On-board Orbit Determination for a Deep-Space CubeSat

Boris Segret
LESIA-ESEP, PSL / Paris Observatory, France

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

- Autonomous AOCS
  - Attitude Determination
  - Attitude Control
  - Orbit Determination
  - Orbit Control
  - ΔV computation
  - Trajectory correction maneuvers

(Quinsac et al., 2016)

(trajecory 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)
1st Context: Birdy in Deep-Space Cruise

Study Case = Earth-Mars-Earth free return trajectory

- Mission Preparation
- Deployment after IOI
- Earth-to-Mars
- Mars Flyby: First Datalink
- Mars-to-Earth = Earth-to-Mars
- End of Mission: Final Datalink

Science mode:
for instance autonomous Space Weather Probe

(trajecotory inspired by Dennis Tito for 2018)
2nd Context: Birdy in “Flying-legs”

Study case = released in situ by Mothercraft

Ground Segment:
- Propagator with Models-in-the-loop
- Next Flying-legs to Mothercraft

Flight Segment
- TCM: set new V~1m/s (1 day)
- Science mode (1 day ~80km)
  - Echo/Doppler (multiple S/C)
  - Imaging surface features
  - Optical astrometry
- Navigation mode (OD+OC)
- S-band TT&C to Mothercraft
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)
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Orbit Determination: Accuracy?

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Models-in-the-loop:
- gravitational
- non-gravitational
- expected

(A.Porquet, IMCCE, 2014)
Simplified Approach

\[ M \ast \tilde{X} - \bar{C} = \bar{0} \]
\[ \chi^2(\tilde{X}) = \| M \ast \tilde{X} - \bar{C} \|^2 \]
\[ \Rightarrow \min(\tilde{X} | \chi^2(\tilde{X})) ? \]

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)

**On-board Orbit Determination for a Deep-Space CubeSat**

without simplified approach

optical errors, validations in 03/2016

\[ \chi^2(\tilde{X}) = \| M \ast \tilde{X} - \bar{C} \|^2 \]

1st simulation on Earth-Mars in 10/2015 without optical errors, validations in 03/2016

(T. Mallet, DAA/NCKU, 2015)
Method for Monte-Carlo simulations

Multidimensional Minimizing:
(a) “Steepest Descent” algorithm
   *preferred for on-board software*
   *not implemented yet*
(b) or “Random search on a grid”
   *may be an alternative, not implemented yet*
(c) or MATLAB / OCTAVE “INV([C])”
   *likely not for on-board software*
   *implemented here for MC simulations*

\[
\begin{align*}
M \cdot \vec{X} - \vec{C} &= \vec{0} \\
\chi^2(\vec{X}) &= \| M \cdot \vec{X} - \vec{C} \|^2 \\
\Rightarrow \min(\vec{X} | \chi^2(\vec{X})) &= \min(\vec{X} | \| M \cdot \vec{X} - \vec{C} \|^2)
\end{align*}
\]

(a) steepest descent along $\nabla \chi^2(\vec{X})$
(b) random search while evaluating $\nabla \chi^2(\vec{X})$
(c) new 19x19 linear system
\[
\nabla \chi^2(\vec{X}) = 0 \Leftrightarrow [C].\vec{X} = \vec{Y} \Leftrightarrow \vec{X} = [C]^{-1}.\vec{Y}
\]

\[
\vec{X} = \begin{pmatrix}
\delta(x) \\
\delta(y) \\
\delta(z) \\
\delta r_{j=1,4}
\end{pmatrix}
\]

“i” measurements
\(i=1..4\) for 19 unknowns

“j” foreground bodies
4 from N foreground bodies
Earth-to-Mars “E2M”: initial results...

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T_0” ➔ do we correctly reconstruct the expected shift wrt T_0?
Monte-Carlo series to estimate the mean reconstructed value <X>=f(σ_{in})

\[ \text{accuracy measurement } \sigma_{in} \ll 1 \text{ arcsec} \]
Earth-to-Mars “E2M”: … and limits

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T₀”
→ do we correctly reconstruct the expected shift wrt T₀?

Monte-Carlo series to estimate the mean reconstructed value <X>=f(σ_{in})

accuracy measurement σ_{in} = 1 arcsec
Earth-to-Mars “E2M”: … and limits

If +1m/s is applied on Y-axis at jettisoning wrt Reference Trajectory “T₀” ➔ do we correctly reconstruct the expected shift wrt T₀?
Monte-Carlo series to estimate the mean reconstructed value <X>=f(σ_{in})

accuracy measurement σ_{in} = 15 arcsec
Elementary dynamic model “Y+1kY”
Elementary dynamic model “Y+1kY”

Rectilinear trajectory of CubeSat at 30km/s along 3 AU with 4 fictional “foreground Bodies”
"Y+1kY" dispersions even at small $\sigma_{in}$

The actual shift is small and constant (1000km) => assumption of "small shift" is not involved (Taylor dev. at 1st order)
Numeric degeneracy is likely involved, due to small angular variations with large distances (begin & end).

$\sigma_{in} = 0 (!)$
“Y+1kY” dispersions even at small $\sigma_{in}$

$\sigma_{in} = 10^{-5}$ arcsec (!)

$\sigma_{out}$ on dY *and* dVy, dVx!

$\sigma_{out}$ larger at large distances, on dV as well
"Y+1kY" dispersions even at small $\sigma_{in}$

$\sigma_{in} = 10^{-3}$ arcsec (!)

$\sigma_{out}$ on $dY$ *and* $dVy, dVx$!

$\sigma_{out}$ larger at large distances, on $dV$ as well
“Y+1kY” dispersions even at small $\sigma_{in}$

$\sigma_{in} = 0.1$ arcsec

$\sigma_{out}$ on dY and dV, dV_x.

$\sigma_{out}$ larger at large distances, on dV as well.
Realistic model “E2M” with small $\sigma_{in}$

$\sigma_{in} = 0.1 \text{ arcsec}$
and
$\sigma_{in} = 1 \text{ arcsec}$
"E2M" dispersions at small $\sigma_{in}$

+1m/s on Y: the actual shift wrt T0 is larger over time => assumption of "small shift" not valid in late scenario @ $\sigma_{in} = 0.1$ arcsec => Mean value ~10km accurate (wrt a few 1000s km expected) in transverse or longitudinal directions

$\sigma_{in} = 0.1$ arcsec
“E2M” dispersions at small $\sigma_{in}$

+1 m/s on Y: the actual shift wrt T0 is larger over time => assumption of “small shift” not valid in late scenario
@ $\sigma_{in} = 1$ arcsec => Mean value ~100km accurate (wrt a few 1000s km expected) in transverse or longitudinal directions

$\sigma_{in} = 1$ arcsec

Transversal shift

Longitudinal shift
“E2M”: \(<\delta x, \delta y, \delta z>\) at small \(\sigma_{in}\)

\[\sigma_{in} = 0.1 \text{ arcsec}\]

\[\Rightarrow \sigma_{out} \approx 300 \text{ m (X,Z)} \ldots 500 \text{ m (Y)}\]

better results in the middle of the cruise?
“E2M”: \( <\delta x, \delta y, \delta z> \) at small \( \sigma_{in} \)

\[
\sigma_{in} = 1 \text{ arcsec} \\
\Rightarrow \sigma_{out} > 2 \text{km (Y)} \ldots 4 \text{km (X,Z)} !!!
\]

Mean value could be acceptable but it cannot be trusted due to \( \sigma_{out} \).
"E2M": $<\delta r>_{\text{foreground bodies}}$ at small $\sigma_{\text{in}}$

$\sigma_{\text{in}} = 0.1$ arcsec
$\Rightarrow \sigma_{\text{out}} \approx 500$ m

Distance shifts are moderate, then increase

$\sigma_{\text{out}}$ few 100s of km
“E2M”: $<\delta r>$ foreground bodies at small $\sigma_{in}$

$\sigma_{in} = 1$ arcsec

$\Rightarrow \sigma_{out} \sim 500$ m

*distance shifts are moderate, then increase*
Velocities vary during On-board OD:
at least 1° in direction
and +/- 0.1 m/s in intensities

\[ \langle \delta V_x, \delta V_y \rangle \text{ at small } \sigma_{in} \]

\[ \sigma_{in} = 0.1 \text{ arcsec} \implies \sigma_{out} > 2 \ldots 5 \text{ m/s} \]

\[ \sigma_{in} = 1 \text{ arcsec} \implies \sigma_{out} > 20 \ldots 50 \text{ m/s (!!)} \]
Temporary assessments

• Lessons from “Y+1kY” fictional model
  ➢ Some dispersion with $0 \sigma_{\text{in}} \rightarrow$ Numeric degeneracy (INV function)
  ➢ $\sigma_{\text{out}}$ vs. $\sigma_{\text{in}}$ is very sensitive, optical accuracy is the 1\textsuperscript{st} driver
  ➢ “close” foreground bodies is the 2\textsuperscript{nd} driver for the overall accuracy
  ➢ Shifts $10^2..10^3$km vs. $10^{-5}..10^{-6}$km/s $\rightarrow$ dimensionless approach

• Lessons from “E2M” realistic model
  ➢ The sensitivity seems to be well explained through “Y+1kY”
  ➢ Periods in the cruise seem more favorable to run the on-board OD
  ➢ Uniform velocity during OD is \textit{not} any realistic assumption
  ➢ (direction of the Sun was not considered)
Conclusion: We've got a roadmap!

- Study about On-board Orbit Determination is still in progress: need to improve by 2-3 orders of magnitude
  - on-board “Steepest descent” algorithm
  - non-uniform velocity, N=5 measurements needed
  - select the N “best” observables

- The required accuracy depends on the “TCM” potential

- A software-bench is functional to quantify the error propagation

- Need to adapt and assess in the “asteroid” context

- Anticipate an Extended Kalman Filter:
  - The right physical model? (sampled, analytical, ...)
  - Set-up of the noise co-variance matrices? (process noise, measurement noise)

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


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

- Students to date (05/2016): J.Vannitsen(8), A.Ansart(15,8), Q.Tahan(15,8), M.Agnan(10,8), J.Velardo(10,3), A.Deligny(10,3), G.Quinsac(11,10,3), A.Porquet(10,3,7), A.Lassissi(10,3), N.Gerbal(15), O.Sleimi(14,8), S.Durand(10,3,4), R.Klajzynger(18), J.Diby(18,10,3), T.Mallet(18,8), J.Foissofa(18), L.Orsatto(18), E.Colin(18), N.Heim(18), J.Lin(8,10,3), A.Tsai(8), A.Chen(8), J.Tsai(8), T.Chang(8), D.Boisseau(15,8), A.Sibue(11), J.Evens(11), A.Schnitzer(10,3), S.Thibault(10,3), H.Poincelin(10,3), S.Delaire(20), I.Berber(20), T.Charay(20), A.Nirello(20), A.Sabir(20), M.Bougadouha(20), F.Le-coz(20), M.Gonzalez(20), M.Romero-Lopez(20), D.Gonzalez(20), I.Ouattara(8), K.Chun(8), F.Rizzitelli(8), E.Fournier-Bidoz(20), S.Wohlgemuth(20), F.Orstdius(20), C.Shen(18), J.Franel(18), T.Guidez(18), S.Sueur(18), A.v.Wesemael(18), B.Kalidas(18), R.Sabrekov(18), N.Traore(10,3,4).

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