Ecole d'Eté 2016

Trajectoires planétaires et interplanétaires

Détermination d'orbite à bord d'un CubeSat interplanétaire

- étude de sensibilité (en cours) -

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C²ERES, Centre et Campus de Recherche pour l'Exploration Spatiale

On-board Orbit Determination for a Deep-Space CubeSat

- sensitivity study (running) -

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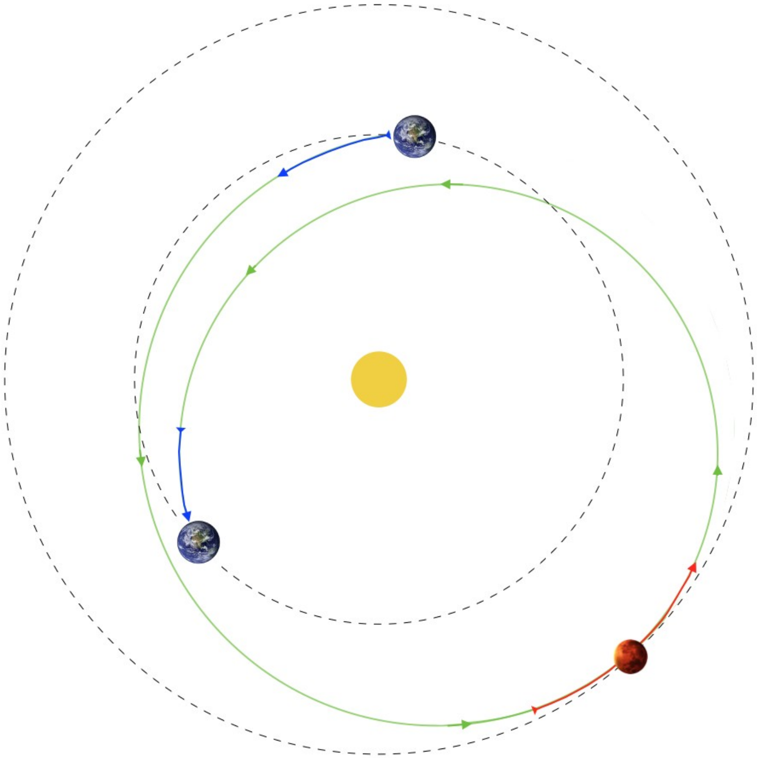
LESIA, PSL / Paris Observatory : Gary Quinsac
D.A.A, N.C.K.U., Taiwan : Tristan Mallet, Jordan Vannitsen, Jiun-Jih Miau
IMCCE, PSL / Paris Observatory : Daniel Hestroffer, Florent Deleflie

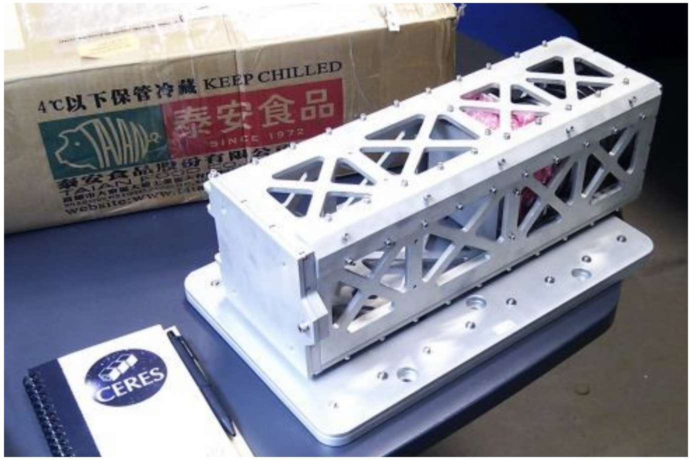
Context

1. <u>Context</u>
2. Method
3. Simulation results
4. Lessons learned

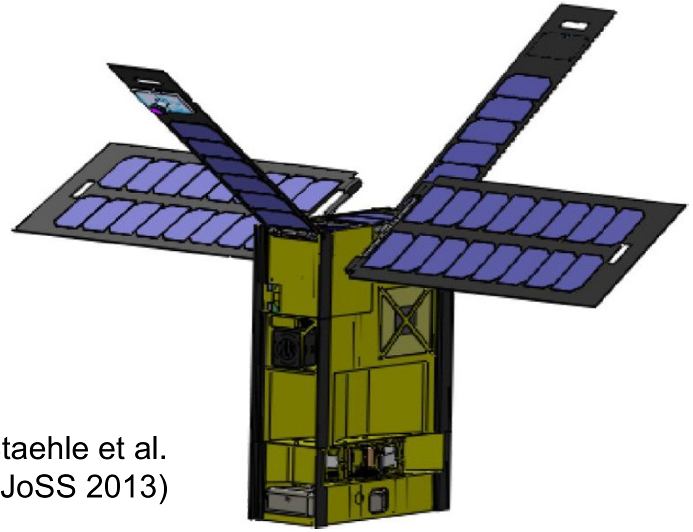


What is a CubeSat?

1U, 2U… question of deployer

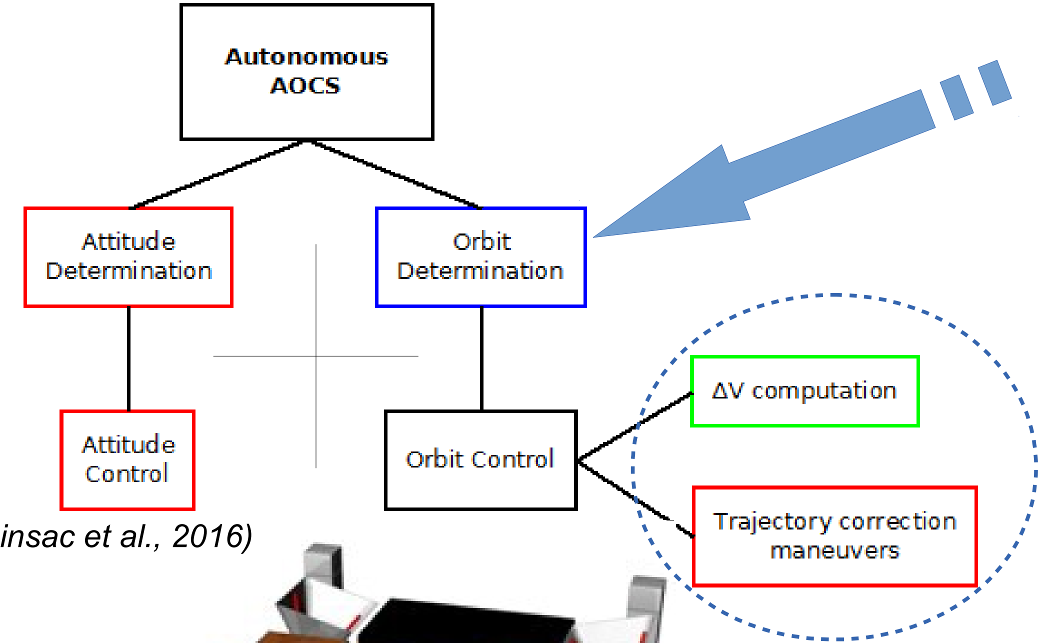


6U vs. 3U for an interplanetary CubeSat



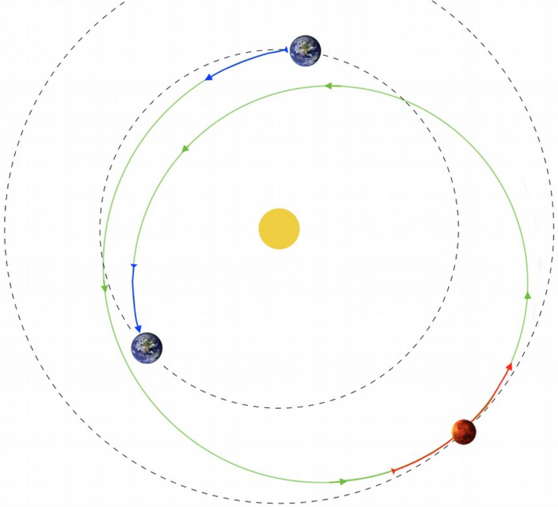
Staehle et al. (JoSS 2013)

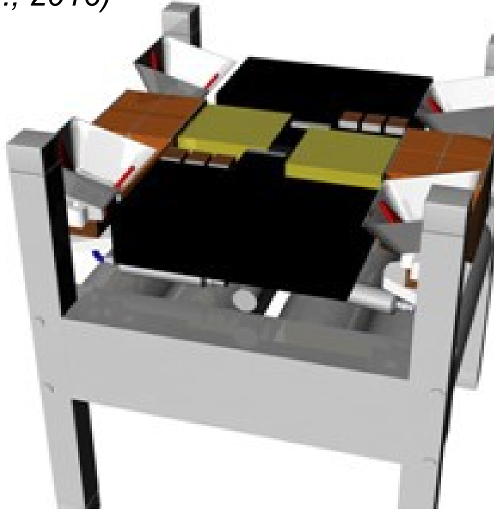
Orbit Determination in Birdy Technology



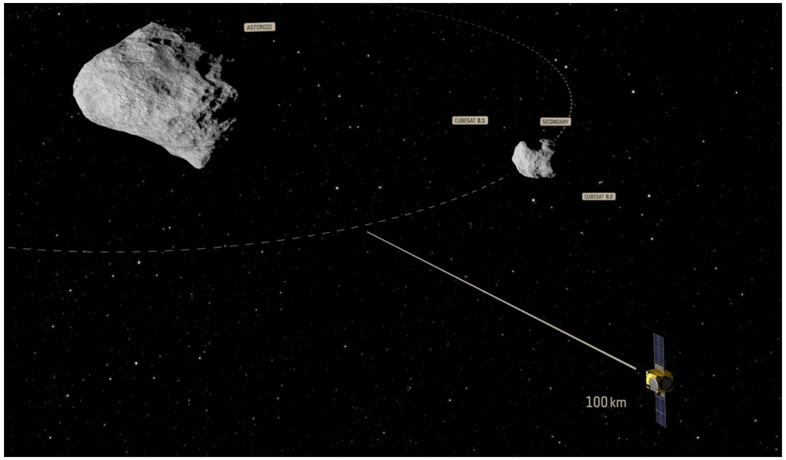
(Quinsac et al., 2016)

(trajectory inspired by Dennis Tito for 2018)





(courtesy LPPT, European consortium for Liquid micro-Pulsed Plasma Thruster, FP7 funded, TRL 3 in 2015)



(ESA's AIM mission to Didymos in 2022)

Stake for an On-board OD

Increase S/C autonomy

- Attempt of on-board OD in NASA's Deep Space 1 (1999+)
- Today OD and TCM are transmitted from the ground to the S/C
- “CubeSat” disruptive technology, but:
  - Cost of Deep-Space Network antennas
  - Increasing number of CubeSat missions, incl. to deep space
  - Ground segment to keep simple
  - Interest for Strategy (“reach this point”) vs. Tactics (on-board ΔV computing)

Not so much bibliography (?)

- Bhaskaran et al., 1996-2001, JPL: NASA's Deep Space 1
- Gaias et al., 2015, DLR: PRISMA… AVANTI, angles-only measurements
- Folta et al., 2000, GSFC: nanosat OD goals better than 10km, 5-100km
- Minimization methods, incl. Huertas / Obs.Paris, Charnoz & Daerr / P7-CEA
- Kalman Filters, incl. Alazard (ISAE-Supaero), Lafarge (ENSG)

1st Context: Deep-Space Cruise

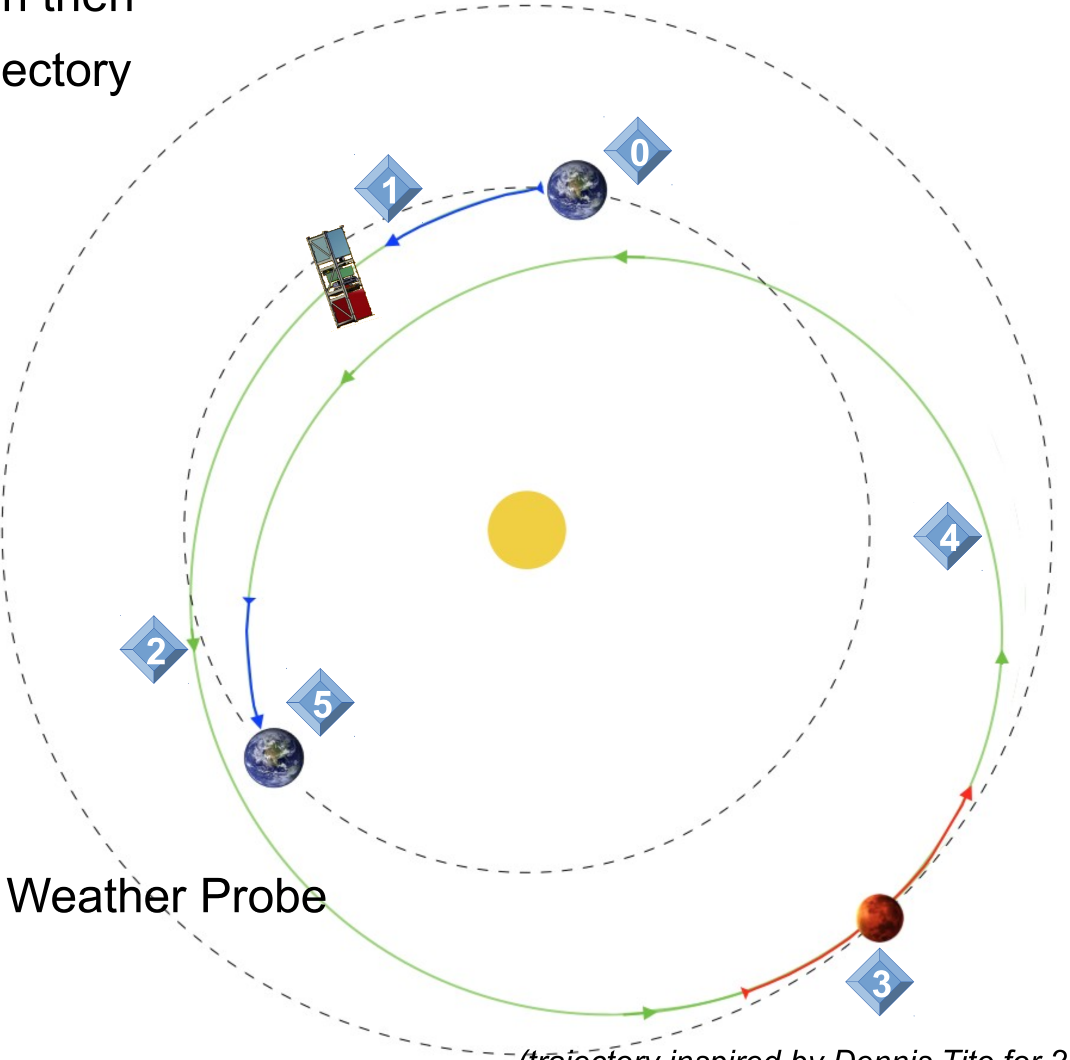
Study Case = IOI by host mission then

Earth-Mars-Earth free return trajectory

0 Mission Preparation
1 Deployment after IOI
2 Earth-to-Mars
3 Mars Flyby: First Datalink
4 Mars-to-Earth = Earth-to-Mars
5 End of Mission: Final Datalink

Science mode:

for instance autonomous Space Weather Probe



(trajectory inspired by Dennis Tito for 2018)

1st Context: Birdy in Deep-Space Cruise

Requirements expected from OD

- Accuracy compatible with TCM potential (manifold error)
- Limited data volume and CPU available
- Flexibility wrt host mission (launch date, collision risk)
- Commissioning

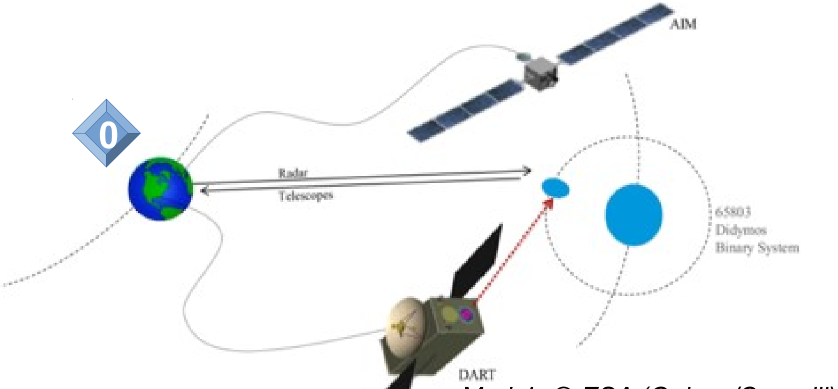
Requirements to allow OD

- Ground segment to produce a Reference Trajectory
- “object tracker” function, accuracy better than 1" tbc (MCC)

2nd Context: Proximity Operations

Study case = released in situ then “Flying-legs”

Science Case = Planetary Geodesy



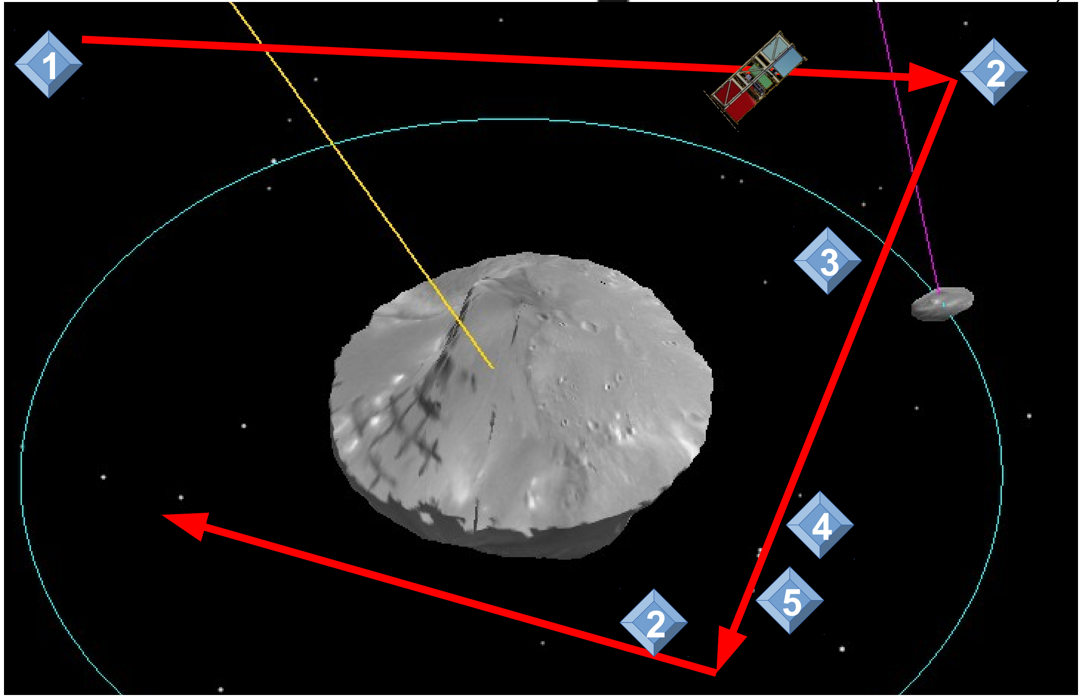
Models © ESA (Galvez/Carnelli)

Ground Segment:

- 0 – Propagator with Models-in-the-loop
- 1 – Next Flying-legs to Mothercraft

Flight Segment

- 2 – TCM: set new V~1m/s (1 day)
- 3 – Science mode (1 day ~80km)
  - Echo/Doppler (multiple S/C)
  - Imaging surface features
  - Optical astrometry
- 4 – Navigation mode (OD+OC)
- 5 – S-band TT&C to Mothercraft



2nd Context: Birdy in “Flying-legs”

Requirements = “deep space cruise” +…

Requirements expected from OD

- Stand-off Avoidance procedure
- Manage non-punctual foreground objects
- Keep TC/TM simple for host mission operations
- Do not expect often tracking from Mothercraft

Requirements to allow OD

- Regular updates of “reference trajectory”
  - Models-in-the-loop
  - relative autonomy: regular corrections from ground (via host… but not often)
- OD dates & TCM strategy to be transferred

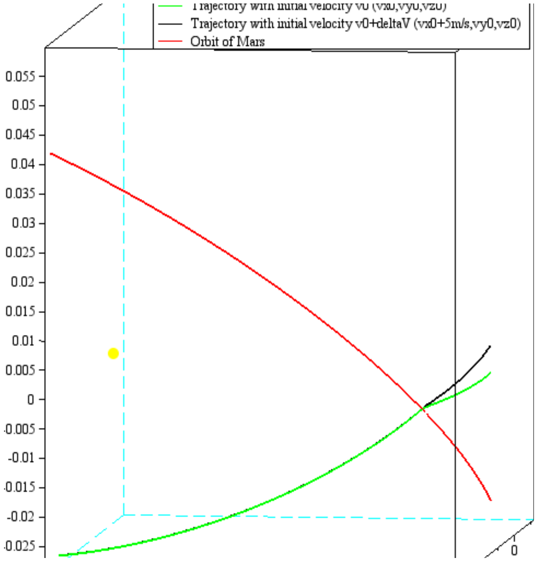
Orbit Determination: Accuracy ?

Trajectory Solver / Ground Segment :

- Reference Trajectory stored on-board
- Expected directions of “foreground objects”

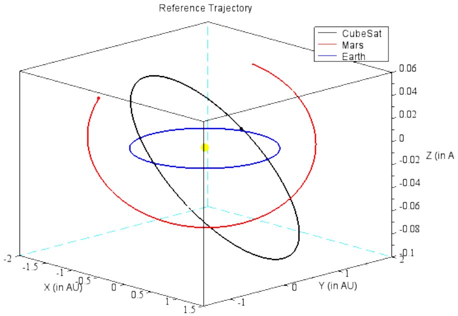
Location determination / Flight Segment

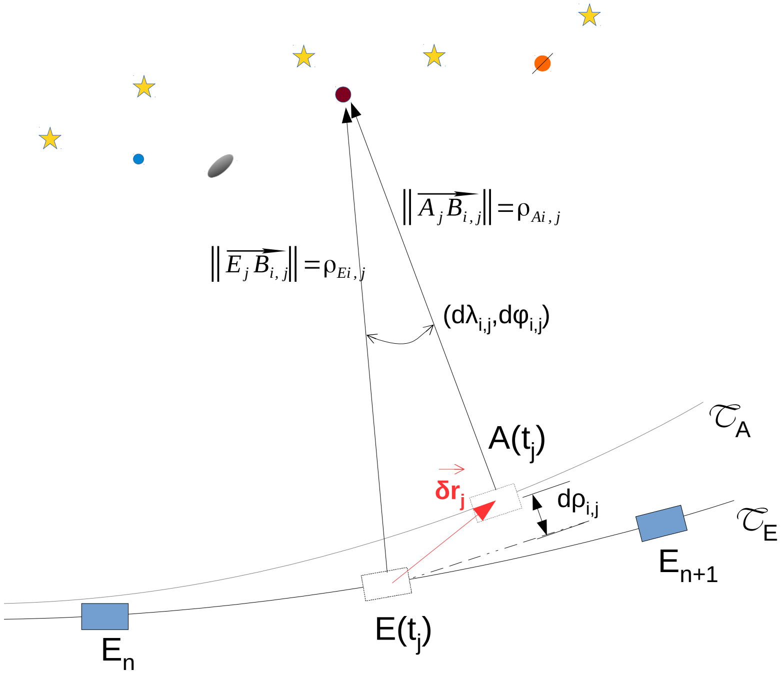
- Star Tracker (ADS) + Object Tracker (ODS)
- Accuracy needed ? Accuracy reached ?



Models-in-the-loop

- gravitational
- non-gravitational
- expected





(A.Porquet, IMCCE, 2014)

Orbit Determination: Accuracy ?

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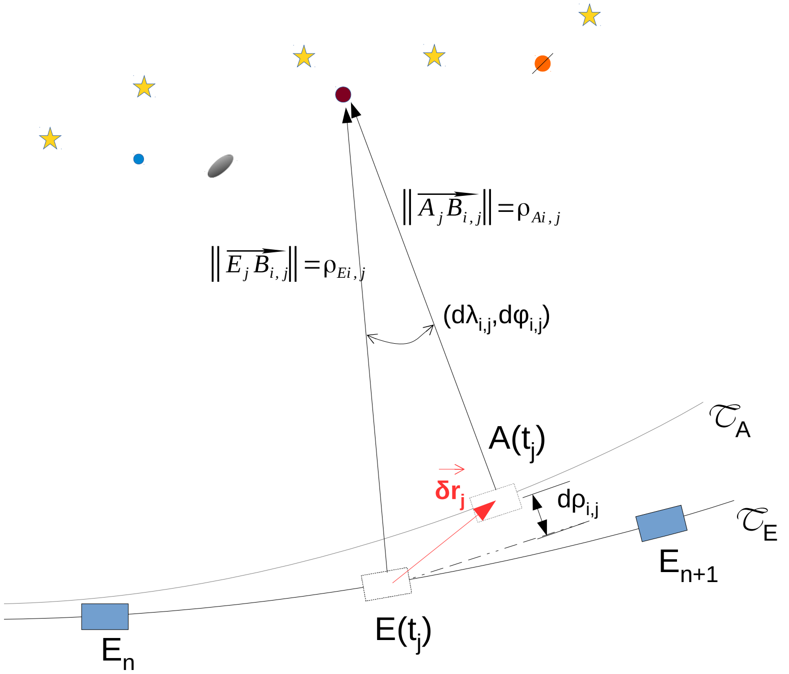

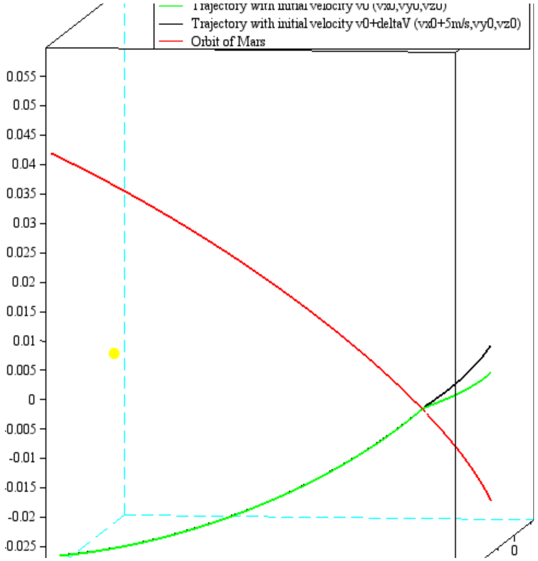

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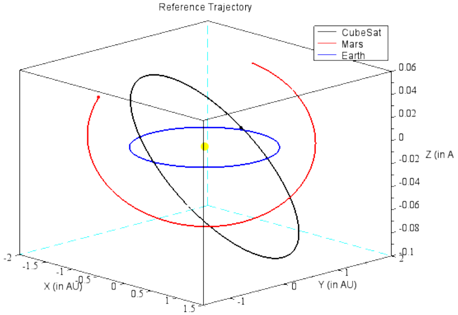
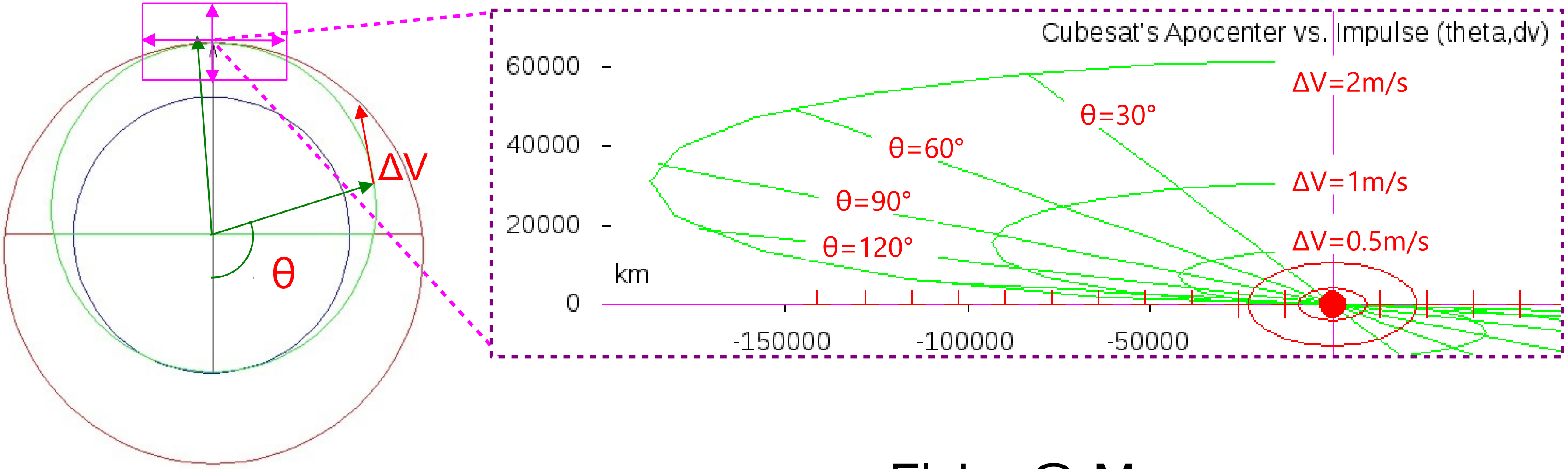


(A.Porquet, IMCCE, 2014)

Shift with +2m/s (ΔV-budget > 80m/s)

175'000 x 30'000 km shift @ Mars with +2m/s, θ=100°

(Segret, Boulder 08/2013)



Effect on apocenter of $\vec{v}'=\vec{v}+\vec{\Delta V}$ at true anomaly θ

$$\vec{e}' = \frac{\vec{v}'\wedge\vec{L}'}{G.M_\odot.m} - \vec{e}'_r = \frac{\vec{v}'_a\wedge\vec{L}'}{G.M_\odot.m} - \vec{e}'_a$$

Flyby @ Mars:

- to transfer data to local orbiter
- to tilt the orbital plane

Method

1. Context
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$$M*\vec{X}-\vec{C} = \vec{0}$$

$$\chi^2(\vec{X}) = \| M*\vec{X}-\vec{C} \|^2$$

$$\Rightarrow \min(\vec{X} \mid \chi^2(\vec{X}))\ ?$$

Natural approach

Make N measurements:

Optical measurements (2D + time)

and / or

Radio-measurements (1D + time)

Build and solve an over-constraint linear system:

Find N “approximate” 3D-solutions (i.e. noisy)

or

Build N ellipsoids and find the best trajectory model (polynomial regression)

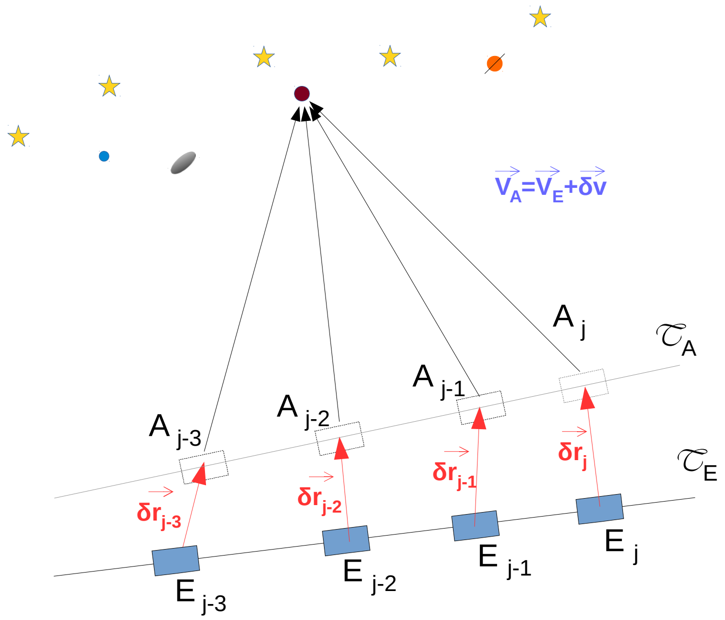
Feed a Kalman Filter:

Build the observable and the prediction models

and

Assess the “noise” on the models

Simplified Approach : N=4



$$M*\vec{X}-\vec{C} = \vec{0}$$

$$\chi^2(\vec{X}) = \| M*\vec{X}-\vec{C} \|^2$$

$$\Rightarrow \min(\vec{X} \mid \chi^2(\vec{X}))\ ?$$

$$\begin{bmatrix}
1&0&0&0&0&0&0&0&0&0&0&0&CC_{i,1}&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&CS_{i,1}&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&0&0&S_{i,1}&0&0&0&0&0&0\\
0&0&0&1&0&0&0&0&0&0&0&0&0&CC_{i,2}&0&0&0&0&0\\
0&0&0&0&1&0&0&0&0&0&0&0&0&CS_{i,2}&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&1&0&0&-1&0&0&0&0&0&0&dt_4
\end{bmatrix}
*
\begin{bmatrix}
\delta x_1\\ \delta y_1\\ \delta z_1\\ \delta x_2\\ \delta y_2\\ \delta z_2\\ \delta x_3\\ \delta y_3\\ \delta z_3\\ \delta x_4\\ \delta y_4\\ \delta z_4\\ dr_{i,1}\\ dr_{i,2}\\ dr_{i,3}\\ dr_{i,4}\\ V_x\\ V_y\\ V_z
\end{bmatrix}
-
\begin{bmatrix}
CSCS_{i,1}\\ CCSS_{i,1}\\ C_{i,1}\\ CSCS_{i,2}\\ CCSS_{i,2}\\ C_{i,2}\\ CSCS_{i,3}\\ CCSS_{i,3}\\ C_{i,3}\\ CSCS_{i,4}\\ CCSS_{i,4}\\ C_{i,4}\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0
\end{bmatrix}
= \vec{0}$$

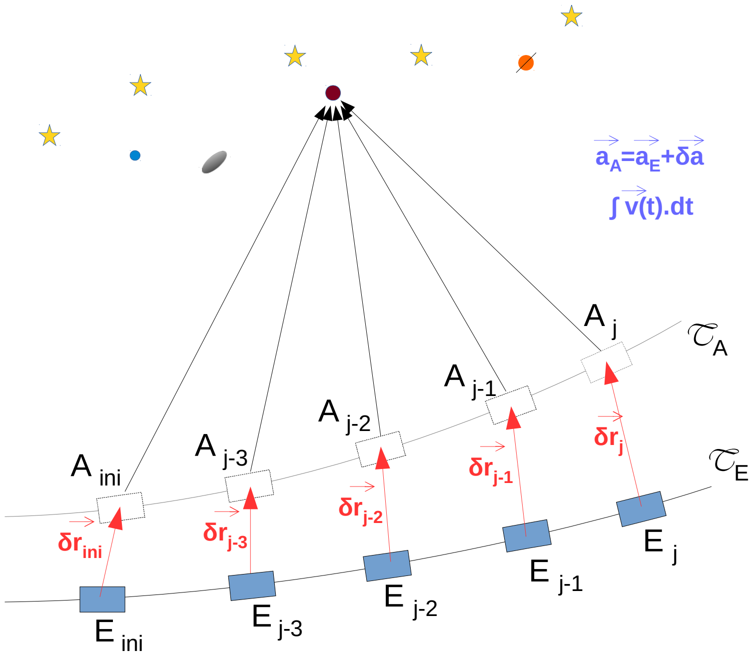
Assumption:

Constant Velocity
during N=4 measurements

=> 19 unknowns
=> 21 equations

1st simulation on Earth-Mars in 10/2015 without optical errors, validations in 03/2016
(T.Mallet, DAA/NCKU, 2015)

N=5 & block matrix



$$\begin{bmatrix} I_{3N} & P_{3NxN} & 0_{3Nx6} \\ \Delta R'_{3(N-1)x3N} & 0_{3(N-1)xN} & -\Delta J'_{3(N-1)x6} \end{bmatrix} . [X']_{(3N+N+6)x1} = \begin{bmatrix} Q'_{3Nx2N} \\ 0_{3(N-1)x2N} \end{bmatrix} . [Z]_{2Nx1}$$

or

$$[C']*[X'] = [D']*[Z]$$

$$[X'_{26x1}] = \begin{bmatrix} \delta x_{j-4}/\rho_{Ei,j-4} \\ \delta y_{j-4}/\rho_{Ei,j-4} \\ \delta z_{j-4}/\rho_{Ei,j-4} \\ \dots \\ \delta x_j/\rho_{Ei,j} \\ \delta y_j/\rho_{Ei,j} \\ \delta z_j/\rho_{Ei,j} \\ d\rho_{j-4}/\rho_{Ei,j-4} \\ \dots \\ d\rho_j/\rho_{Ei,j} \\ \delta v_{x,ini}.T_{max}/\rho_{Ei,ini} \\ \delta v_{y,ini}.T_{max}/\rho_{Ei,ini} \\ \delta v_{z,ini}.T_{max}/\rho_{Ei,ini} \\ \delta a_x.T_{max}^2/\rho_{Ei,ini} \\ \delta a_y.T_{max}^2/\rho_{Ei,ini} \\ \delta a_z.T_{max}^2/\rho_{Ei,ini} \end{bmatrix} \qquad [Z_{10x1}] = \begin{bmatrix} \delta\lambda_{j-4} \\ \delta\phi_{j-4} \\ \delta\lambda_{j-3} \\ \delta\phi_{j-3} \\ \delta\lambda_{j-2} \\ \delta\phi_{j-2} \\ \delta\lambda_{j-1} \\ \delta\phi_{j-1} \\ \delta\lambda_j \\ \delta\phi_j \end{bmatrix}$$

Assumption:

Constant "acceleration"
during N=5 measurements

=> 26 unknowns (4N+6)
=> 27 equations (6N-3)

2nd simulations on Earth-Mars in 08/2016

What can we expect? (1/2)

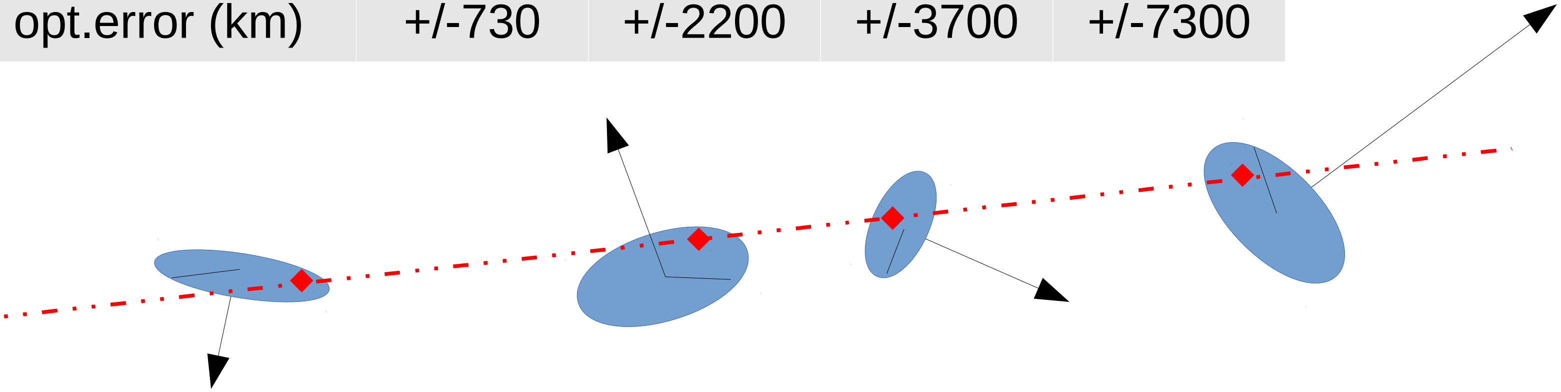
$$\begin{bmatrix}1&0&0&\cos\phi_{Ei}\cos\lambda_{Ei}\\0&1&0&\cos\phi_{Ei}\sin\lambda_{Ei}\\0&0&1&\sin\phi_{Ei}\end{bmatrix}\cdot\begin{pmatrix}\delta x\\ \delta y\\ \delta z\\ d\rho_i\end{pmatrix}=\begin{bmatrix}\rho_{Ei}\cos\phi_{Ei}\sin\lambda_{Ei}&\rho_{Ei}\sin\phi_{Ei}\cos\lambda_{Ei}\\-\rho_{Ei}\cos\phi_{Ei}\cos\lambda_{Ei}&\rho_{Ei}\sin\phi_{Ei}\sin\lambda_{Ei}\\0&-\rho_{Ei}\cos\phi_{Ei}\end{bmatrix}\cdot\begin{pmatrix}d\lambda_i\\ d\phi_i\end{pmatrix}\Longrightarrow\left\{\begin{matrix}\phi_{Ei}=0\\ \lambda_{Ei}=0\\ d\lambda_i=0\end{matrix}\right\}\Rightarrow\delta z=-\rho_{Ei}\,d\phi_i$$

Error propagation from the optical measurements

1" ($d\varphi_i$) on a foreground body at 1 AU (ρ_{Ei})

=> δz=730km error transversely

	Mars	Ceres	Jupiter	Saturn
typ.dist. (AU)	1	3	5	10
opt.error (km)	+/-730	+/-2200	+/-3700	+/-7300



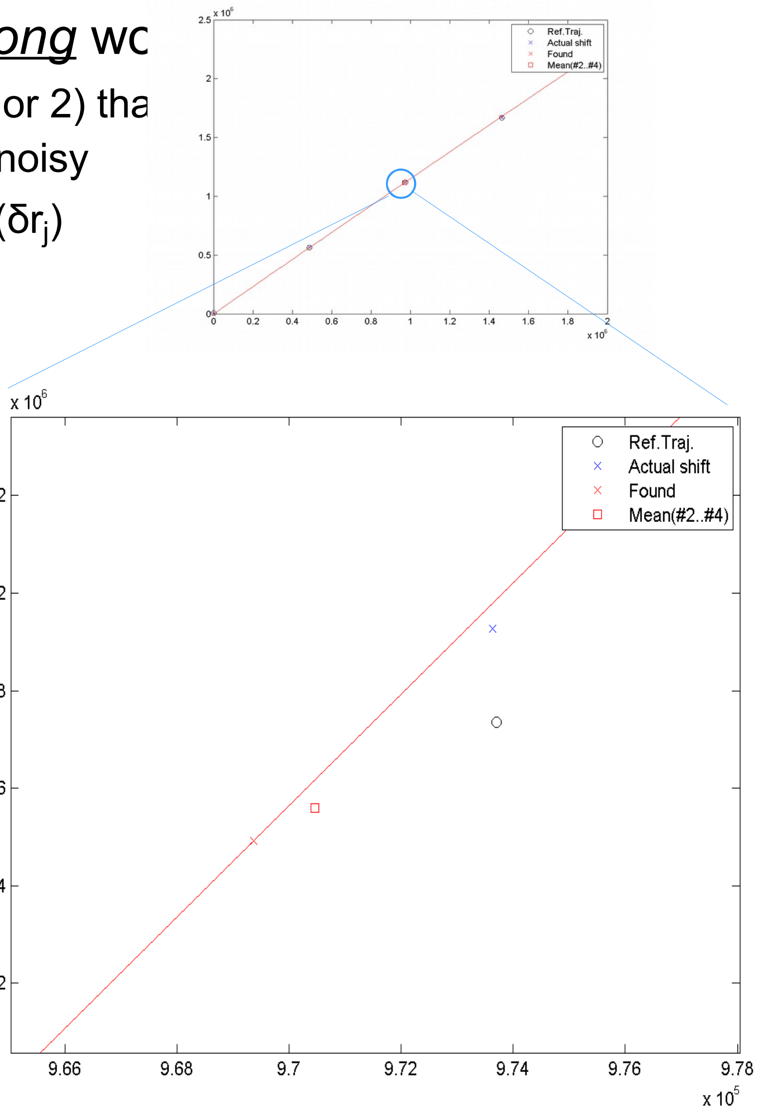
What can we expect? (2/2)

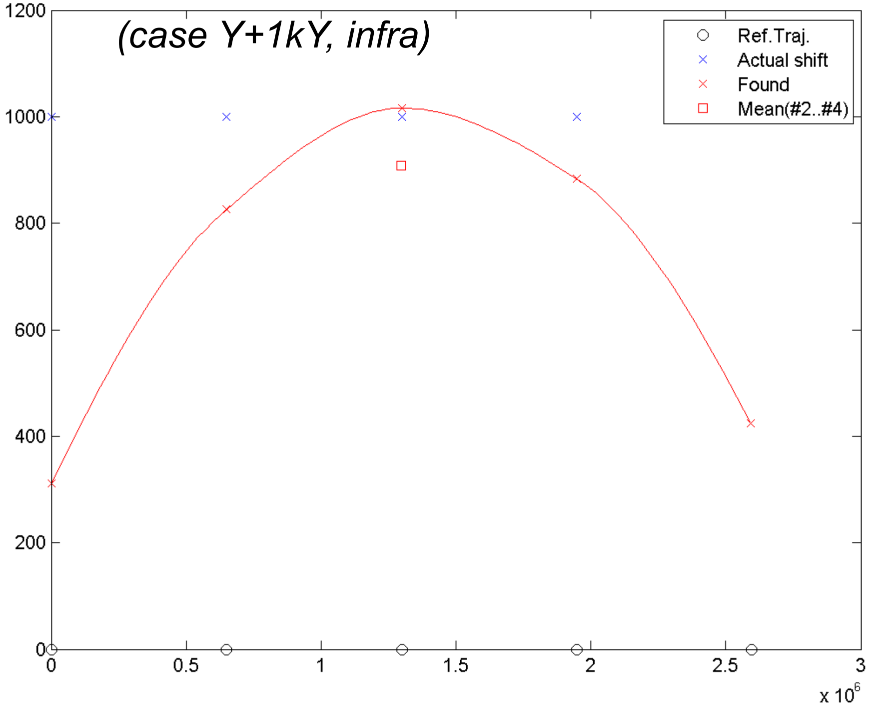
Constant “velocity” or “acceleration” is a *wrong* wc

The found (δr_j) is the polynomial solution (order 1 or 2) tha the measurements … but the measurements are noisy

=> it is *not* any polynomial regression among the (δr_j)

=> a selection of 1 solution among N is adopted





Method for Monte-Carlo simulations

Multidimensional Minimizing:

(a) “Steepest Descent” algorithm

preferred for on-board software

<u>not</u> implemented yet

(b) or “Random search on a grid”

may be an alternative, <u>not</u> implemented yet

(c) or MATLAB / OCTAVE “INV([C])”

likely not for on-board software

<u>implemented</u> here for MC simulations

$$\boxed{\begin{aligned} M*\vec{X}-\vec{C} &= \vec{0} \\ \chi^2(\vec{X}) &= \| M*\vec{X}-\vec{C} \|^2 \\ \Rightarrow \min(\vec{X} \mid \chi^2(\vec{X}))\ ? \end{aligned}}$$

(a) steepest descent along $\vec{\nabla}\chi^2(\vec{X})$

(b) random search while evaluating $\vec{\nabla}\chi^2(\vec{X})$

(c) new 19x19 (or 26x26) linear system

$$\vec{\nabla}\chi^2(\vec{X}) = 0 \Leftrightarrow [C].\vec{X}=\vec{Y} \Leftrightarrow \vec{X}=[C]^{-1}.\vec{Y}$$

$$\vec{X}=\begin{pmatrix} \delta\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{j=1..N} \\ \delta\rho_{j=1..N} \\ \cdots \end{pmatrix}$$

N found positions, 1 selected

“j” foreground bodies

Simulation Results

1. Context
2. Method
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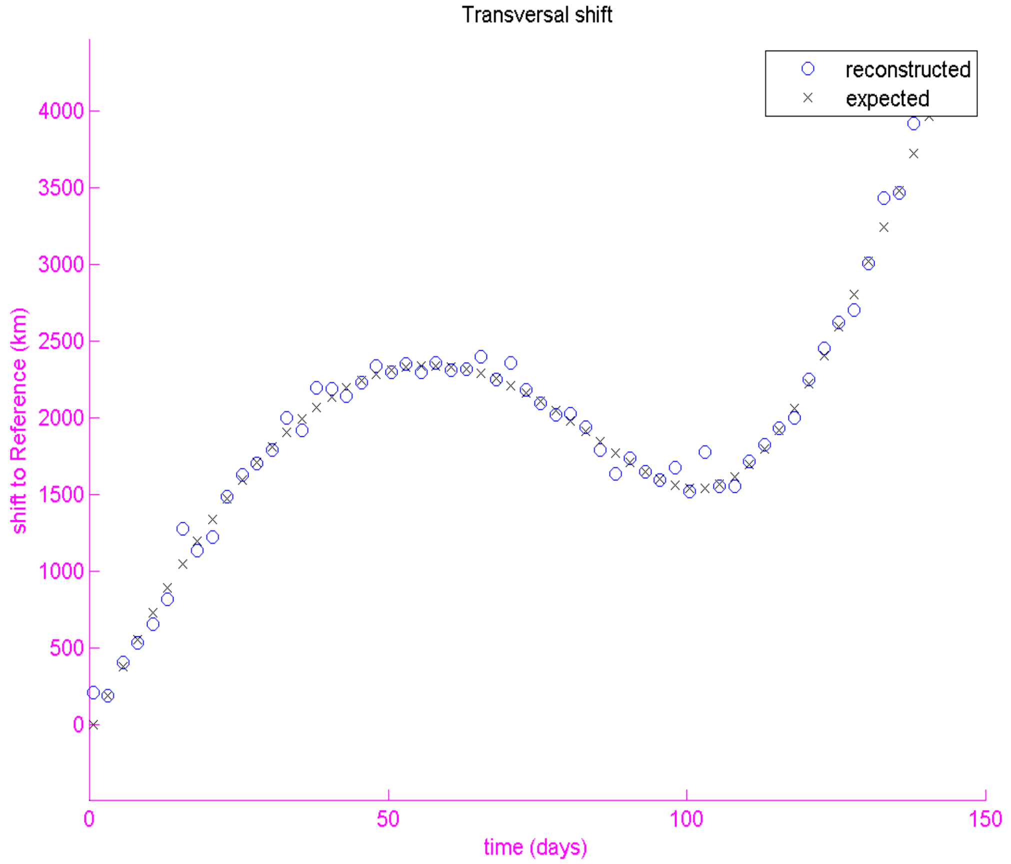


Earth-to-Mars “E2M”: initial results...

Ground Segment: “T_E” is computed “as good as possible”

(status)

- SCILAB/CelestLab Trajectory Solver with basic functions
- Migration of the “Propagator” part to RK4/RK45 in Python with models-in-the-loop approach

T_E: Earth-to-Mars trajectory propagated from a “host trajectory” (Dennis Tito 2018 Free-return)

- Propagation starts after IOI = “jettisoning”
- Ephemeris of Earth, Mars, Ceres, Jupiter, Saturn

Simulation: “T_A” also computed

- T_A: 2nd trajectory propagated with +1m/s along Y-axis at jettisoning
- T_A is **not** known by the simulated OD, only Ephemeris provided as “observations”

=> do we correctly reconstruct the expected shift of T_A wrt T_E?

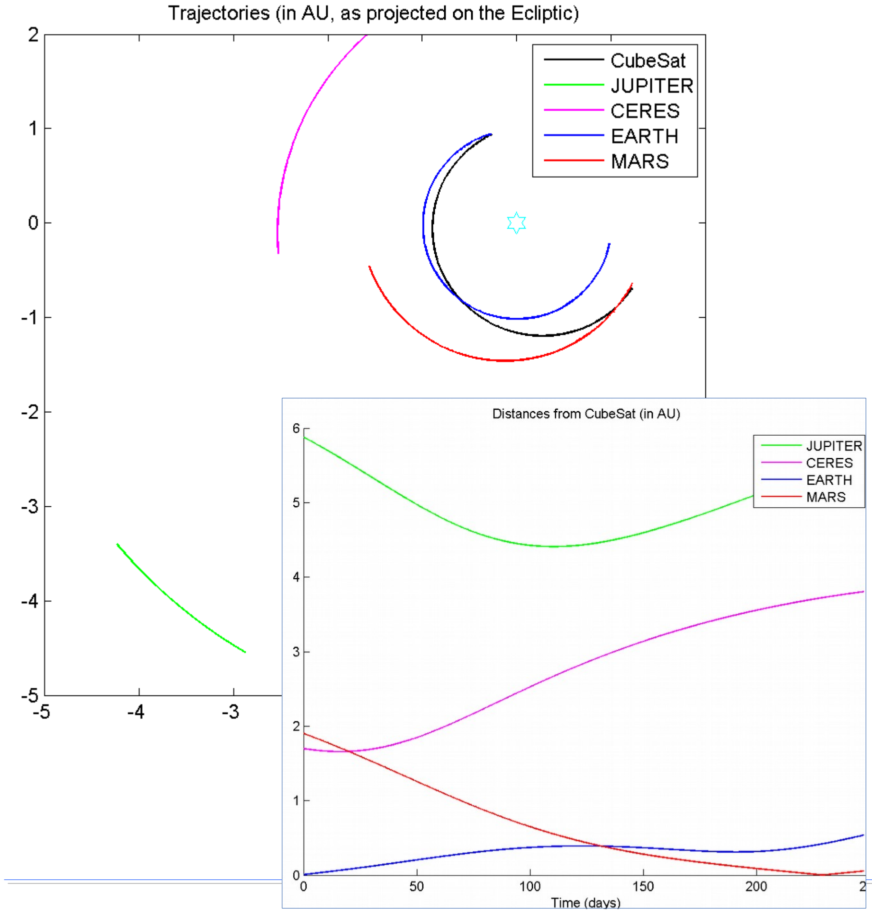
=> Monte-Carlo series to simulate the optical error “σ_{in}” and estimate “σ_{out}”

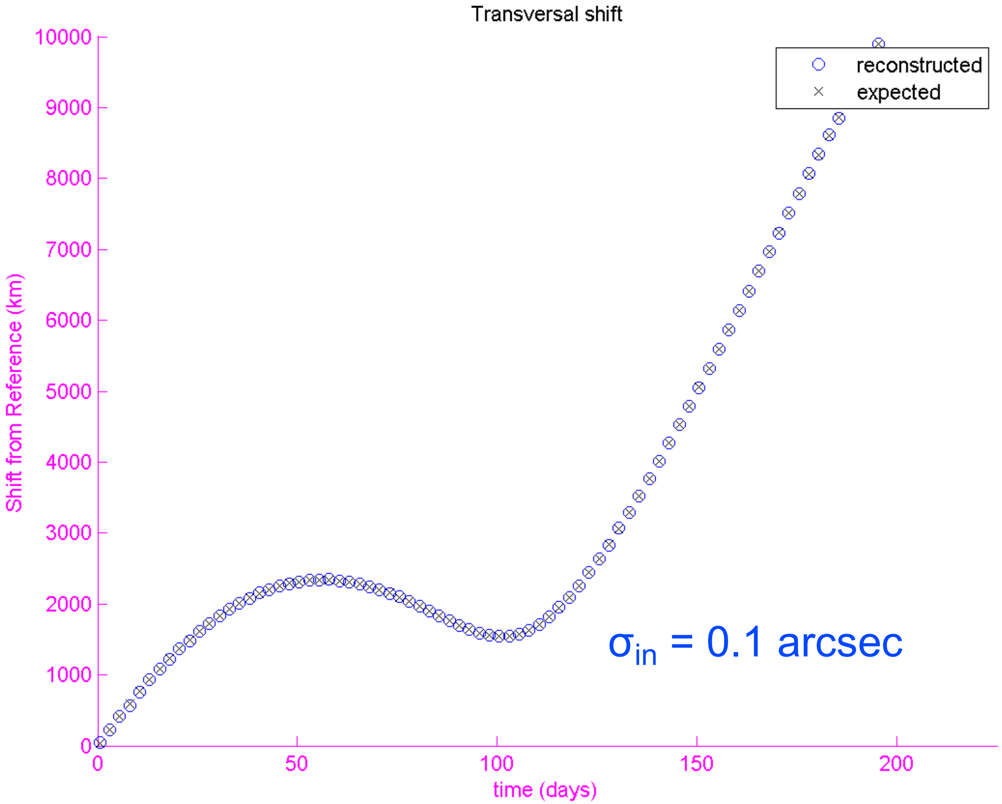
1°) the mean reconstructed value $<X>=f(\sigma_{in})$

2°) the standard deviation “σ_{out}”

Earth-to-Mars “E2M”: initial results...

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T_E”
=> do we correctly reconstruct the expected shift of T_A wrt T_E?

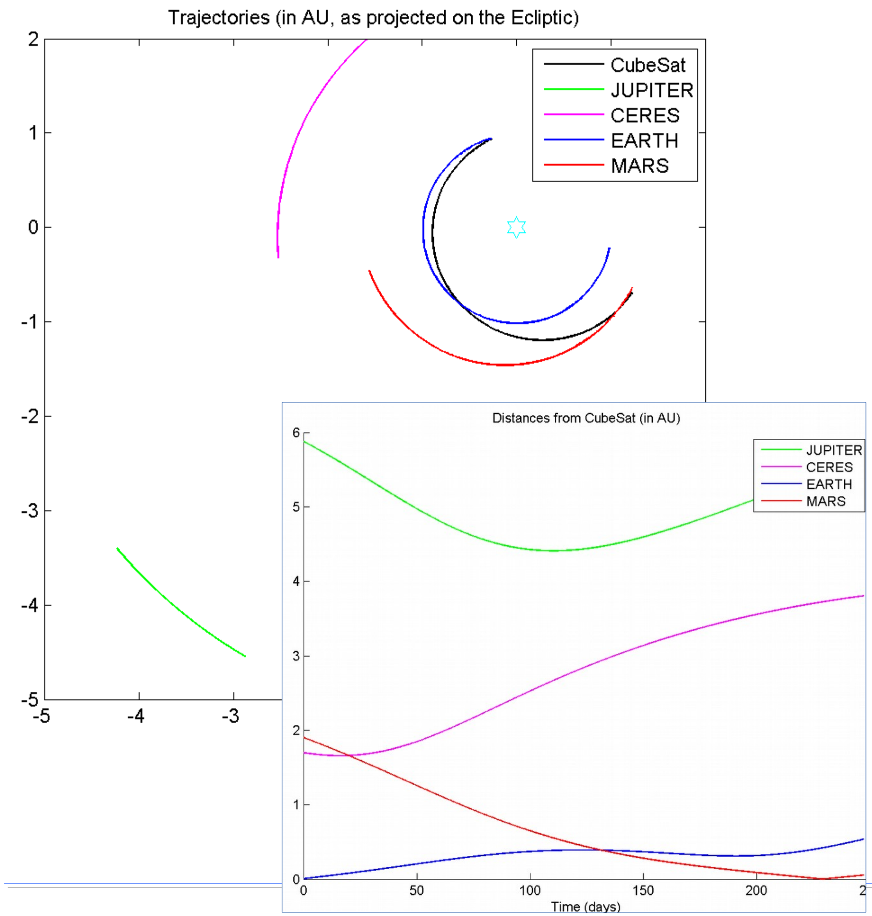


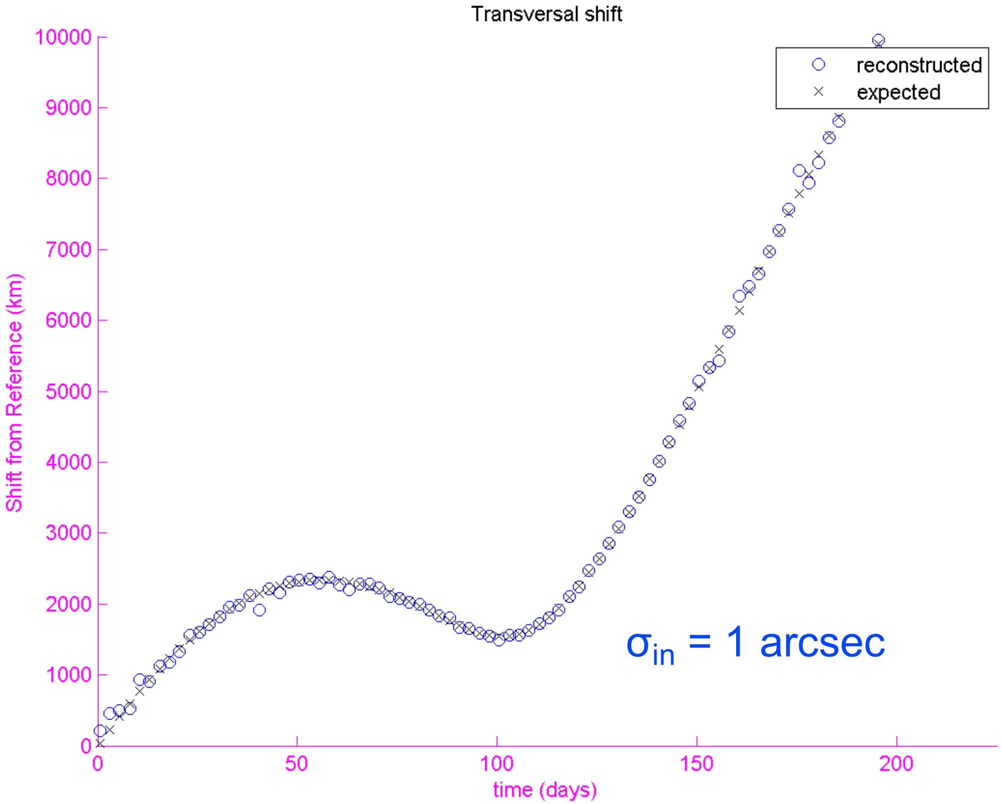


σ_{in} = 0.1 arcsec

Earth-to-Mars “E2M”: initial results...

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T_E”
=> do we correctly reconstruct the expected shift of T_A wrt T_E?

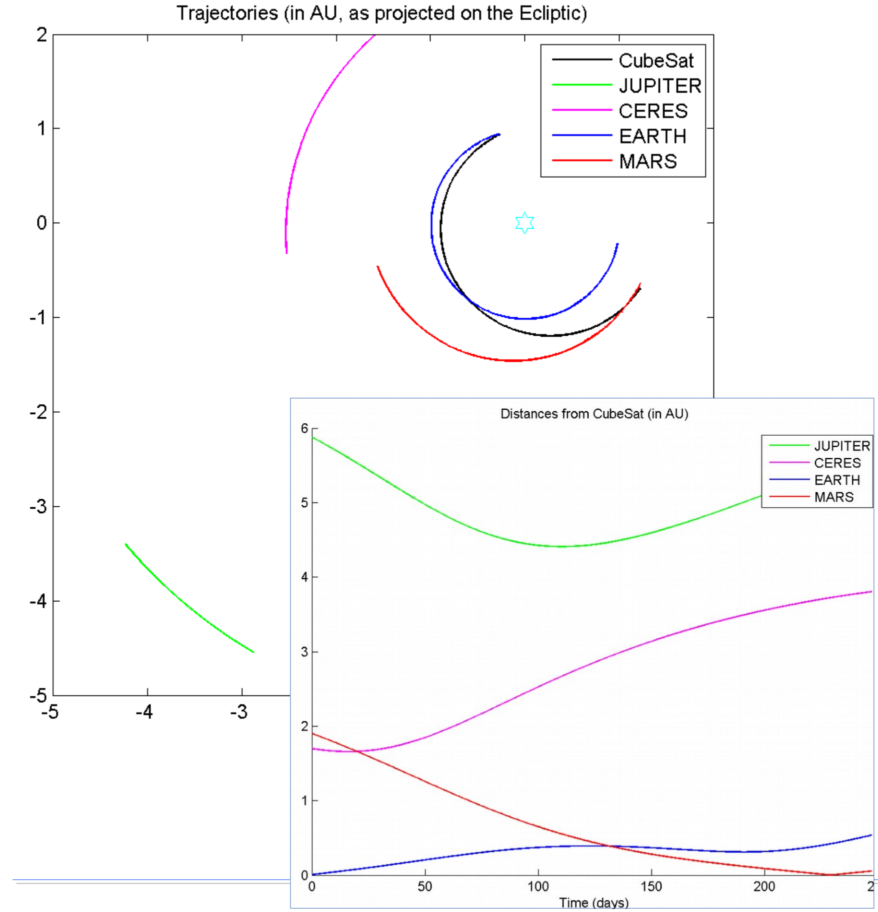


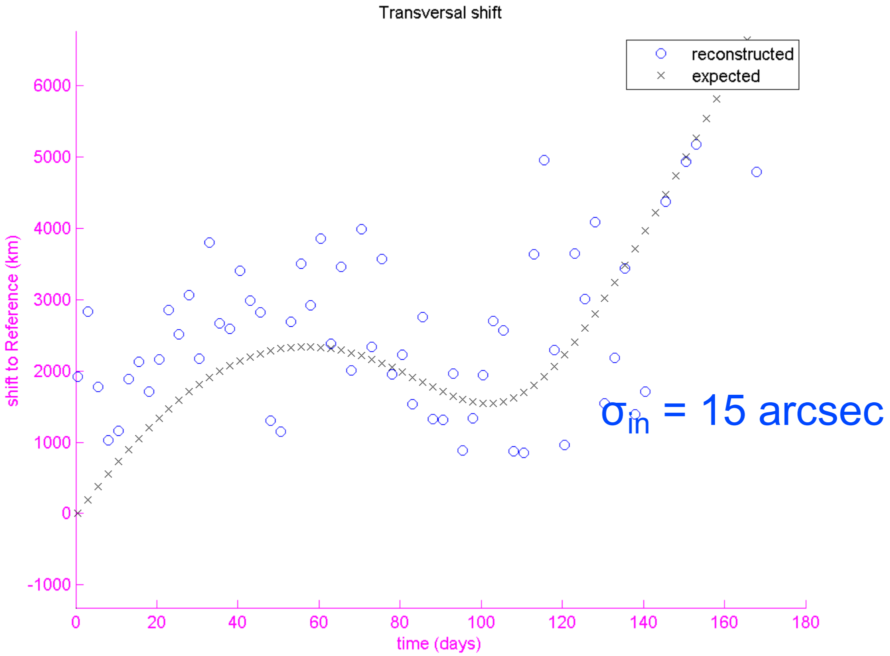


σ_{in} = 1 arcsec

Earth-to-Mars “E2M”: … and limits

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T_E”
=> do we correctly reconstruct the expected shift of T_A wrt T_E?

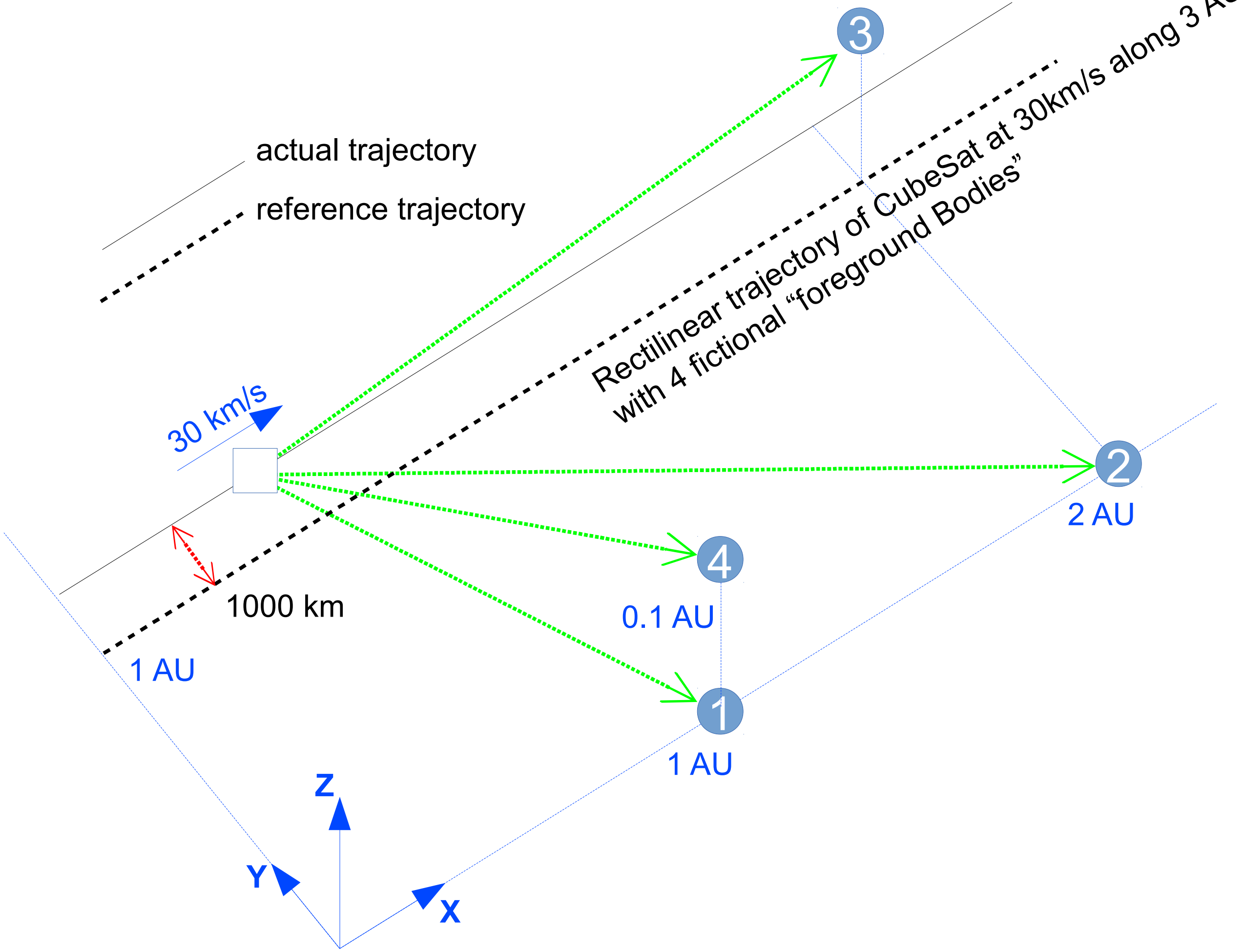




σ_{in} = 15 arcsec

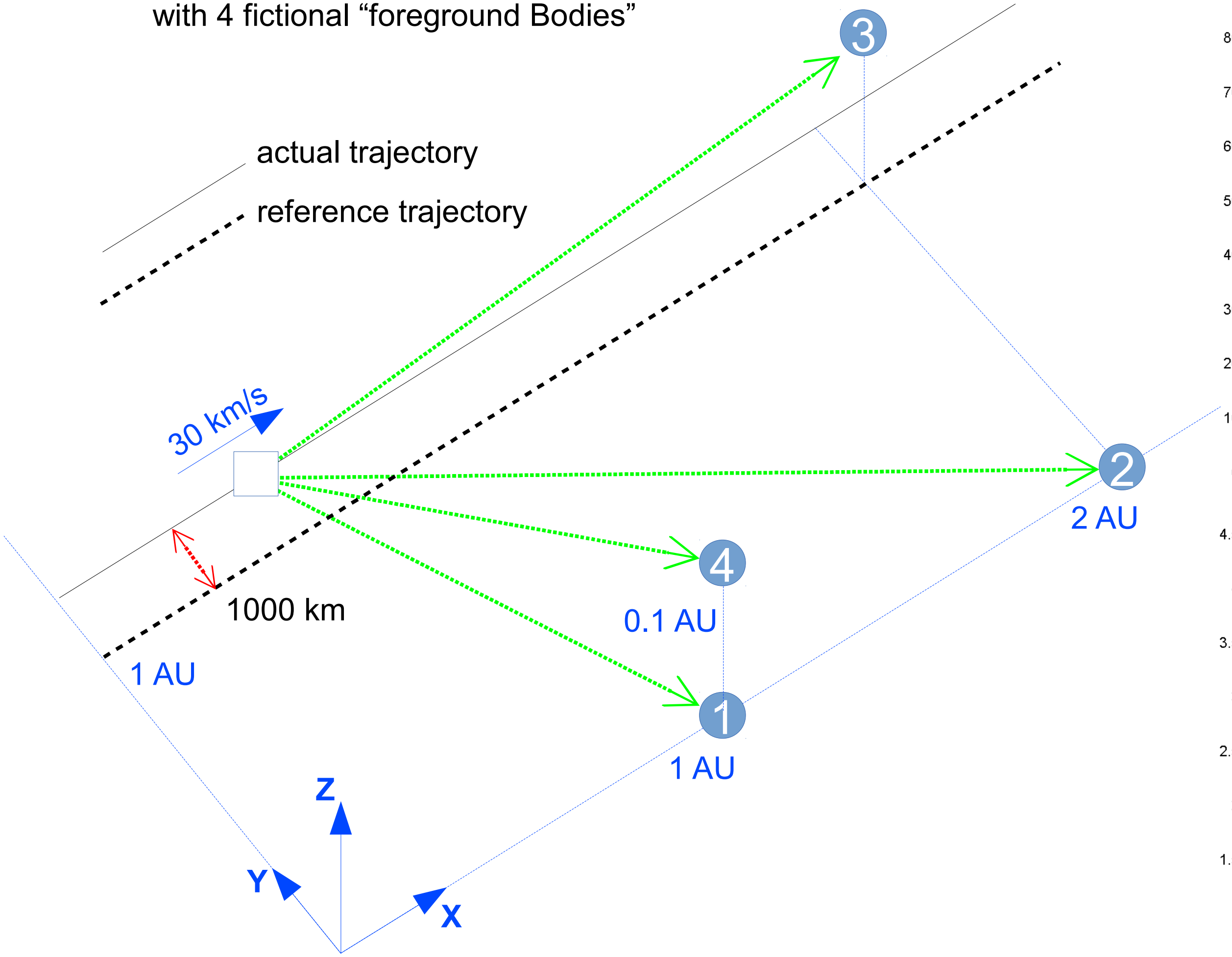
Elementary dynamic model “Y+1kY”

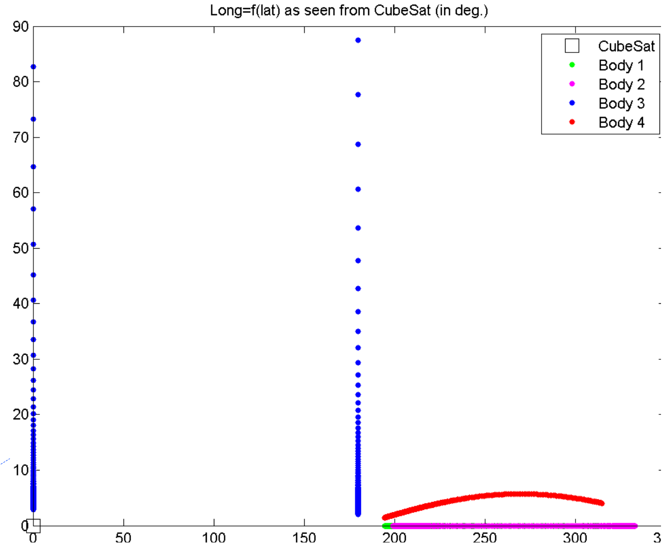
“Y+1kY”

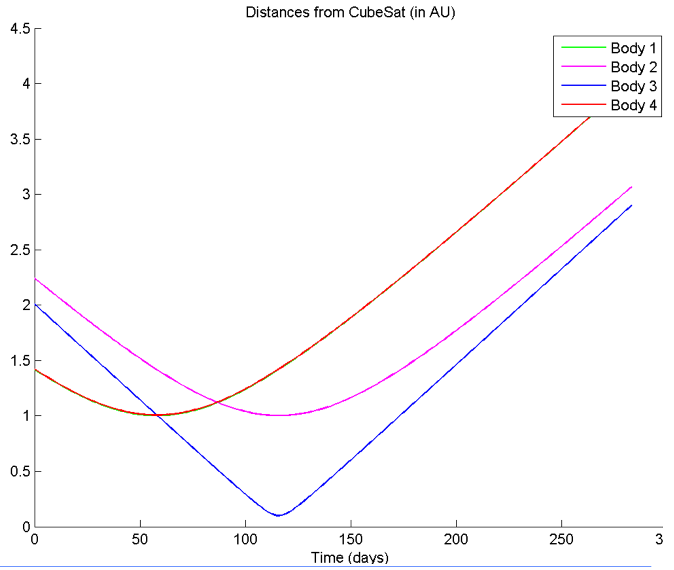


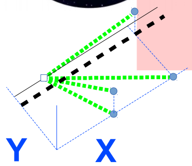
Elementary dynamic model “Y+1kY”

Rectilinear trajectory of CubeSat at 30km/s along 3 AU
with 4 fictional “foreground Bodies”



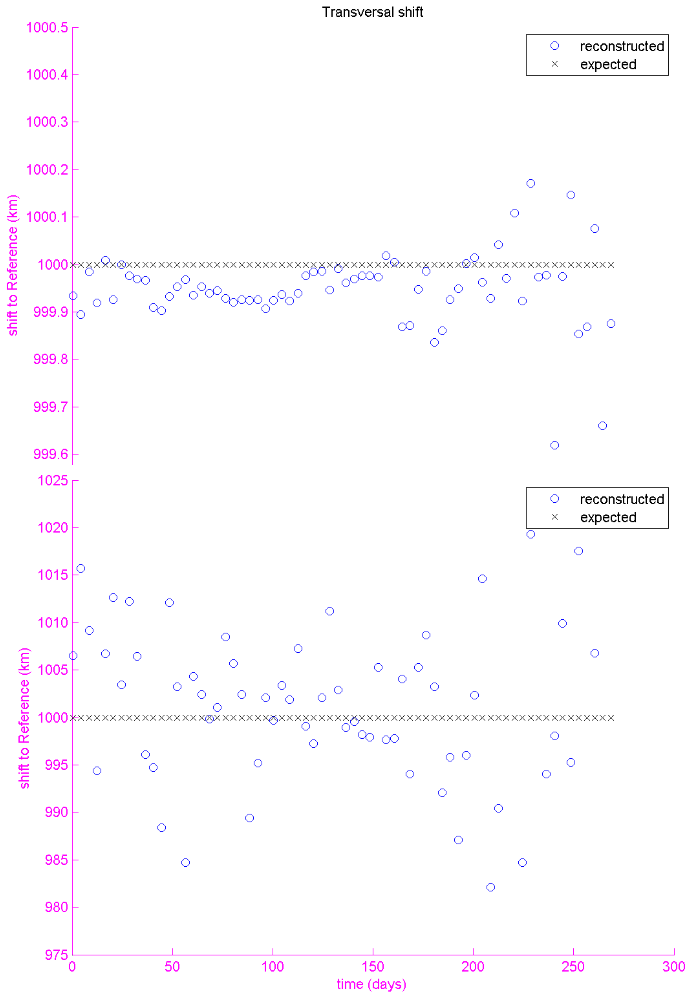






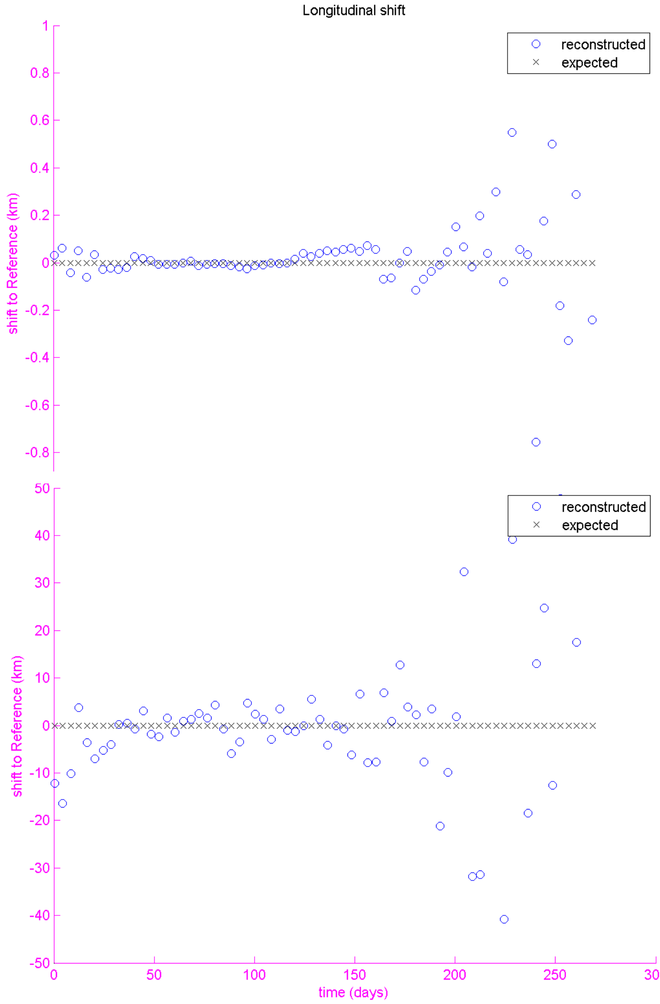
“Y+1kY” sensitivity at small σ_{in}

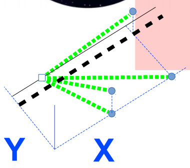
It works! But numeric degeneracy is a concern (small angular variations with large distances)



σ_{in} = 10^{-5} arcsec (!)
N=4

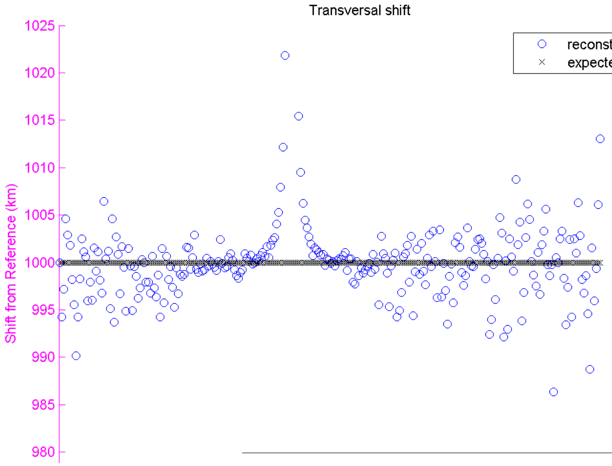
σ_{in} = 0.1 arcsec
N=4





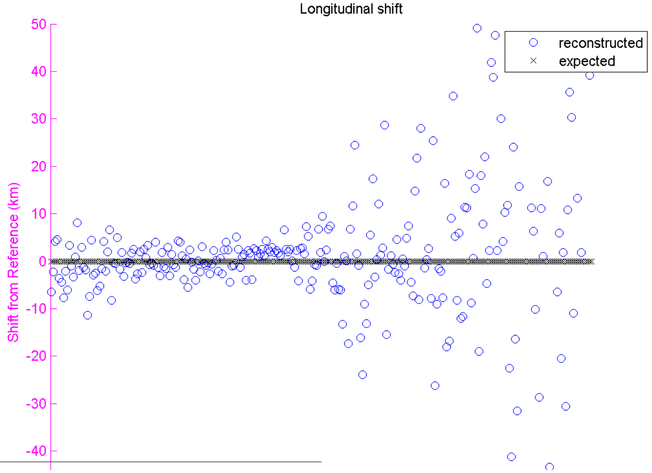
"Y+1kY" sensitivity (N=5)

The selection of the foreground bodies is critical
(reminder: the 3rd found location is kept, from 5 found locations in the inverted problem)

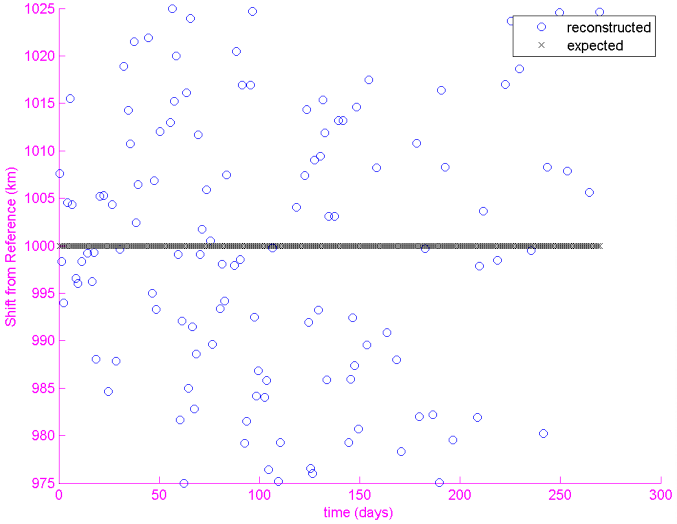


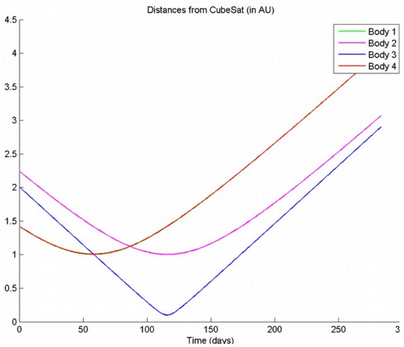
σ_{in} = 0.1 arcsec

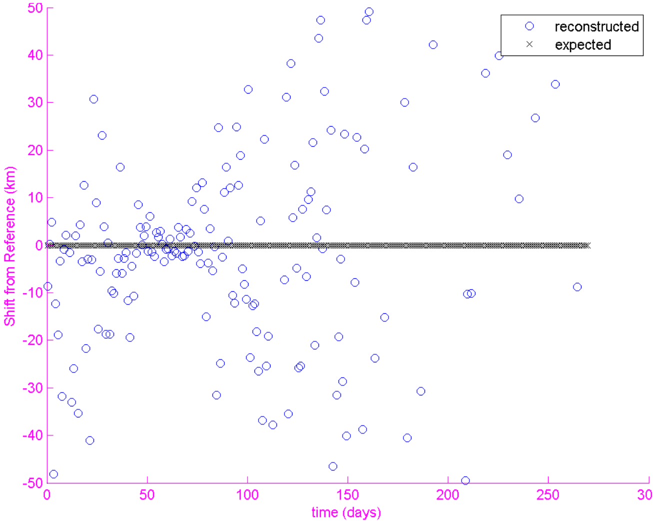
Bodies 4-1-<u>3</u>-2-4

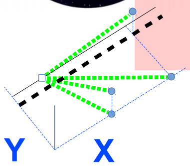


Bodies 1-3-<u>4</u>-2-1



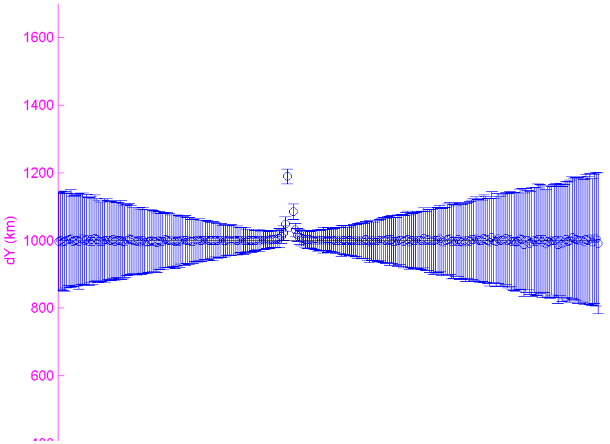


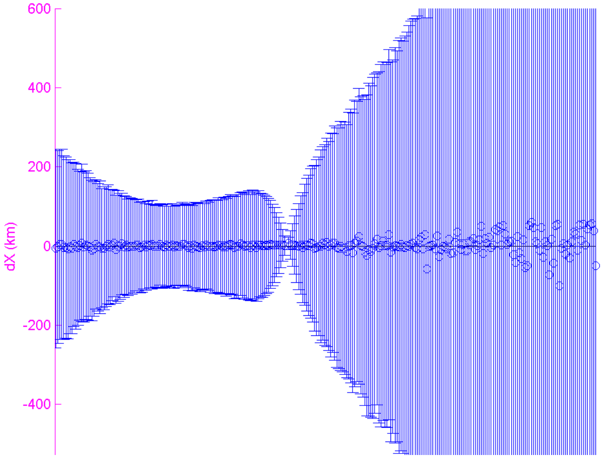




"Y+1kY" sensitivity (N=5)

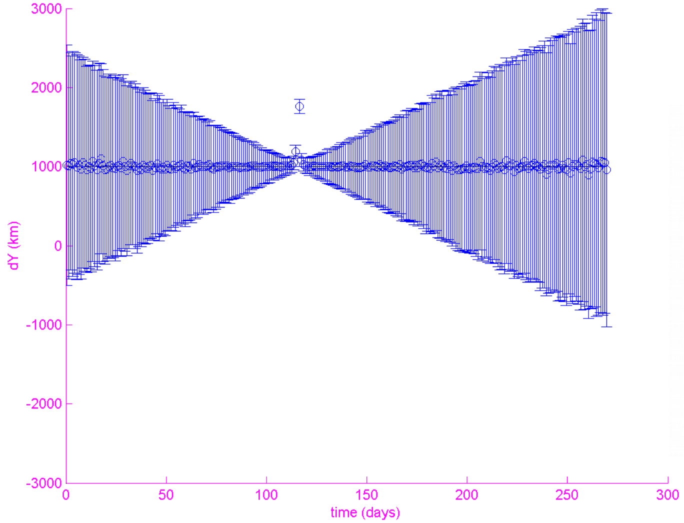
Resulting σ_{out} = 100..200 km with σ_{in} = 0.1"
Resulting σ_{out} = 1000..2000 km with σ_{in} = 1" => non operational (?)

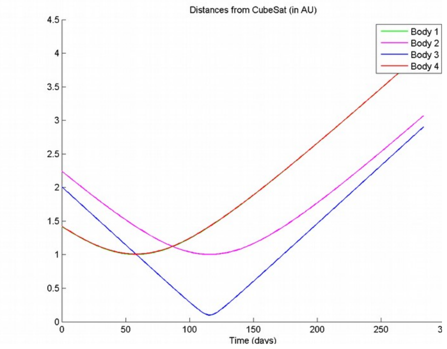




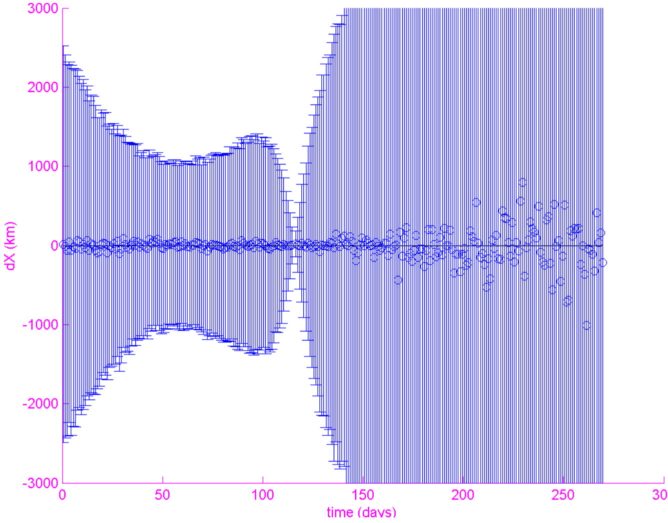
σ_{in} = 0.1 arcsec

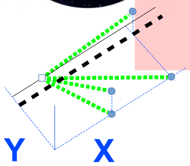
σ_{in} = 1 arcsec





Bodies 4-1-3-2-4

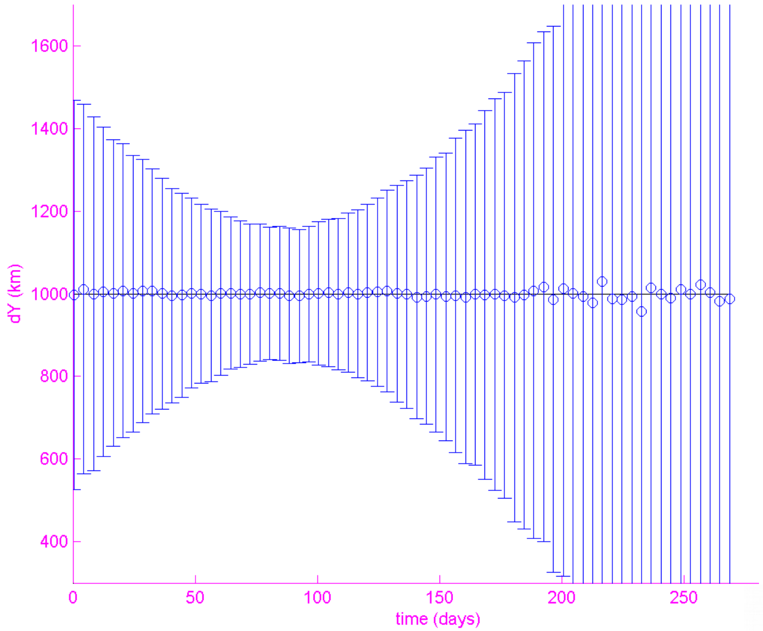




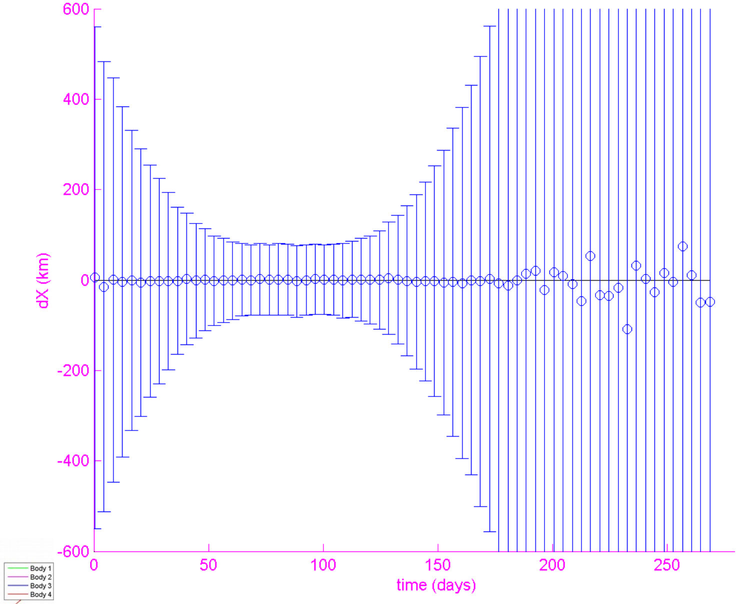
“Y+1kY” sensitivity (back to N=4)

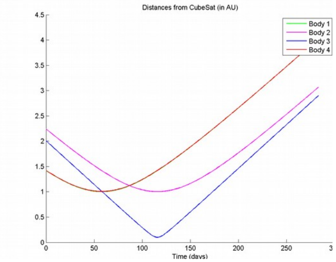
with σ_{in} = 0.1” : resulting σ_{out} = 200..400 km transversely
σ_{out} = 100..400 km longitudinally

σ_{in} = 0.1 arcsec



N=4





Bodies 1-2-3-4

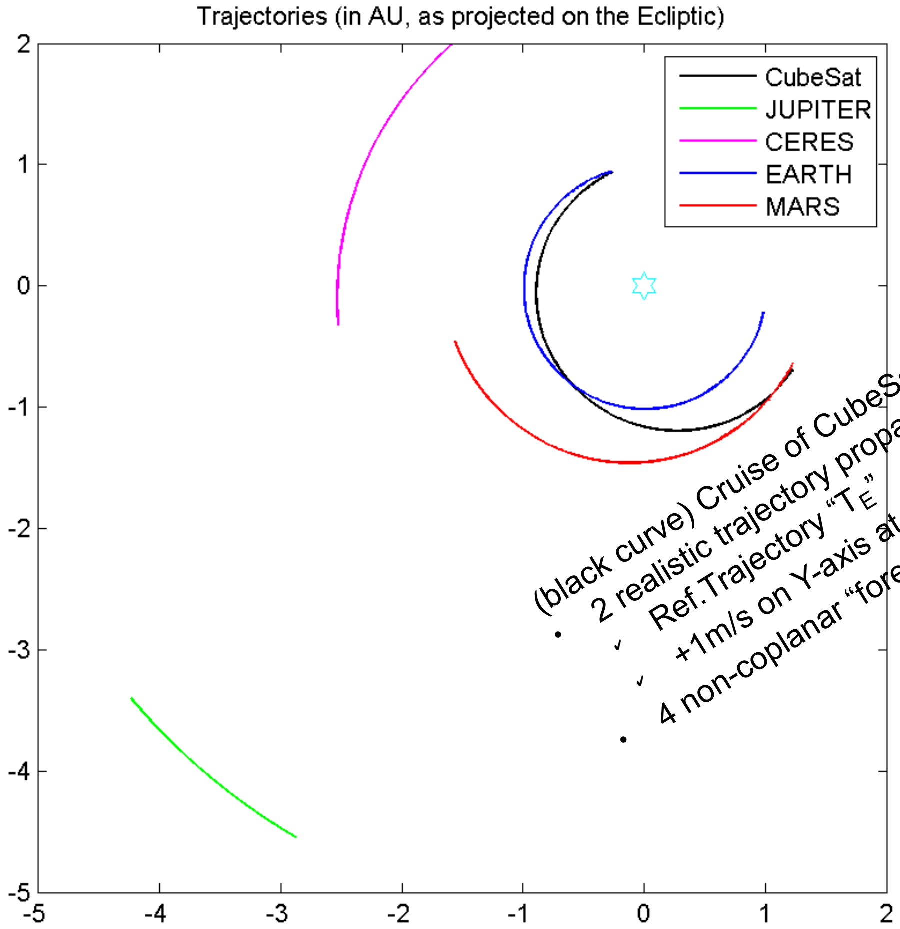
Realistic model "E2M"

"E2M"

σ_{in} = 0.1 arcsec

vs.

σ_{in} = 1 arcsec



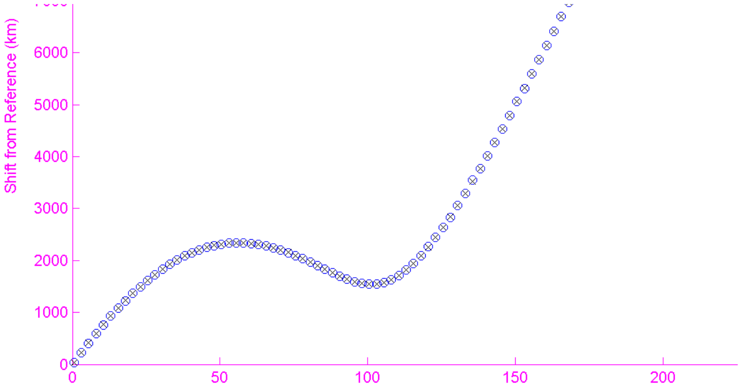
(black curve) Cruise of CubeSat from Earth to Mars in 2018

- 2 realistic trajectory propagations
  - ✓ Ref. Trajectory "T_E"
  - ✓ +1m/s on Y-axis at jettisonning wrt "T_E"
- 4 non-coplanar "foreground Bodies"

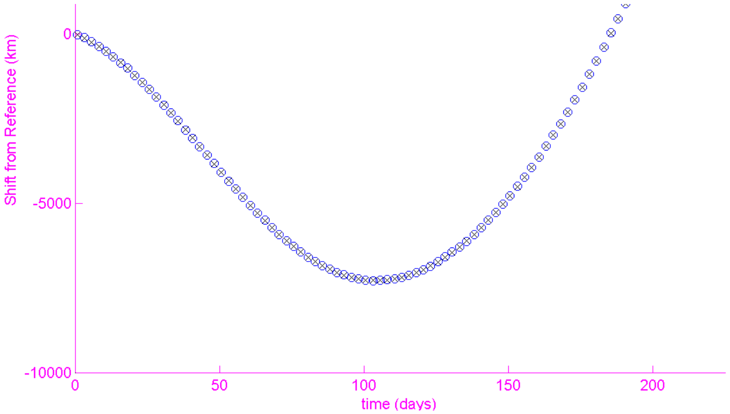
“E2M” sensitivity (N=5) at σ_{in} = 0.1"

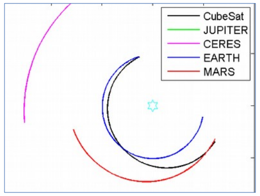
+1m/s on Y: the actual shift wrt T_E is larger over time => assumption of “small shift” not valid in late scenario

@ σ_{in} = 0.1 arcsec => Mean value σ_{out} = 5..10km accurate in transverse or longitudinal directions



σ_{in} = 0.1 arcsec

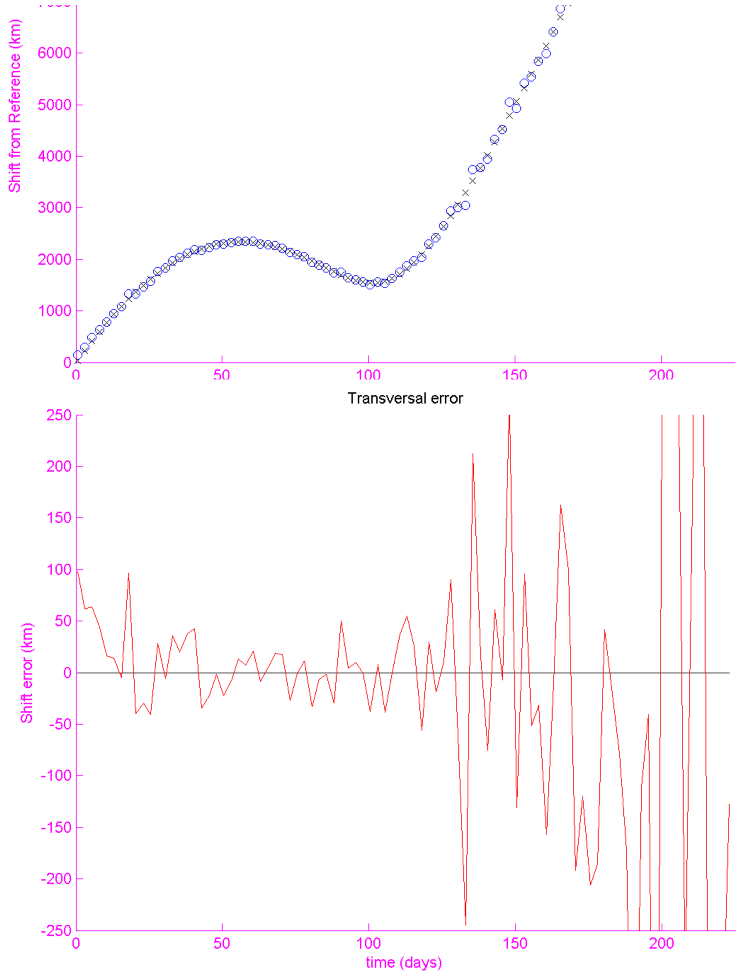




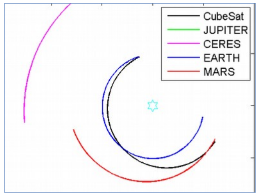
"E2M" sensitivity (N=5) at σ_{in} = 1"

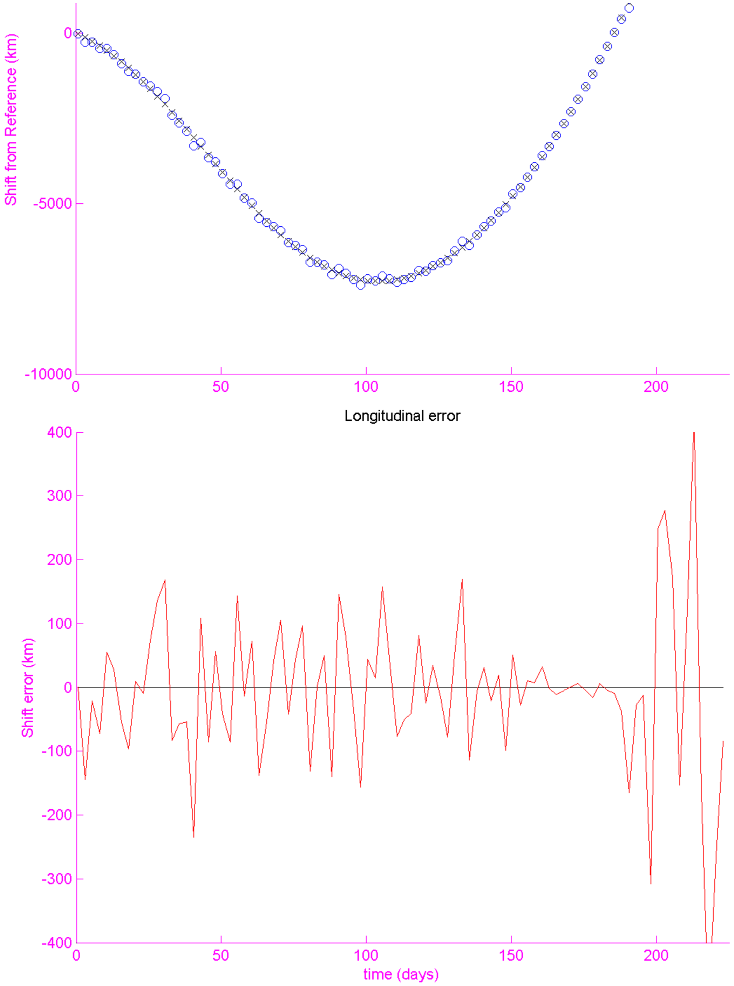
+1m/s on Y: the actual shift wrt T_E is larger over time => assumption of "small shift" not valid in late scenario

@ σ_{in} = 1 arcsec => Mean value σ_{out} = ~50km (transverse) .. ~150km (longitudinal)

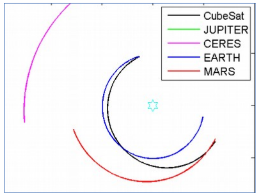


σ_{in} = 1 arcsec



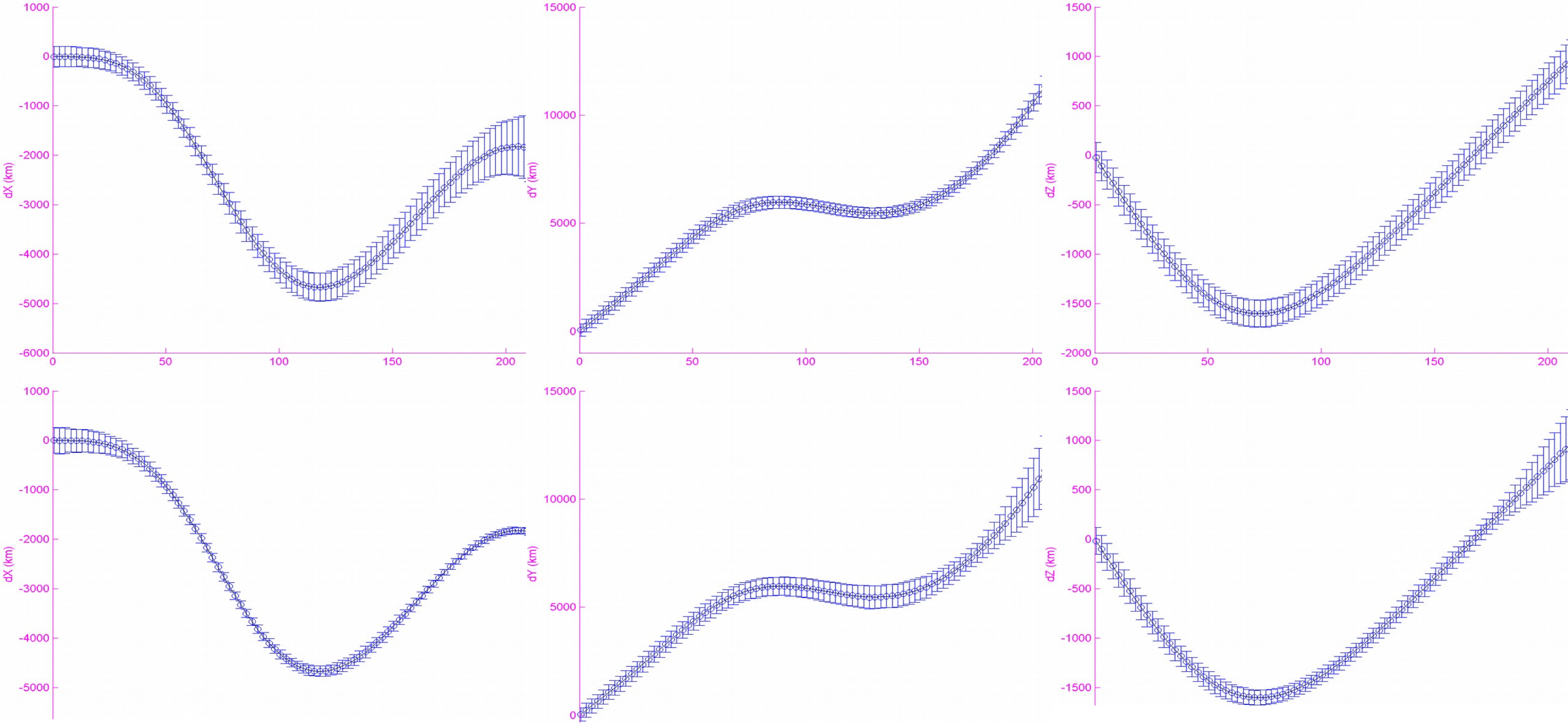


“E2M”, N=4 vs. N=5 (σ_{in} = 0.1")



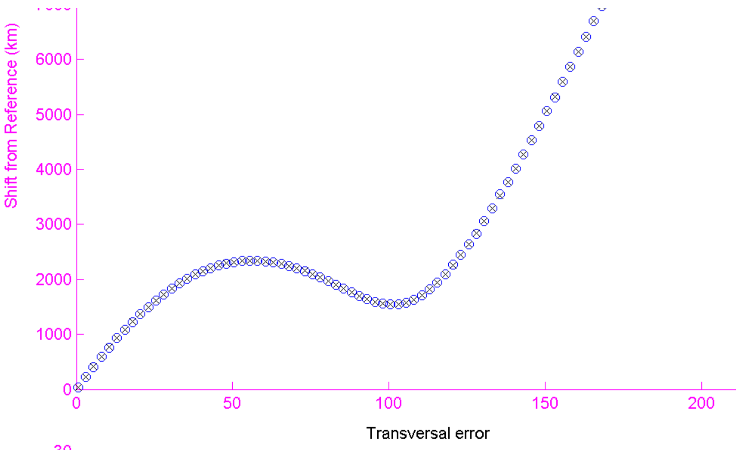
Bodies J-C-E-M (top, N=4)
vs.
Bodies E-C-M-J-E (bottom, N=5)

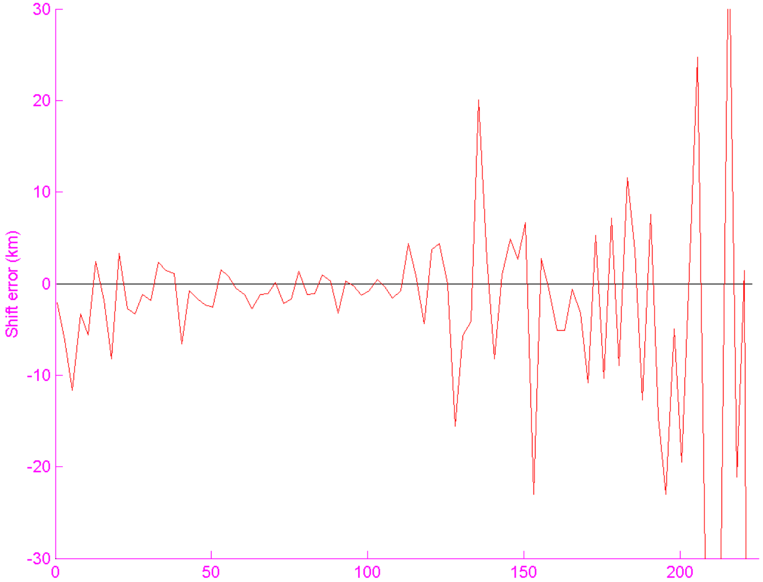
@ σ_{in} = 0.1 arcsec
=> No significant improvements in σ_{out} ~500..1000km



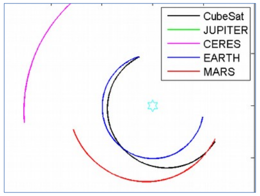
“E2M” transverse sensitivity at σ_{in} = 0.1"

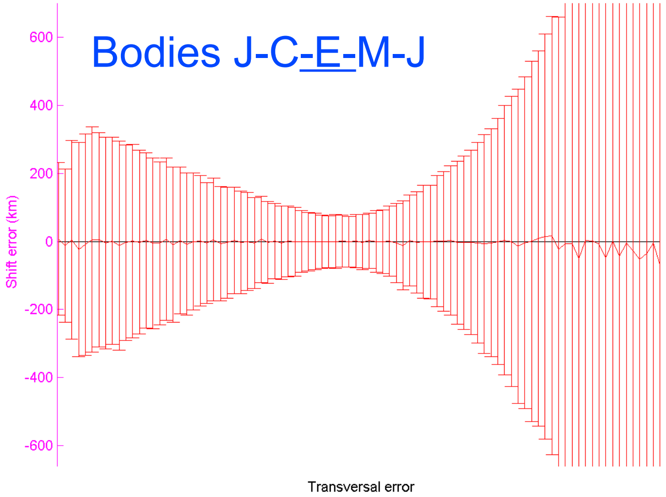
The selection of foreground bodies is still critical
@ σ_{in} = 0.1 arcsec => Mean value σ_{out} = 100..300 km (transverse)

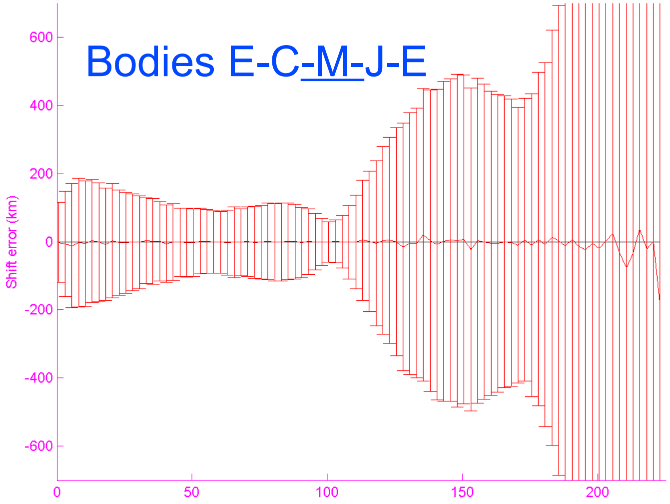




σ_{in} = 0.1 arcsec

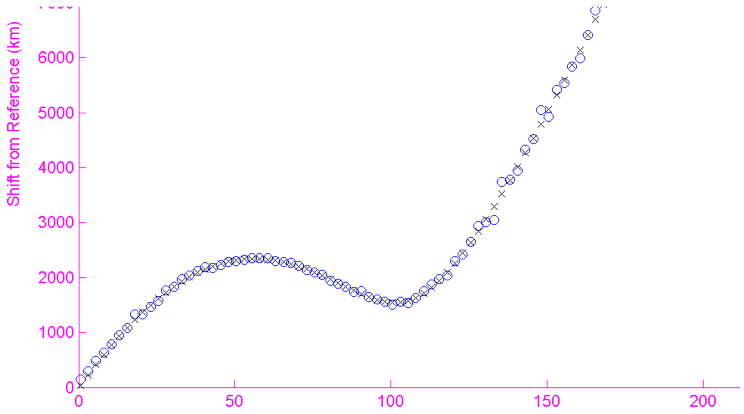



Bodies J-C-E-M-J

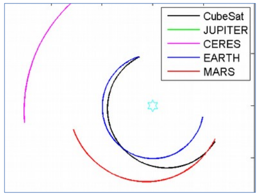

Bodies E-C-M-J-E

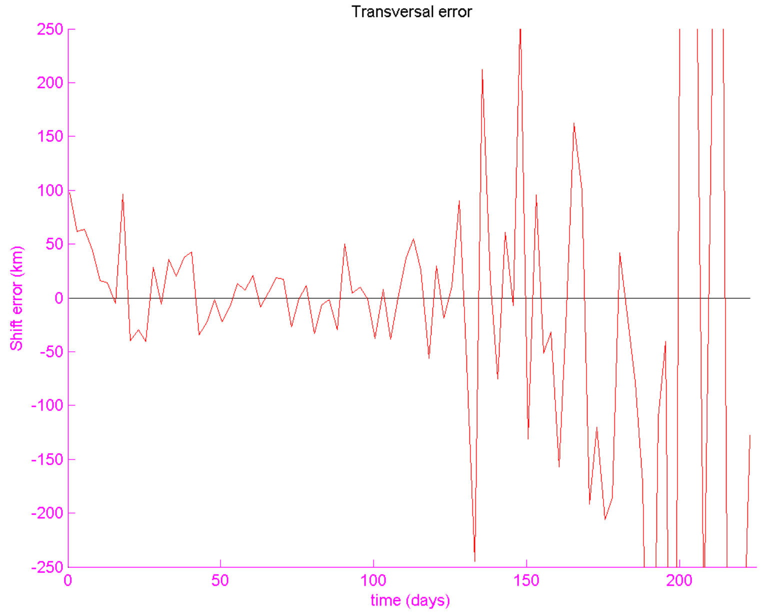
“E2M” transverse sensitivity at σ_{in} = 1"

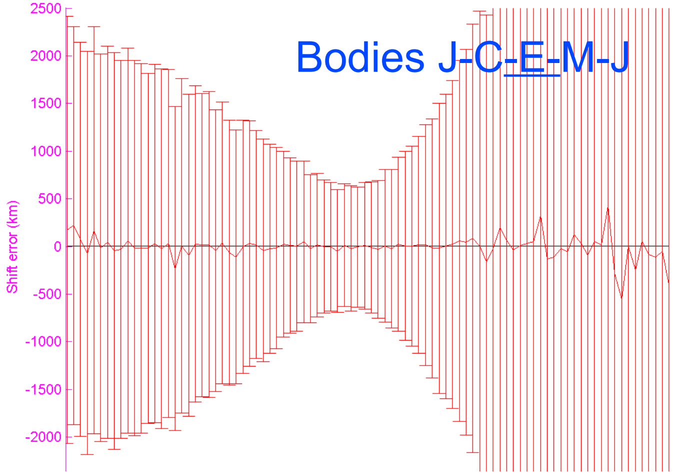
The selection of foreground bodies is still critical
@ σ_{in} = 1 arcsec => Mean value σ_{out} = 1000..2000km (transverse), non operational (?)



σ_{in} = 1 arcsec

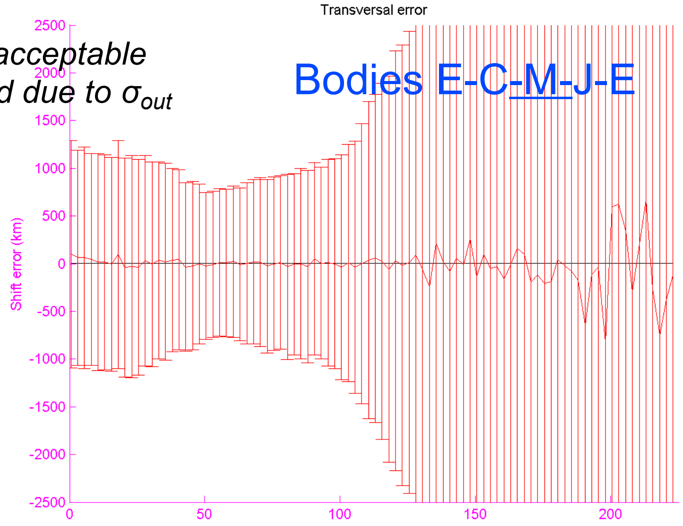






Bodies J-C-E-M-J

Mean value could be acceptable but it cannot be trusted due to σ_{out}



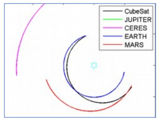
Bodies E-C-M-J-E

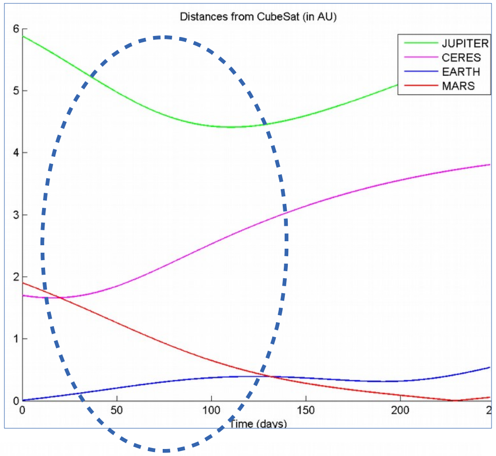
“E2M”: <δρ>$_{\text{foreground bodies}}$ at σ_{in} = 0.1"

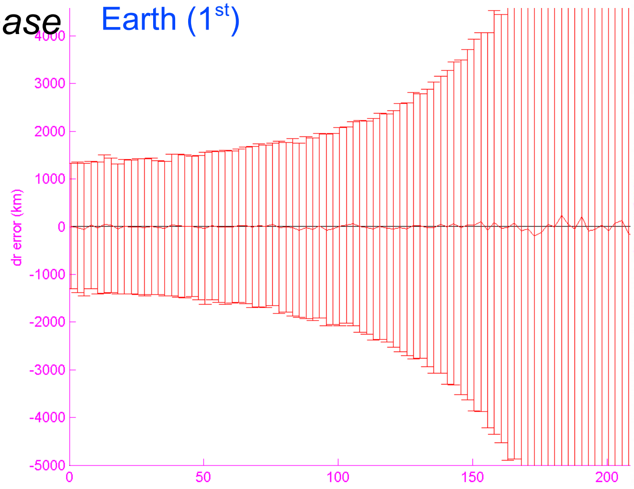
Not obvious + anti-intuitive! (after +1m/s at jettisoning, expected δρ range in 0..10'000 km)
1st and 5th found δρ to bodies have greater errors than 2nd, 3rd, 4th

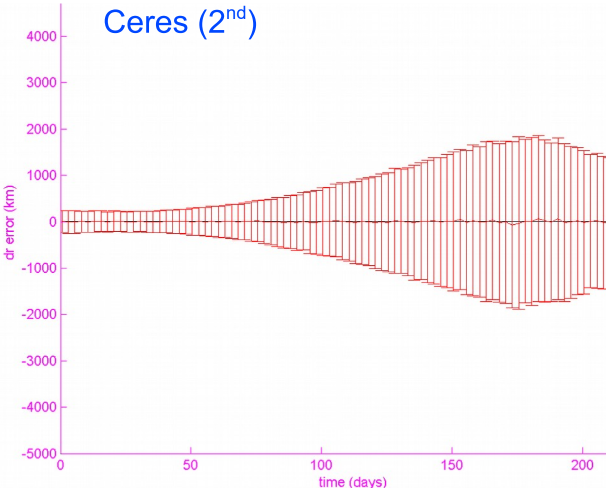
σ_{in} = 0.1 arcsec

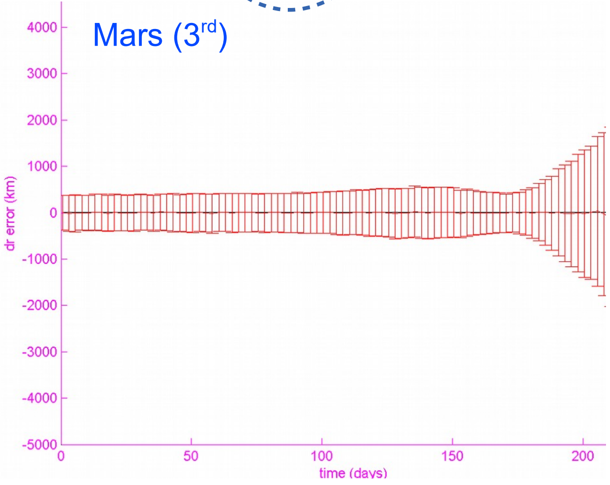
distance shifts are moderate, then increase

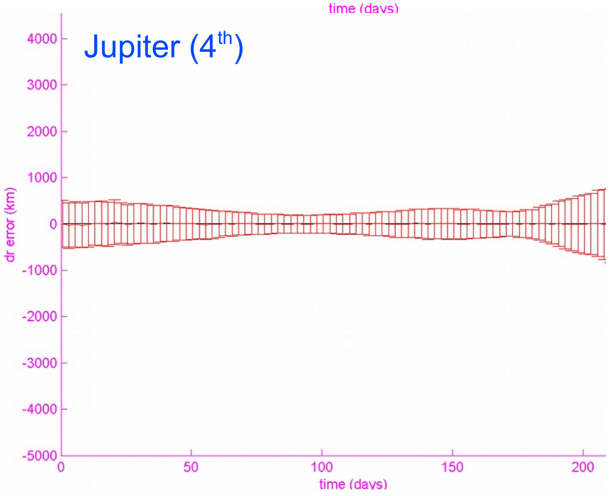


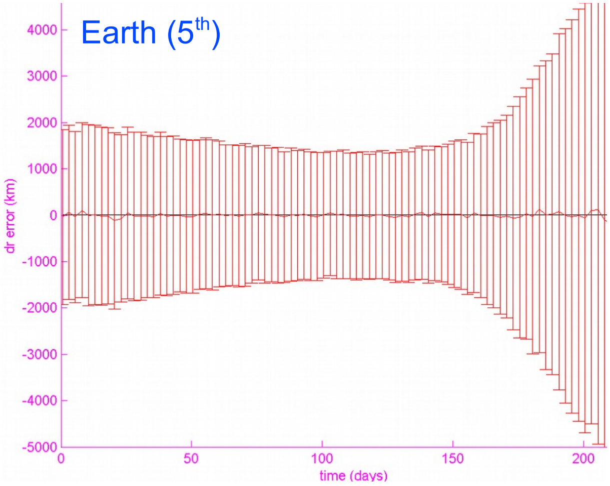



Earth (1st)


Ceres (2nd)

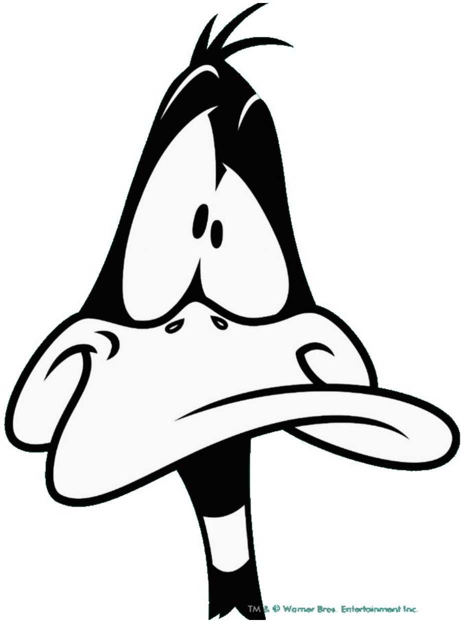

Mars (3rd)


Jupiter (4th)


Earth (5th)

Lessons learned

1. Context
2. Method
3. Simulation results
4. Lessons learned



Temporary assessments

- Lessons from “Y+1kY” fictional model
  - σ_{out} vs. σ_{in} is very sensitive, optical accuracy is the 1st driver
  - selection of foreground bodies is the 2nd driver
  - More favorable periods (in cruise) to perform OD
    - Sun direction not considered
    - 1D-measurements (radio-ranging?) not considered
- Lessons from “E2M” realistic model
  - The sensitivity seems to be well explained through “Y+1kY”
  - is $\underline{\sigma_{out}}$ ~200 km transversely acceptable to feed an Ext.Kalman Filter (EKF)?
    => $\underline{\sigma_{in}}$ =0.1" on optical measurement (object tracker with MCC?)
  - N=4 or N=5 measurements does not improve a lot:
    - The inversion finds a polynomial that joins noisy measurements
    - Instead: fit a “propagation model” through N ellipsoids of uncertainty, but…
      - » i.e. “polynomial regression”… linearity of an over-constraint system?
      - » Equivalent to EKF feeded with noisy (σ_{out}) locations?

Assumptions for Proximity Operations

Assumptions to be overcome:

1. No “constant velocity” => probably not an issue
2. No punctual foreground objects => Extended
3. Photometric dynamics for Foreground vs. Background

Main assumptions still valid:

- Multiple flying-legs in “free fall”
- Star tracking provides Attitude determination while spinning (stability makes interpolations valid)

Additional assumptions:

- Gravitation is unknown, but early images must be available
- Measurements performed “far” from the asteroids (few 10s km)
- Standard “OD sequence” at the end of a flying-leg

Conclusion: We've got a roadmap!

- Functional software-bench to propagate the errors
- The required accuracy depends on the “TCM” potential

- Study still in progress :
  - define & feed an Extended Kalman Filter
    - σ_{in}=0.1" with an “object tracker” => σ_{out} ~200km
    - Observable and Propagation models
    - Process noise, measurement noise (σ_{out})
  - select the N “best” observables
  - on-board “Steepest descent” algorithm
  - implement an OBC architecture (GERICOS/LESIA)
  - alternative approach? (polynomial regression to fit N ellipsoids)

- Need to adapt to the “proximity operations” context
  - Reference frame? Time sampling?
  - Adding 1D-radio measurements?

BIRDY Technology is also a student project: More than 54 students have participated from 2014 in France and in Taiwan

<u>Involved Institutions:</u> 1.Association Planète Mars, 2.Mars Society Switzerland, 3.Observatoire de Paris, 4.Laboratoire d’Etudes Spatiales et d’Instrumentation en Astrophysique, 5.Laboratoire Atmosphères, Milieux, Observations Spatiales, 6.Centre National de la Recherche Scientifique, 7.Institut de Mécanique Céleste et de Calcul des Ephémérides, 8.National Cheng Kung University, 9.LabEx Exploration Spatiale des Environnements Planétaires, 10.Centre d'Etudiant pour la Recherche et l’Exploration Spatiale, 11.Research University Paris Sciences Lettres, 12.Pierre and Marie Curie University, 13.Université Lille 1 Sciences et Technologies, 14.Institut Polytechnique des Sciences Avancées, 15.École d'Ingénierie des Sciences Aérospatiales, 16.Consortium Liquid Micro Pulsed Plasma Thruster, 17.KopooS Consulting Ind., 18.Ecole Centrale Lille, 19.Joint Institute for VLBI in Europe , 20.Ecole Centrale-Supelec

Involved actors *(chronological order, number in brackets = institution)*

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