7th International Conference on Astrodynamics Tools and Techniques

LOTNAV: A LOW-THRUST INTERPLANETARY NAVIGATION TOOL

6-9 November 2018

DLR Oberpfaffenhofen, Germany

@ElecnorDeimos

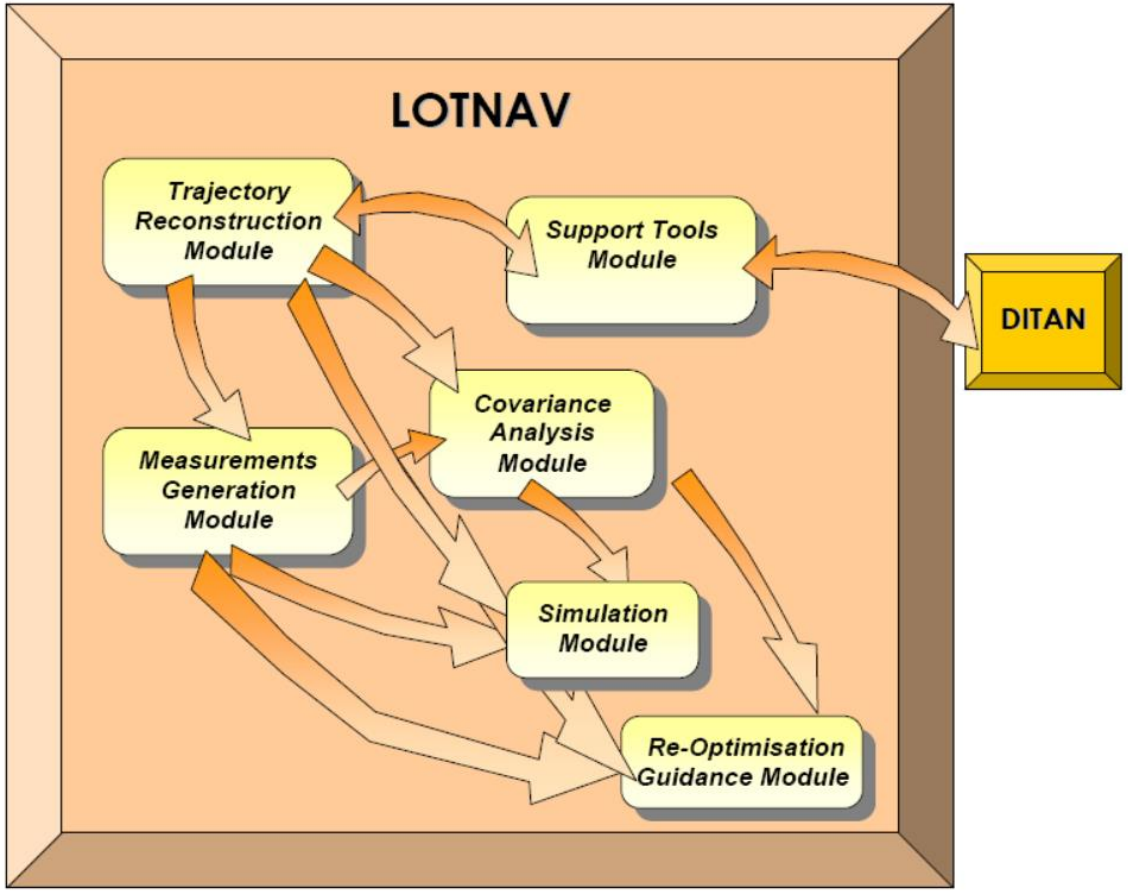
AGENDA

LOTNAV: A LOW-THRUST INTERPLANETARY NAVIGATION TOOL

INTRO: “Mr. LOTNAV”

1. TRAJECTORY GENERATION
2. MEASUREMENTS GENERATION
3. COVARIANCE ANALYSIS
4. SIMULATION
5. TRAJECTORY REOPTIMISATION

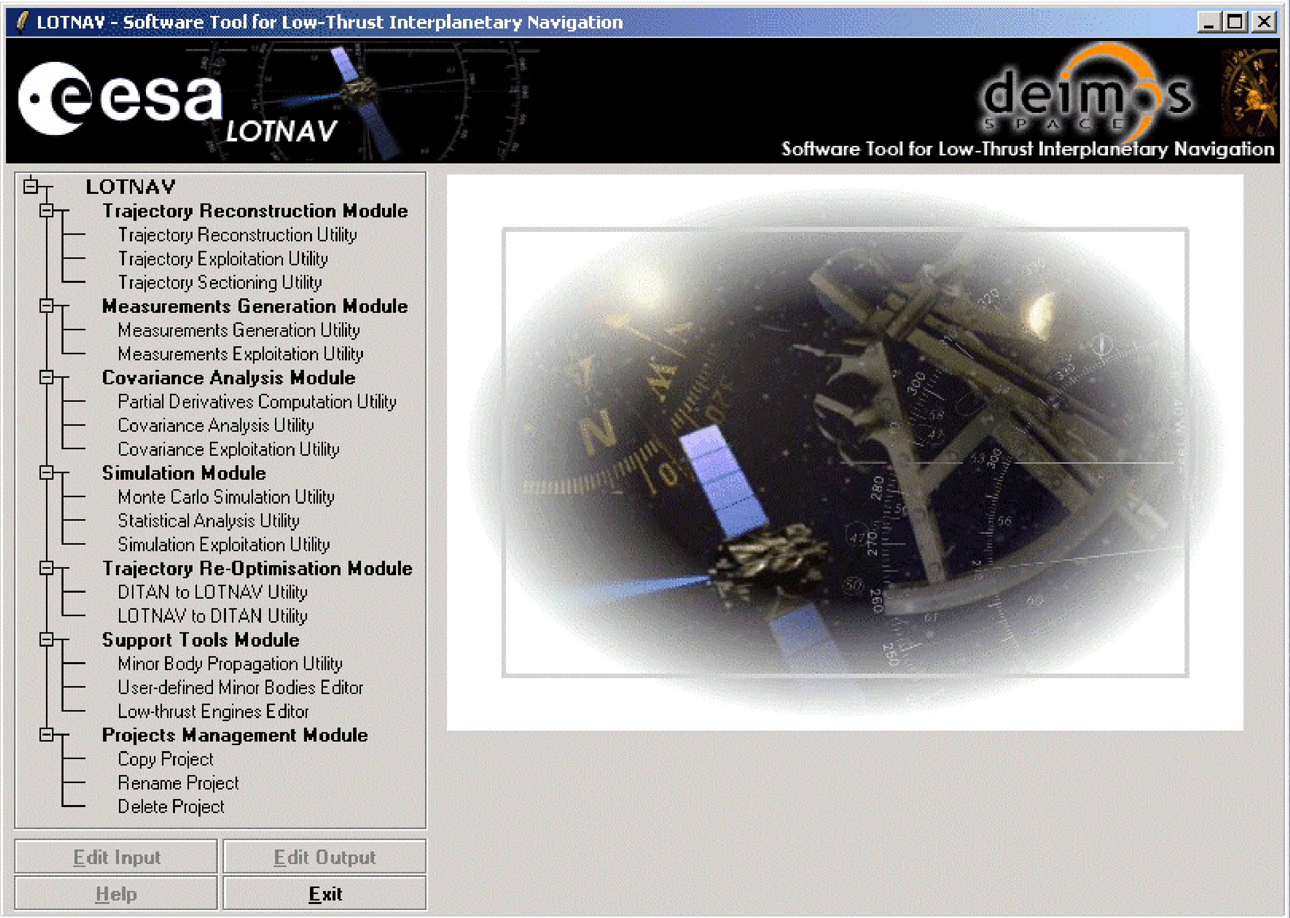
CONCLUSIONS



INTRODUCTION

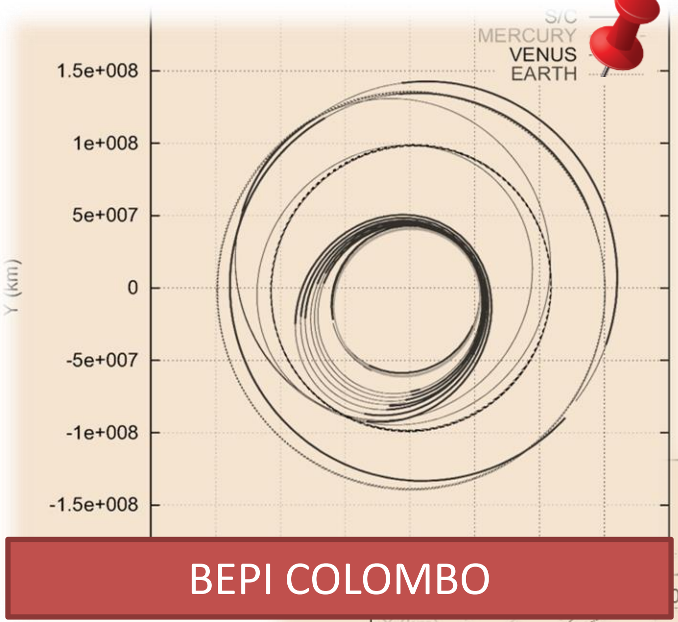
LET ME FIRSTLY INTRODUCE YOU "Mr. LOTNAV"

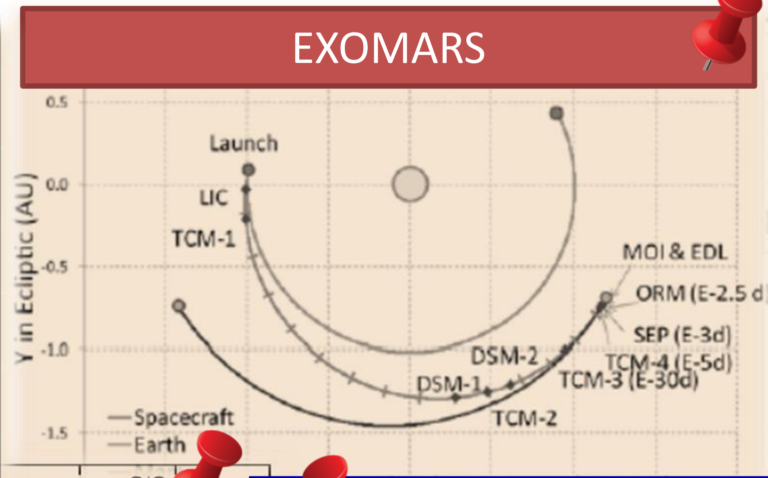
- 15 years of development (pretty an old guy in this field!)
- A long record of successful application in ESA missions
- A living tool, always looking for performances extension and improvement
- Definitely a reference point for new SW developments in DMS

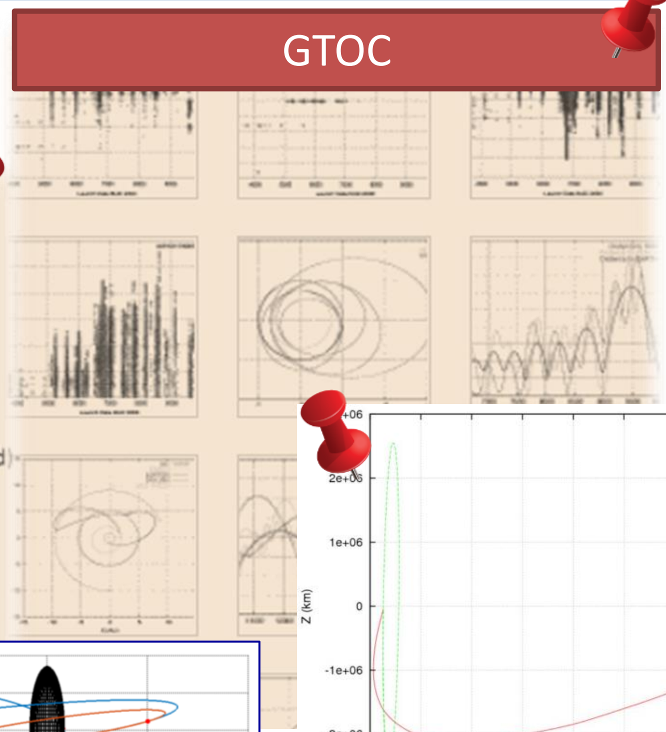


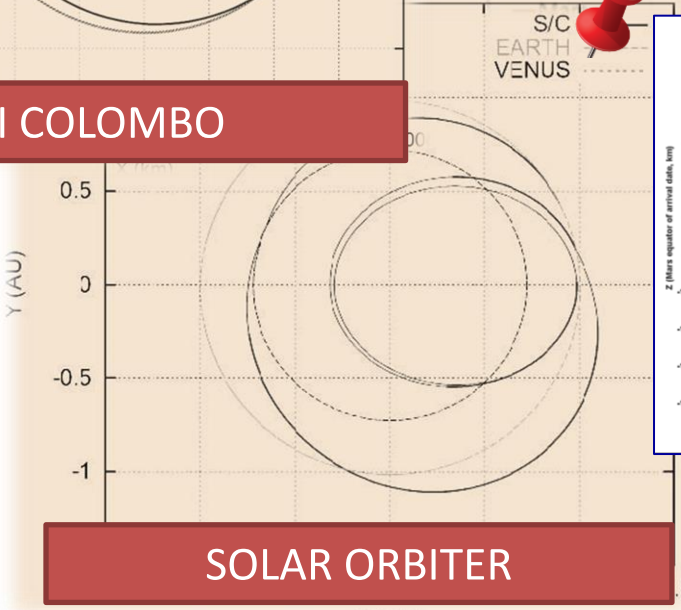
LOTNAV PHOTOBOOK

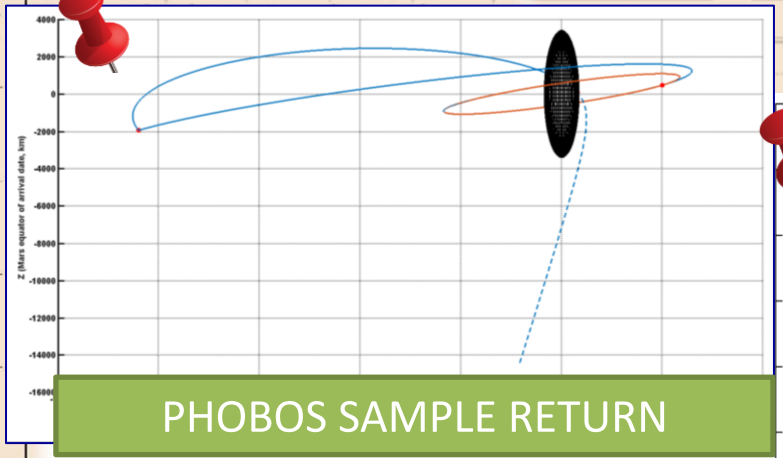
INTRODUCTION

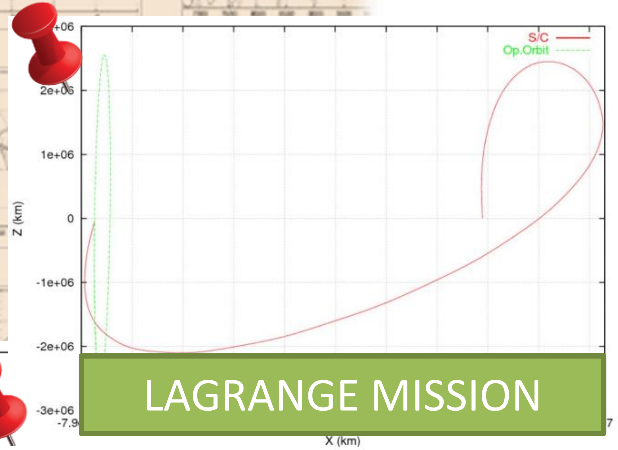


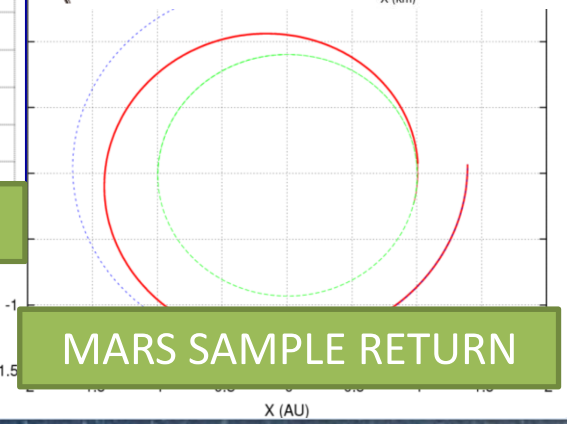












INTRODUCTION

LOTNAV PURPOSES

- optimised low-thrust trajectory
- encounters with massive and minor bodies
- measurement simulation for OD
- covariance analyses
- full Monte Carlo navigation analysis
- low-thrust guidance generation
- interface with other global trajectory optimisation tools
- trajectory re-optimisation after possible failure scenarios

1. TRAJECTORY GENERATION

INITIAL VALUE PROBLEM SOLVER

- SPICE recently added

BOUNDARY VALUE PROBLEM SOLVER

- Optimisers: OPXRQP / SNOPT
- Departure from orbit or launcher performances
- Flyby conditions
- Deep Space Manoeuvres size and epoch
- Low Thrust: engines DB, power constraints, etc.
- Arrival at fixed state or at celestial body

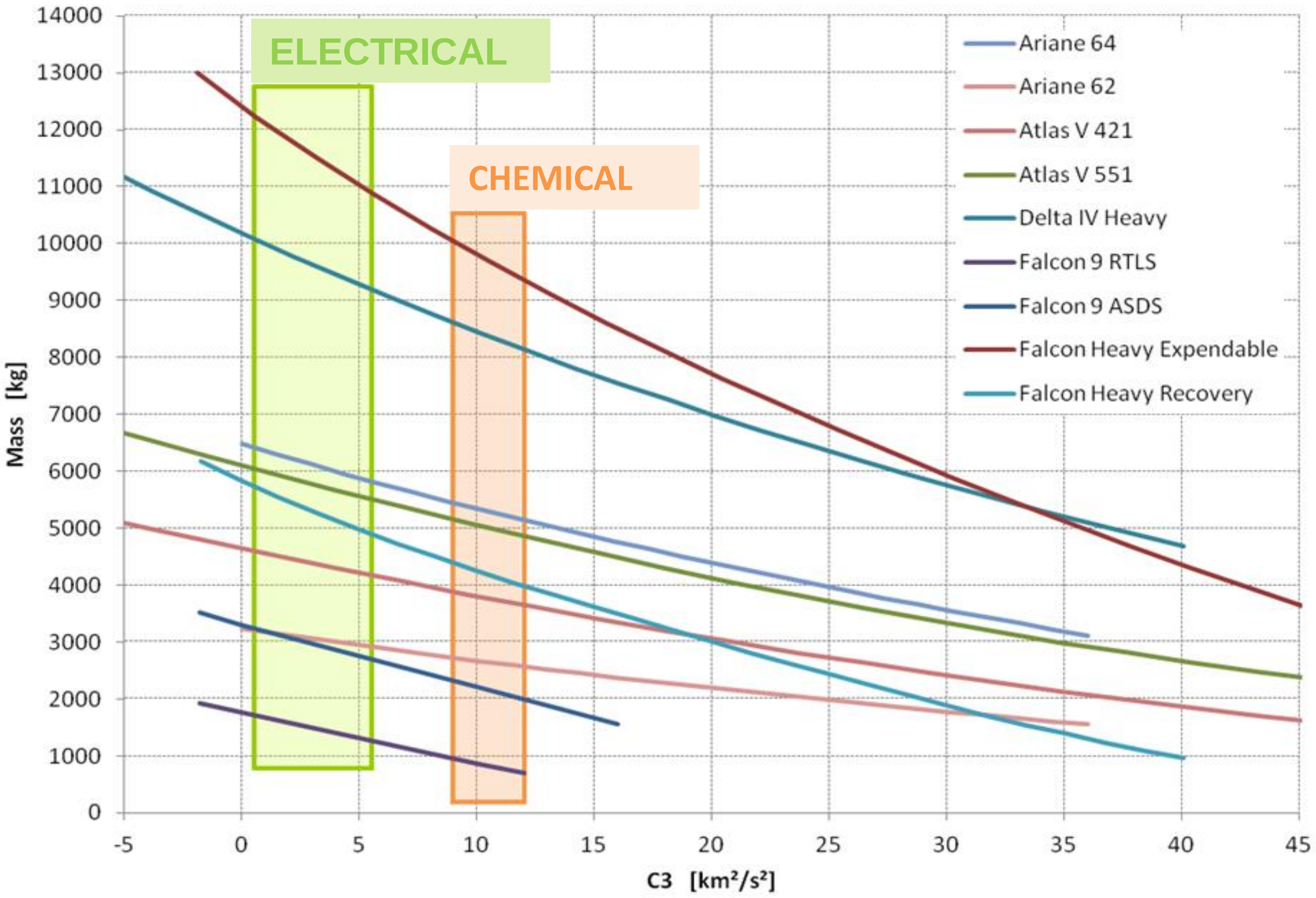
REFINED BOUNDARY VALUE PROBLEM SOLVER

- Central body gravity field, with expansions
- Gravity of third bodies assumed as mass points
- Low-thrust forces
- SRP as a Lambertian reflection model
- Atmospheric drag forces
- Residual forces

1. TRAJECTORY GENERATION - LAUNCHERS LIBRARY (LAULIB)

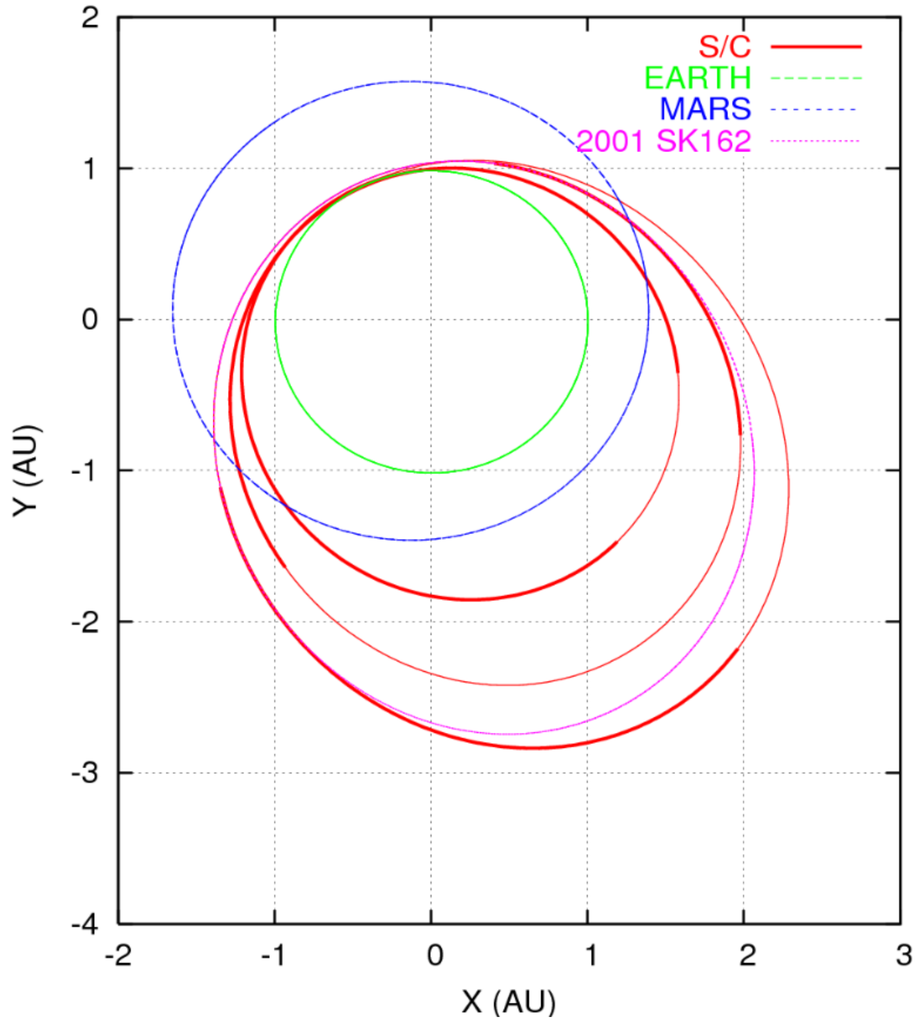
Database with the performance of different launcher vehicles depending on C3 and declination of the escape trajectory

Departure conditions optimisation to maximise the mass delivered at the target body/state

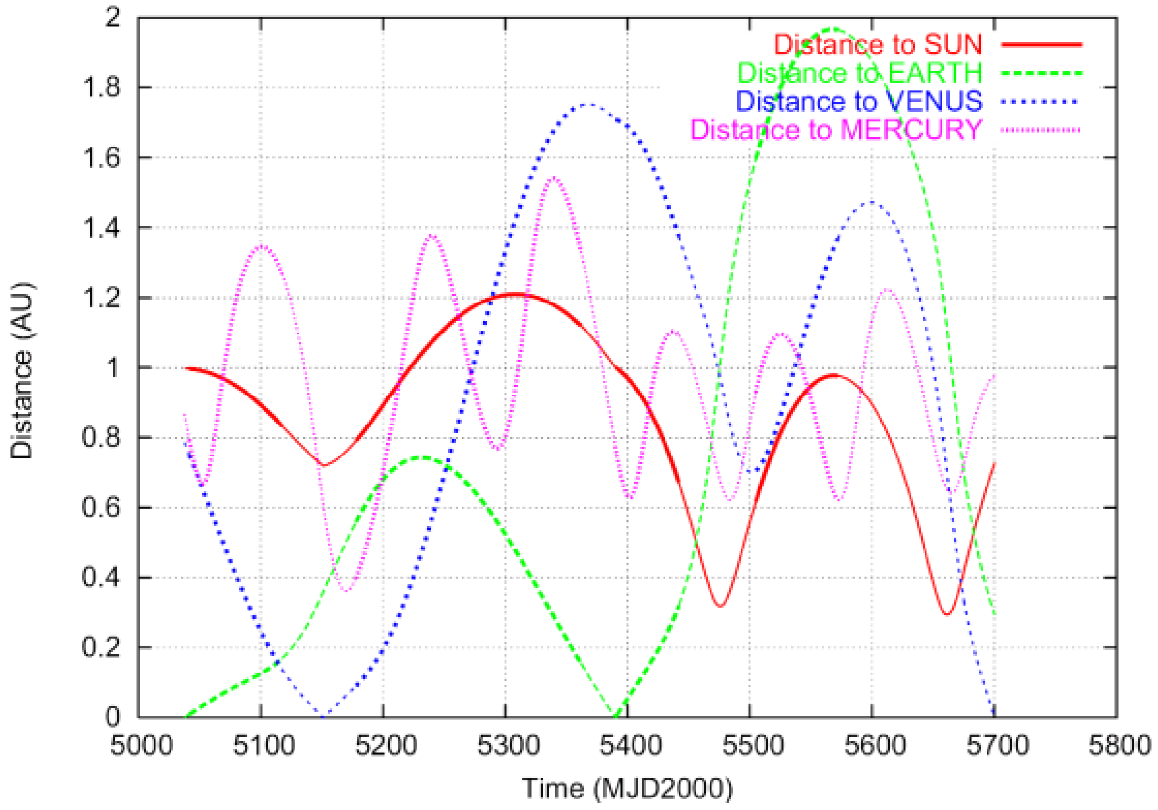


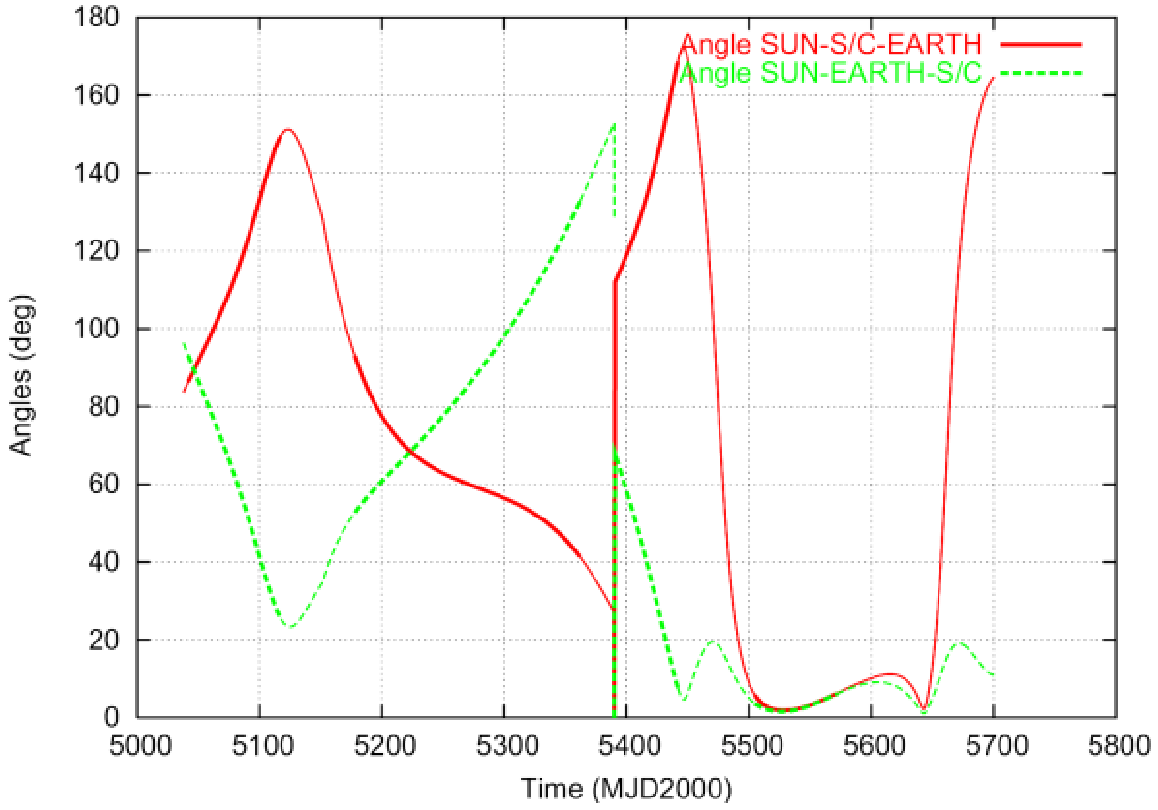
1. TRAJECTORY GENERATION – EXPLOITATION (1/4)

- Projection of the spacecraft trajectory and the orbit of a number of bodies in different reference frames
- Time evolution of distance and distance rates to a number of bodies
- Time evolution of a number of angles of interest for trajectory analysis purposes
- Time evolution of the thrust variables and the spacecraft mass
- Time evolution of the orbital elements
- Satellite ground-track on different bodies

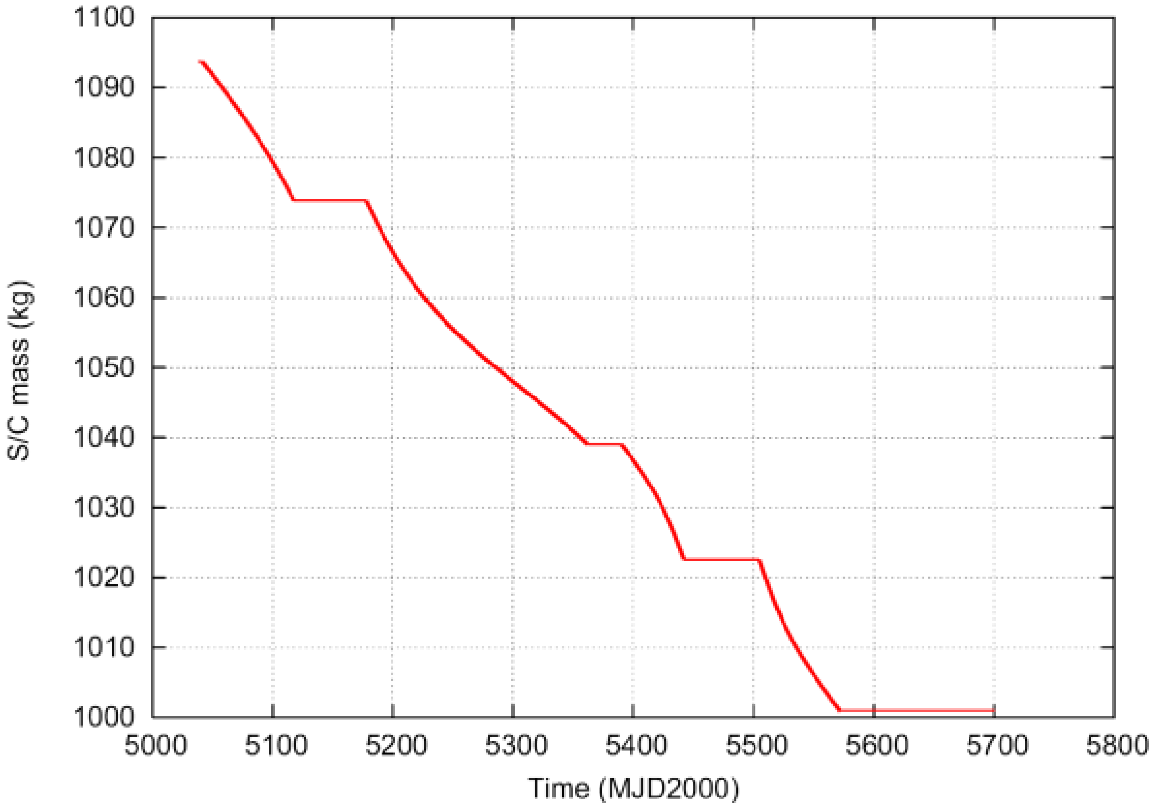


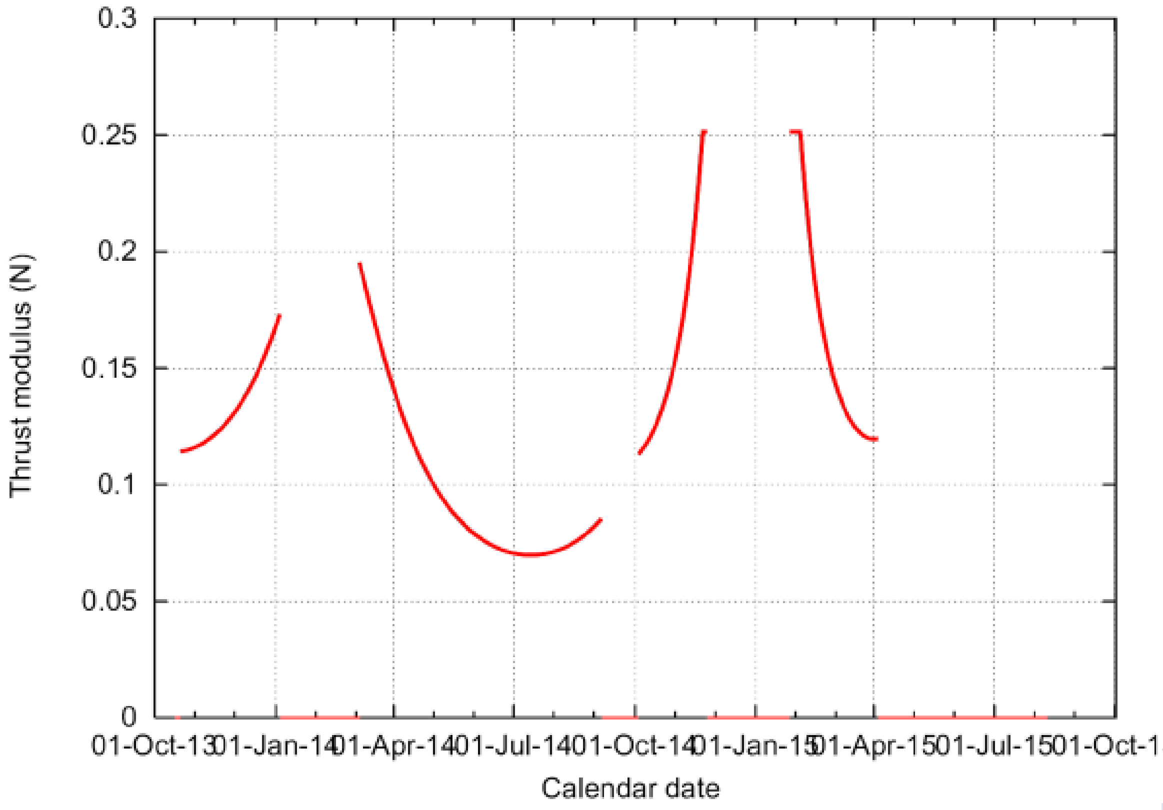
1. TRAJECTORY GENERATION – EXPLOITATION (2/4)





1. TRAJECTORY GENERATION – EXPLOITATION (3/4)





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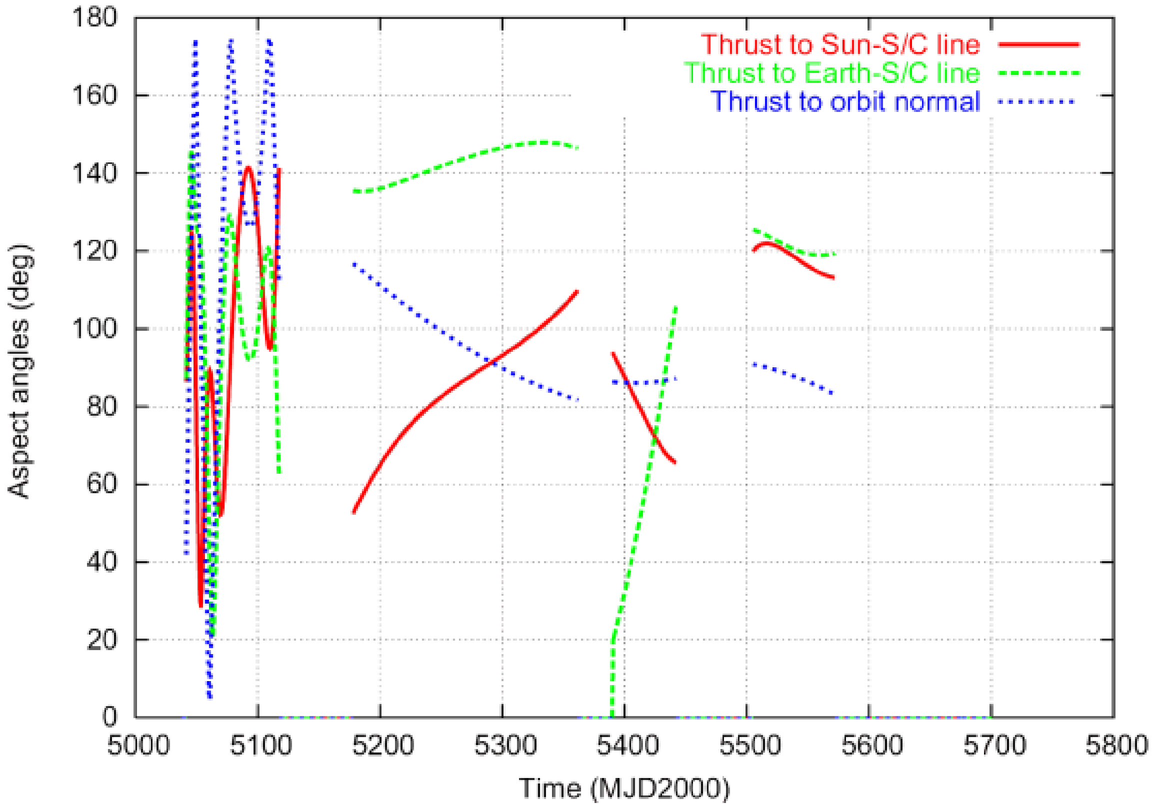
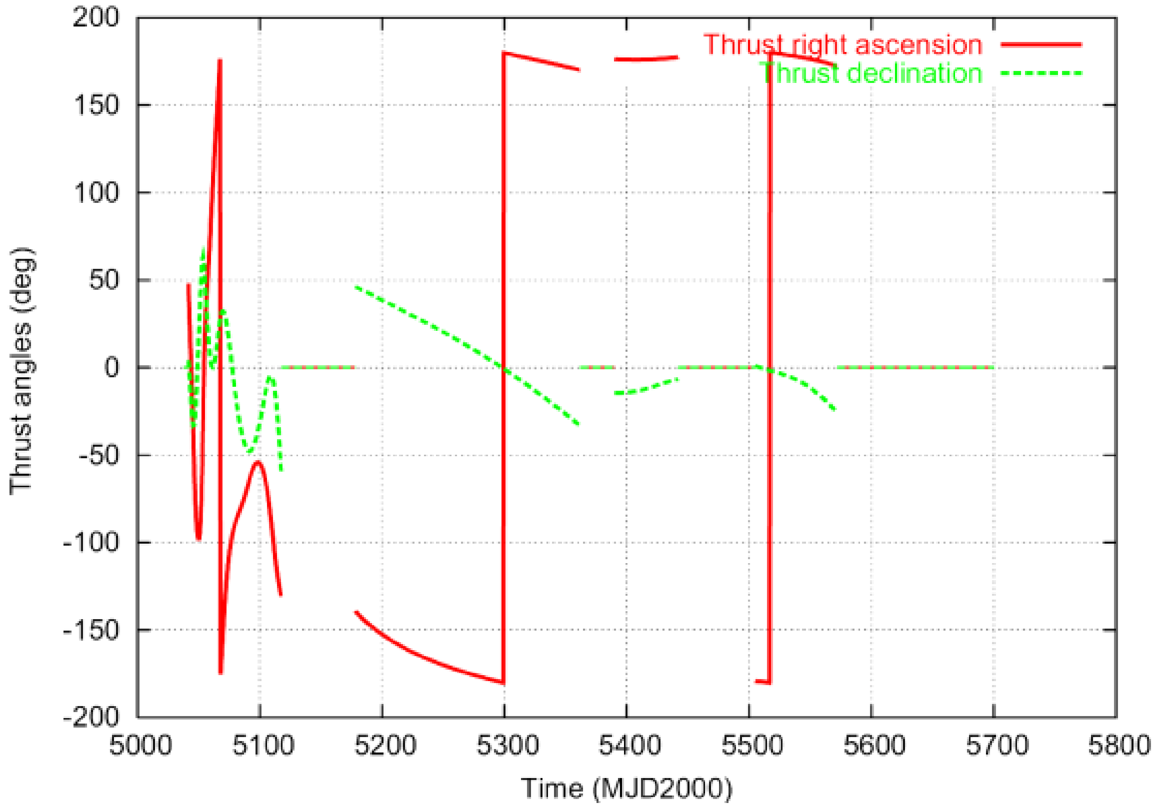
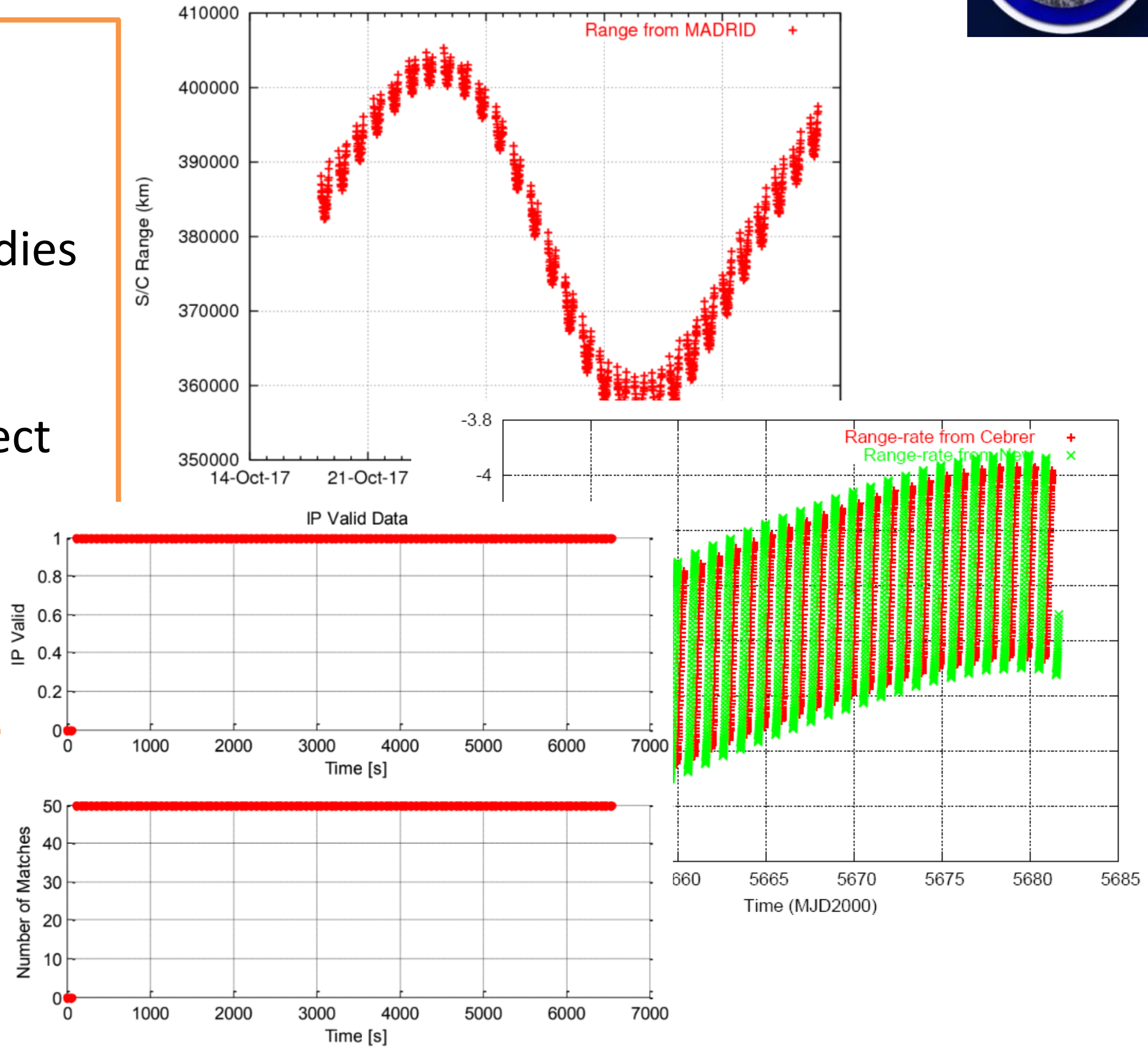
1. TRAJECTORY GENERATION – EXPLOITATION (4/4)





2. MEASUREMENTS: GENERATION & EXPLOITATION

- Range and range rate
- DOR and ΔDOR from a number of GS baselines
- On-board optical measurements of celestial bodies
- On-board accelerometer measurements
- On-board radar measurements of a nearby object
- **NEW!** Feature tracking and landmark measurements
- **NEW!** GNSS measurements



3. COVARIANCE ANALYSIS

WHY THE COVARIANCE ANALYSIS?

To calculate theoretical accuracy in:

1. knowledge of the spacecraft state
2. further estimation parameters

SRIF

Batch filter mixing: a priori info + associated dynamics + measurements.

1. deviation in state vector estimated at the beginning of the mapping time interval
2. augmented state and covariance matrix propagated to next mapping time

```
ALONG TRACK POSITION ERROR (KM): 0.227148D+00
CROSS TRACK POSITION ERROR (KM): 0.274805D+00
RADIAL      POSITION ERROR (KM): 0.118543D+00
 1 - SIGMA  POSITION ERROR (KM): 0.375721D+00

ALONG TRACK VELOCITY ERROR (KM/S): 0.176534D-03
CROSS TRACK VELOCITY ERROR (KM/S): 0.605170D-03
RADIAL      VELOCITY ERROR (KM/S): 0.140272D-03
 1 - SIGMA  VELOCITY ERROR (KM/S): 0.645810D-03

 PERTURBATIONS DUE TO GROUND STATION LOCATIONS
 RADIAL SOLAR RAD. PRES. (PER UNIT)        0.49255622E-05
 X-COOR(KM/S**2) NON-GRAV. ACCE. 1         0.17425085E-15
 Y-COOR(KM/S**2) NON-GRAV. ACCE. 1         0.59289286E-15
 Z-COOR(KM/S**2) NON-GRAV. ACCE. 1         0.27567533E-16
 LOW-THR. FORCE MOD. ENG1 (PER UNIT)       0.00000000E+00
 LOW-THR. VECTOR ANGLE 1 ENG1 (DEG)        0.00000000E+00
 LOW-THR. VECTOR ANGLE 2 ENG1 (DEG)        0.00000000E+00
 SPACECRAFT X-COOR(KM)                     0.26621604E-03
 SPACECRAFT Y-COOR(KM)                     0.14062597E-02
 SPACECRAFT Z-COOR(KM)                     0.57817542E-02
 SPACECRAFT VX-COOR(KM/S)                  0.14676988E-05
 SPACECRAFT VY-COOR(KM/S)                  0.11000718E-05
 SPACECRAFT VZ-COOR(KM/S)                  0.31842481E-05
 SPACECRAFT MASS(KG)                       0.00000000E+00
```

3. COVARIANCE ANALYSIS - PARTIAL DERIVATIVE

Estimation process require to compute the PARTIAL DERIVATIVES with respect to the ESTIMATION VARIABLES

DYNAMICS

TRANSITION MATRIX

Map covariance into next time interval

OBSERVABLES

MEASUREMENTS MATRIX

Update knowledge covariance matrix

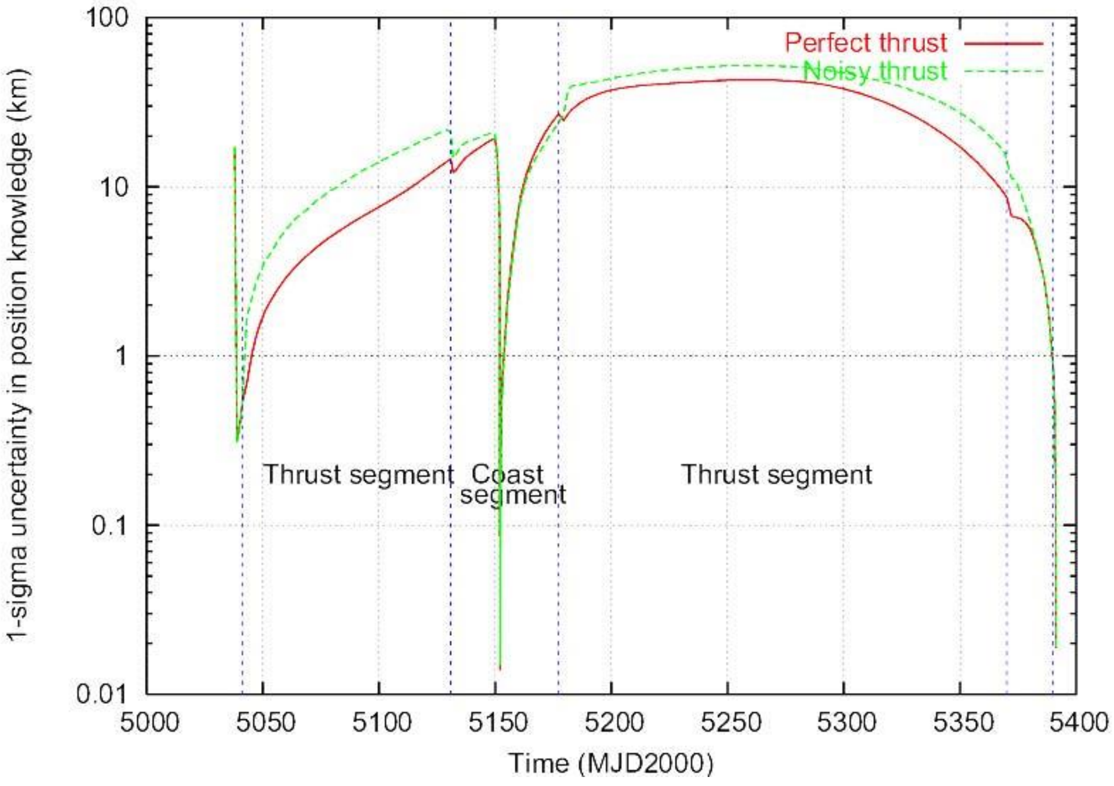
3. COVARIANCE ANALYSIS – EXPLOITATION

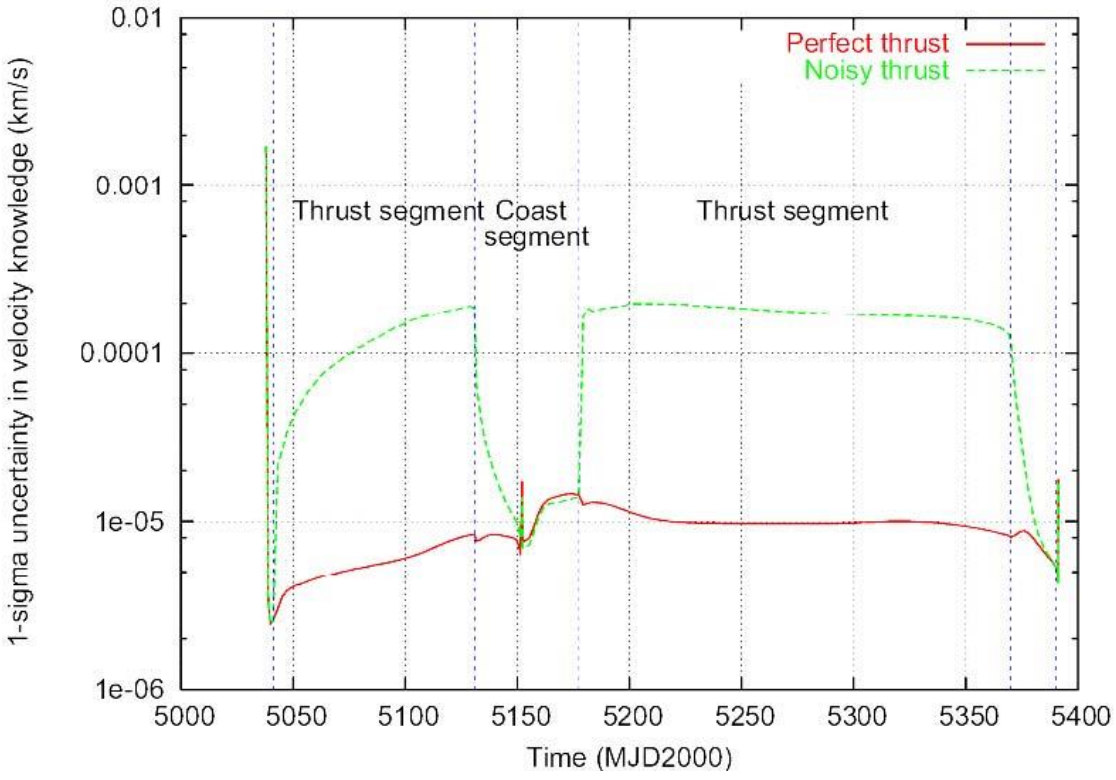
BEPICOLOMBO from Earth departure to Earth SB with Venus FB in between

- Mapping:
  - every two days in the long arcs
  - every 0.25 days for short arcs (planets SOI)
- Initial uncertainty at Earth launch:
  - Position. 10 km
  - Velocity: 1 m/s
  - Mass: 0.1 kg
- Thrust variables as ECRVs, uncertainty at:
  - 1%
  - 0.6º
  - autocorrelation time of 1d
- Residual acceleration as ECRV of:
  - 10-11 km/s^2
  - autocorrelation time of 1 day
- Range and range-rate from GS at:
  - Perth
  - Madrid
- Range noise at:
  - 10 m random
  - 2 m bias
- Range rate at:
  - 0.3 mm/s random
  - no bias
- Ground station position errors:
  - 1 m in X and Y position
  - 2 m in Z position

3. COVARIANCE ANALYSIS – EXPLOITATION

BEPICOLOMBO from Earth departure to Earth SB; Venus FB in between





4. SIMULATION - MONTE CARLO

WHY THE MONTE CARLO UTILITY?

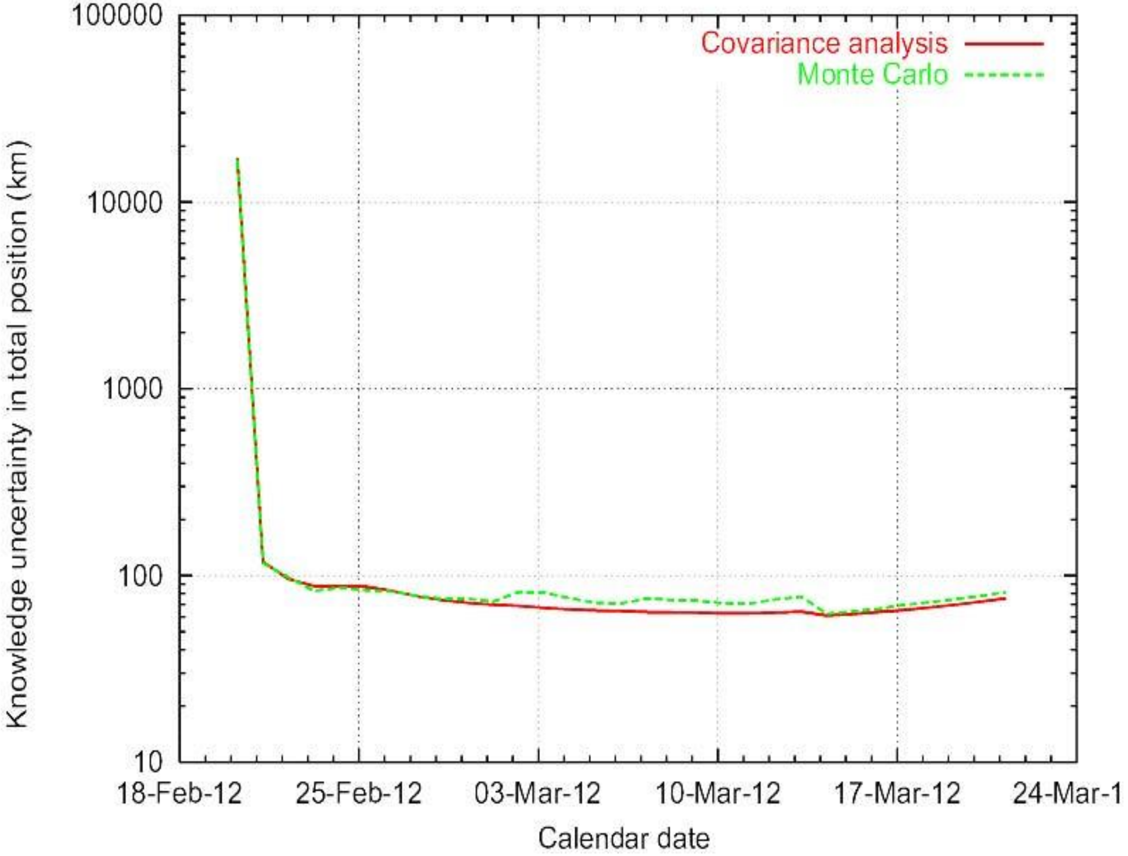
To simulate the navigation process over a number of cases with random conditions.

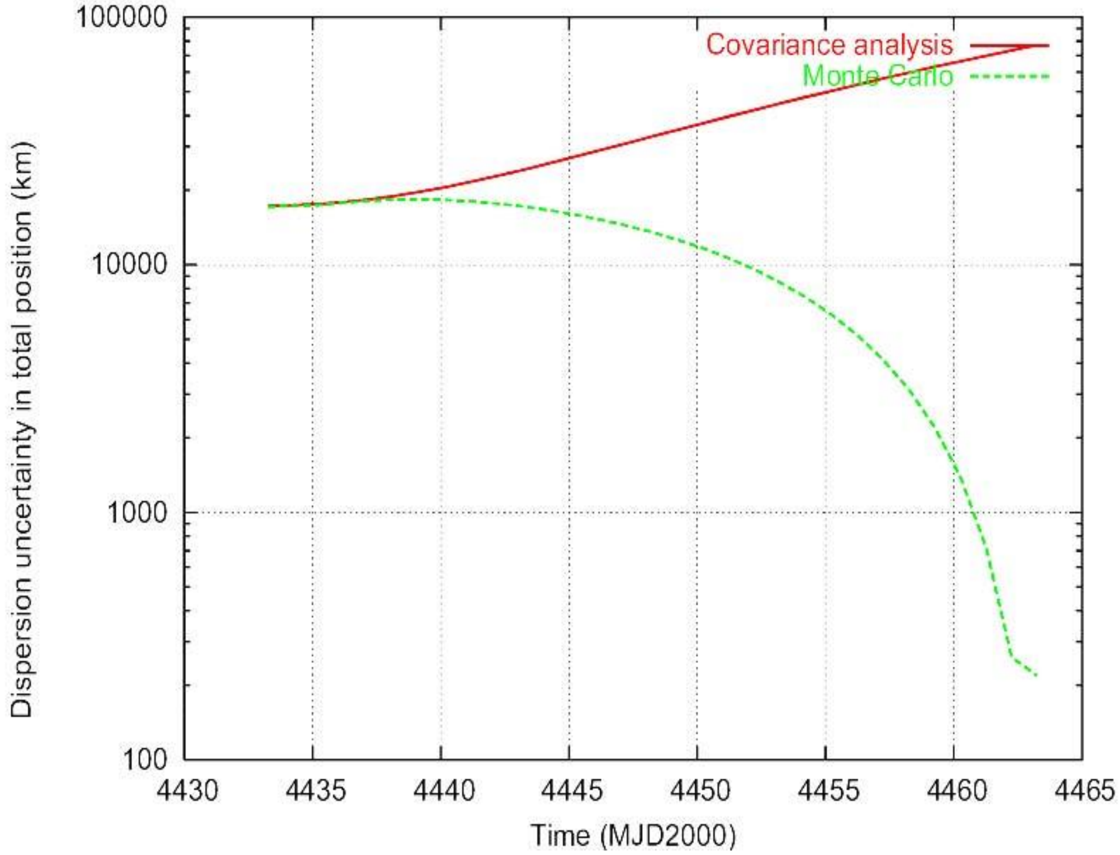
Navigation process is repeated for all the simulations, performing:

1. Propagation of the simulated *real world* and *estimated world*
2. Calculation of the *simulated real world measurements* and the *reconstructed measurements*
3. Estimation of the *augmented state vector* at the beginning of each mapping interval
4. Mapping of the *estimated state* to the end of each interval
5. Performance of the guidance process both for electrical and chemical propulsion

4. SIMULATION - MONTE CARLO

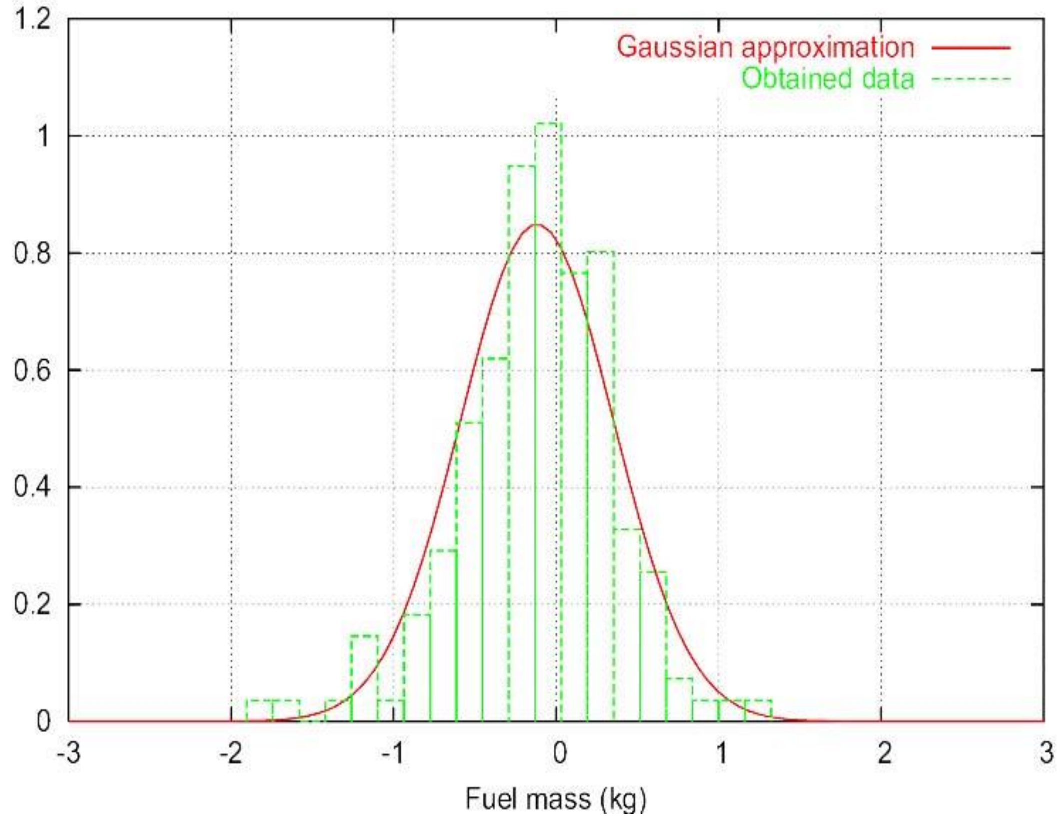
MC for BEPICOLOMBO on knowledge and dispersion uncertainty in tot position

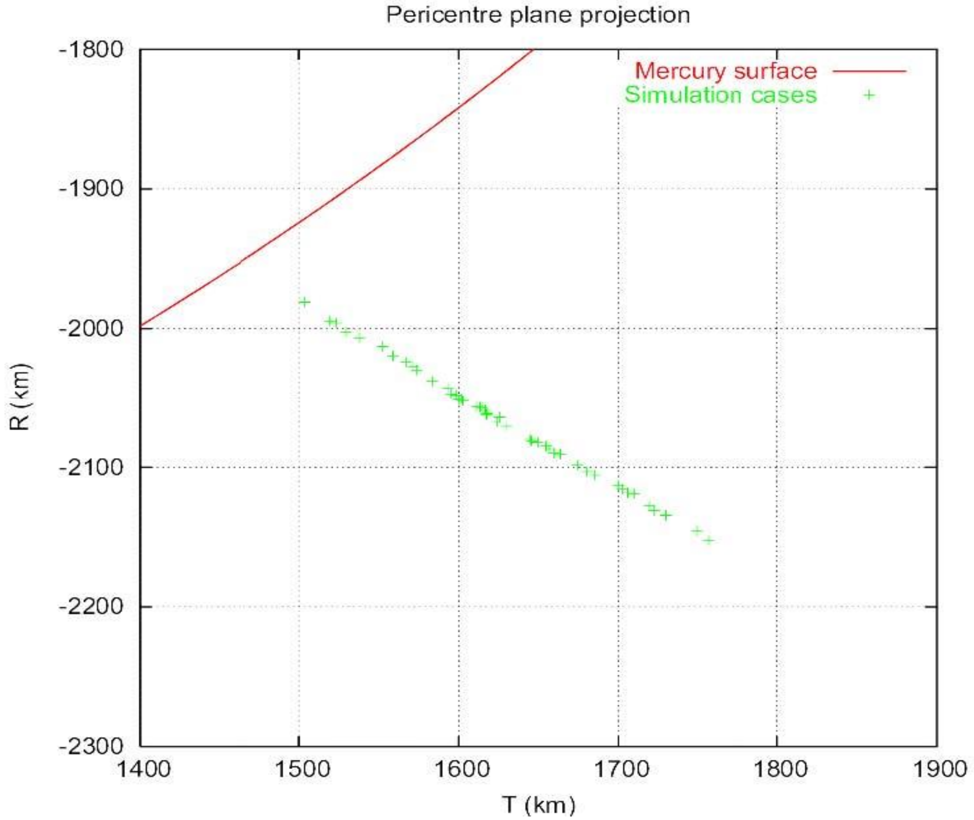




4. SIMULATION - MONTE CARLO

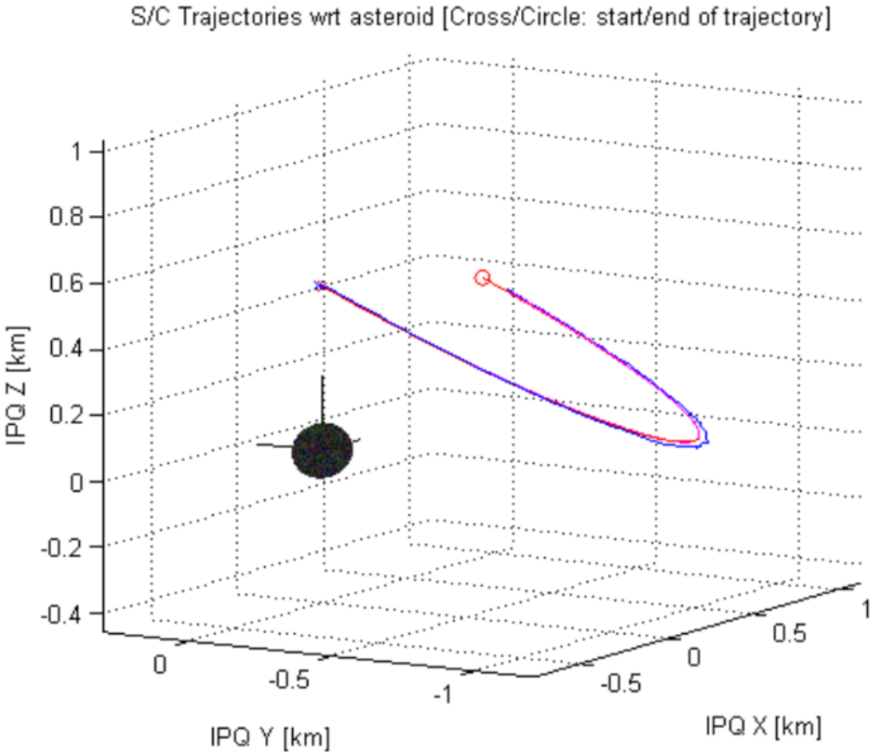
MC for BEPICOLOMBO on fuel consumption and final dispersion in the pericentre plane of GAM 2 in Mercury

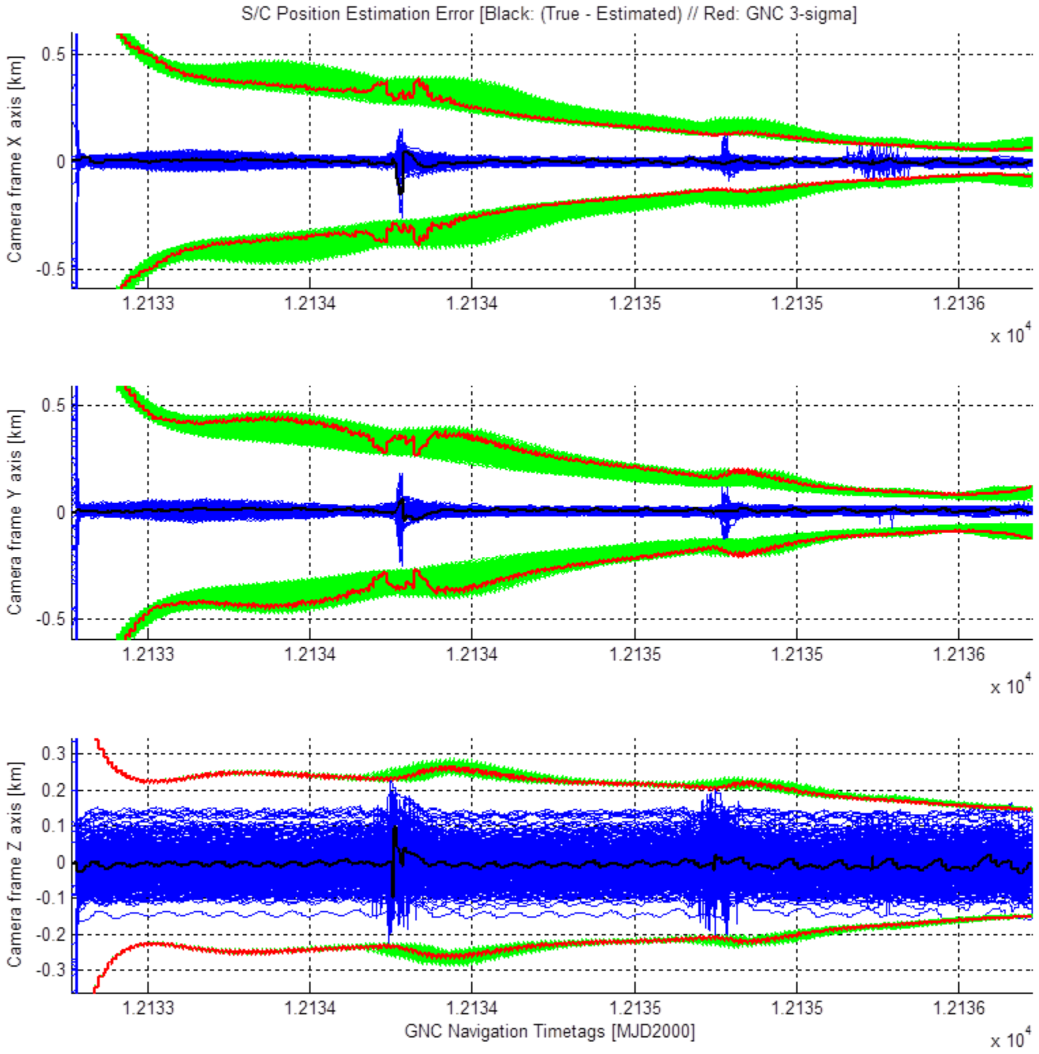




4. SIMULATION - MONTE CARLO

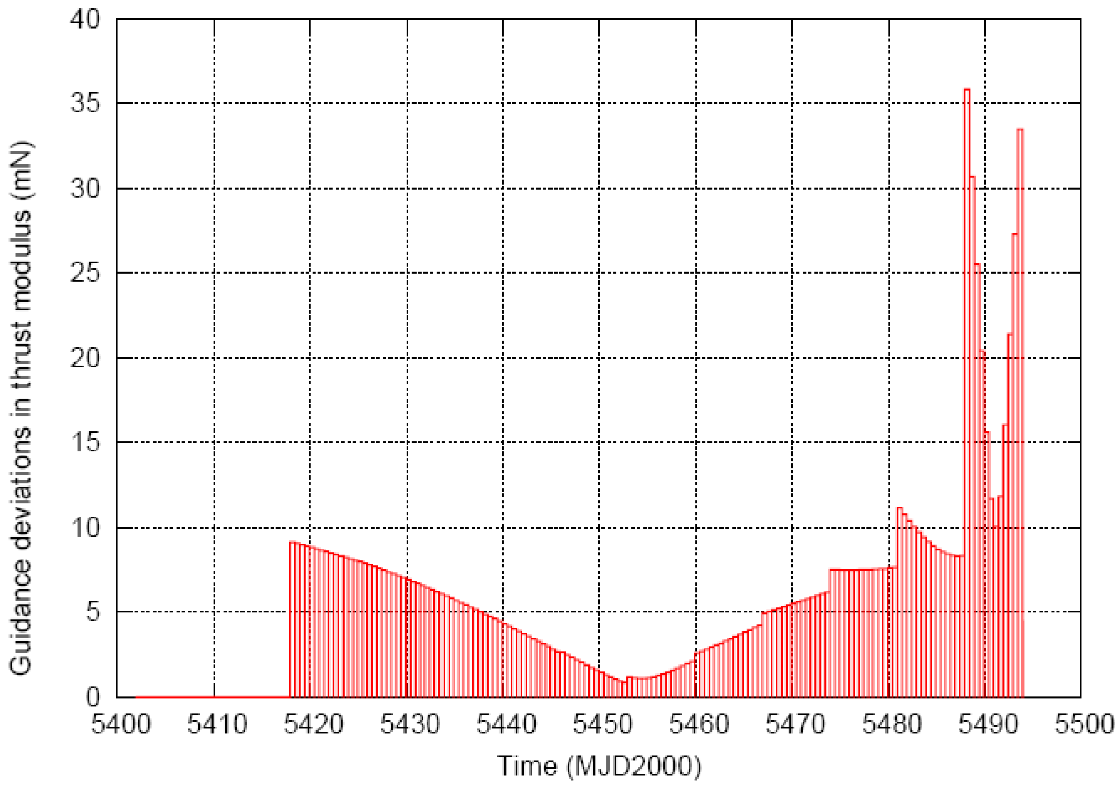
MC for NEOShield-2: close approach phase mixing on-ground and on-board measurements

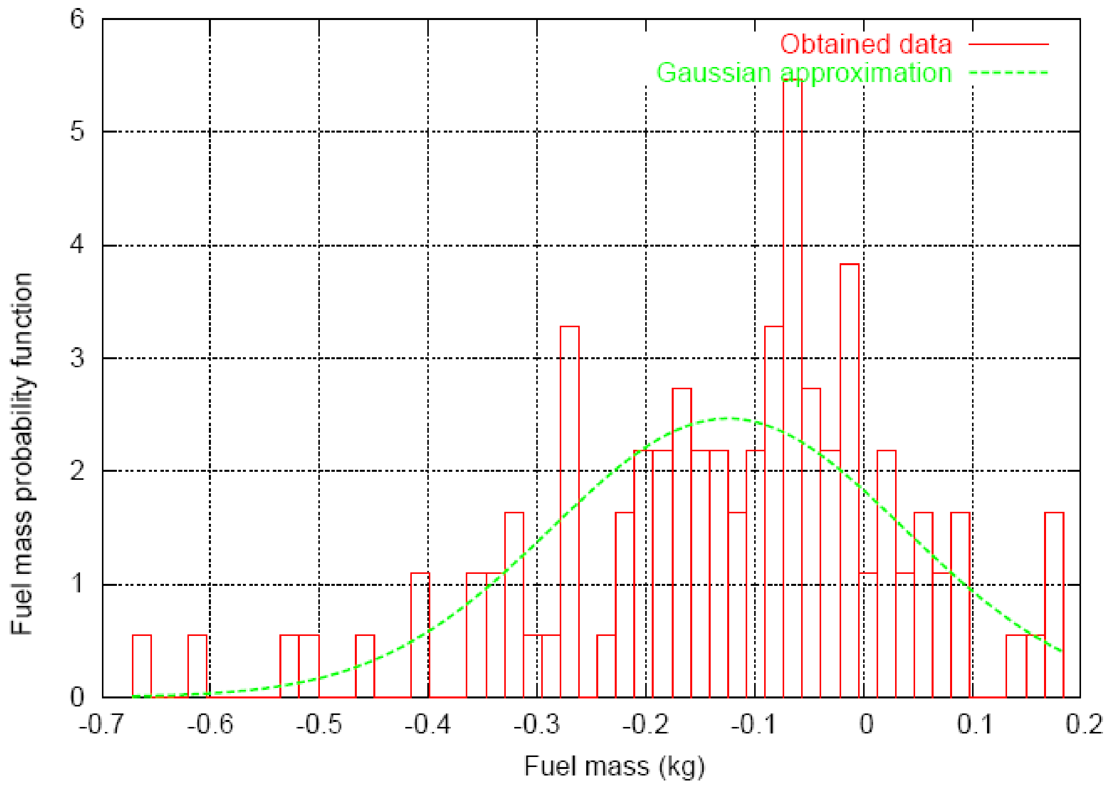




4. SIMULATION - STATISTICAL ANALYSIS

BEPICOLOMBO 1-σ values of the deviations in the low-thrust controls to meet the final state and distribution of fuel mass consumption





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5. TRAJECTORY REOPTIMISATION

WHY RE-OPTIMISE THE TRAJECTORY?

Because the optimal trajectory changes if we deviate from the nominal solution.

A full simulation of the navigation process, with a full navigation and guidance loop is needed for each of the shots of the calculation.

Two different options:

a) Internal to LOTNAV
b) External (i.e. DITAN)

On top on navigation errors, implemented failure cases are:

- Ignition delay of the propulsion engine
- Engine flame-out
- Non-nominal performance of the low-thrust engine
- Non-nominal launch into escape orbit
- Non-nominal planetary flyby

CONCLUSIONS

LOTNAV IS A POWERFUL AND LIVING TOOL

- A versatile multi-platform navigation & mission analysis tool:
  - to produce trajectory profiles of application to navigation
  - to perform quick and thorough analysis of achievable OD performances
  - to characterise the guidance requirements together with the validation of the OD results
- Capable to interface with other reference tools for mission re-optimisation
- Successfully applied to numerous ESA projects and in several editions of the GTOC
- Continuously updated and improved to expand its capabilities:
  - Now highly modularised to integrate different modules in external simulators
  - With SPICE ephemerides available
  - Incorporating features tracking and landmarks navigation
  - Including GNSS measurements

THANK YOU

simone.centuori@deimos-space.com
pablo.hermosin@deimos-space.com