Enhancing PPP-AR with satellite attitude data from ORBEX Files

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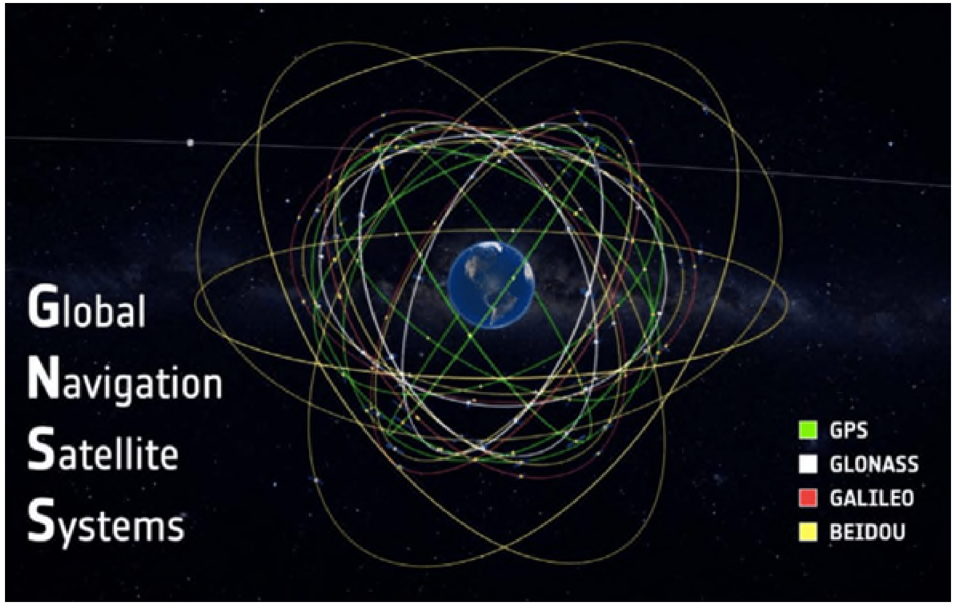
GNSS

- Satellites in orbits around the Earth emitting signals
- These satellites rotate to be optimally orientated
- Usually: Yaw-steering mode



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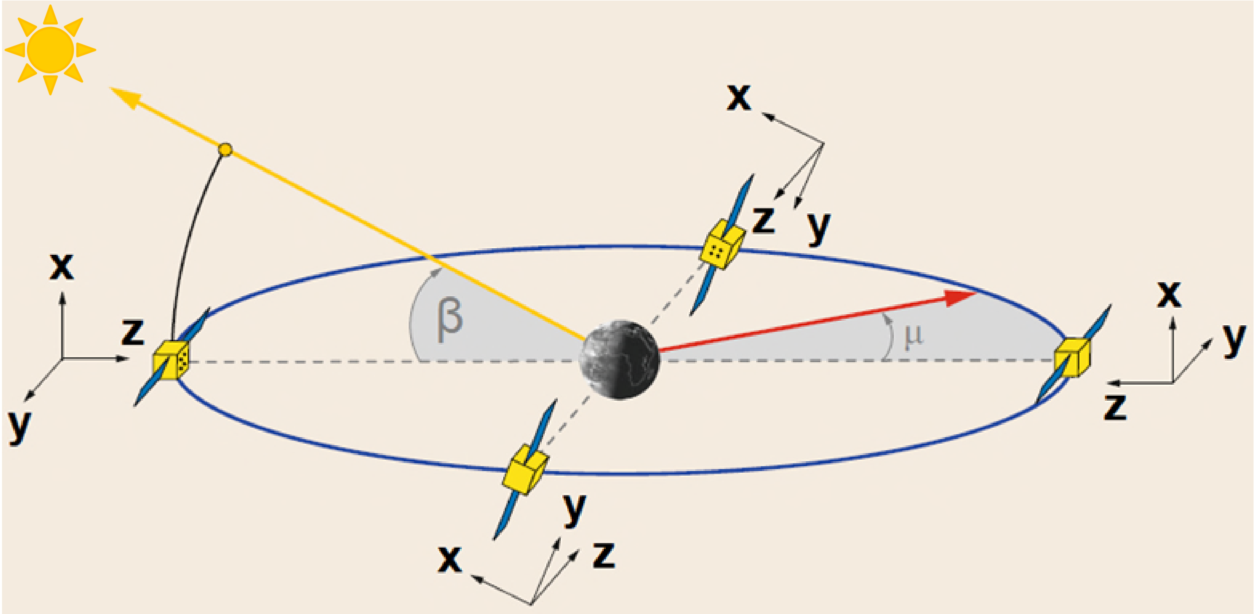
Yaw-steering mode



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IGS convention (IGSC)

Z-axis = antenna's boresight direction

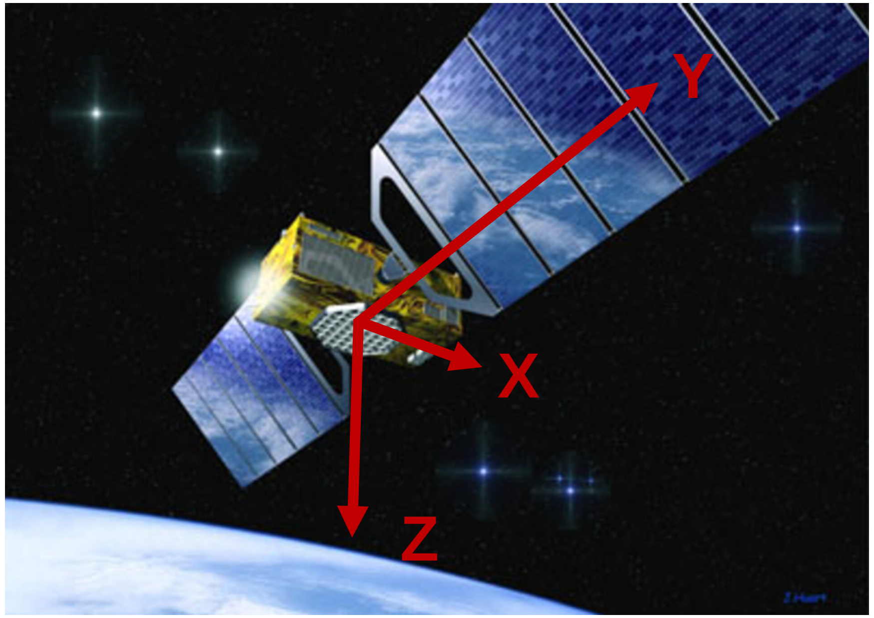
Y-axis = solar panels' rotation axis

X completes the right-handed system

$$Z = \frac{-\boldsymbol{r}^{sat}}{\|\boldsymbol{r}^{sat}\|}$$

$$Y = Z \times \frac{\boldsymbol{r}_{sun} - \boldsymbol{r}^{sat}}{\|\boldsymbol{r}_{sun} - \boldsymbol{r}^{sat}\|}$$

$$X = Y \times Z$$



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$\mathbf{r}^{sat}$ satellite position (ECEF)

$\mathbf{r}_{sun}$ sun position (ECEF)

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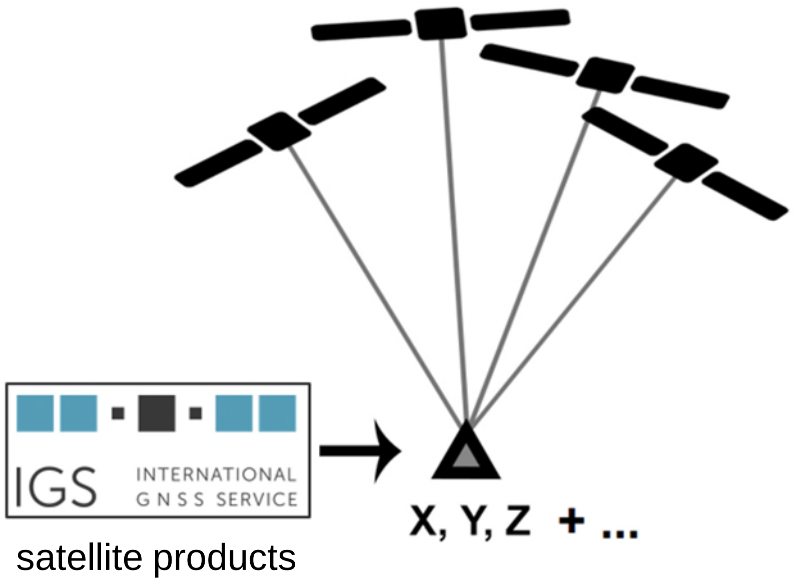
Eclipse season

- GNSS satellite crossing the Earth‘s shadow
- Nominal attitude mode degraded
- Potentially rapid rotations

Precise Point Positioning

- PPP relies on precise satellite products
- Complex models and algorithms
- Satellite orientation needed for
  - converting COM to APC
  - modeling Phase-Wind Up



PPP with integer ambiguity resolution → PPP-AR

ORBEX

- Orbit Exchange Format (Loyer et al., 2019)
- Larger flexibility than existing formats
- GNSS and LEO orbit data
- 0.1 mm orbit precision
- Attitude information as quaternions

Quaternions

```
*REC ID_                N q0_scalar_ ___q1_x___ ___q2_y___ ___q3_z___
## 2023 01 12 00 00  0.000000000000  78
 ATT E01                4  0.1508605 -0.4254516  0.6459186  0.6156470
 ATT E02                4  0.4203492  0.1510023 -0.6106092  0.6539582
 ATT E03                4  0.2345662 -0.0138759 -0.9477903  0.2155918
 ATT E04                4 -0.1747897  0.0728869  0.3802387  0.9052925
 ATT E05                4  0.5335113  0.0090219 -0.8446365 -0.0432836
```

...

© GRG0OPSFIN_20230120000_01D_30S_ATT.OBX

attitude entries

$$R = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix}$$

rotation matrix

→ for example:

$$\boldsymbol{dx}_{ECEF}^{pco} = R\ \boldsymbol{dX}_{sat}^{pco}$$

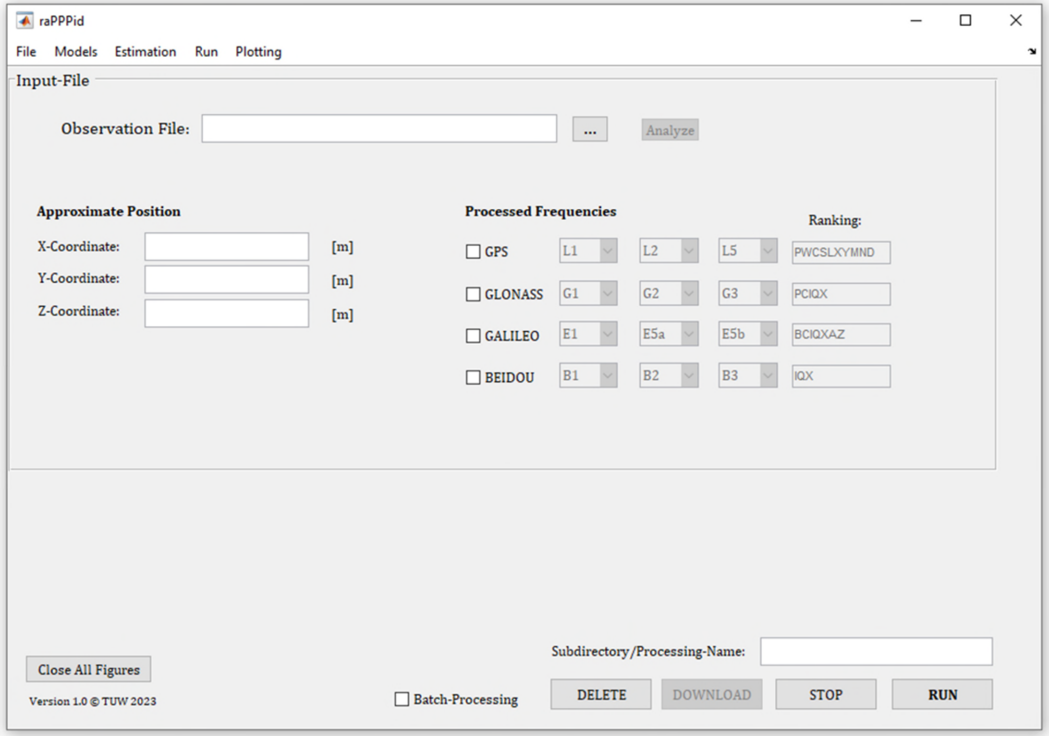
$\boldsymbol{dx}_{ECEF}^{pco}$ satellite phase center offset (ECEF coordinates)

$\boldsymbol{dX}_{sat}^{pco}$ satellite phase center offset (satellite body frame coordinates)

Vienna VLBI and Satellite Software

raPPPid

- Open-source PPP software
- PPP-AR for GPS, Galileo, and BeiDou
- GitHub:
  https://github.com/TUW-VieVS/raPPPid
- Documentation:
  https://vievswiki.geo.tuwien.ac.at/en/raPPPid



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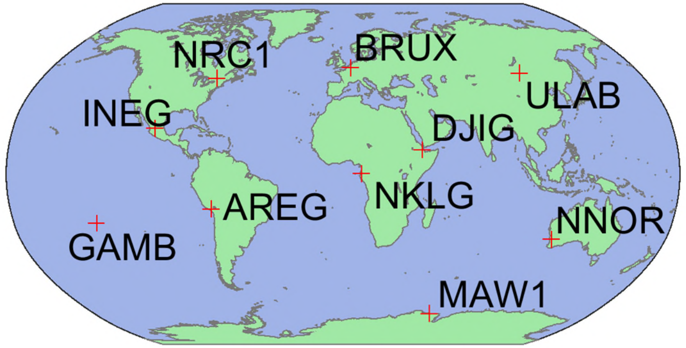
Test case

Software	raPPPid
Data	10 IGS MGEX stations, January 31, 2023
Observations	GPS: L1+L2, Galileo: E1+E5a 30 sec interval, reset of solution: every 30 min
Satellite products	CODE **or** CNES MGEX
Satellite attitude	IGSC **or** ORBEX
Processing mode	static **or** static-kinematic



Software	raPPPid (VieVSPPP)
Data	10 globally distributed IGS MGEX stations (January 31, 2023)
Observations	GPS: L1+L2, Galileo: E1+E5a
Observation ranking	GPS: WC, Galileo: CQX
Observation interval	30 sec, reset of solution: every 30min
Processing mode	post-processing, ionosphere-free LC, static or static-kinematic
Raw observation noise	Code 30cm, phase 2mm
Observation weighting	Elevation weighted, $\sin^2(elev)$, cutoff angle 5°
Correction models	Phase Wind-Up, solid Earth tides, relativistic effects, PCO + PCV, ocean loading
Troposphere model	VMF3 + GRAD, residual zenith wet delay is estimated, process noise 5mm $/\sqrt{h}$
Adjustment	Kalman Filter (float solution) and Least-Squares-Adjustment (fixed solution)
Float ambiguities	Constant, zero-difference, cycle-slip detection: dL1-dL2
PPP-AR	Fixing cutoff 10°, reference satellite = highest satellite, fixing start after 120s
Fixing	WL with HMW LC of the last 5minutes, NL with LAMBDA method
Satellite products	CODE or CNES MGEX (orbits, clocks, and biases)
Satellite attitude	IGSC or attitude from ORBEX

Results

CODE	Mean TTFF [min]	Median 3D error [cm]
IGSC	4.748 / 5.511	3.276 / 3.533
ORBEX	4.737 / 5.466	3.265 / 3.524

slight improvement

CNES	Mean TTFF [min]	Median 3D error [cm]
IGSC	4.874 / 5.907	3.373 / 3.716
ORBEX	4.846 / 5.877	3.362 / 3.707

slight improvement

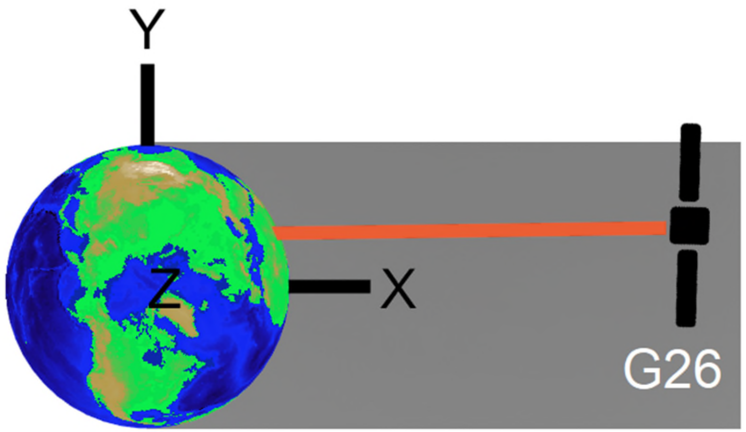
static / static-kinematic

IGSC + cylindric model performs worse

TTFF is achieved when 2D < 5 cm for the complete remaining period

Exemplary case

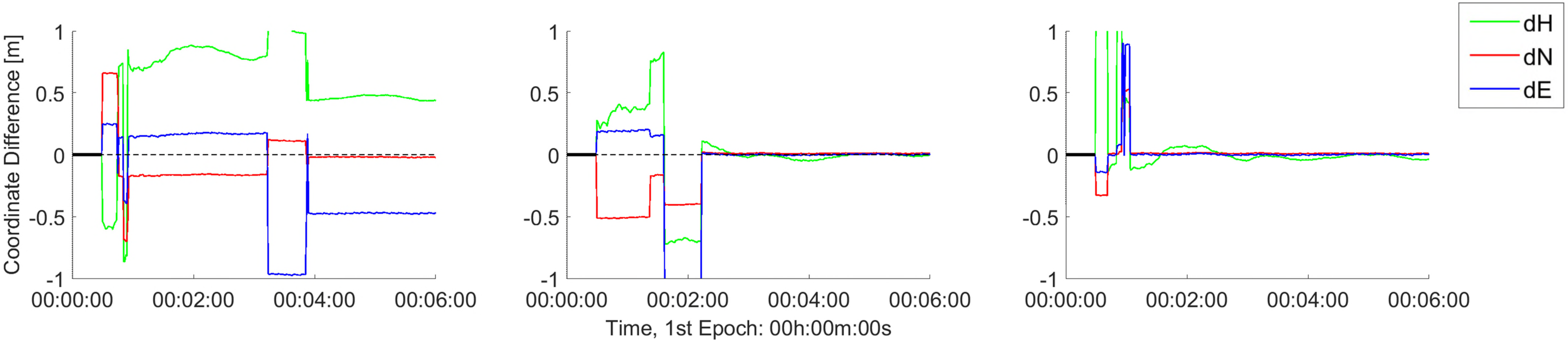
- Station NKLG (Libreville, Gabon, Africa)
- Satellite products from TU Graz (Strasser, 2022)
- GPS + Galileo (1 s interval) → interpolate quaternions for high-rate data?
- January 1, 2020, 0:00 h



G26 in satellite eclipse

Time to first fix

	IGSC	IGSC (G26 excluded)	ORBEX
TTFF:	>> 6 min	$2^m\ 14^s$	$1^m\ 04^s$



ORBEX summary

- Easy to implement and ensures consistency to satellite products
- Slight overall improvement in all regards
- Particularly useful in eclipse seasons

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Thank you
for your attention!

Float Results

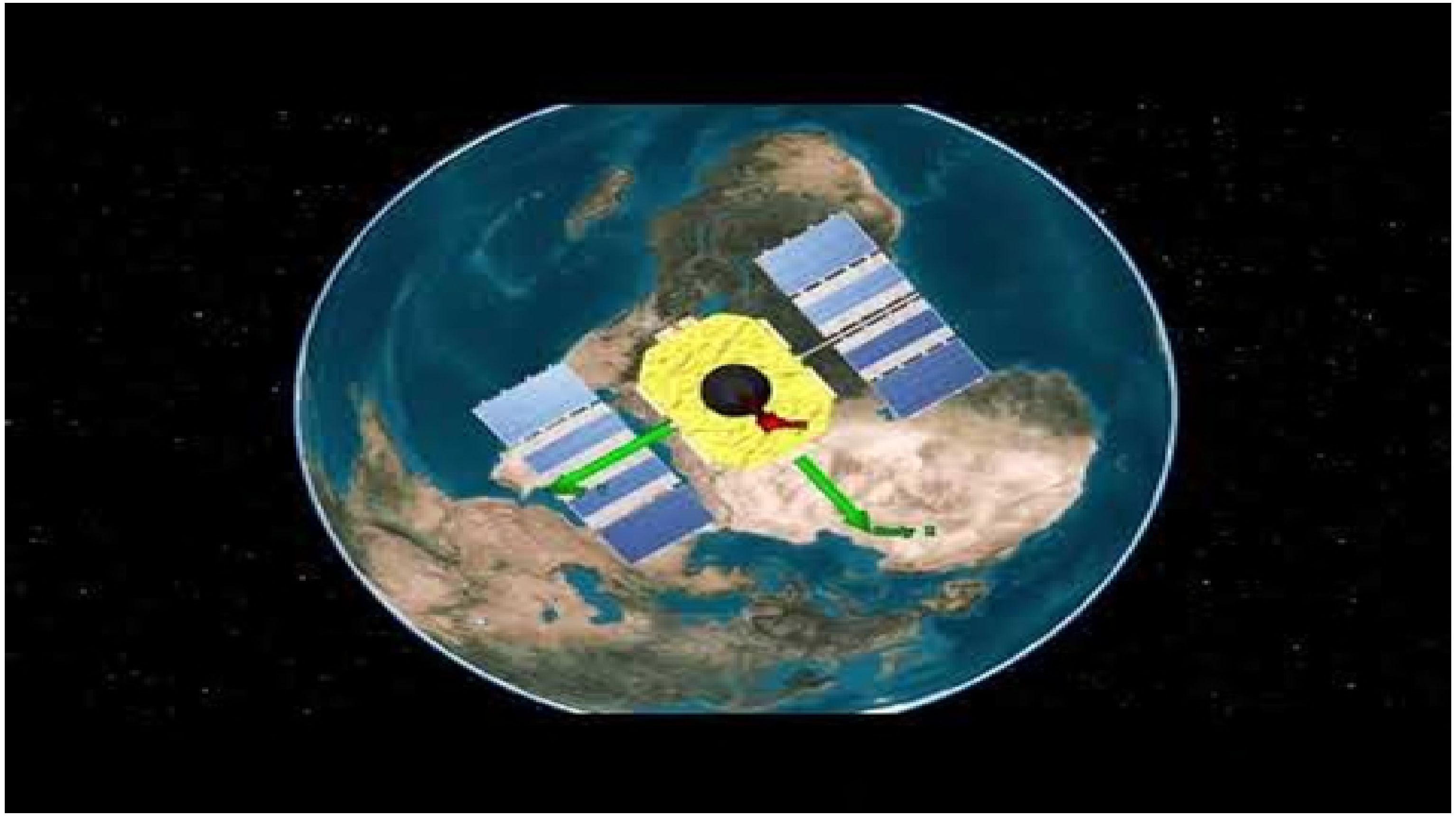
CNES	Mean convergence [min]	Median 3D error [cm]
IGSC	8.433 / 10.816	9.742 / 12.982
ORBEX	8.502 / 10.720	9.749 / 12.960

CODE	Mean convergence [min]	Median 3D error [cm]
IGSC	8.314 / 10.804	9.712 / 12.917
ORBEX	8.255 / 10.807	9.712 / 12.869

static / static-kinematic

Convergence is achieved when 2D < 10 cm for the complete remaining period

Eclipse visualization



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https://youtu.be/cWt0BQ2jzdM