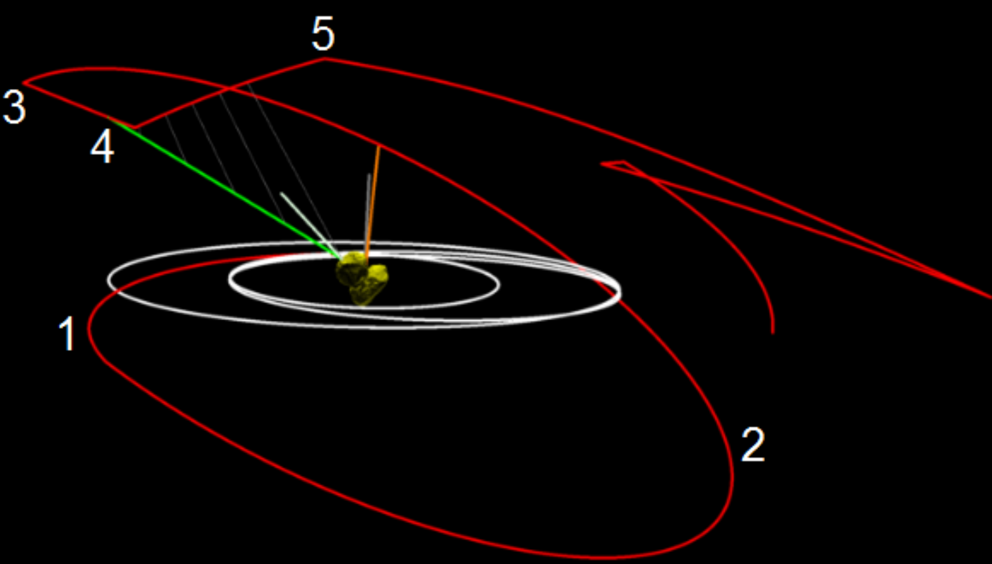
SDP - Lander Delivery Phase

- Objectives:
  - Deliver lander Philae to the selected landing site
  - Keep communications with the lander during descent and immediately after landing
  - Take images of lander descent and landing
- To satisfy all constraints a manoeuvre before separation is required => mis-performance impacts navigation accuracy
- Trajectory:
  - Parking orbit: 30x30 km with orbital plane slightly tilted from terminator plane
  - Pre-delivery manoeuvre (~0.8 m/s) to drive the S/C in a hyperbolic trajectory with 5 km miss-distance
  - Lander separates at ~23 km distance
  - Orbiter performs post-delivery manoeuvre, to avoid going to the night side and assure communications with the lander
  - Touch down is ~7 hours after separation

SDP - Lander Delivery Phase

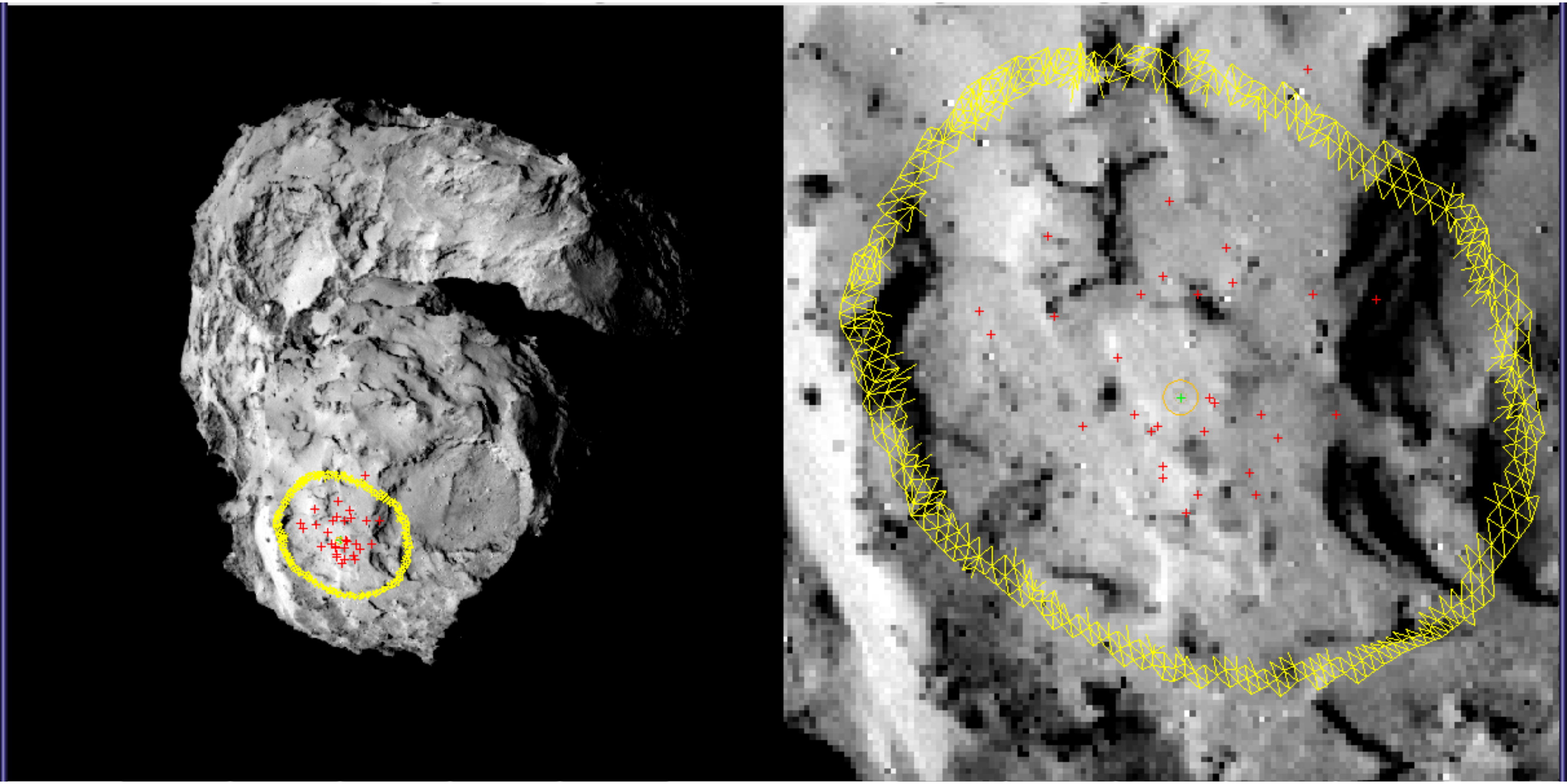


View from Sun



View from ~terminator

SDP - Lander Descent Simulations



RP - Relay Phase

- Objectives:
  - Maximize lander visibility to establish communication link Philae–Rosetta–Earth
  - Slow down the spacecraft velocity after lander delivery and reinsert the spacecraft in a bounded orbit around the comet

- Trajectory:
  - Hyperbolic arcs in which the spacecraft is restricted to the space covered by the beam of the lander antenna in one revolution of the comet
  - At the end of this phase the spacecraft is back in a 30x30 km orbit

Rosetta Navigation Concepts (III)

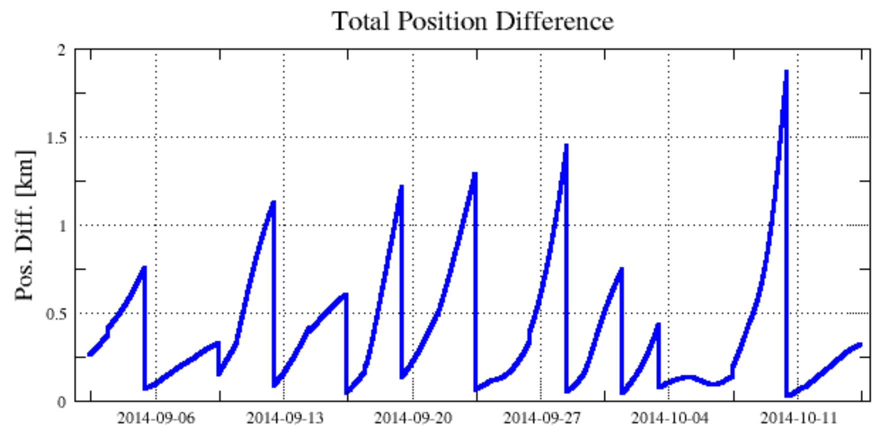
- Main tasks:
  - Design the trajectories around the comet
  - Orbit determination (OD) and **trajectory reconstruction**
  - **Prediction of future trajectory**
  - Optimization of next manoeuvres
  - Calibration of executed manoeuvres

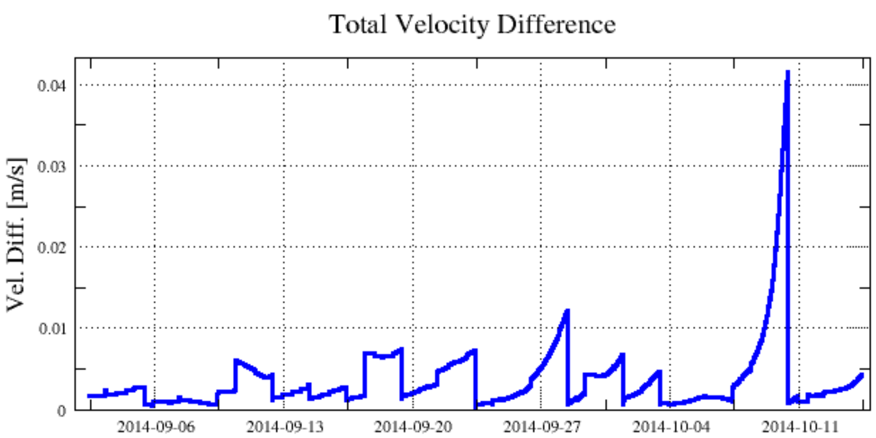
- Relative navigation around the comet:
  - Image processing for comet detection and landmark identification
  - Determination and prediction of comet orbit and attitude
  - Estimation of additional comet parameters:
    - Mass, gravity field
    - Coma density => nebulae of gas and dust around the nucleus
    - Centre of mass position
    - Landmark coordinates
    - Shape model

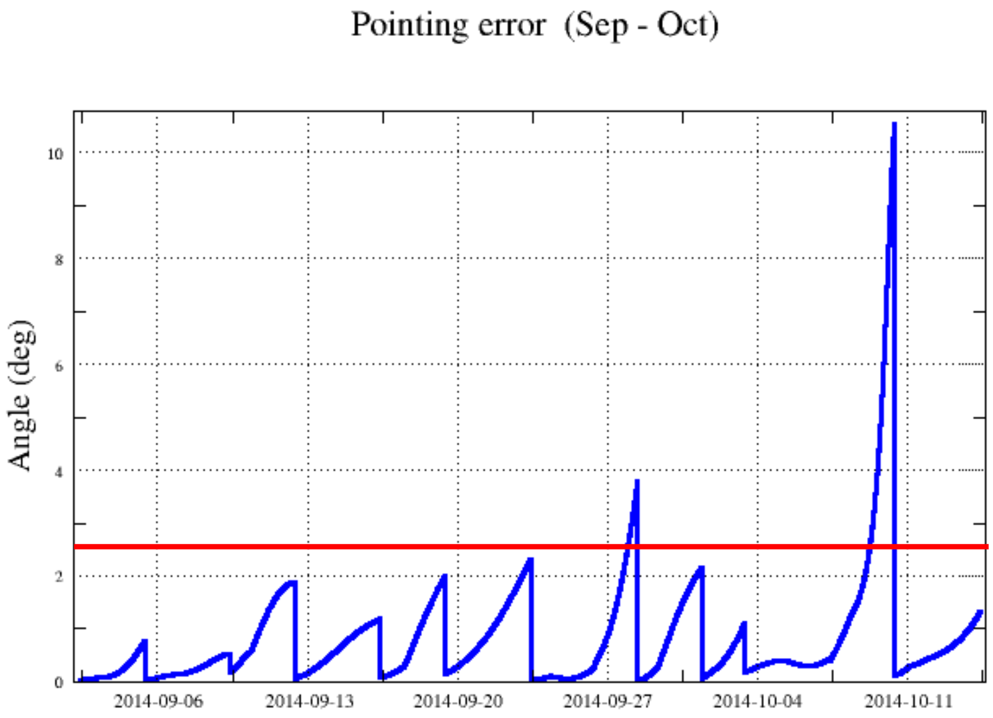
Navigation Accuracy

- Orbit reconstruction typical errors: ~10s metres
- Orbit prediction errors in 4-5 days: < 2 km
- Prediction errors are caused by:
  - Propagation of the orbit determination error
  - Acceleration model errors
  - Manoeuvre mis-performance
  - Wheel-off-loadings residual delta-V
  - Unexpected delta-V (spacecraft outgassing)
- S/C attitude commands (pointing) are generated based on predicted trajectory (about 4-5 days in the future)
- Error in predicted S/C position relative to comet translates to comet pointing errors
- Objective is to keep pointing errors below 2.5 degrees (half NAVCAM's field of view) up to data cut-off of next commanding cycle

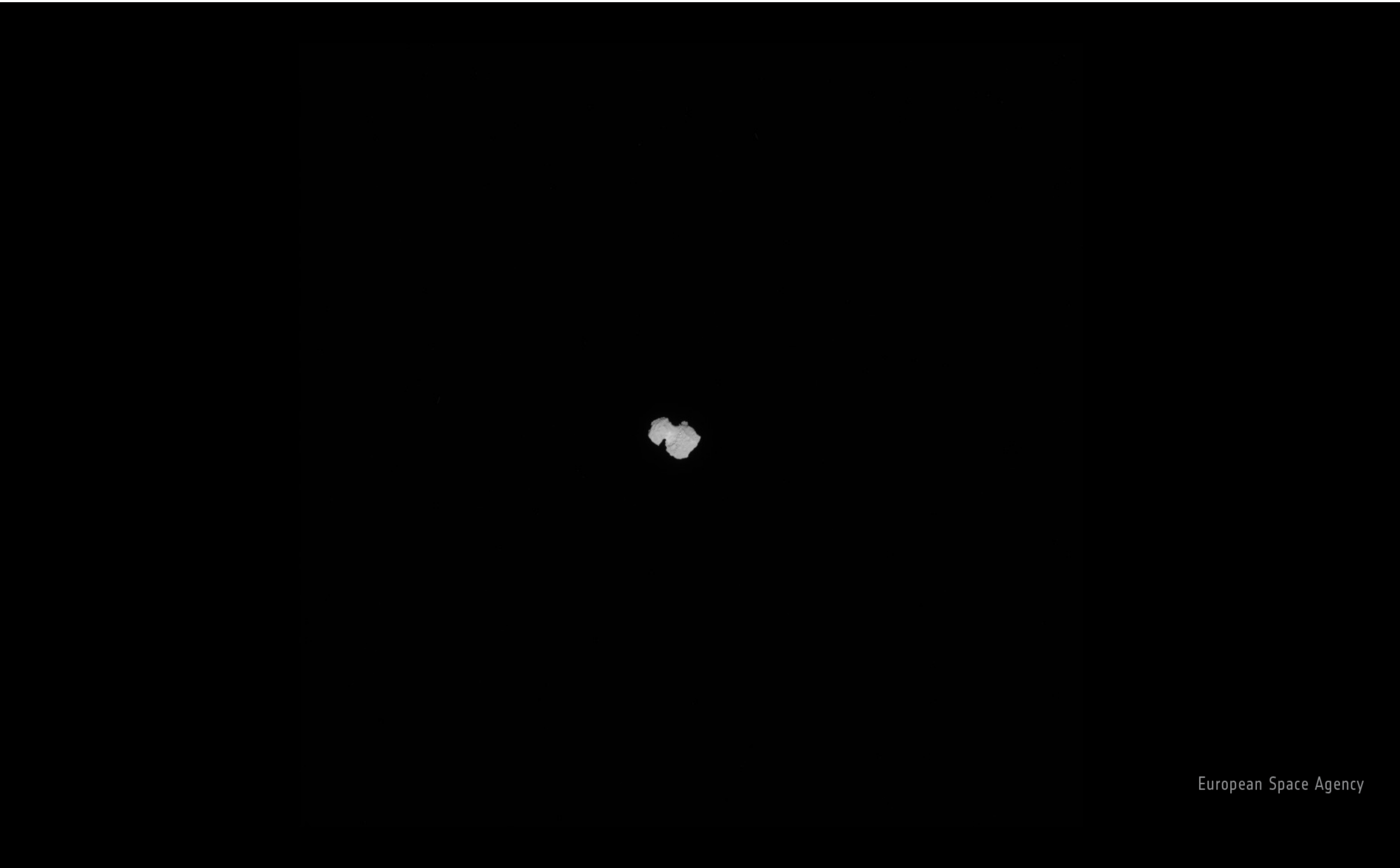
Orbit Prediction Errors (Sep – Oct 2014)



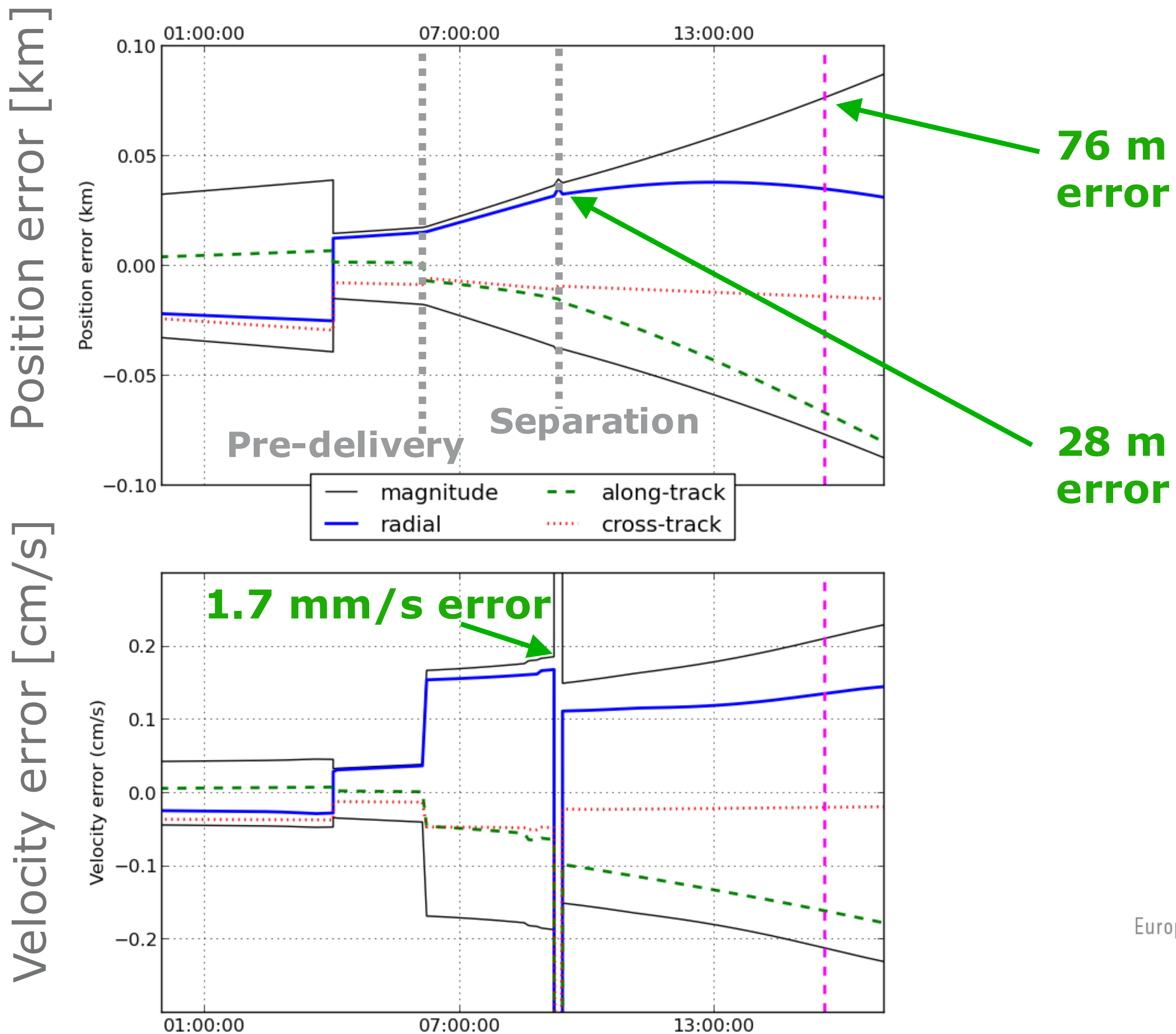




NAVCAM Movie: Comet Arrival



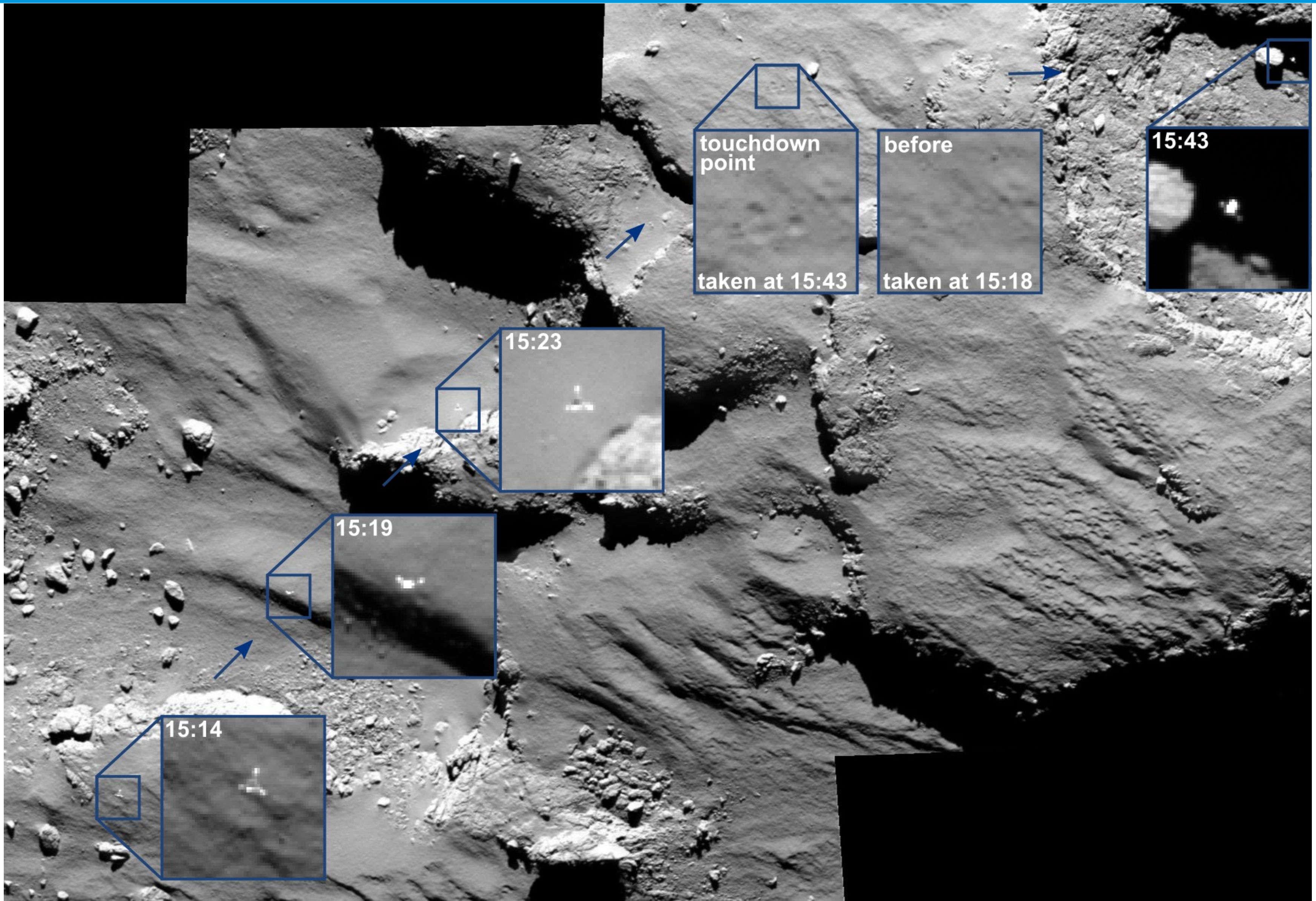
Orbit Prediction Errors (Lander Delivery)



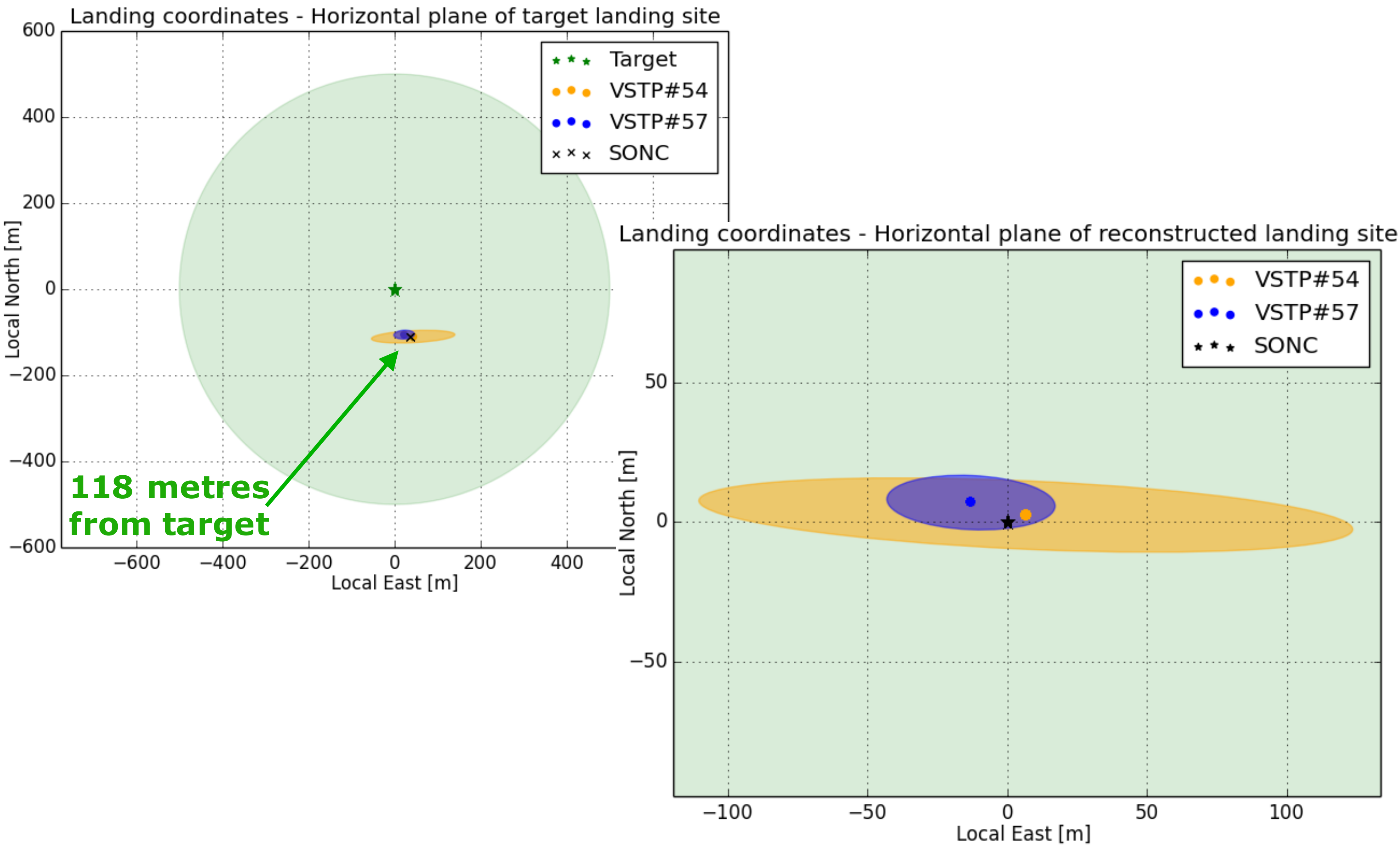
Philae's Descent Reconstruction

- After execution of post-delivery manoeuvre, Rosetta pointed its instruments towards the predicted descent trajectory of Philae in order to take images of its descent
- The observations of Philae in the images were used to derive a measurement of the direction from Rosetta to Philae
- The observations were fed to the orbit determination software to determine the descent trajectory of Philae
- This provided an initial estimation of the 1st touchdown point (accuracy of ~15 m), which later could be confirmed with the reconstruction done by the lander team based on ROLIS data
- First touchdown point was ~120 m away from the target landing site, well within the 500 m error radius that was initially considered
- After the rebound Philae was observed in 2 more images, one NAVCAM immediately after, and one OSIRIS-NAC.
- In both images Philae's shadow was identified and it could be used also as a measurement for the OD
- Based on optical data only, the conditions of the 1st rebound could be reconstructed

Philae's descent observed by Rosetta (OSIRIS)

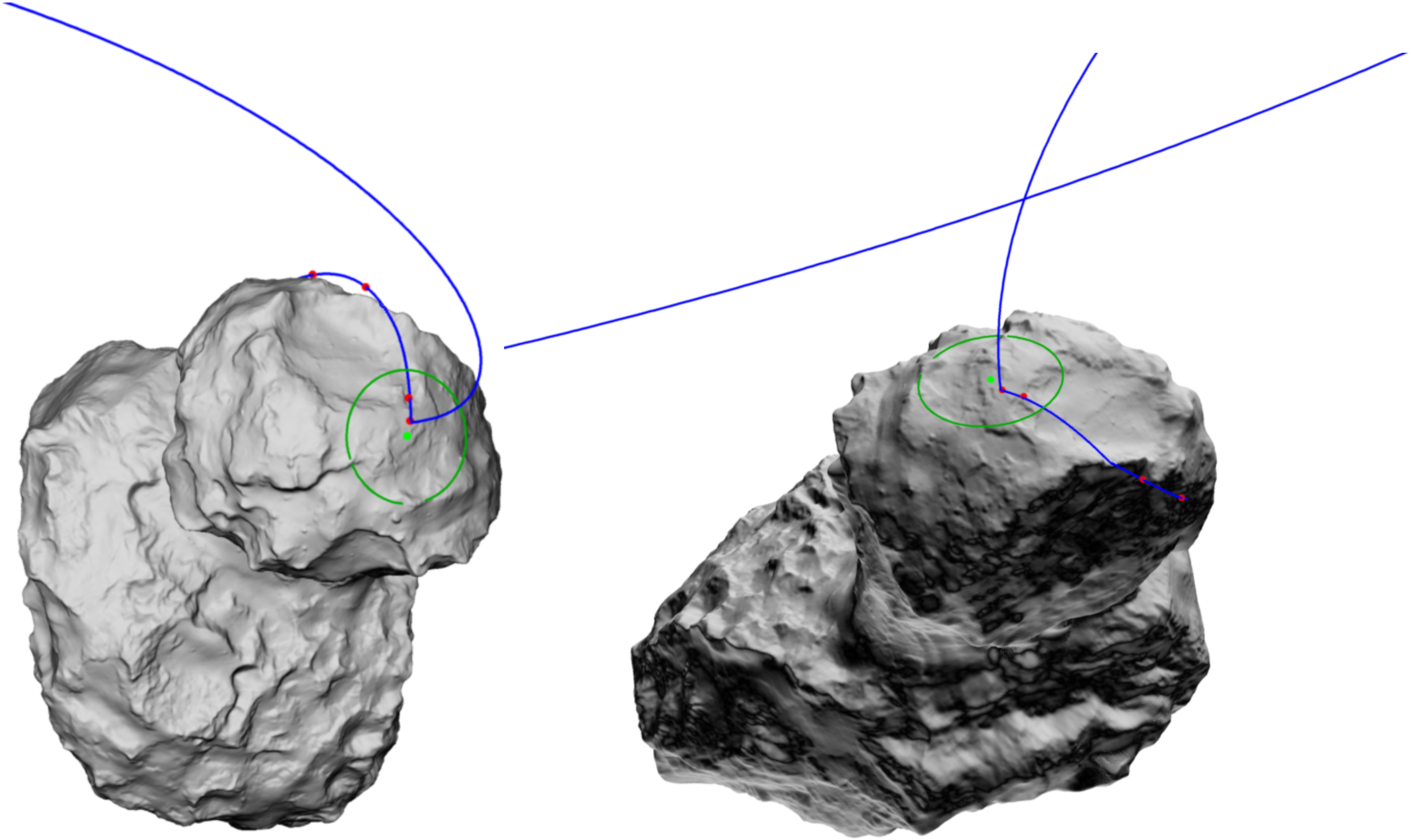


Reconstruction of 1st Touchdown Point



Candidate Observation of Philae

Reconstructed Philae's Trajectory



Rosetta Navigation Concepts (IV)

- Main tasks:
  - **Design the trajectories around the comet**
  - Orbit determination (OD) and trajectory reconstruction
  - Prediction of future trajectory
  - **Optimization of next manoeuvres**
  - Calibration of executed manoeuvres

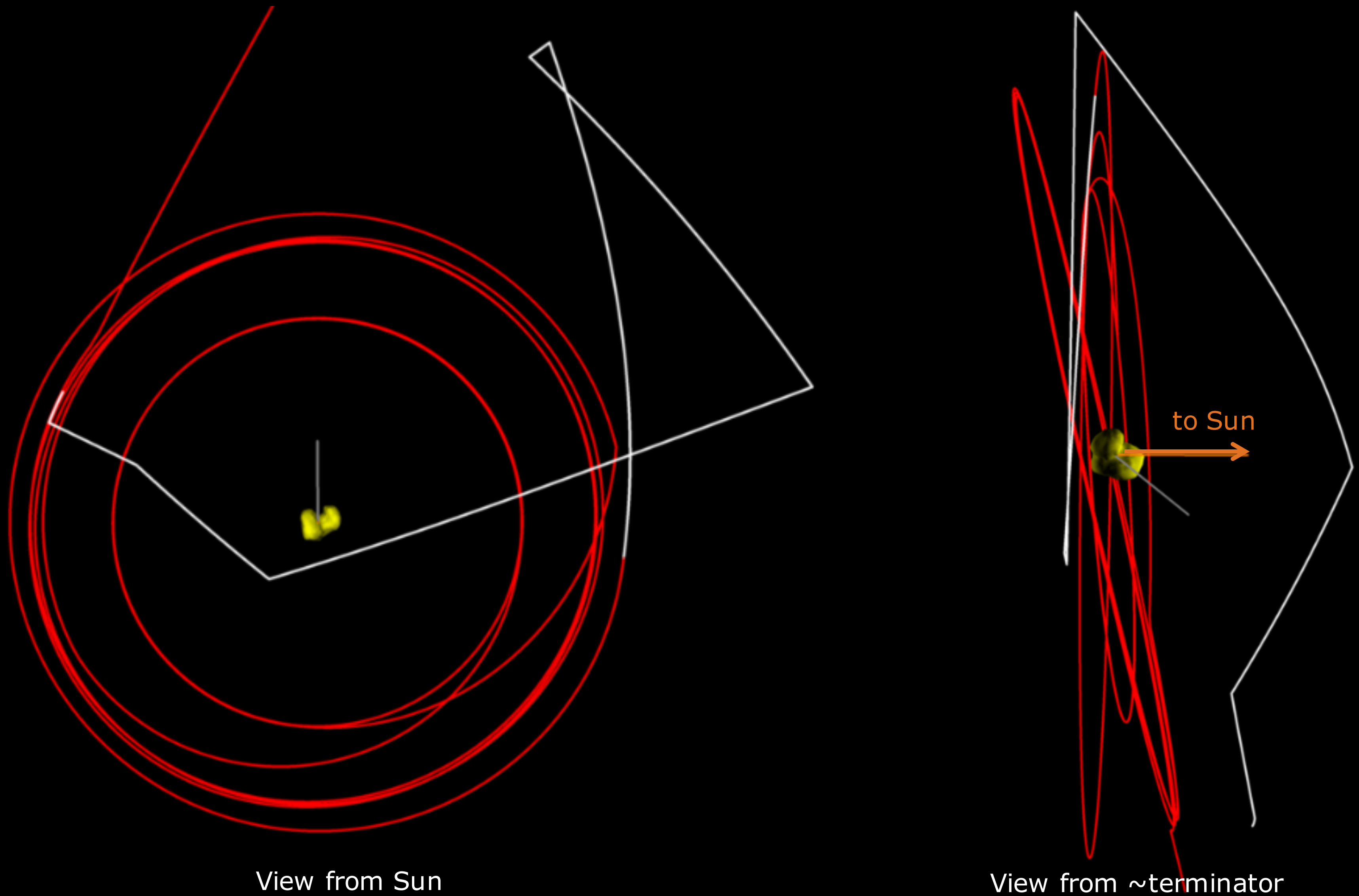
- Relative navigation around the comet:
  - Image processing for comet detection and landmark identification
  - Determination and prediction of comet orbit and attitude
  - Estimation of additional comet parameters:
    - Mass, gravity field
    - Coma density => nebulae of gas and dust around the nucleus
    - Centre of mass position
    - Landmark coordinates
    - Shape model

EMP - Extended Monitoring Phase

- Objectives:
  - Escort the comet in its perihelion passage to observe its increasing activity

- Trajectory:
  - In December 2014 and January 2015 circular orbits of 20 to 30 km radius in the terminator plane
  - After that, comet activity was expected to increase so that it was not safe staying so close to the comet
  - Starting in February 2015, the spacecraft was moved further away flying hyperbolic arcs
  - To still observe the comet nucleus in detail, sequences of far (50 - 100 km) and close (10-20 km) fly-bys are flown
  - This trajectory strategy was initially planned to be kept during perihelion and beyond

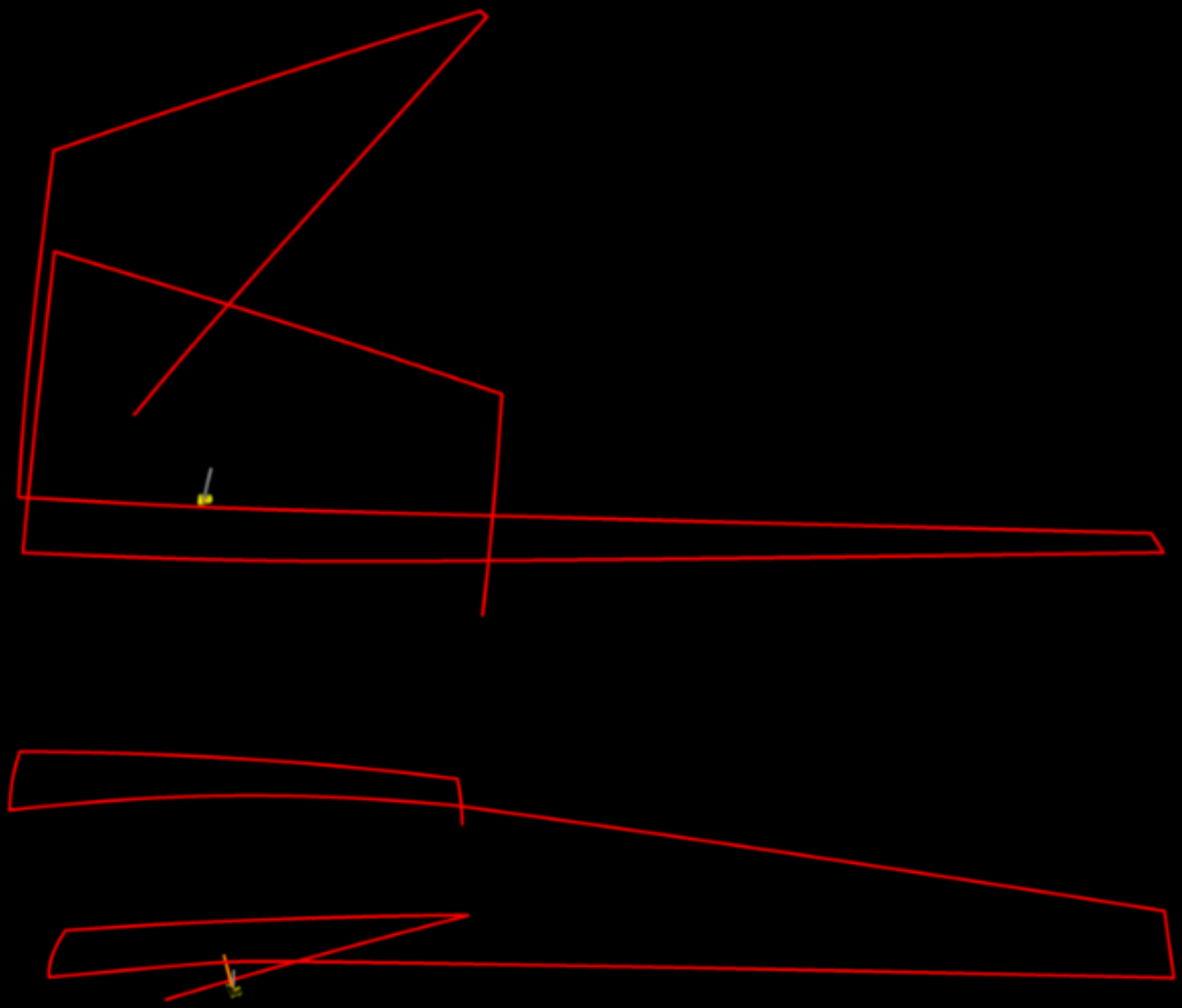
EMP - Bound Orbits



View from Sun

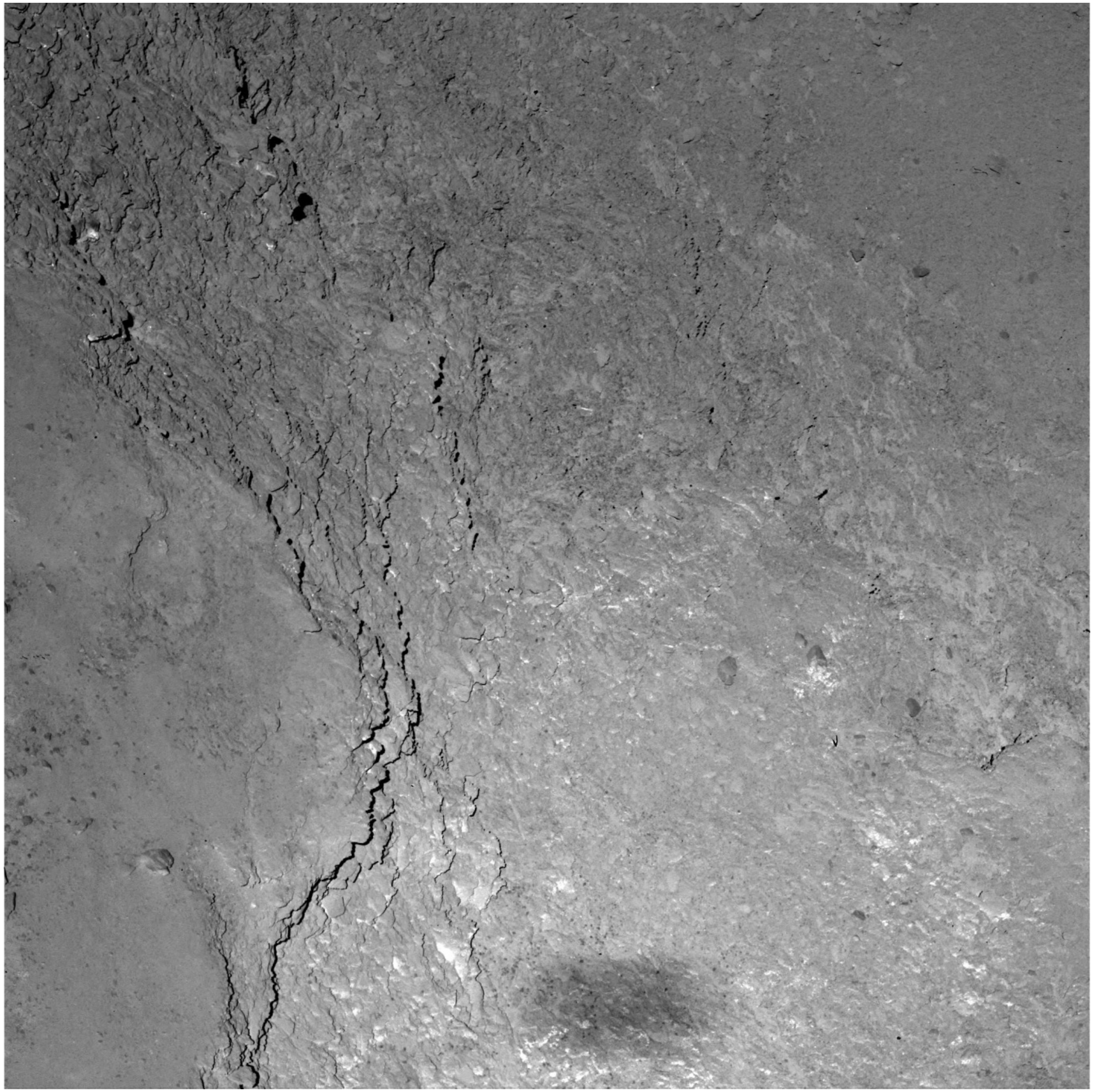
View from ~terminator

EMP – Far and Close Flybys



European Space Agency

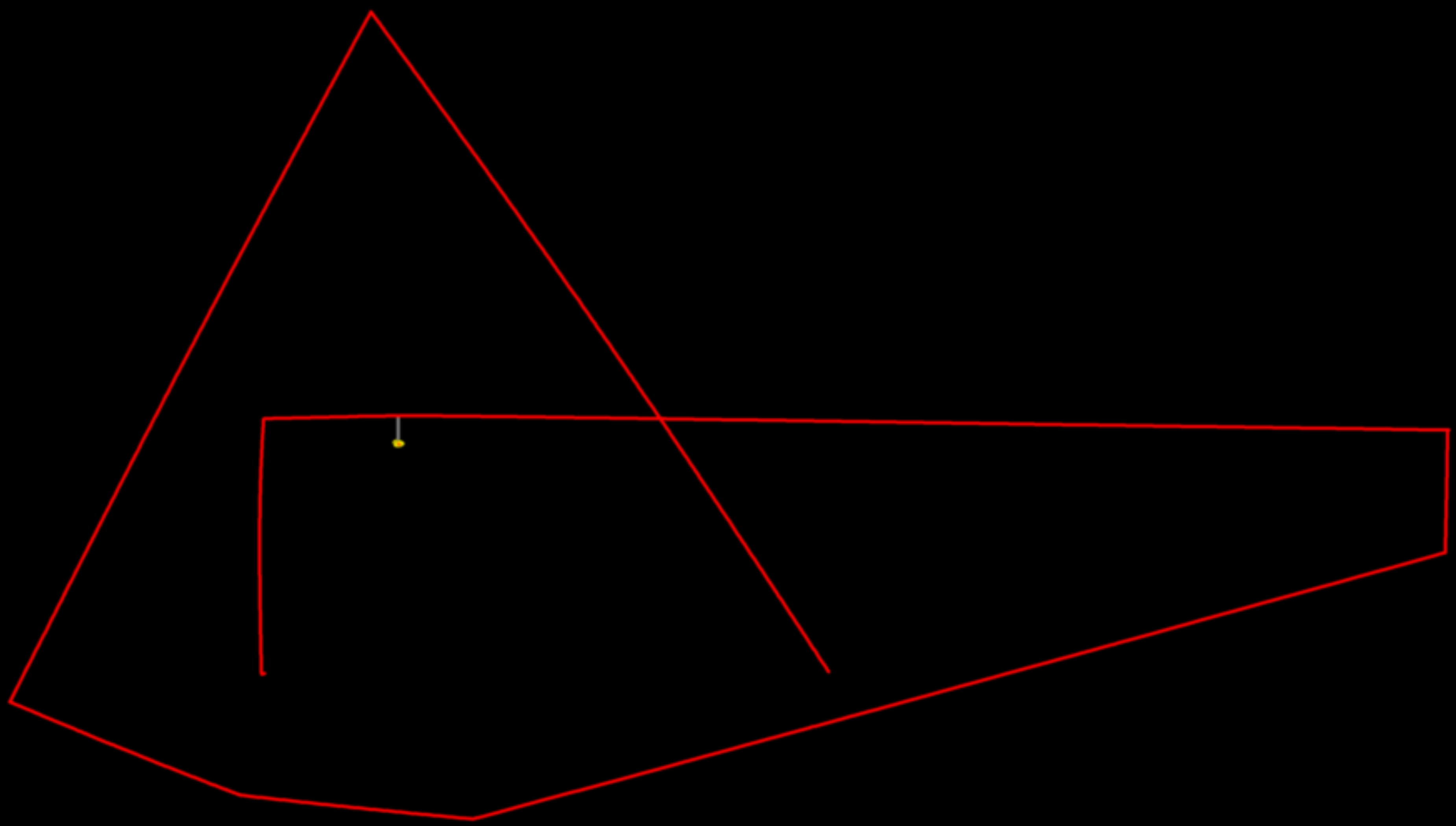
EMP – OSIRIS Image - 6km above Surface



EMP – Star Tracker Issues

- Spacecraft autonomously controls its attitude (orientation) based on the measurements from star trackers (orientation w.r.t. stars) and gyroscopes (angular velocity)
- Comet activity => dust particles in star tracker field of view
- Illuminated dust particles increase the background noise level and can be misinterpreted as stars
- First star tracker problems occurred in the close fly-by on Feb 14th 2015 (8 km distance)
- Mitigation measures were taken for the following one on Mar 28th (15 km distance), but still lots of problems, finally leading to a safe mode:
  - S/C attitude control was based only on gyroscopes for 24h
  - S/C off-pointing rose up to 0.6 deg, endangering the communication link with ground => high risk for the mission
  - At ~75 km distance, the star tracker successfully re-acquired
  - The spacecraft could then be recovered to normal mode

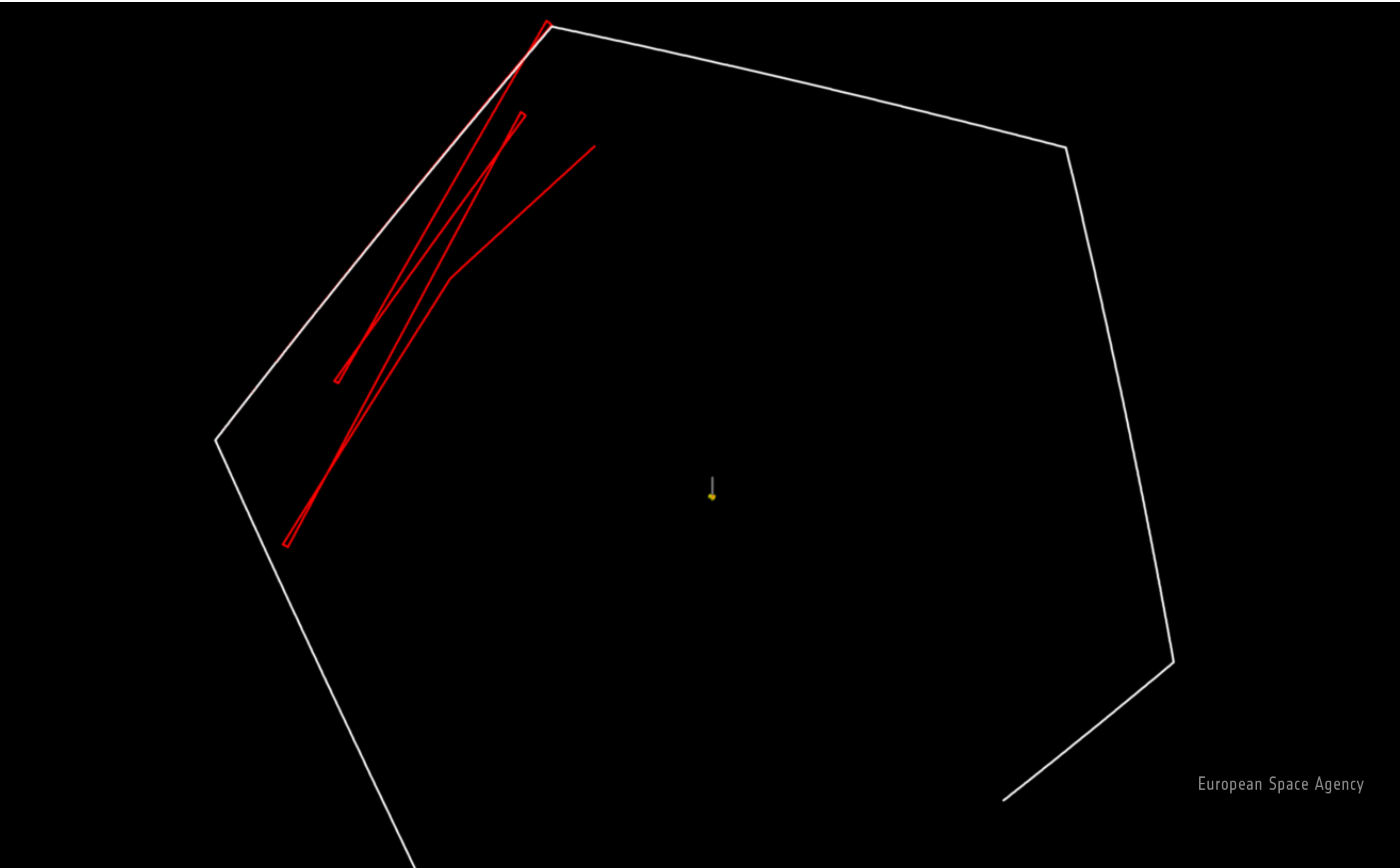
EMP – Safe Mode Recovery



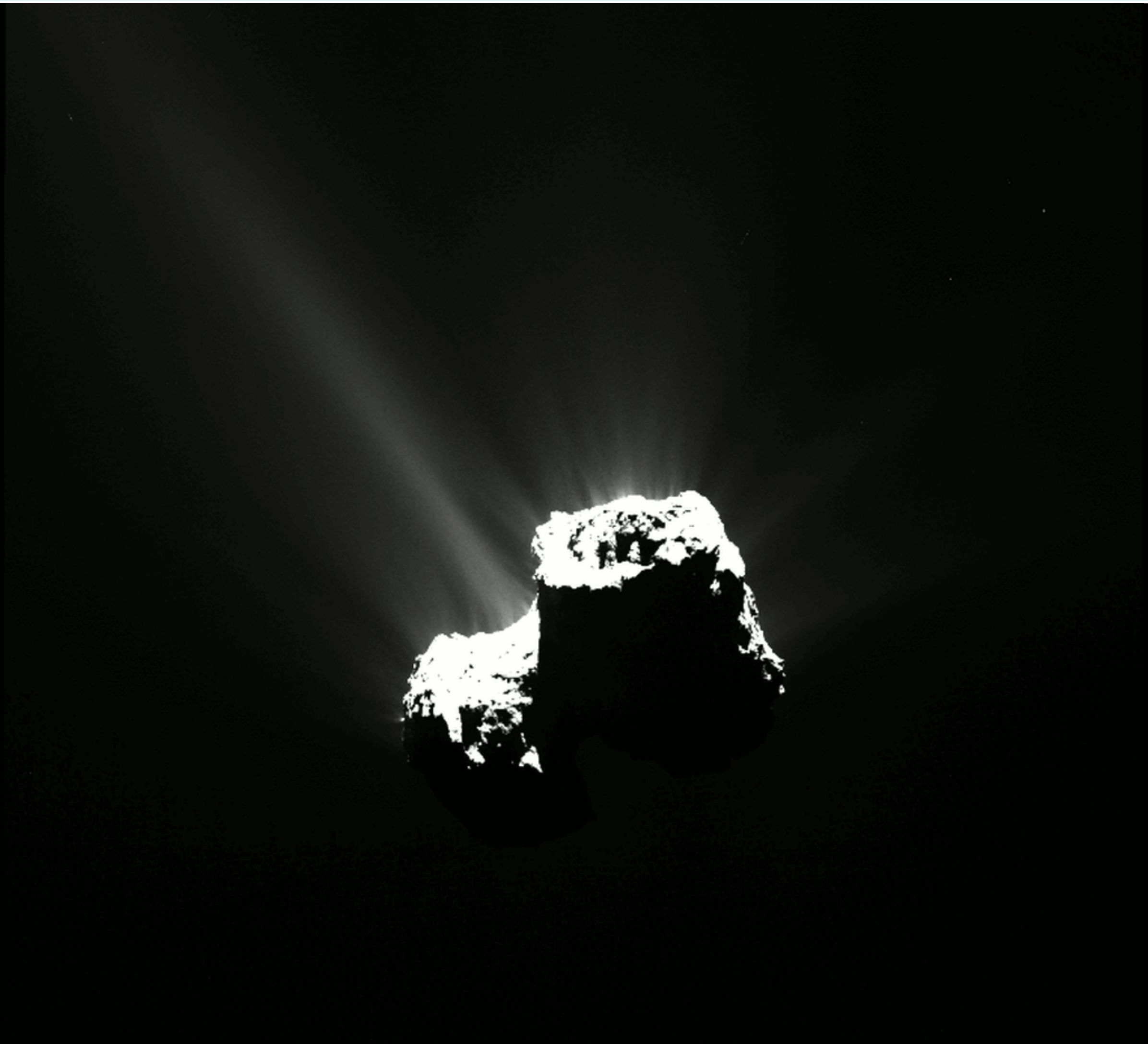
EMP – New Planning Strategy

- Not possible to follow a reference trajectory anymore
- During each planning day, the performance of the star trackers are assessed to determine whether the current minimum distance is safe, or has to be increased, or can be lowered
- High level objectives:
  - Fly hyperbolic arcs as close as possible (ACAP)
  - Alternating between:
    - Terminator plane trajectories
    - Pyramid arcs: similar to the Initial Characterization Phase, tilted 30 deg w.r.t. the terminator plane
- In actual operations, each manoeuvre is computed to target certain set of constraints on the subsequent arc, such as:
  - Pericentre distance
  - Relative velocity magnitude
  - Angle between orbital plane normal and Sun direction
  - Distance/coordinates/latitude/phase angle of the target point

EMP – Terminator Arcs (2015)... Philae!

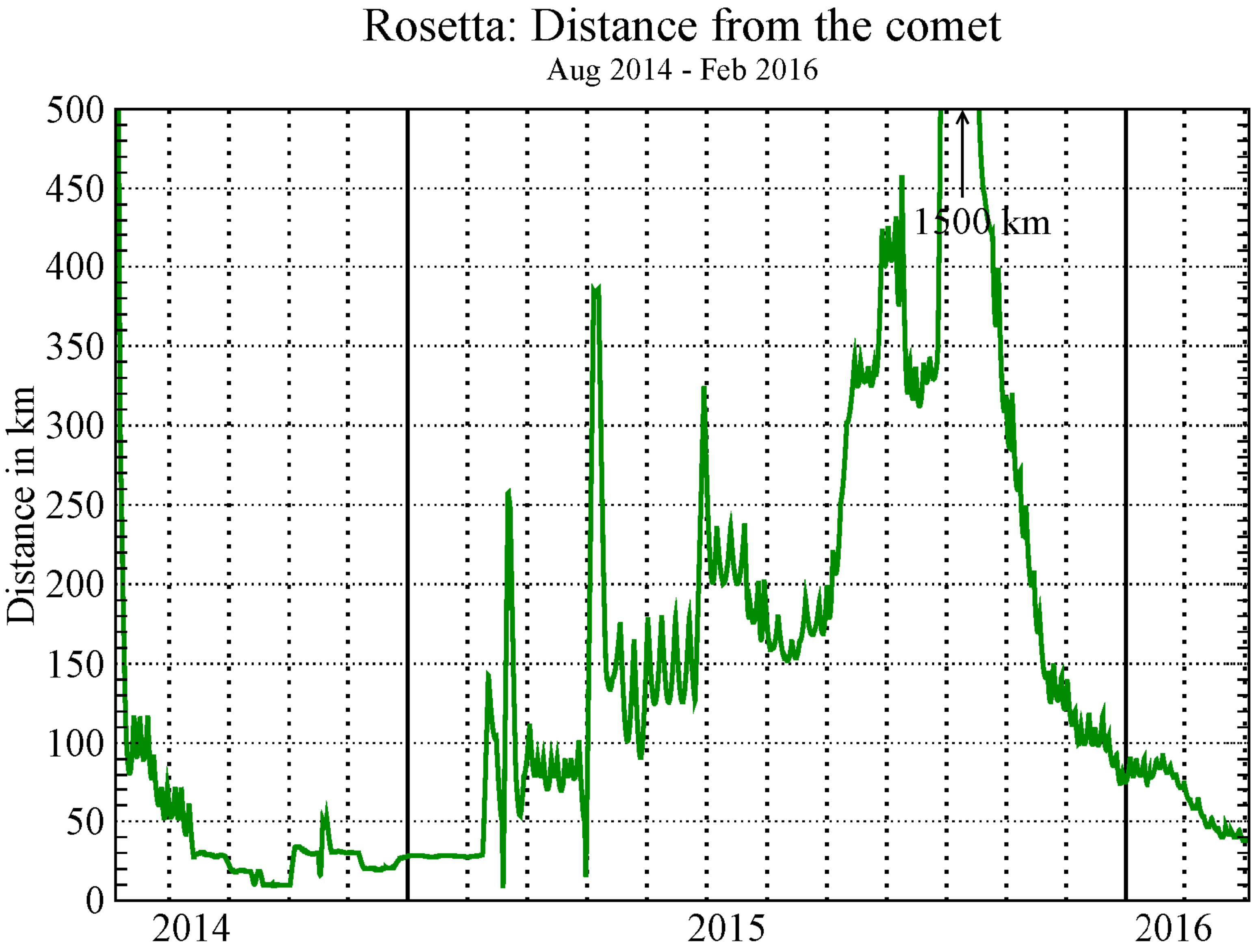


Comet Activity around Perihelion (Aug 2015)

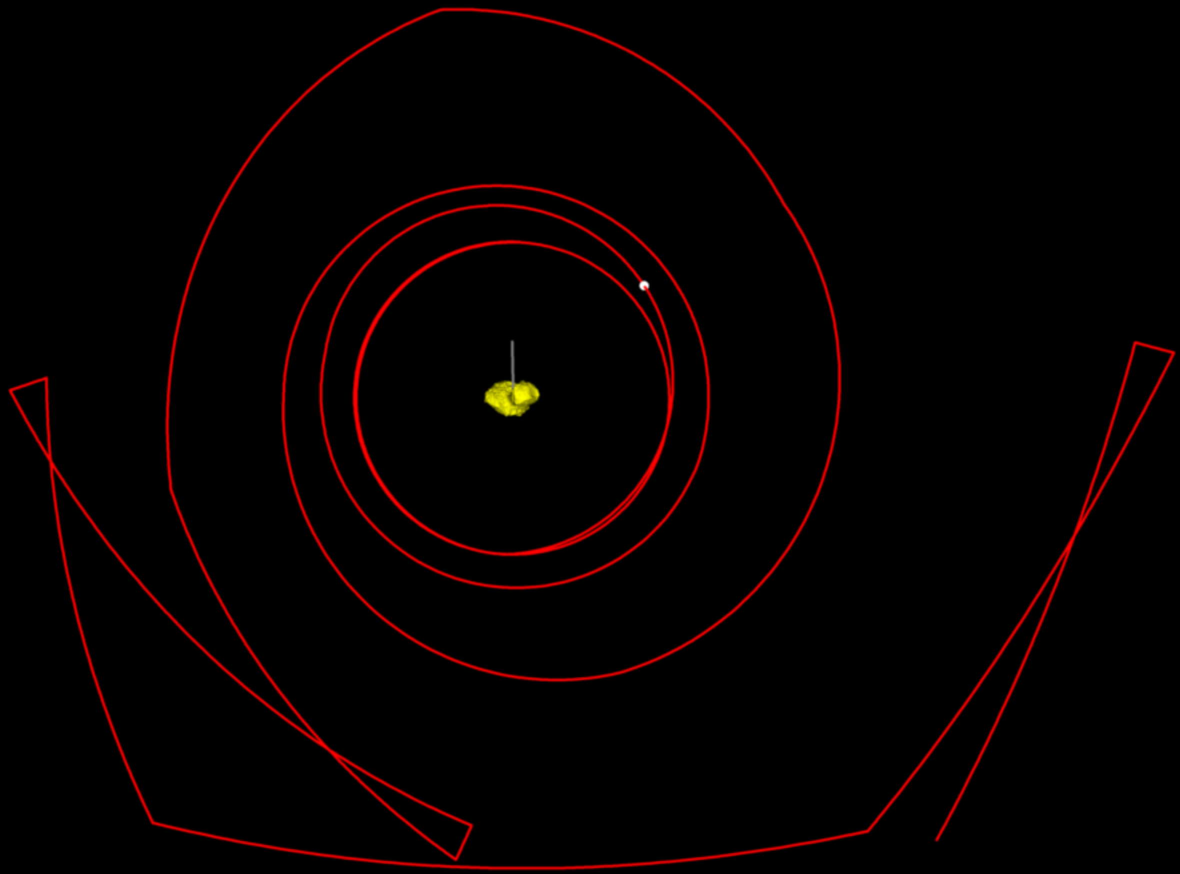


OSIRIS-NAC – Aug 12th 2015

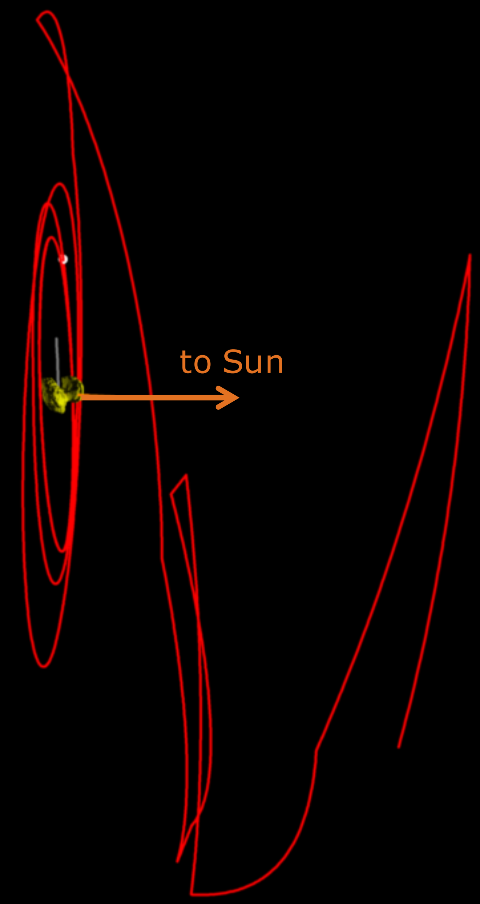
Distance to the comet



Rosetta Now

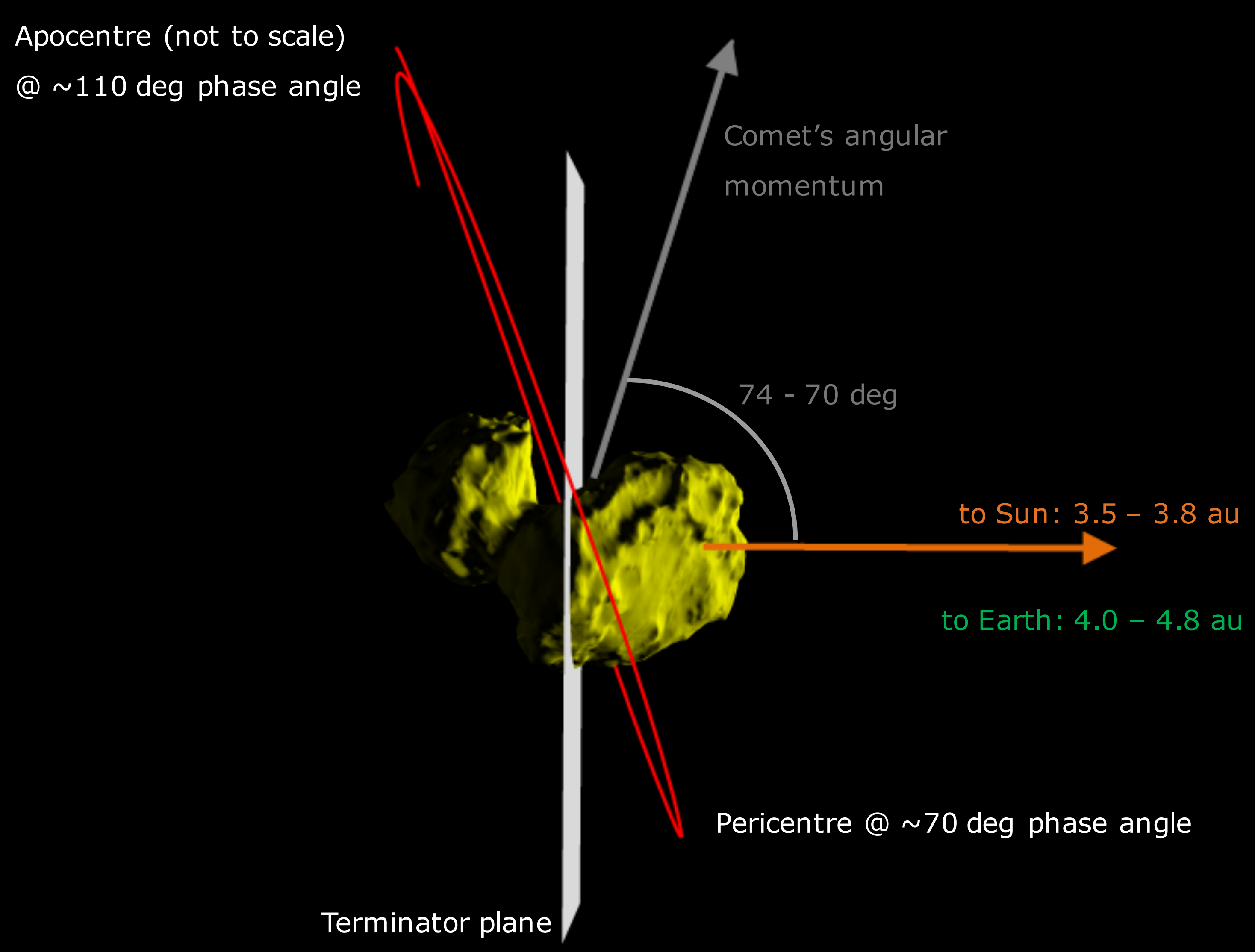


View from Sun

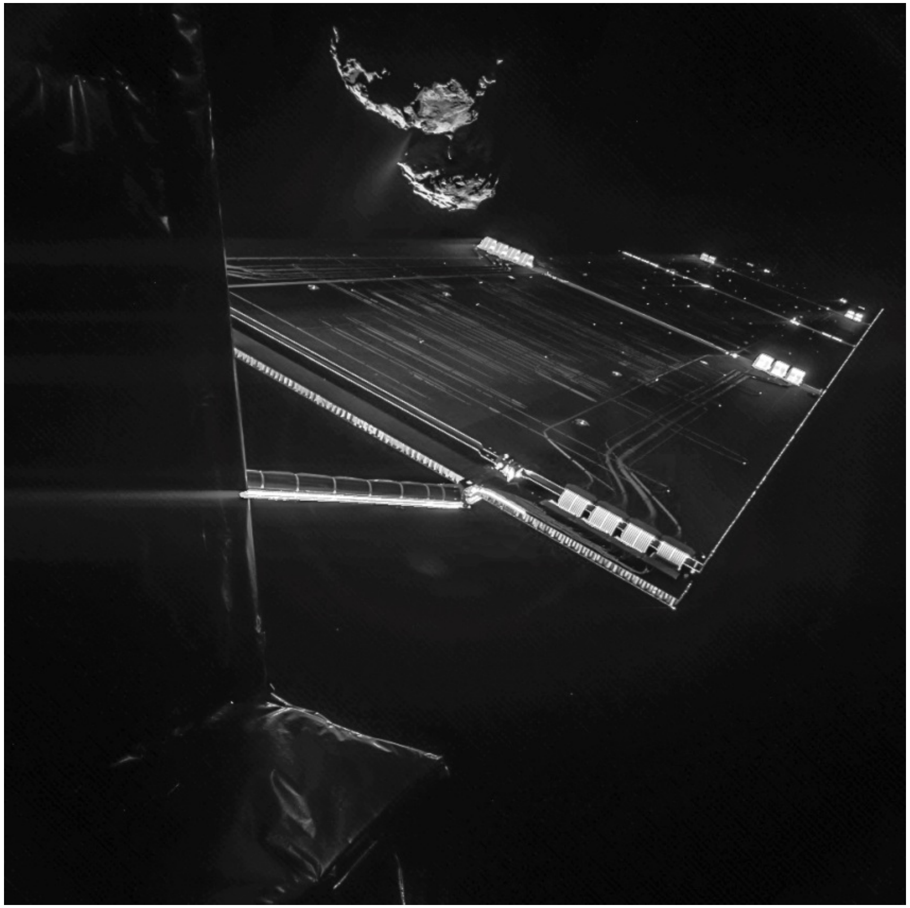


View from ~terminator

End of Mission Operations (Aug & Sep 2016)



That's all!



Thank you for your attention

European Space Agency

Pablo Muñoz – Pablo.Munoz@esa.int