JDRAGON/JOSCAR:

TOOLS FOR MANEUVER STRATEGY COMPUTATION DEVELOPED IN JAVA AND USING PATRIUS

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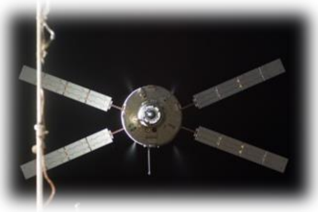
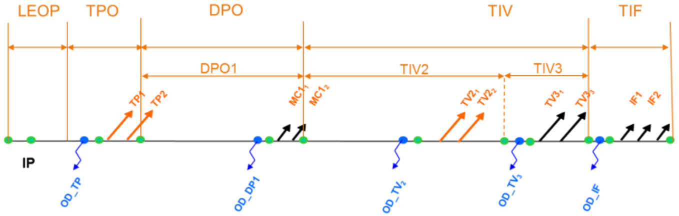
SUMMARY

INTRODUCTION

- DRAGON/OSCAR Fortran version [1]:



  - ATV program (1997-2014)
    - ATV phasing and rendezvous maneuvers strategy towards ISS (International Space Station)

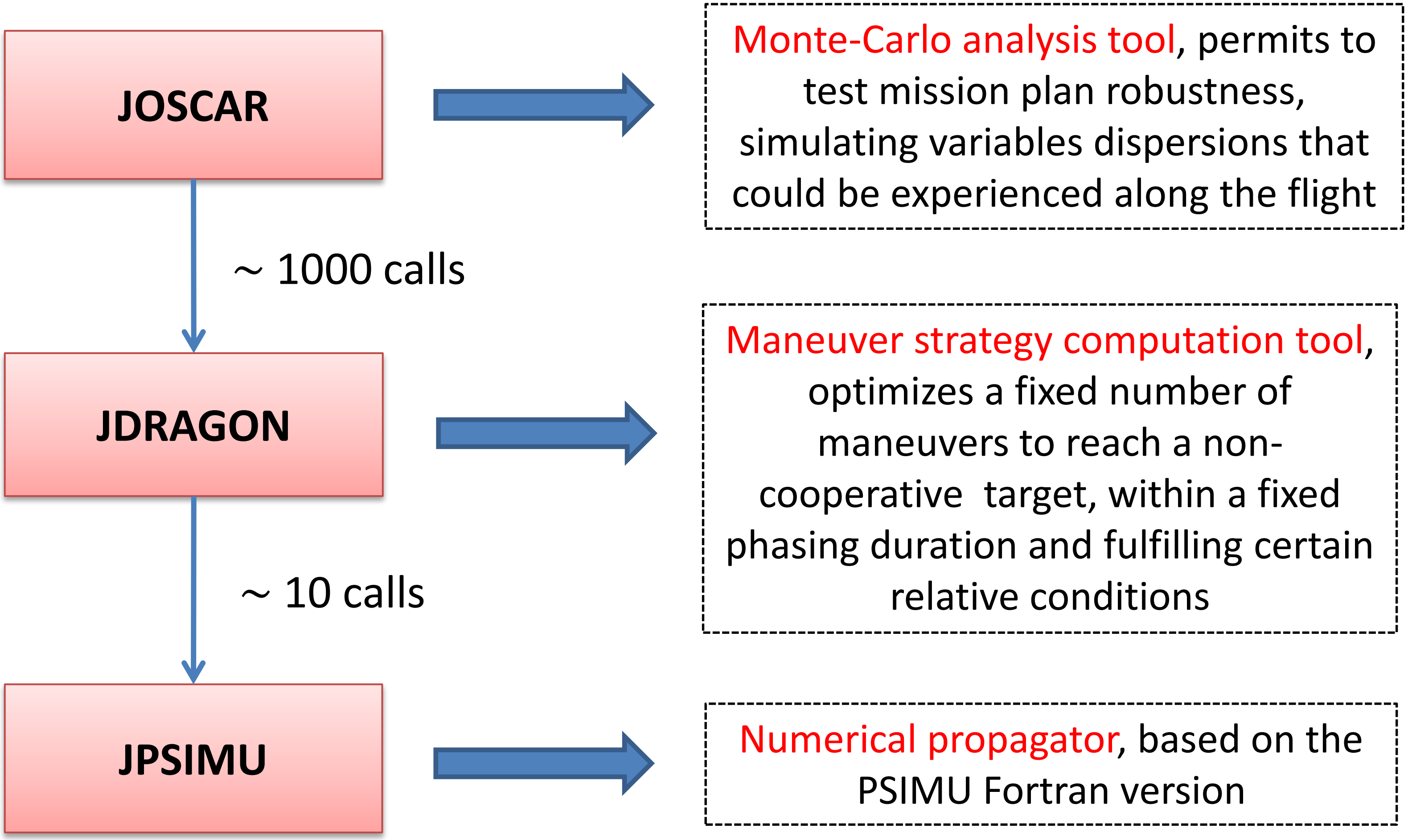


  - GALILEO missions (2011-today)
    - Operational design of LEOP (Launch and Early Orbit Phase), phasing and rendezvous scenarios
    - Compliant with quality and operational constraints → directly integrated into the Flight Dynamics Centre

- Decision to use JAVA technology → SIRIUS project [2]: basic software layout (PATRIUS) and operational tools (FDS) already started.

- JDRAGON/JOSCAR: not a simple porting from Fortran to JAVA, but redefinition of certain functionalities!

INTRODUCTION



JOSCAR

~ 1000 calls

JDRAGON

~ 10 calls

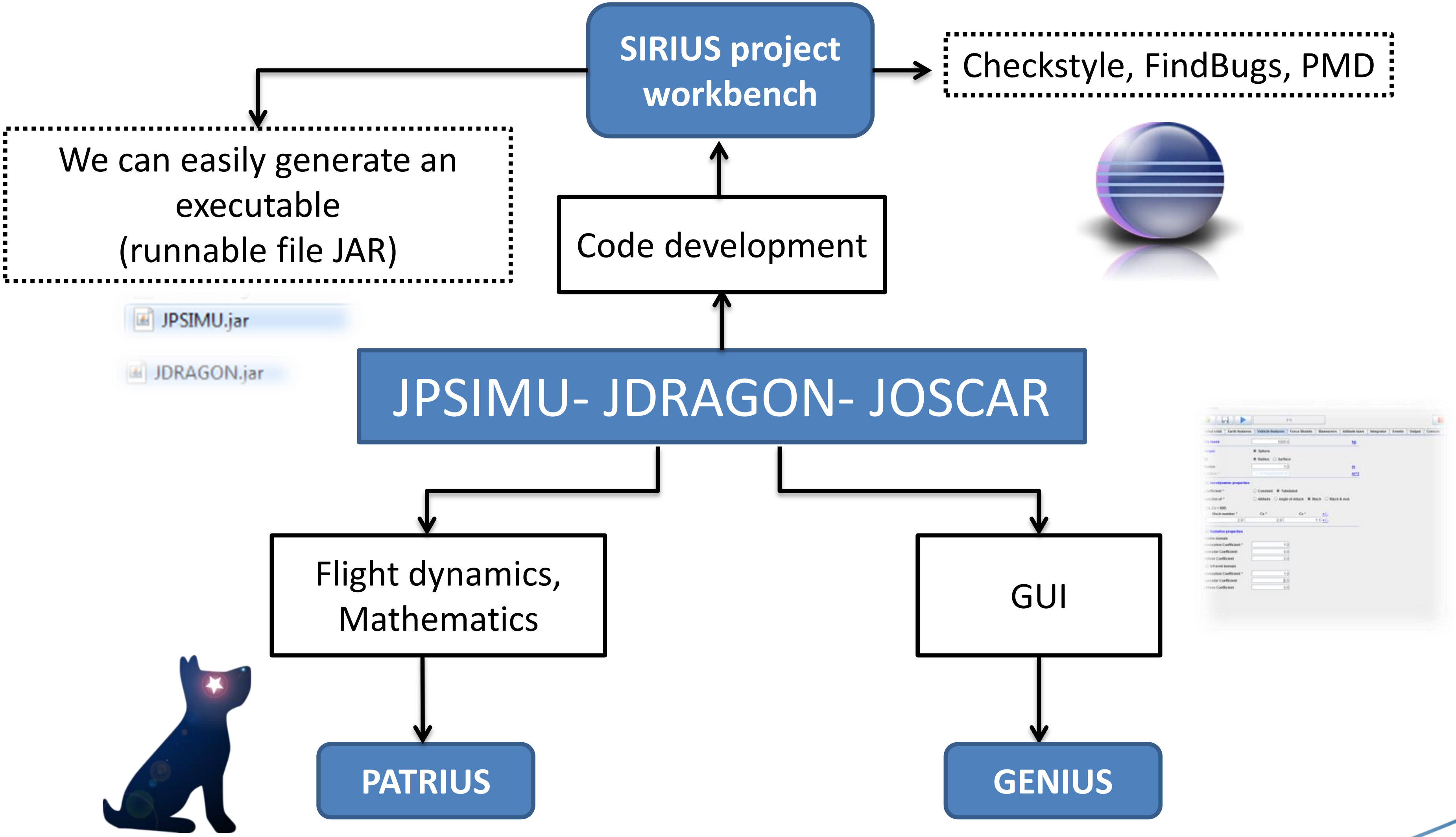
JPSIMU

Monte-Carlo analysis tool, permits to test mission plan robustness, simulating variables dispersions that could be experienced along the flight

Maneuver strategy computation tool, optimizes a fixed number of maneuvers to reach a non-cooperative target, within a fixed phasing duration and fulfilling certain relative conditions

Numerical propagator, based on the PSIMU Fortran version

DEVELOPMENT ENVIRONMENT



SIRIUS project workbench

Checkstyle, FindBugs, PMD

We can easily generate an executable (runnable file JAR)

JPSIMU.jar

JDRAGON.jar

Code development

JPSIMU- JDRAGON- JOSCAR

Flight dynamics, Mathematics

GUI

PATRIUS

GENIUS

DEVELOPMENT ENVIRONMENT

PATRIUS [3]

(PATrimoine de base de siRIUS)

Mathematics: Dispersions, Matrices, Rotations, Interpolations, Geometry, Numerical Integration

Flight dynamics: Time, Orbits, Frames, Celestial Bodies, SpacecraftState

Attitude: Attitude Laws, Kinematics, Transformations, Guidance Commands, Slew

Orbit Determination: Propagation, Physical Models, Measure and Filtering

Spacecraft: Assembly, Sensors, Mass and Forces

Mission: Events Detection, Maneuvers, Postprocessing

GENIUS

(Generation of Interface for Users of Scientific S/W)

- Units management
- Performing conditional display
- Simplified approach, in particular about events , management (setting actions before/after a certain event is reached)
- Read/write for files directly integrated
- Process management compatible in all OS (thanks to JAVA)

Orbit *
Date: 01/01/2000 00h00m00s UTC
Frame: GCRF
Type: Equinoctial
Equinoctial Parameters *
a: * 7000.0 km
ex: * 0.0
ey: * 0.0
hx: * 0.0
hy: * 0.0
Longitude: * true 0.0 deg
μ: 398600.4415 km^3/s^2

JPSIMU: THE NUMERICAL PROPAGATOR

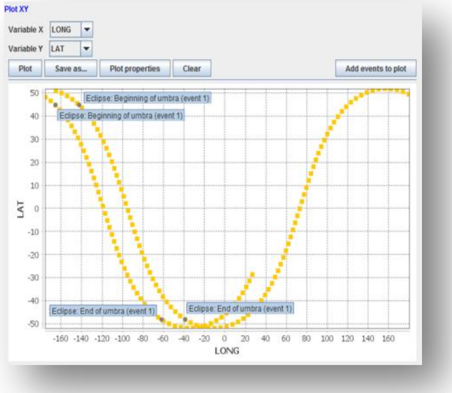
Extrapolate the orbit around the Earth

- Taking into account different forces:
  - Earth potential
  - Third body perturbations
  - Aerodynamic forces
  - Solar Radiation Pressure
  - Ocean/Terrestrial tides
- Defining a maneuver sequence
- Defining an attitude sequence
- Using different numerical integrators
- Identifying orbital events

Frames configuration management

From	To	Phenomena	Corrections
GCRF	**CIRF**	Earth rotation axis around Ecliptic pole	Precession, Nutation
CIRF	**TIRF**	Diurnal motion	UT1-UTC difference
TIRF	**ITRF**	Earth rotation axis wrt Earth's crust	Tides, libration, S' effects, EOPs

Event detectors



Plot XY

Variable X LONG

Variable Y LAT

Eclipse: Beginning of umbra (event 1)

Eclipse: Beginning of umbra (event 1)

Eclipse: End of umbra (event 1)

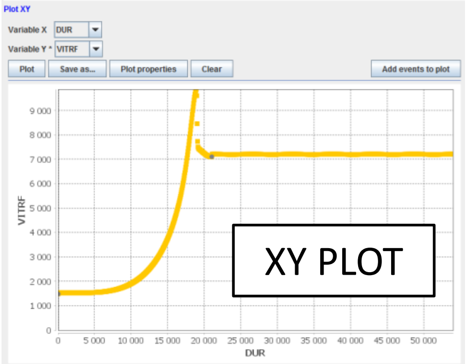
Eclipse: End of umbra (event 1)

- To stop propagation
- To switch between attitude laws
- To trigger impulsive maneuvers
- To define the beginning/end of spread maneuvers
- To identify orbital events of interest: ascending/descending nodes, station visibilities, entering/existing eclipse, AOLs, …

JPSIMU: THE NUMERICAL PROPAGATOR

Utilization modes

- Subroutine mode (called from JDRAGON): Containing the pure tool computations
- Batch mode: Read a configuration file (".xml") and calls the subroutine mode
- GUI mode: Graphical User Interface permits to create scenarios and launch computations (via the batch mode)
  - Output: +80 variables, ephemeris & detected events files (".txt")


Plot XY

Variable X: DUR

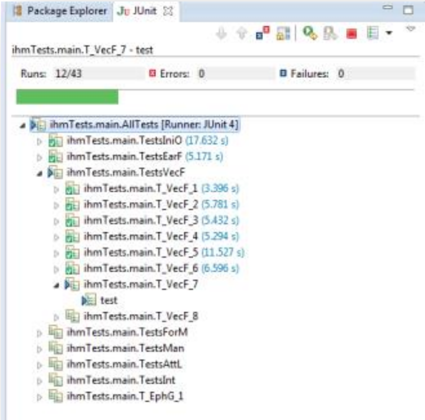
Variable Y *: VITRF

XY PLOT

Validation

- Battery of tests validating ephemeris generation (coverage > 80%):
  - Thematic validation: 42 test performed, divided in 7 different tests: initial orbit, earth features/frames configuration, vehicle, force models, maneuver scenario, attitude laws and integrator
  - GUI mode validation

JUNIT



ihmTests.main.T_VecF_7 - test

Runs: 12/43 Errors: 0 Failures: 0

```
ihmTests.main.AllTests [Runner: JUnit 4]
  ihmTests.main.TestsIniO (17.632 s)
  ihmTests.main.TestsEarF (5.171 s)
  ihmTests.main.TestsVecF
    ihmTests.main.T_VecF_1 (3.396 s)
    ihmTests.main.T_VecF_2 (5.781 s)
    ihmTests.main.T_VecF_3 (5.432 s)
    ihmTests.main.T_VecF_4 (5.294 s)
    ihmTests.main.T_VecF_5 (11.527 s)
    ihmTests.main.T_VecF_6 (6.596 s)
    ihmTests.main.T_VecF_7
      test
    ihmTests.main.T_VecF_8
  ihmTests.main.TestsForM
  ihmTests.main.TestsMan
  ihmTests.main.TestsAttL
  ihmTests.main.TestsInt
  ihmTests.main.T_EphG_1
```

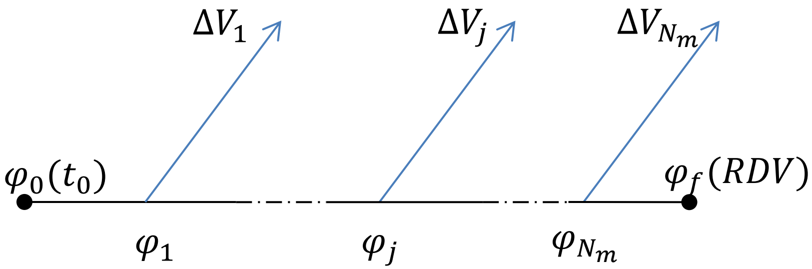
- Code's quality tests: compliant with CNES coding standard rules
  - FindBugs, Checkstyle

JDRAGON: COMPUTING MANEUVERS

Problem statement

Find $x := \left\{\overrightarrow{\Delta V_j}, \varphi_j\right\}_{j=1,N_m}$

To minimize $J(x) := \sum_{j=1}^{N_m} \left|\overrightarrow{\Delta V_j}\right|$



With :

- $\overrightarrow{\Delta V_j}$: Maneuver *j* to optimize
- φ_j: Maneuver location → $2\pi\left(N_{ch}^j - 1\right) + \alpha_j$

  $\varphi_j := 2\pi\left(N_{ch}^j - 1\right) + \alpha_j$
  N_{ch}^j: orbit number
  α_j: argument of latitude
- N_m: # Maneuvers to optimize
- T: « Real world » propagation
- V_{aim}: Aimed vector

Constraints

$\mathbf{C_0}$, the rendezvous condition:

- $E_{ta}(t_f) + V_{aim} = T\left(\overrightarrow{\Delta V_j}, \varphi_j, E_{ch}(t_0)\right) j = 1, N_m$

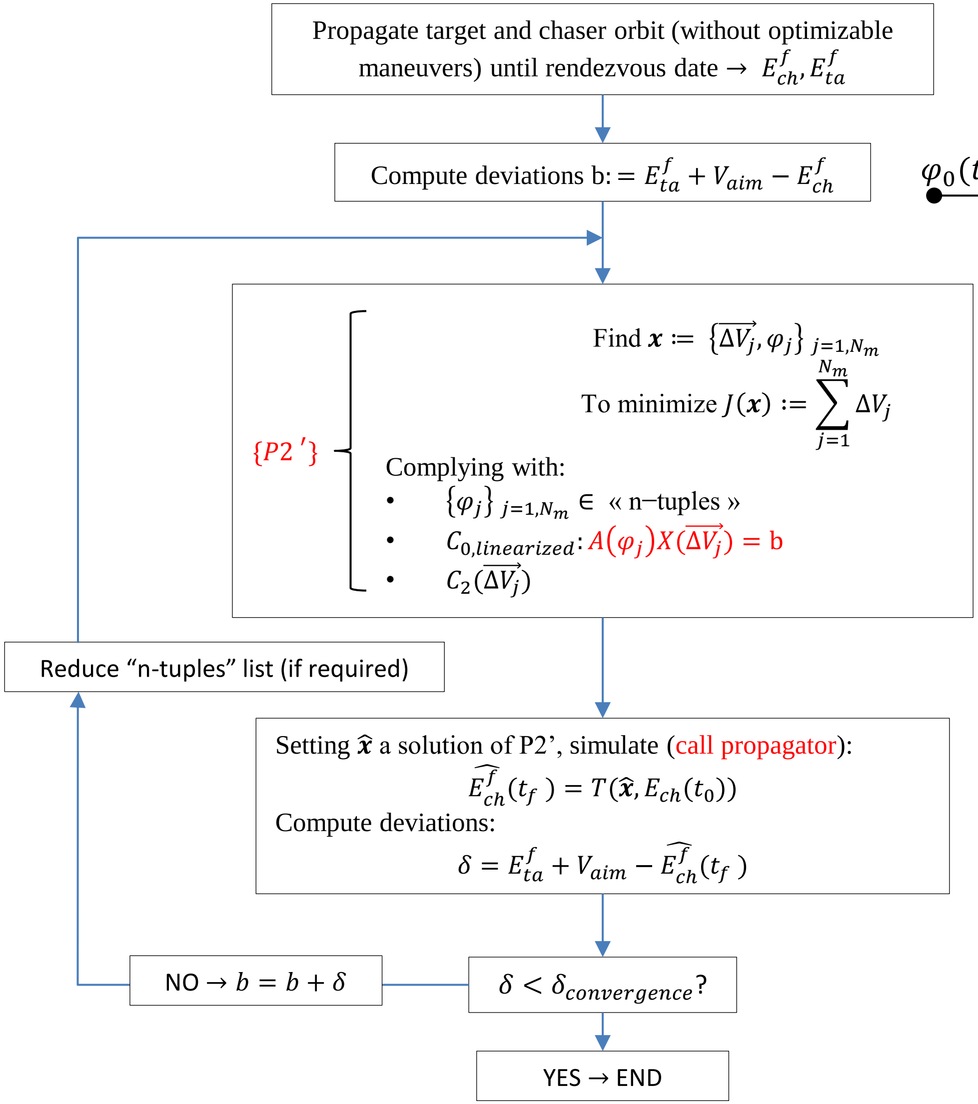
$\mathbf{C_1}(\varphi_j)$, location limitations:

- $\varphi_j \in (\varphi_j{}^{min}, \varphi_j{}^{max})$
- $\varphi_{j+1} - \varphi_j \in \left[\Delta\varphi_j{}^{min}, \Delta\varphi_j{}^{max}\right]$

$\mathbf{C_2}(\overrightarrow{\Delta V_j})$, module limitations:

- $\Delta V_j \in [\Delta V_j{}^{min}, \Delta V_j{}^{max}]$
- $R_j, T_j, N_j \in \left[Val_j{}^{min}, Val_j{}^{max}\right]$

JDRAGON: COMPUTING MANEUVERS



Propagate target and chaser orbit (without optimizable maneuvers) until rendezvous date → E_{ch}^f, E_{ta}^f

Compute deviations b: $= E_{ta}^f + V_{aim} - E_{ch}^f$

$\{P2'\}$

Find $\boldsymbol{x} := \{\overrightarrow{\Delta V_j}, \varphi_j\}_{j=1,N_m}$

To minimize $J(\boldsymbol{x}) := \sum_{j=1}^{N_m} \Delta V_j$

Complying with:

- $\{\varphi_j\}_{j=1,N_m} \in$ « n–tuples »
- $C_{0,linearized}$: $A(\varphi_j)X(\overrightarrow{\Delta V_j}) = \mathrm{b}$
- $C_2(\overrightarrow{\Delta V_j})$

Setting $\hat{\boldsymbol{x}}$ a solution of P2’, simulate (call propagator):

$$\widehat{E_{ch}^f}(t_f) = T(\hat{\boldsymbol{x}}, E_{ch}(t_0))$$

Compute deviations:

$$\delta = E_{ta}^f + V_{aim} - \widehat{E_{ch}^f}(t_f)$$

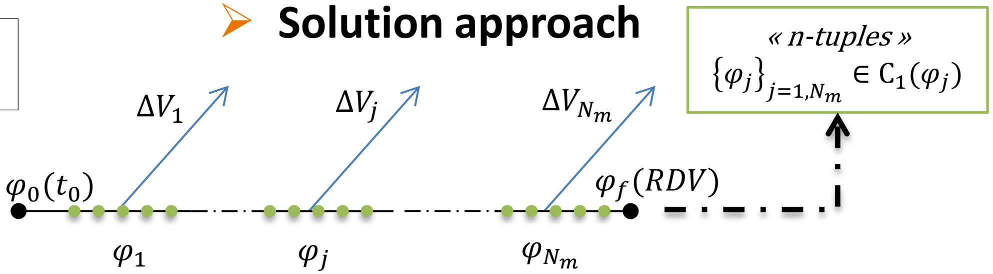
$\delta < \delta_{convergence}$?

NO → $b = b + \delta$

Reduce “n-tuples” list (if required)

YES → END

Solution approach



{P2’} requires solving a linear problem $AX = b$ iteratively, with $A \in \mathbb{R}^{n_e \, x \, m}, X \in \mathbb{R}^m, b \in \mathbb{R}^{n_e}$:

- #Unknowns: $m = \sum_{j=1}^{N_m} N_{c_j}, N_{c_j} \in \{1,2,3\}$
- #Equations: n_e

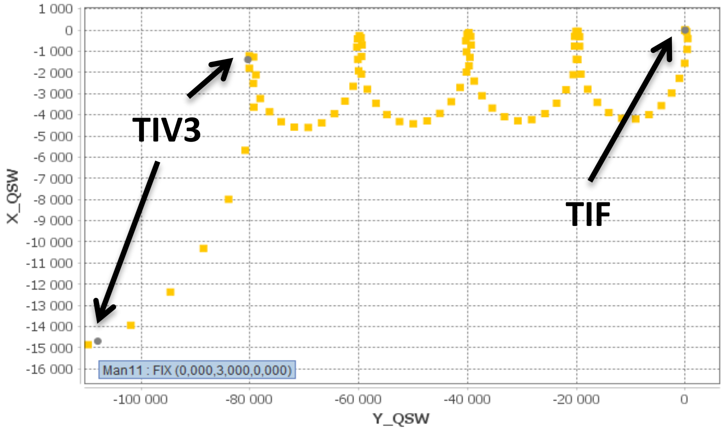
Linear System type	# Solutions	Resolution method
Undetermined ($\mathbf{n_e} > \mathbf{m}$)	0	Least Squares
Determined ($\mathbf{n_e} = \mathbf{m}$)	1	System Inversion
Overdetermined ($\boldsymbol{n_e} < \boldsymbol{m}$)	∞	Pseudo-Inverse & Minimization of sum of norms

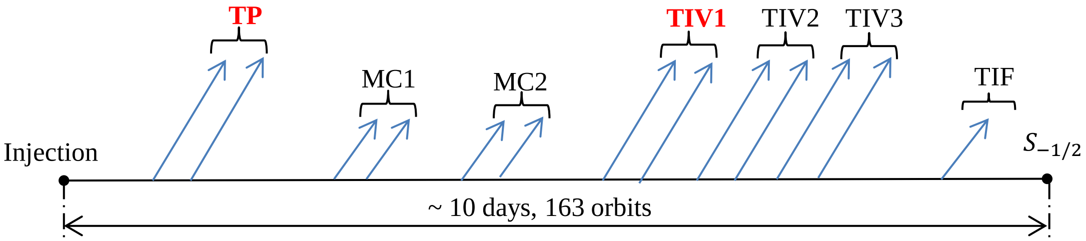
Problem types	Parameters	# Equations (n_e)
Transfer 2D	a, e_x, e_y	3
Rendezvous 2D	a, e_x, e_y, τ	4
Transfer 3D	a, e_x, e_y, i, Ω	5
Rendezvous 3D	$a, e_x, e_y, \tau, i, \Omega$	6

JDRAGON: COMPUTING MANEUVERS (DEMO)

Example: ATV3-Johannes Kepler

Problem type: Rendezvous 3D
Unknowns: 6 (TP and TV1)





Classical Approach (TN-TN-T-T strategy)

Method	System inversion
“n-tuples”	194481
#JPSIMU calls	8
Total DV (m/s)	**55.27**
CPU time including ephemeris generation	1min 54s

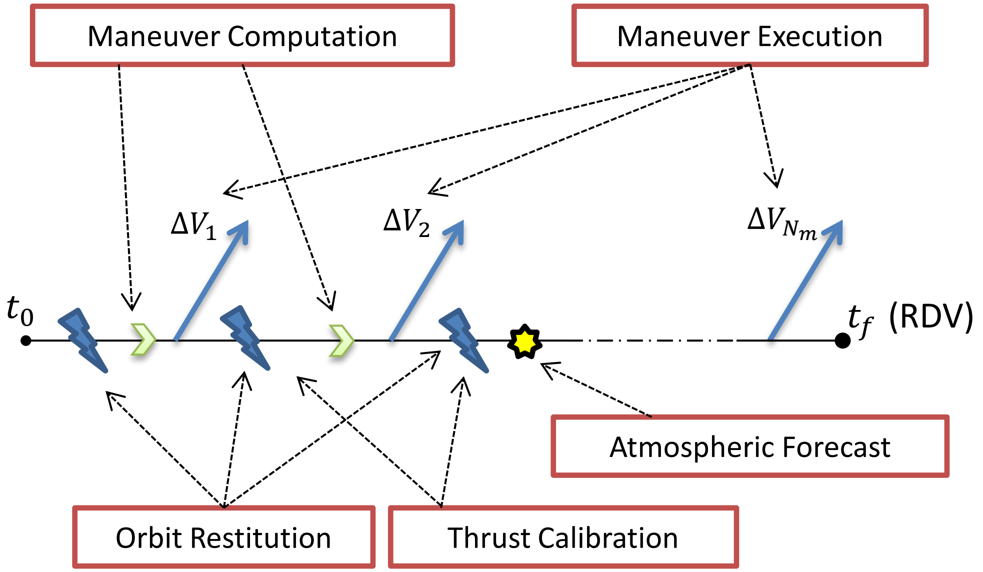
(TN-TN-TN-TN strategy)

Method	Pseudo-Inverse	Min sum norms
Min criterion	$\sum_{j=1}^{N_m} \left\|\overrightarrow{\Delta V_j}\right\|^2$	$\sum_{j=1}^{N_m} \left\|\overrightarrow{\Delta V_j}\right\|$
“n-tuples”	194481	28561
#JPSIMU calls	7	7
Total DV (m/s)	**55.04**	**55.03**
CPU time	2min	3min 11s

JOSCAR: END-END SIMULATIONS

- Objective: Perform Monte-Carlo simulations → Testing maneuver strategy robustness

Time consuming : Many calls to JPSIMU, JDRAGON are required !



Maneuver Computation

Maneuver Execution

Atmospheric Forecast

Orbit Restitution

Thrust Calibration

ATV-CC (Toulouse, France)

Real world: real parameters (forces models, engines performance, vehicle features, …). They are generated by dispersion (gaussian, uniform)

vs

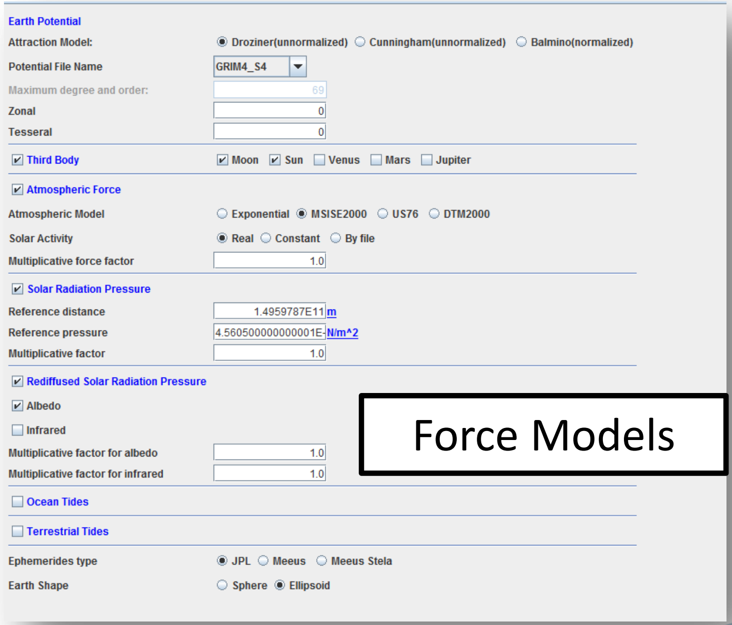
Predicted world: lack of knowledge of the real world (chaser/target restituted orbits, engines calibrations, atmospheric forecasts,…)

JOSCAR: END-END SIMULATIONS

- Genoscar → Defining the variables to disperse and the End-to-End scenario to be simulated:
  - Chaser orbit restitution
  - Target localization
  - Thrusters calibration
  - Maneuver computation
  - Rendezvous point change
  - Sequence of maneuvers
  - Atmospheric forecast

File (".xml) containing **random variables**

- Exoscar → Defining data required for the simulation propagation:
  - Chaser/Target vehicle
  - Force Models
  - Attitude Sequence
  - Output files of interest



Earth Potential

Attraction Model: ● Droziner(unnormalized) ○ Cunningham(unnormalized) ○ Balmino(normalized)

Potential File Name: GRIM4_S4

Maximum degree and order: 69

Zonal: 0

Tesseral: 0

☑ Third Body: ☑ Moon ☑ Sun ☐ Venus ☐ Mars ☐ Jupiter

☑ Atmospheric Force

Atmospheric Model: ○ Exponential ● MSISE2000 ○ US76 ○ DTM2000

Solar Activity: ● Real ○ Constant ○ By file

Multiplicative force factor: 1.0

☑ Solar Radiation Pressure

Reference distance: 1.4959787E11 m

Reference pressure: 4.560500000000001E- N/m^2

Multiplicative factor: 1.0

☑ Rediffused Solar Radiation Pressure

☑ Albedo

☐ Infrared

Multiplicative factor for albedo: 1.0

Multiplicative factor for infrared: 1.0

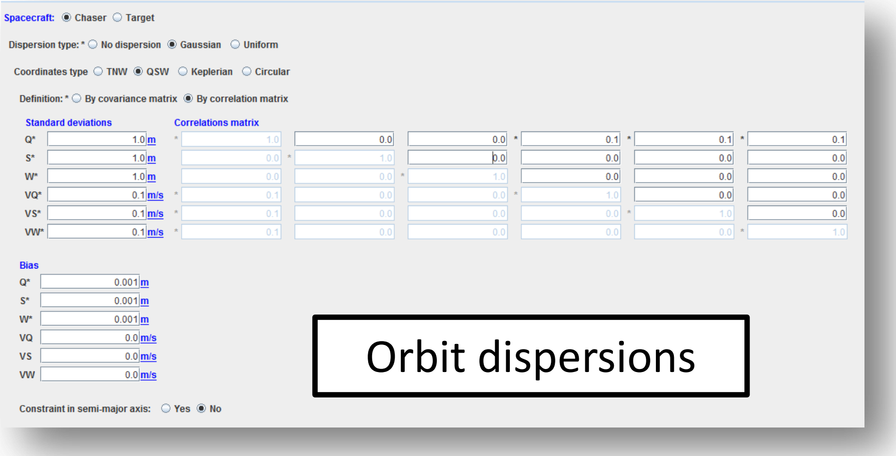
☐ Ocean Tides

☐ Terrestrial Tides

Ephemerides type: ● JPL ○ Meeus ○ Meeus Stela

Earth Shape: ○ Sphere ● Ellipsoid

Force Models



Spacecraft: ● Chaser ○ Target

Dispersion type: * ○ No dispersion ● Gaussian ○ Uniform

Coordinates type ○ TNW ● QSW ○ Keplerian ○ Circular

Definition: * ○ By covariance matrix ● By correlation matrix

	Standard deviations	Correlations matrix					
Q*	1.0 m	* 1.0	0.0	0.0	* 0.1	* 0.1	* 0.1
S*	1.0 m	0.0	* 1.0	0.0	0.0	0.0	0.0
W*	1.0 m	0.0	0.0	* 1.0	0.0	0.0	0.0
VQ*	0.1 m/s	* 0.1	0.0	0.0	* 1.0	0.0	0.0
VS*	0.1 m/s	* 0.1	0.0	0.0	0.0	* 1.0	0.0
VW*	0.1 m/s	* 0.1	0.0	0.0	0.0	0.0	* 1.0

Bias

Q*	0.001	m
S*	0.001	m
W*	0.001	m
VQ	0.0	m/s
VS	0.0	m/s
VW	0.0	m/s

Constraint in semi-major axis: ○ Yes ● No

Orbit dispersions

CONCLUSIONS

- Initial difficulties:
  - Validation: JPSIMU has been strongly validated against PATRIUS. JDRAGON validated against DRAGON for different phasing problems (ATV, GALILEO, Mango-Picard,..) obtaining same delta-V budgets (±1mm/s).
  - Performance: Expected penalty x2 (wrt Fortran) has been retrieved. For typical RDV scenarios (ATV, GALILEO), computations last from 1 to 2 min → Acceptable.
- JAVA porting advantages:
  - Faster development: Easier to write, compile and debug than other programming languages.
  - Object-oriented: Modular programs and reusable codes.
  - Platform-independent: Always same results (Windows, Linux, …).
  - Robustness: Early checking for possible errors. Many problems are detected in advance!
  - GUI: Its development has been easier thanks to GENIUS and its simplified approach.
  - New features have been proposed: After 20 years usage feedback, obsolete functionalities have been erased, new improvements have been implemented!

Thank you for your attention! Questions?

REFERENCES

- [1] P. Labourdette, A. Gaudel-Vacaresse, D.Carbonne *« Oscar/Dragon: Tools for maneuver strategy computation »,* 5th International Conference on Astrodynamics Tools and Techniques, ESTEC/ESA, The Netherlands, 29 May – 1 June 2012

- [2] I. Llamas, Y. Tanguy, M. Lacotte, J.J. Wasbauer *« SIRIUS-DV: Then new Flight Dynamics algorithms for the future CNES missions »*, 6th International Conference on Astrodynamics Tools and Techniques, Darmstadt, Germany, 14-17 Mars 2016

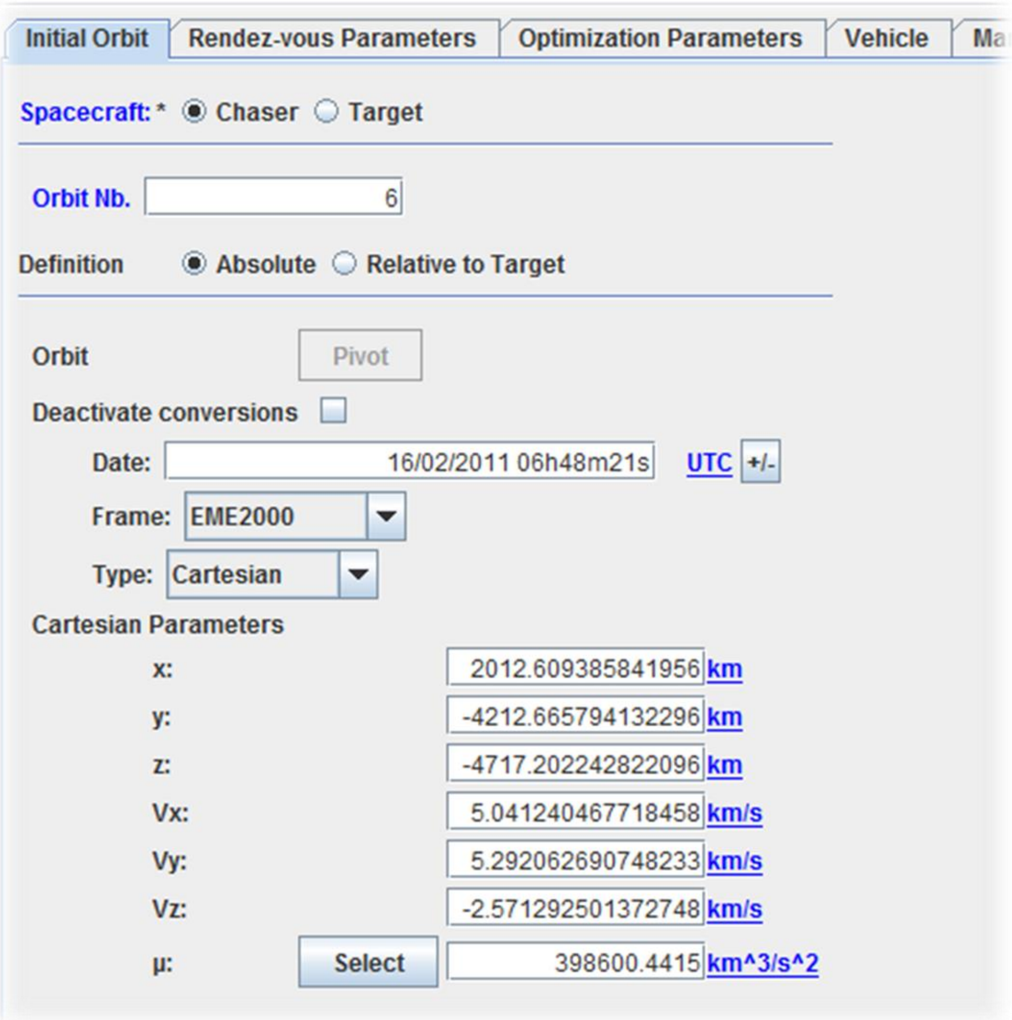
- [3] D. Carbonne, Y. Tanguy *« The SIRIUS Flight Dynamics Library for the next 25 years ».* 5th International Conference on Astrodynamics Tools and Techniques, ESTECT/ESA, The Netherlands, 29 May – 1 June 2012

SCREENSHOTS (DEMO)

Initial orbit definition

- Timescales
  - UTC, TAI, TT, GPS, GST
- Frames
  - GCRF, CIRF, …
- Orbital parameters
  - Keplerian
  - Cartestian
  - Circular
  - Equinoctial
  - Equatorial
  - Apogee/Perigee
  - Reentry parameters

*Relative to target also possible



Spacecraft: * ● Chaser ○ Target

Orbit Nb. 6

Definition ● Absolute ○ Relative to Target

Orbit

Deactivate conversions ☐

Date: 16/02/2011 06h48m21s UTC +/-

Frame: EME2000

Type: Cartesian

Cartesian Parameters

x: 2012.609385841956 km

y: -4212.665794132296 km

z: -4717.202242822096 km

Vx: 5.041240467718458 km/s

Vy: 5.292062690748233 km/s

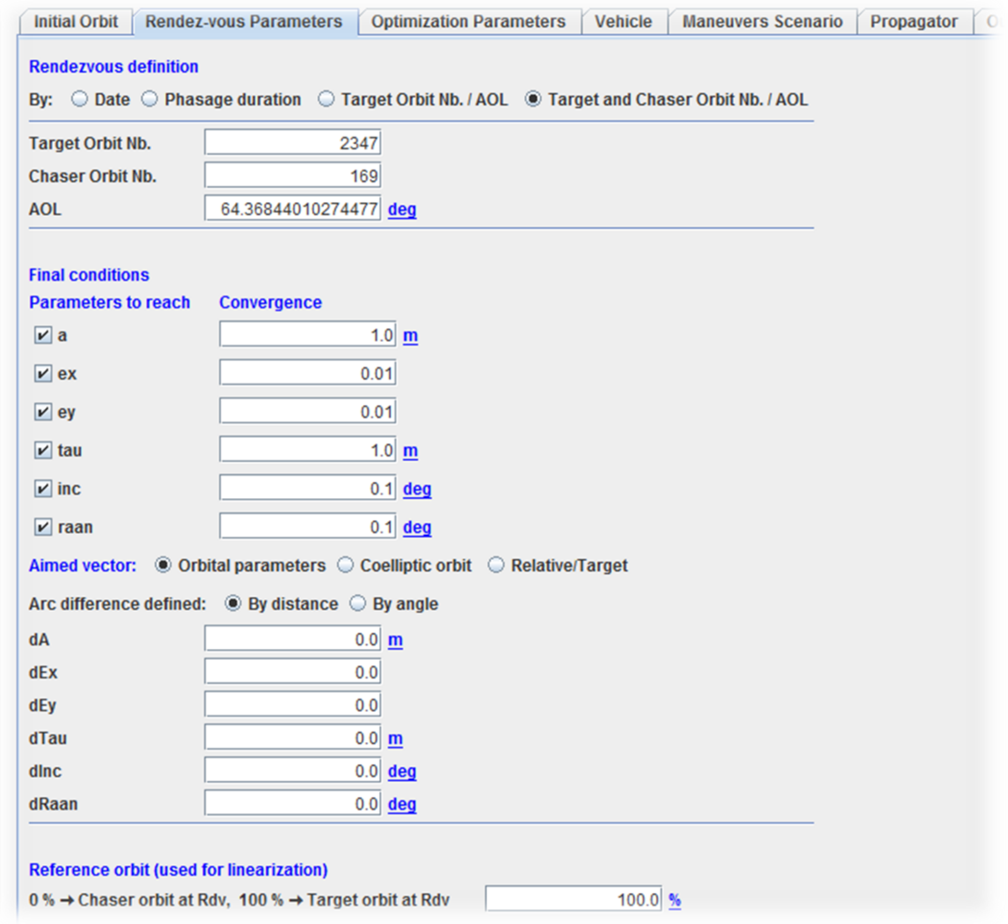
Vz: -2.571292501372748 km/s

μ: 398600.4415 km^3/s^2

SCREENSHOTS (DEMO)

Rendezvous Parameters

- Rendezvous definition
  - By date
  - By phasing duration
  - Target Orbit Nb./AOL
  - Target/Chaser Orbit Nb./ AOL
- Parameters to reach
- Convergence threshold
- Aimed vector
  - Orbital parameters
  - Coelliptic orbit
  - Relative/Target (LVLH)
- Reference orbit (linearization)



Rendezvous definition

By: ○ Date ○ Phasage duration ○ Target Orbit Nb. / AOL ● Target and Chaser Orbit Nb. / AOL

Target Orbit Nb. 2347

Chaser Orbit Nb. 169

AOL 64.36844010274477 deg

Final conditions

Parameters to reach	Convergence
☑ a	1.0 m
☑ ex	0.01
☑ ey	0.01
☑ tau	1.0 m
☑ inc	0.1 deg
☑ raan	0.1 deg

Aimed vector: ● Orbital parameters ○ Coelliptic orbit ○ Relative/Target

Arc difference defined: ● By distance ○ By angle

dA	0.0 m
dEx	0.0
dEy	0.0
dTau	0.0 m
dInc	0.0 deg
dRaan	0.0 deg

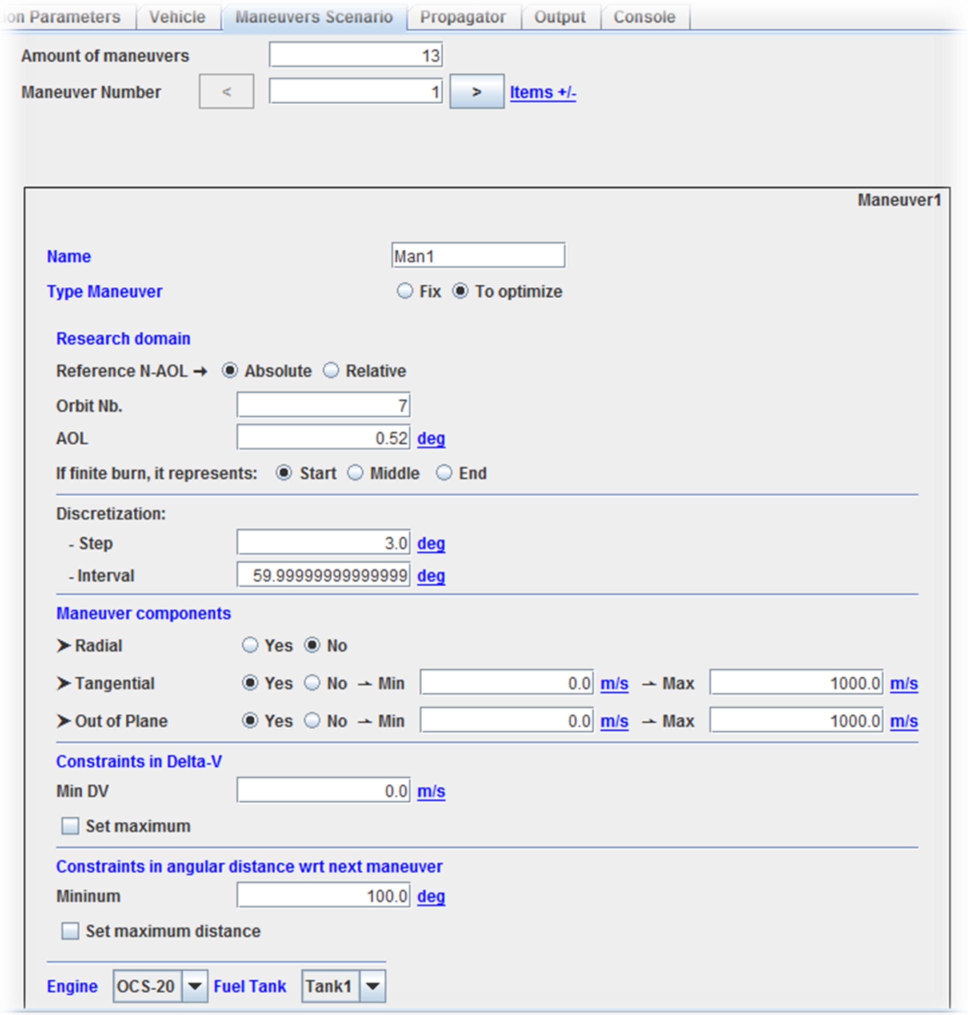
Reference orbit (used for linearization)

0 % → Chaser orbit at Rdv, 100 % → Target orbit at Rdv 100.0 %

SCREENSHOTS (DEMO)

Maneuvers scenario

- Engines
  - Name
  - ISP
  - Thrust
- Fuel tanks
  - Name
  - Thrust
- Maneuvers to optimize
  - Location research domain
  - Components to optimize
  - Constraints in DV
  - Constraints in angular distance
- Trim maneuvers (fixed in value and location)



Amount of maneuvers 13

Maneuver Number 1

Maneuver1

Name Man1

Type Maneuver ○ Fix ● To optimize

Research domain

Reference N-AOL → ● Absolute ○ Relative

Orbit Nb. 7

AOL 0.52 deg

If finite burn, it represents: ● Start ○ Middle ○ End

Discretization:

- Step 3.0 deg
- Interval 59.99999999999999 deg

Maneuver components

➤ Radial ○ Yes ● No

➤ Tangential ● Yes ○ No → Min 0.0 m/s → Max 1000.0 m/s

➤ Out of Plane ● Yes ○ No → Min 0.0 m/s → Max 1000.0 m/s

Constraints in Delta-V

Min DV 0.0 m/s

☐ Set maximum

Constraints in angular distance wrt next maneuver

Mininum 100.0 deg

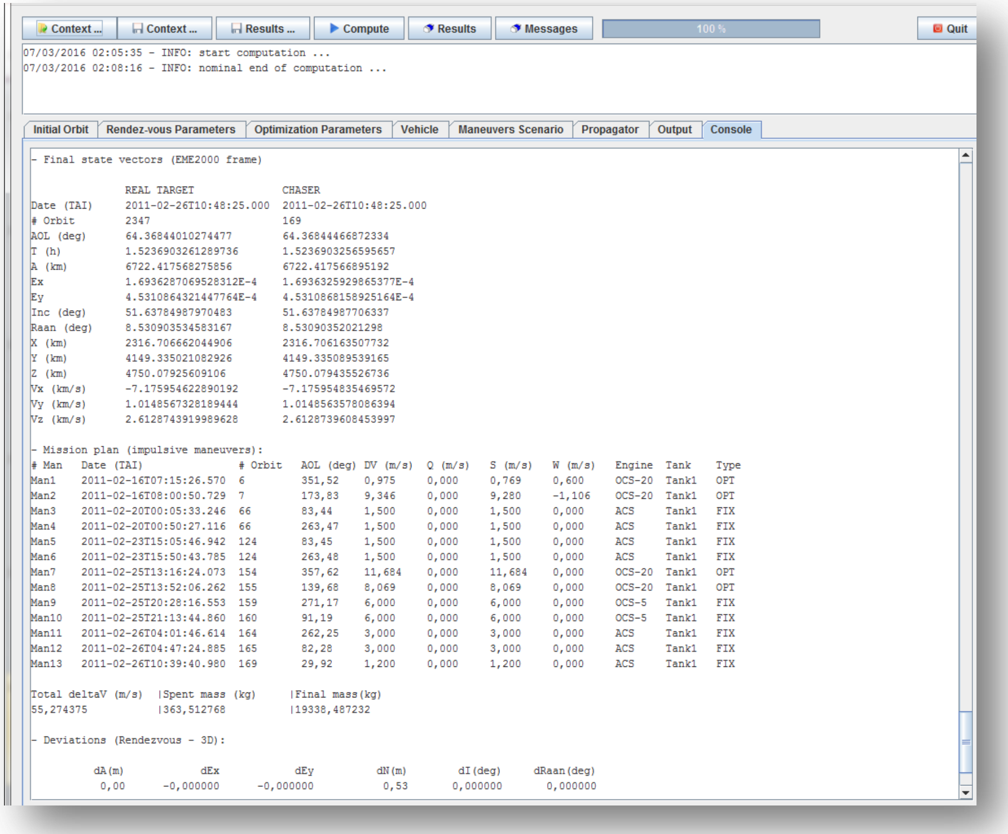
☐ Set maximum distance

Engine OCS-20 Fuel Tank Tank1

SCREENSHOTS (DEMO)

Output

- Output files
  - Synthesis file
  - Relative ephemeris
  - Target ephemeris
  - Chaser ephemeris
- Plot XY
  - Duration
  - Chaser orbital parameters (target LVLH, QSW)
- Intermediate results
  - Progress bar
  - Remaining “n-tuples”
  - Mission plans
  - Orbital parameters deviations



```
07/03/2016 02:05:35 - INFO: start computation ...
07/03/2016 02:08:16 - INFO: nominal end of computation ...
```

```
- Final state vectors (EME2000 frame)

               REAL TARGET              CHASER
Date (TAI)     2011-02-26T10:48:25.000  2011-02-26T10:48:25.000
# Orbit        2347                     169
AOL (deg)      64.36844010274477        64.36844466872334
T (h)          1.5236903261289736       1.5236903256595657
A (km)         6722.417568275856        6722.417566895192
Ex             1.6936287069528312E-4    1.6936325929865377E-4
Ey             4.5310864321447764E-4    4.5310868158925164E-4
Inc (deg)      51.63784987970483        51.63784987706337
Raan (deg)     8.530903534583167        8.53090352021298
X (km)         2316.706662044906        2316.706163507732
Y (km)         4149.335021082926        4149.335089539165
Z (km)         4750.07925609106         4750.079435526736
Vx (km/s)      -7.175954622890192       -7.175954835469572
Vy (km/s)      1.0148567328189444       1.0148563578086394
Vz (km/s)      2.6128743919989628       2.6128739608453997

- Mission plan (impulsive maneuvers):
# Man   Date (TAI)               # Orbit   AOL (deg) DV (m/s)   Q (m/s)    S (m/s)    W (m/s)    Engine  Tank    Type
Man1    2011-02-16T07:15:26.570  6         351,52    0,975      0,000      0,769      0,600      OCS-20  Tank1   OPT
Man2    2011-02-16T08:00:50.729  7         173,83    9,346      0,000      9,280      -1,106     OCS-20  Tank1   OPT
Man3    2011-02-20T00:05:33.246  66        83,44     1,500      0,000      1,500      0,000      ACS     Tank1   FIX
Man4    2011-02-20T00:50:27.116  66        263,47    1,500      0,000      1,500      0,000      ACS     Tank1   FIX
Man5    2011-02-23T15:05:46.942  124       83,45     1,500      0,000      1,500      0,000      ACS     Tank1   FIX
Man6    2011-02-23T15:50:43.785  124       263,48    1,500      0,000      1,500      0,000      ACS     Tank1   FIX
Man7    2011-02-25T13:16:24.073  154       357,62    11,684     0,000      11,684     0,000      OCS-20  Tank1   OPT
Man8    2011-02-25T13:52:06.262  155       139,68    8,069      0,000      8,069      0,000      OCS-20  Tank1   OPT
Man9    2011-02-25T20:28:16.553  159       271,17    6,000      0,000      6,000      0,000      OCS-5   Tank1   FIX
Man10   2011-02-25T21:13:44.860  160       91,19     6,000      0,000      6,000      0,000      OCS-5   Tank1   FIX
Man11   2011-02-26T04:01:46.614  164       262,25    3,000      0,000      3,000      0,000      ACS     Tank1   FIX
Man12   2011-02-26T04:47:24.885  165       82,28     3,000      0,000      3,000      0,000      ACS     Tank1   FIX
Man13   2011-02-26T10:39:40.980  169       29,92     1,200      0,000      1,200      0,000      ACS     Tank1   FIX

Total deltaV (m/s)  |Spent mass (kg)     |Final mass(kg)
55,274375           |363,512768          |19338,487232

- Deviations (Rendezvous - 3D):

          dA(m)         dEx           dEy          dN(m)      dI(deg)   dRaan(deg)
           0,00   -0,000000     -0,000000           0,53     0,000000     0,000000
```