POLITECNICO MILANO 1863

Trajectory Design in High-Fidelity Models

F. TOPPUTO, D.A. DEI TOS, K. V. MANI, S. CECCHERINI, **C. GIORDANO**, V. FRANZESE, Y. WANG

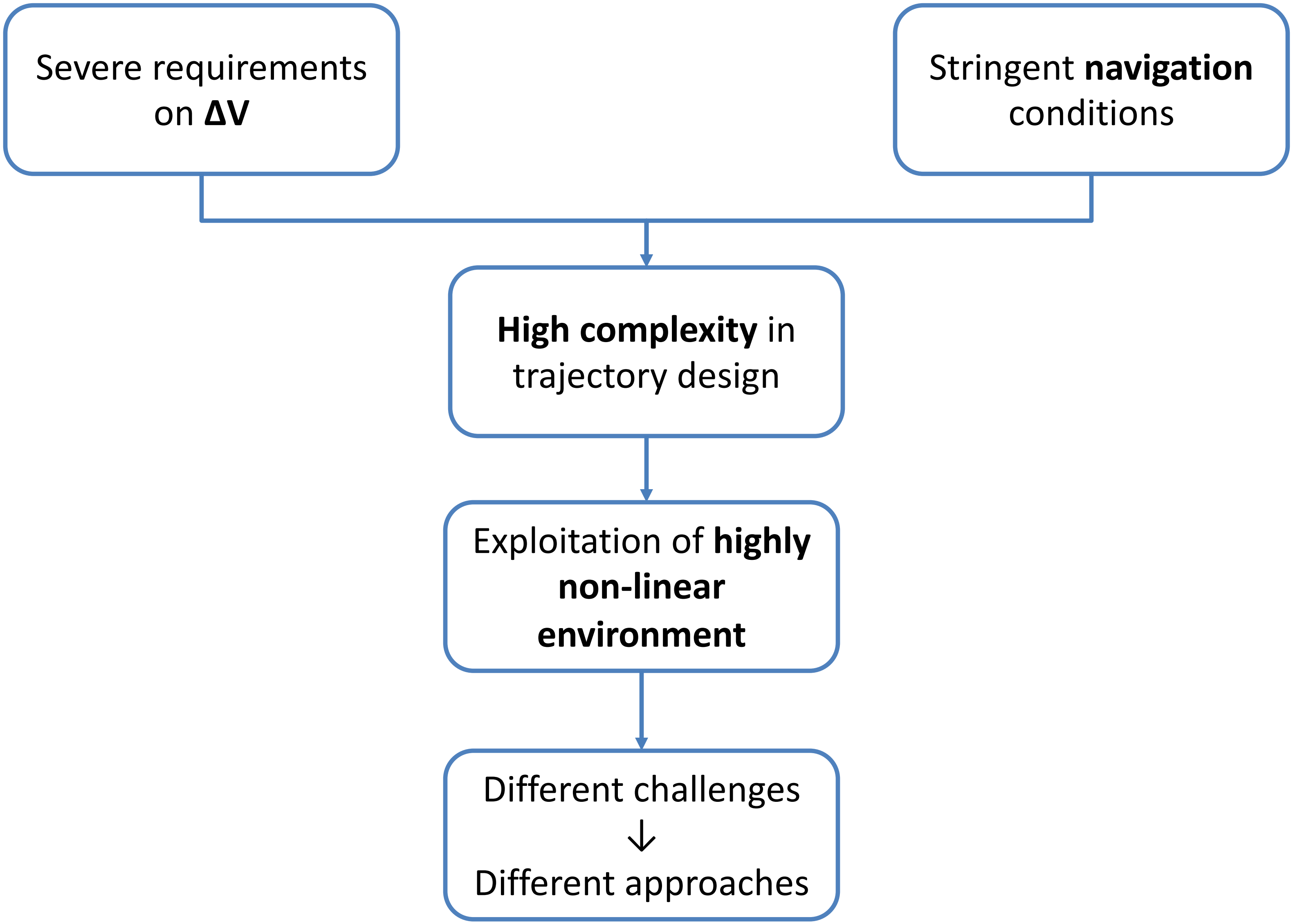
Department of Aerospace Science and Technology, Politecnico di Milano, Italia

Carmine Giordano carmine.giordano@polimi.it
Francesco Topputo francesco.topputo@polimi.it

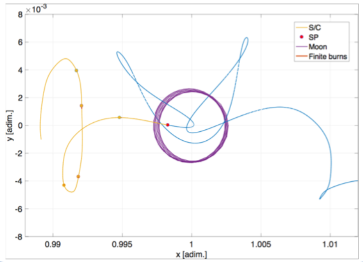
Outline

- Introduction
- General Overview
- PoliMi astrodynamics tools
  - ULTIMAT (Ultra Low-Thrust Interplanetary Mission Analysis Tool)
  - LT20 (Low-thrust Trajectory Optimization)
  - DIRETTO (DIREct collocation tool for Trajectory Optimization)
  - GRATIS (GRAvity TIdal Slide)
- Conclusions and future work

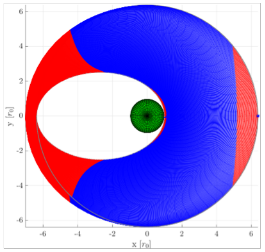
Introduction



Limited-control authority spacecraft
ULTIMAT

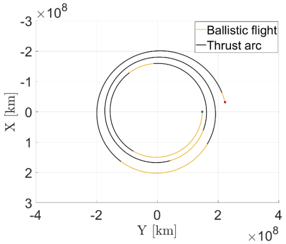


Low-thurst multispiral trajectories
LT20

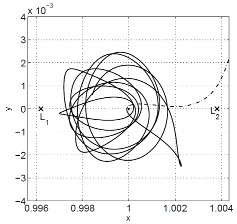


CHALLENGES IN SPACE TRAJECTORY DESIGN

Direct trajectory optimization
DIRETTO



Highly non-linear dynamics exploitation
GRATIS



Ultra Low Thrust Interplanetary Mission Analysis Tool

Why?

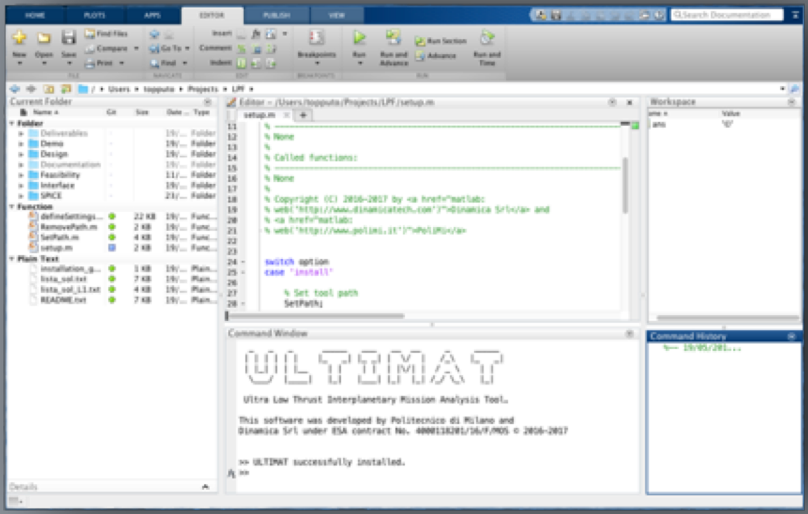
- Limited capability spacecrafts
- Impulsive, low thrust
- High navigation accuracy

Features

- Written in Matlab
- SPICE fully integrated
- Extensively tested
- Propagators validated (GMAT)

25k lines, 270 files

Updates managed with GIT

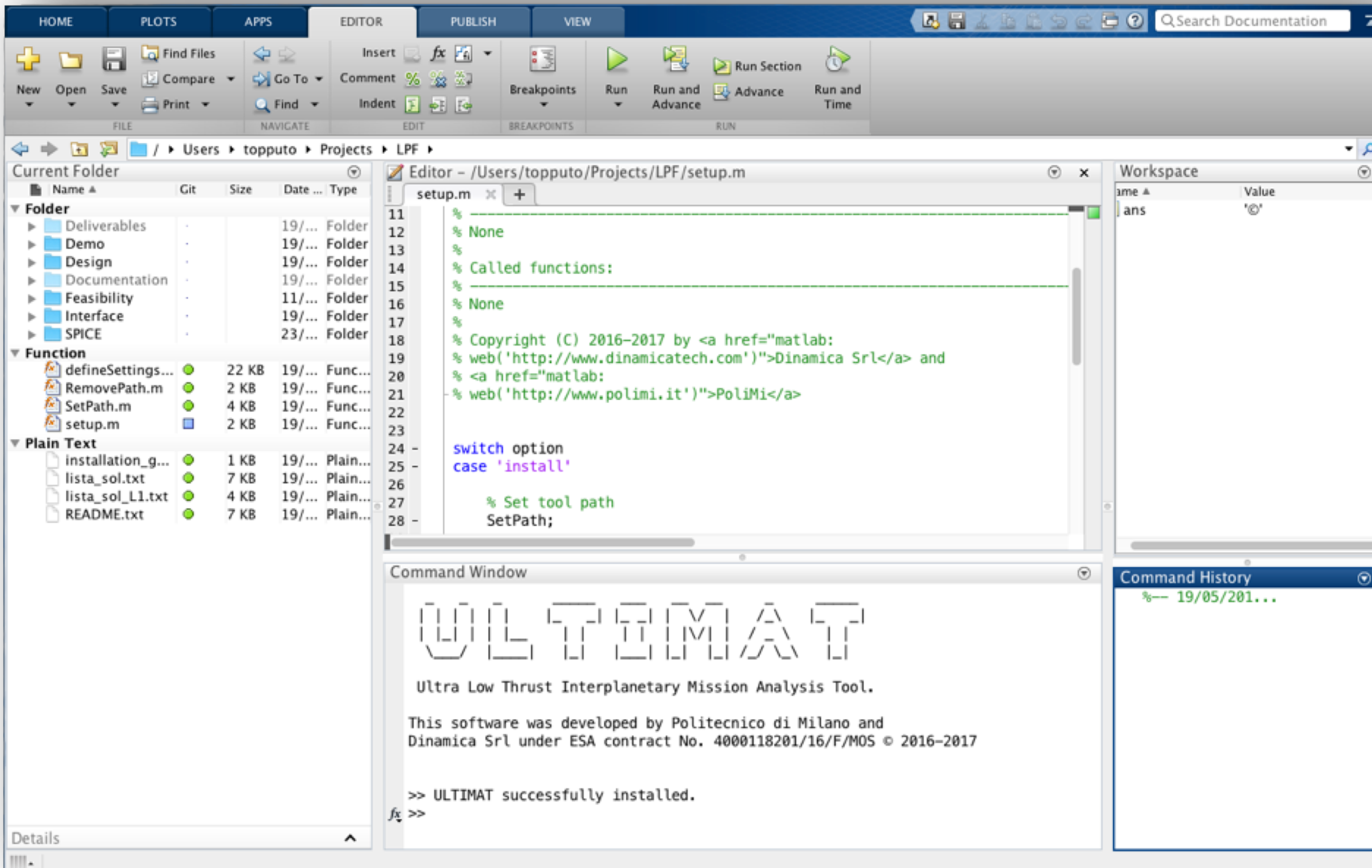


ULTIMAT: Ultra Low Thrust Mission Analysis Tool

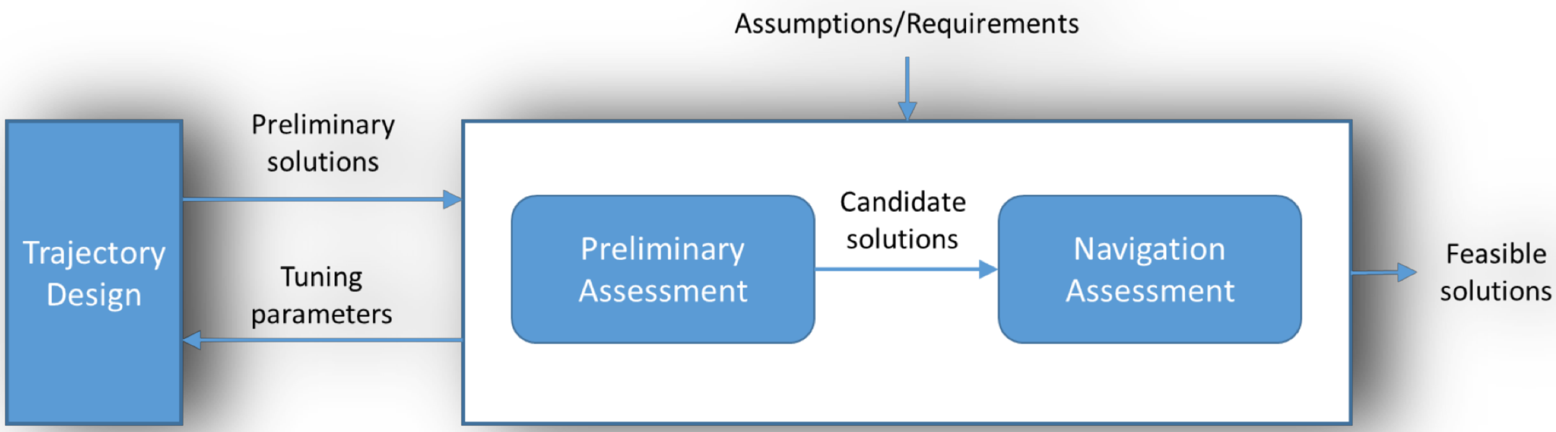
General-purpose: hierarchical trajectory design, geometrical analysis, design sensitivity, orbit determination, navigation cost.

Completely developed from scratch (Oct 2016-Nov 2018)
Kick off given by ESA Contract No. 4000118201/16/F/MOS

Look and feel



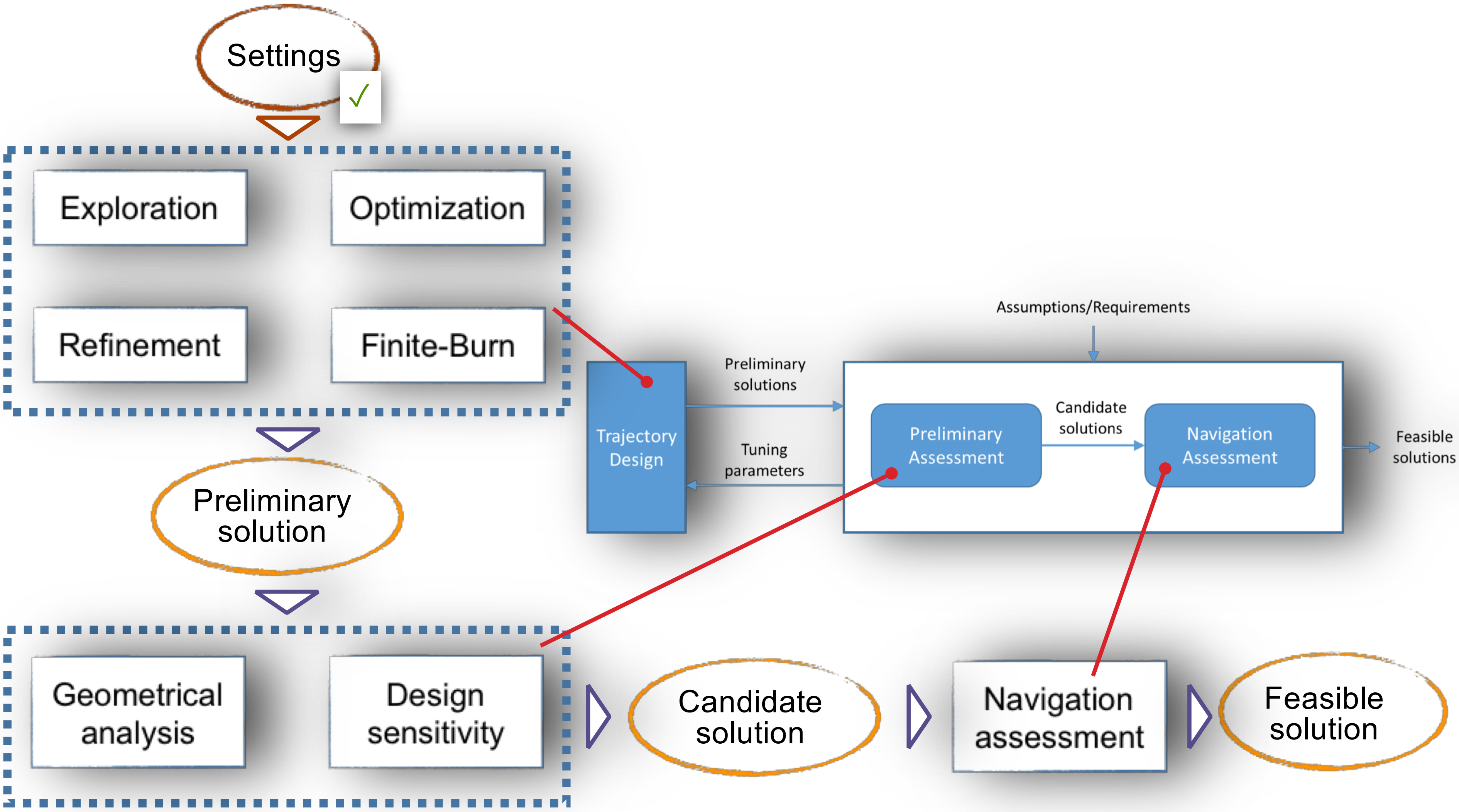
Methodology



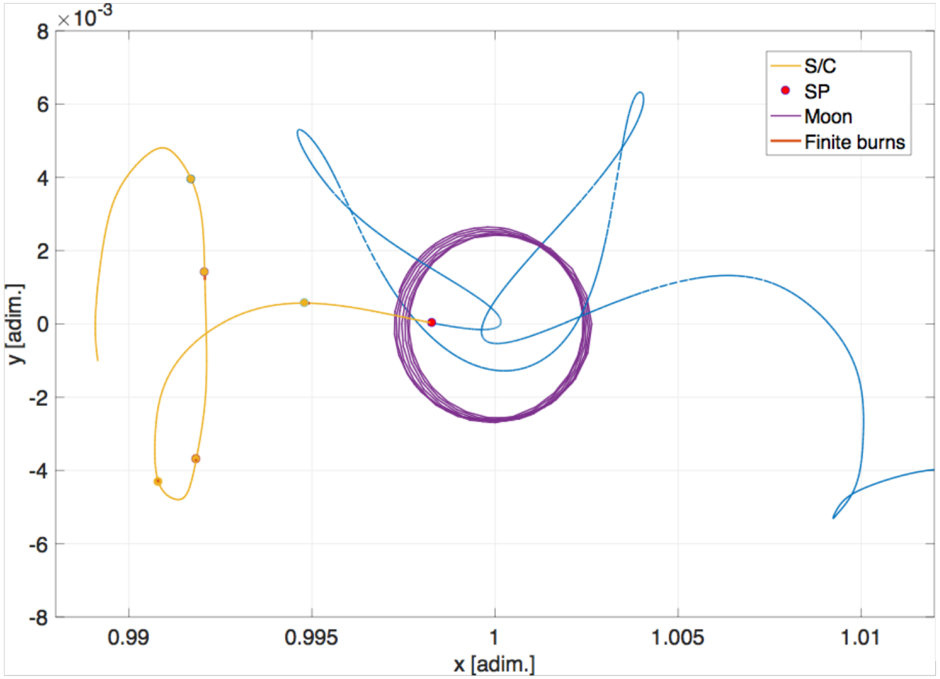
- **Design**. Developing *methods* and *tools* to derive orbits
  - Defined in highly nonlinear vector fields
  - Having very limited control authority

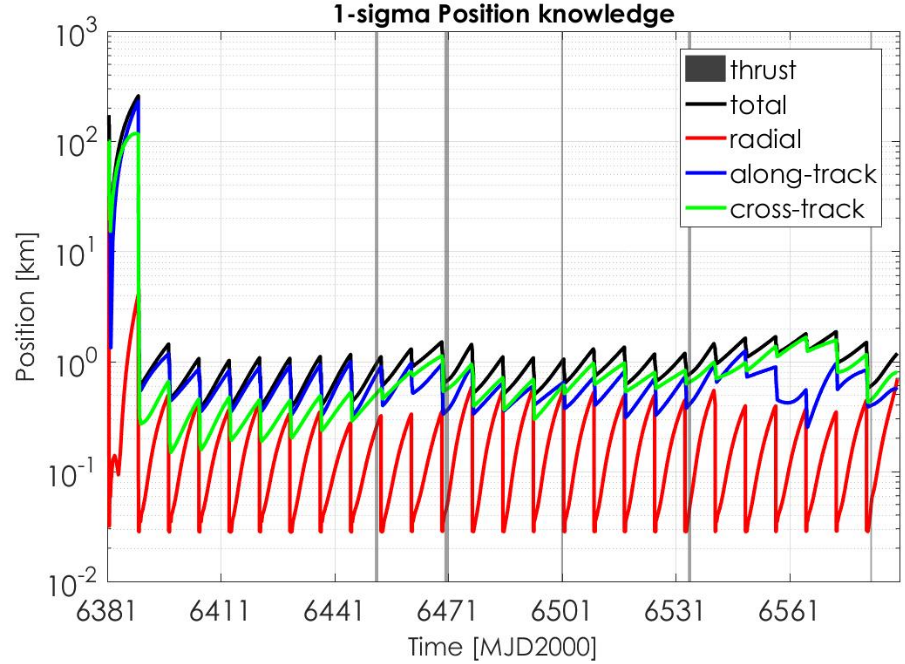
- **Navigation**. Developing *methods* and *tools* to assess feasibility of highly nonlinear, limited control orbits
  - High fidelity models for ground and space systems
  - Requirements needed to fly such orbits

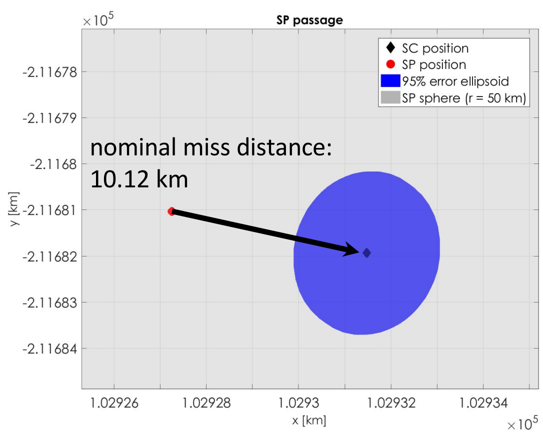
Workflow


Settings
Exploration
Optimization
Refinement
Finite-Burn
Preliminary solution
Geometrical analysis
Design sensitivity
Candidate solution
Navigation assessment
Feasible solution
Assumptions/Requirements
Trajectory Design
Preliminary solutions
Tuning parameters
Preliminary Assessment
Candidate solutions
Navigation Assessment
Feasible solutions

LPF-to-SP mission extension example

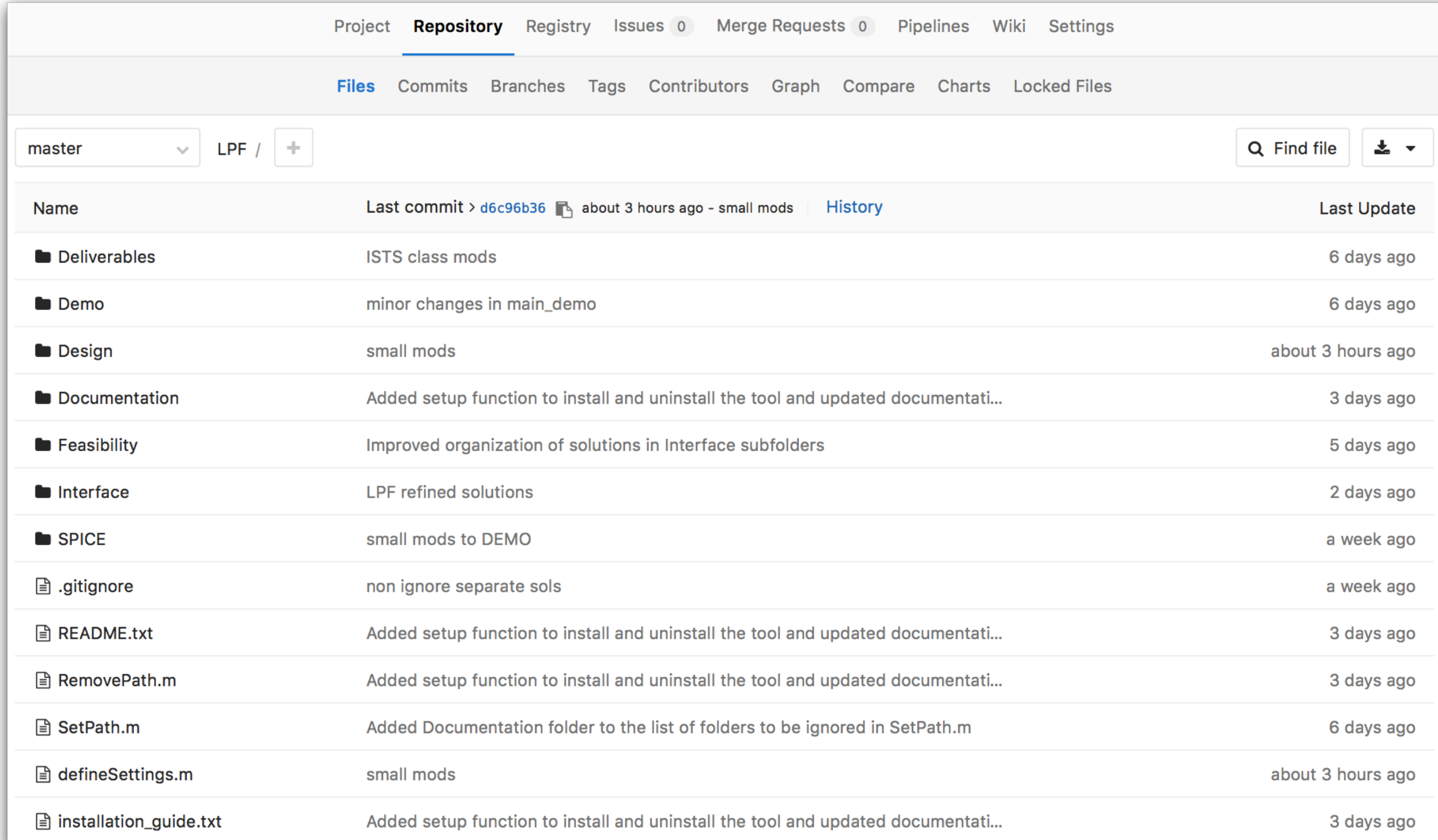






- Original, state-of-the-art trajectory design methodologies formulated and implemented
- Hundreds of potentially applicable solutions derived
- Parametric analyses for feasibility assessment performed
- General purpose tool developed, can be used for future similar applications

Project repository > Structure



Name	Last commit	Last Update
Deliverables	ISTS class mods	6 days ago
Demo	minor changes in main_demo	6 days ago
Design	small mods	about 3 hours ago
Documentation	Added setup function to install and uninstall the tool and updated documentati...	3 days ago
Feasibility	Improved organization of solutions in Interface subfolders	5 days ago
Interface	LPF refined solutions	2 days ago
SPICE	small mods to DEMO	a week ago
.gitignore	non ignore separate sols	a week ago
README.txt	Added setup function to install and uninstall the tool and updated documentati...	3 days ago
RemovePath.m	Added setup function to install and uninstall the tool and updated documentati...	3 days ago
SetPath.m	Added Documentation folder to the list of folders to be ignored in SetPath.m	6 days ago
defineSettings.m	small mods	about 3 hours ago
installation_guide.txt	Added setup function to install and uninstall the tool and updated documentati...	3 days ago

Project repository > Statistics

Commit statistics for master Aug 30 - Oct 17

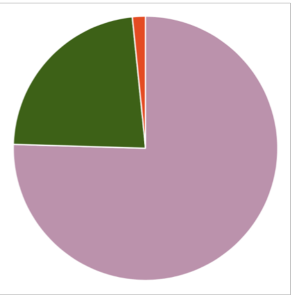
master

LPF

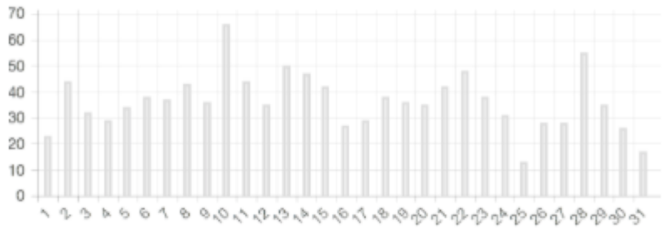
- Total: **1126 commits**
- Average per day: **1.4 commits**
- Authors: **14**

Programming languages used in this repository

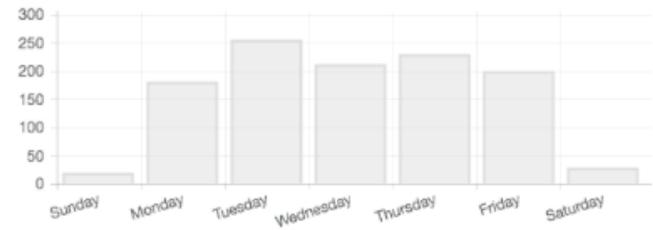
Language	%
Matlab	75.48 %
TeX	22.92 %
HTML	1.61 %
Objective-C	0.0 %



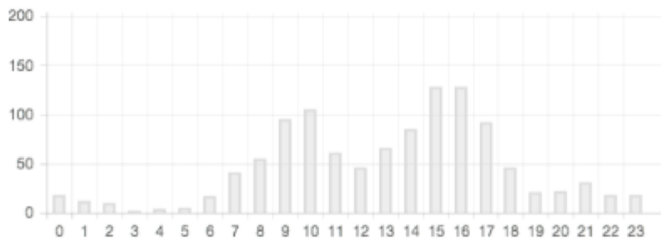
Commits per day of month



Commits per weekday



Commits per day hour (UTC)



Documentation

Extensive documentation in html

Matlab Index

Matlab Directories

- ULTIMAT
- ULTIMAT/Design/Common
- ULTIMAT/Design/Exploration/EvolutionaryAlgorithm/EA_R
- ULTIMAT/Design/Exploration/GridSearch/GS_RFBP
- ULTIMAT/Design/Exploration/GridSearch/GS_RNBP-RPF
- ULTIMAT/Design/Exploration/GridSearch/GS_RTBP
- ULTIMAT/Design/Exploration/LPF
- ULTIMAT/Design/FiniteBurn/FBM_RFBP
- ULTIMAT/Design/FiniteBurn/FBM_RFBP/Integration
- ULTIMAT/Design/FiniteBurn/FBM_RNBP-RPF
- ULTIMAT/Design/Models/EME2000
- ULTIMAT/Design/Models/RFBP/Integration
- ULTIMAT/Design/Models/RFBP/Transformations
- ULTIMAT/Design/Models/RNBP-RPF/Integration
- ULTIMAT/Design/Models/RNBP-RPF/Transformations
- ULTIMAT/Design/Models/RNBP-RPF/testing_RNBP-RPF
- ULTIMAT/Design/Models/RTBP/Basics
- ULTIMAT/Design/Models/RTBP/Integration
- ULTIMAT/Design/Models/RTBP/Manifolds
- ULTIMAT/Design/Models/RTBP/Orbits
- ULTIMAT/Design/Models/RTBP/Transformations
- ULTIMAT/Design/Optimization/MS_RFBP
- ULTIMAT/Design/Optimization/MS_RNBP-RPF
- ULTIMAT/Design/Refinement/EME2000
- ULTIMAT/Design/SaddlePoint/SP_RFBP
- ULTIMAT/Design/SaddlePoint/SP_RNBP
- ULTIMAT/Design/SaddlePoint/SP_RTBP
- ULTIMAT/Feasibility/General
- ULTIMAT/Feasibility/Navigation_assessment
- ULTIMAT/Feasibility/Preliminary_assessment
- ULTIMAT/Interface/Relevant_ephemerides/Auxiliary_files

plotThrustProfile
plotTrajectory
plot_mulutiGArunResult
prep_OBJECT
printFigure
printMessage
processNoise
progress
propagateSolution
pseudoMeasurements
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r3bpFlow3D
r3bpOrbit3D
r3bpOrbit3D_1dV
r3bpOrbit3D_eval
r3bpSymmetry3D
r3bpVectorField3D
r4bpFlow
r4bpFlow_compact
r4bpFlow_thrust
r4bpFlow_thrust_compact
r4bpOrbit
r4bpOrbit_NdV
r4bpOrbit_compact
r4bpOrbit_eval
r4bpOrbit_minSP
r4bpOrbit_thrust
r4bpOrbit_thrust_compact
r4bpVectorField
r4bpvarFlow
r4bpvarFlow_compact
r4bpvarOrbit

setFolders
setObjectParam
setStationParam
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setsolNam
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setup
setupEstin
sing2sub
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sph2cart_
ssb2syn
start
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synodic2P
test_rnbpt
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testinterp3
thrust_hist
trial_and_
turn_thrus
unix2dos
validateSo
writeInput

StopFcn_msrfbp
StopFcn_msrpf
StopFcn_msrpf_LPF
StopFcn_refine
accLT
accSRP
act
act_fg
addFolder
angle2dir
anglesyn2ssb
assign_deta
automatise_ms
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build_nbstate
build_state
checkBodyDistance
checkCoverage
checkEclipses
checkGA
checkMCresults
checkNavResults
checkSP
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crash_on_EarthMoon
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createStation
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geometricAnalysis
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gradvar_rpf
indirect_lt_traj
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isTooClose
linspaceNdim
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loadMAT
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mainPreliminary
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main_REFINE_EME2000
main_ga
main_gamultiobj
main_missDis_1dV
main_missDis_DNS
main_missDis_mani

Developed by Politecnico di Milano and Dinamica Srl under ESA contract No. 4000118201/16/F/MOS © 2016-2017

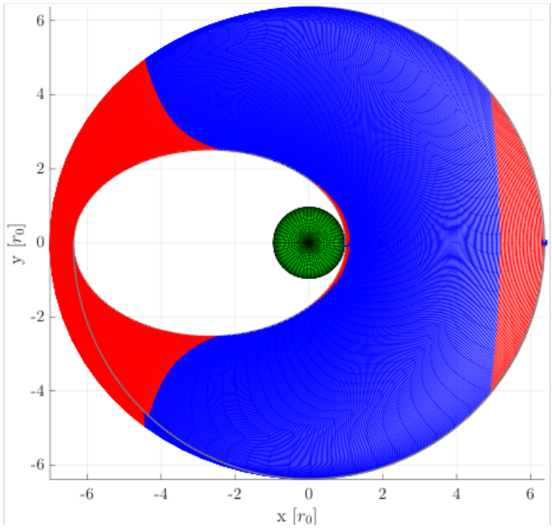
Low-Thrust Trajectory Optimization

Last trend in space engineering is the exploitation of **electric propulsion**

↑↑ Isp ↓↓ T

Managing path propelled by EP becomes crucial in designing feasible missions

High time-of-flight | Multi-revolution transfers | Low-control authority



GTO to GEO fuel-optimal transfer, T/m = 2.5 × 10–4m/s2,
Isp = 3000 s and transfer time ≈ 150 days.

New challenges in trajectory optimization answered by **LT2O**

Low-Thrust Trajectory Optimizer — Features

Different Dynamics model and Coordinates Systems

A. Restricted Two-Body problem
   i) Cartesian Coordinates and Earth's oblateness
   ii) Modified Equinoctial Elements

B. Restricted three-body problem, Cartesian Coordinates

C. Restricted four-body problem, Cartesian Coordinates

Indirect Methods Optimization for TPBVP

A. Time-optimal problems $J = \int 1 dt$

B. Energy-optimal problems $J = \int u - u\varepsilon(1-u) dt$

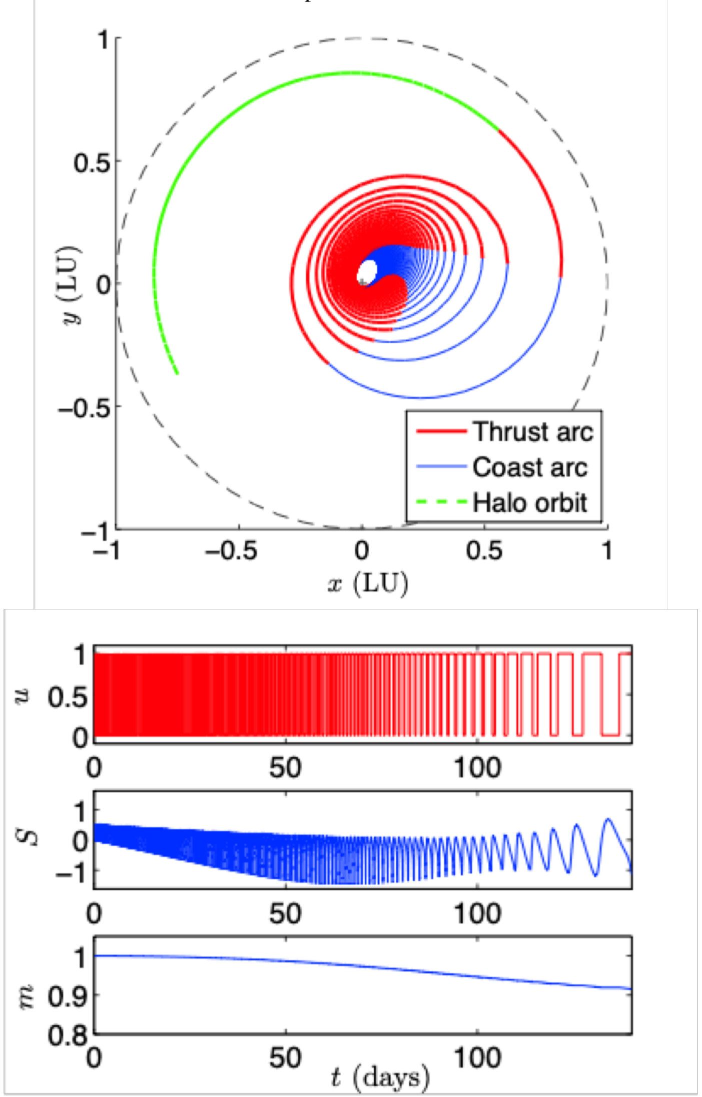
C. Fuel-optimal problems $J = \int u dt$

End-to-end optimization needs

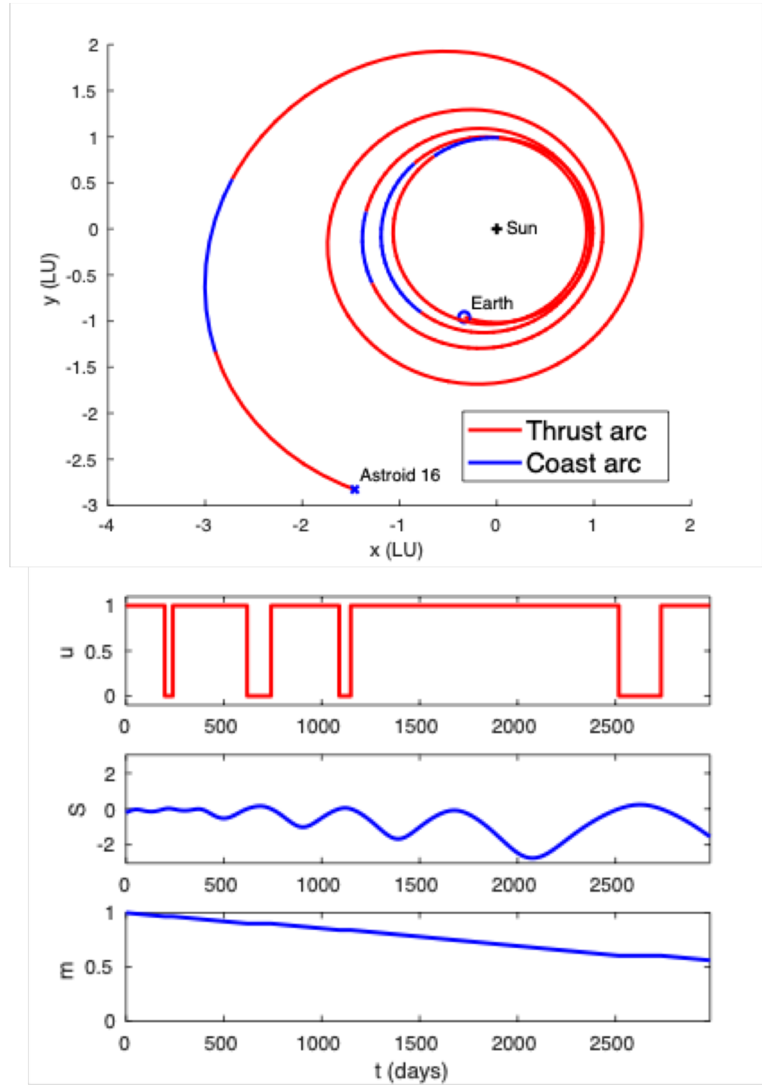
- Shooting Methods for initial costate
- Homotopy procedures on
  - → Thrust level
  - → Epsilon value
  - → Orbital parameters
- Switching Technique and STM propagation for bang-bang control

Low-Thrust Trajectory Optimizer — Case study (1)

GTO-L1 EM fuel-optimal transfer with 150 switches
$T/m_0 = 4 \times 10^{-4}$ m/s^2, $I_{sp} = 3000$ s; cartesian coordinates

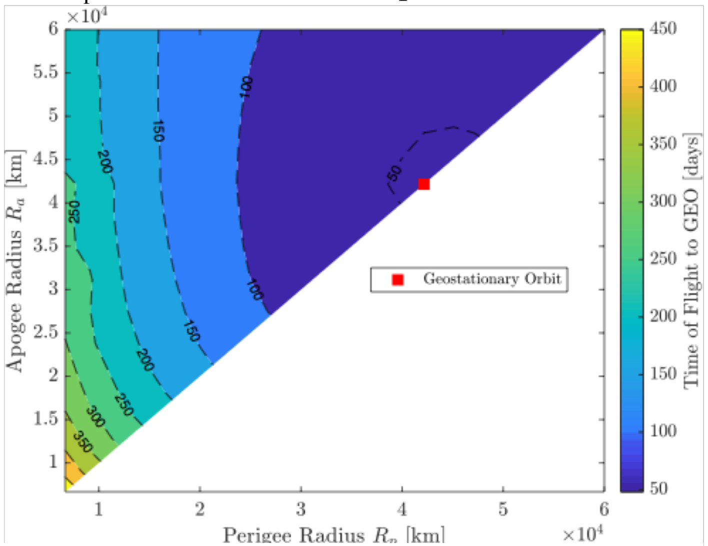


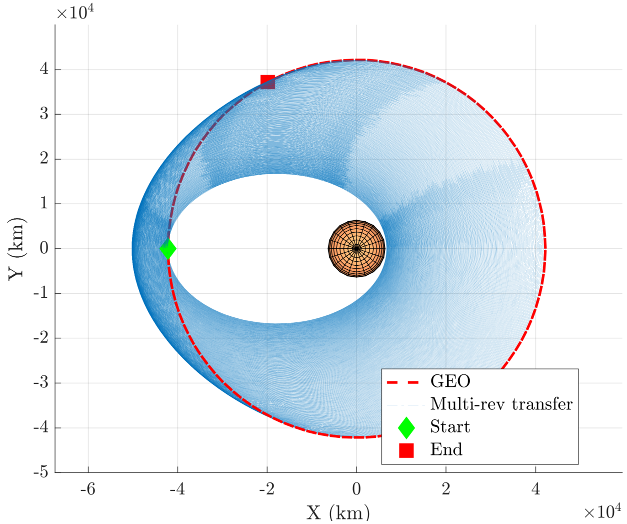
Fuel-optimal transfer from the Earth to the Asteroid 16.
$T/m_0 = 8.7\times10^{-3}$ m/s^2, $I_{sp} = 2640$ s, cartesian coordinates.



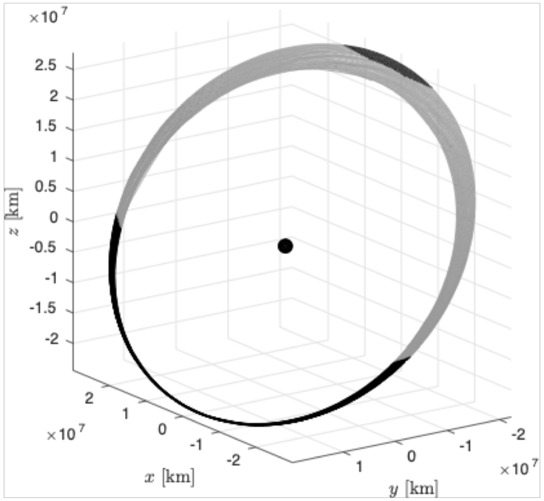
Low-Thrust Trajectory Optimizer — Case study (2)

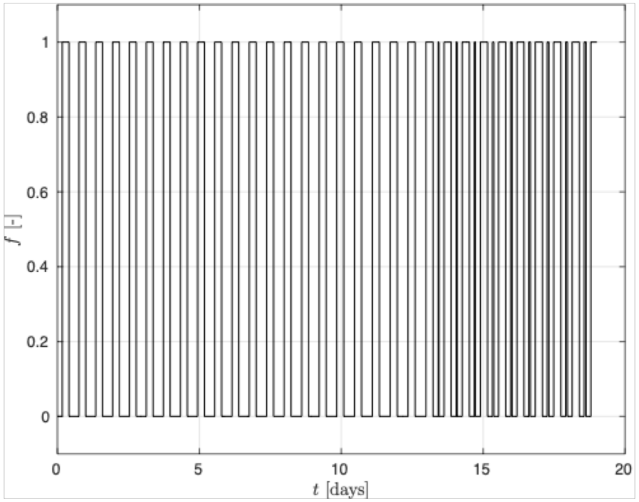
Time-optimal transfers to GEO, $T/m_0 = 1\times10^{-4}$ m/s^2 and I_{sp} = 2000 s; modified equinoctial elements





End-of-Life disposal of a Galileo satellite via a fuel- optimal strategy, $T/m_0 = 2.2\times10^{-4}$ m/s^2, specific impulse of 4000 s, and transfer time ≈ 19 days; modified equinoctial elements





DIREct collocation Tool for Trajectory Optimization

- Direct transcription to solve optimal control problems
- State and control variables are discretized and non-linear optimal control problem (NLOC) is converted to a non-linear programming (NLP) problem

Why?

- NLOC
  - Non-linear dynamics of states and costates
  - Two point BVP needs to be solved
  - Accurate but complex and time consuming
- NLP
  - A decisional problem with a scalar objective function and a vector of constraints
  - Does not involve dynamics of costates
  - Less accurate than NLOC but fast

Features

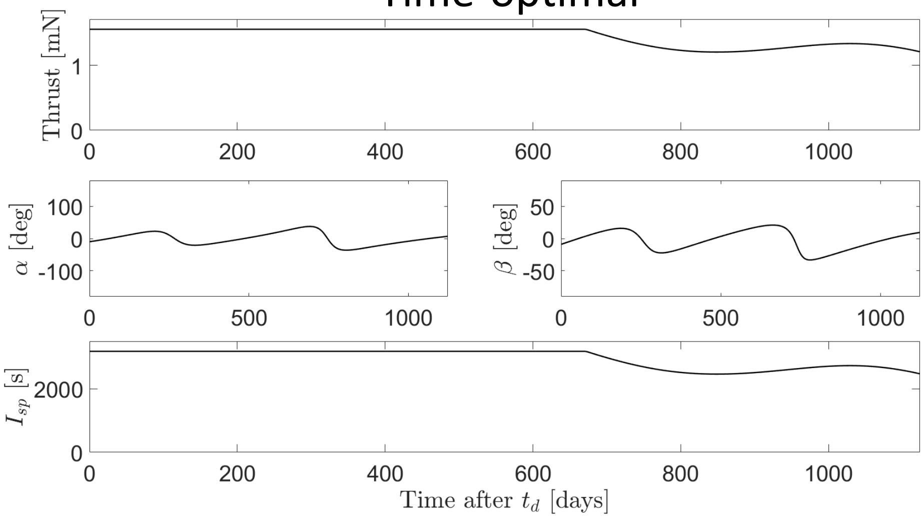
- **Equations of motion** transcribed into a set of **equality constraints**
- **Time domain discretized** as nodes (uniform and non-uniform)
- **Discretized states and control variables** treated as NLP variables
- **Differential equations** replaced by **defect constraints**
- Defect constraints derived from the **collocation method**
- Collocation methods
  - Hermite-Simpson (low-order)
  - Gauss-Lobatto (variable and high-order)
- Gradients of objective function and constraints assembled and supplied to NLP solver

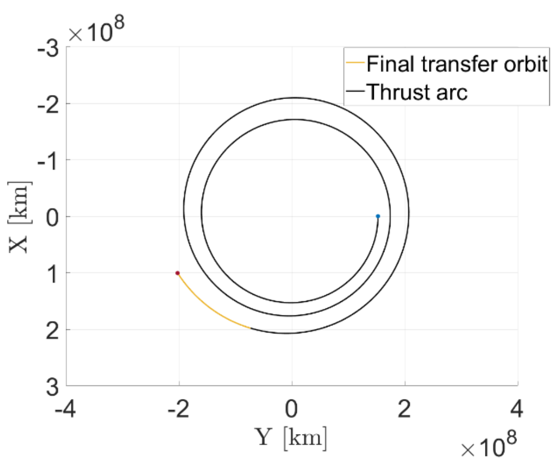
DIRETTO

- Objective functions for minimization
  - Time
  - Fuel
  - Energy
- Implemented dynamics
  - 2-body problem with spherical dynamics
  - Circular restricted 3-body problem
  - Real solar system dynamics (incl. ephemerides obtained from SPICE)
- Low-thrust options
  - Engine model with fixed and variable Thrust & Specific Impulse
- NLP Solver
  - Fmincon
  - IPOPT

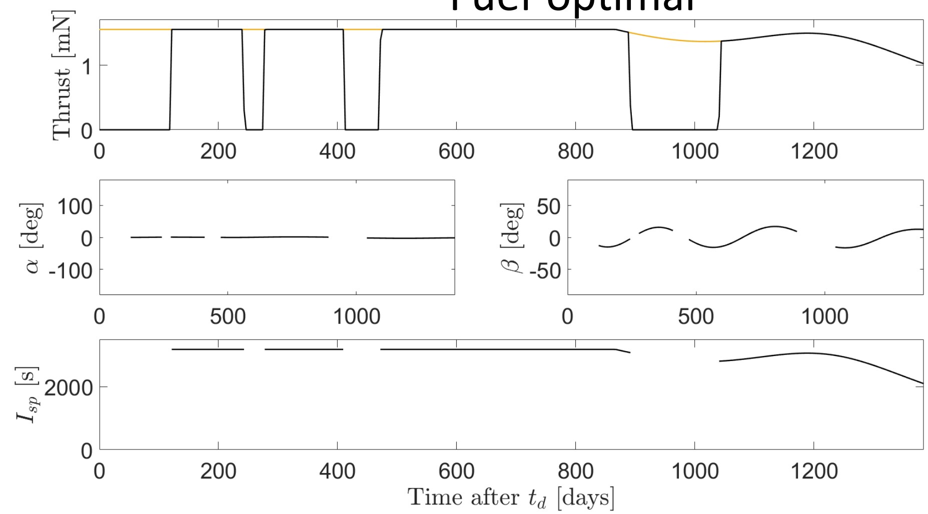
Example: Low-thrust trajectory optimization of a stand-alone 16U CubeSat to Mars

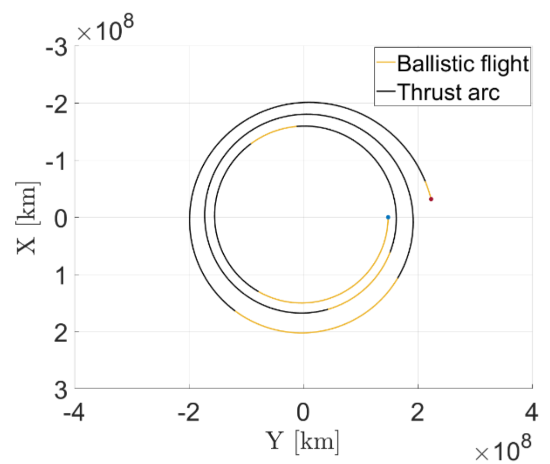
Time-optimal





Fuel-optimal





GRAvity Tidal Slide

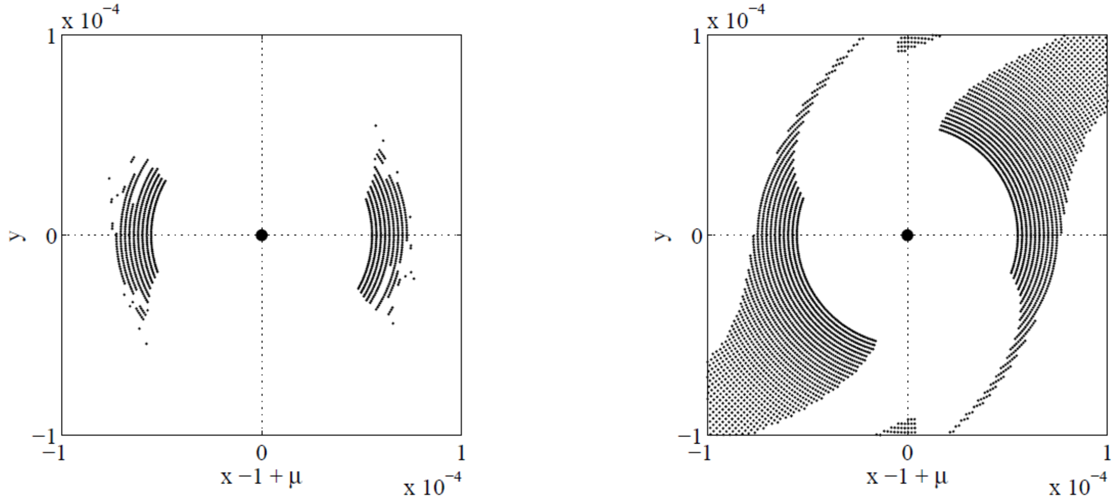
Why?

- Find a way to exploit nonlinear gravity fields unique features
- Allow small satellites to have *free transfers*
- Overcome single-point failures

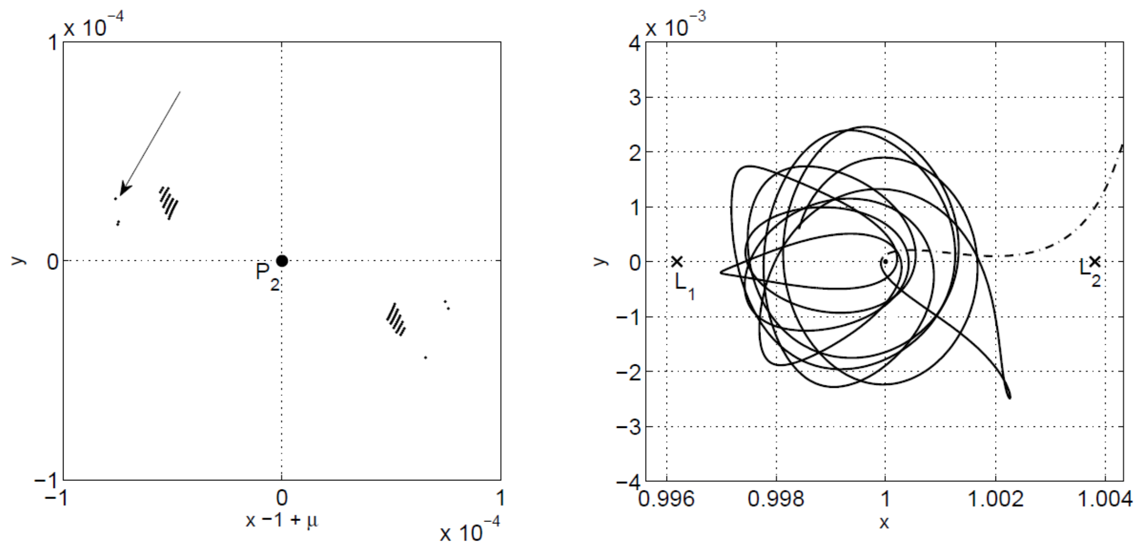
Aim

- **Compute and classify** stable and unstable sets associate to ballistic capture by
  - Sampling
  - Integration
- Different models implemented
  - CR3BP
  - ER3BP
  - RFBP
  - Real solar-system model (RnBP) with SRP and non-spherical gravity

GRATIS - Results



(a) $\mathcal{W}_9(0, 0.95)$ (b) $\mathcal{W}_{-1}(0, 0.95)$



(a) $\mathcal{C}^9_{-1}(0, 0.95)$ (b) A sample orbit in $\mathcal{C}^9_{-1}(0, 0.95)$

Sample of Mercury ballistic captures with 9 stable revolutions

Conclusions

- Different astrodynamics tools are able to cope with diverse mission specs
- Dedicated solutions with general software can be generated
- Tools can design current and future trajectories for space missions

Future work

ULTIMAT
- Implement different navigation and station keeping techniques
- Stochastic mission analysis

LT20
- Add perturbations and eclipses
- Add radiation optimal trajectory
- Include real-engine models

DIRETTO
- Pseudospectral methods

References

ULTIMAT

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- Topputo, F., Dei Tos, D. A., & Rasotto, M. (2017). Feasibility of ultra-low thrust transfers in L1/L2 Sun–Earth–Moon systems. *Final Report, ESA Contract No. 4000118201/16/F/MOS*
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LT2O

- Zhang, C., Topputo, F., Bernelli-Zazzera, F., & Zhao, Y. S. (2015). Low-thrust minimum-fuel optimization in the circular restricted three-body problem. *Journal of Guidance, Control, and Dynamics*, *38*(8), 1501-1510

DIRETTO

- Zhang, C., Topputo, F., Bernelli-Zazzera, F., & Zhao, Y. S. (2013). An Exploration of Numerical Methods for Low-Thrust Trajectory Optimization in n-Body Models. In *64th International Astronautical Congress (IAC)*

GRATIS

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- Luo, Z. F., Topputo, F., Bernelli-Zazzera, F., & Tang, G. J. (2014). Constructing ballistic capture orbits in the real solar system model. *Celestial Mechanics and Dynamical Astronomy*, *120*(4), 433-450
- Topputo, F., & Belbruno, E. (2009). Computation of weak stability boundaries: Sun–Jupiter system. *Celestial Mechanics and Dynamical Astronomy*, *105*(1-3), 3

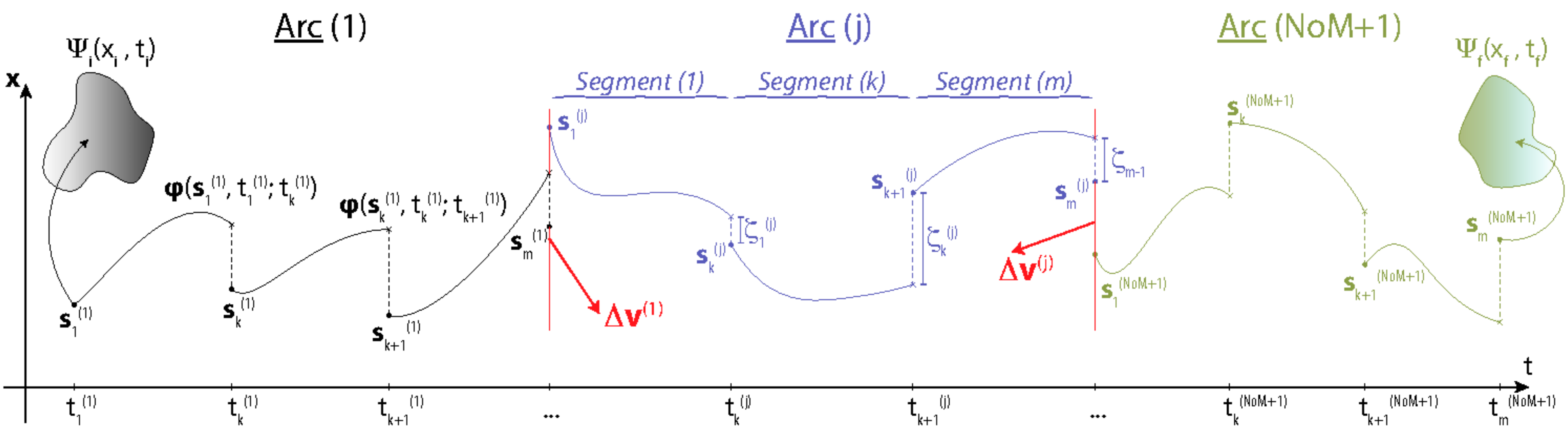
Trajectory Design in High-Fidelity Models

THANK YOU FOR THE ATTENTION

QUESTIONS?

F. TOPPUTO, D.A. DEI TOS, K. V. MANI, S. CECCHERINI, C. GIORDANO, V. FRANZESE, Y. WANG

Department of Aerospace Science and Technology, Politecnico di Milano, Italia



maneuvers (NoM)

segments (m-1)

→ *fixed parameters*

Segment Multiple shooting discretization domain (m-1) → $t_1^{(j)} < t_k^{(j)} < \cdots < t_m^{(j)}$

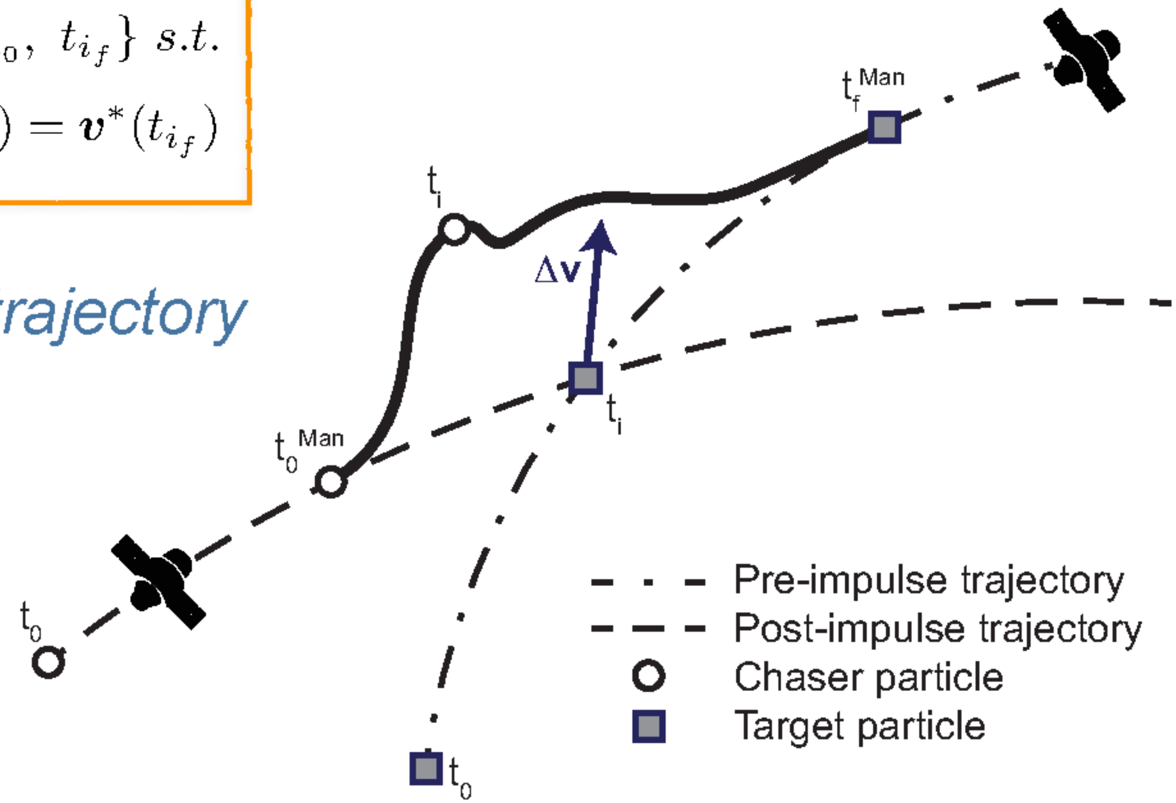
Arc Ballistic arc separated by maneuvers (NoM+1) → *Standard MS*

Find $\{u(t),\ \alpha(t),\ \beta(t),\ t_{i_0},\ t_{i_f}\}\ s.t.$

$$\boldsymbol{r}(t_{i_f}) = \boldsymbol{r}^*(t_{i_f}) \qquad \boldsymbol{v}(t_{i_f}) = \boldsymbol{v}^*(t_{i_f})$$

Post-impulse trajectory

Finite burn trajectory



The **finite burn** optimization problem for a single impulse is **treated as a pseudo-rendezvous** problem where the **target particle flies along the post-impulse trajectory**

ULTIMAT – Preliminary assessment

First exploration of the computed solutions and initial pruning of those not compliant with geometric and/or sensitivity constraints.

SETTINGS | **STATION** | **OBJECT**

Geometric Analysis routines

Relative geometry
Evaluation of several geometrical conditions.

Coverage windows
Computation and filtering of visibility windows.

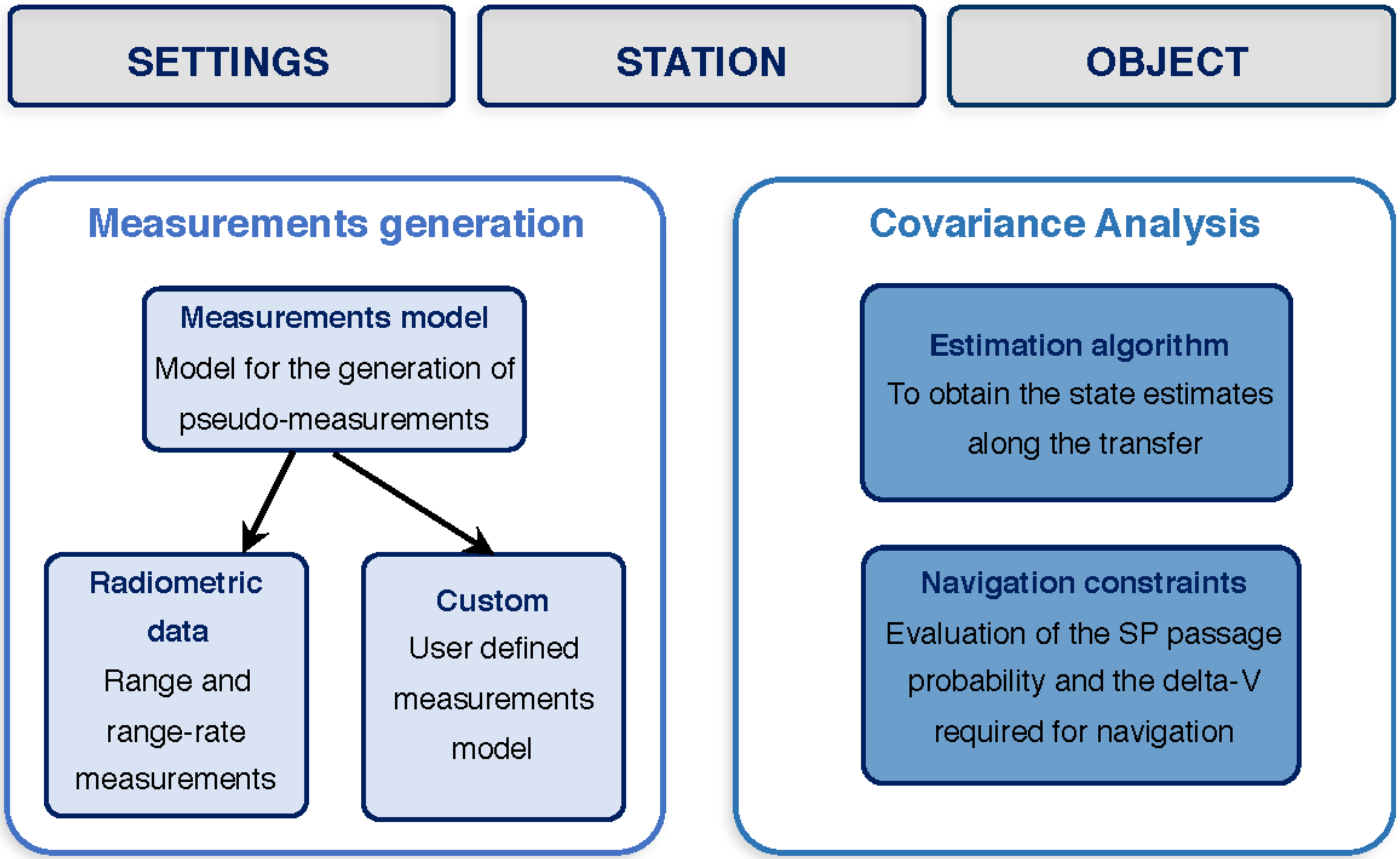
Sensitivity Analysis routines

Uncertainty generation
Generate a set of noisy control profiles.

Monte Carlo
Run Monte Carlo simulations.

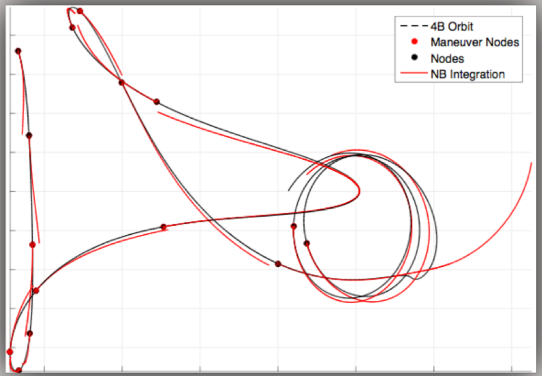
ULTIMAT – Navigation assessment

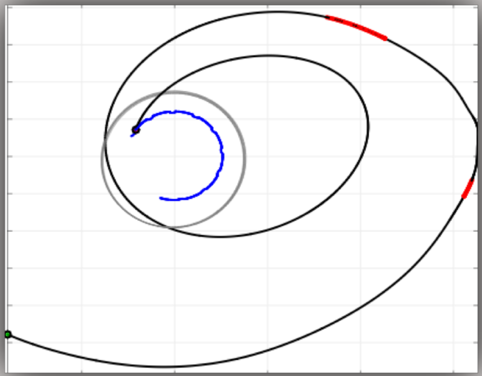
Detailed feasibility assessment through the simulation of radiometric data and computation of the achievable position and velocity knowledge during the entire transfer trajectory.

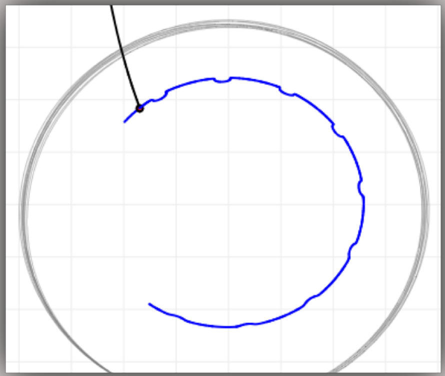


Work performed (in a nutshell)

Developed methods implementing *advanced techniques* in trajectory optimization in *sophisticated models*

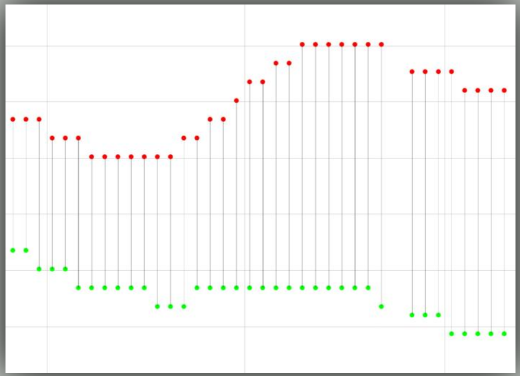


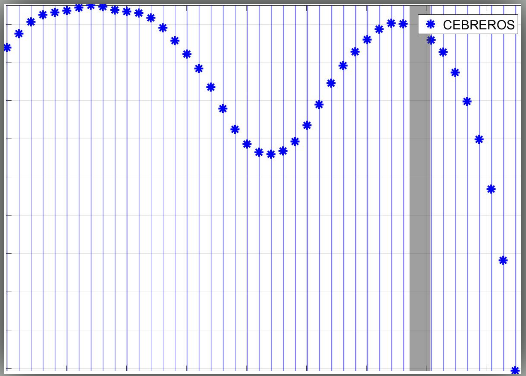


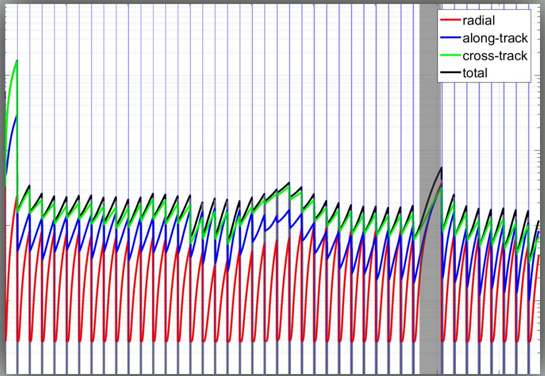


Work performed (in a nutshell)

Developed methods to assess *solution feasibility* (OD, navigation, sensitivity, geometrical analyses)







Work performed (in a nutshell)

Applied methods to *LPF*, derived top-level *requirements*, gained *knowledge* to treat similar problems