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Institute of Geodesy and Photogrammetry

The potential of large LEO satellite constellations to form a GNSS network in space for geodetic Earth observation

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21 July 2022

Motivation

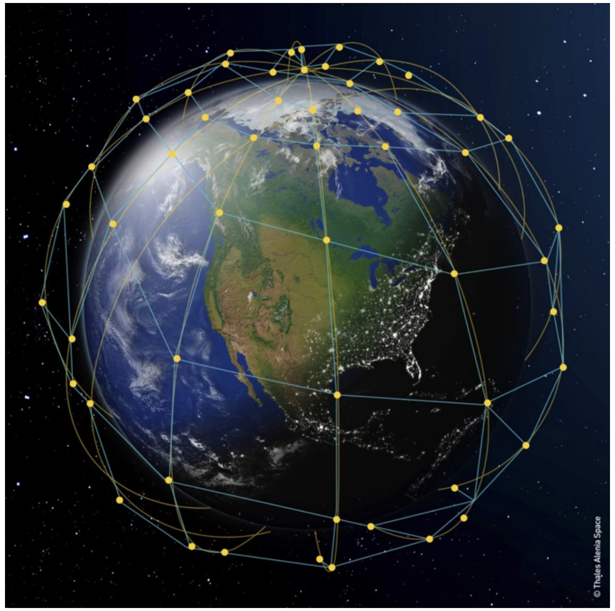
- Rapid increase in number of nanosatellites in space
- Low-cost GNSS receivers for positioning and navigation
- Example: Astrocast CubeSat constellation

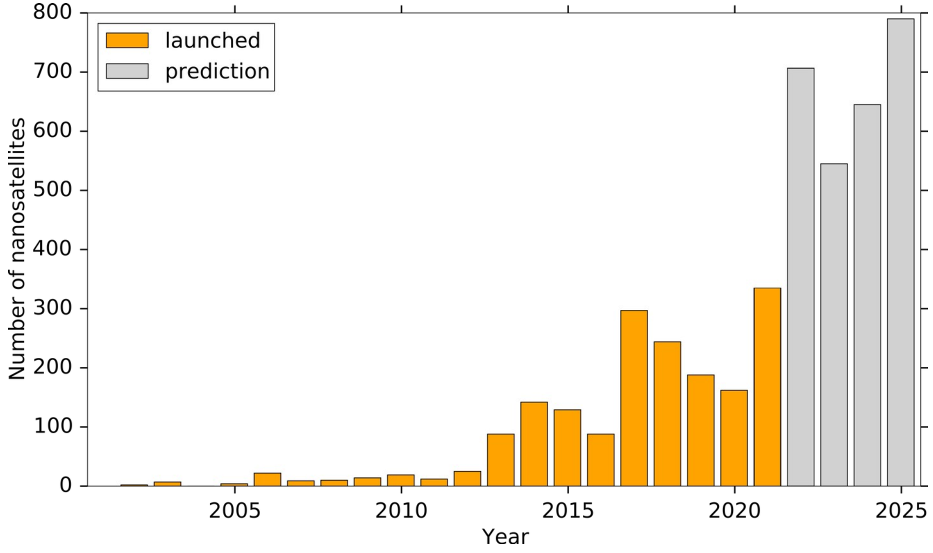
➡ Dense network of GNSS observations around the Earth

- **Idea:** Use the large nanosatellite constellations to estimate parameters related to ...
  - LEO and GNSS satellite orbits
  - Earth’s gravity field
- **Study objectives:**

  1. Double-difference processing of a simulated GPS network in space: Effect of constellation design, parameterization and simulated errors on the LEO orbit determination

  2. Ambiguity resolution in a space-based GPS network

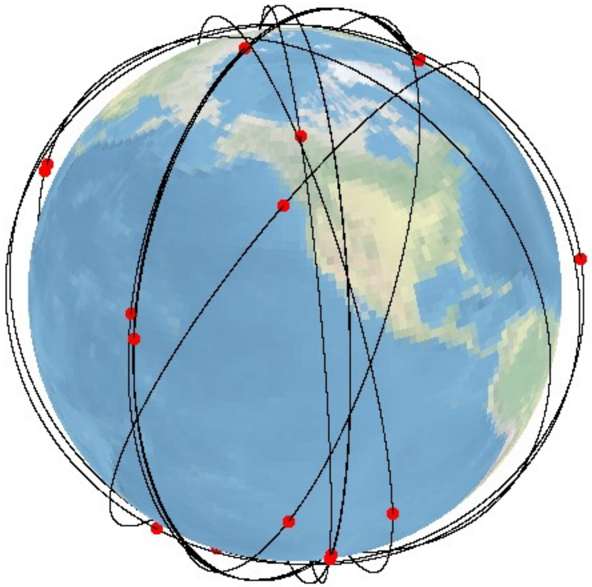




(Nanosats, 2021; Millan et al., 2019)

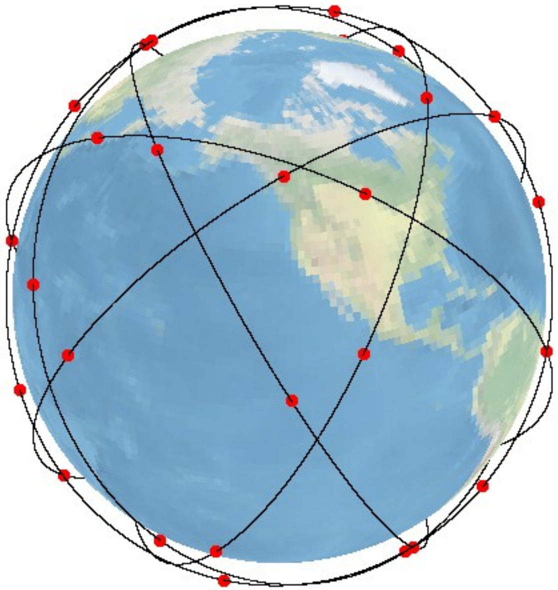
Constellation scenarios

a) Existing satellite missions
16 satellites



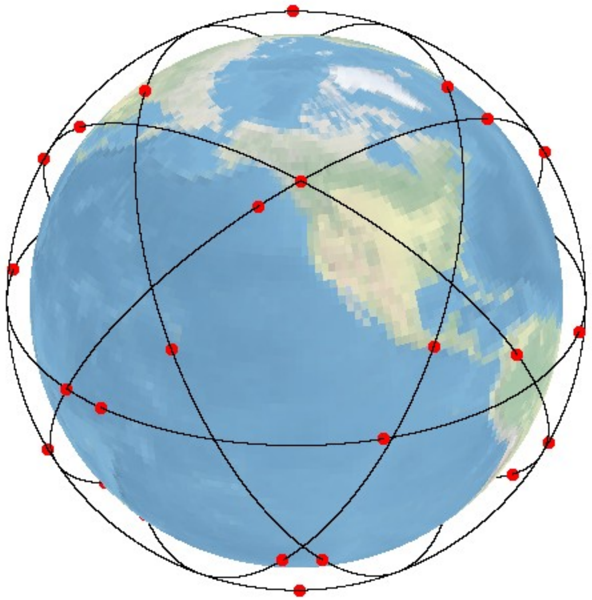
- GRACE-FO A and B
- Jason-1,-2,-3
- Sentinel-1A to -3B
- SWARM A, B, C
- TanDEM- and TerraSAR-X

b) Walker constellation
36 satellites



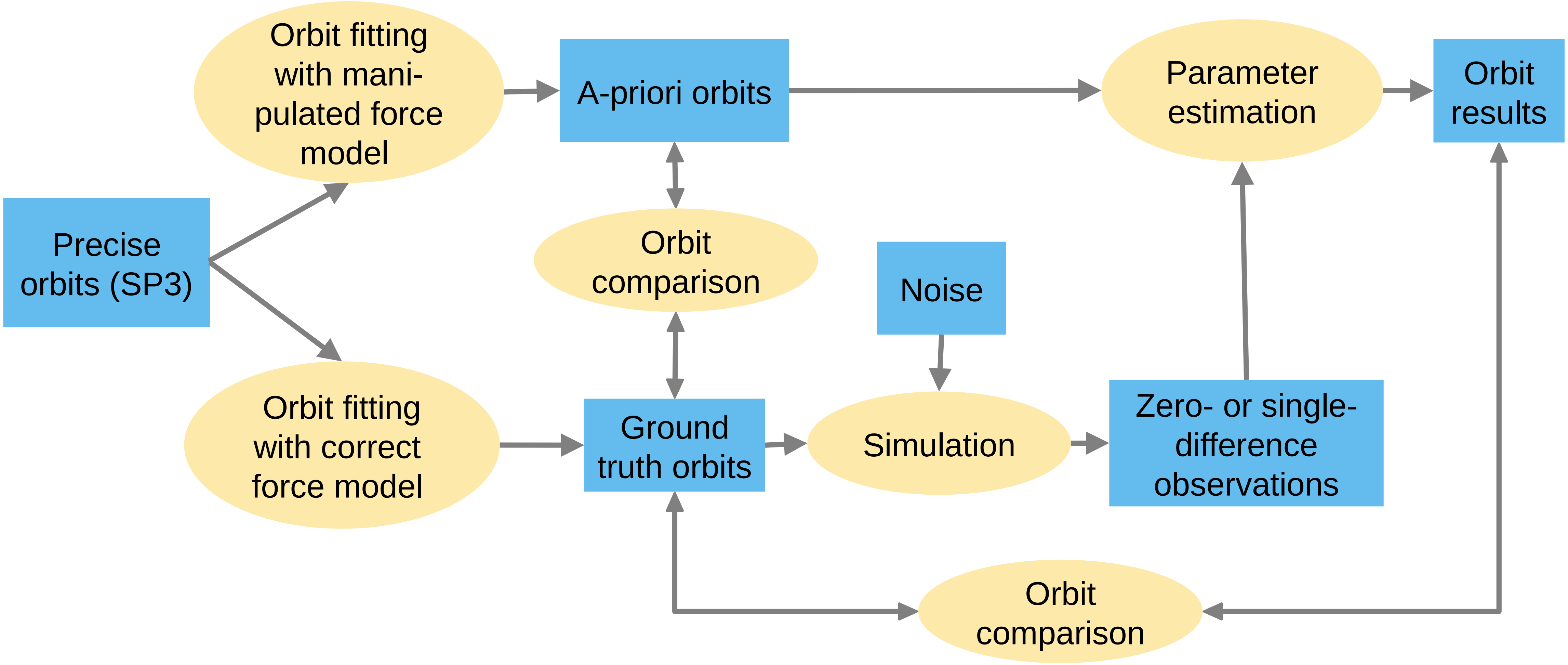
- 6 equally distributed orbital planes with inclination of 60°
- 6 satellites per plane

c) Astrocast constellation
36 satellites



- 5 equally distributed orbital planes with inclination of 60°
- One equatorial plane
- 6 satellites per plane

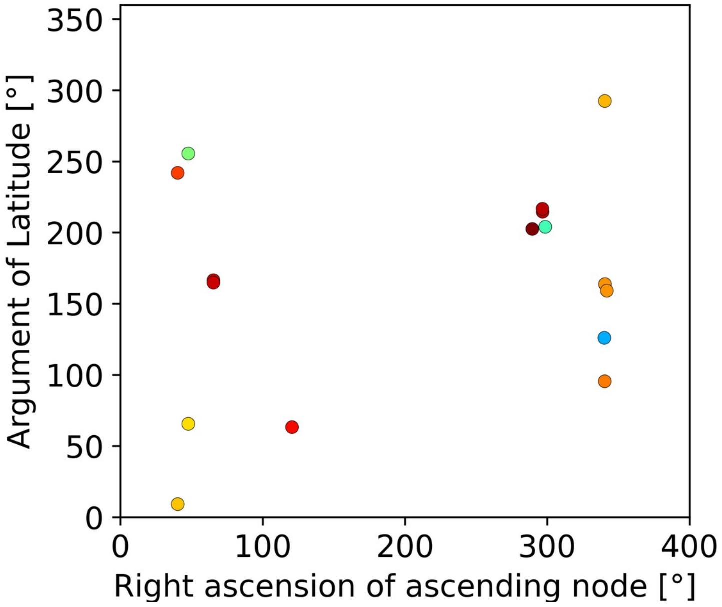
Simulation and processing scheme



Difference between a-priori LEO orbits and ground-truth orbits

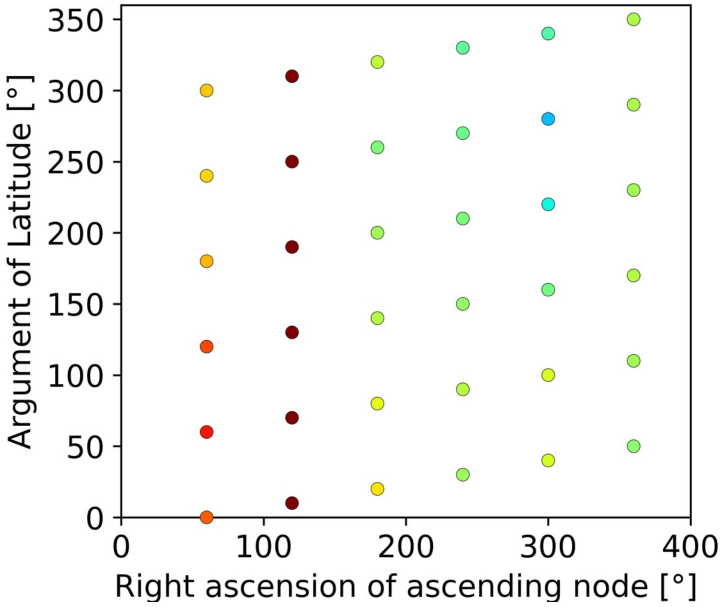
- Time period: 3 revolutions (4 h 48 min)
- A-priori LEO orbits without ocean tides, ground-truth orbits with ocean tides up to degree 50

Existing satellite missions



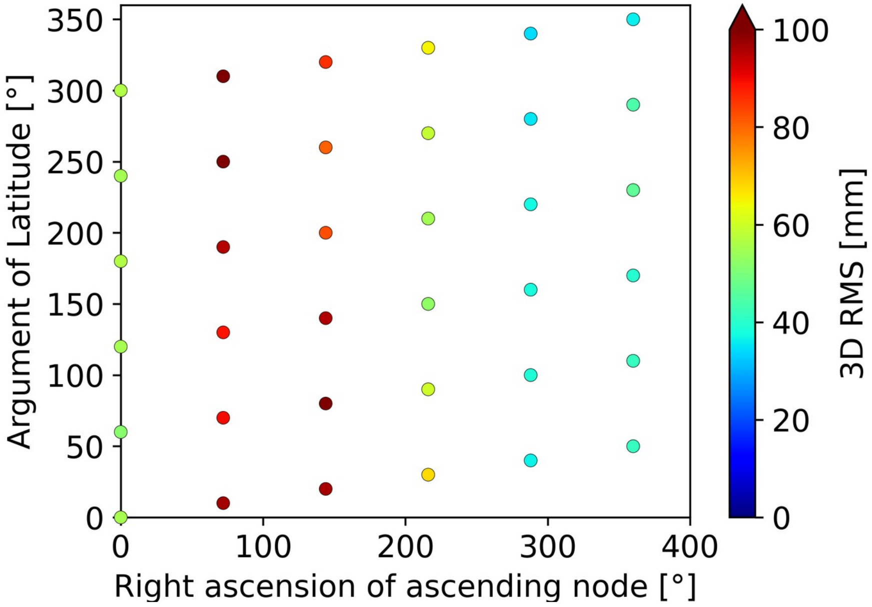
Radial	Along-track	Cross-track
19.2 mm	67.2 mm	37.8 mm

Walker constellation



Radial	Along-track	Cross-track
20.4 mm	63.7 mm	41.8 mm

Astrocast constellation



Radial	Along-track	Cross-track
17.7 mm	50.1 mm	42.9 mm

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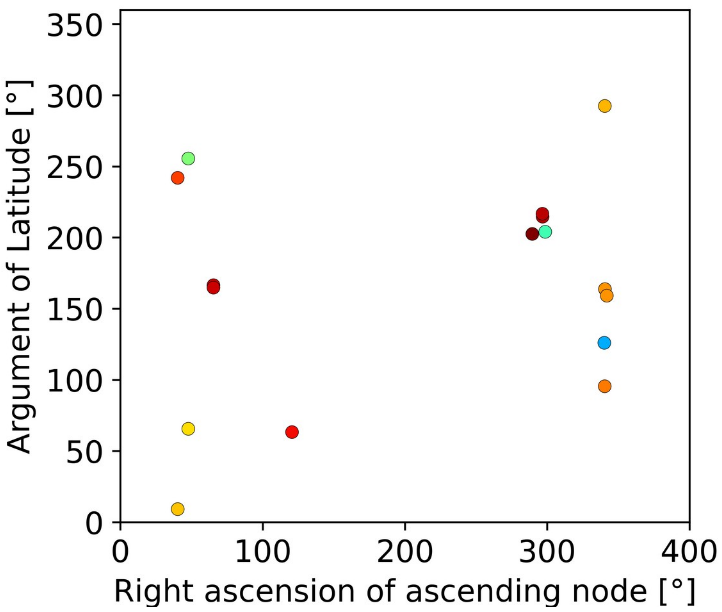

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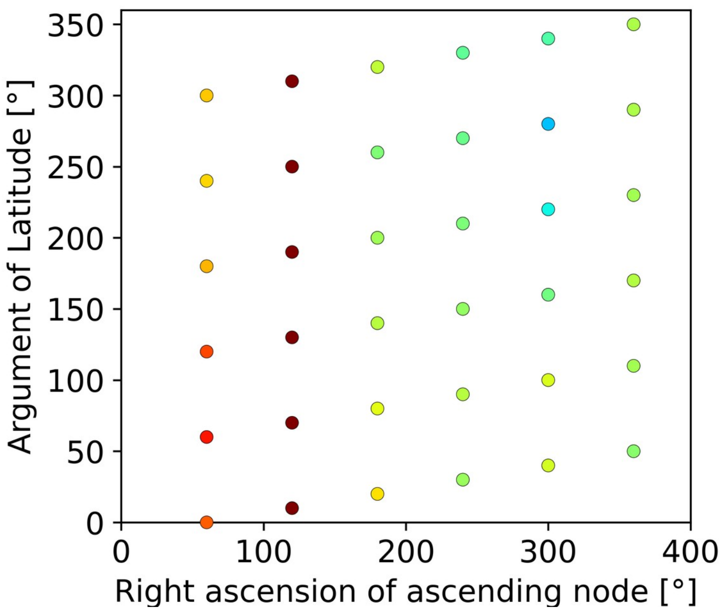
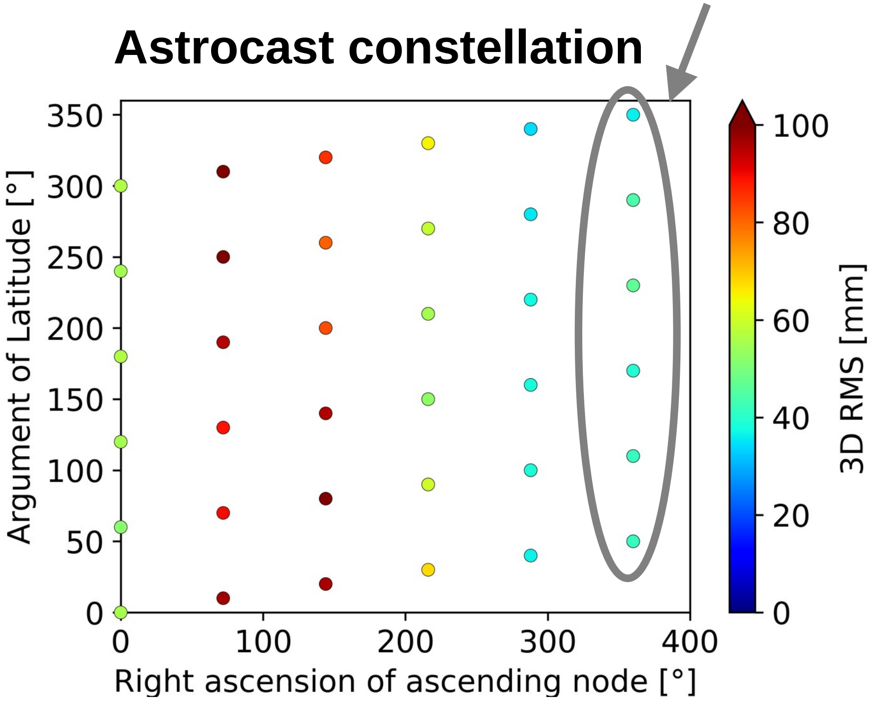
Walker constellation



Radial	Along-track	Cross-track
20.4 mm	63.7 mm	41.8 mm

Equatorial plane

Astrocast constellation

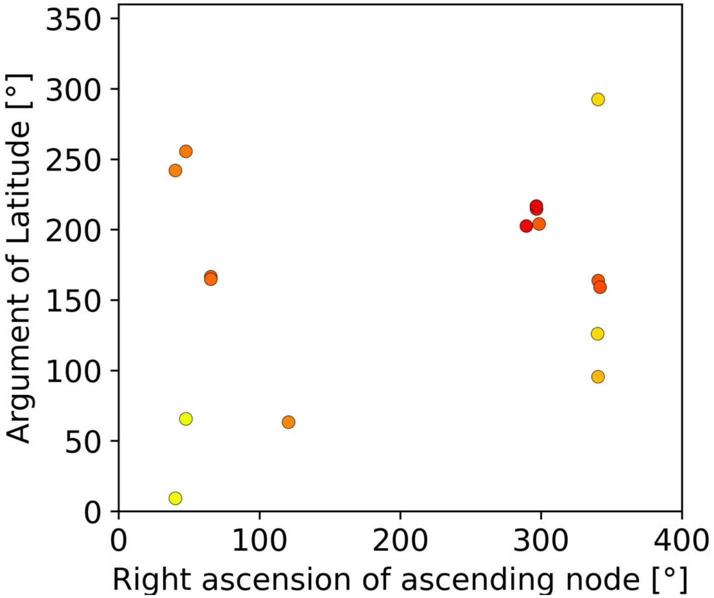


Radial	Along-track	Cross-track
17.7 mm	50.1 mm	42.9 mm

Difference between estimated LEO orbits and ground-truth orbits

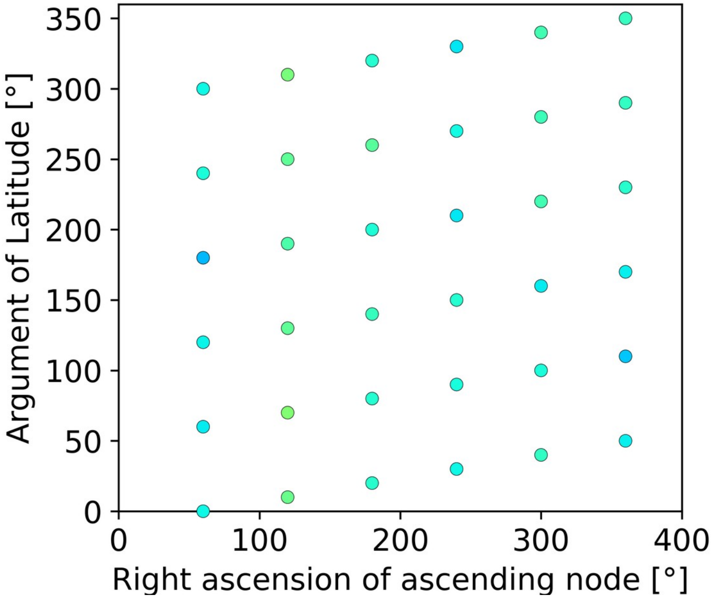
- Time period: 3 revolutions (4 h 48 min)
- Introduced error: A-priori orbit without ocean tides + noise of 2 mm in phase observations
- Parameterization: 6 Keplerian elements + stochastic pulses (velocity changes) every 15 minutes

Existing satellite missions



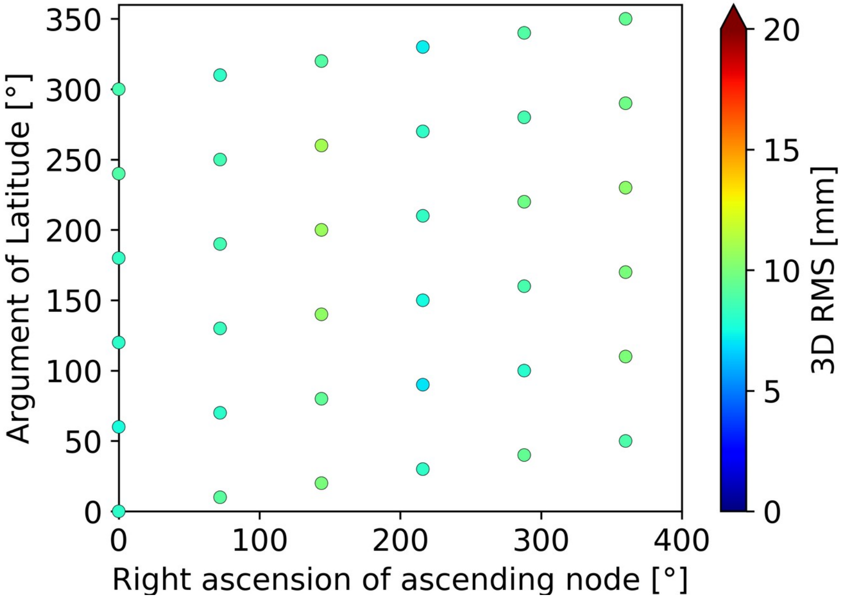
Radial	Along-track	Cross-track
6.5 mm	9.3 mm	11.4 mm

Walker constellation



Radial	Along-track	Cross-track
6.0 mm	3.4 mm	5.4 mm

Astrocast constellation



Radial	Along-track	Cross-track
5.9 mm	4.2 mm	5.9 mm

Orbit differences for different introduced errors and parameterization

Example for Walker constellation

Introduced errors	Estimated parameters	A-priori vs. ground-truth (3D RMS in mm)	Estimated vs. ground-truth (3D RMS in mm)
LEO-TID0 + 0 mm	K + S	71 (LEO)	7.8 (LEO)
LEO-TID0 + 2 mm	K + S	71 (LEO)	8.0 (LEO)
GPS-POT5 + 2 mm	K + S	29 (GPS)	3.5 (LEO)
LEO-TID0 + 2 mm	K	71 (LEO)	72.0 (LEO)
LEO-TID0 + 2 mm	K + S + A	71 (LEO)	20.0 (LEO)

Errors:

- **LEO-TID0:** LEO orbits without ocean tides
- **GPS-POT5:** GPS orbits with gravity potential only up to degree 5
- Noise of 0 mm or 2 mm

Parameters:

- **K:** 6 Keplerian elements
- **S:** Stochastic pulses every 15 minutes
- **A:** Ambiguities

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Parameters:

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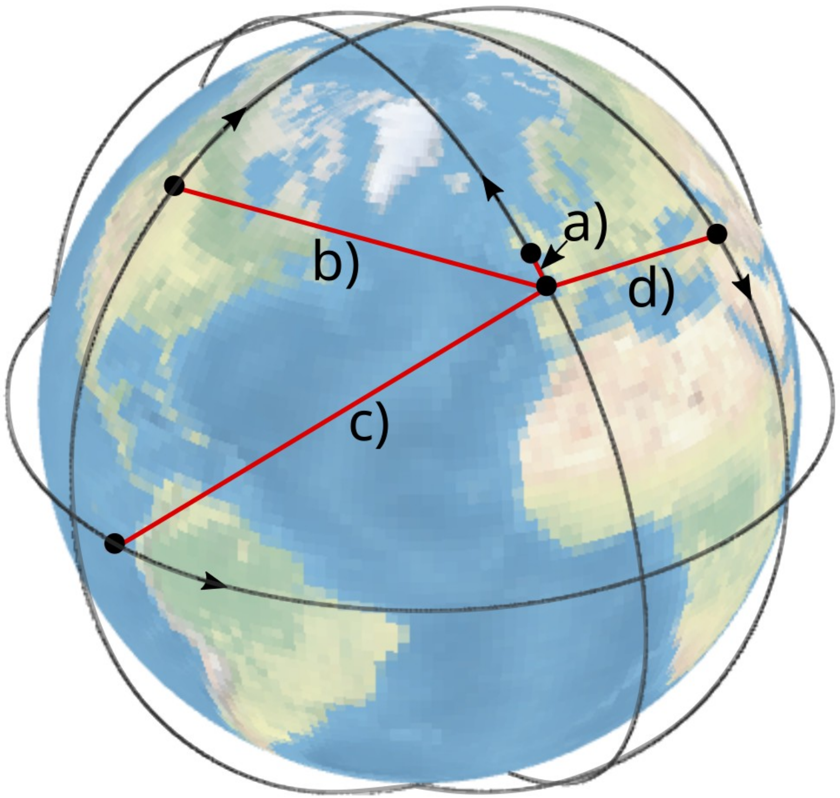
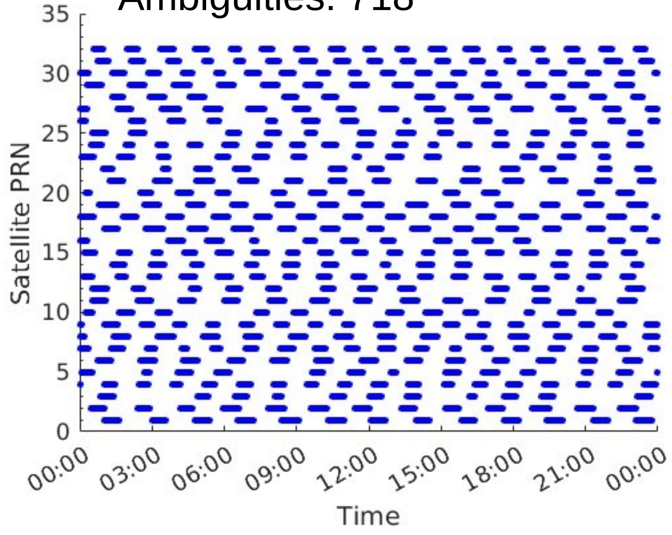
- **S:** Stochastic pulses every 15 minutes
- **A:** Ambiguities

GPS satellite tracking for 4 baseline scenarios

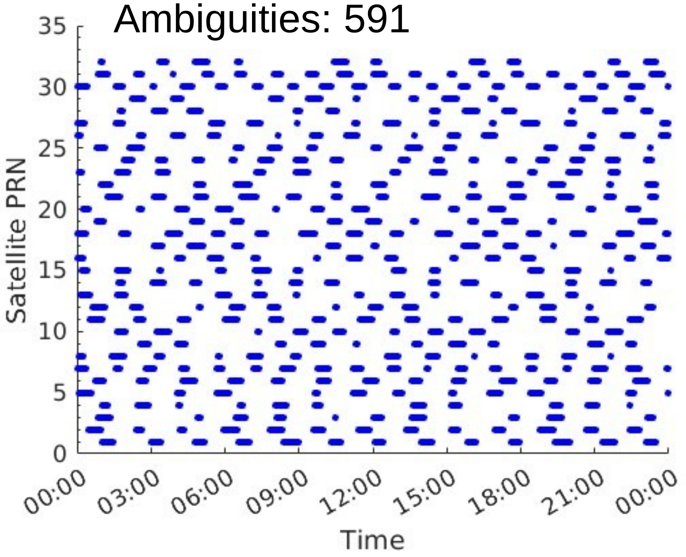
Elevation cut-off angle of 0° for all simulations



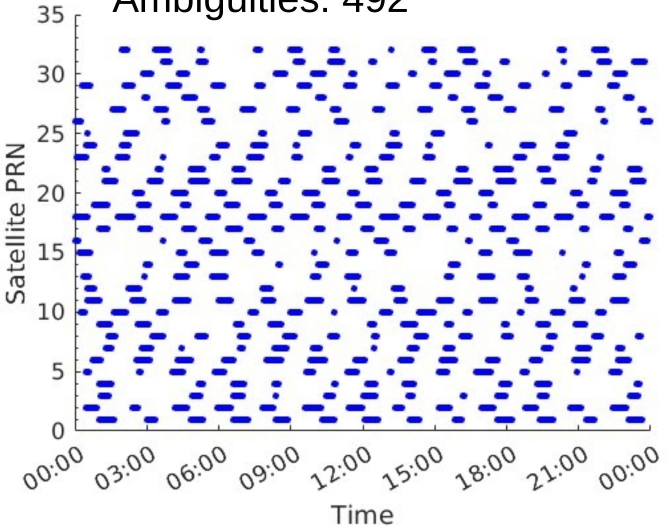
a) Observations: 21321
Ambiguities: 718



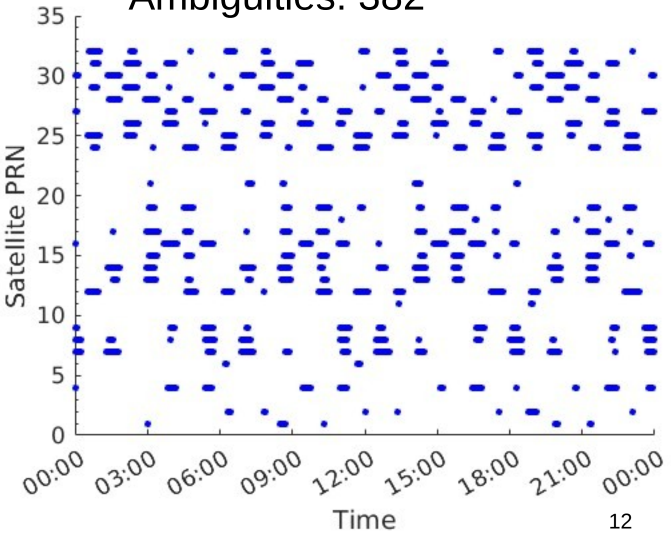
b) Observations: 12024
Ambiguities: 591



c) Observations: 10209
Ambiguities: 492

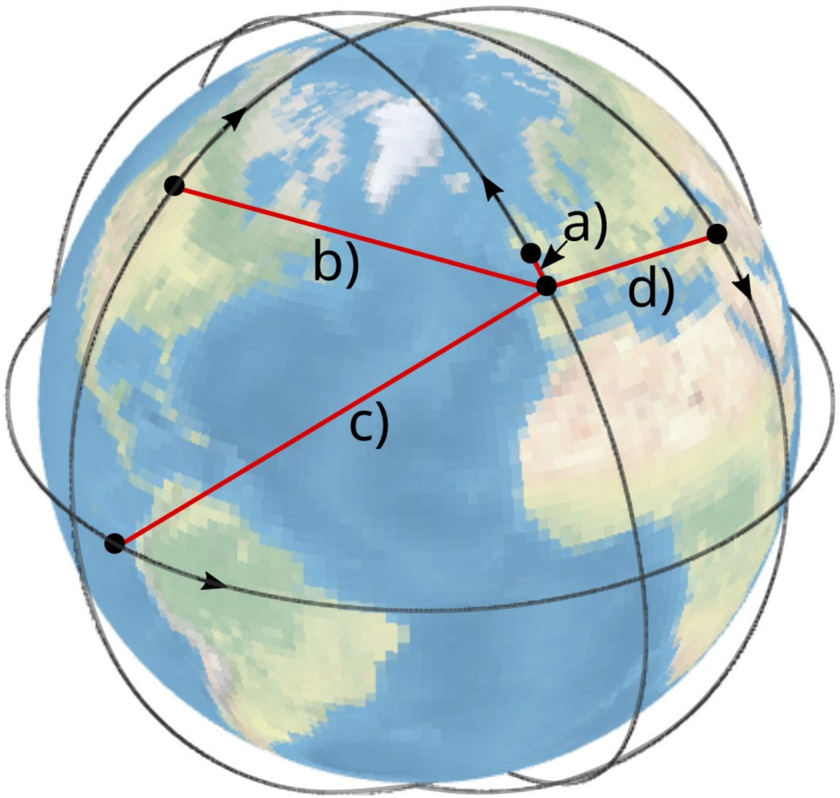


d) Observations: 6108
Ambiguities: 382

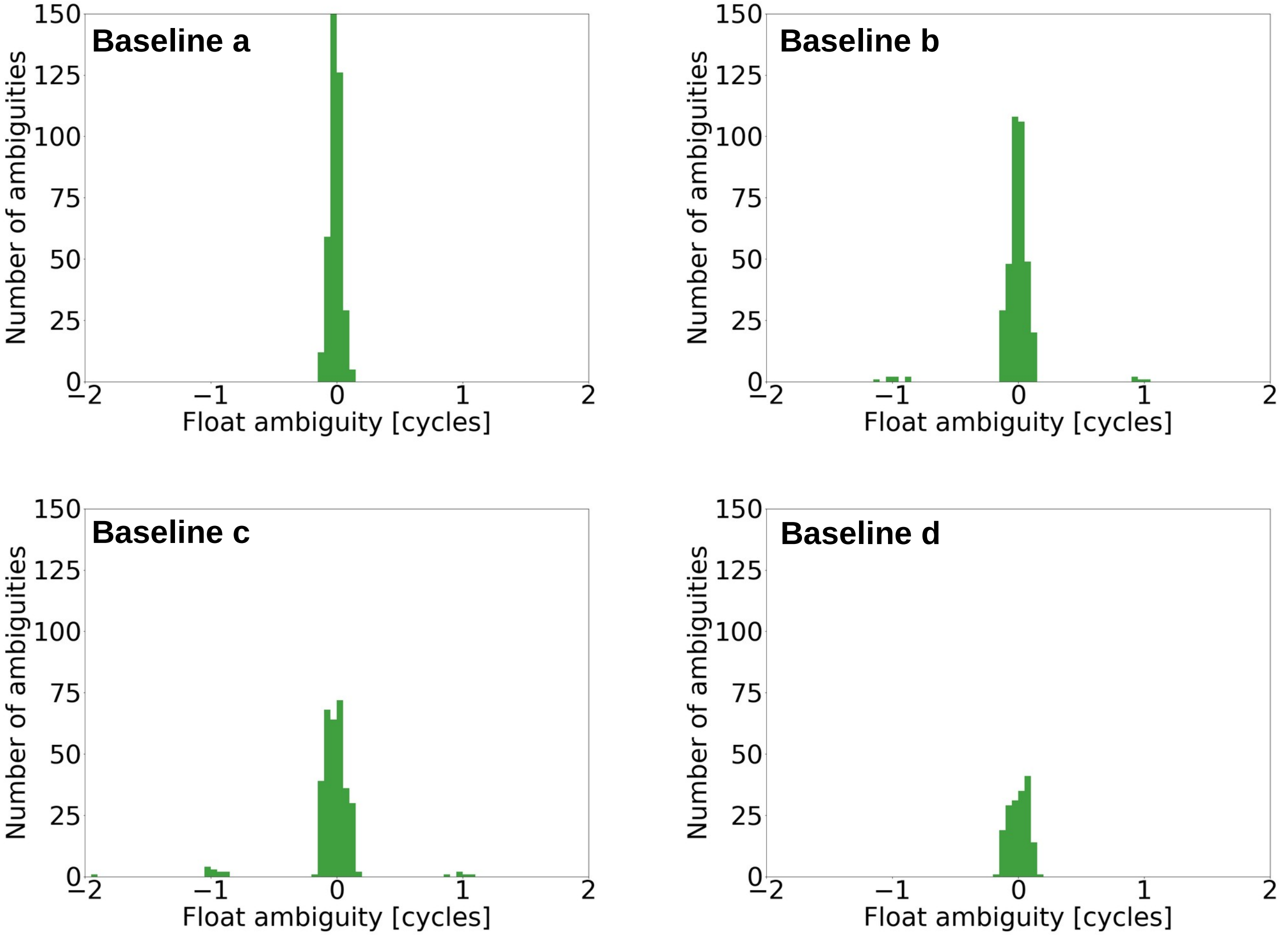


Estimation of float ambiguities for 4 baseline scenarios

Elevation cut-off angle of 0° for all simulations

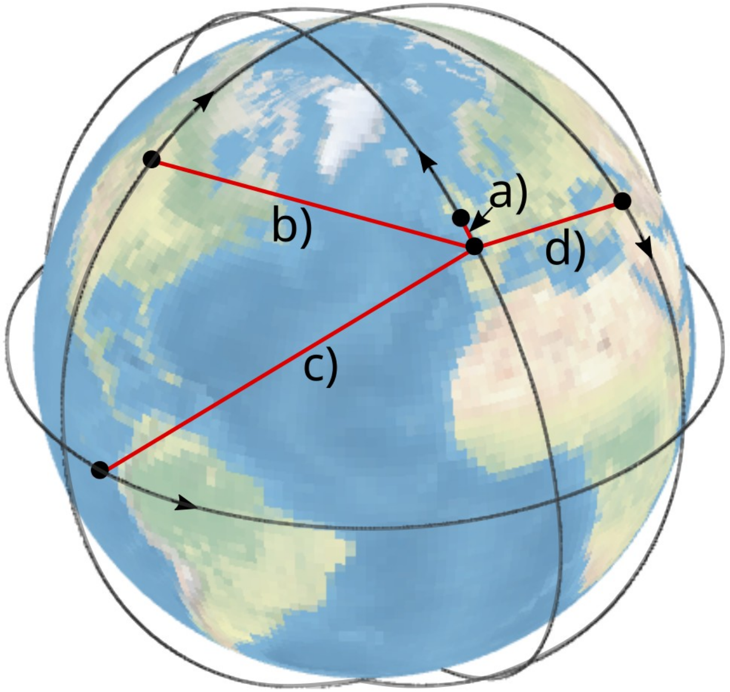


Manipulation of a-priori LEO orbits: Development of ocean tides only up to degree 15 instead of 50 → orbit errors of 1-2 cm



Integer ambiguity resolution for 4 baseline scenarios

Elevation cut-off angle of 0° for all simulations



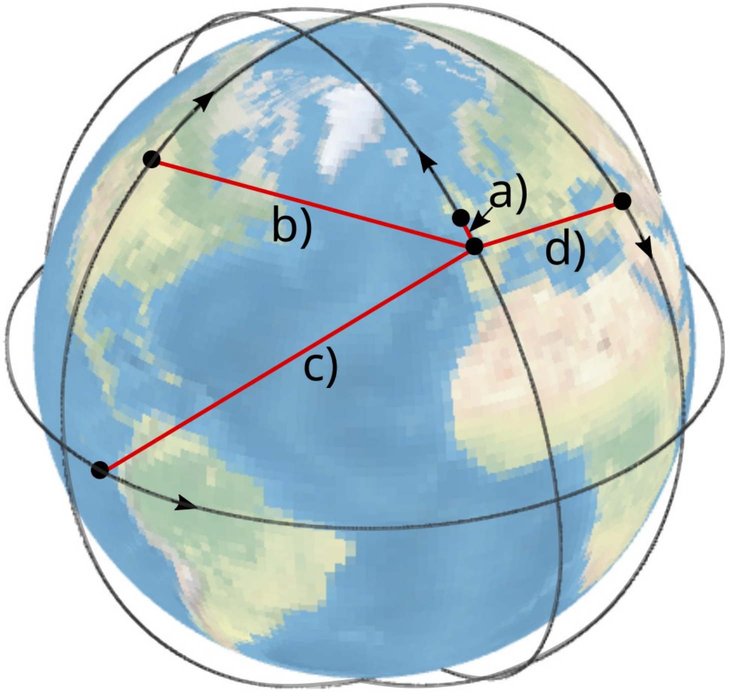
	Baseline a		Baseline b		Baseline c		Baseline d	
Introduced errors	**%RED**	**%BAD**	**%RED**	**%BAD**	**%RED**	**%BAD**	**%RED**	**%BAD**
LEO-TID15 + 0mm	99	0	96	6	93	29	69	0
LEO-TID15 + 2mm	99	0	85	2	85	20	54	0
LEO-TID15 + 4mm	94	0	11	0	20	0	0	0
LEO-TID35 + 2mm	99	0	95	0	94	0	64	0
GPS-POT5 + 2mm	99	0	94	0	92	0	60	0

- **LEO-TID15/35:** Ocean tides of LEO a-priori orbit only up to degree 15 or 35, respectively
- **GPS-POT5:** Gravity potential of GNSS a-priori orbits only up to degree 5
- Noise of 0 mm, 2 mm or 4 mm

- **%RED:** Reduction of the number of ambiguity parameters in percent
- **%BAD:** Percentage of ambiguities solved incorrectly

Integer ambiguity resolution for 4 baseline scenarios

Elevation cut-off angle of 0° for all simulations



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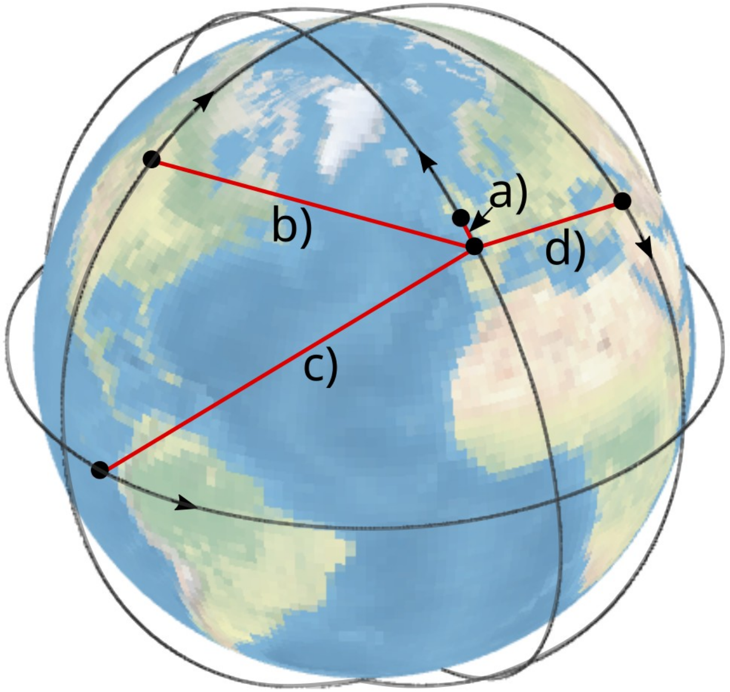
Integer ambiguity resolution for 4 baseline scenarios

Elevation cut-off angle of 0° for all simulations



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Integer ambiguity resolution for 4 baseline scenarios

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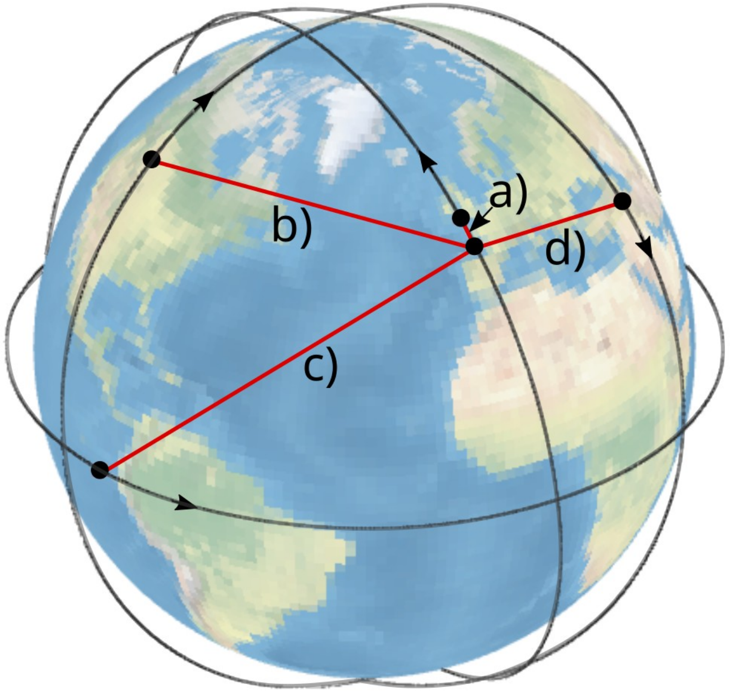

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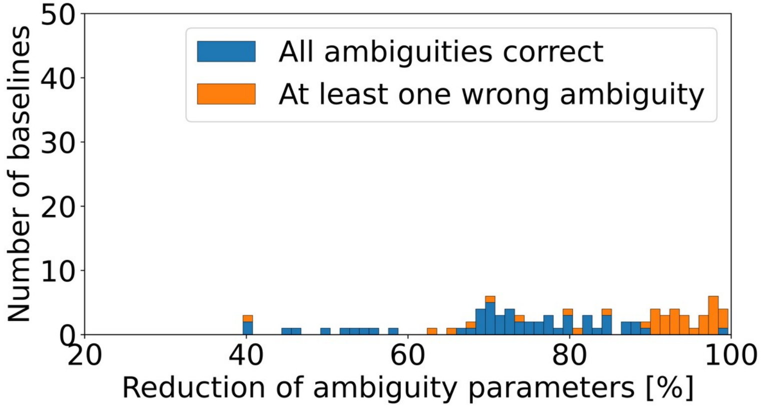
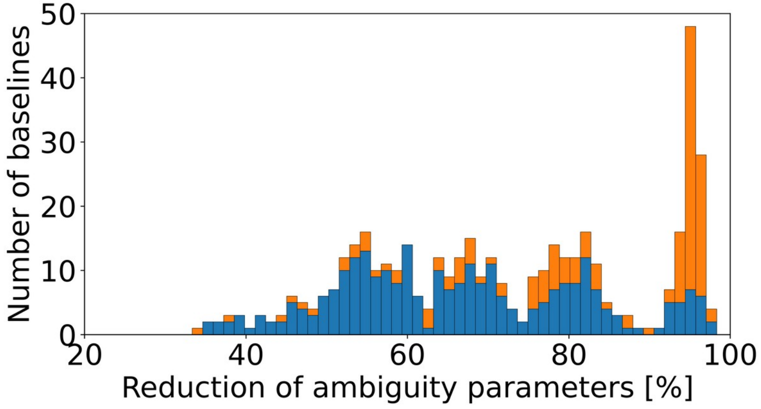
Integer ambiguity resolution for entire constellations

1) Large introduced error in a-priori LEO orbits, ocean tides up to degree 15 → 10 - 20 mm

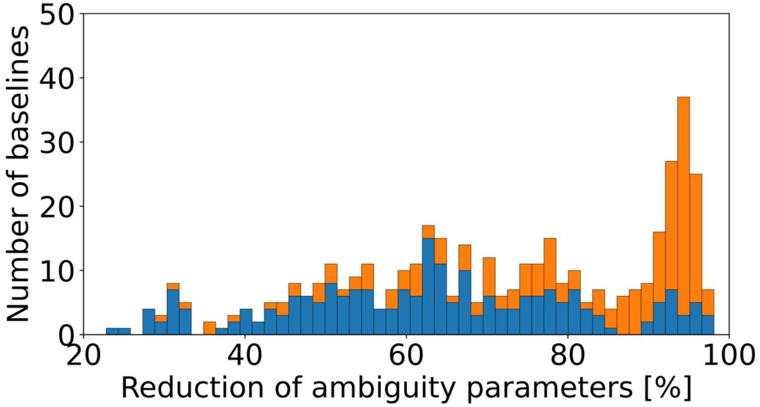
Existing satellite missions



Walker constellation

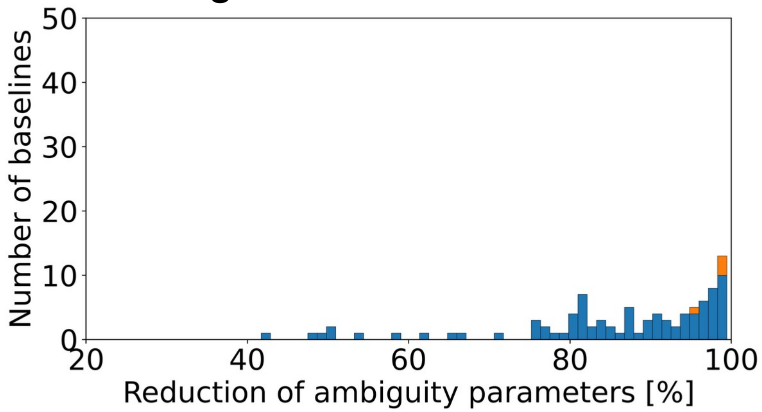


Astrocast constellation

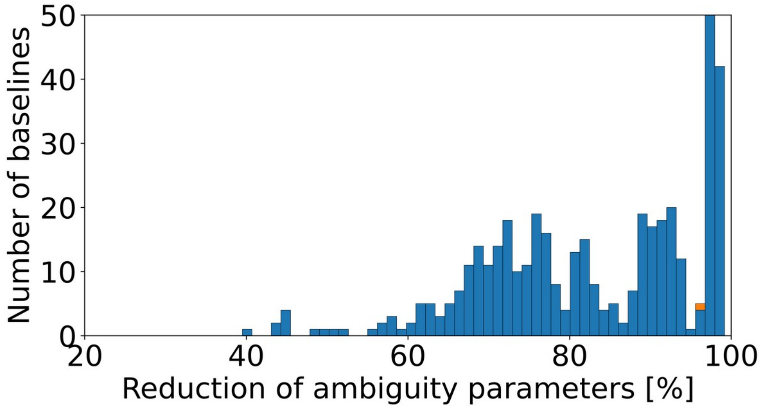


2) Small introduced error in a-priori LEO orbits, ocean tides up to degree 35 → 3 - 4 mm

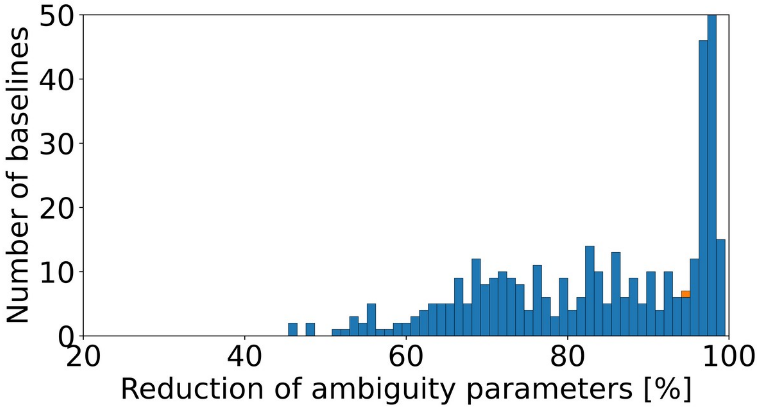
Existing satellite missions



Walker constellation



Astrocast constellation



Conclusions

1) LEO orbit determination with introduced integer ambiguities

- Constellation geometry: Benefits of the Astrocast and Walker constellations due to the large number and homogeneous distribution of observations
- Simulated errors on the level of 30-70 mm in LEO and GPS orbits
  - No significant improvement when estimating only 6 Keplerian elements
  - Orbit improvement to 4-8 mm by estimating additional stochastic pulses every 15 min
  - Additional estimation of ambiguity parameters: Significantly larger number of parameters and reduced accuracy of about 20 mm

2) Ambiguity resolution

- Dependent on baseline length, relative motion and introduced errors
- Reduction of ambiguity parameters highly dependent on the noise level: Much higher number of ambiguity parameters with noise of 4 mm than with 2 mm
- Good results for integer ambiguity resolution only with LEO-orbit errors smaller than 10 mm

Thank you!