Analysis of uncertainty information of real-time SSR corrections from a regional network & impact on PPP-AR

Lotfi Massarweh, Andreas Brack,

GFZ Helmholtz Centre for Geosciences

TU Delft

IGS Workshop 2026, Santiago de Chile, 02 June 2026

Contents

- **Introduction**
  - Background information & considerations
- **Methodology**
  - Regional network & PPP-AR user models
- **Analysis of RT satellite corrections**
- **Assessment impact on PPP-AR model**
- **Conclusions**

GFZ Helmholtz Centre for Geosciences

TU Delft

Introduction

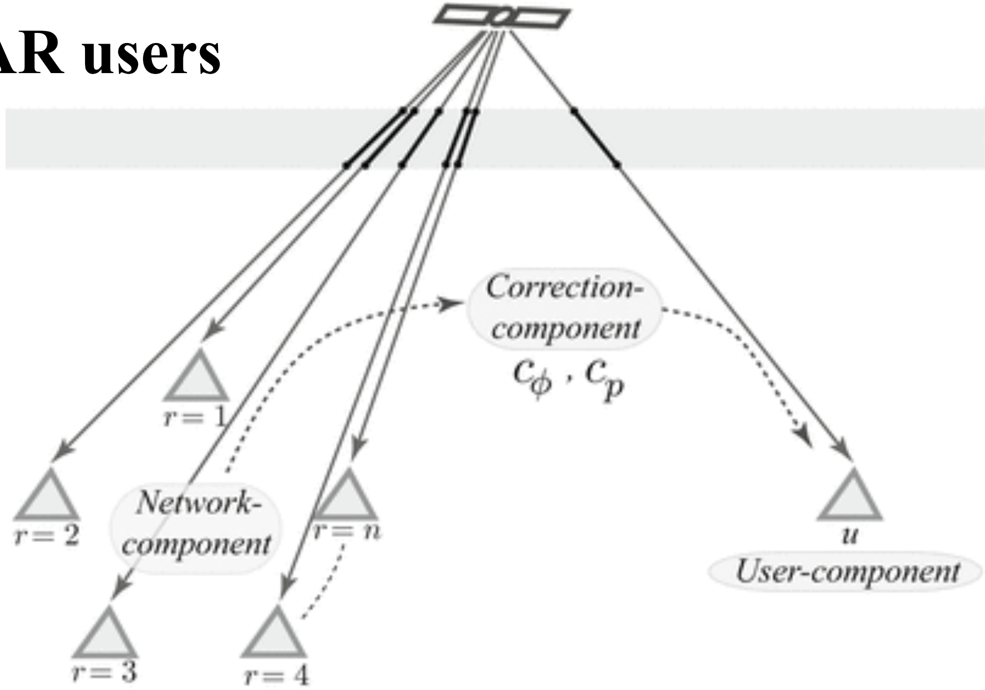
Background information

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).

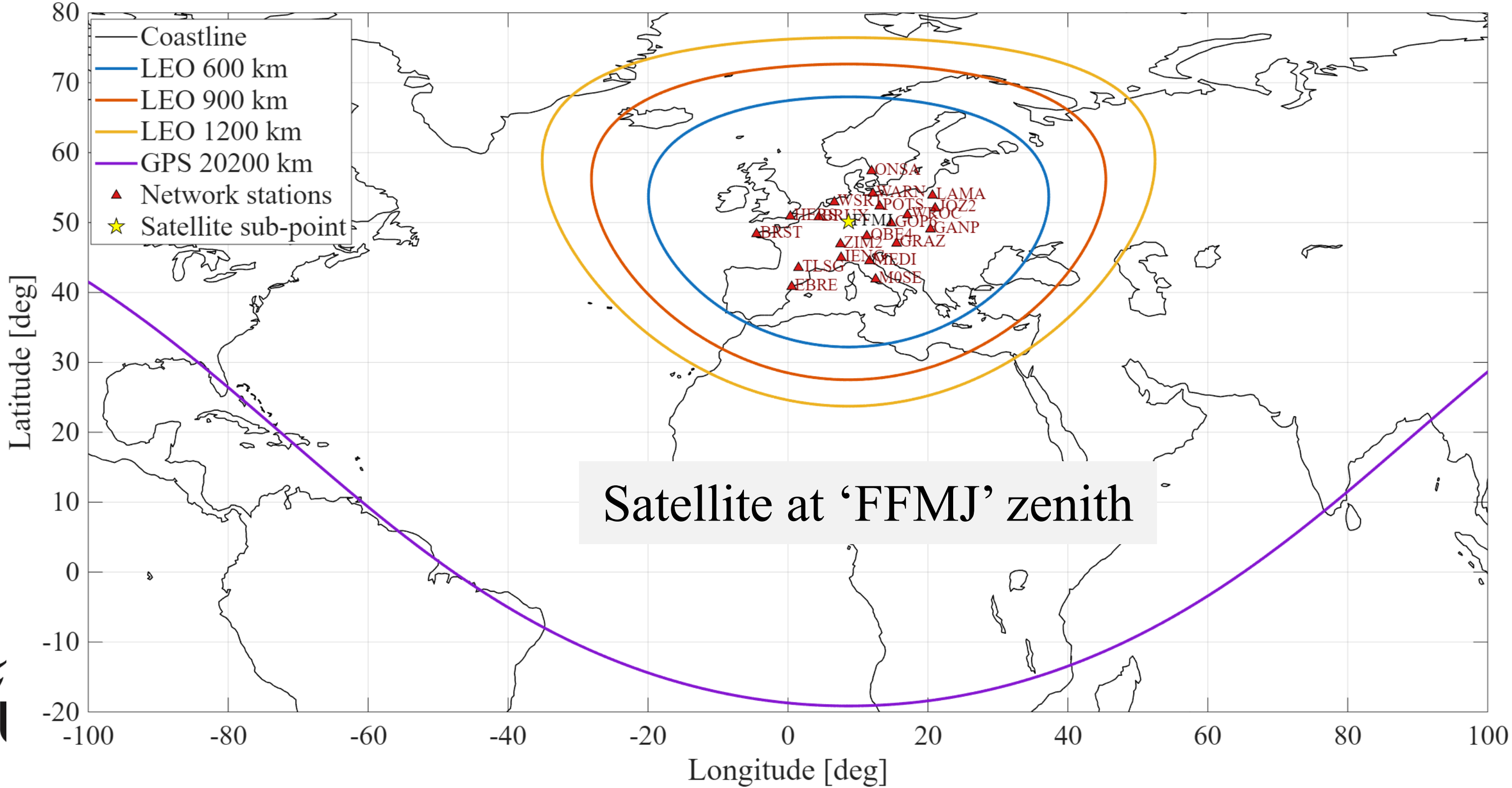


Teunissen, P.J.G., Khodabandeh, A., Zhang, B. (2016). Multi-GNSS PPP-RTK: Mixed-Receiver Network and User Scenarios. In: Freymueller, J.T., Sánchez, L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. International Association of Geodesy Symposia, vol 147. Springer,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

TU Delft

Regional network considerations

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



Methodology (Network & User models)

Regional network model

Mathematical formulation (undifferenced/uncombined)

For each network receiver, we consider code and phase observations

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

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

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

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

DEFINITIONS:

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

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	$\tilde{\delta}^s_{,j} = \left(\delta^s_{,j} - \left[d^s_{,IF} - \mu_j d^s_{,\mathrm{GF}}\right]\right) - (\cdots)_q - \lambda_j N^s_{q,j}$		
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!)	$r \neq q$	$s \neq p$

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

PPP-AR user model

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

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

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

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

Analysis of real-time satellite corrections (via regional network)

Sampling 5s

RT corrections' raw format

XYZ (APC) | Clk | XYZ (Vel) | XYZ (CoM) | Cb1/Cb2 | Pb1/Pb2

```
* 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

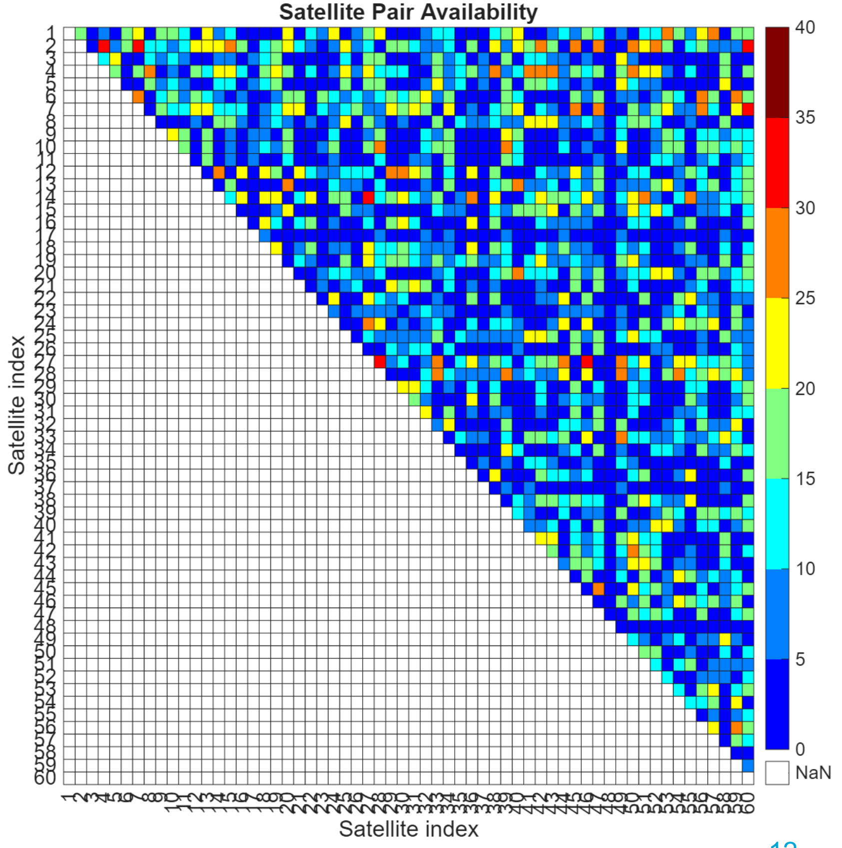
Extremely large amount of data!

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

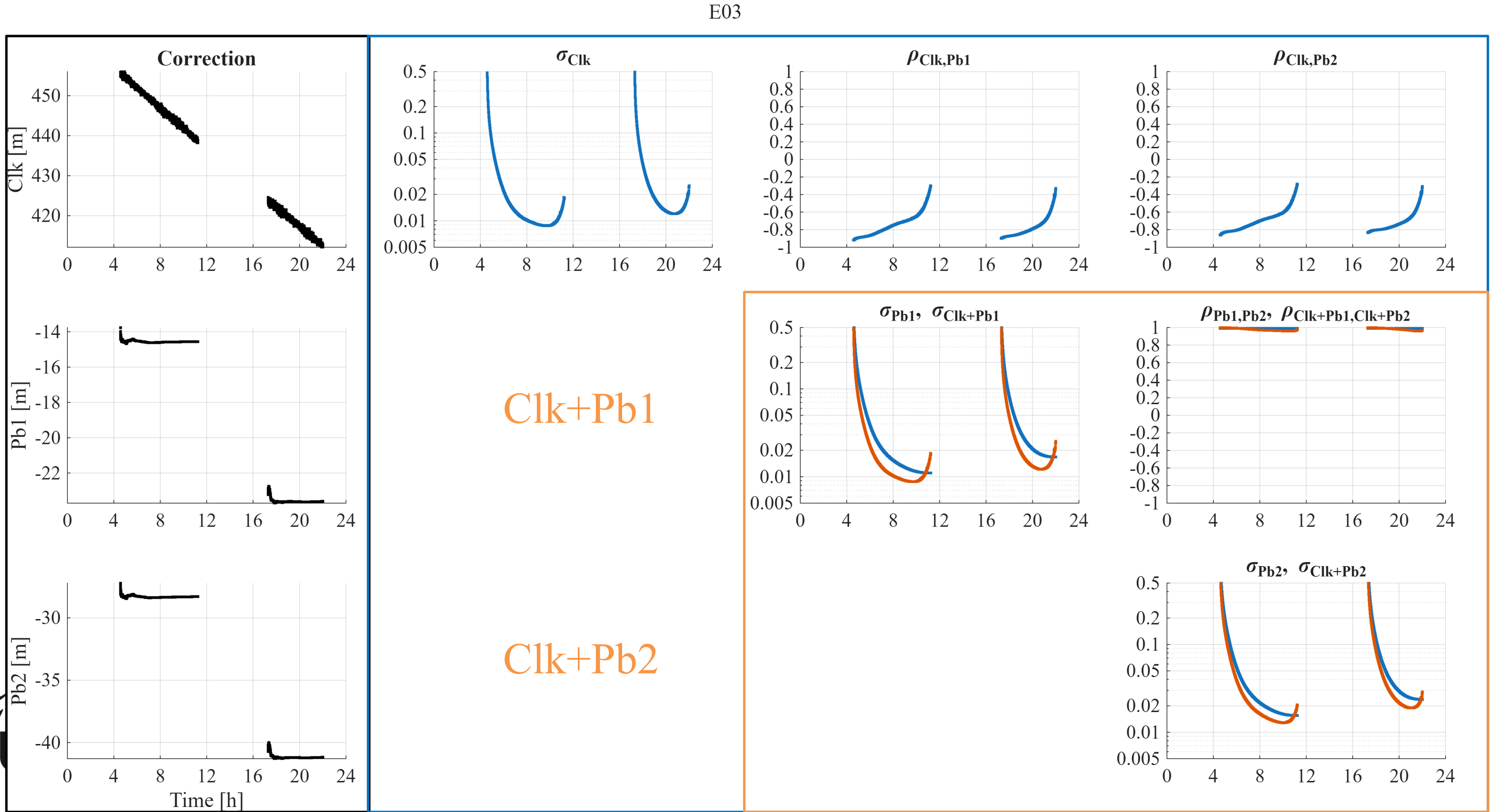
e.g. M = 60 satellites

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

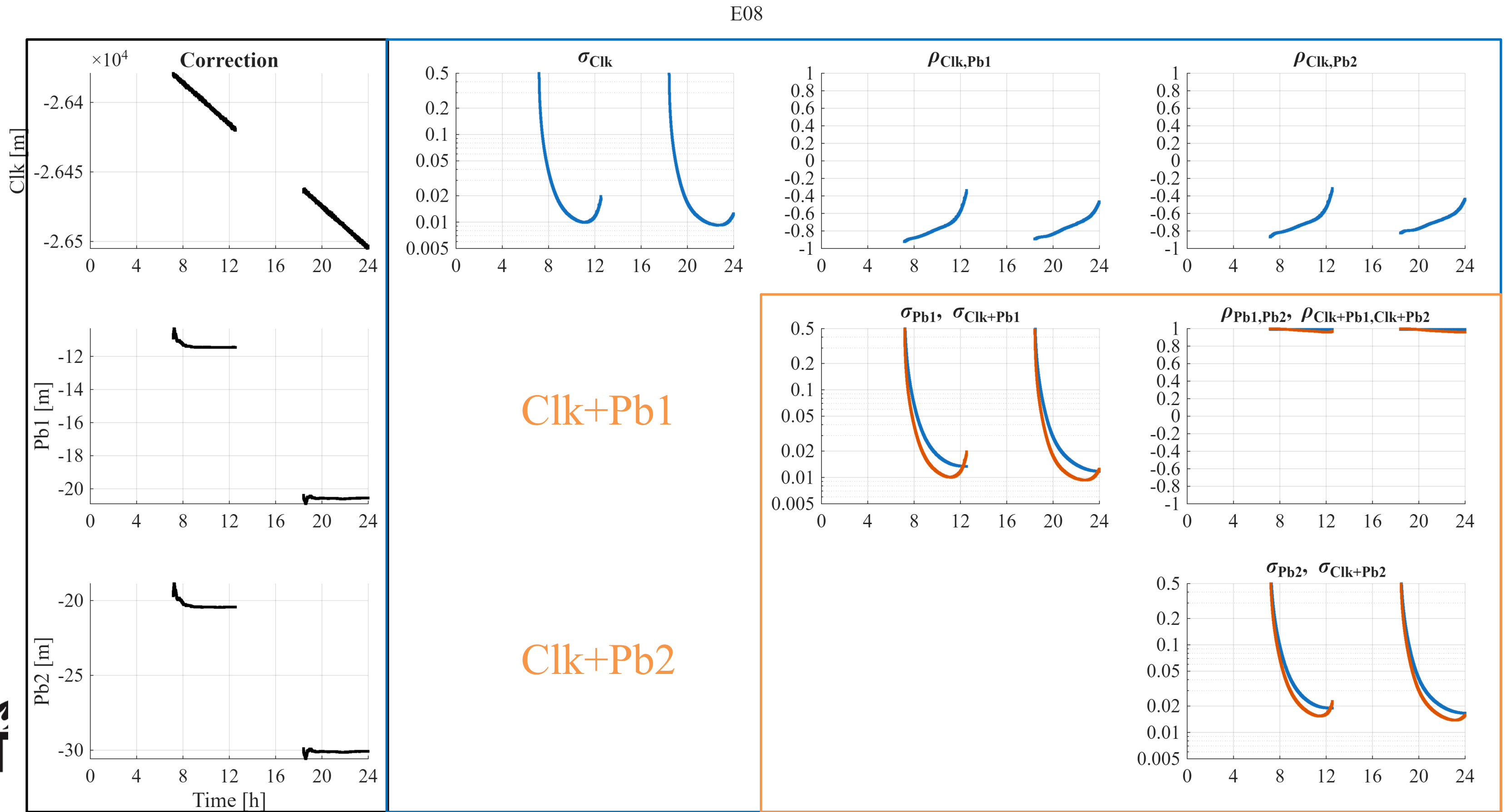
- ➢ Which strategy might be convenient?



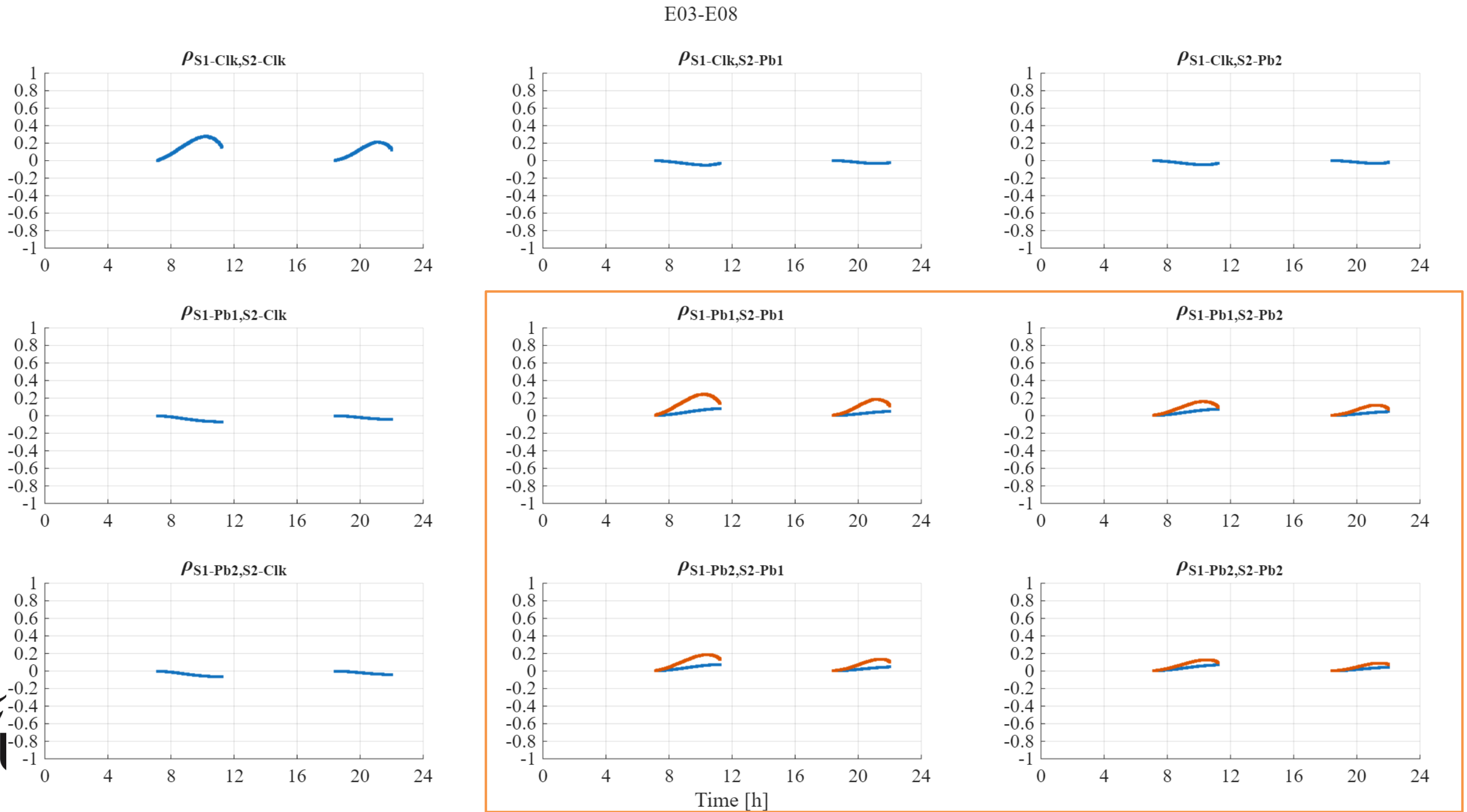
Uncertainty for satellite E03



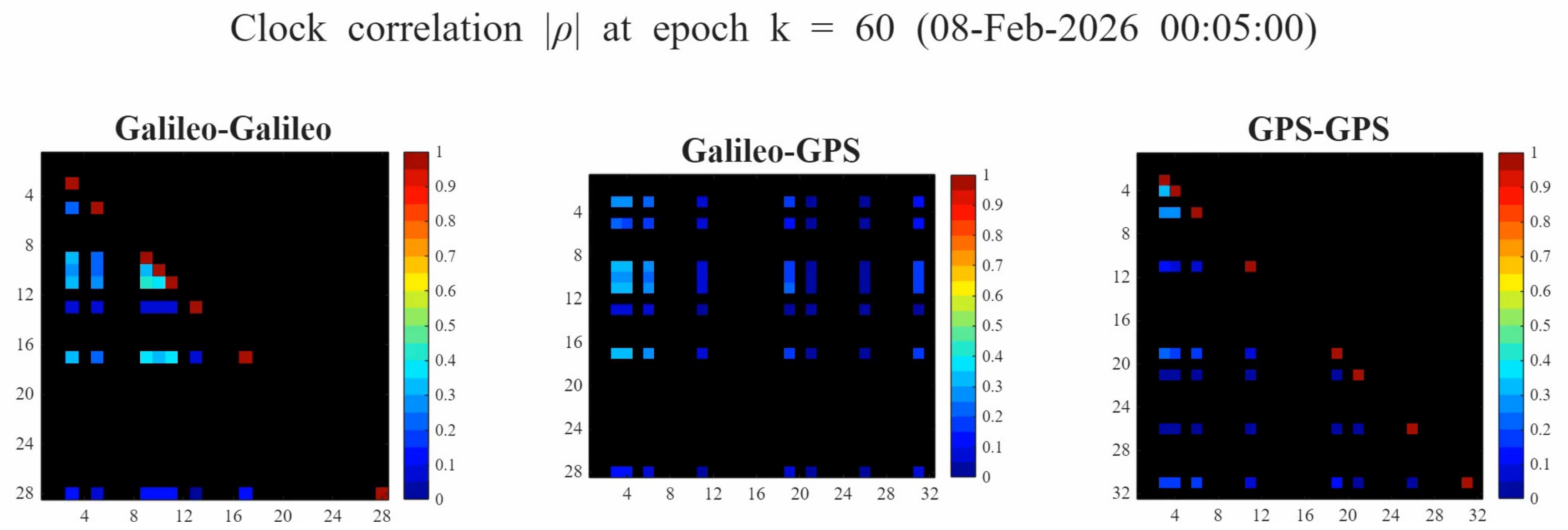
Uncertainty for satellite E08



Correlation between two satellites



Correlation among all satellites



Video shows correlation among all satellites at 5-minute interval, where the blue color refers to a low correlation, i.e. generally $|\rho| < 0.3$.

TUDelft

Assessment impact on PPP-AR model

Assessment impact to users

Correction model (without latency)

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

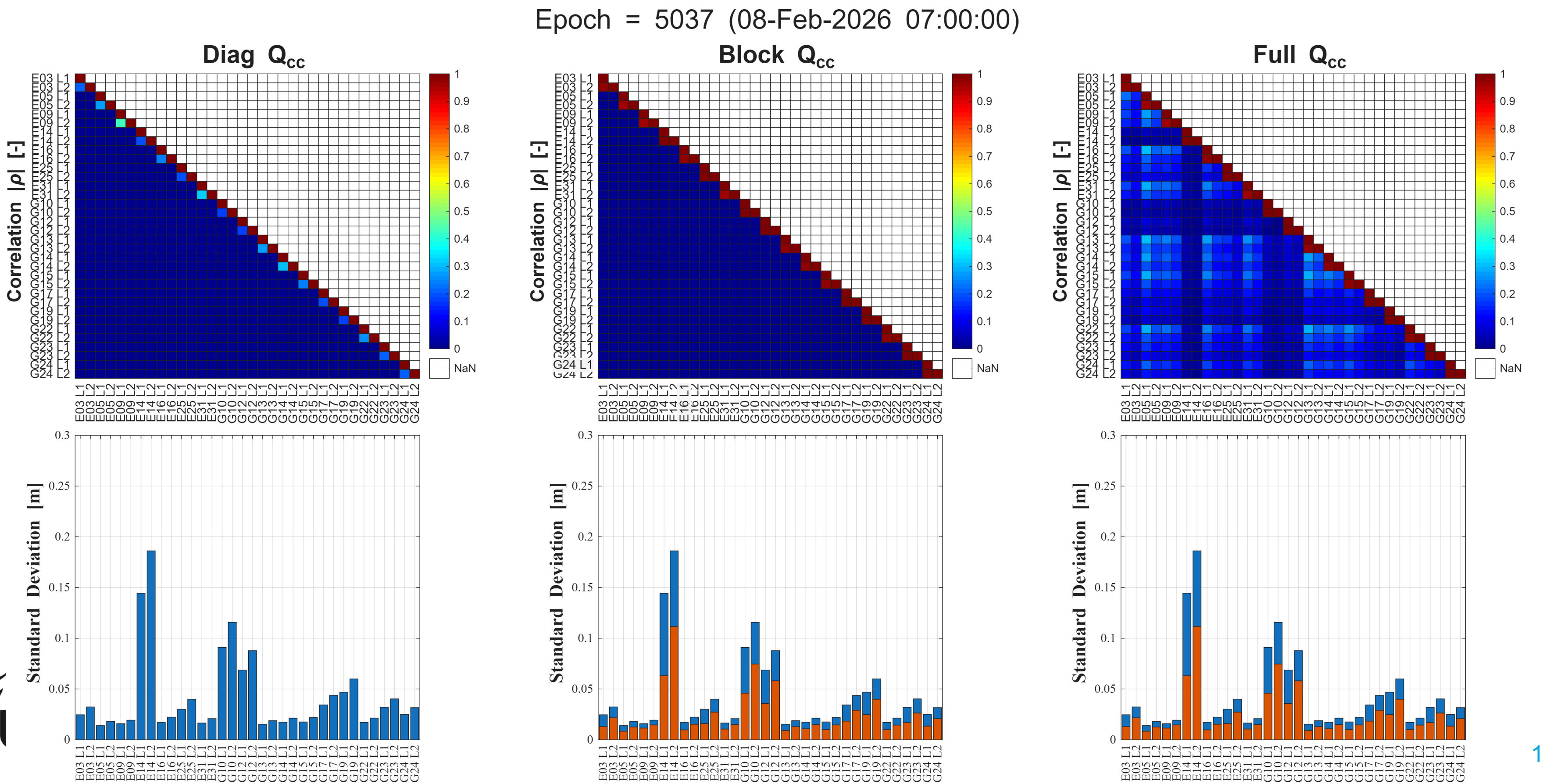
$$A_k = \mathrm{blkdiag}(A^{s_1}, \dots, A^{s_m}), \qquad A^s = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

while

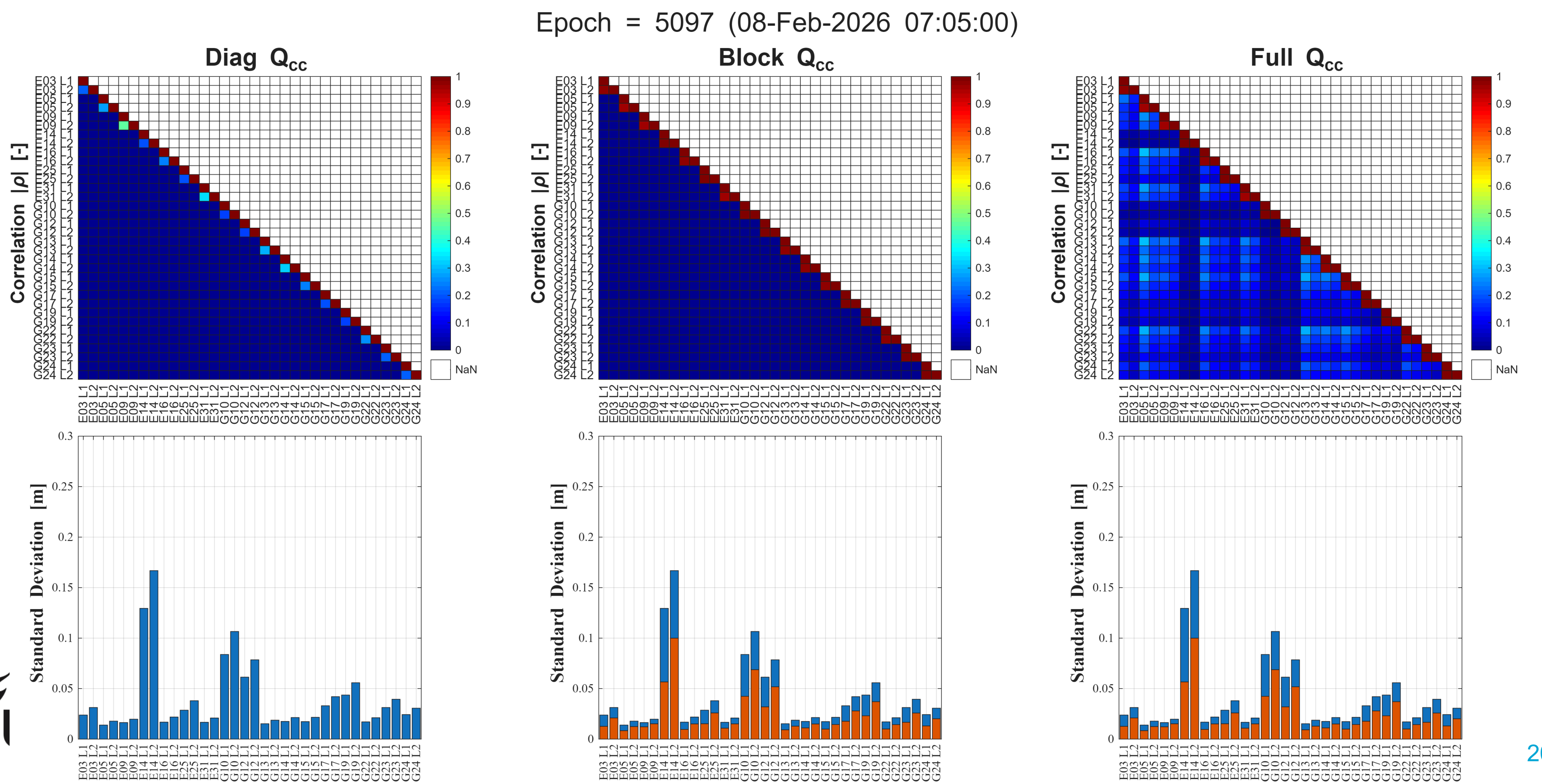
$$Q_{\bar{y}_k \bar{y}_k} = Q_{y_k y_k} + \underbrace{A_k Q_{c_k c_k} A_k^T}_{Q_{\bar{c}_k \bar{c}_k}}, \qquad Q_{y_k y_k} = \mathrm{diag}\left(\sigma^2_{P_1^{s_1}}, \sigma^2_{P_2^{s_1}}, \sigma^2_{L_1^{s_1}}, \sigma^2_{L_2^{s_1}}, \dots\right)$$

TUDelft

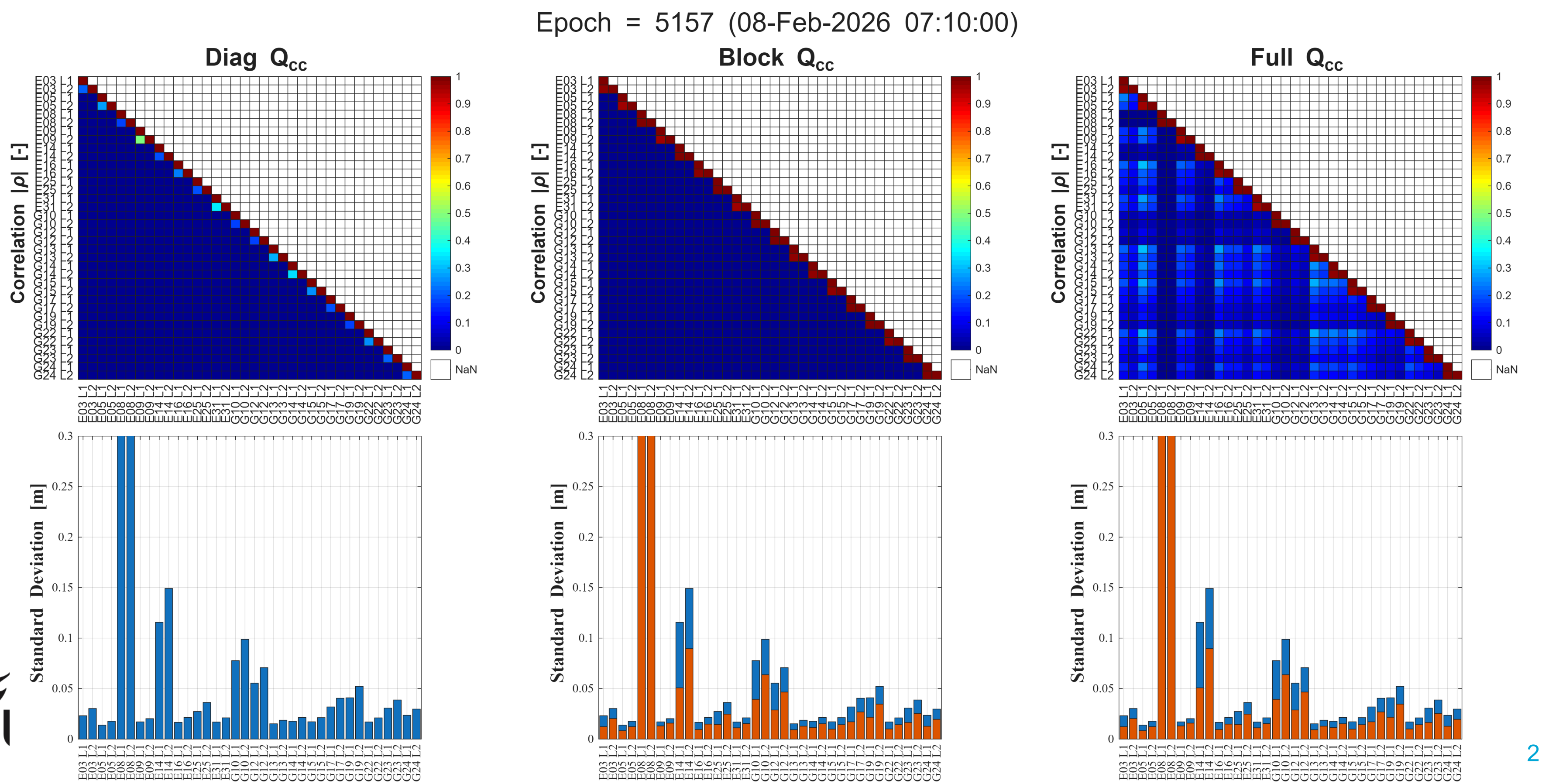
Example $Q_{\bar{c}_k \bar{c}_k}$ for UD phase data



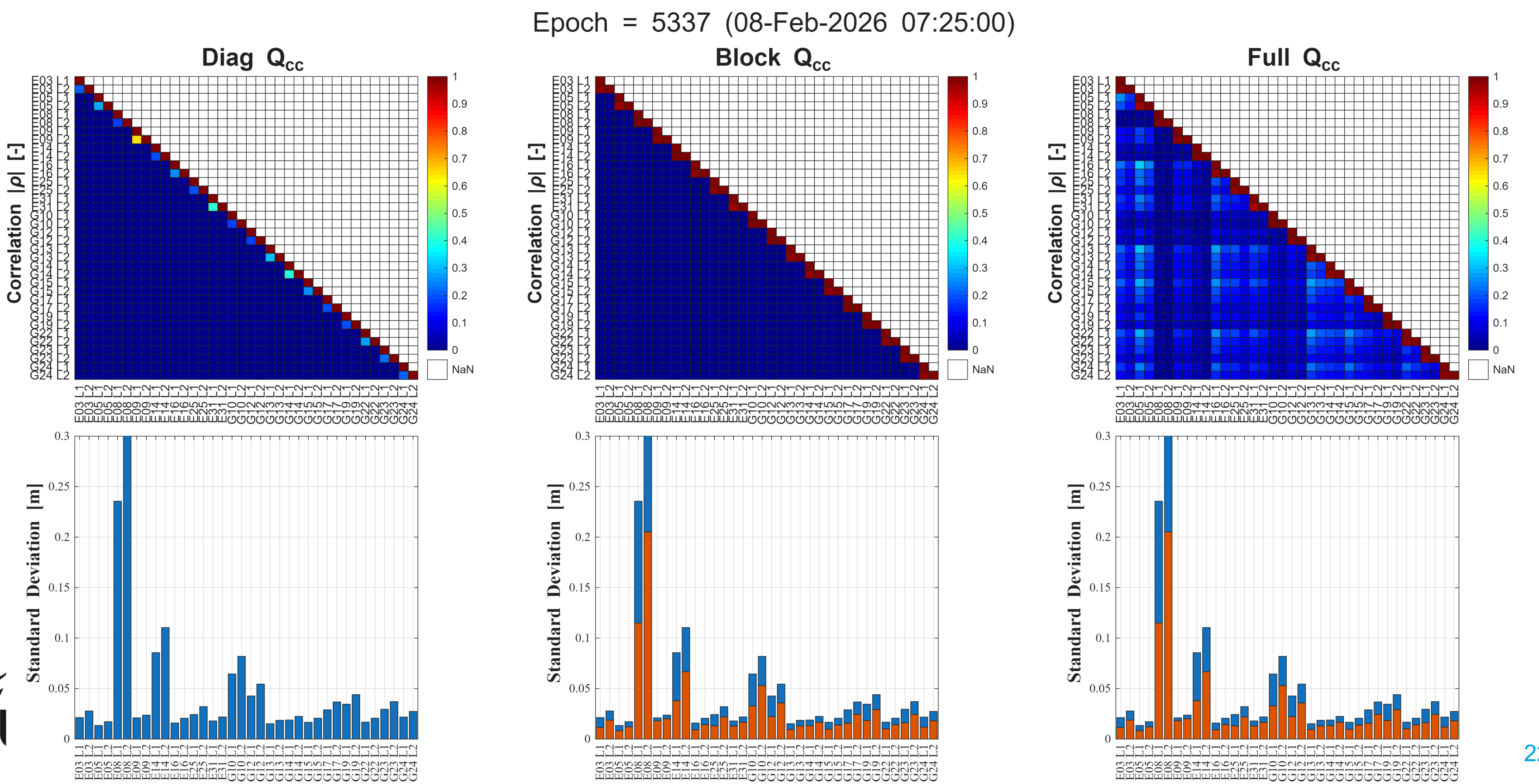
Example $Q_{\bar{c}_k\bar{c}_k}$ for UD phase data



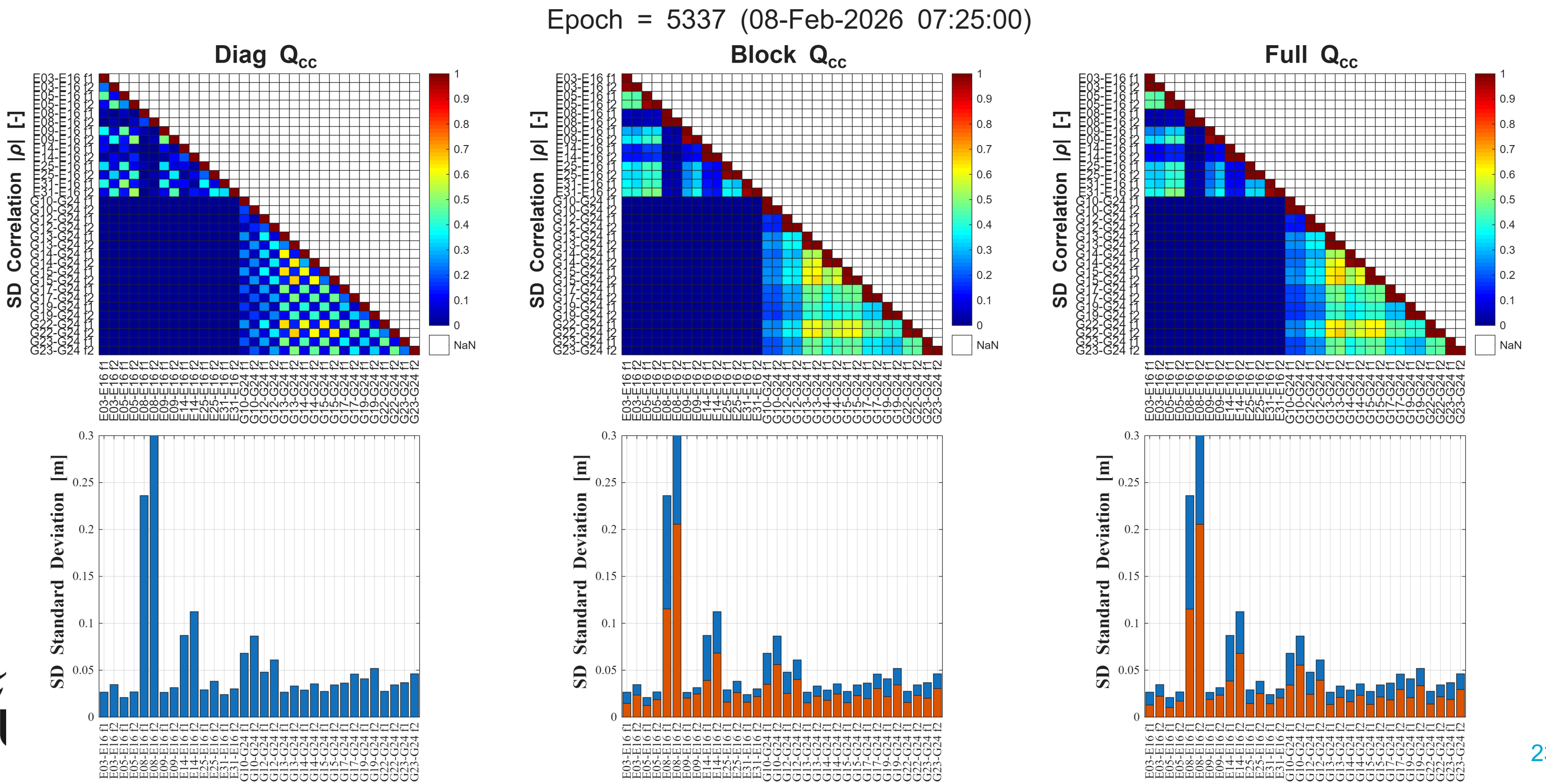
Example $Q_{\bar{c}_k\bar{c}_k}$ for UD phase data



Example $Q_{\bar{c}_k \bar{c}_k}$ for UD phase data



Example $Q_{\bar{c}_k \bar{c}_k}$ for SD phase data



Conclusions

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 → **discussion at IGS RTS Splinter Meeting?** ☺

NOTE: Uncertainty of 'clk+phb' corrections will surely be critical for future LEO-PNT system, with potentially several issues foreseen in their (regional) network estimation → **discussion at IGS LEO-PNT Splinter Meeting? ☺**

TU Delft

Questions?

Thanks for your attention

Courtesy of ASI (Agenzia Spaziale Italiana)

TU Delft

GFZ Helmholtz Centre for Geosciences

Lotfi Massarweh
L.Massarweh@tudelft.nl