Ginan Supporting Future LEO-PNT

Amir Allahvirdi-Zadeh, Ahmed El-Mowafy, Simon McClusky, Sebastien Allgeyer, Aaron Hammond

GNSS-SPAN GROUP, SCHOOL OF EARTH AND PLANETARY SCIENCES, CURTIN UNIVERSITY

GEOSCIENCE AUSTRALIA

Outline

- Why do we need LEO-PNT?
- Precise orbit determination of LEO satellites (LEO POD)
- LEO POD modules in Ginan
- LEO-PNT simulation
- Processing LEO-PNT observations by Ginan
- Summary and conclusion

Why do we need LEO-PNT?

- Challenges in using GNSS in critical environments, such as urban area and indoor spaces, etc.

LEO-PNT systems

Signals of opportunity (SoP)

Navigation signals from LEO-PNT constellation

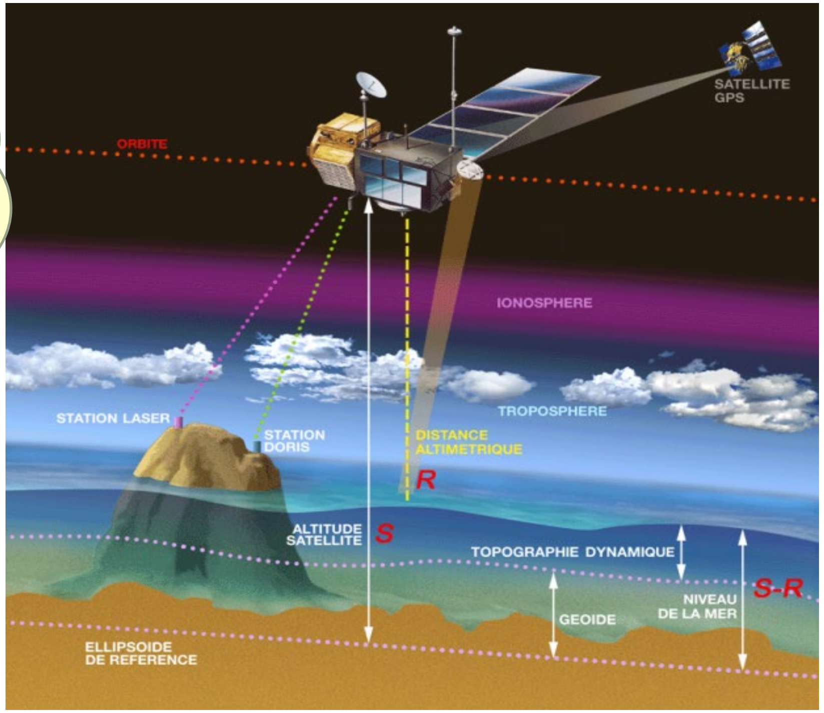
Precise orbit determination of LEO satellites (LEO POD)

Satellites in Low Earth Orbit (LEO) are used for:

- Satellite Gravimetry (SWARM, GRACE-FO)
- GNSS radio occultation (COSMIC-1, -2)
- Satellite altimetry (Jason)
- InSAR (Sentinel 1-6)
- Future LEO-PNT system

Precise Orbits are required for these missions

(Cm- to dm-level of accuracy)



Project Title: Developing and incorporating Low Earth Orbiter (LEO) GNSS data analysis capability into Ginan

FRONTIER SI

Curtin University

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Australian Government
Geoscience Australia

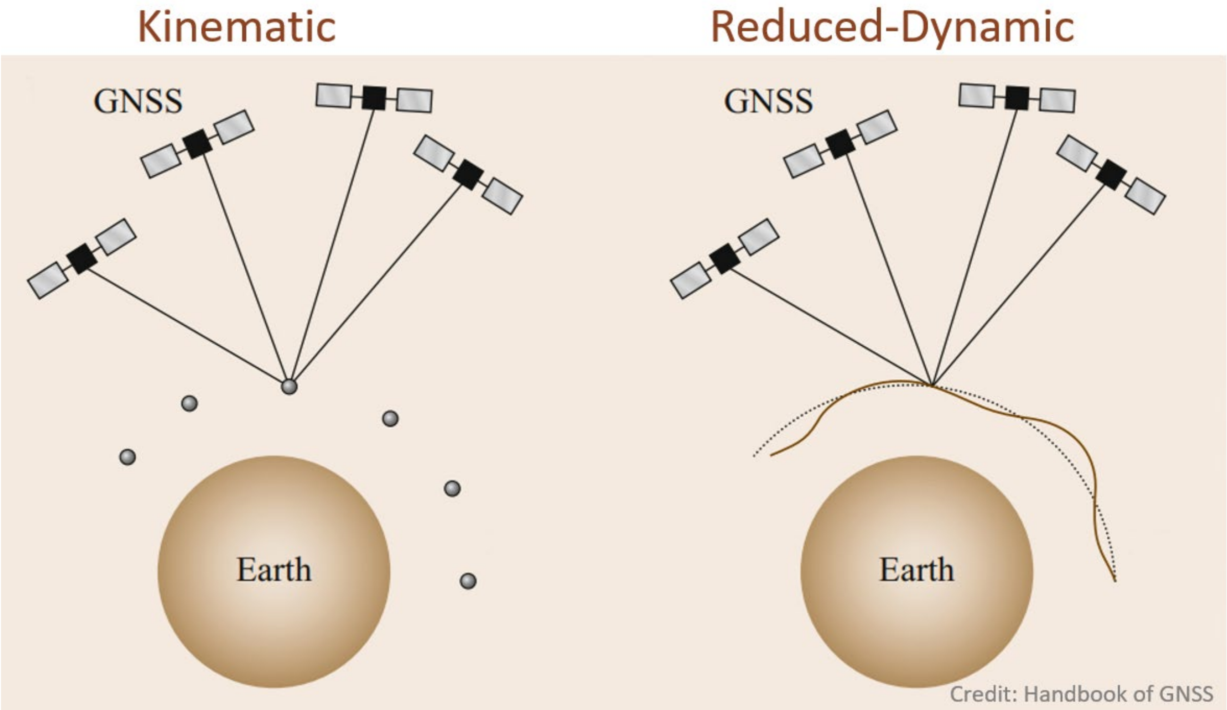
Precise orbit determination of LEO satellites (LEO POD) (Cont.)

Kinematic POD:

- Based on kinematic Precise Point Positioning (PPP)
- Sensitive to outliers
- No observation → No orbit
- Bad observation → Low accuracy

Reduced-Dynamic POD

- Based on solving the equation of motion
- Integrating with the GNSS observations
- Estimating stochastic accelerations to compensate for dynamic model deficiencies
- Continuous and more accurate orbit
- Cumbersome processing



Credit: Handbook of GNSS

Kinematic POD in Ginan

- Ginan is the Australian open-source comprehensive software developed by Geoscience Australia and its partners for processing GNSS observations (for classical PPP, PPP-AR, PPP-RTK and POD).

$$\begin{aligned} P_{r,f} &= \left[p^{1}_{r,f},\dots,p^{m}_{r,f}\right]^{T} \\ \Phi_{r,f} &= \left[\varphi^{1}_{r,f},\dots,\varphi^{m}_{r,f}\right]^{T} \end{aligned} \quad \rightarrow \quad \left.\begin{aligned} P &= \left[P^{T}_{r,1},\dots,P^{T}_{r,f}\right] \\ \Phi &= \left[\Phi^{T}_{r,1},\dots,\Phi^{T}_{r,f}\right] \end{aligned}\right\} \; y_t = [P \quad \Phi]^{T}$$

All observations collected by LEO satellites at epoch t

Observation model

$$E(y_t) = A_t x_t + \varepsilon_t$$

Unknown State vector

$$x = \left[r^{T}, \dot{r}^{T}, dt_r, d\dot{t}_r, n^{T}, i^{T}_{STEC}\right]^{T}$$

Position

Velocity

Receiver clock offset error and its rate

Ambiguities

Ionospheric slant delay

Kinematic POD in Ginan

POD in Ginan is based on Extended Kalman Filtering (EKF) including Time update and Measurement update steps

State transition matrix (STM)

- Identity matrix for all states

$$F_t = \mathbf{1}$$

- Except for states with rate terms

$$F_t = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix}$$

POD at Ginan is Based on Extended Kalman Filter

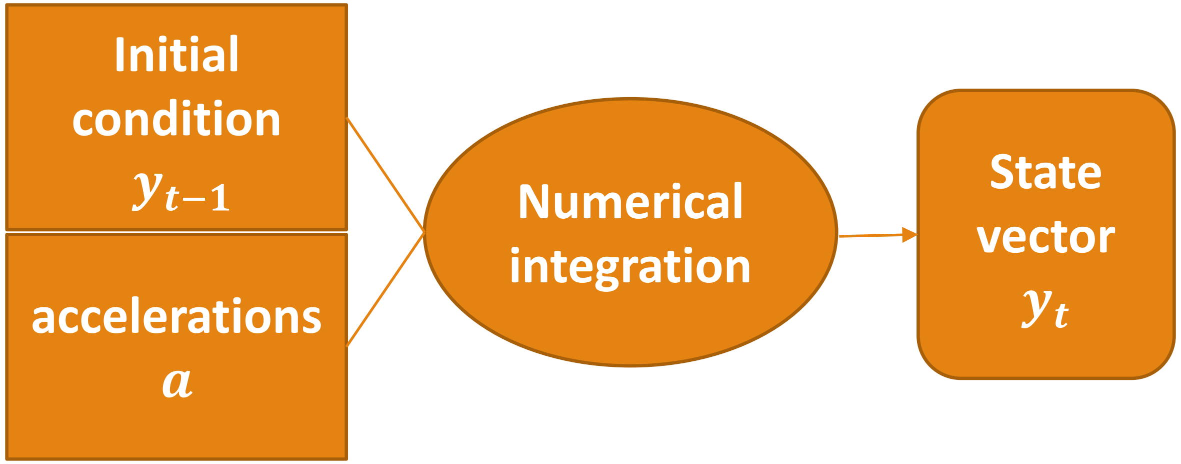
Time difference between two consecutive epochs

Reduced-dynamic POD in Ginan

Satellite state vector: $y = \begin{pmatrix} r \\ \dot{r} \end{pmatrix}$

Equation of motion:

$$\frac{d^2 r}{dt} = a(t, r, \dot{r}, p) \rightarrow \frac{dy}{dt} = \begin{pmatrix} \dot{r} \\ a \end{pmatrix}$$



Observation model

$$E(y_t) = A_t x_t + \varepsilon_t$$

Unknown state vector

$$x = [r^T, \dot{r}^T, dt_r, n^T, i_{STEC}^T, emp_{RTN}^T]^T$$

- r^T: orbit
- $\dot{r}^T$: Velocity
- dt_r: Receiver clock offset error
- n^T: Ambiguities
- i_{STEC}^T: Ionospheric slant delay
- emp_{RTN}^T: Empirical accelerations in radial (R), along-track (T), and cross-track (N) directions

POD in Ginan – Models and initial values

Item	Description
Dynamic models	**Gravity field**: Earth gravitational model (EGM 2008); **Tidal corrections**: Finite element solution tidal model – FES2014b; **General Relativity**: IERS 2010; **Planets ephemeris**: JPL DE436.1950.2050; **Empirical acceleration:** in RTN directions
Observation models	**Observation**: Ionospheric-free of code and phase; **Attitude**: quaternions in ORBEX files; **Antenna corrections**: PCO, PCV, antenna sensor offsets

Initial values for the state vector in the EKF in Ginan

State	Standard deviation (σ)	STD of Process noise
Position	30 m	0 m
Position rate (velocity)	5000 m/s	1000 m/s
Clock	500 m	500 m
Clock rate	500 m/s	0.0001 m/s
Ambiguity	6000 m	0 m
Ionosphere slant TEC	1000 m	8000 m
Empirical acceleration (RTN)	$50\ m/s^2$	$0.2\ m/s^2$

POD validation in Ginan (Tested satellite GRACE-FO C)

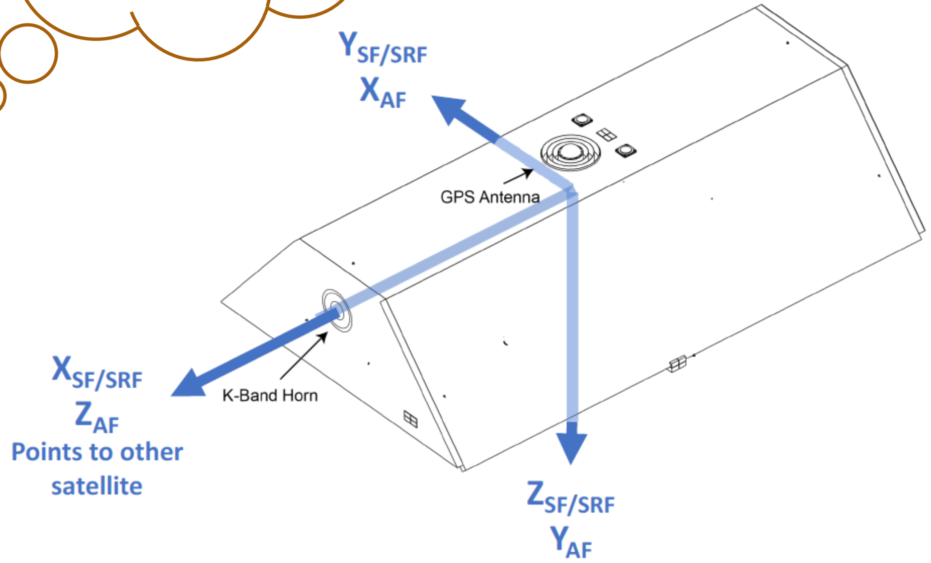
External validation: comparing to the JPL reference orbit

RMSE of Kinematic POD

Date	RMSE X (cm)	RMSE Y (cm)	RMSE Z (cm)	3D RMSE (cm)
2019-02-14	5.2	5.3	6.6	9.9
2019-02-15	7.2	7.9	7.6	13.1
2019-02-16	5.1	5.6	6.2	9.7
2019-02-17	4.6	4.6	6.8	9.4
2019-02-18	5.1	5.1	6.9	9.9
2019-02-19	4.8	4.5	6.8	9.4
2019-02-20	4.3	3.4	5.3	7.6

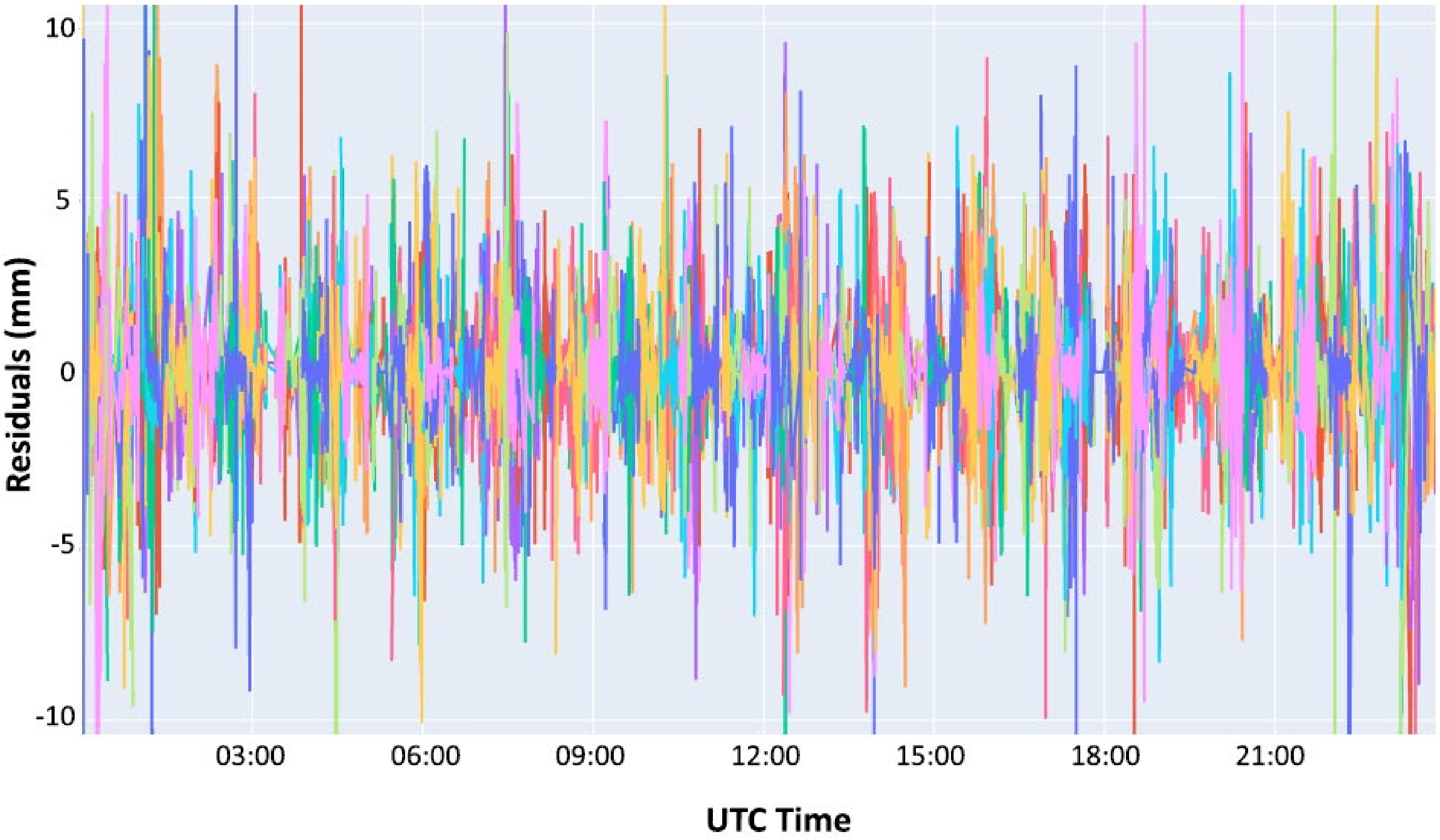
RMSE of Reduced-dynamic POD

Date	RMSE X (cm)	RMSE Y (cm)	RMSE Z (cm)	3D RMSE (cm)
2019-02-14	3.2	1.2	1.9	3.9
2019-02-15	1.5	1.1	1	2.1
2019-02-16	1.6	1.4	0.9	2.3
2019-02-17	1.6	1	1	2.1
2019-02-18	1.3	1.2	0.9	1.9
2019-02-19	1.5	1.2	1.3	2.3
2019-02-20	2.4	2.5	2.3	4.1



POD validation in Ginan (Tested satellite GRACE-FO C)

Internal validation: Residuals of ionosphere-free phase observations



Residuals of phase observations RMS = 2mm

(Each satellite's phase residual is represented by a distinct color)

Positioning using Ginan from LEO-PNT systems

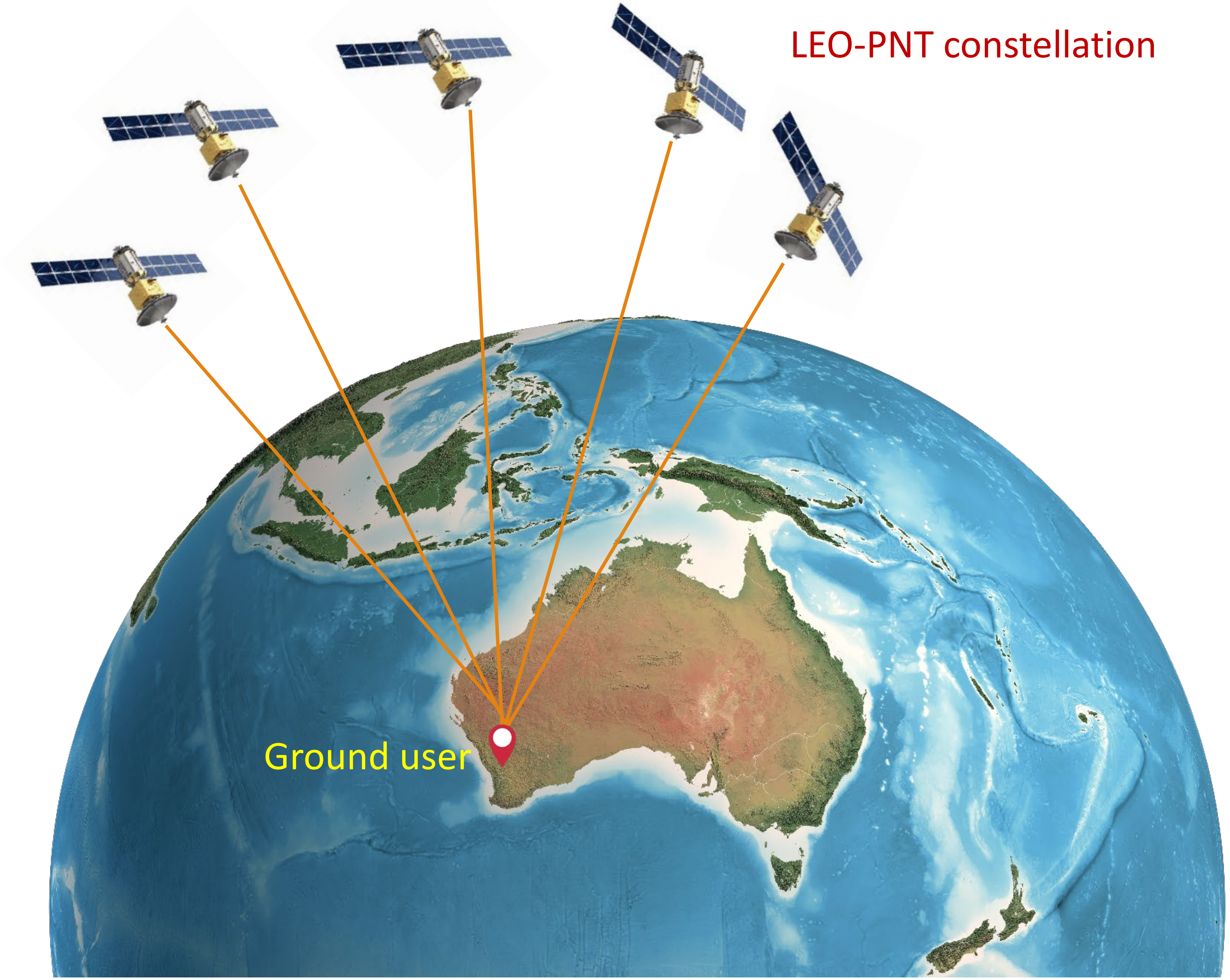
Use future LEO-PNT systems for the positioning of ground users:

I- independent from GNSS, as a backup.

II- combined with GNSS

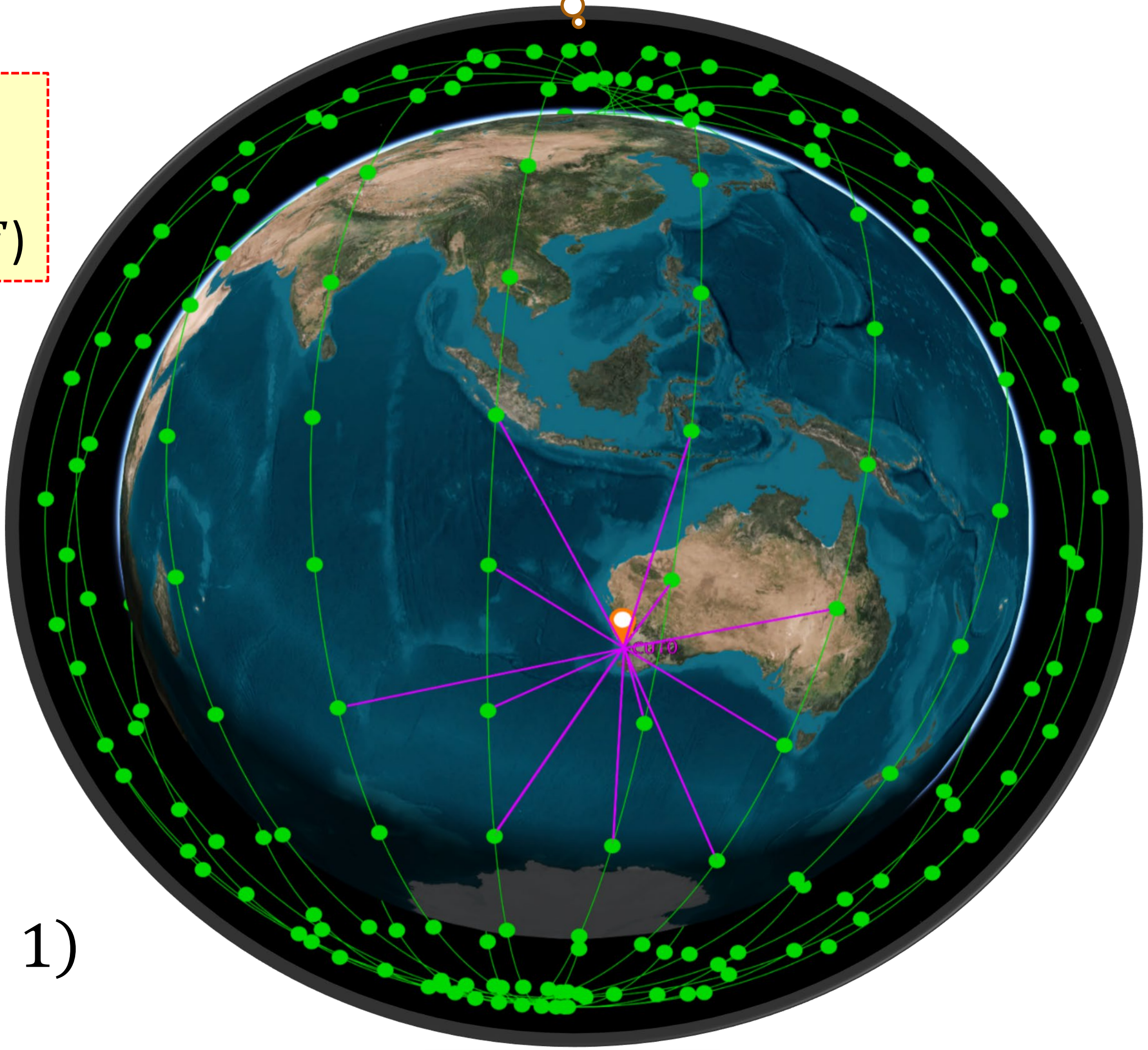
Why Ginan?

EKF ➔ suitable for real-time applications, low-cost receivers, low-budget CPUs, etc.



Simulating LEO-PNT Constellations

240 satellite constellation
with 1000 km altitude



Walker Delta Pattern:
85.64°: 240/12/6

inclination

total number of satellites (T)

number of equally spaced orbital planes (P)

interplane phase increment (F)

Right ascension of ascending node

$$\Omega_{ij} = \frac{2\pi}{P}(i-1)$$

Mean anomaly

$$M_{ij} = \frac{2\pi P}{T}(j-1) + \frac{2\pi}{T}F(i-1)$$

Simulating LEO-PNT Observations

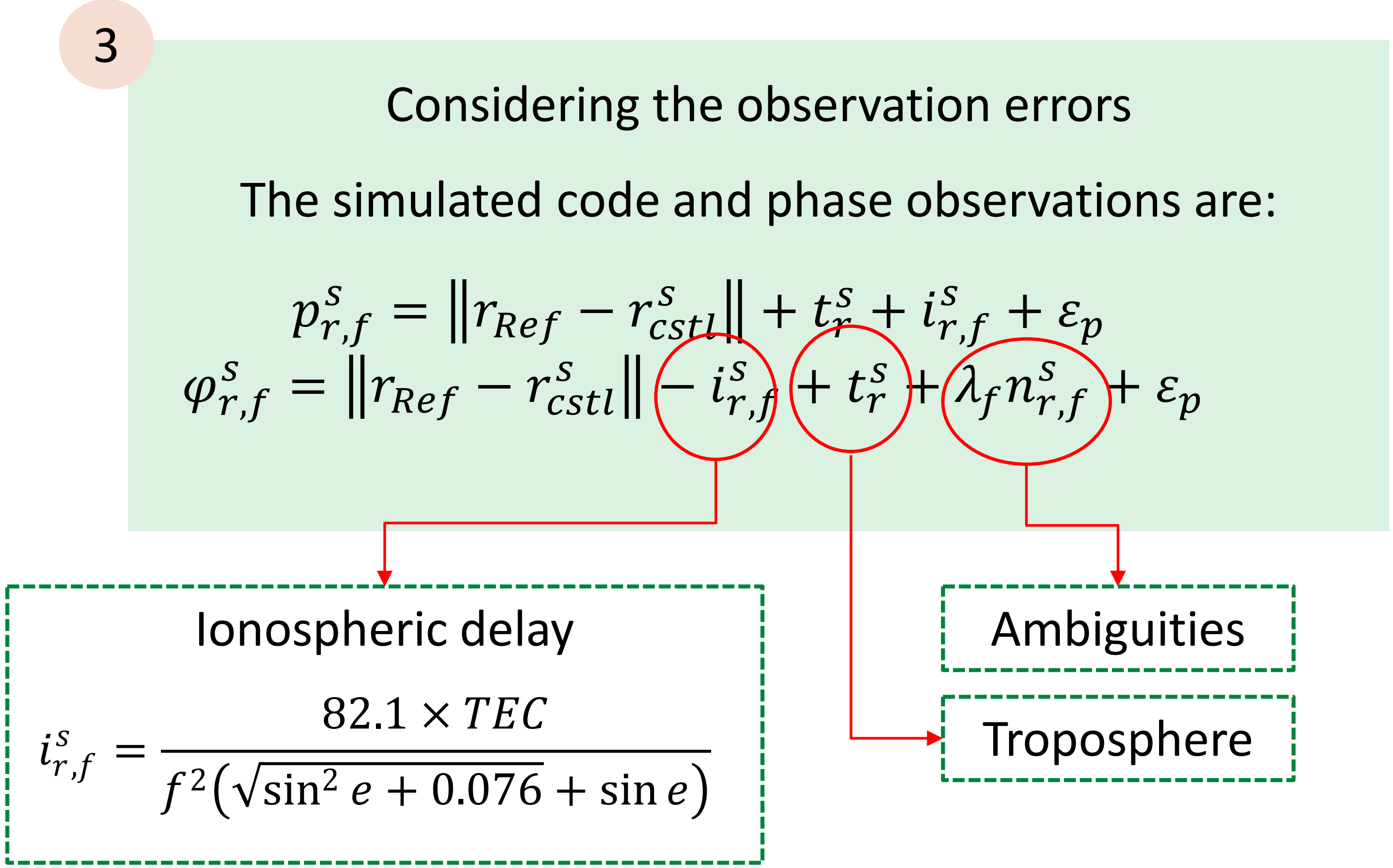
Target: Simulating 1 Hz observations from LEO-PNT system to CUT0 CORS on Curtin campus

1

Ground truth of CUT0 (derived from AUSPOS) $\boldsymbol{r_{Ref}}$

2

Orbits of the LEO-PNT constellation $\boldsymbol{r^{s}_{cstl}}$



3

Considering the observation errors

The simulated code and phase observations are:

$$p^{s}_{r,f} = \left\| r_{Ref} - r^{s}_{cstl} \right\| + t^{s}_{r} + i^{s}_{r,f} + \varepsilon_{p}$$

$$\varphi^{s}_{r,f} = \left\| r_{Ref} - r^{s}_{cstl} \right\| - i^{s}_{r,f} + t^{s}_{r} + \lambda_{f} n^{s}_{r,f} + \varepsilon_{p}$$

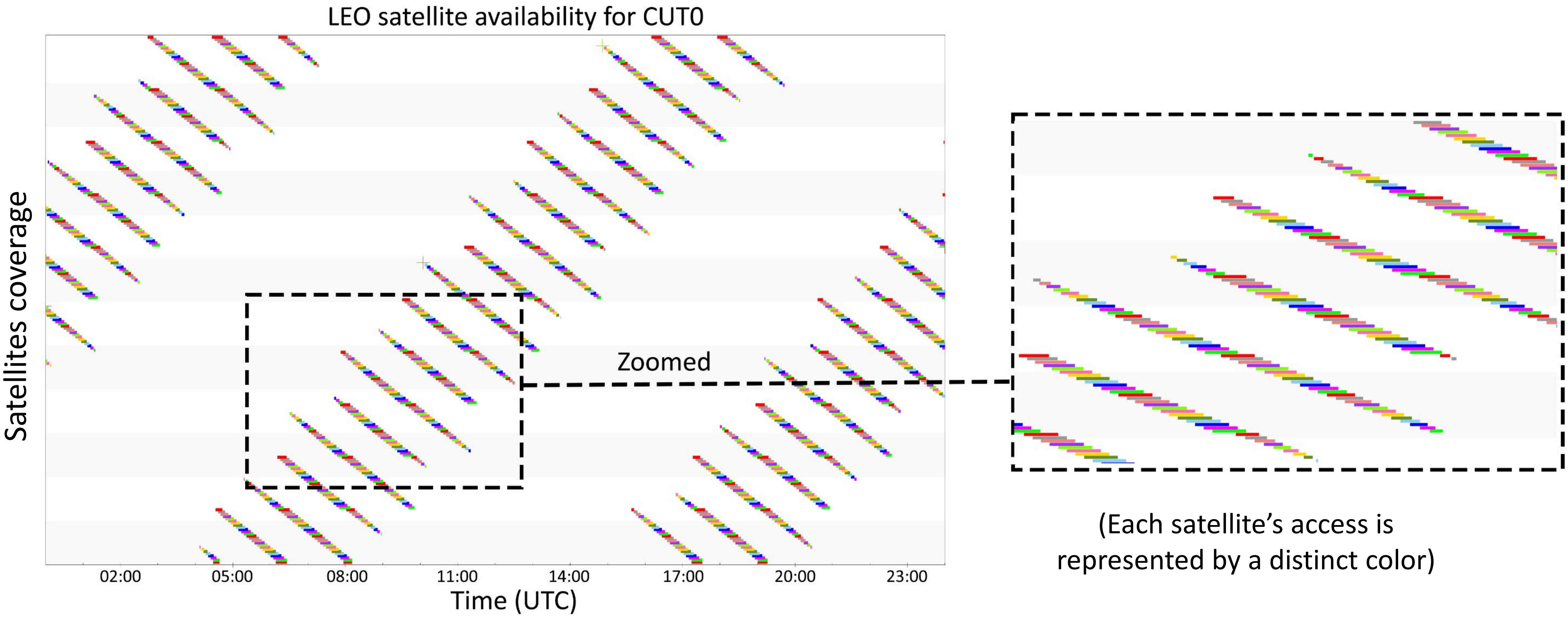
Ionospheric delay

$$i^{s}_{r,f} = \frac{82.1 \times TEC}{f^{2}\left(\sqrt{\sin^{2} e + 0.076} + \sin e\right)}$$

Ambiguities

Troposphere

Coverage of the simulated LEO-PNT constellations for CUT0

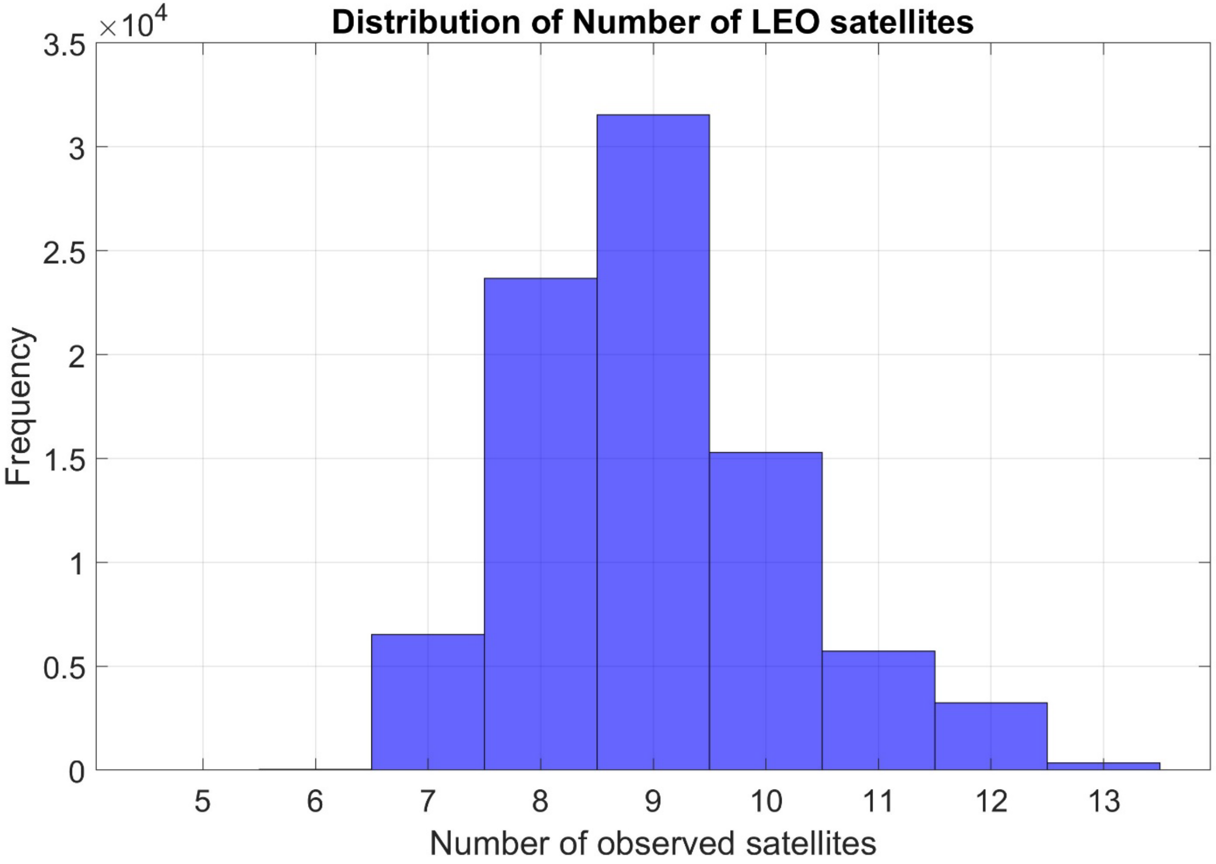


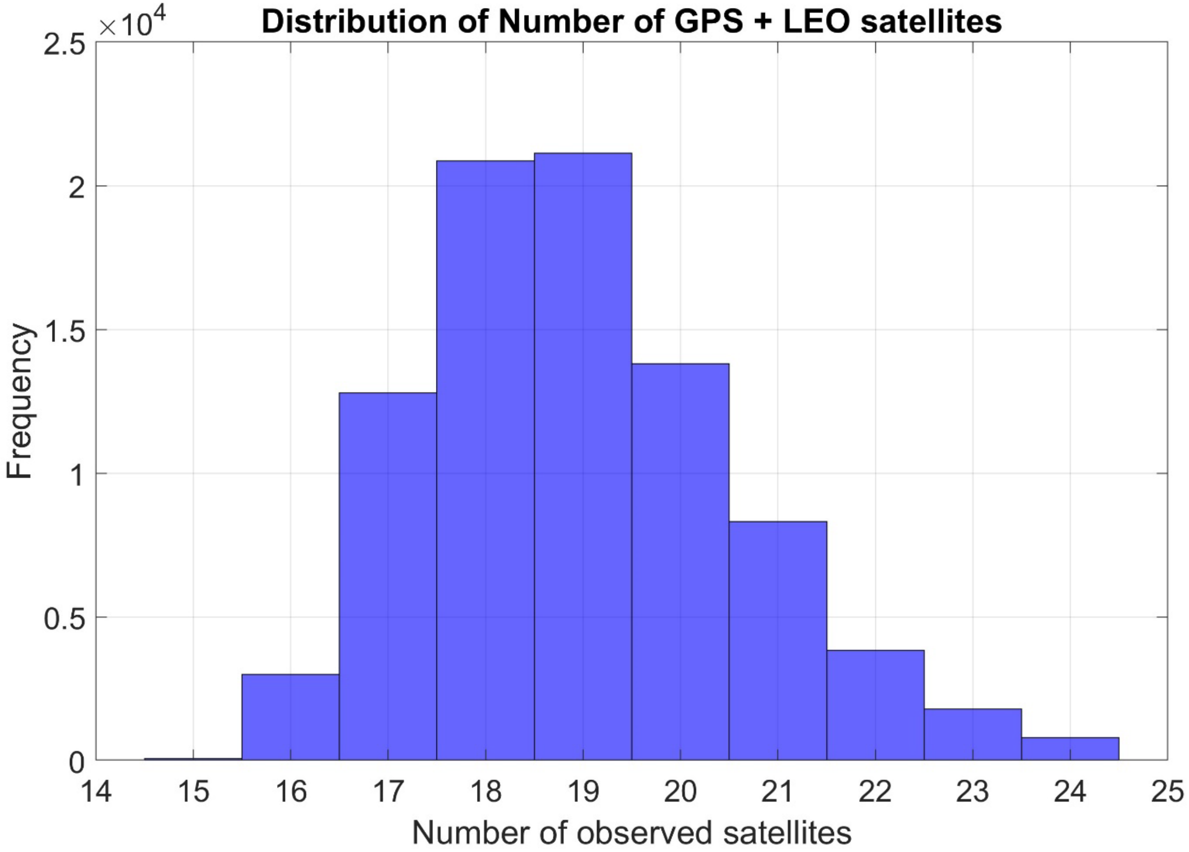
(Each satellite's access is represented by a distinct color)

Number of the satellites in the simulated LEO-PNT Observations

7 ≤ Number of available **LEO** satellites ≤ 13

15 ≤ Number of available **GPS+LEO** satellites ≤ 24





Processed LEO-PNT observations by Ginan

Ginan has been compiled on a Raspberry Pi 4 equipped with ARM CPU v8 for precise point positioning (PPP) of CUT0

Less than 1 second for processing each epoch

Showing the capability of Ginan for real-time LEO-PNT applications

Comparing the positioning results with AUPOS output

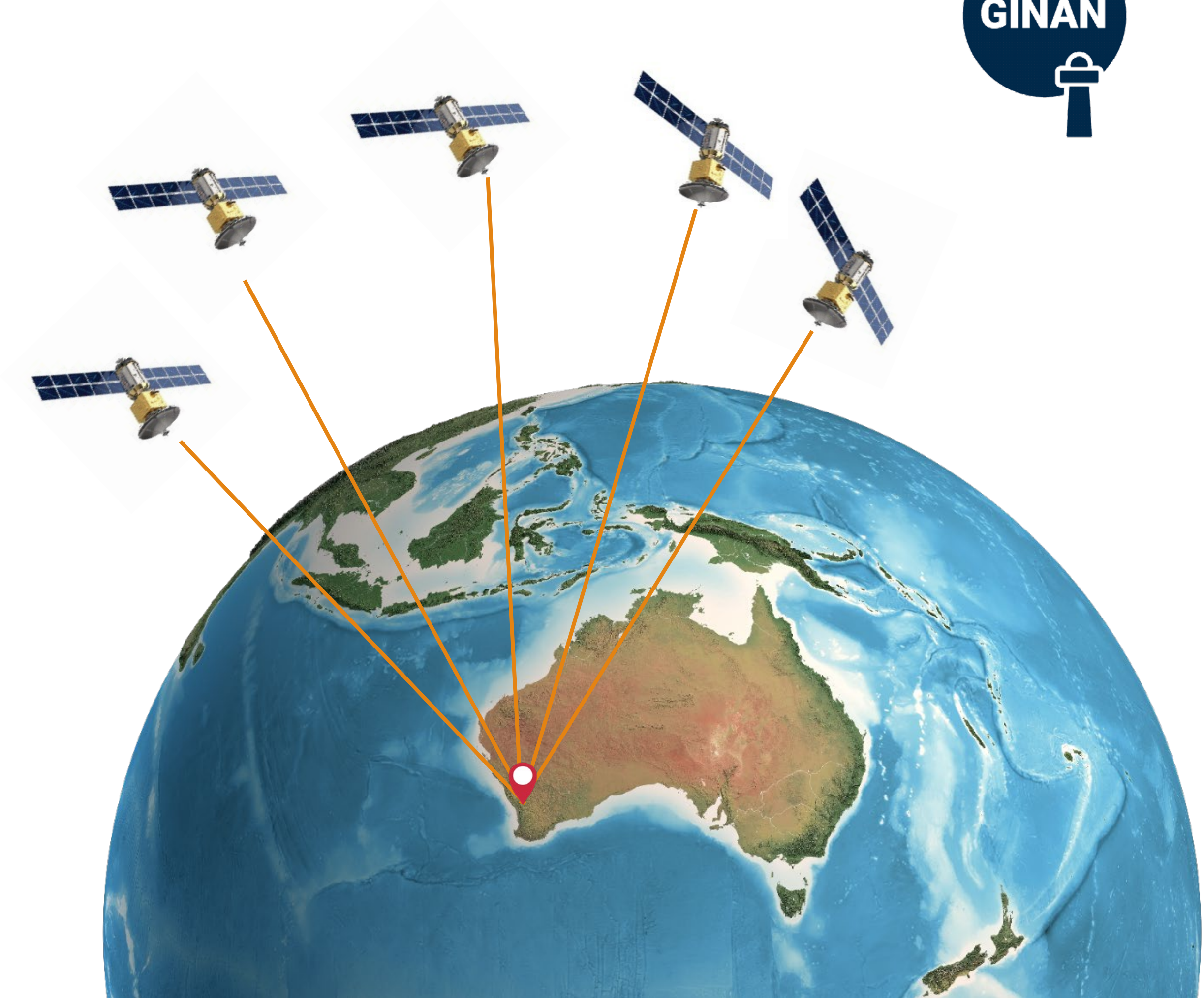
Processing case	RMSE X (m)	RMSE Y (m)	RMSE Z (m)
LEO-PNT	0.042	0.059	0.070
GPS only	0.023	0.018	0.031
GPS + LEO-PNT	0.020	0.017	0.026

Summary and conclusion

Ginan has the capability to be used for LEO-PNT applications:

- The LEO POD module can perfume both reduced-dynamic and kinematic POD of LEOs.
- With 85.64°: 240/12/6 constellation at 1000 km altitude, 7 to 13 LEO satellites were available for a tested CORS: CUT0 at the Curtin campus
- Processing of simulated LEO-PNT observations were provide PPP accuracy of few centimeters compared to the AUSPOS output
- Adding LEO to the GPS-only case brings more observations and improves the PPP accuracy.

Using Ginan is promising for the LEO-PNT applications, it can be used in both LEO-POD and LEO-PNT parts.



Thanks

http://gnss.curtin.edu.au/

ACKNOWLEDGMENTS

We would like to acknowledge Spirent for providing access to the SimGEN software, and LEAP Australia for providing access to the Ansys Satellite Tool Kit (Ansys STK) for the LEO-PNT simulation.