Autonomous Navigation for KaNaRiA: A Mission into the Asteroid Main Belt

G. González Peytaví, A. Probst, R. Förstner and B. Eissfeller

graciela.gonzalez@unibw.de

Universität der Bundeswehr München

INSTITUTE OF SPACE TECHNOLOGY & SPACE APPLICATIONS

KaNaRia

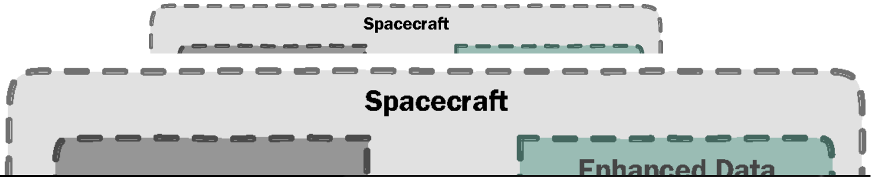
- KaNaRiA = **K**ognitionsbasierte **a**utonome **N**avigation **a**m Beispiel des **R**essourcenabbaus **i**m **A**ll

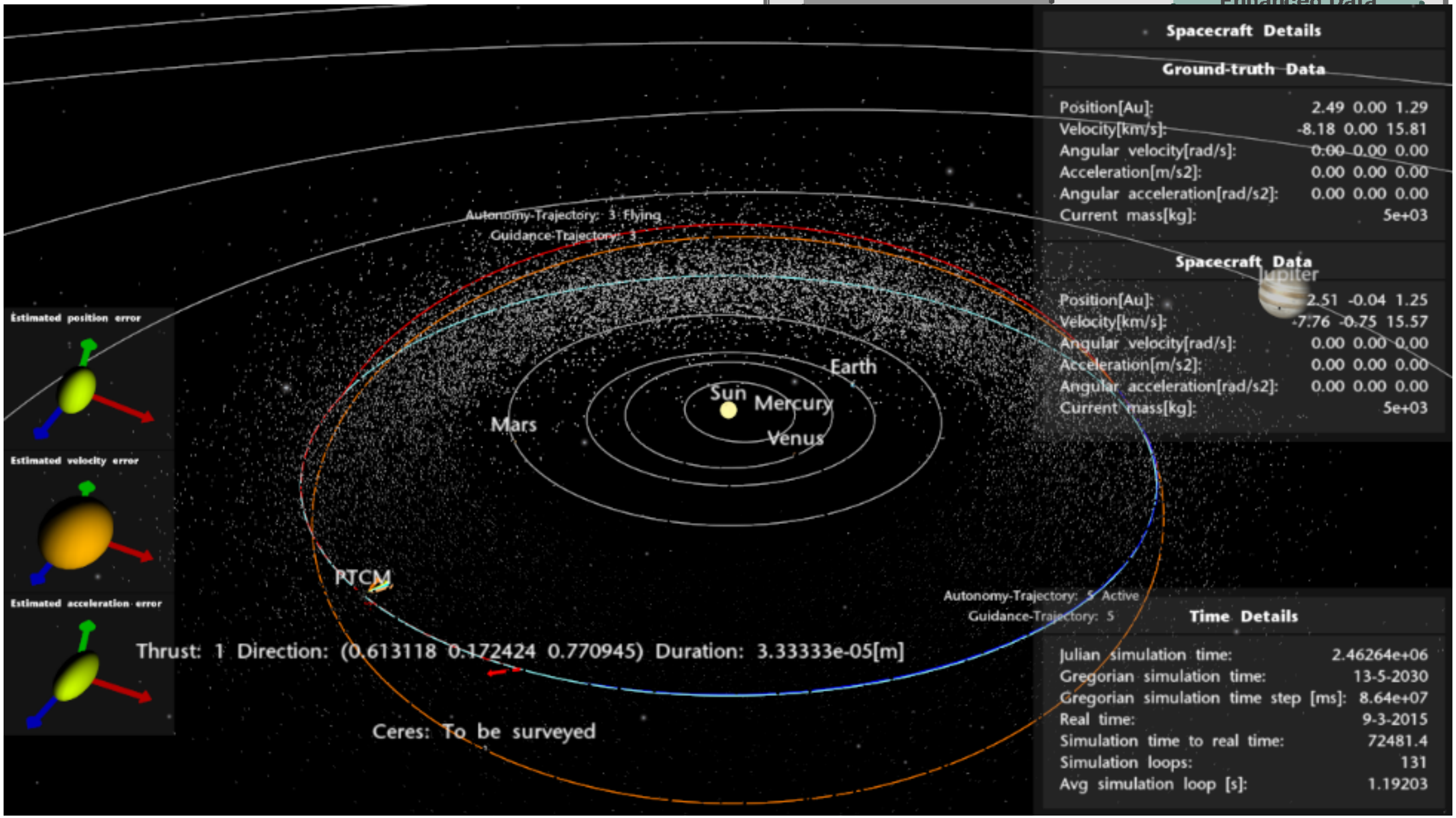
Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

KaNaRiA project goals





Navigation for KaNaRiA

NAVIGATION

LEADING PROFESSOR

Univ.-Prof. Dr.-Ing. habil.
B. Eissfeller

RESEARCH ASSOCIATE

M.Sc. Satellite Application Eng.
Graciela G. Peytaví

Navigation and Instrumentation

Spacecraft Orbit Determination (OD)

- Concept for precise **on-board orbit determination**
- **Autonomous** absolute **positioning** in space
- Position and attitude **filtering strategies**

Inertial and Relative Navigation

- Concept for precise **asteroid-relative navigation**
- Development of a **navigation transfer strategy** from **absolute to relative** navigation

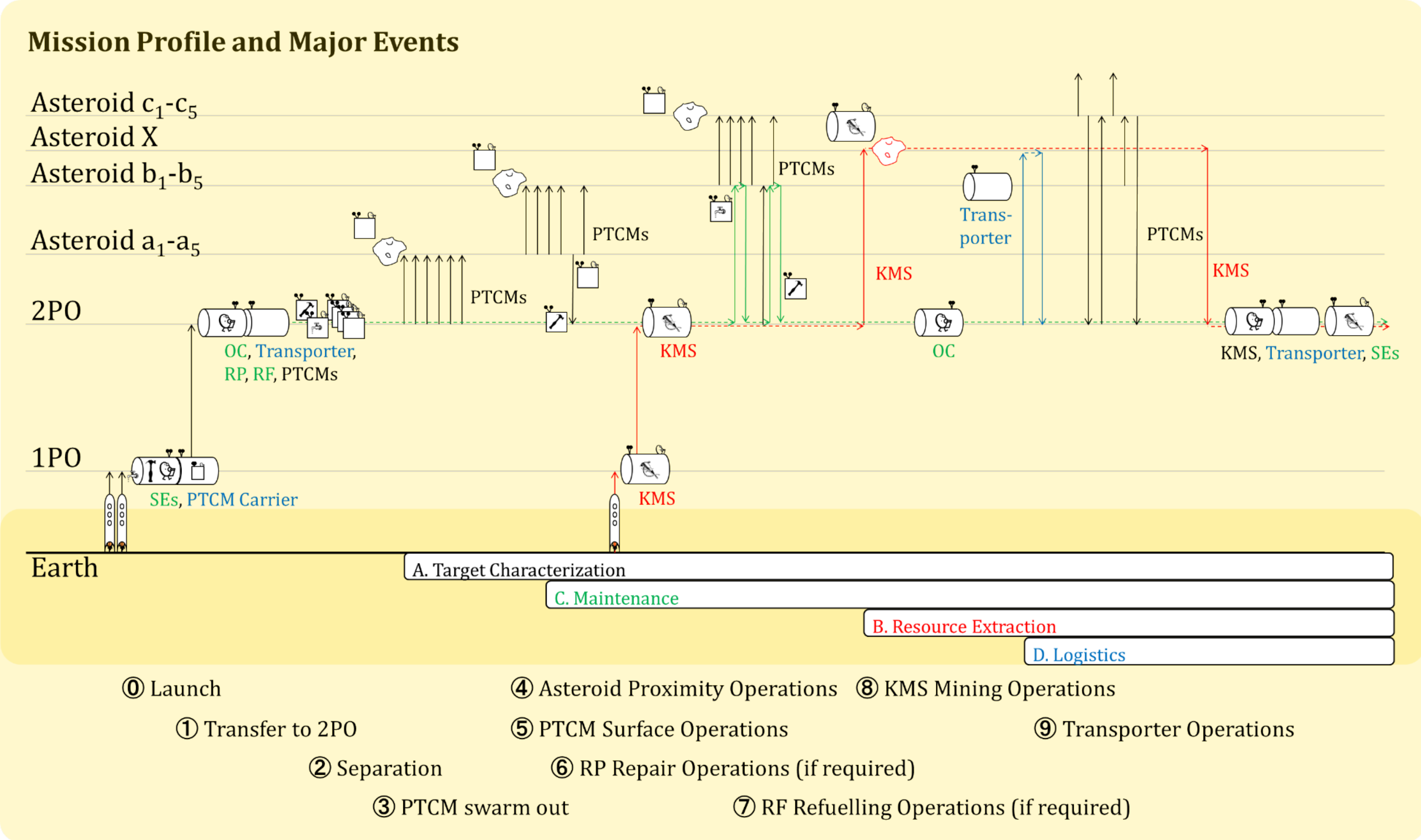
Spacecraft Instrumentation

- Selection of **optical, laser, inertial and radar sensors** and study of theirs suitability for the asteroid mission KaNaRiA
- **Asteroid orbit determination** and **dynamic characterization** from flight observation

Outline

- KaNaRiA mission scenario
- Navigation requirements
- Navigation system design
- Optical Sun Doppler Navigation (OSDN)

KaNaRiA: The mission



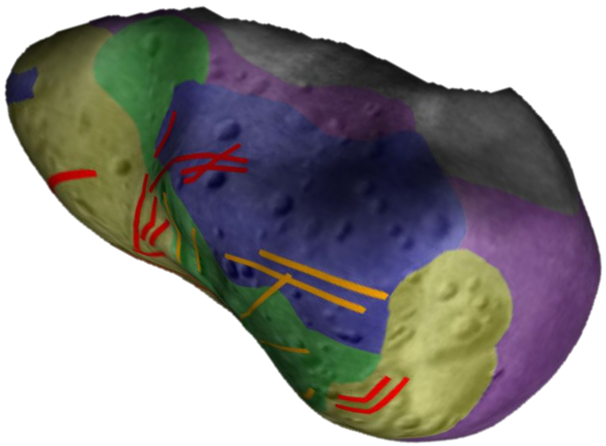
A. Probst et al. *Reference Mission Scenario Selection for Main Belt Asteroid Mining Missions*. PTMSS Proceedings. Montreal, May 2015.

KaNaRiA: The mission

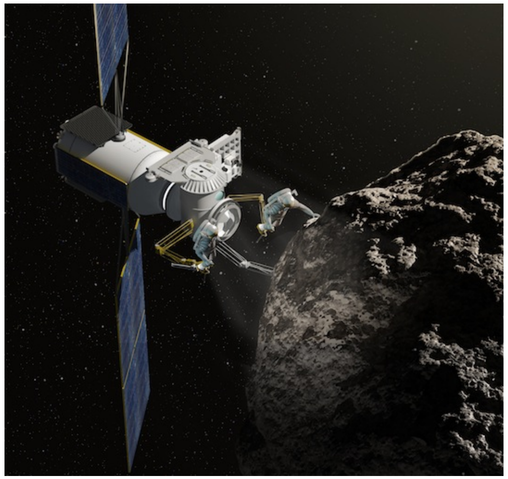
Mapping, Characterization and Resource Determination (MCRD)

Resource Extraction and Exploitation

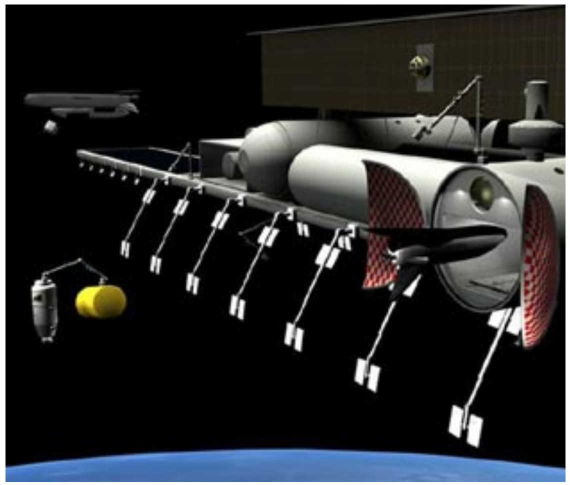
Maintenance & Logistics



Gaspra Geologic Map. Celestia.

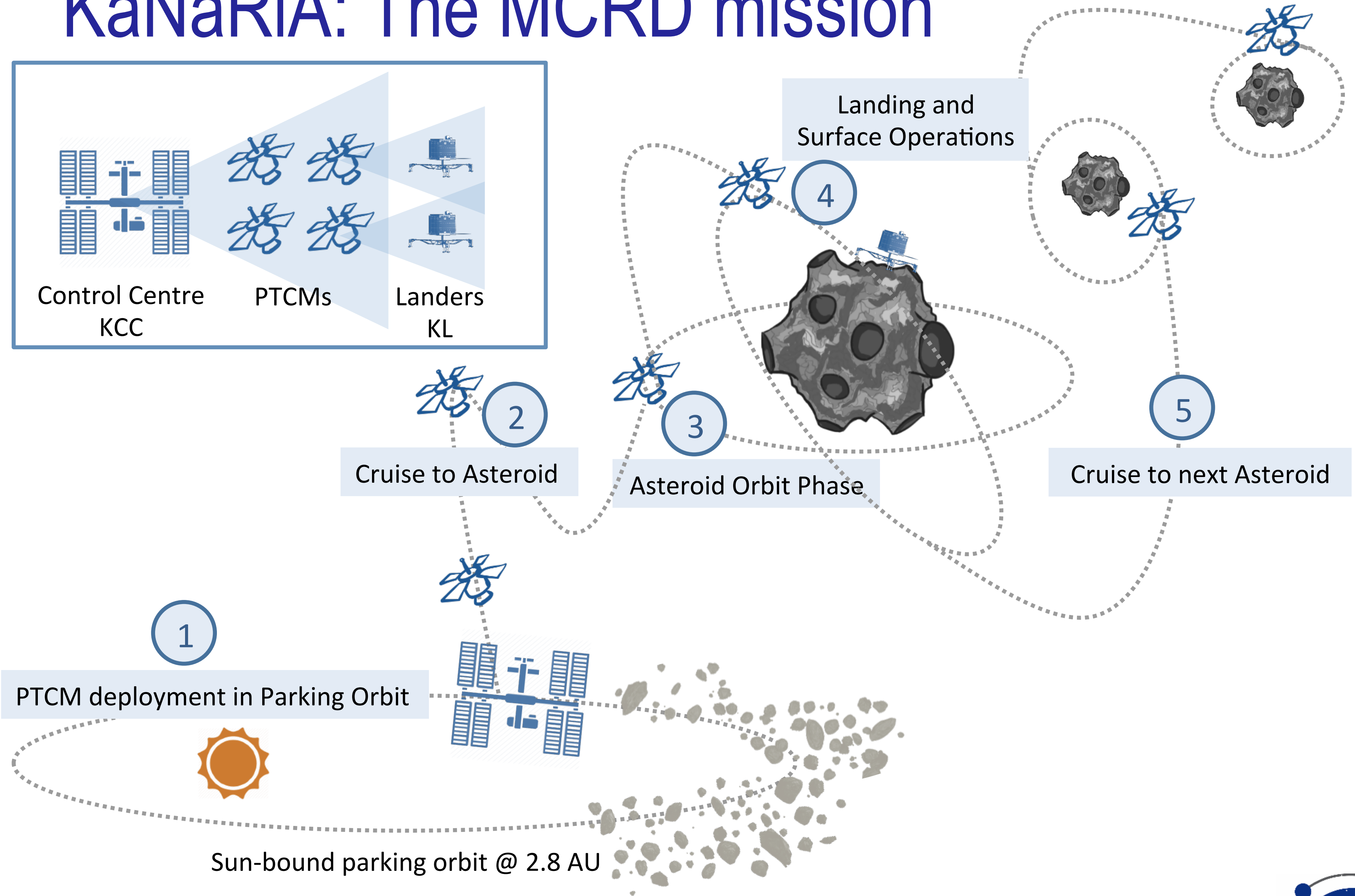


SEP Airlock Concept



Space logistics concept. M. Snead

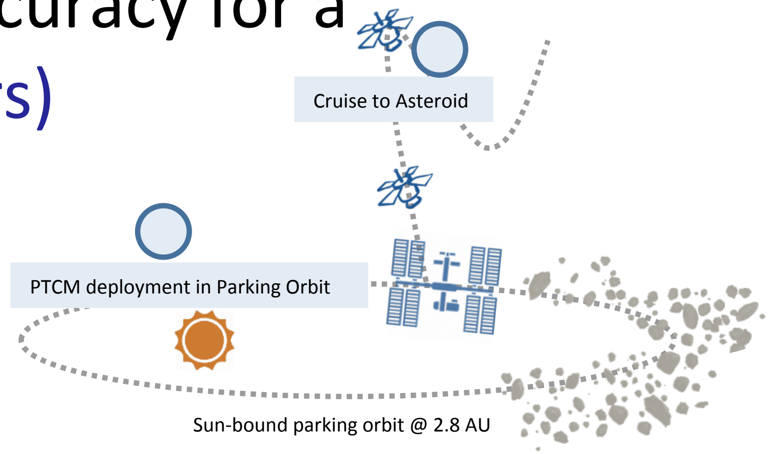
KaNaRiA: The MCRD mission



Navigation Requirements: Cruise Phase

- 3D orbit determination (OD) error for PTCM < 100 km

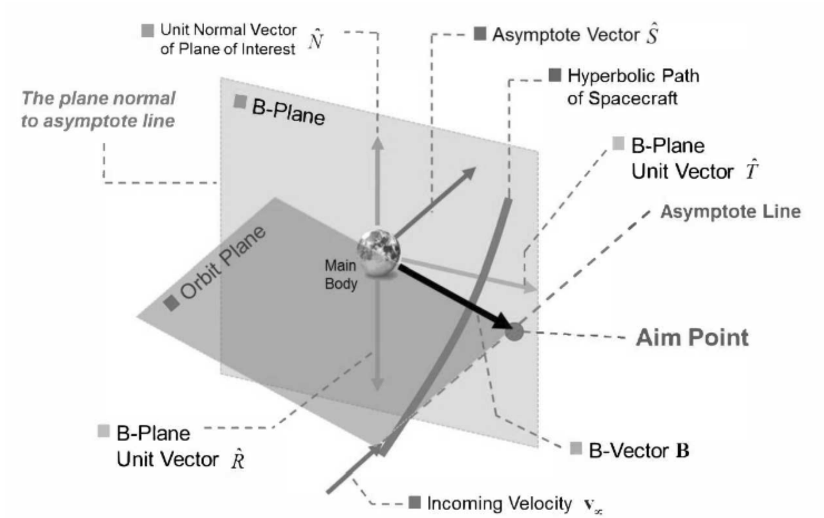
- OD shall be performed autonomously on-board ensuring the required accuracy for a the complete transfer (3-4 years)

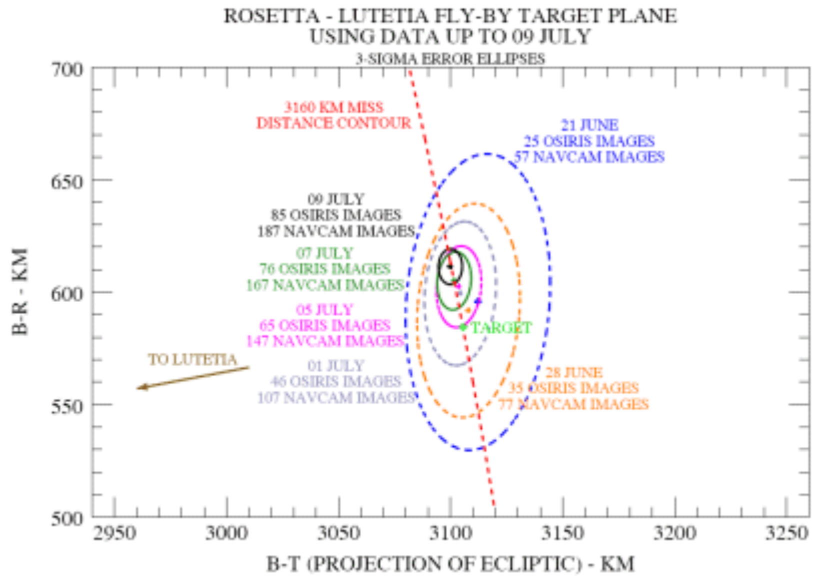


- Ground-based OD aid with a maximum tracking interval of 1 week/5 months

Navigation Requirements: Rendezvous

- The PTCM shall be targeted to a B-plane aim point between 100-500 km from the asteroid surface
- The 3-sigma error ellipsoid at rendezvous condition shall be constraint to 100 m

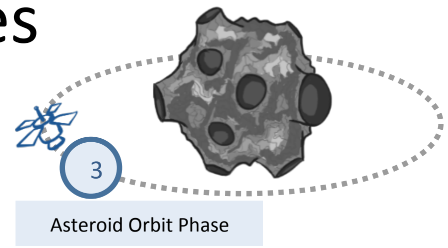


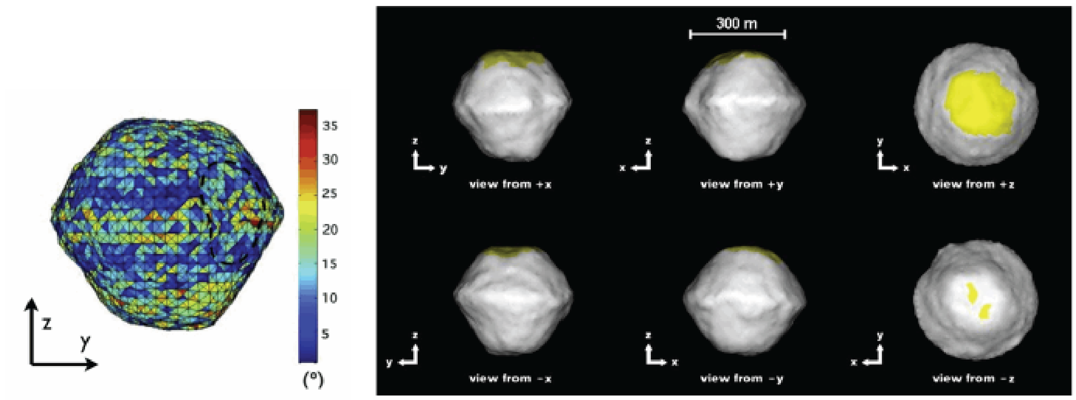


Source: ESA

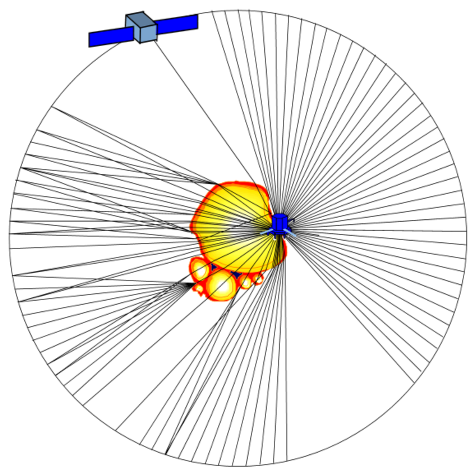
Navigation Requirements: In-Orbit Phase

- from asteroid characterization objectives
  - Vertical positioning ~ 1 m
  - Horizontal positioning ~ 0.5 m
  - Vertical & Horizontal velocity ~ 1 cm/s



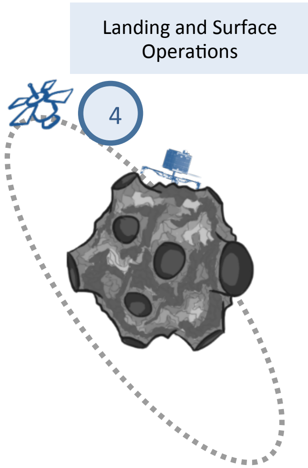


Shape model of asteroid 2008 EV5 showing the gravitational slopes.
Credits: Marco-Polo-R consortium.



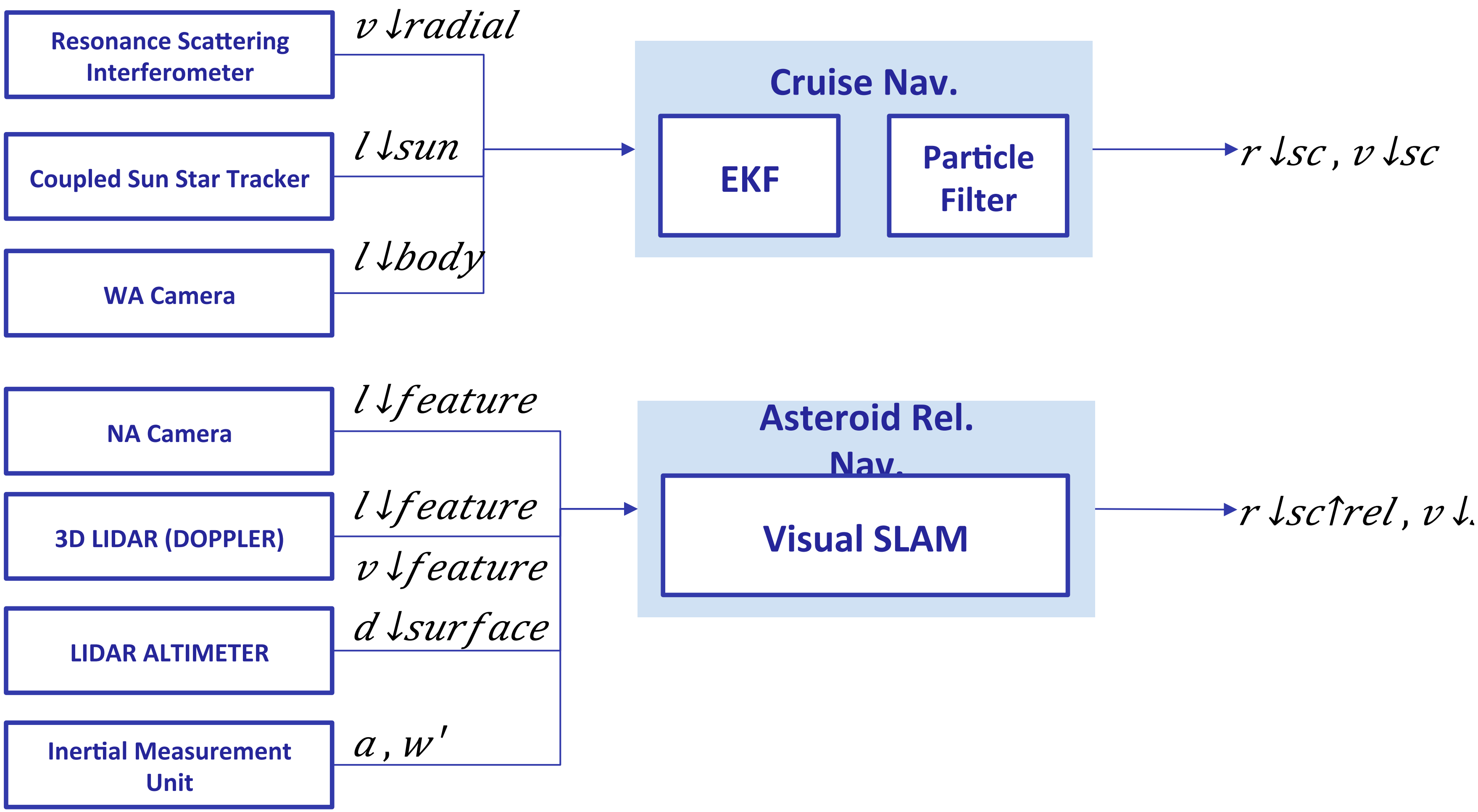
Radar tomography schematic. Herique et al. 2006

Navigation Requirements: Landing



- Soft landing of a legged structure:
  - Touchdown vertical velocity < 1 m/s
  - Touchdown horizontal velocity < 0.5 m/s
  - Touchdown angle rates < 1 deg/s
- Safe landing (site slopes < 10 deg; biggest site hazards 10 – 50 cm)
  - Pin-point landing accuracy < 5 m
- Autonomy – Hazard Detection and Avoidance (HDA)
  - Detection of unmapped hazards > 50 cm within 5 m of target landing site
  - Online planning of new landing trajectory/avoidance manoeuvre within 10 minutes from touchdown

Navigation System Design

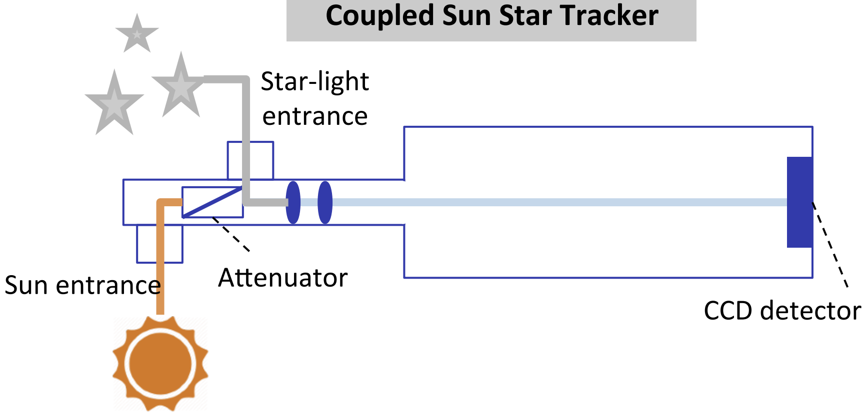


Optical Sun Doppler Navigation (OSDN)

The concept

Sun Direction

Coupled Sun Star Tracker



σ = 0.026 rad

- Modes:
  - Sun imager – Sun line-of-sight
  - Conventional imaging system (Wide-angle camera)

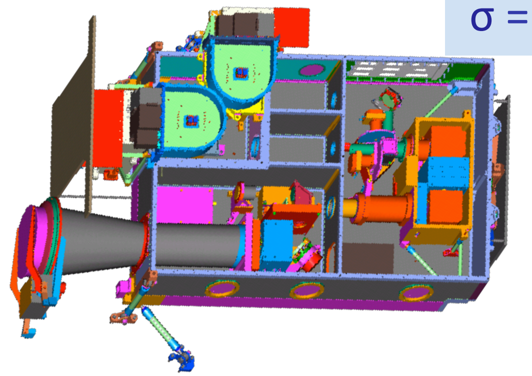
Optical Sun Doppler Shift

$$f_{Doppler} = f v/c$$

LOS Velocity	Signal Frequency	Doppler Shift f_D
1 mm/s	8×10^{9} Hz (radio)	0.027 Hz
1 mm/s	5×10^{14} Hz (visible)	1667 Hz

Resonance Scattering Interferometer

σ = 1 cm/s



Helioseismic and magnetic Imager (HMI) aboard the Solar Dynamics Observatory. Scherrer, 2005

Optical Sun Doppler Navigation (OSDN)

Observation Model (1/2)

- Radial velocity v_r derived from Sun Doppler measurements:

$$\dot{r} \equiv v_r = \mathbf{r}\cdot\dot{\mathbf{r}}/r = \mathbf{r}\cdot\mathbf{v}/r$$

- Sun line-of-sight unit vector (being $\mathbf{r} = r\boldsymbol{l}$):

$$\boldsymbol{l} = \cos\theta\cos\phi\,\mathbf{n}_1 + \cos\theta\sin\phi\,\mathbf{n}_2 + \sin\theta\,\mathbf{n}_3$$

with

$$r = \sqrt{x^2 + y^2 + z^2} \qquad \theta = \tan^{-1}(y/z)$$

$$\phi = \sin^{-1}(z/r)$$

  - Elevation angle, θ
  - Azimut angle, ϕ

Optical Sun Doppler Navigation (OSDN)

Observation Model (2/2)

- Line-of-sight unit vector to a planet, as derived from a CCD camera:

$$\boldsymbol{l}_{P_i} = \cos\theta_{P_i}\cos\phi_{P_i}\,\boldsymbol{n}_1 + \cos\theta_{P_i}\sin\phi_{P_i}\,\boldsymbol{n}_2 + \sin\theta_{P_i}\,\boldsymbol{n}_3$$

with

$$r_{P_i} = \sqrt{x_{P_i}^2 + y_{P_i}^2 + z_{P_i}^2}$$

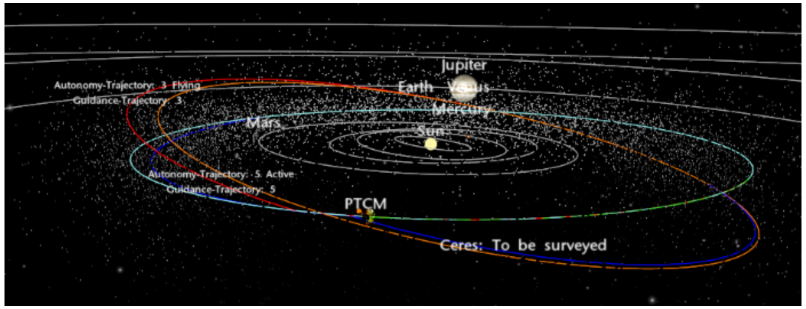
$$\boldsymbol{r}_{P_i} = r_{P_i}\,\boldsymbol{l}_{P_i}$$

$$\theta_{P_i} = \tan^{-1}\left(\frac{y_{P_i} - y}{z_{P_i} - z}\right)$$

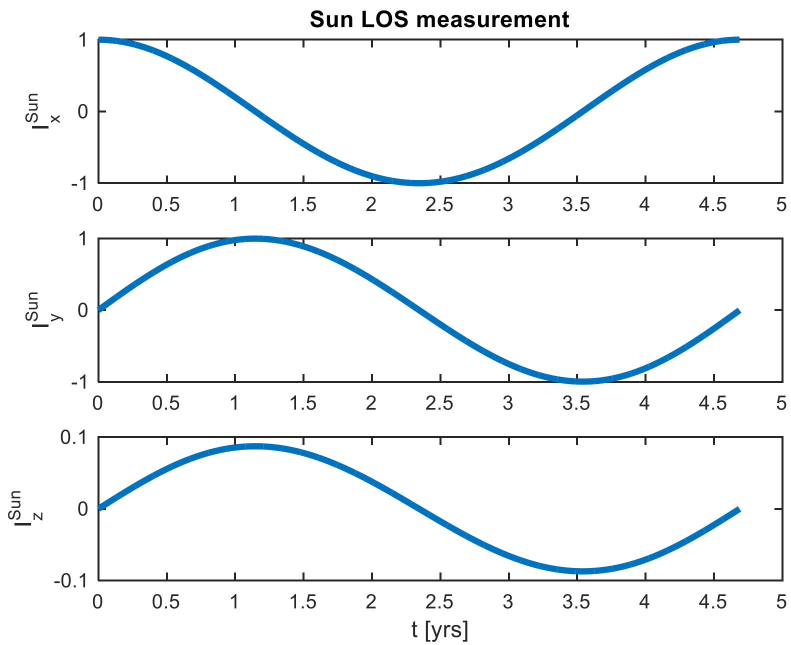
$$\phi_{P_i} = \sin^{-1}\left(\frac{z_{P_i} - z}{r_{P_i} - r}\right)$$

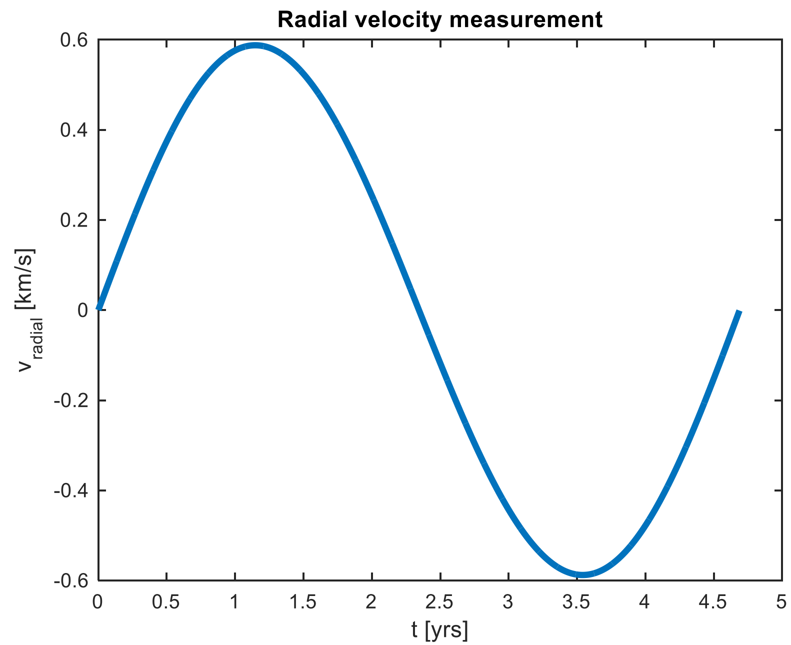
Optical Sun Doppler Navigation (OSDN)

Observables



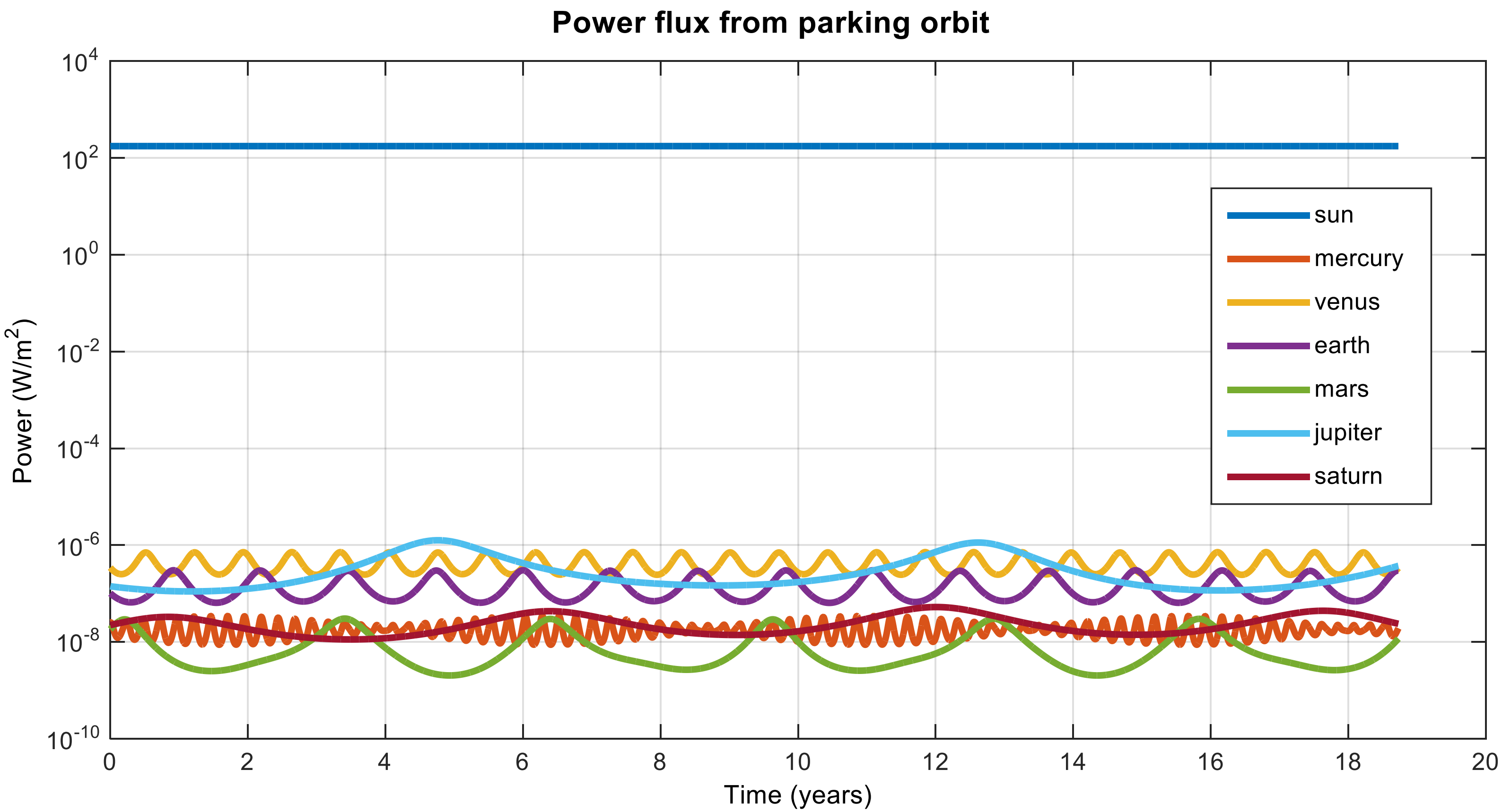
Parking Orbit	
Semi-major axis	2.8 AU
Eccentricity	0.033
Inclination	5 deg





Optical Sun Doppler Navigation (OSDN)

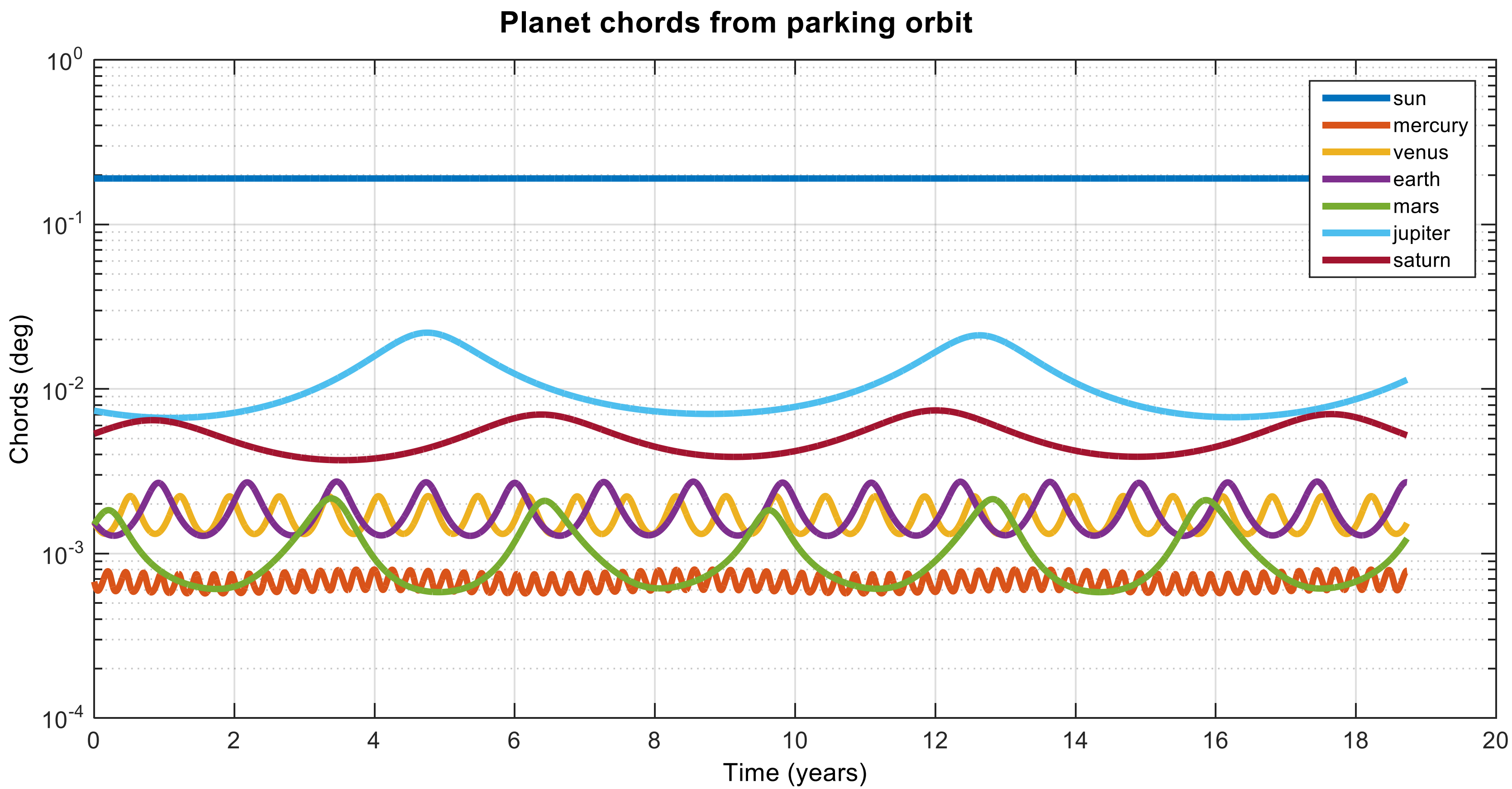
Observables



- Power flux from Jupiter: ~1-0.1 μW/m² @ parking orbit

Optical Sun Doppler Navigation (OSDN)

Observables



- Chord length of Jupiter: 0.9-0.04 deg @ parking orbit

Optical Sun Doppler Navigation (OSDN)

Dynamic Model

- Spacecraft dynamic model, $\boldsymbol{f}(\boldsymbol{x},t)$:
  - 2-body problem with the Sun as central body

$$\boldsymbol{r} = \boldsymbol{v}$$

$$\boldsymbol{r} = -\mu_s / \boldsymbol{r}^3 \ \boldsymbol{r}$$

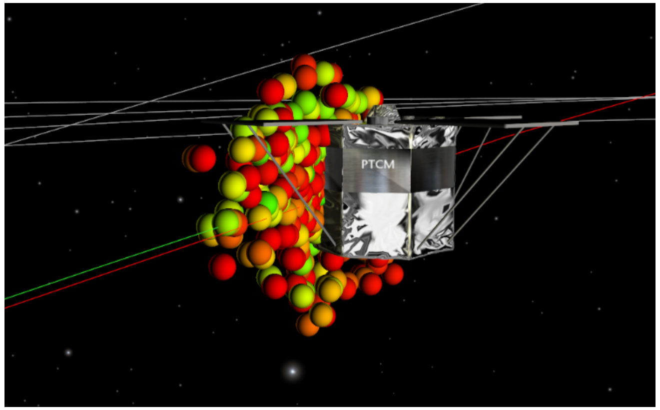
- Extension to third-body perturbations:
  - Planets or asteroids at fly-by

$$\boldsymbol{r} = -\mu_s / \boldsymbol{r}^3 \ \boldsymbol{r} - \sum_{\boldsymbol{i}} \mu_{Pi} / \boldsymbol{r}_{\boldsymbol{i}}^3 \ \boldsymbol{r}_{\boldsymbol{i}}$$

Optical Sun Doppler Navigation (OSDN)

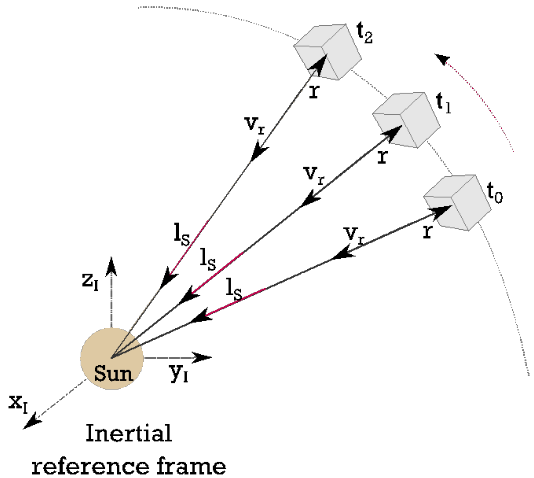
State estimation

- Sequential estimators:
  - Extended Kalman Filter
  - Particle filter



- Sun-relative geometry variations of 0.25° per day in parking orbit

- On-going work:
  - filter tuning
  - measurement frequency set-up
  - LOS occultations



Thank you!