Propagation of satellite orbit modelling deficiencies into the global GNSS solutions – simulation-based study

Maciej Kalarus, Rolf Dach, Arturo Villiger, and Adrian Jaeggi

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Abstract

The Non-Gravitational Perturbations (**NGP**), out of which the Solar Radiation Pressure (**SRP**) is the largest, have a significant impact on GNSS satellite orbits. In addition to the SRP, other relevant perturbations should also be taken into account, as this may result in substantial modelling errors if underestimated. Particularly, the force model should also consider Earth's albedo in terms of the emitted and reflected radiation, as well as a physical satellite model (box-wing) with its optical and thermal properties.

GNSS satellite orbit modelling may suffer from deficiencies for various reasons (simplification of the complexity of the used model or uncertainty of the input information). The impact of such model errors on global GNSS data analyses is assessed in an error propagation study based on simulated observations. The influence of artificially introduced orbit errors on estimated parameters, e.g. Earth rotation parameters, orbit parameters (initial conditions and dynamical orbit parameters), station coordinates, station-wise troposphere parameters, as well as receiver and satellite clock corrections is investigated.

In this study a dedicated simulation environment is used to analyse the relation between results (e.g. orbits, satellite clocks, Earth orientation parameters) and certain individual shortcomings in the **NGP** models. In addition, apart from a commonly used epoch-wise clock estimation, the analytical models for satellite clock corrections are introduced in order to exploit the high stability of the passive H-masers on-board the Galileo satellites. The simulation environment also allows to assess the impact of float- versus fixed-ambiguities. Finally, simulation-based analyses offer an excellent framework for more detailed validations and further refinements of the physical satellite models, which will consequently stabilize the global solution.

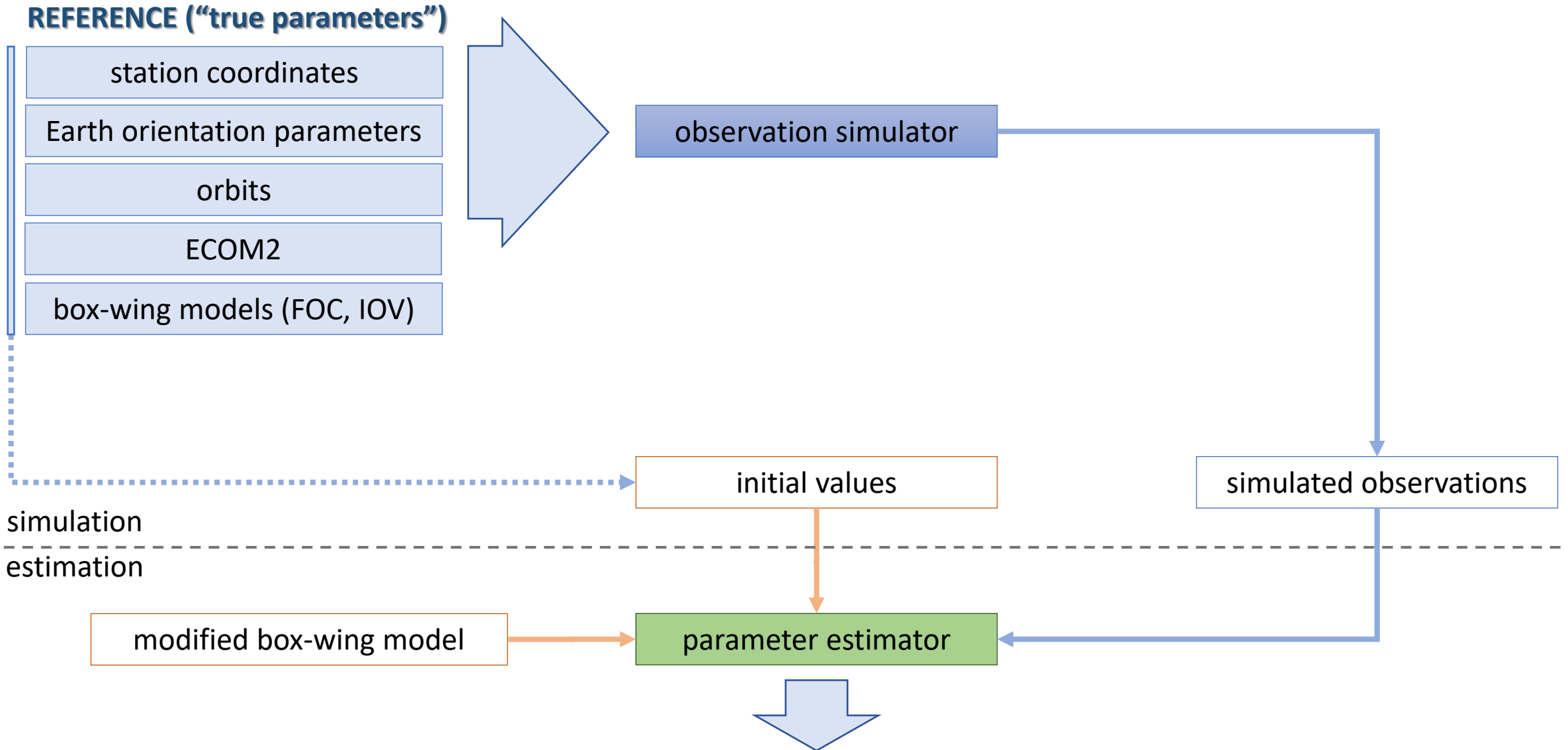Astronomical Institute, University of Bern

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Motivation

- understand how the results of precise orbit determination (POD) are affected by mismodelled non-gravitational forces acting on the satellites

- assess how the potential exploitation of the stable passive H-masers (by applying linear clock model) may influence the POD solution in a presence of mismodelled non-gravitational forces

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Simulation setup – observation sites, satellite constellation
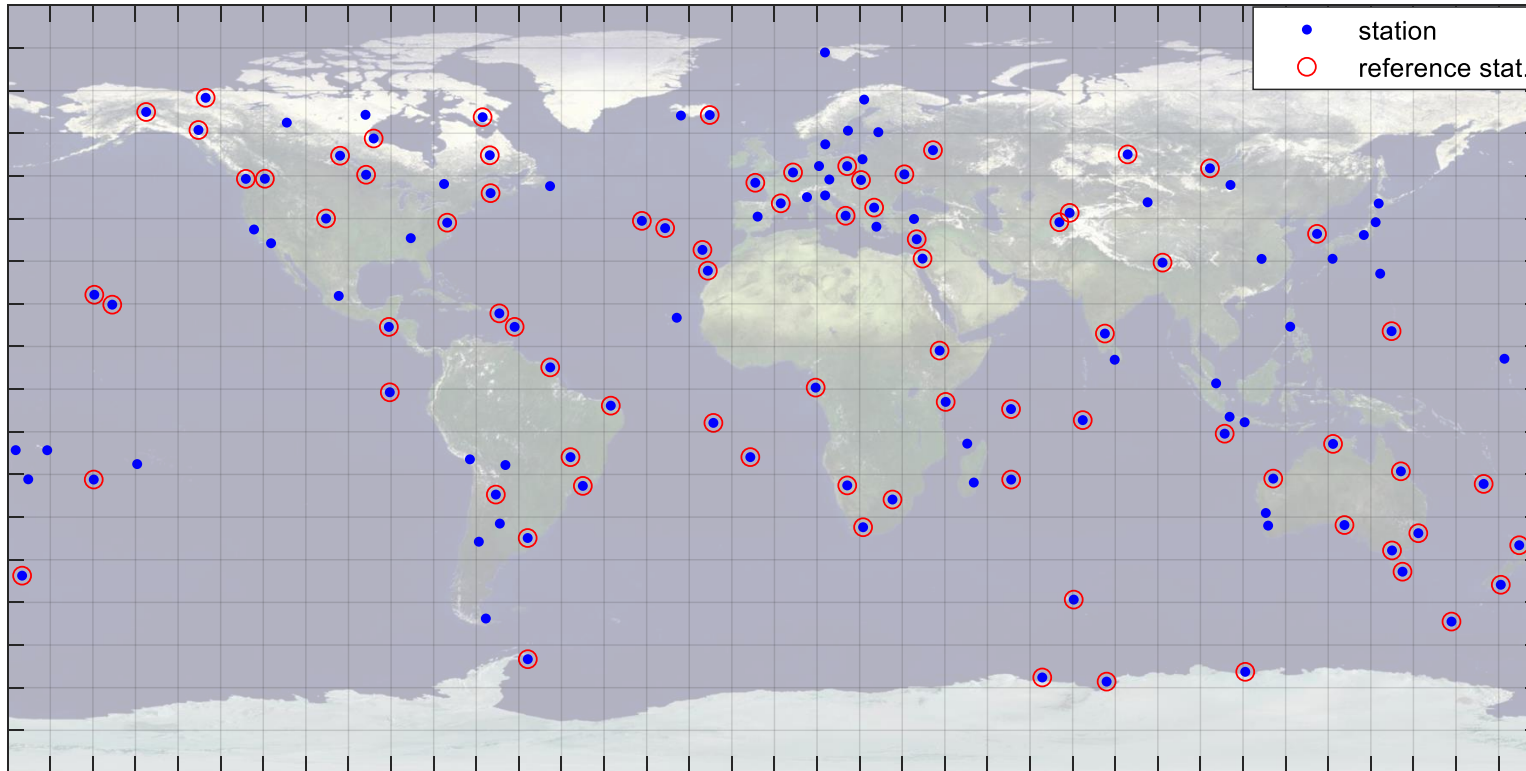
- stations contributing to the solution: 129 stations (79 reference stations)
  - phase observations with 1mm noise level (366 daily batches)

- Galileo constellation (as in 2020):
  - 3x IOV (In Orbit Validation)
  - 21x FOC (Full Operational Capability)   (including 2 satellites on elliptical orbits)

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Simulation setup – processing scheme (simulation)

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Simulation setup – processing scheme (estimation)

simulation

estimation

initial values

simulated observations

modified box-wing model

REFERENCE box-wing model
(for validation)

parameter estimator

ESTIMATED CORRECTIONS

station coordinates

orbits

ECOM2

satellite clocks

Earth orientation parameters

identification of characteristic signatures corresponding to the modified parameters of the box-wing model

ESTIMATION OPTIONS

epoch-wise satellite clock

versus

satellite clock modelling
$\Delta CLK = K_0 + K_1 u$

float ambiguity estimates

versus

all ambiguities resolved

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Simulation setup – processing scheme (estimation details)

EOP: Earth Orientation Parameters

orbit — initial values — station coordinates, EOP, …

simulated observations

simulation
— —
estimation

parameter estimator

modified box-wing model → initial orbit fit — orbit, ECOM2 → full estimation process

orbit & ECOM2

ESTIMATION OPTIONS

ESTIMATED CORRECTIONS
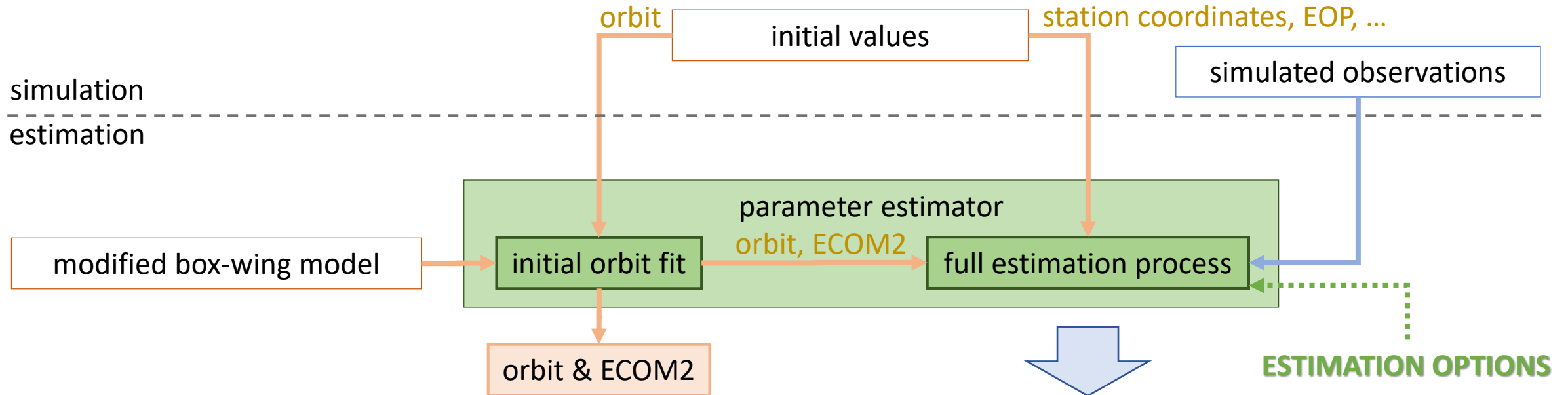
This solution indicates how much of the mismodelled non-gravitational terms can be captured by ECOM2 parameters.

This solution indicates how the mismodelled non-gravitational forces impact POD estimates.

Mismodelled NGP not absorbed by ECOM2 will affect other parameters like station coordinates, clock corrections, EOPs, etc.

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Simulation setup – ECOM model used

CODE: Center for Orbit Determination in Europe
ECOM: Empirical CODE Orbit Model

ECOM2 frame:

$\mathbf{D}$: satellite-Sun direction

$\mathbf{Y}$: along the solar panels

$\mathbf{B}$: completes the right-handed system

ECOM2 terms (empirical accelerations):

D_0, Y_0, B_0 : constant terms

D_{1S}, B_{1C}, B_{1S} : one per revolution terms (cosine, sine)

D_{2C}, D_{2S} : two per revolution terms (cosine, sine)

$$ECOM2 = \begin{cases} D_0 + D_{2C} + D_{2S} \\ Y_0 \\ B_0 + B_{1C} + B_{1S} \end{cases}$$

$$ECOM2\text{-}D1 = \begin{cases} D_0 + D_{2C} + D_{2S} + \boxed{D_{1S}} \\ Y_0 \\ B_0 + B_{1C} + B_{1S} \end{cases}$$

active if $|\beta| < 12^o$

$$ECOM2\text{-}YD1 = \begin{cases} D_0 + D_{2C} + D_{2S} + \boxed{D_{1S}} \\ \boxed{Y_0} \\ B_0 + B_{1C} + B_{1S} \end{cases}$$

active in eclipses to capture thermal effects during Earth's shadow transitions

active in eclipses for the Galileo FOC satellites to capture the thermal imbalance between the +Y and –Y faces of these spacecraft

β: elevation of the Sun with respect to the orbital plane

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Simulation setup – non-gravitational perturbations acting on the satellite (example)

Satellite box-wing model:

- **size (area of each satellite box plane, area of solar panels)**
- mass
- thermal properties
- surface optical properties
  - diffuse reflection coefficients
  - specular reflection coefficients

Solar irradiance

~1nm/s²

~0.6nm/s²

navigation antenna thrust

~100nm/s²

thermal radiation

~1nm/s²

Earth radiation (thermal and visual)
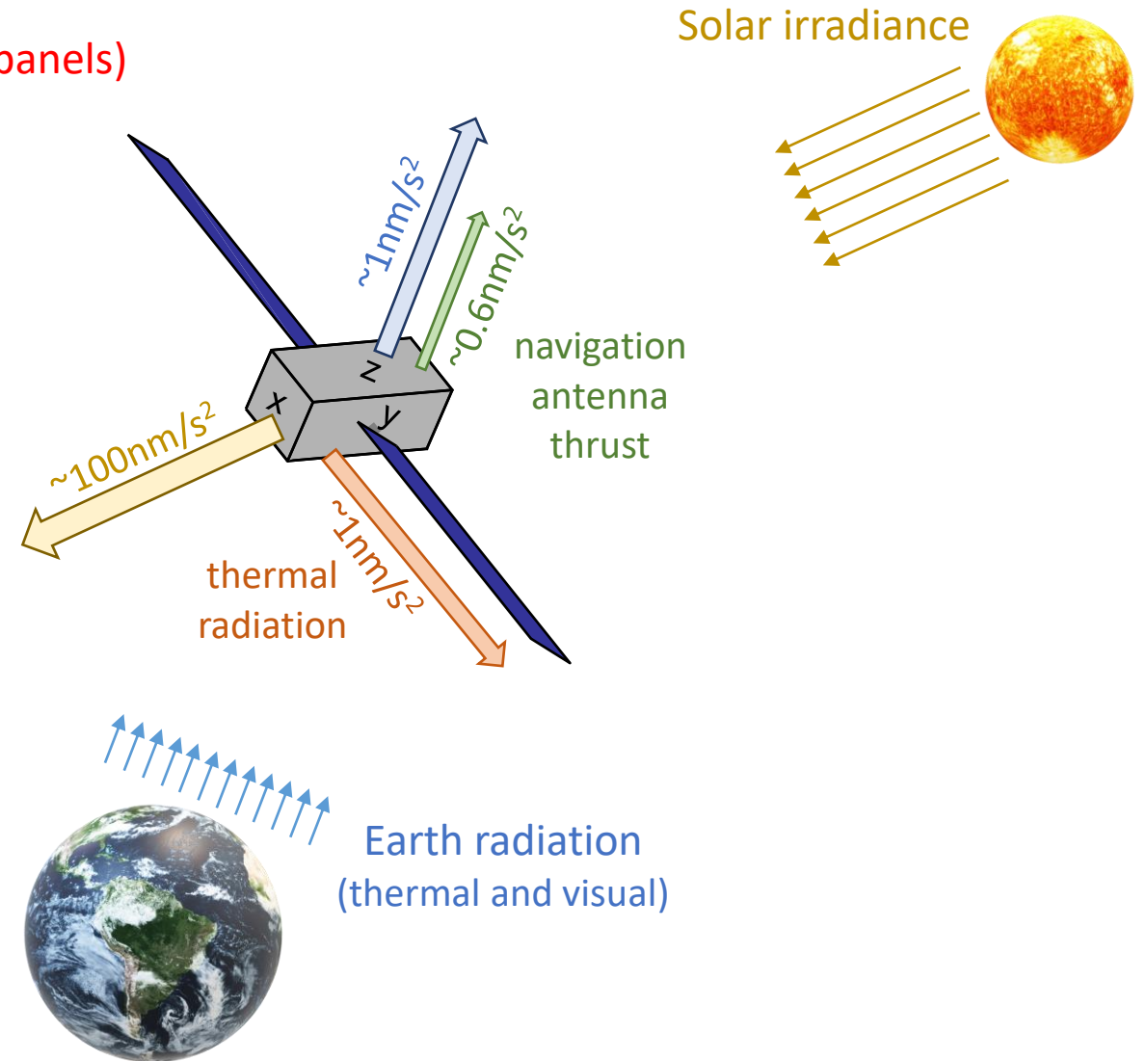
In this study, the propagation of uncertainties in a box-wing model (currently limited to the size of the plates) into a GNSS solution is investigated.

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Simulation setup – box-wing mismodelling
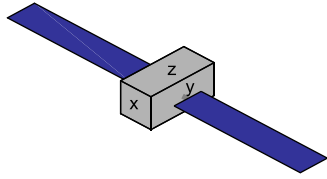
REFERENCE satellite box-wing model (used to generate **REFERENCE** solution)

ref. https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata

modified box-wing models

case 1
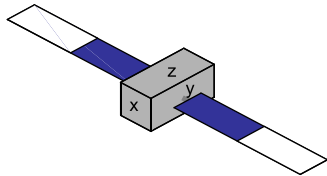
area of solar panels reduced by 50%

case 2
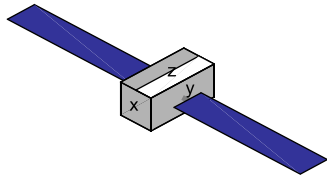
area of plane **-z** and **+z** (facing the Earth's surface) reduced by 50%
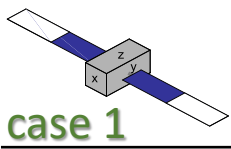
case 3
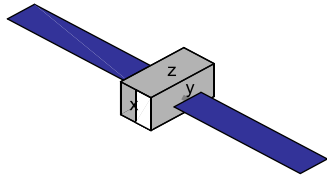
area of plane **-x** and **+x** reduced by 50%

Note:
    Substantial box-wing mismodelling was applied to emphasise the effect in the solution. This can be scaled down to more reasonable values.

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Results – residuals of initial orbit fit

RMS [mm] (average over the year)

R [mm] (radial)

β of orbital planes [deg]

S [mm] (along track)

W [mm] (out of plane)
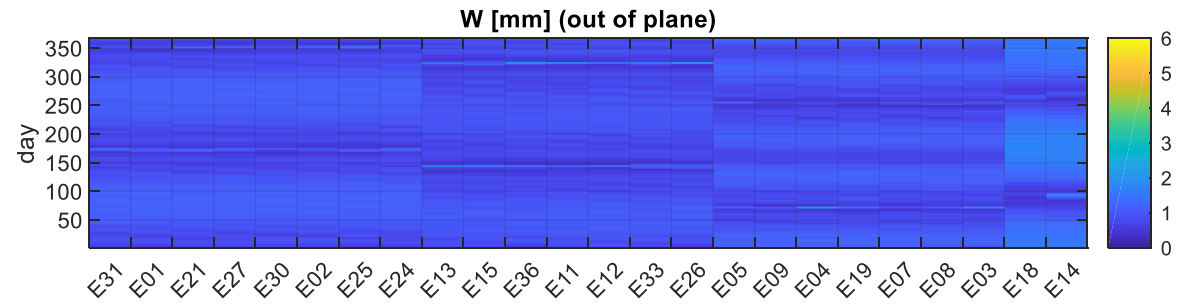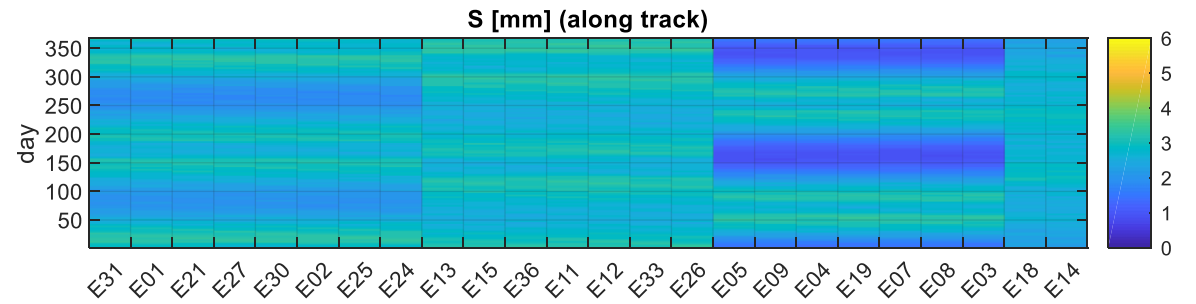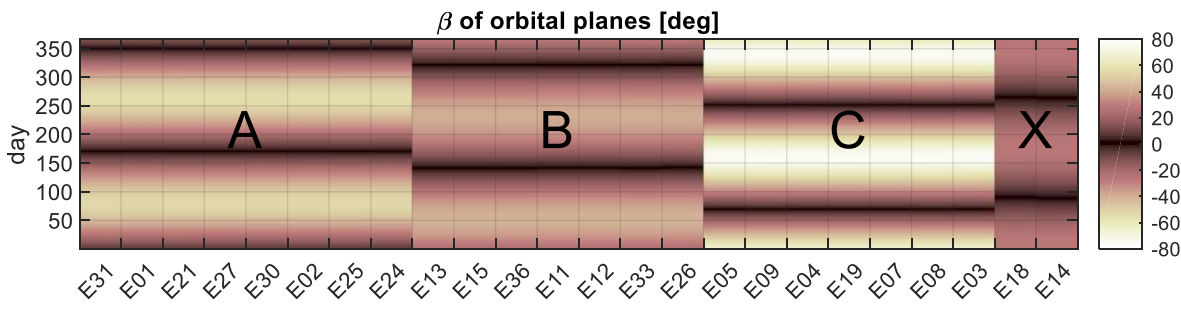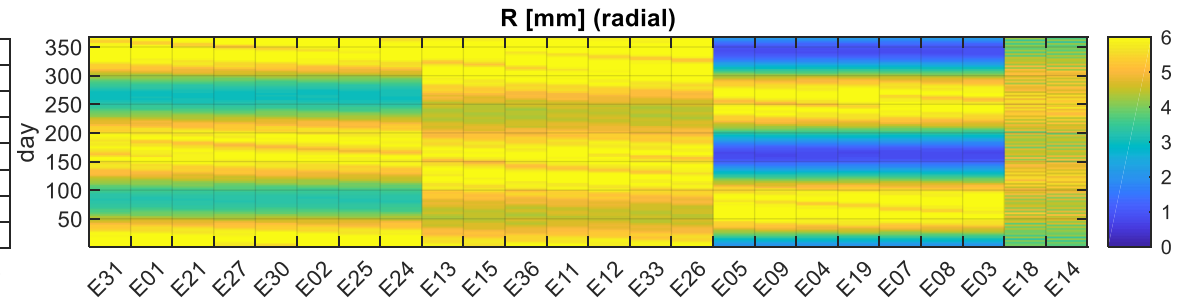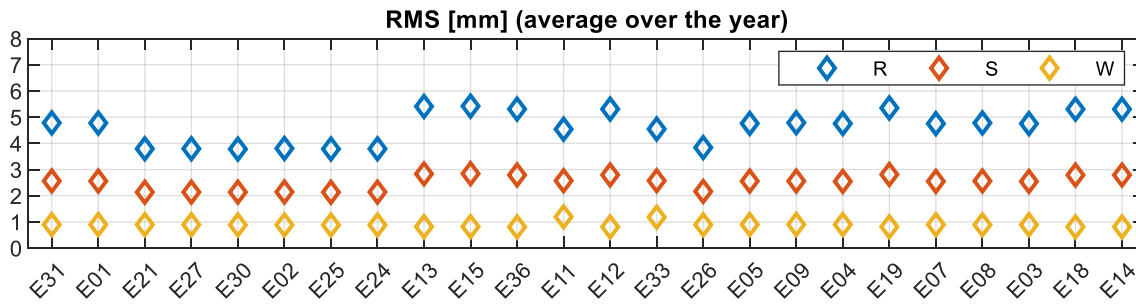
- ECOM2 cannot fully capture mismodelled NGP
- ECOM2 performs better for higher β angles in case the NGP model assumes incorrect area of solar panel
  (in hypothetical case of β=90° NGP mismodelling would be fully captured by D_0 coefficient)

Note: satellites are ordered according to the orbital plane and the slot

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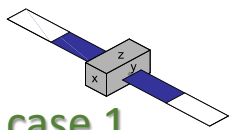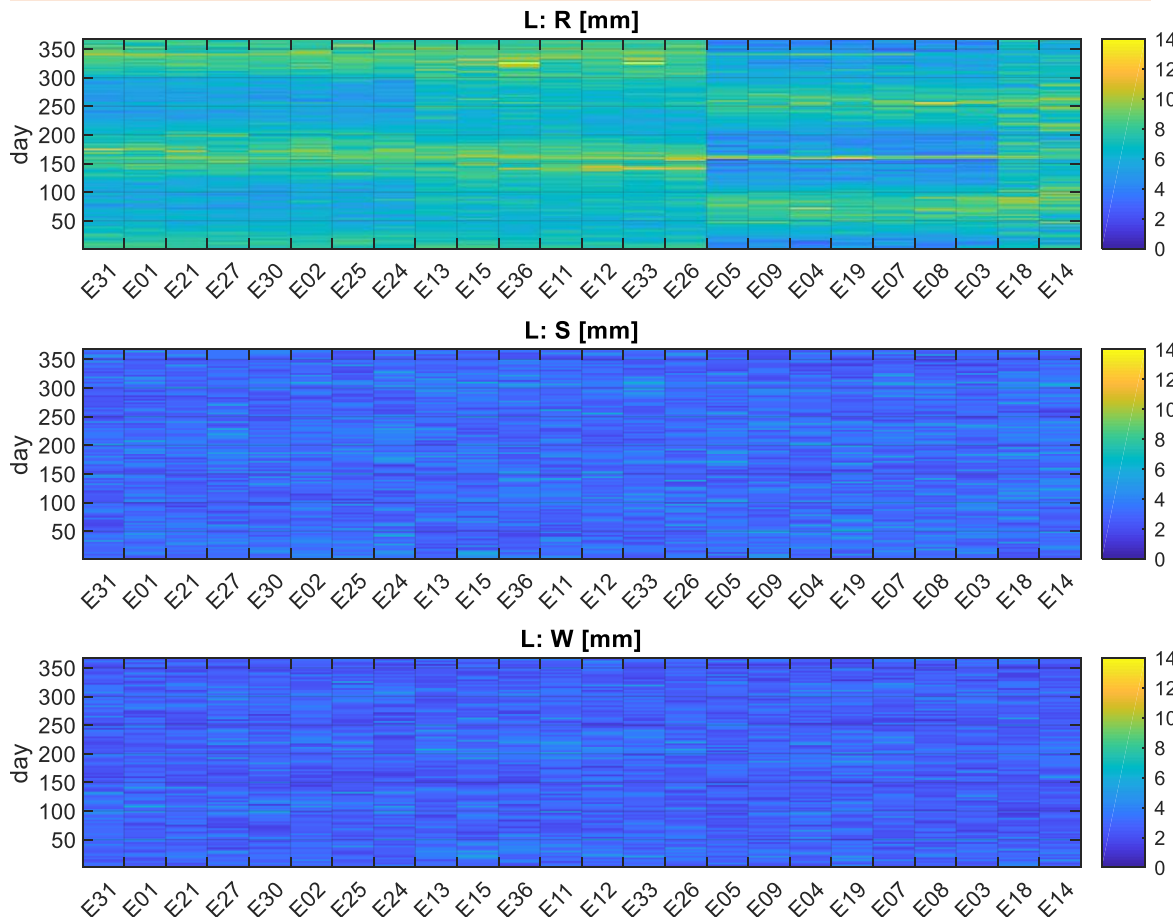
Results – orbits: RMS error (ambiguities resolved)
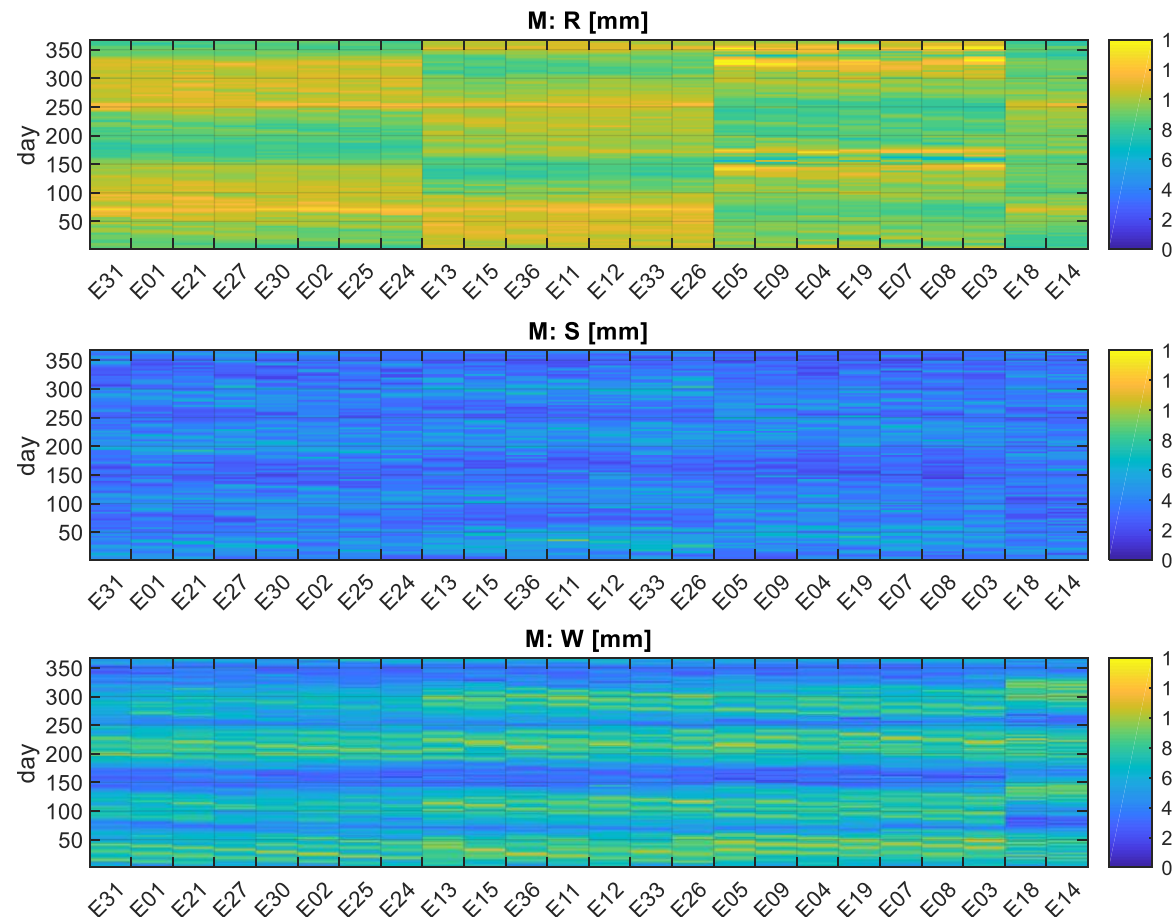
- clock modelling considerably reduces number of estimated parameters
  (e.g. for one satellite the number of parameters drops from 288 epoch-wise (every 5 min.) clock corrections to 2 values: offset and drift)
- orbit errors can be absorbed by epoch-wise estimated satellite clock corrections but not when the clocks are modelled

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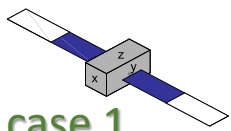
Results – orbits: RMS error (float ambiguities)
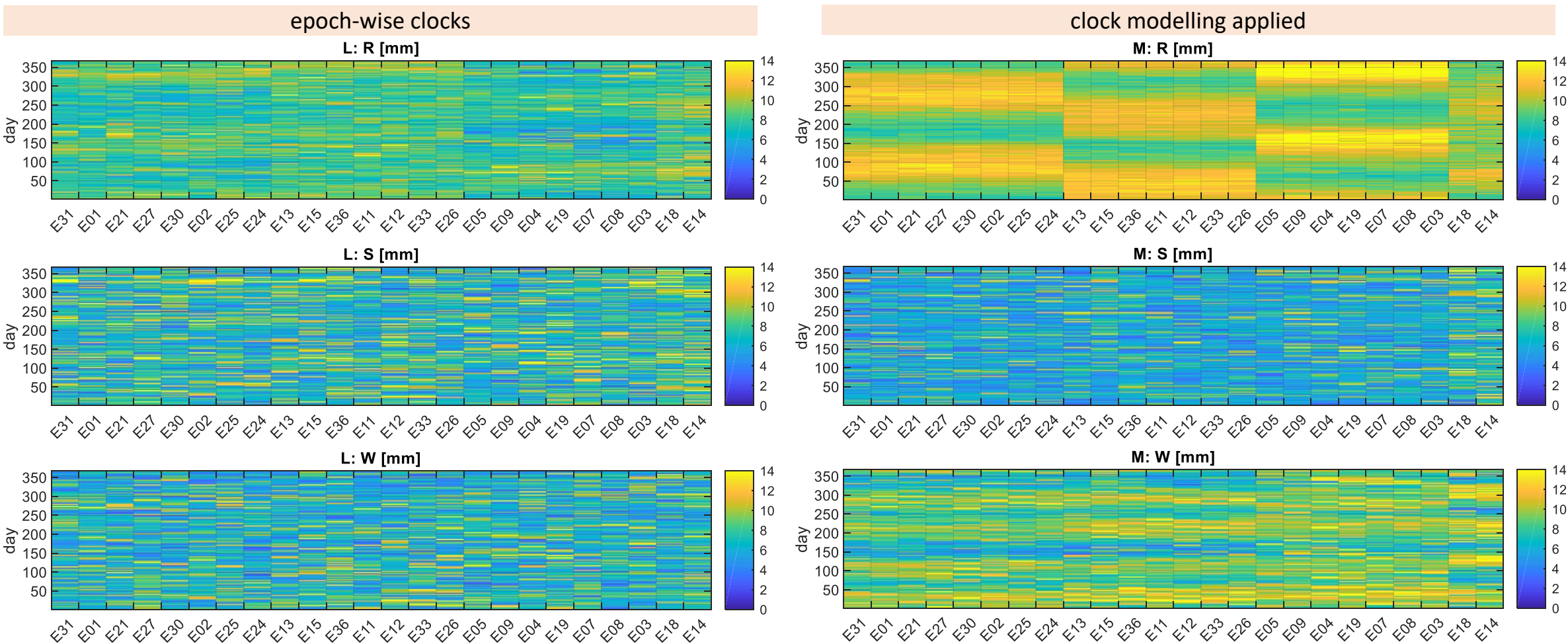
- also ambiguity parameters estimated to their real value can absorb a part of the orbit mismodelling
  (compare to previous slide)

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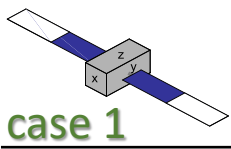
Results – orbits (summary)

RMS values averaged over the year
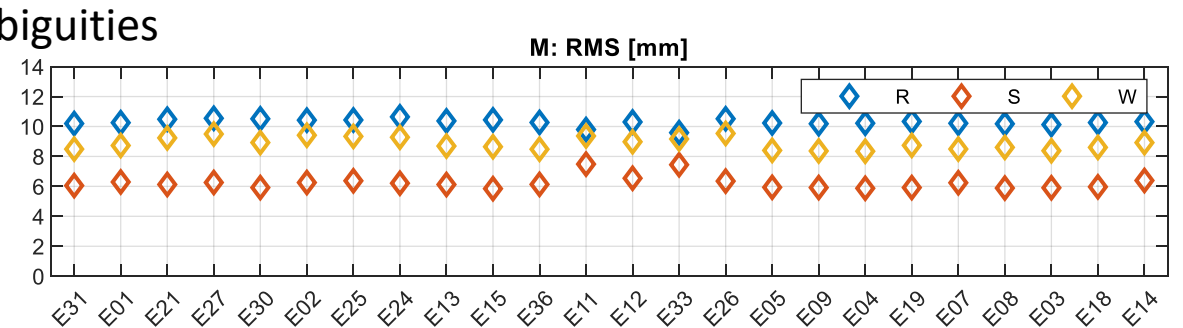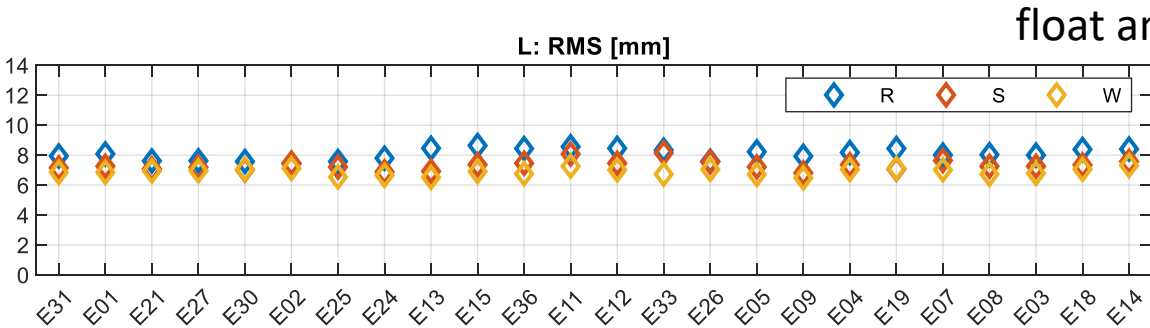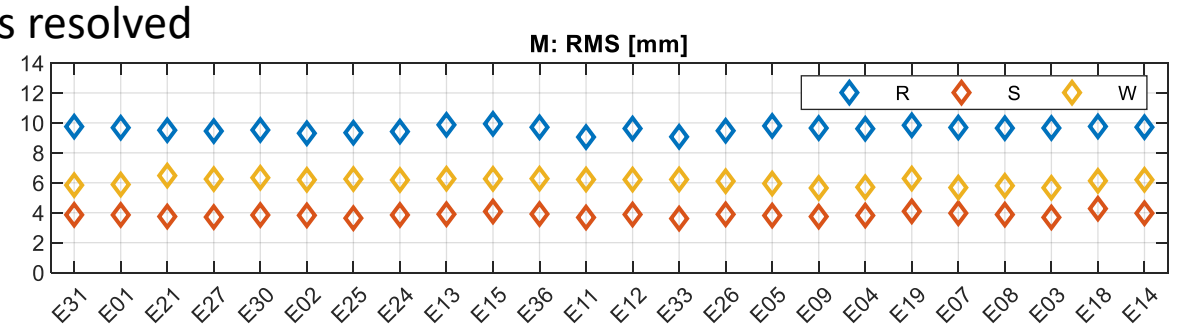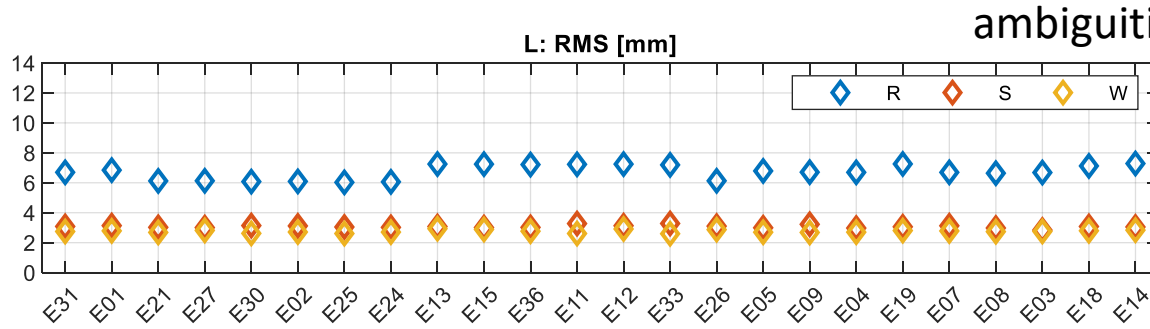
- estimation strategy (including applied models, constraints, …) has a clear impact on the results
- the more degrees of freedom is provided by the parametrization (epoch-wise satellite clock corrections, estimated ambiguity parameters freely estimated as real numbers), the more from the (mainly radial) orbit errors is absorbed.

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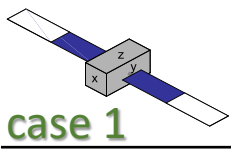
Results – ECOM2 constant terms (ambiguities resolved)
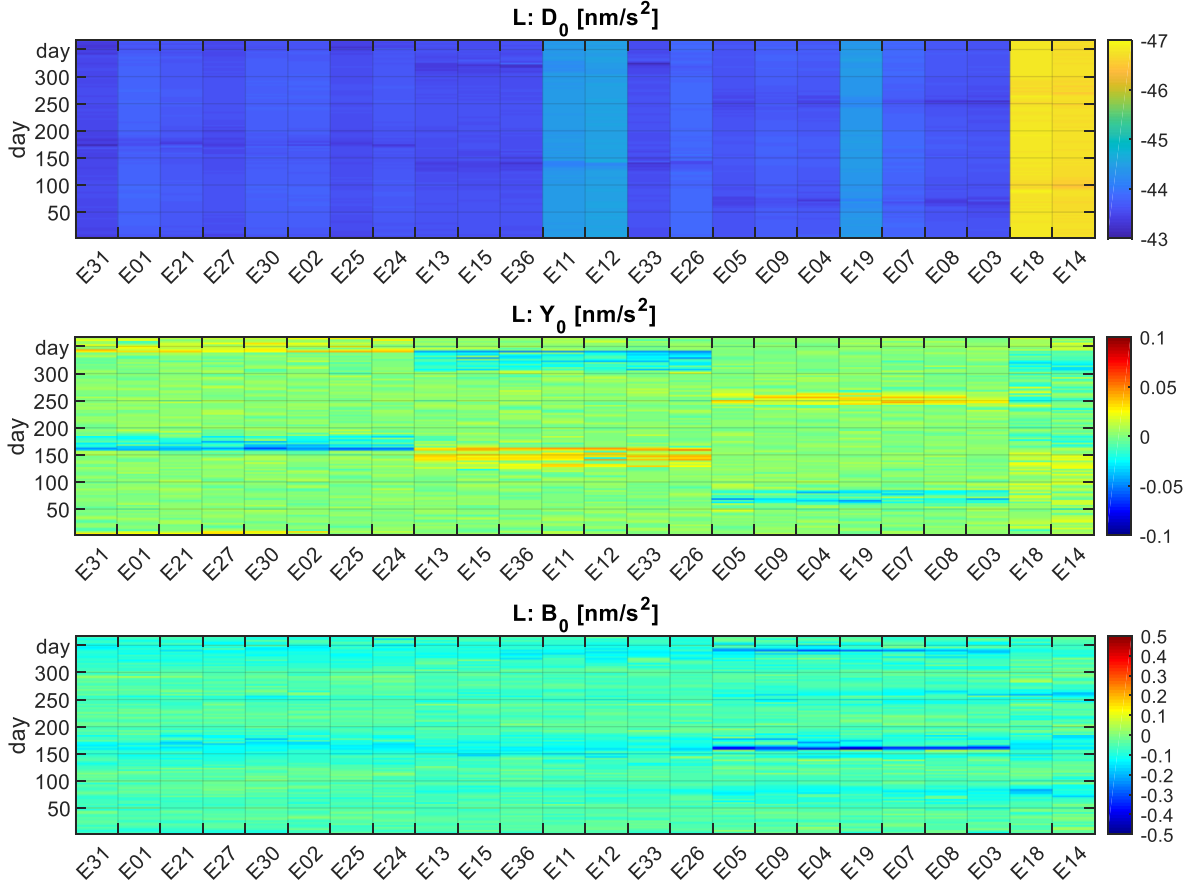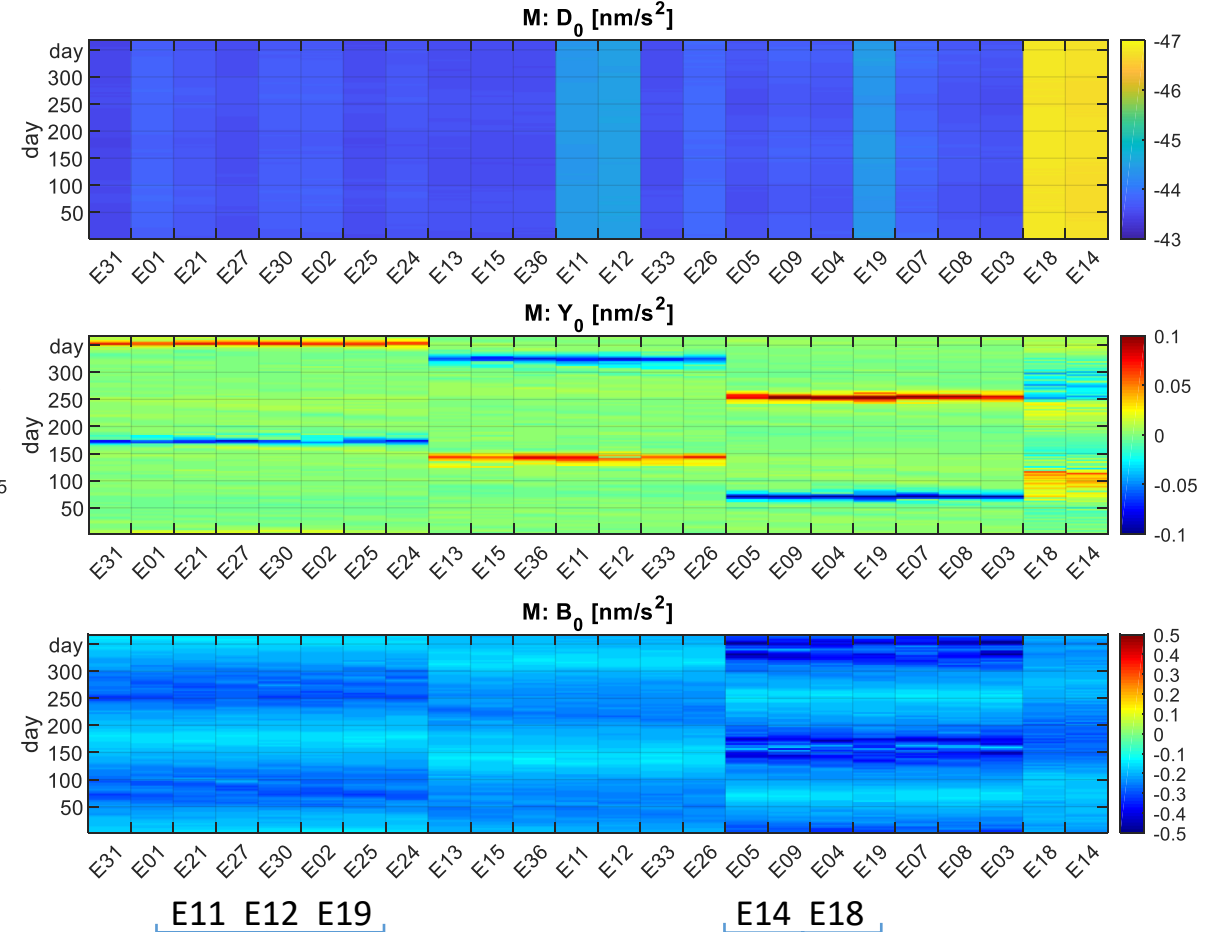
- D_0 captures the main part of the mismodelled NGP (different values for IOV, FOC and satellites on elliptical orbits can be observed)
- Y_0 partially captures NGP mismodelling due to the modified yaw steering law that is applied for small β angles
- B_0 coefficient is more pronounced (especially for higher β angles) if clock modelling is applied

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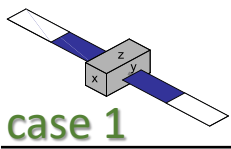
Results – ECOM2 periodic terms (ambiguities resolved)

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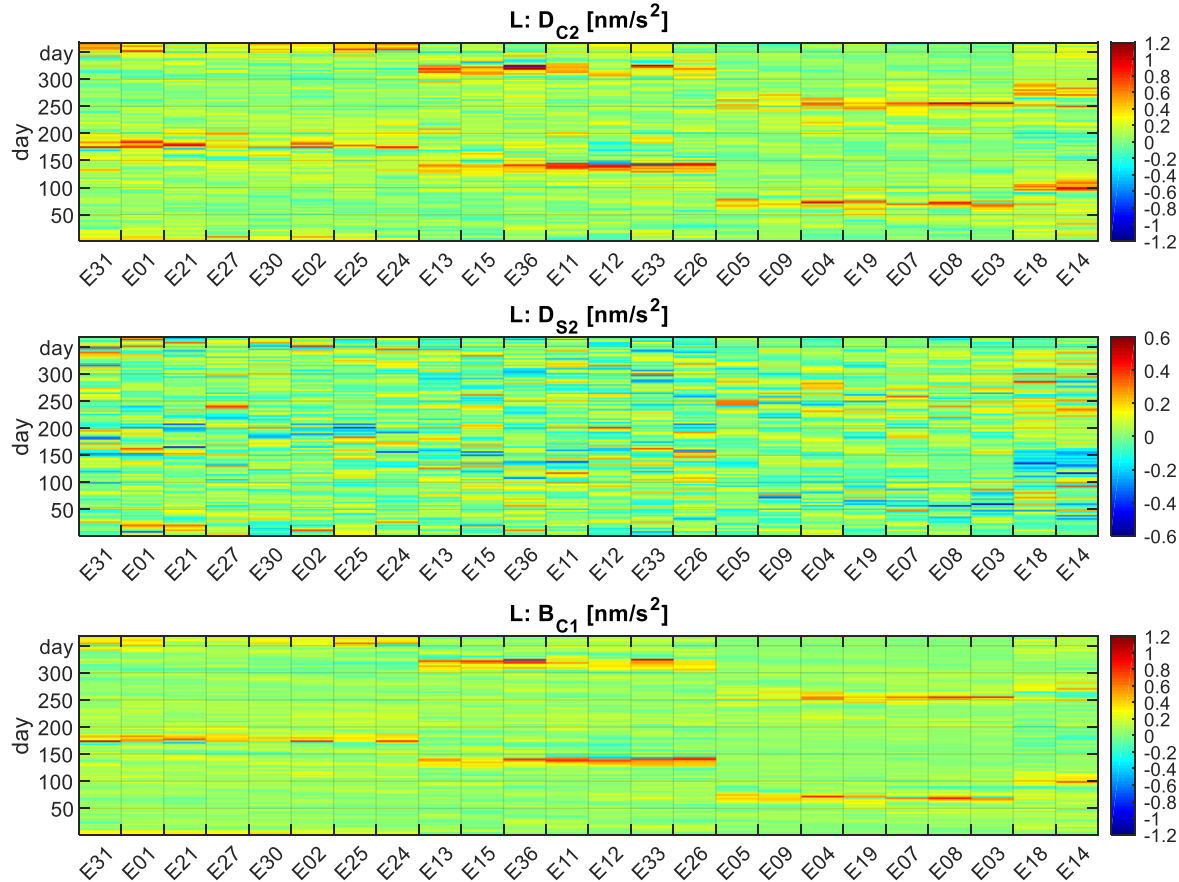
| epoch-wise clocks | clock modelling applied |
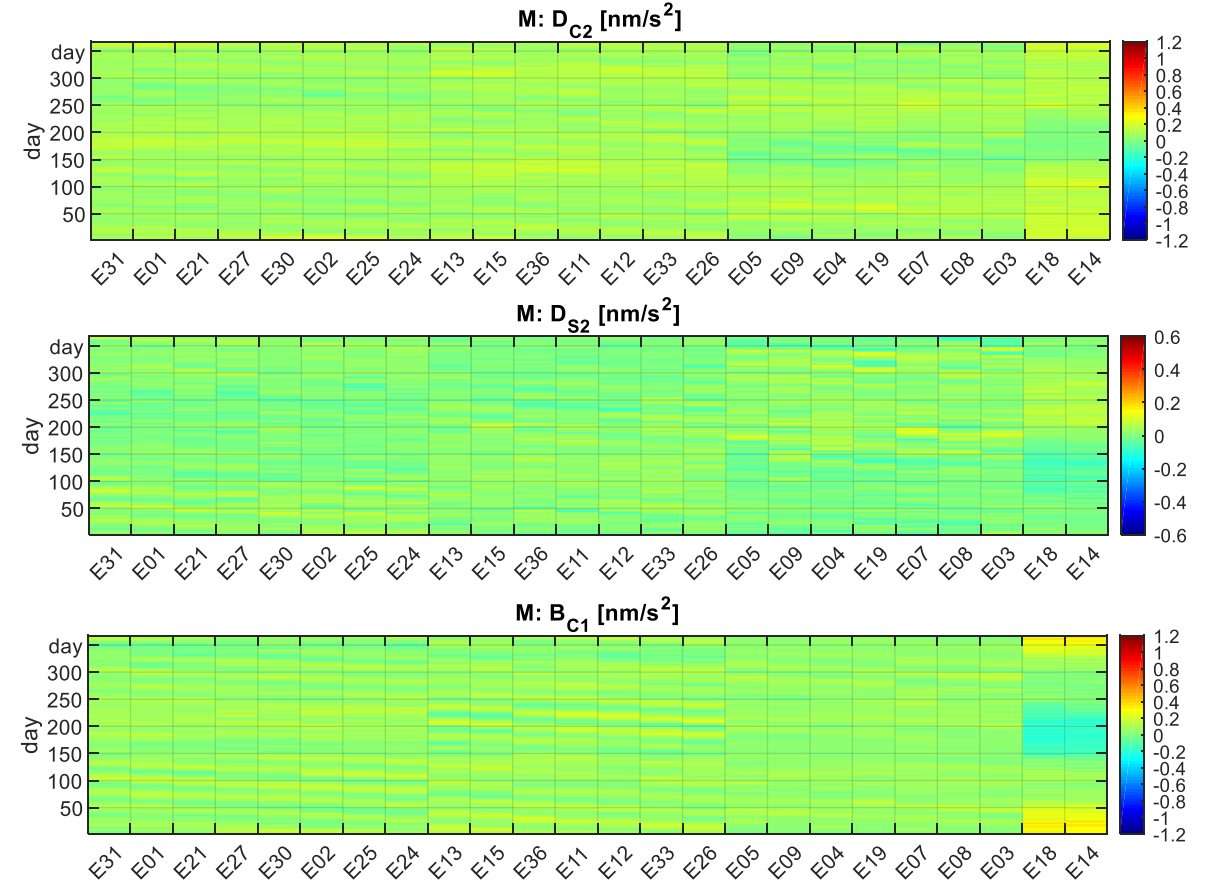
- scatter of ECOM2 parameters is considerably reduced by application of satellite clock modelling

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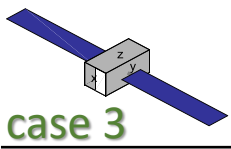
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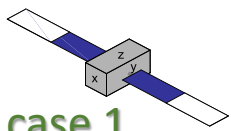
Results – **station coordinates** (ambiguities resolved)

epoch-wise clocks

clock modelling applied
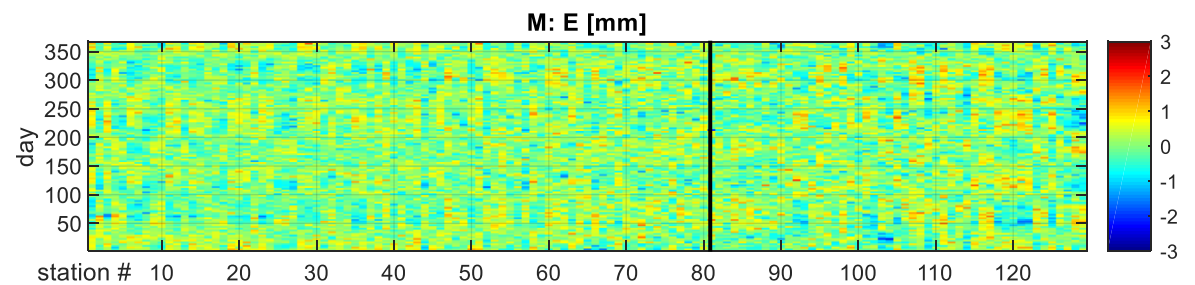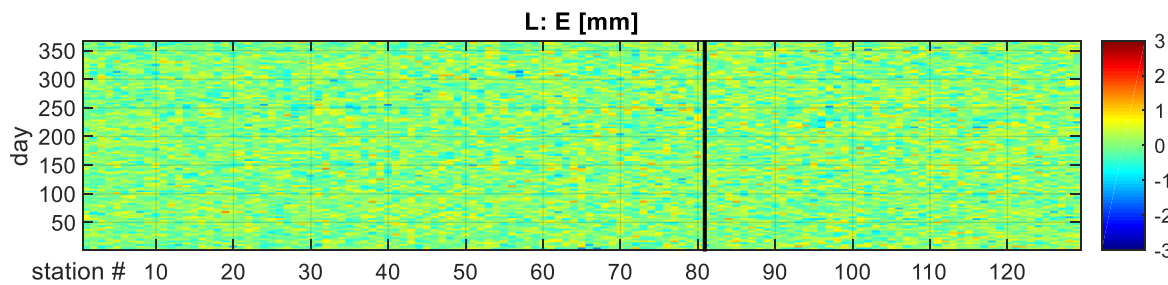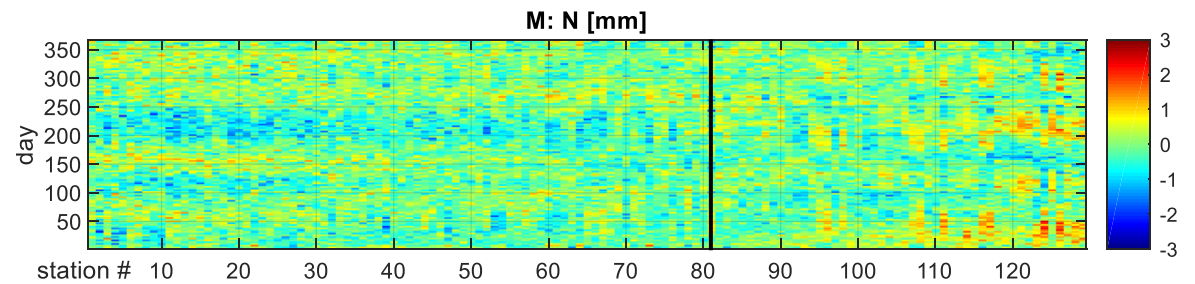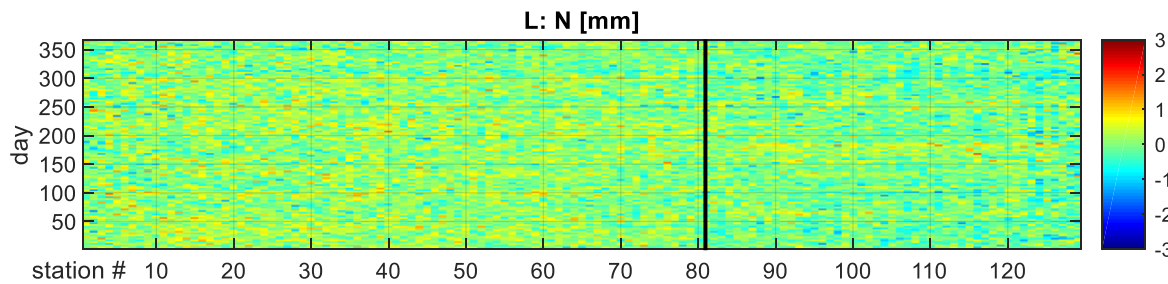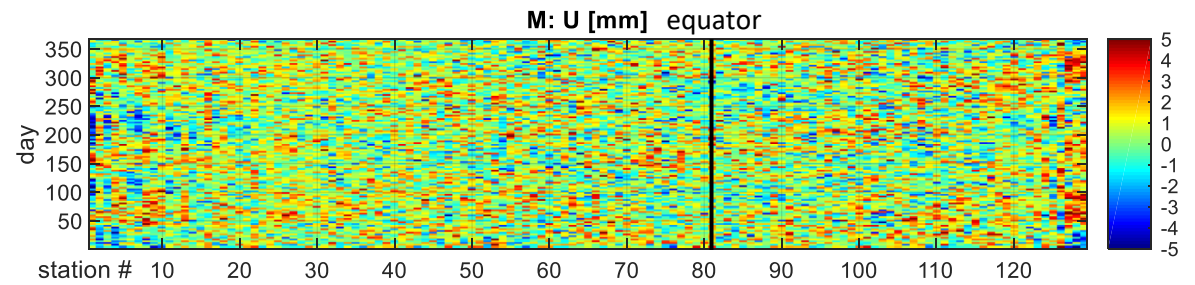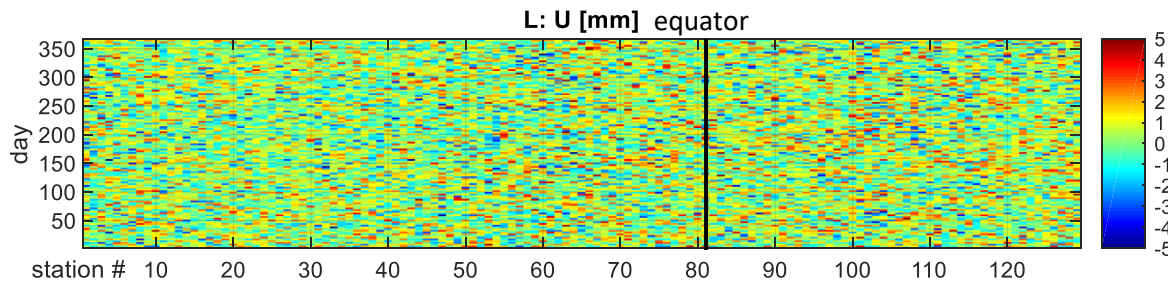
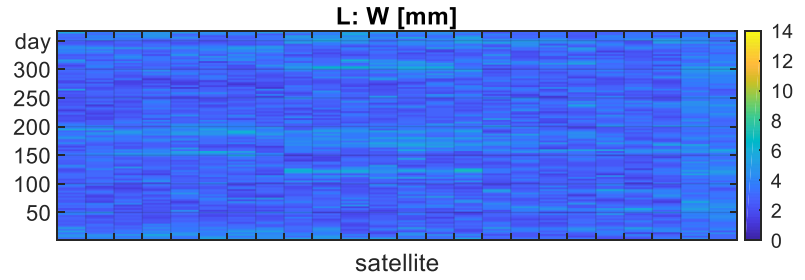- stations coordinates are more affected by NGP mismodelling if satellite clock modelling is applied
- effect is more pronounced for stations with higher latitude
- results for 'up' component reflect the radial orbit errors

Note: stations are ordered according to the latitude (north ⇒ south)

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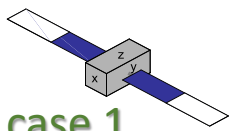
Results – **station coordinates** (float ambiguities)
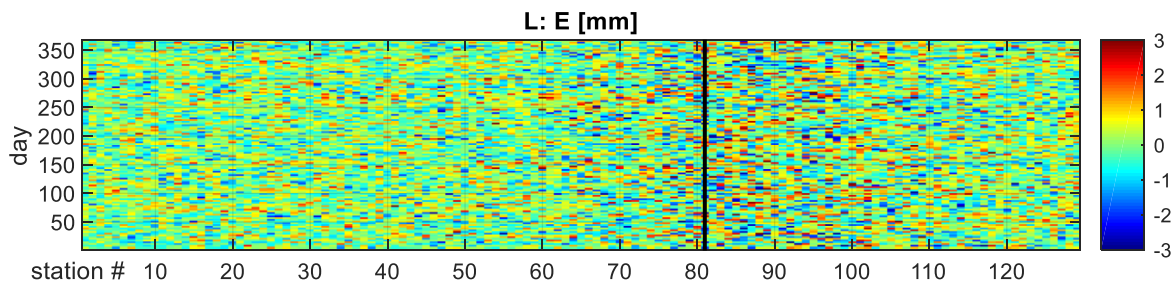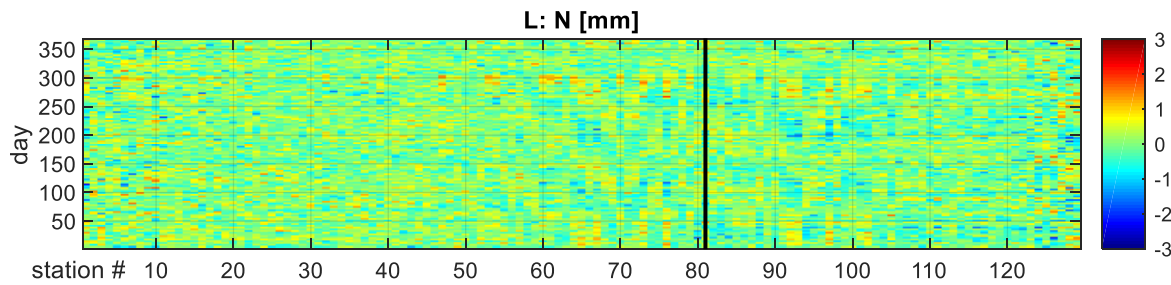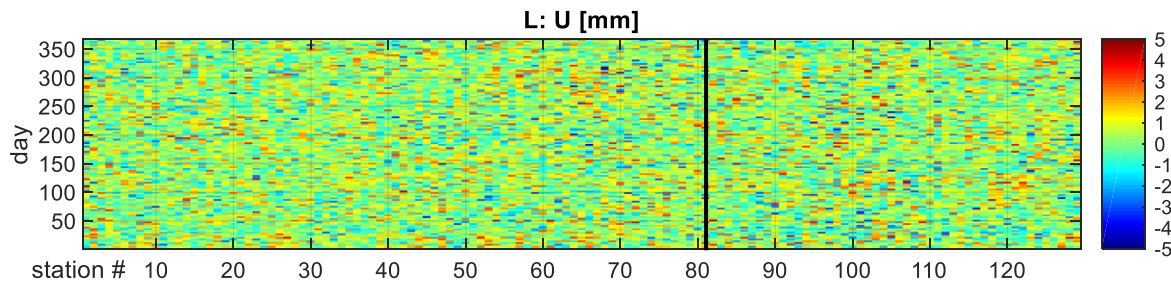
epoch-wise clocks | clock modelling applied
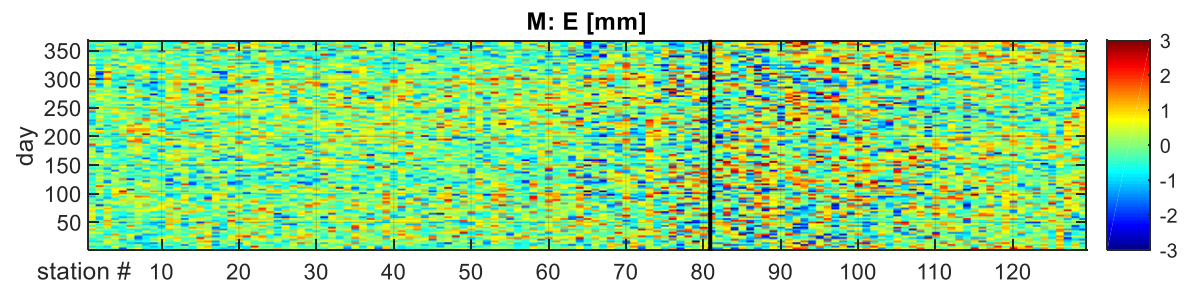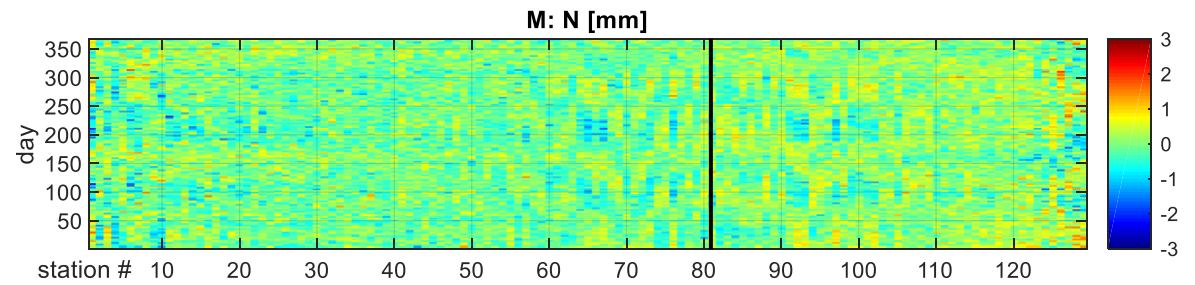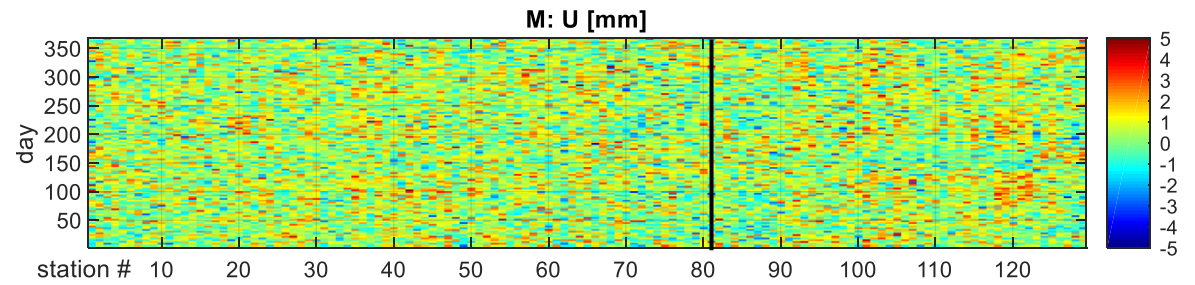
- 'up' component is less noisy if float ambiguities remain in the system
- asymmetric result for 'east' component reflects the uneven distribution of stations (more on the northern hemisphere)
    - stations closer to equator are more affected by NGP mismodelling

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Results – satellite clocks (ambiguities resolved)

epoch-wise clocks

clock modelling applied
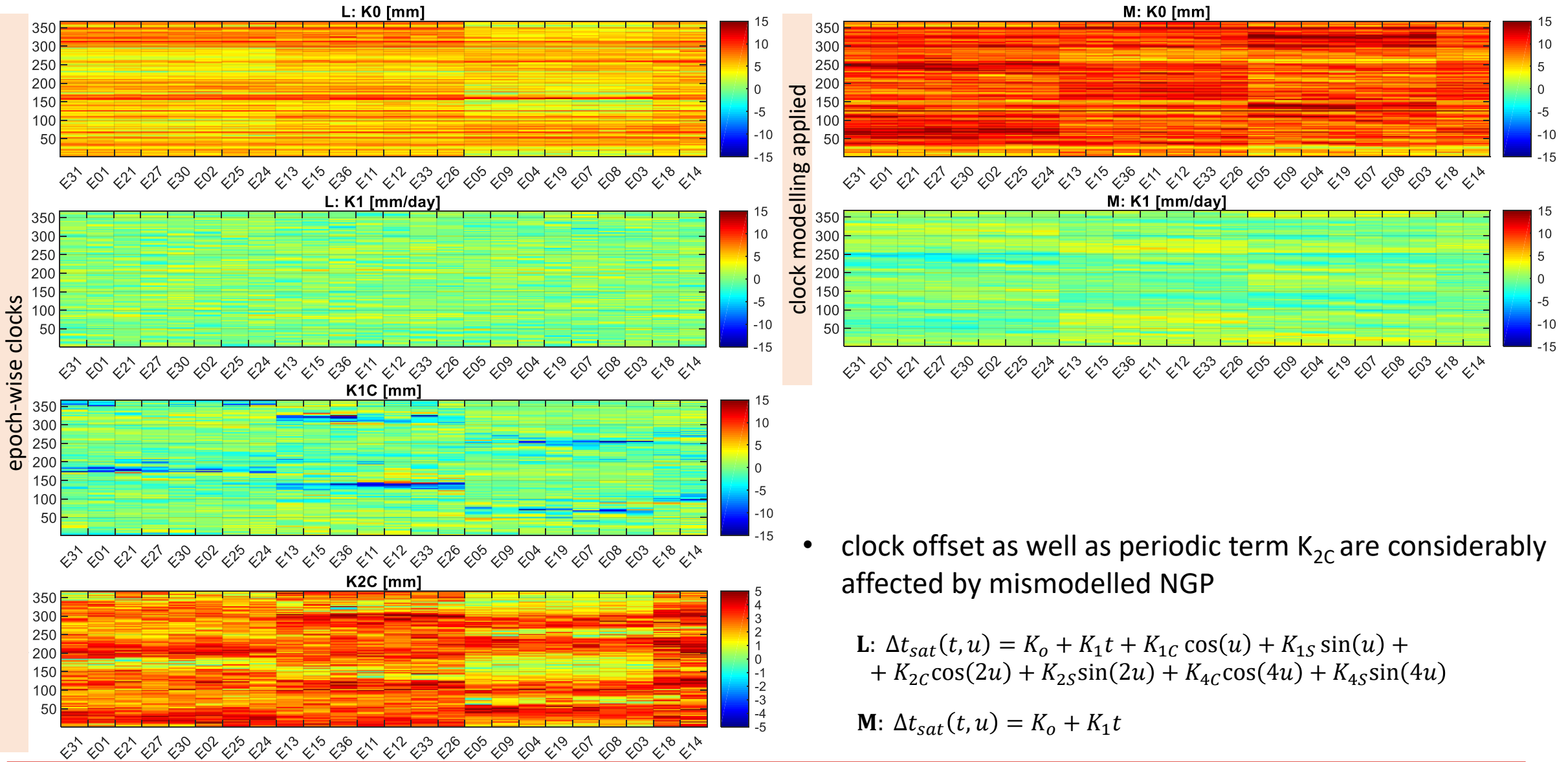
- clock offset as well as periodic term K_{2C} are considerably affected by mismodelled NGP

L: $\Delta t_{sat}(t, u) = K_o + K_1 t + K_{1C} \cos(u) + K_{1S} \sin(u) +$
$+ K_{2C} \cos(2u) + K_{2S} \sin(2u) + K_{4C} \cos(4u) + K_{4S} \sin(4u)$

M: $\Delta t_{sat}(t, u) = K_o + K_1 t$
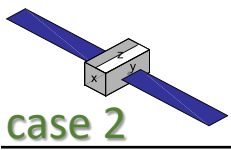
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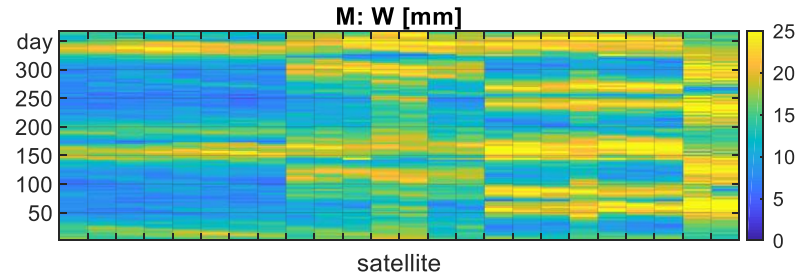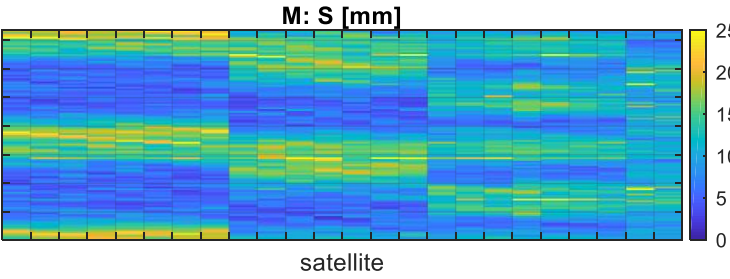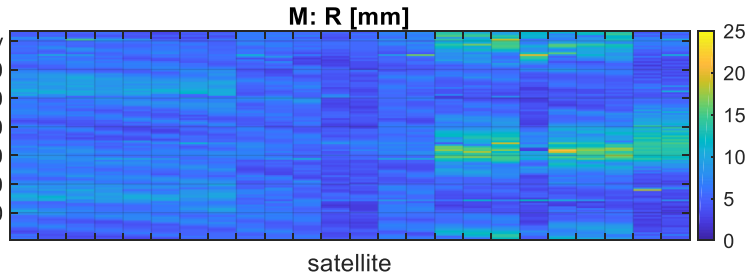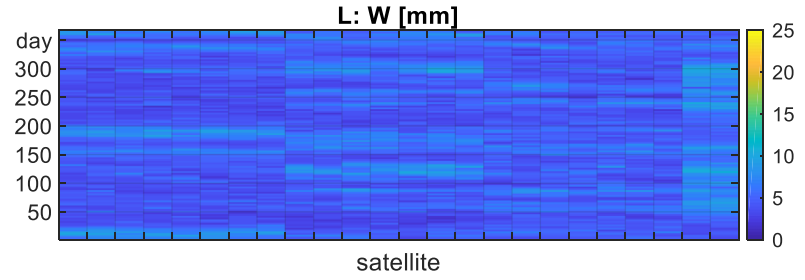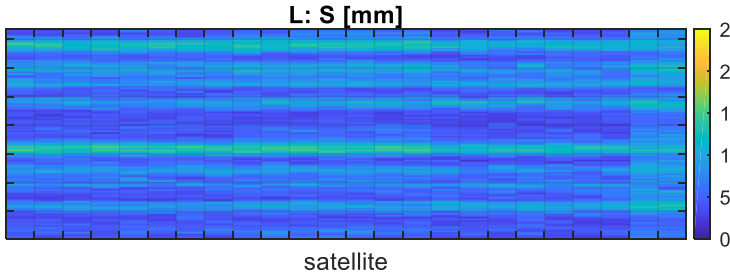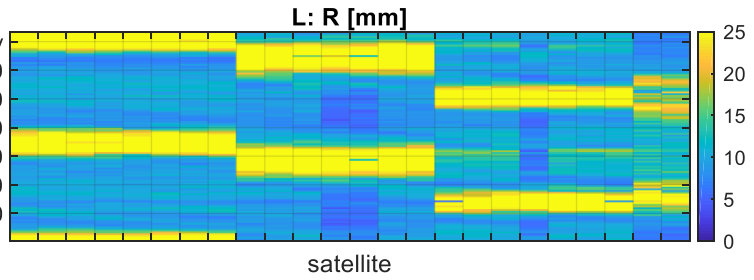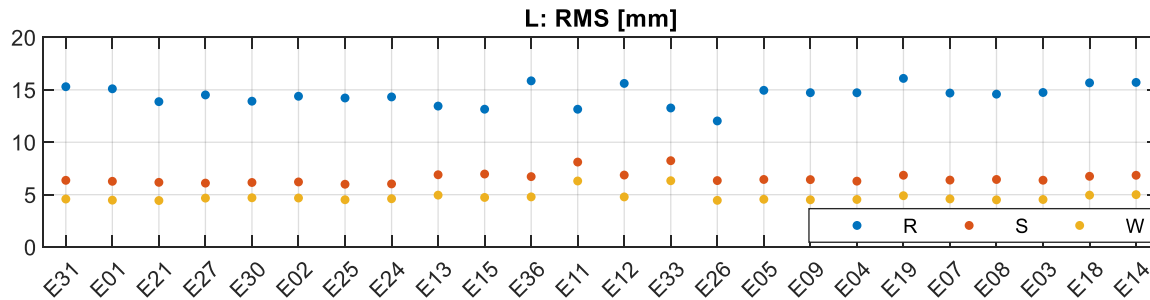
Results – orbits RMS error (ambiguities resolved)
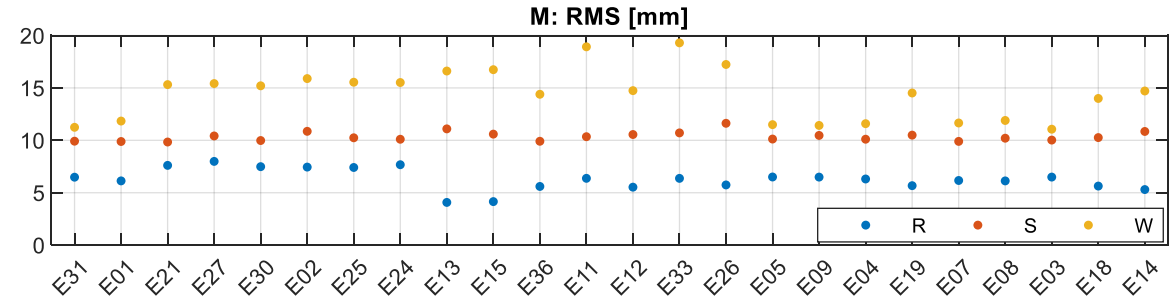
- different origins of NGP mismodelling lead to different pattern observed in orbit residuals

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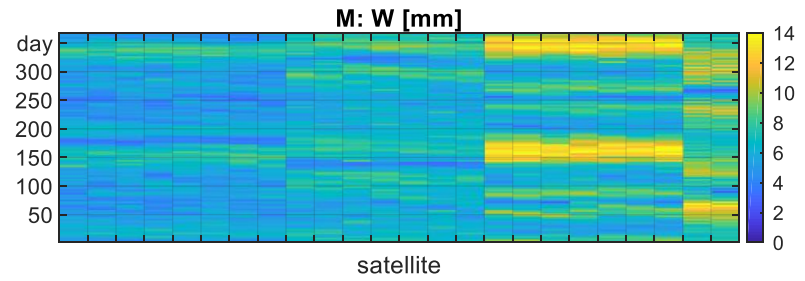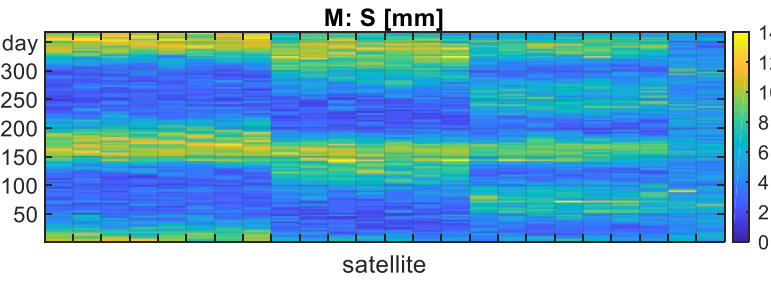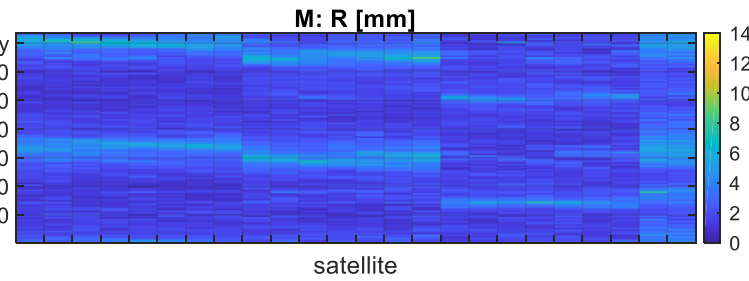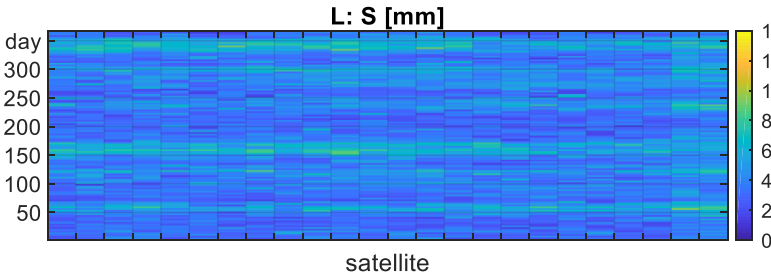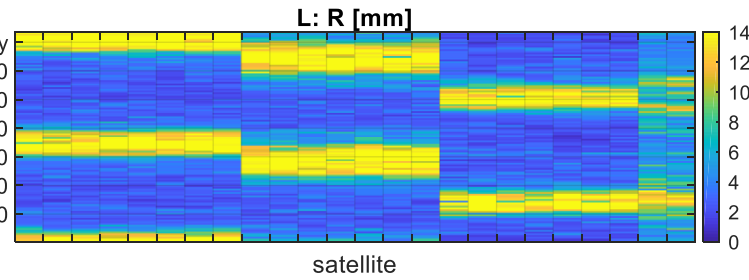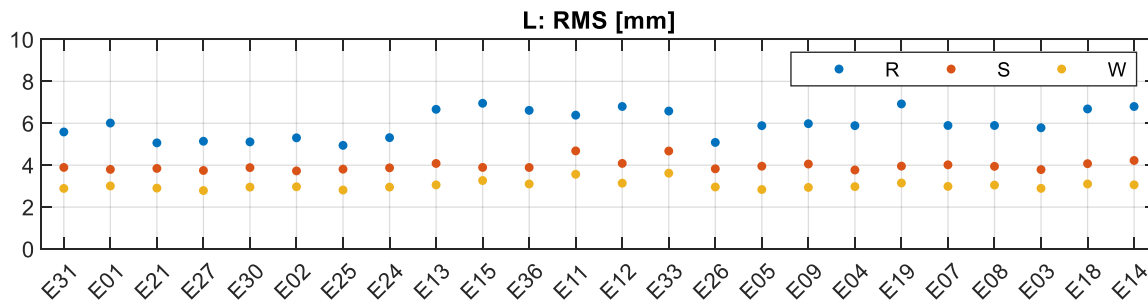
Results – orbits RMS error (ambiguities resolved)
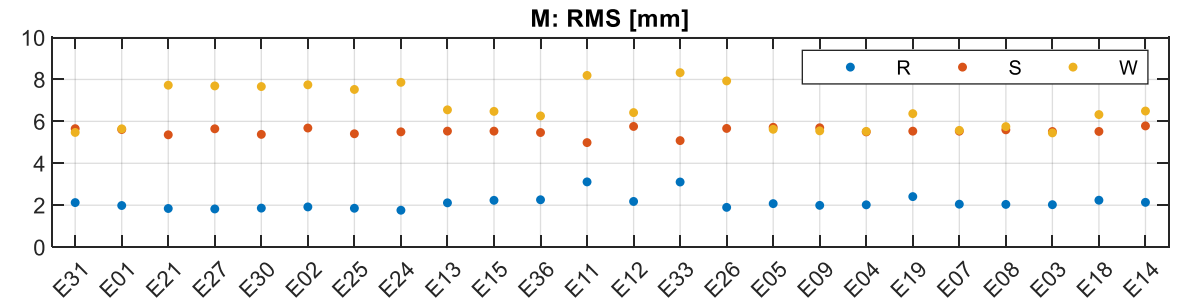
- ECOM2 cannot fully capture mismodelled NGP especially for low β angles

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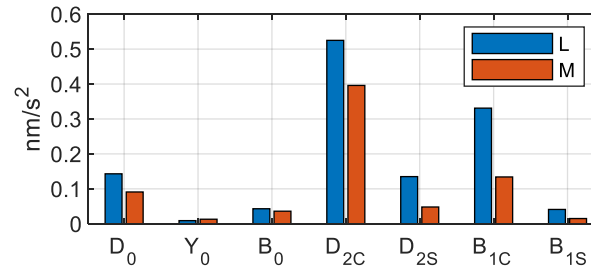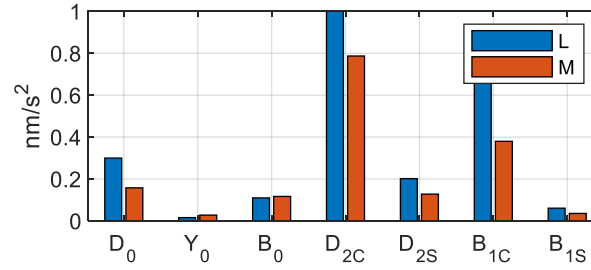
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Results – signatures of the NGP mismodelling

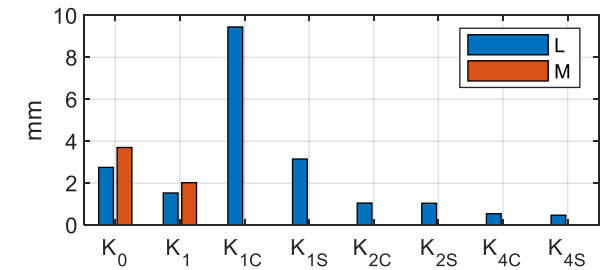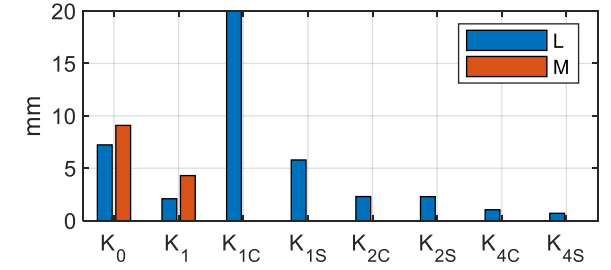**L:** epoch-wise clocks   **M:** clock modelling applied
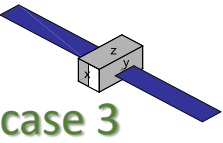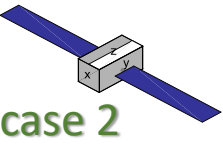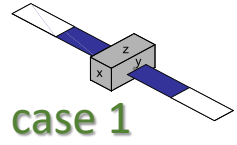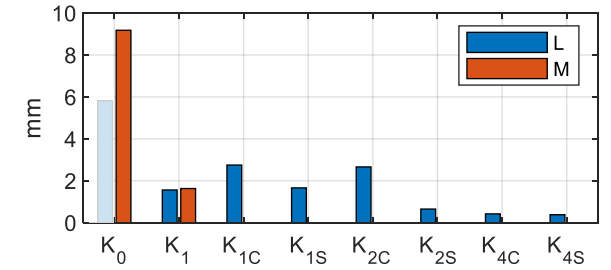
- signatures (values averaged over one year) are based on the solution with all ambiguities resolved
- signatures may give a hint regarding the possible origin of the mismodelled NGP
- another signatures are needed to clearly distinguish between case 2 and 3

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Results – signatures of the NGP mismodelling (orbit)
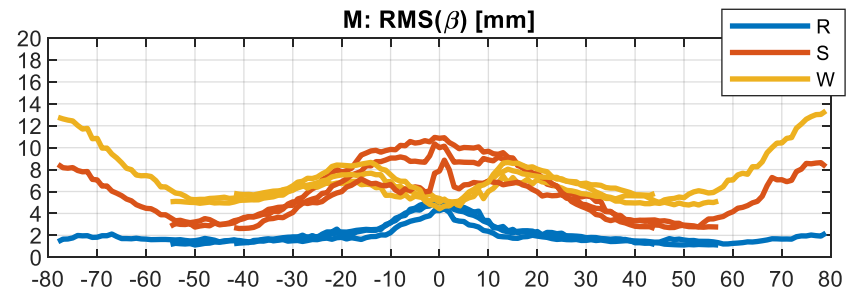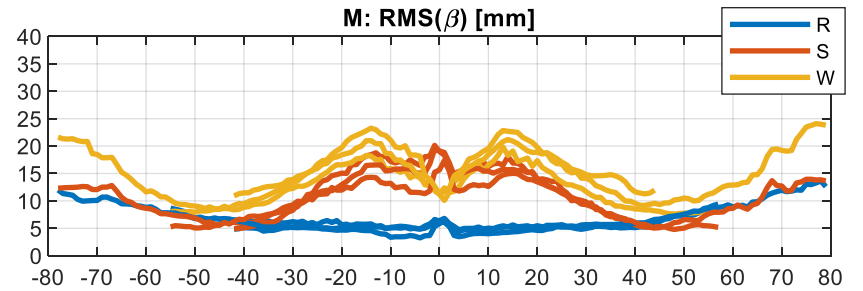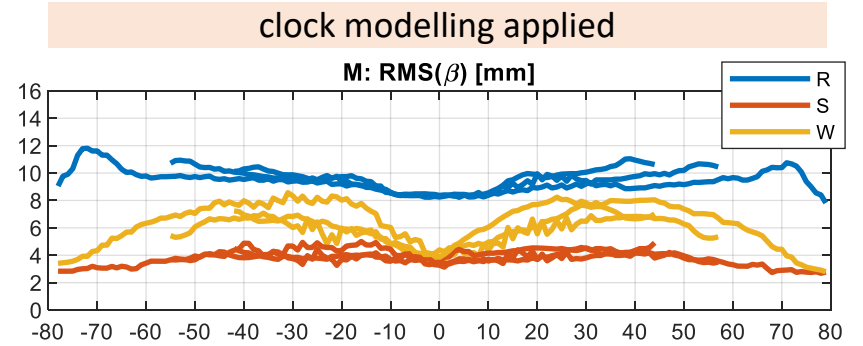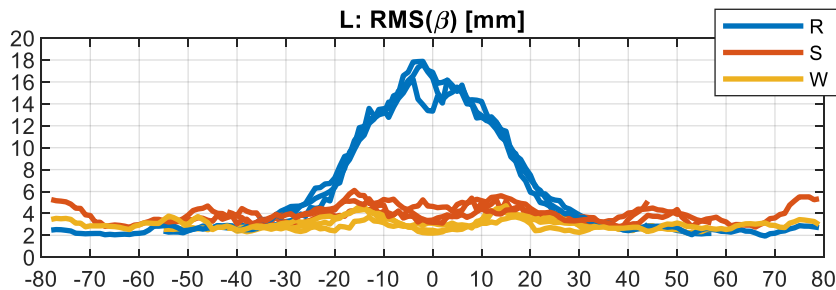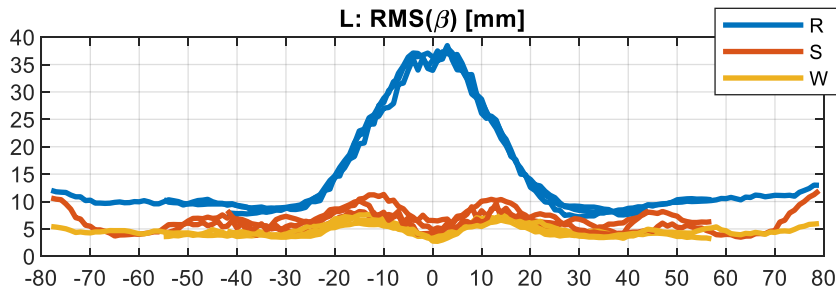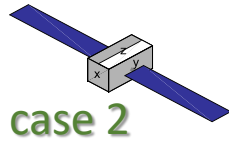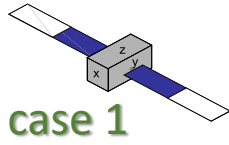
Note:
- satellites on elliptical orbits are **not** included in these (and subsequent) plots
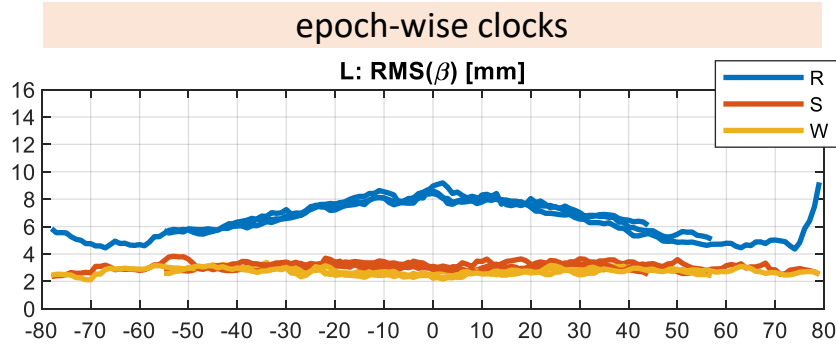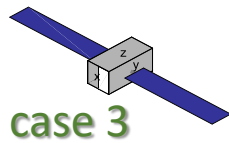- separate line is plotted for each orbital plane
- moving average filter with a 3° window is applied to the data

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Results – signatures of the NGP mismodelling (ECOM2)
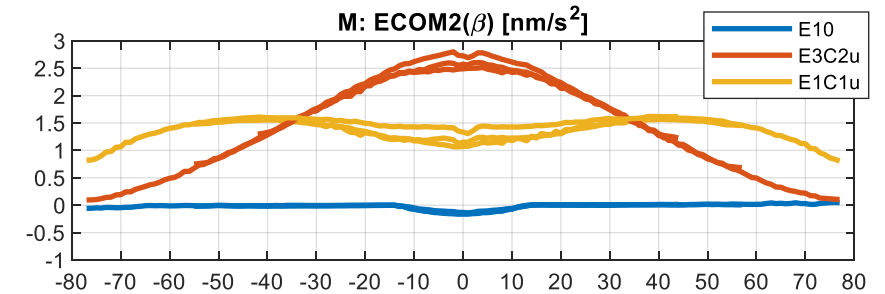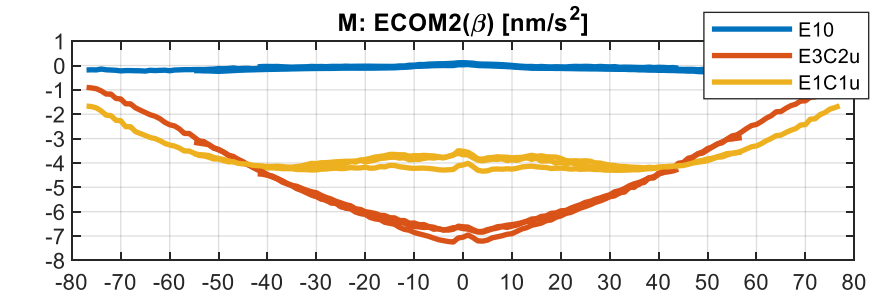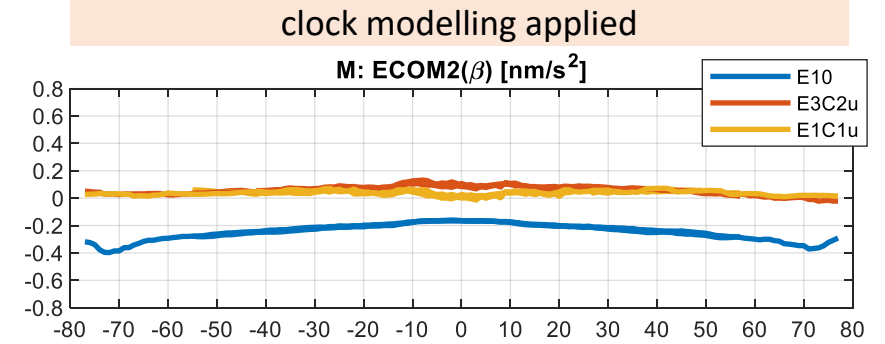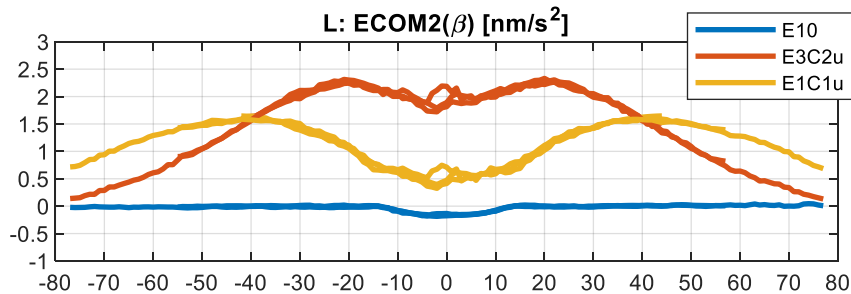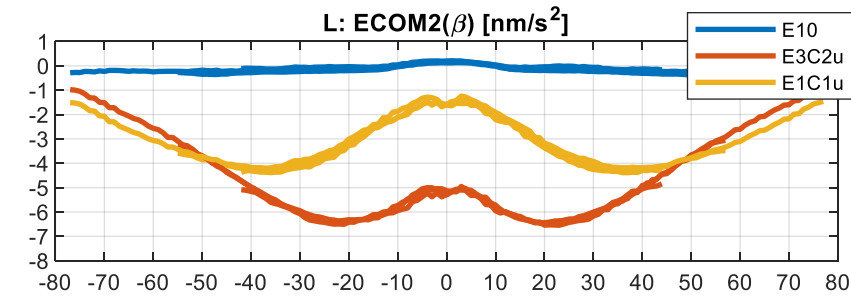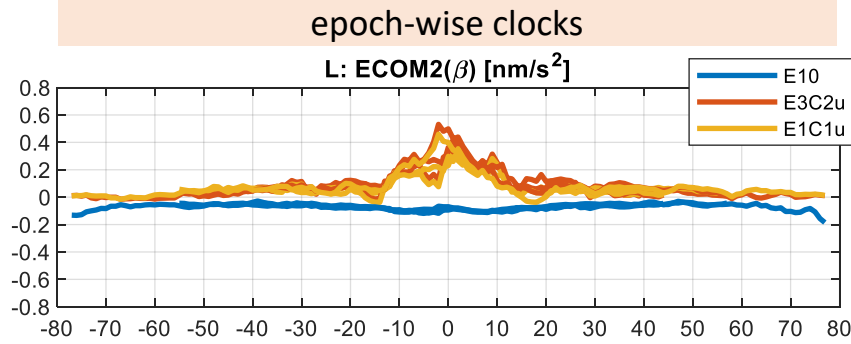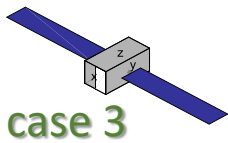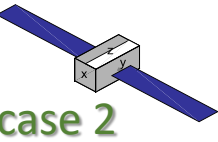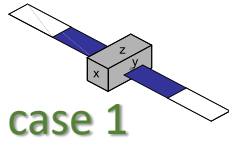
- clock modelling considerably influences the ECOM2 estimates
- signatures for all the cases are distinguishable

Maciej Kalarus, Rolf Dach, Arturo Villiger, and Adrian Jaeggi
Propagation of satellite orbit modelling deficiencies into the global GNSS solutions – simulation-based study
EGU General Assembly 2021

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L: epoch-wise clocks

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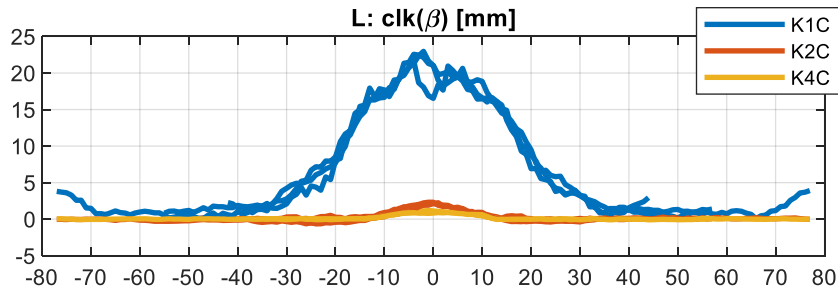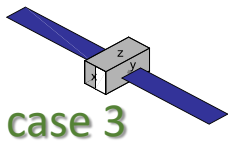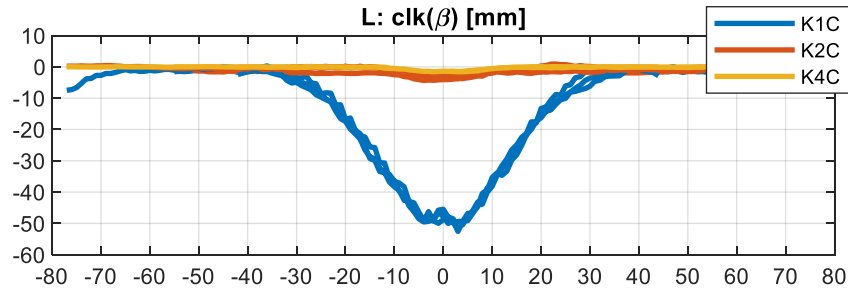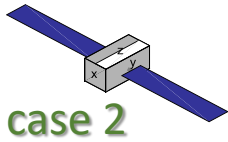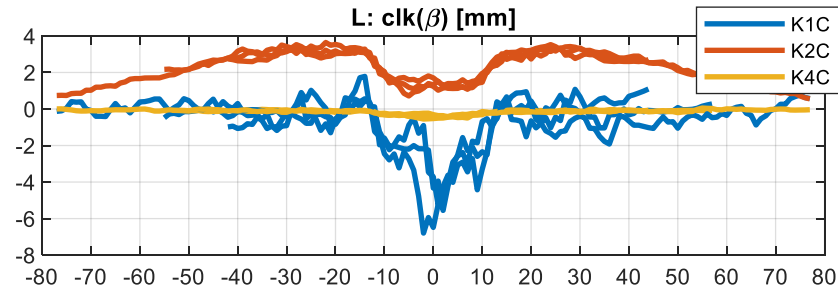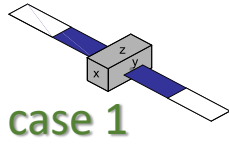
Summary

- Deficiencies of the non-gravitational force models (here introduced by modification of the box-wing model) are only partially captured by ECOM2 parameters. The remaining parts affect satellite clock estimates and are also visible in satellite orbit and station coordinates.

- Careful analysis of some parameters (mainly ECOM2 and satellite clock corrections) can lead to valuable clues about a possible source of mismodeled NGPs.

- Estimation options considerably change the signatures of mismodelled NGPs. Signatures can be defined individually for particular estimation scenarios in the simulated environment.

- Clock modelling stabilizes the entire solution by reducing the number of estimated parameters. Unmodelled NGPs are then more visible in the orbits.

Maciej Kalarus, Rolf Dach, Arturo Villiger, and Adrian Jaeggi
Propagation of satellite orbit modelling deficiencies into the global GNSS solutions – simulation-based study
EGU General Assembly 2021

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Thank you

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Propagation of satellite orbit modelling deficiencies into the global GNSS solutions - simulation-based study -

M. Kalarus, R. Dach, A. Villiger, A. Jaeggi
AIUB
Astronomical Institute, University of Bern, Switzerland

- how the results of precise orbit determination are affected by mismodelled non-gravitational forces
- how the potential exploitation of stable passive H-masers (e.g. by linear clock modelling) can influence the solution

- box-wing models with known deficiencies (3 cases)

- REFERENCE ("truth")
  - set of stations
  - Galileo constellation
  - box wing models (IOV, FOC)

- observation simulator (366 daily batches)

- **Precise Orbit Determination**

- station coordinates
- orbits
- ECOM2
- satellite clocks
- Earth orientation parameters

- identification of characteristic **signatures** corresponding to the modified parameters of the box-wing model

- different deficiencies of the box-wing model lead to different characteristic signatures observed in the estimated parameters
- the clear signatures are mainly seen in ECOM2 parameters and satellite clock corrections
- clock modelling stabilizes the solution and also considerably changes the signatures of mismodelled NGPs
- …