Uncertainty of clock+phase bias SSR corrections

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EGU2026-SPM64, Vienna (Austria), 07 May 2026

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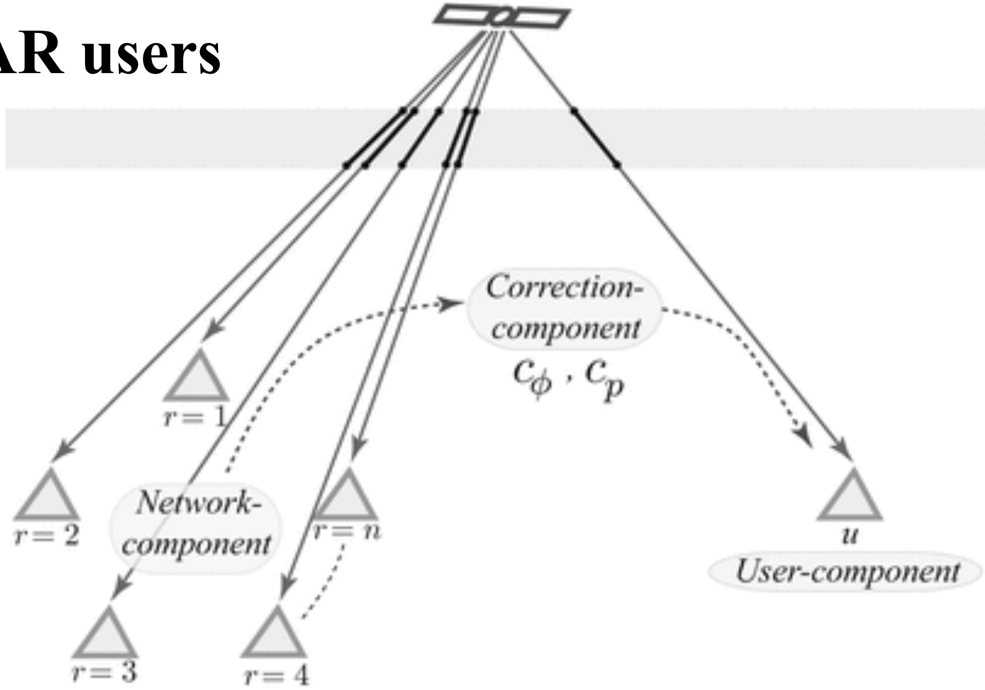
Introduction

Background information

Satellite corrections for PPP-AR users

Estimated via a network of ground station receivers, tracking different signals of multi-GNSS constellations.



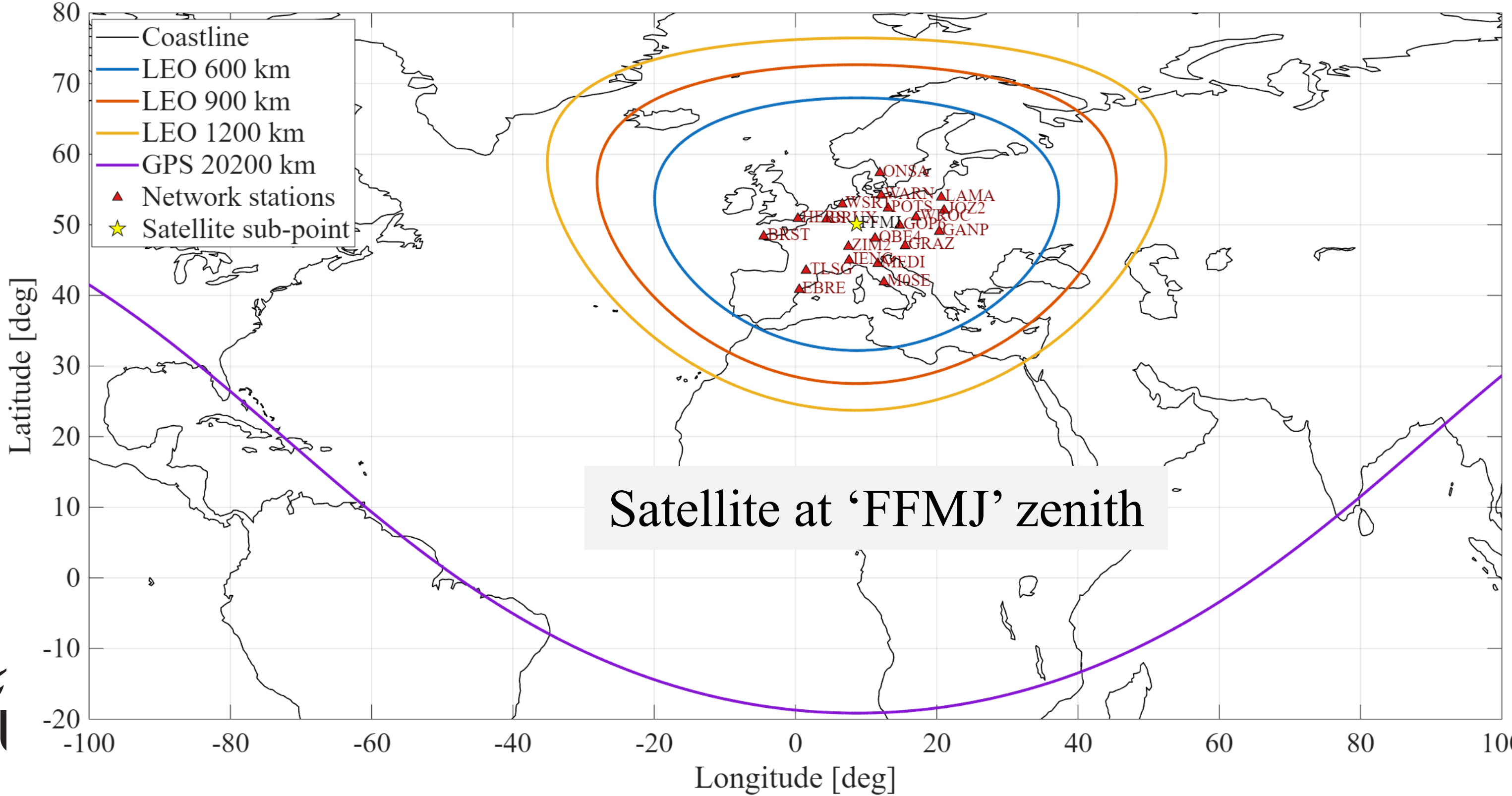
Objective

Investigate practical aspects in the uncertainty of satellite clock+phase corrections (via regional networks).

Teunissen, P.J.G., Khodabandeh, A., Zhang, B. (2016). Multi-GNSS PPP-RTK: Mixed-Receiver Network and User Scenarios. In: Freymueller, J.T., Sánchez, L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. International Association of Geodesy Symposia, vol 147. Springer, Cham. https://doi.org/10.1007/1345_2016_232

Regional network considerations

European example with around 20 stations (7° elev. mask)



Methodology & assumptions

Regional network model

Mathematical formulation (undifferenced/uncombined)

For each network receiver, we consider code and phase observations

$$\mathrm{E}\{p_{r,j}^s\} = \rho_r^s + m_r^s \tau_r + (dt_r - dt^s) + \mu_j i_{r,1}^s + (d_{r,j} - d_{,j}^s)$$

$$\mathrm{E}\{\phi_{r,j}^s\} = \rho_r^s + m_r^s \tau_r + (dt_r - dt^s) - \mu_j i_{r,1}^s + (\delta_{r,j} - \delta_{,j}^s) + \lambda_j N_{r,j}^s$$

with *rank deficiencies*, e.g. we introduce *estimable* parameters like

$$dt_r \;\rightarrow\; \widetilde{dt}_r \overset{\text{def}}{=} dt_r + d_{r,\mathrm{IF}}$$

<u>DEFINITIONS:</u>

$$\mu_j = \frac{f_1^2}{f_j^2} \quad \rightarrow \quad \xi_{\mathrm{IF}} = \frac{\mu_2 \xi_1 - \mu_1 \xi_2}{\mu_2 - \mu_1}, \qquad \xi_{\mathrm{GF}} = \frac{\xi_2 - \xi_1}{\mu_2 - \mu_1}$$

Regional network model

Home > Journal of Geodesy > Article

On the estimability of parameters in undifferenced, uncombined GNSS network and PPP-RTK user models by means of $\mathcal{S}$-system theory

Original Article | Published: 05 November 2015

Volume 90, pages 15–44, (2016) Cite this article

Source: Odijk et al. (2016)

Common Clock (pivot) Receiver | $\mathcal{S}$-system

The estimable regional network parameters are

Rx coordinates	$\Delta x_r = [\Delta E_r, \Delta N_r, \Delta U_r]$	(optional)	
Rx tropo ZWD	$\tilde{\tau}_r^s = \tau_r^s - \tau_q^s(1)$		
Rx clock offset	$\widetilde{dt}_r = \left(dt_r + d_{r,\mathrm{IF}}\right) - (\cdots)_q$	$r \neq q$	
Tx clock offset	$\widetilde{dt}^s = \left(dt^s + d^s_{,\mathrm{IF}}\right) - (\cdots)_q - m_q^s \tau_q^s(1)$		
Rx code bias	$\tilde{d}_{r,j} = \left(d_{r,j} - \left[d_{r,\mathrm{IF}} + \mu_j d_{r,\mathrm{GF}}\right]\right) - (\cdots)_q$	$r \neq q$	$j > 2$
Tx code bias	$\tilde{d}^s_{,j} = \left(d^s_{,j} - \left[d^s_{,\mathrm{IF}} + \mu_j d^s_{,\mathrm{GF}}\right]\right) - (\cdots)_q$		$j > 2$
Rx phase bias	$\tilde{\delta}_{r,j} = \left(\delta_{r,j} - \left[d_{r,\mathrm{IF}} - \mu_j d_{r,\mathrm{GF}}\right]\right) - (\cdots)_q + \lambda_j \left(N^p_{r,j} - N^p_{q,j}\right)$	$r \neq q$	
Tx phase bias	$\tilde{\delta}^s_{,j} = \left(\delta^s_{,j} - \left[d^s_{,\mathrm{IF}} - \mu_j d^s_{,\mathrm{GF}}\right]\right) - (\cdots)_q - \lambda_j N^s_{q,j}$		
Slant iono delay	$\tilde{\imath}_r^s = i_r^s + d_{r,\mathrm{GF}} - d^s_{,\mathrm{GF}}$		
Phase ambiguities	$\tilde{N}^s_{r,j} = \left(N^s_{r,j} - N^s_{q,j}\right) - \left(N^p_{r,j} - N^p_{q,j}\right) \in \mathbb{Z}$ (i.e. integer estimable!)	$r \neq q$	$s \neq p$

PPP-AR user model

References
Further details in Teunissen et al. (2016)
https://doi.org/10.1007/1345_2016_232

Uncertainty neglected? (Psychas et al. 2022)
https://doi.org/10.1007/s10291-021-01214-y

Mathematical formulation (full-rank)

For the $u$ser receiver, we obtain

$$\mathrm{E}\{p_{u,j}^{s} + c_{p,j}^{s}\} = \rho_u^s + m_u^s \tilde{\tau}_u + \widetilde{dt}_u + \mu_j \tilde{\iota}_{u,1}^s + \tilde{d}_{u,j>2}$$

$$\mathrm{E}\{\phi_{u,j}^{s} + c_{\phi,j}^{s}\} = \rho_u^s + m_u^s \tilde{\tau}_u + \widetilde{dt}_u - \mu_j \tilde{\iota}_{u,1}^s + \tilde{\delta}_{u,j} + \lambda_j \tilde{N}_{u,j}^{s\neq p}$$

where

$$c_{p,j}^{s} \stackrel{\text{def}}{=} \widetilde{dt}^s + \tilde{d}_{,j}^s = (dt^s + d_{,j}^s) - (dt_q + d_{q,j} + \mu_j d_{q,\mathrm{GF}}) - (\mu_j d_{,\mathrm{GF}}^s)$$

$$c_{\phi,j}^{s} \stackrel{\text{def}}{=} \widetilde{dt}^s + \tilde{\delta}_{,j}^s = \underbrace{(dt^s + \delta_{,j}^s)}_{\text{absolute}} - \underbrace{(dt_q + \delta_{q,j} + \mu_j d_{q,\mathrm{GF}})}_{\text{receiver}} + \underbrace{(\mu_j d_{,\mathrm{GF}}^s)}_{\text{iono}} - \underbrace{\boxed{(\lambda_j N_{q,j}^s)}}_{\text{amb.}}$$

NOTE: ultimately, we look at the accuracy of the *combined corrections*!

On real-time satellite corrections (via regional network)

RT corrections' raw format

XYZ (APC) Clk XYZ (Vel) XYZ (CoM) Cb1/Cb2 Pb1/Ph2

```
* 2026 02 08 00 00  5.00000000
+RTNET
 1 E02 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 2 E03 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 3 E04 APC 3    22934454.0999     334168.8930   18713561.8359 Clk 1     -19362.2132 Vel 3    -1593.4986     991.5151    1936.5218 CoM 3   22934454.8657     334168.9272   18713562.3054 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -18.8779 5Q  -32.2921
 4 E05 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 5 E06 APC 3    26232113.7020   -7876728.3537   11218023.7309 Clk 1     -68883.4083 Vel 3     -968.1038     577.8442    2666.5213 CoM 3   26232114.5403   -7876728.4841   11218024.0472 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -21.7820 5Q  -33.8531
 6 E07 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 7 E08 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 8 E09 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
 9 E10 APC 3    26135052.1738    3666881.7400   13410590.5649 Clk 1    -230856.0400 Vel 3     1265.5378     484.6730   -2598.7106 CoM 3   26135053.0053    3666881.8223   13410590.8566 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -30.1893 5Q  -54.2195
10 E11 APC 3    20487315.7597   -4670377.2485   20851787.3400 Clk 1    1179598.0075 Vel 3     1904.4100     878.0865   -1672.3180 CoM 3   20487316.3143   -4670377.4885   20851788.1149 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -17.0206 5Q  -29.6731
11 E12 APC 3    27283856.9271   10374974.0008    4998933.5867 Clk 1      -7309.5028 Vel 3      520.0048      85.8836   -3014.9615 CoM 3   27283857.6620   10374974.4640    4998933.7035 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -27.2955 5Q  -44.1150
12 E13 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
13 E14 APC 3     7706138.6325  -19558901.4483   11460204.0569 Clk 1    2190099.1228 Vel 3     1988.1143    -365.8666   -2711.5430 CoM 3    7706139.0673  -19558902.0905   11460204.5023 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -11.9131 5Q  -21.2005
14 E15 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
15 E16 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
16 E18 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
17 E19 APC 3     5502262.9452   16102556.8180   24229027.7470 Clk 1     811069.2009 Vel 3    -2031.0738    1332.2868    -423.9614 CoM 3    5502262.9526   16102557.3493   24229028.5675 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -18.8563 5Q  -37.4060
18 E21 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
19 E23 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
20 E25 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
21 E26 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
22 E27 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
23 E29 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
24 E30 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
25 E31 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
26 E33 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
27 E34 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B    0.0000 5Q    0.0000
28 E36 APC 3     2480030.3169  -16451307.5403   24487255.3083 Clk 1    -156009.4826 Vel 3     2173.6507    1151.2329     554.9577 CoM 3    2480030.5066  -16451307.9901   24487256.0416 CodeBias 2 1B   0.0000 5Q   0.0000 PhaseBias 2 1B  -14.5399 5Q  -28.8403
29 G01 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.3130 2P   0.6400 PhaseBias 2 1C    0.0000 2P    0.0000
30 G02 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.5530 2P   2.2790 PhaseBias 2 1C    0.0000 2P    0.0000
31 G03 APC 3    12090964.4410   20641209.4585   11469642.7169 Clk 1     172723.4440 Vel 3      163.1107    1476.0472   -2771.7529 CoM 3   12090965.4563   20641210.4123   11469643.3587 CodeBias 2 1C   0.2070 2P  -1.4410 PhaseBias 2 1C  -27.7778 2P  -41.0126
32 G04 APC 3    11253788.7780   10078196.7865   21883621.8309 Clk 1      12852.7201 Vel 3    -2089.4715    1814.7076     222.1029 CoM 3   11253789.2220   10078197.2326   21883622.8308 CodeBias 2 1C   0.1000 2P  -0.2080 PhaseBias 2 1C  -12.6534 2P  -21.2385
33 G05 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2470 2P   0.9310 PhaseBias 2 1C    0.0000 2P    0.0000
34 G06 APC 3    17555852.7236   -7169244.4021   18730583.1723 Clk 1    -182540.6918 Vel 3     2200.3406     836.4042   -1733.6572 CoM 3   17555853.9404   -7169244.6006   18730583.9643 CodeBias 2 1C   0.1310 2P  -1.8870 PhaseBias 2 1C  -29.9151 2P  -28.5581
35 G07 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.0110 2P   1.0130 PhaseBias 2 1C    0.0000 2P    0.0000
36 G08 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.2470 2P  -2.0490 PhaseBias 2 1C    0.0000 2P    0.0000
37 G09 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.1360 2P  -1.2530 PhaseBias 2 1C    0.0000 2P    0.0000
38 G10 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.0250 2P  -1.6530 PhaseBias 2 1C    0.0000 2P    0.0000
39 G11 APC 3     2589084.3178  -15099953.5711   21753455.2940 Clk 1    -133889.2098 Vel 3     2596.7118     899.2798     309.0485 CoM 3    2589084.3731  -15099954.2749   21753456.2492 CodeBias 2 1C   0.1560 2P   0.5820 PhaseBias 2 1C  -12.8056 2P   -7.1705
40 G12 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2240 2P   1.2620 PhaseBias 2 1C    0.0000 2P    0.0000
41 G13 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.0660 2P   1.0640 PhaseBias 2 1C    0.0000 2P    0.0000
42 G14 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.1450 2P   0.4570 PhaseBias 2 1C    0.0000 2P    0.0000
43 G15 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2920 2P   1.0110 PhaseBias 2 1C    0.0000 2P    0.0000
44 G16 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.4730 2P   0.9120 PhaseBias 2 1C    0.0000 2P    0.0000
45 G17 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.1710 2P   1.0560 PhaseBias 2 1C    0.0000 2P    0.0000
46 G18 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.1990 2P   0.5350 PhaseBias 2 1C    0.0000 2P    0.0000
47 G19 APC 3    20310329.8984  -16605723.7683    1389674.8132 Clk 1     206603.8776 Vel 3      351.5587     151.8714   -3198.5684 CoM 3   20310330.4589  -16605724.2163    1389674.8545 CodeBias 2 1C  -0.6950 2P   1.8990 PhaseBias 2 1C   -1.0793 2P   -3.8867
48 G20 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.6820 2P   0.5330 PhaseBias 2 1C    0.0000 2P    0.0000
49 G21 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2280 2P   0.7500 PhaseBias 2 1C    0.0000 2P    0.0000
50 G22 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.2930 2P   1.0080 PhaseBias 2 1C    0.0000 2P    0.0000
51 G23 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.1850 2P   0.5380 PhaseBias 2 1C    0.0000 2P    0.0000
52 G24 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2760 2P  -1.6000 PhaseBias 2 1C    0.0000 2P    0.0000
53 G25 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.2250 2P  -2.2120 PhaseBias 2 1C    0.0000 2P    0.0000
54 G26 APC 3    -7281294.5376   18570102.5566   17106216.4435 Clk 1     -97038.6229 Vel 3     -956.1029   -2046.4814    1830.3613 CoM 3   -7281294.5607   18570103.6086   17106217.4938 CodeBias 2 1C  -0.0370 2P  -2.4270 PhaseBias 2 1C  -12.5834 2P  -26.1230
55 G27 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.0520 2P  -1.5640 PhaseBias 2 1C    0.0000 2P    0.0000
56 G28 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.1670 2P   0.7460 PhaseBias 2 1C    0.0000 2P    0.0000
57 G29 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C   0.2500 2P   0.8150 PhaseBias 2 1C    0.0000 2P    0.0000
58 G30 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.2260 2P  -1.9080 PhaseBias 2 1C    0.0000 2P    0.0000
59 G31 APC 3    -8203171.3648   13160916.5584   21307532.3330 Clk 1     -50431.0552 Vel 3    -2620.4626    -902.6551    -414.9928 CoM 3   -8203171.6265   13160916.9713   21307533.0124 CodeBias 2 1C   0.2490 2P   1.4870 PhaseBias 2 1C  -11.1418 2P  -18.5224
60 G32 APC 3           0.0000          0.0000          0.0000 Clk 1      99999.9900 Vel 3        0.0000       0.0000       0.0000 CoM 3          0.0000          0.0000          0.0000 CodeBias 2 1C  -0.0240 2P  -1.3150 PhaseBias 2 1C    0.0000 2P    0.0000
-RTNET
```

GAL
1B
5Q

GPS
1C
2P

RT corrections' uncertainty

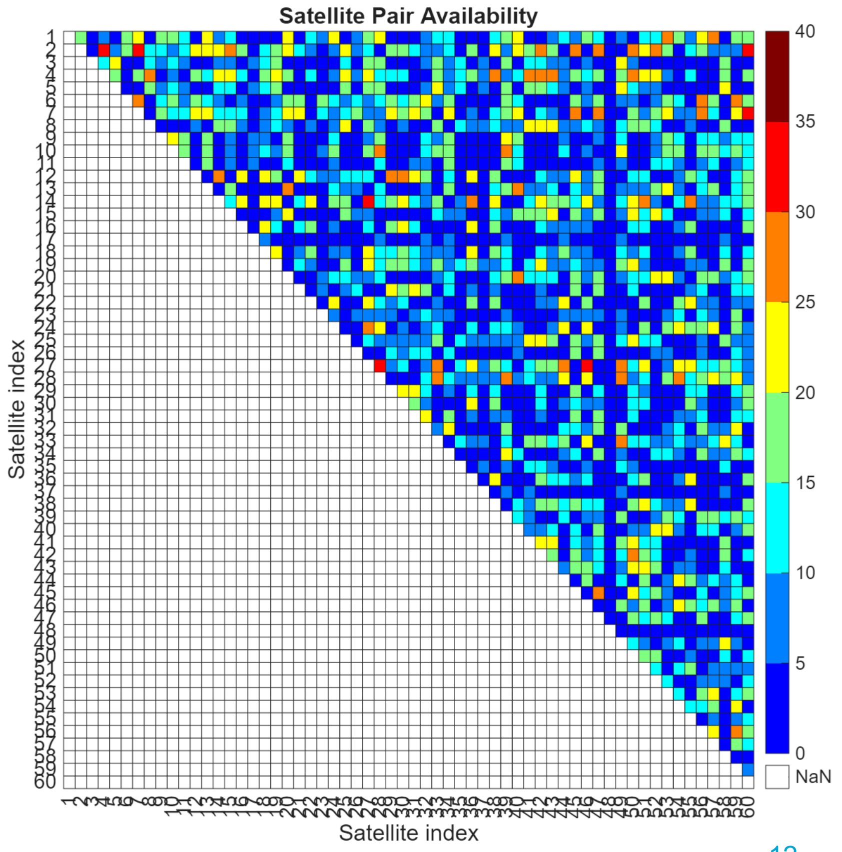
Extremely large amount of data!

At each epoch, e.g. 5 seconds, we would have a 3Mx3M variance-covariance (vc-) matrix to provide to the user in real time.

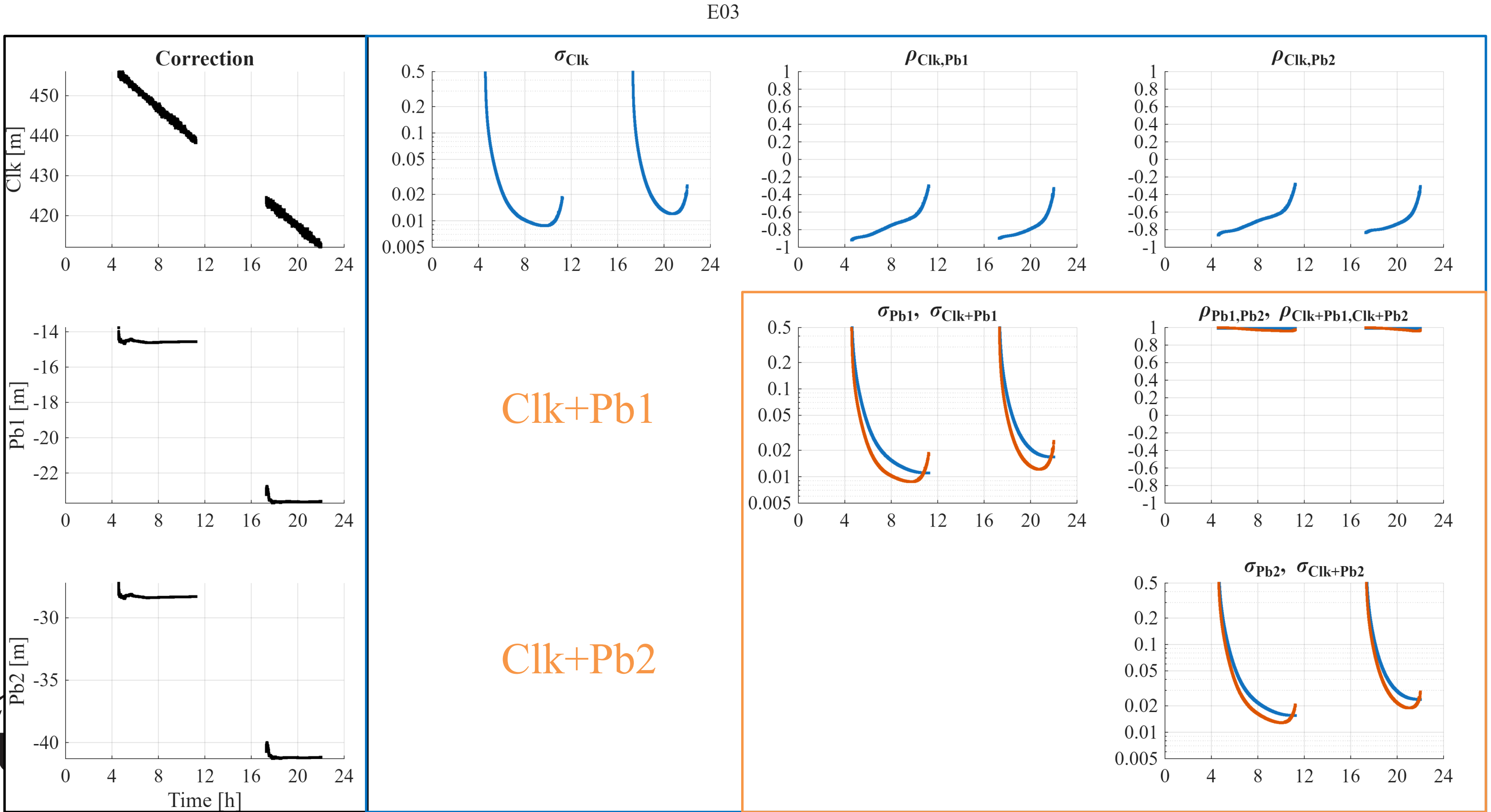
e.g. M = 60 satellites

However, in regional networks we might not have all satellites in view.

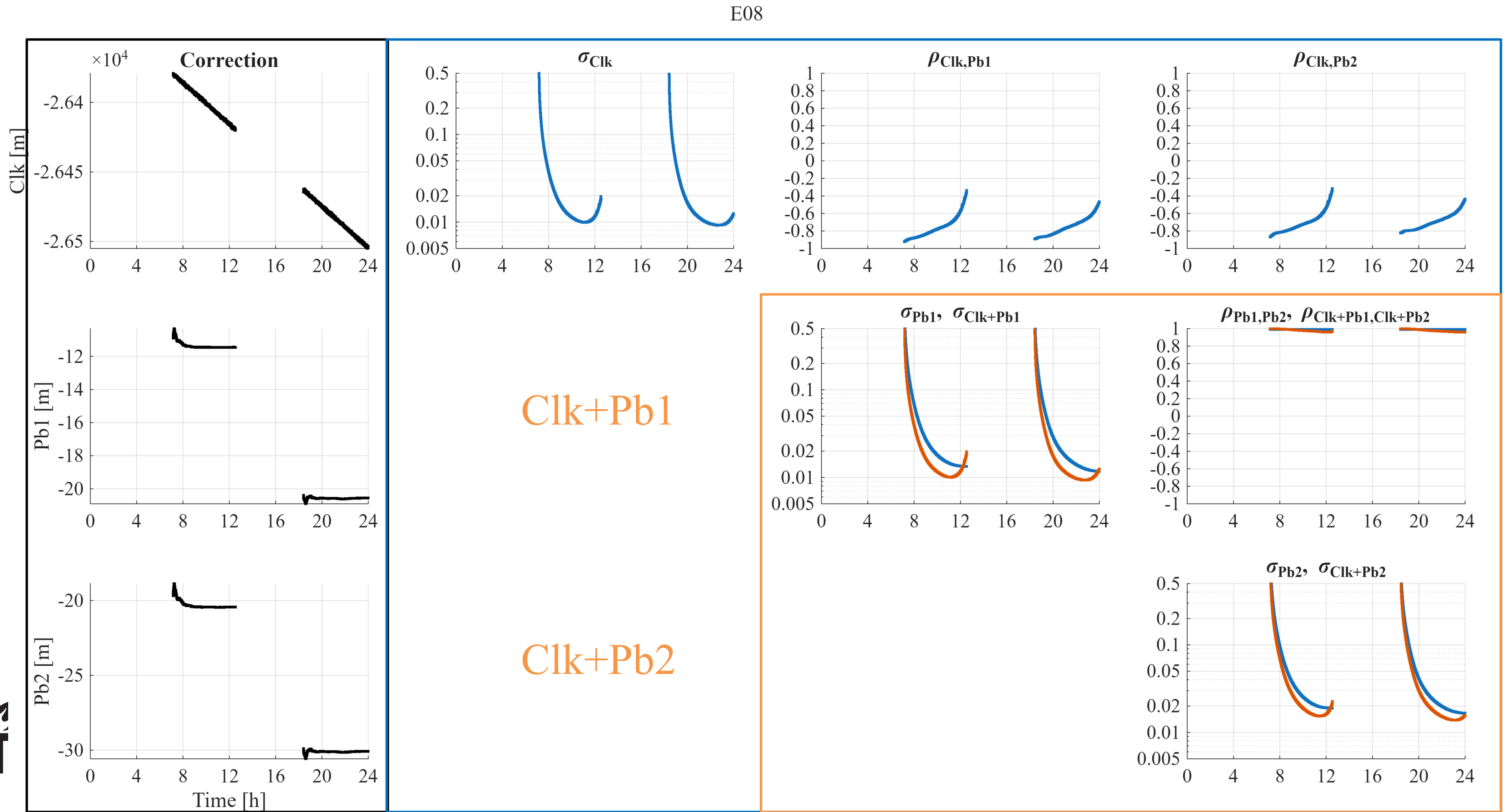
- Which format might be convenient?



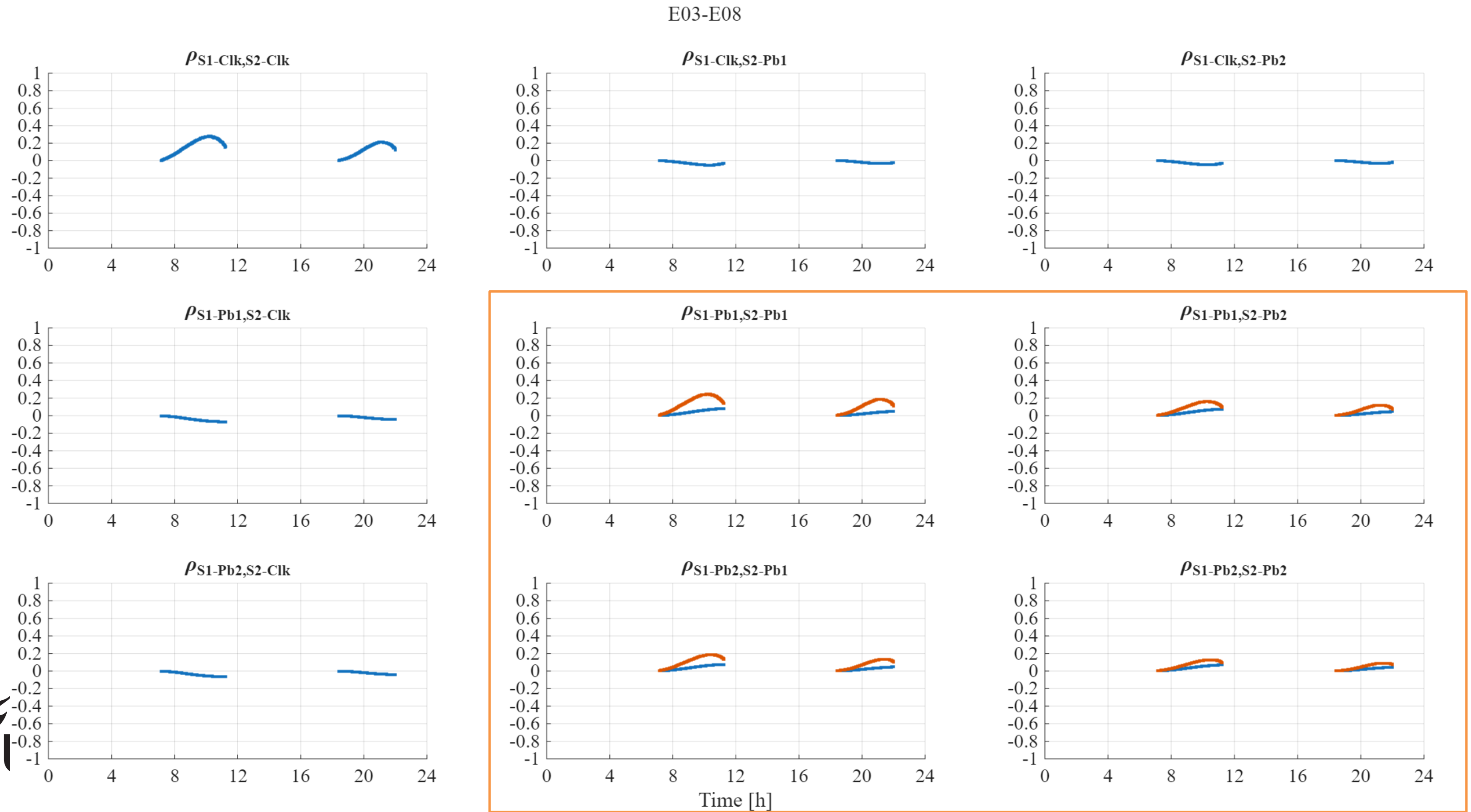
Uncertainty for each satellite



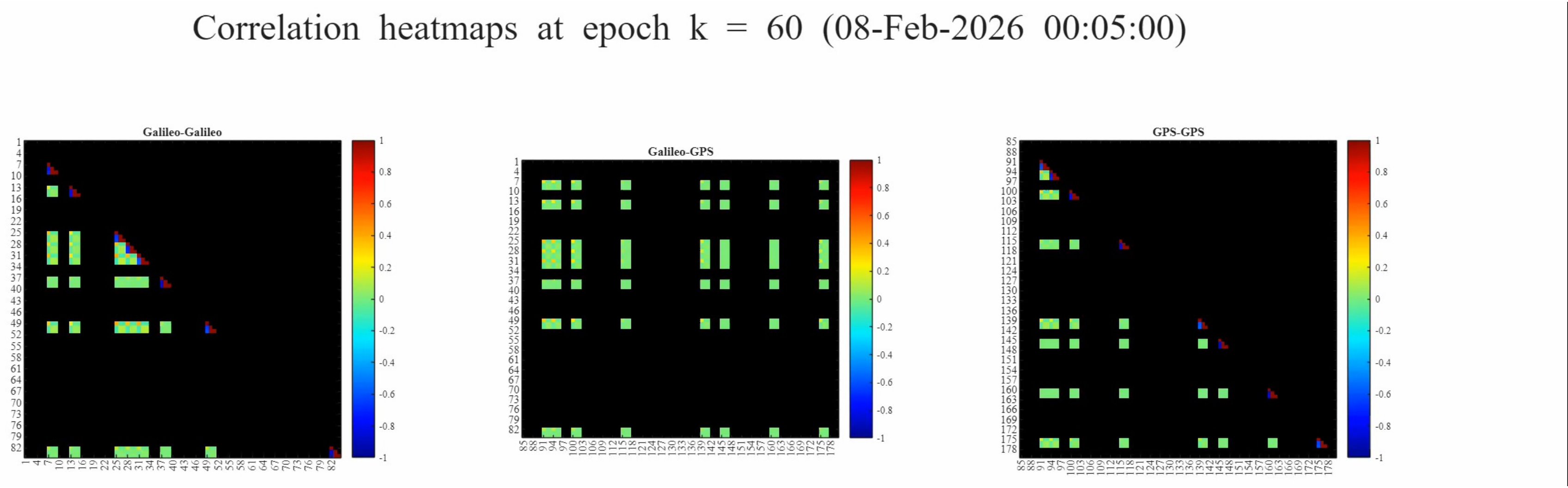
Uncertainty for each satellite



Correlation between two satellites



Correlation among all satellites



Video shows correlation among all satellites at 5-minute interval, where green color refers to a low correlation generally within $[-0.2, +0.2]$.

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Assessment impact to users

Correction model

Given

$$y_k = \left[y_k^{s_1}, \dots, y_k^{s_m}\right]^T, \qquad y_k^s = (P_1^s, P_2^s, L_1^s, L_2^s)_\mathrm{k}^T$$

we consider $\bar{y}_k = y_k - A_k c_k$, where

$$A_k = \mathrm{blkdiag}(A^{s_1}, \dots, A^{s_m}), \qquad A^s = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

while

$$Q_{\bar{y}_k\bar{y}_k} = Q_{y_k y_k} + \underbrace{A_k Q_{c_k c_k} A_k^T}_{Q_{\bar{c}_k\bar{c}_k}}, \qquad Q_{y_k y_k} = \mathrm{diag}\left(\sigma^2_{P_1^{s_1}}, \sigma^2_{P_2^{s_1}}, \sigma^2_{L_1^{s_1}}, \sigma^2_{L_2^{s_1}}, \dots\right)$$

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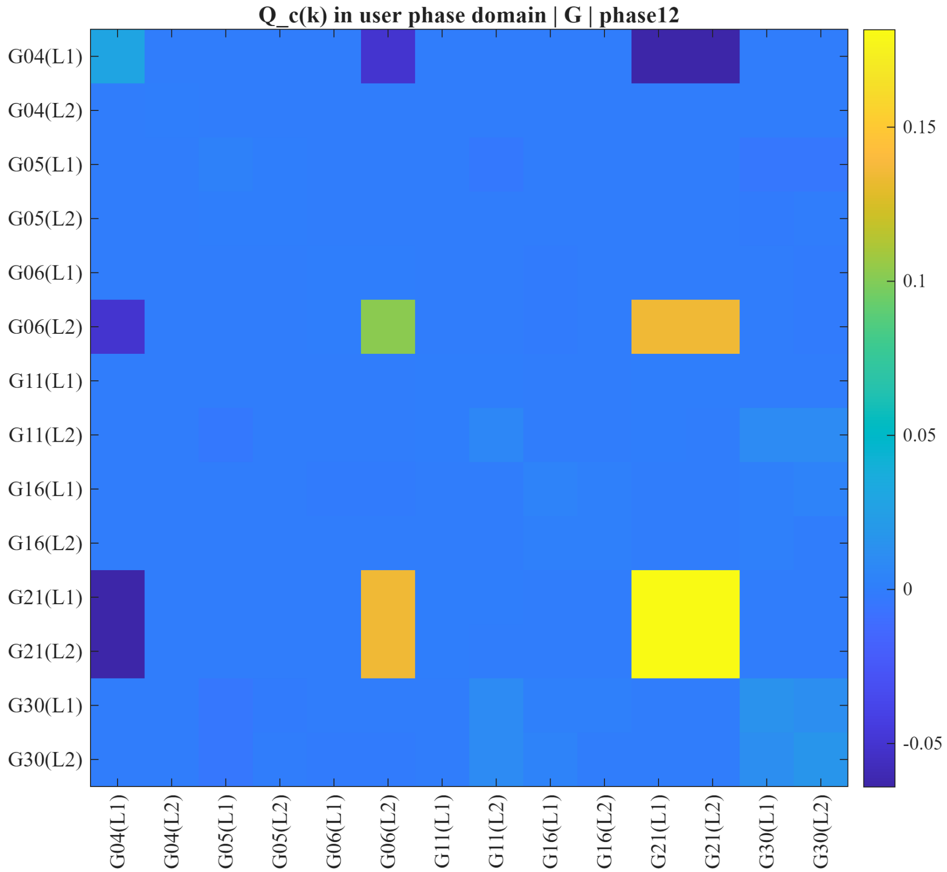
Example for GPS L1+L2

"G04(L1)"	0.17291
"G04(L2)"	0.016399
"G05(L1)"	0.046261
"G05(L2)"	0.026218
"G06(L1)"	0.028647
"G06(L2)"	0.31998
"G11(L1)"	0.027484
"G11(L2)"	0.082931
"G16(L1)"	0.061238
"G16(L2)"	0.041581
"G21(L1)"	0.42551
"G21(L2)"	0.42616
"G30(L1)"	0.12186
"G30(L2)"	0.12866



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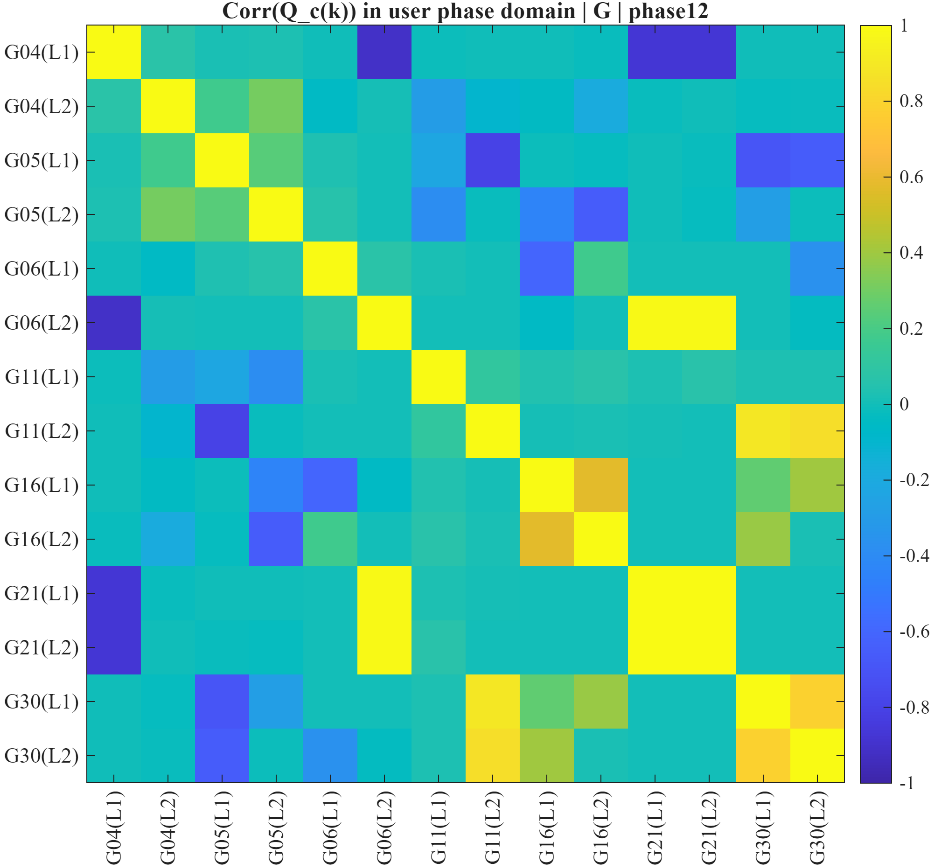

Remarks on future LEO-PNT systems (SIMULATIONS)

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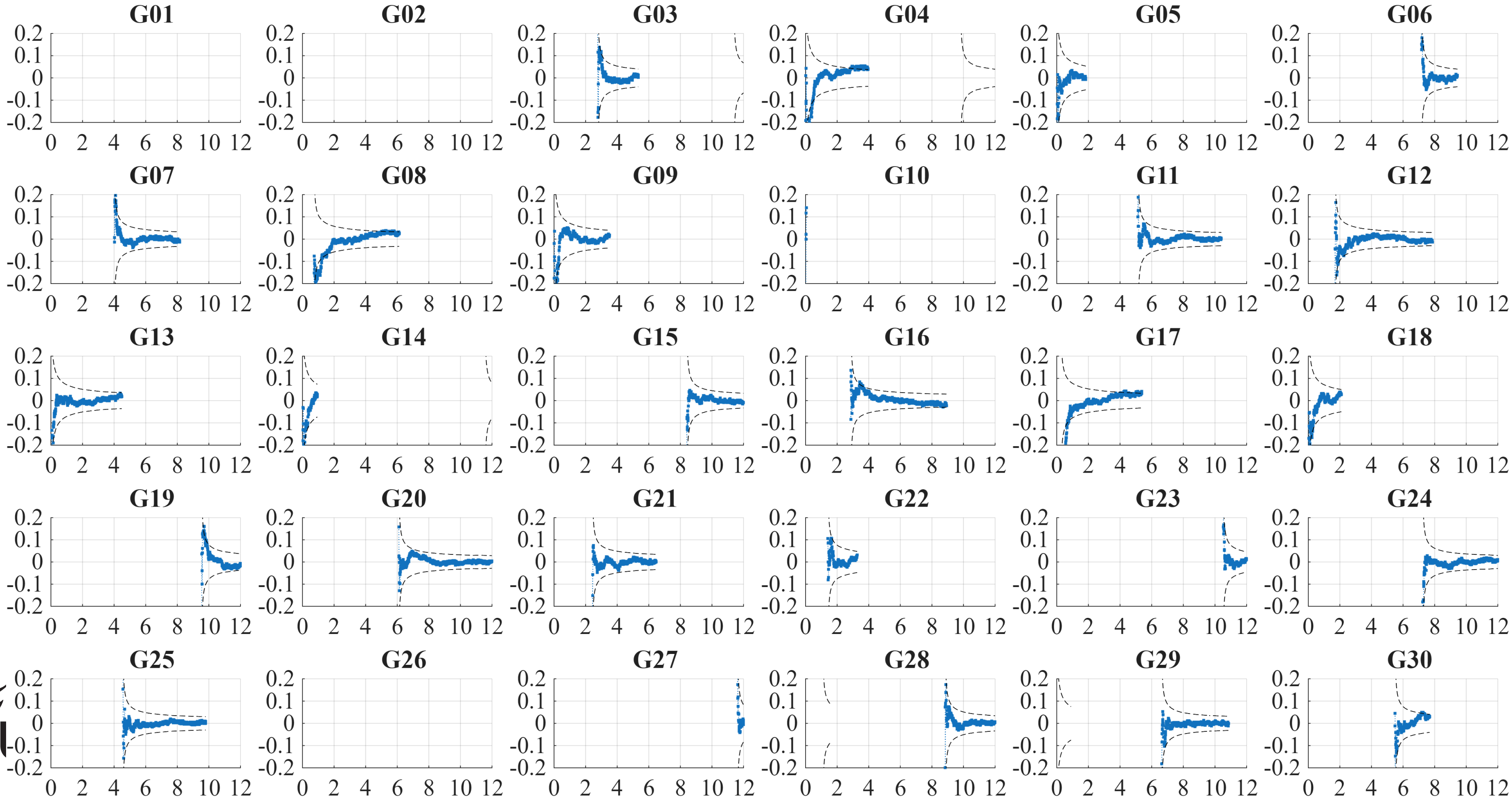
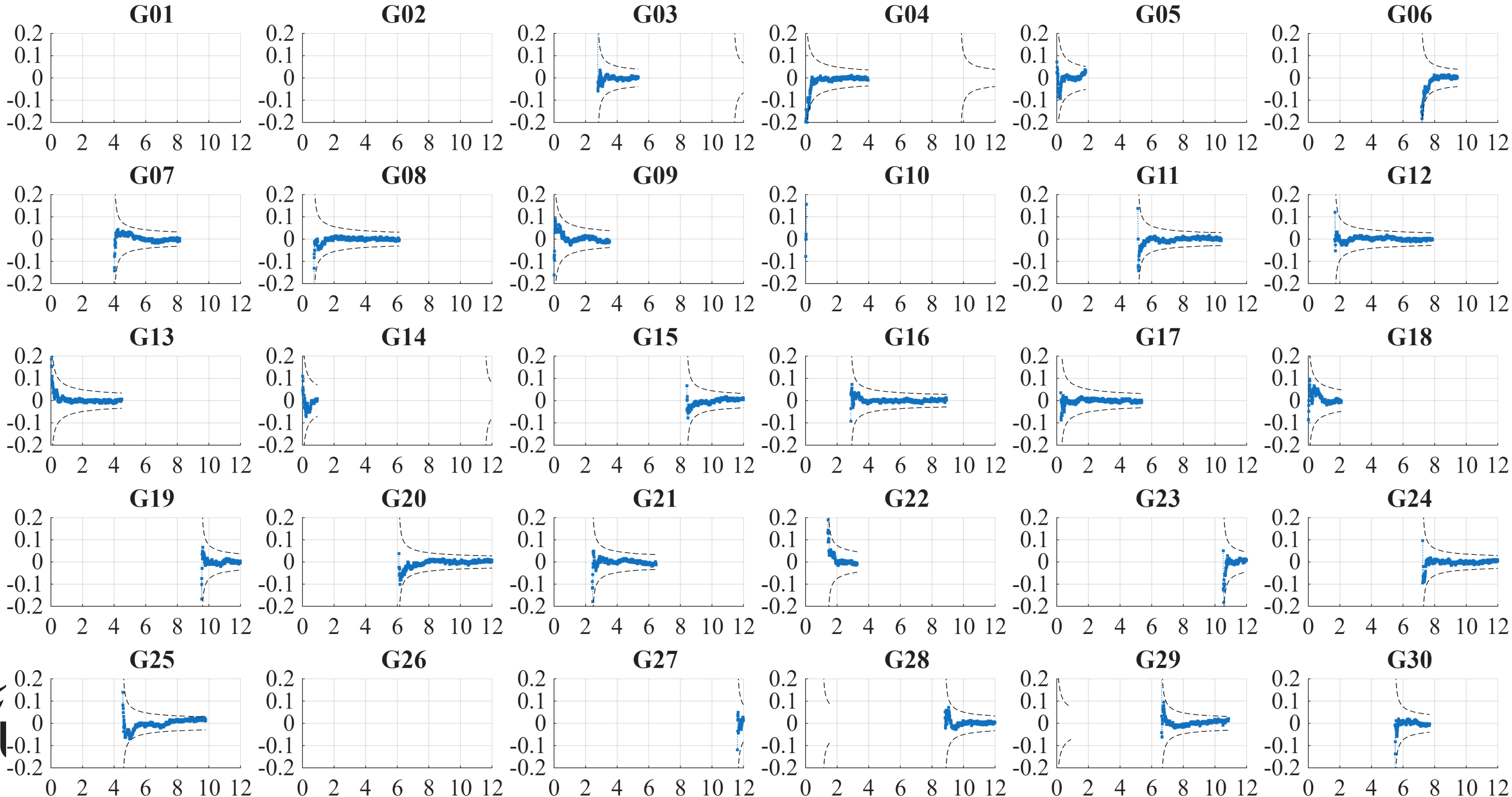
GPS-only estimation error

LEGEND:
Clk+Pb1 (±3σ)



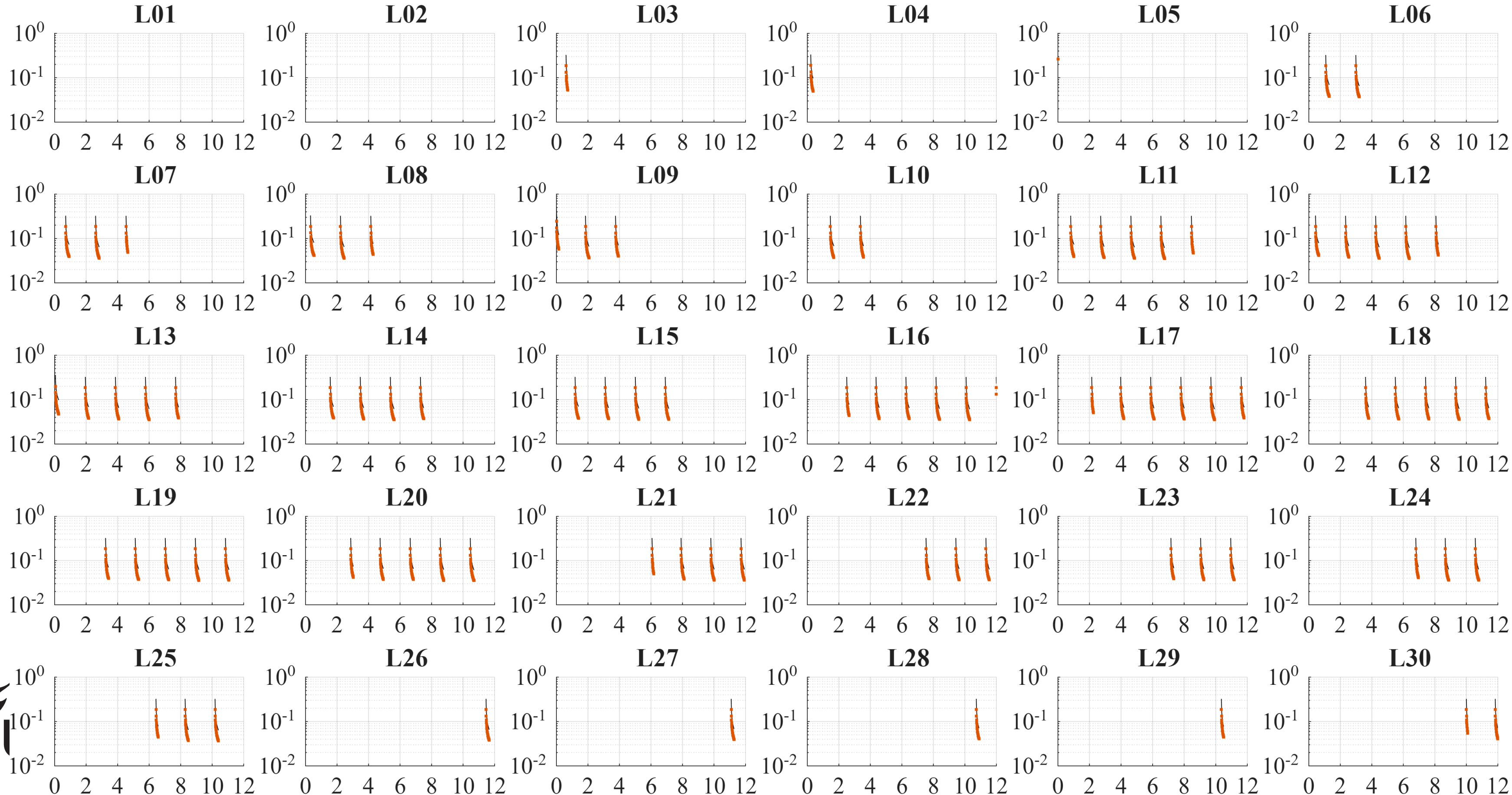
GPS+LEO estimation error

LEGEND:
Clk+Pb1 ($\pm 3\sigma$)



GPS+LEO estimation error

LEGEND:
Clk+Pb1 vs Pb1



IGS LEO-PNT Pilot Project

Formally approved by IGS Governing Board 73rd meeting.

The primary goal of this Pilot Project is

- to investigate the feasibility of integrating LEO-PNT technology in IGS components.

As of April 2026, co-chaired by

- Francesco Gini (ESA)
- Lotfi Massarweh (TUD)

TU Delft

Website currently under construction:

Conclusions

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Summary

- Accounting for **uncertainty of (lumped) satellite corrections** is extremely important for PPP-AR users.
- However, no IGS format is currently available, and potential data limitations exist for making use of this information.
- Some approximations seem necessary and should be further investigated → **proposal to IGS RTS**.
- Uncertainty of clk+phb corrections will surely become even more critical in future LEO-PNT system, nonetheless several issues are foreseen in their (regional) network estimation.

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Questions?

Thanks for your attention

Courtesy of ASI (Agenzia Spaziale Italiana)

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L.Massarweh@tudelft.nl

BACKUP SLIDES

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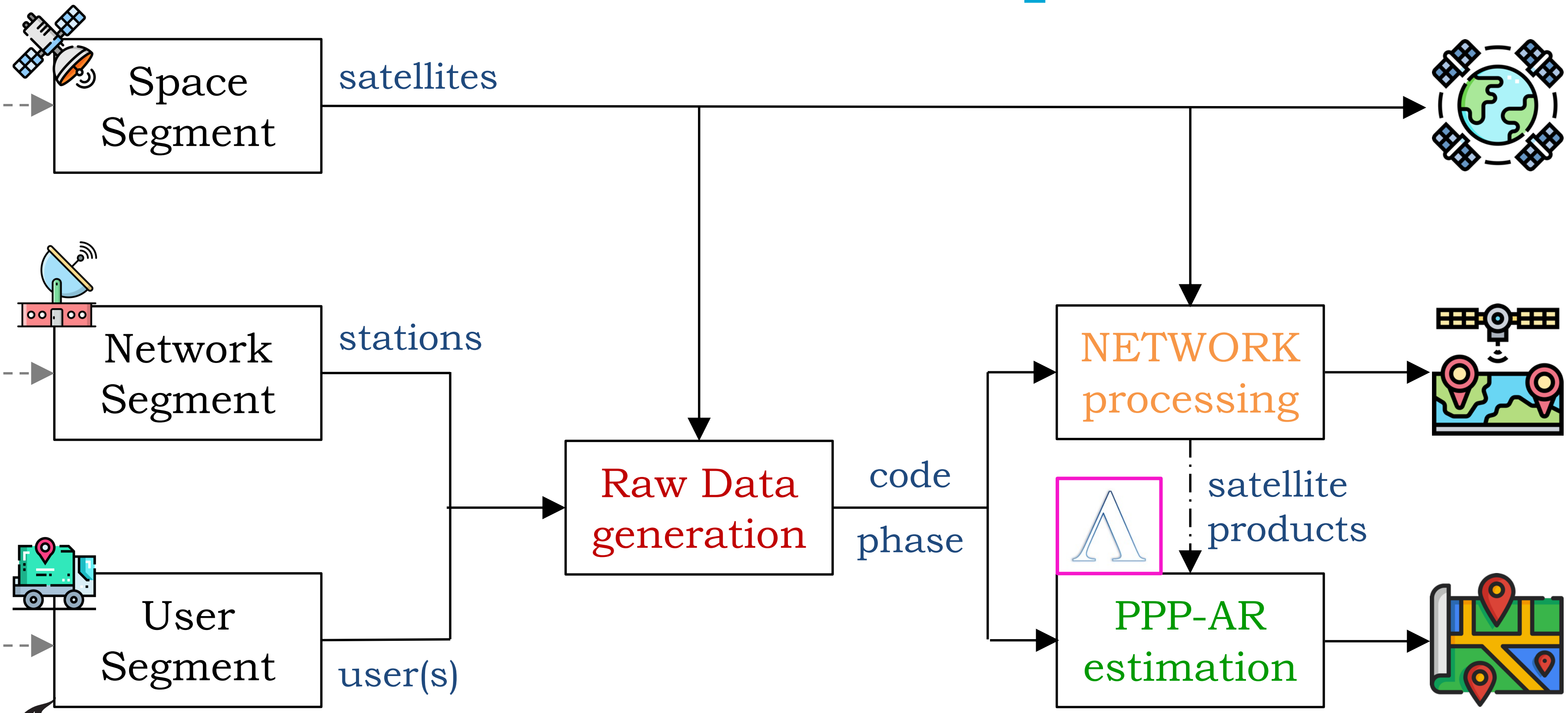
End-to-end simulation platform



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Integer Ambiguity Resolution is performed via LAMBDA 4.0 (Massarweh et al. 2025)