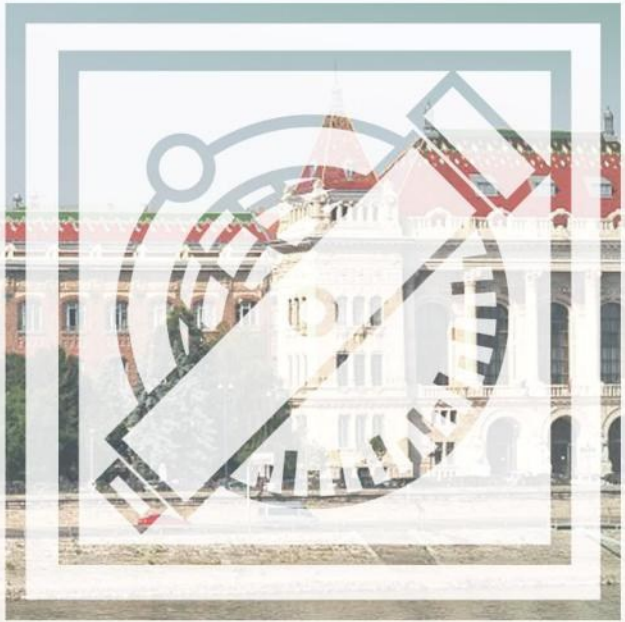


Differential GNSS and Correction Services

GNSS Under Attack course

Szabolcs RÓZSA

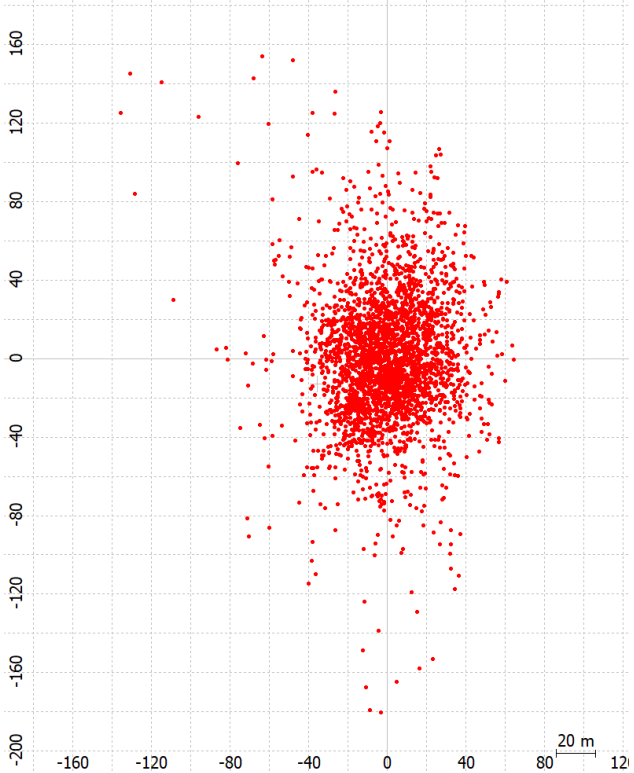
February 5, 2026

BME | FACULTY OF CIVIL ENGINEERING | DEPARTMENT OF GEODESY AND SURVEYING

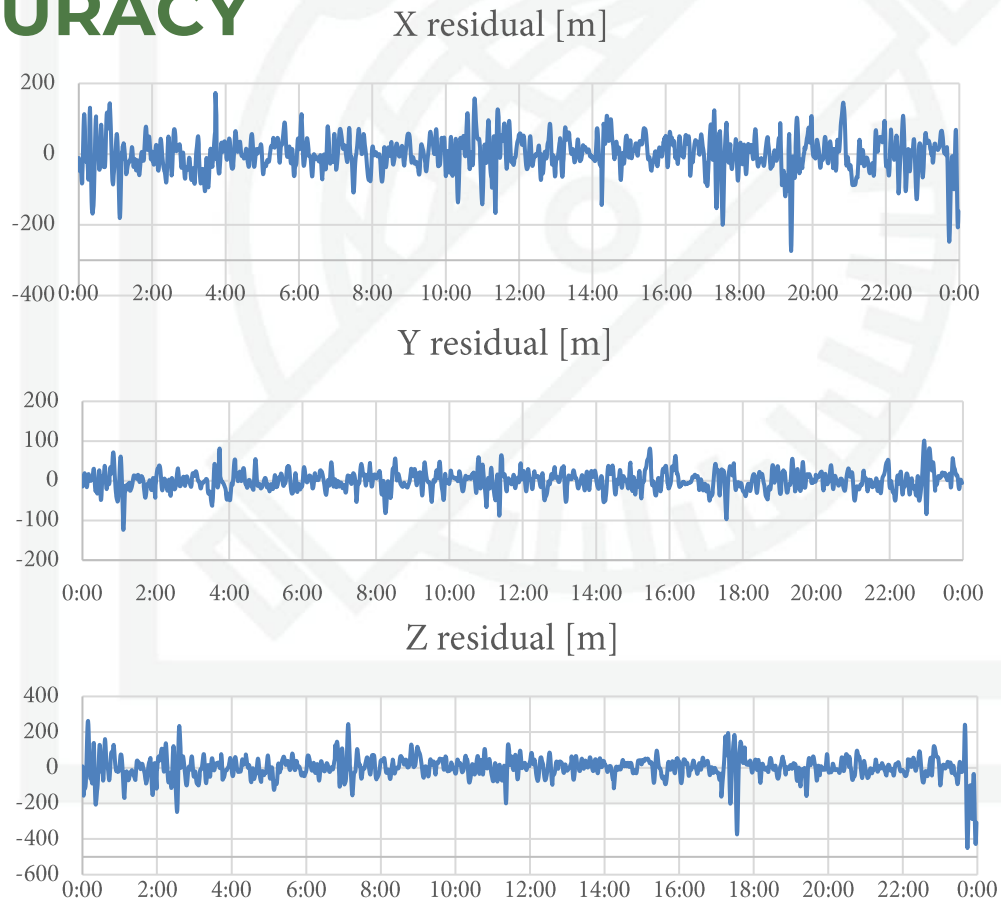
Content

- Motivation of DGNSS services
- Handling systematic error: Observation vs State Space Representation
- DGNSS/RTK/PPP positioning techniques
- Structure of correction services
- Standalone and networked correction services
- Conclusions

Motivation 1 : Accuracy



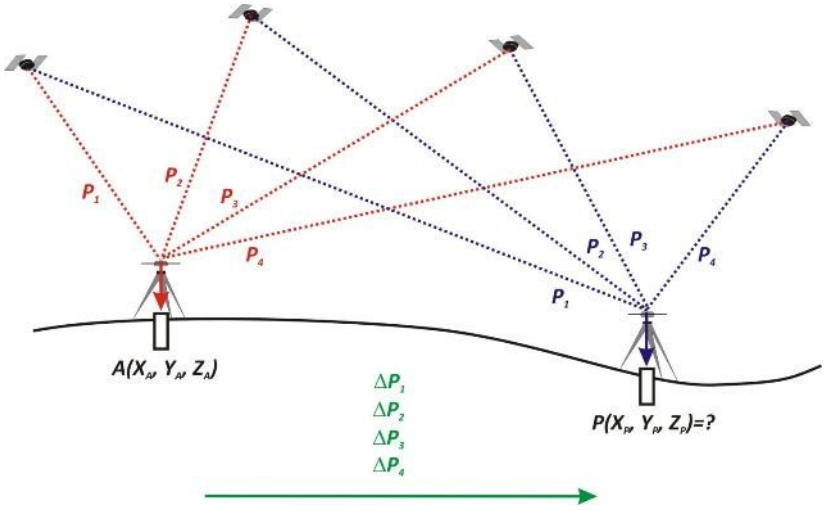
GPS SPP under Selective Availability
(PENC, April 30, 2000)



Handling Systematic Error

$$R = \rho + c\delta^S - c\delta_R + T + I$$

Observation **S**pace **R**epresentation (differential positioning):



Principle of DGNSS Positioning

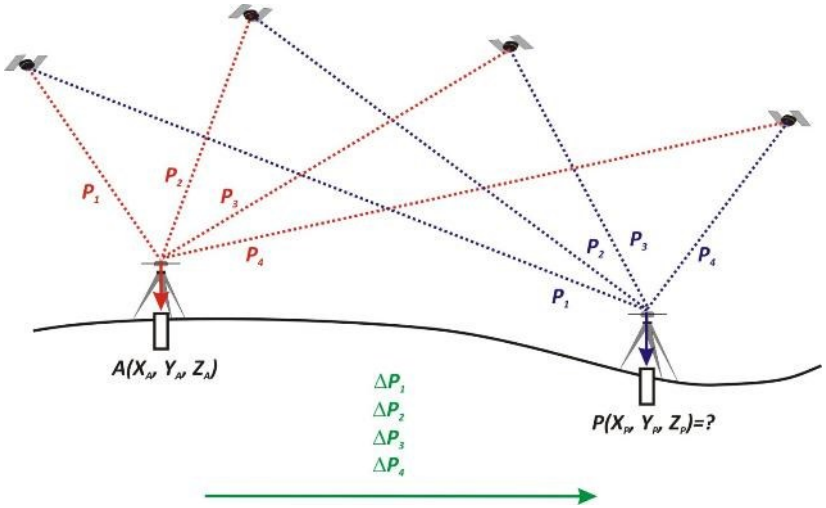
$$R_A^S = \rho_A^S + c\delta^S - c\delta_A + T + I$$

$$\Delta R^S = \rho_A^S - R_A^S = -c\delta^S + c\delta_A - T - I$$

$$R_B^S = \rho_B^S + c\delta^S - c\delta_B + T + I$$

$$R_B^S + \Delta R^S = \rho_B^S + c(\delta_B - \delta_A)$$

Differential GNSS Method (DGNSS/DGPS)

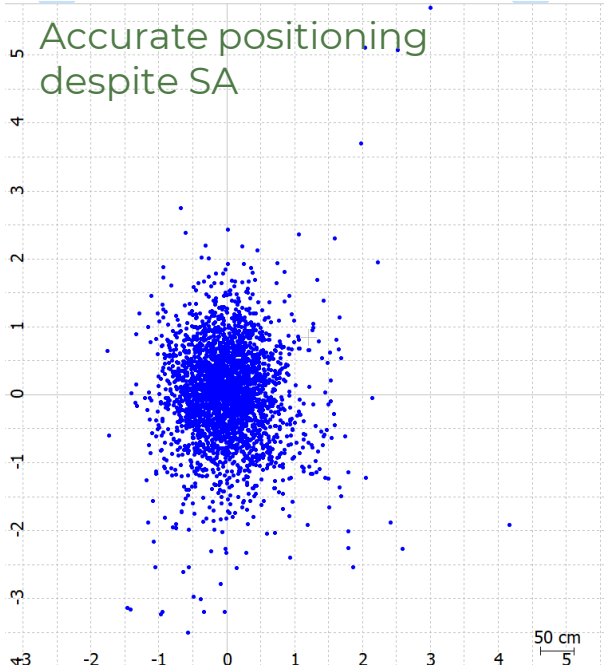


Principle of DGNSS Positioning

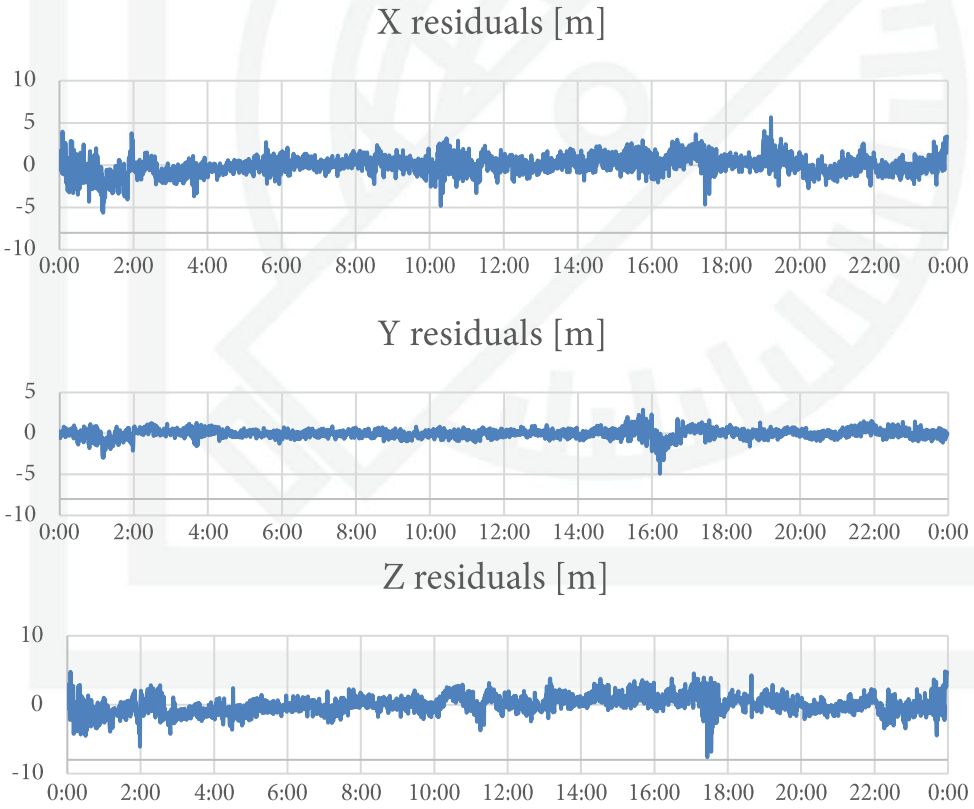
Differential corrections:

- range correction is a lump sum of range error at the reference receiver
- realtime transmission of range corrections
- submeter accuracy (GIS)

Differential GNSS Method (DGNSS/DGPS)

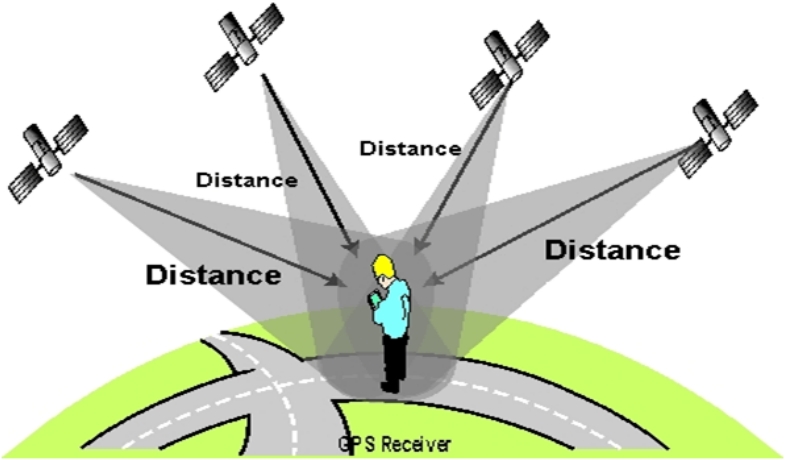


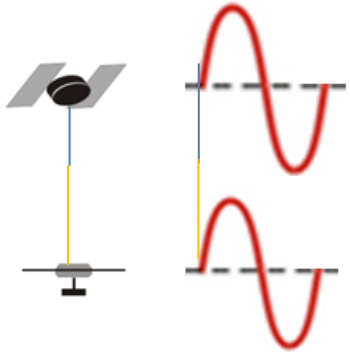
DGPS under Selective Availability
(**GRAZ -> PENC**, April 30, 2000)



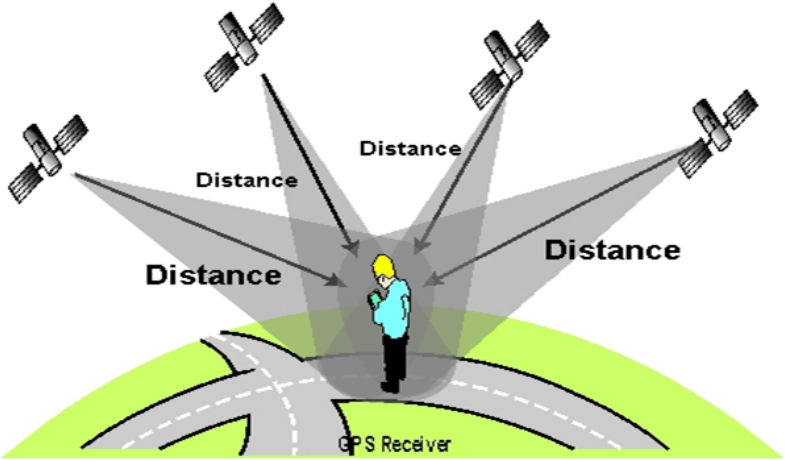
Ranging with carrier waves

Carrier waves → phase ranges

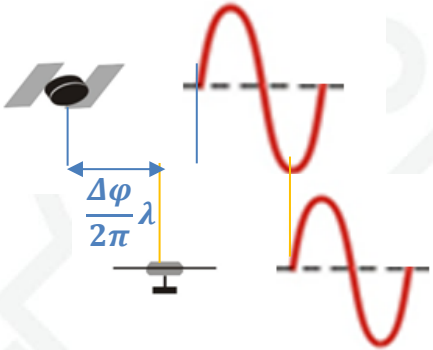




Ranging with carrier waves

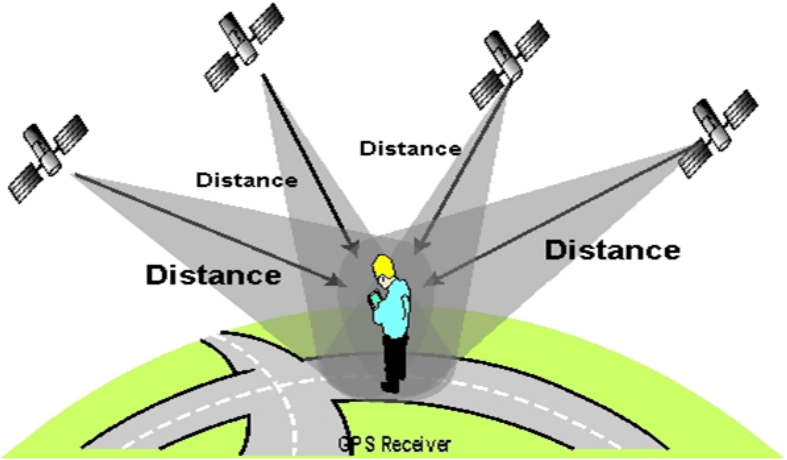


Carrier waves → phase ranges

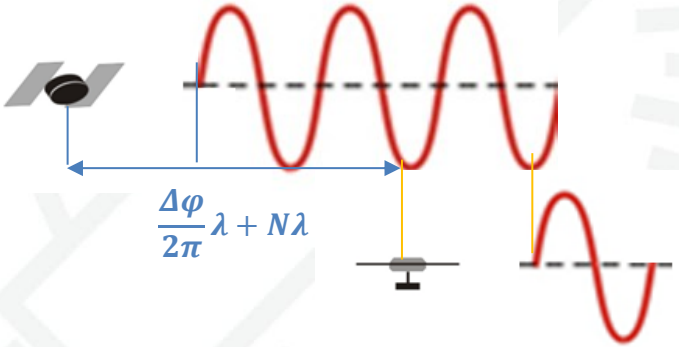


Ranging accuracy: ~3 mm → could be suitable for geodetic observations

Ranging with carrier waves



Carrier waves → phase ranges



Ranging accuracy: ~3 mm → suitable for geodetic observations

Ambiguous observation: *N* is unknown

When *N* is resolved as integer → accurate ranging from satellite → accurate positions

RANGING WITH CARRIER WAVES

$$\Psi_R^S \left(= \frac{\Delta\varphi}{2\pi}\lambda \right) = \rho + c\delta^S - c\delta_R - N\lambda + T - I$$

where:

$\Psi_R^S \left(= \frac{\Delta\varphi}{2\pi}\lambda \right)$ phase range (satellite-receiver range, observed)

$\rho = \sqrt{(X^S - X_R)^2 + (Y^S - Y_R)^2 + (Z^S - Z_R)^2}$ geometrical distance

δ^S satellite clock bias

δ_R receiver clock bias

N phase ambiguity (integer)

λ wavelength

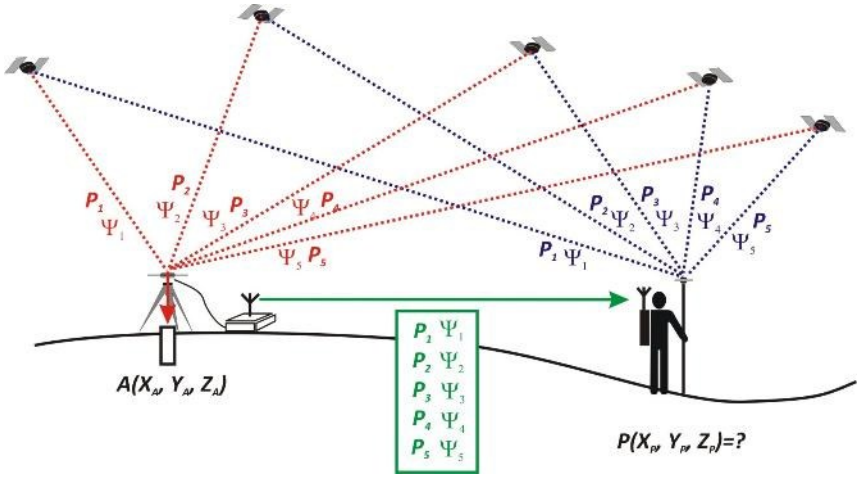
T troposphere

I ionosphere

time dependent | time independent | known | slowly changing

RELATIVE POSITIONING - DIFFERENCING

$$\Psi_R^S \left(= \frac{\Delta\varphi}{2\pi}\right) = \rho + c\delta^S - c\delta_R - N\lambda + T - I$$



Single differences (between stations):

$$\Delta\Psi_{AP}^S = \Psi_P^S - \Psi_A^S$$

eliminates satellite clock bias
reduces atmospheric effects, orbit error

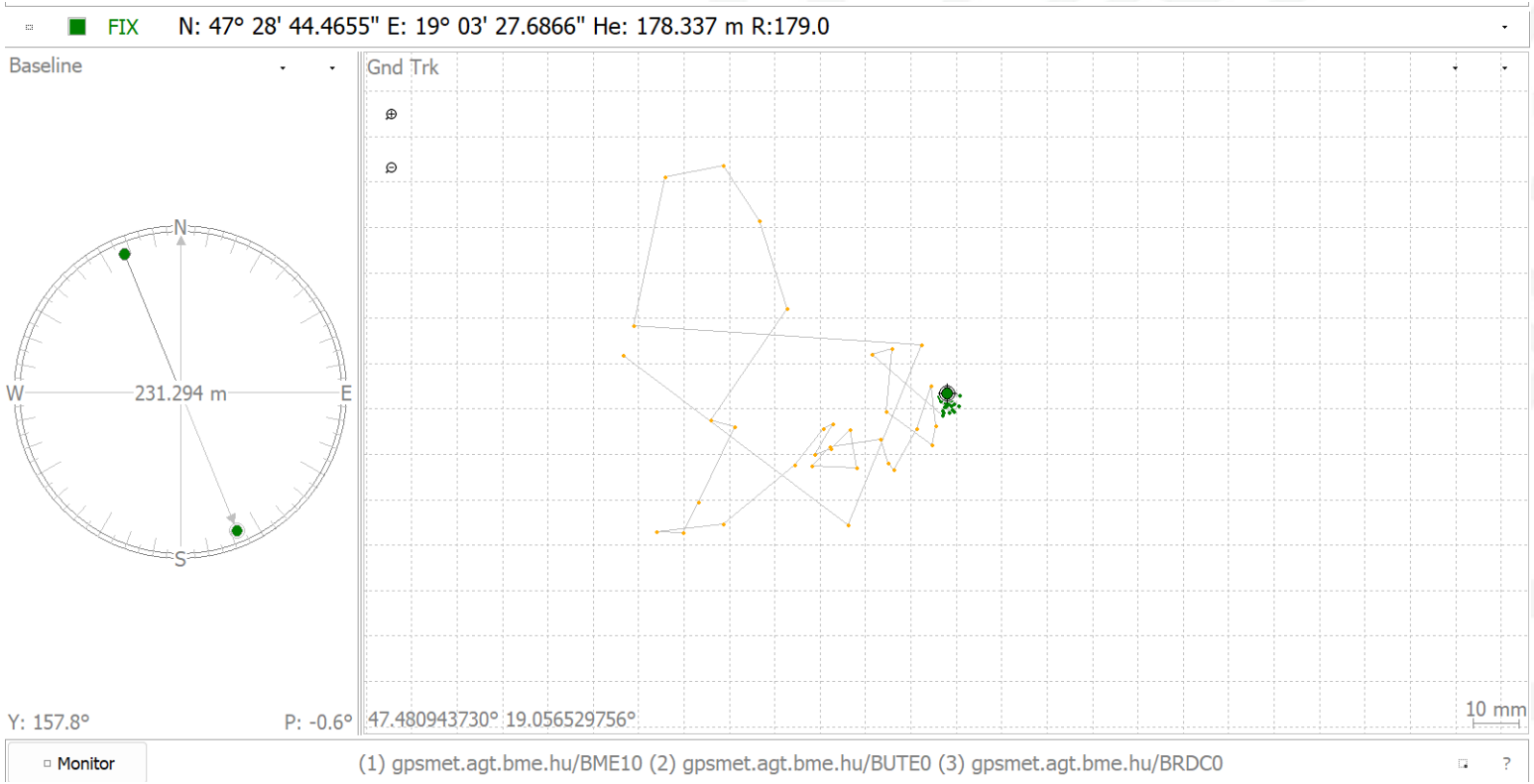
Double differences (between satellites):

$$\Delta\Delta\Psi_{AP}^{SQ} = \Delta\Psi_{AP}^S - \Delta\Psi_{AP}^Q$$

eliminates receiver clock bias

$$\Delta\Delta\Psi_{AP}^{SQ} = f(\rho, N)$$

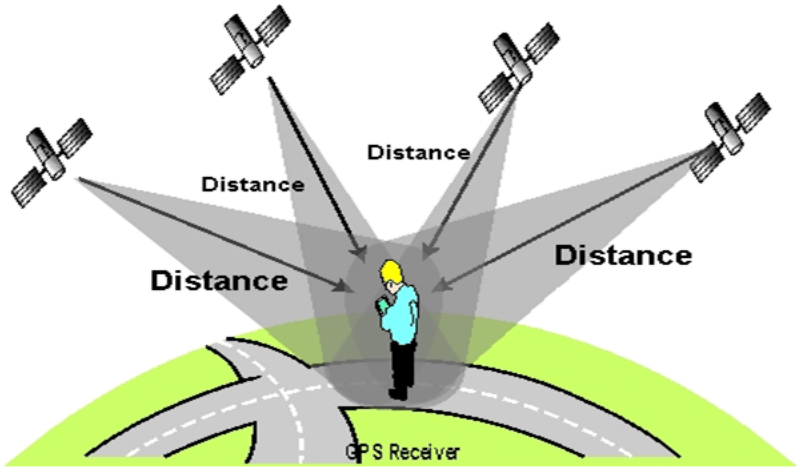
RELATIVE POSITIONING - DIFFERENCING



Another Way of Handling Systematic Error

$$R = \rho + c\delta^S - c\delta_R + T + I$$

State **S**pace **R**epresentation (absolute positioning with corrections):



Principle of Absoluite Positioning

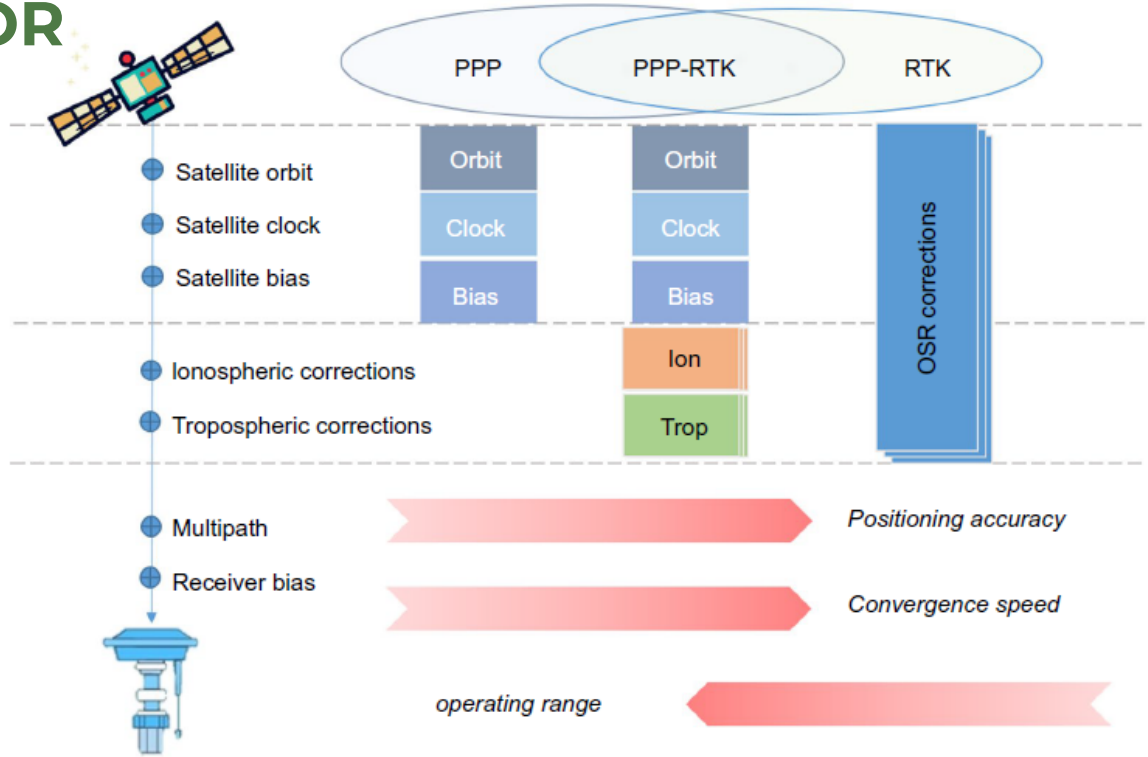
model model model

$$R_B^S = \rho_B^S + c\delta^S - c\delta_B + T + I \quad \text{SPP}$$

$$\Psi_B^S = \rho_B^S + c\delta^S - c\delta_B + \lambda N + T - I \quad \text{PPP}$$

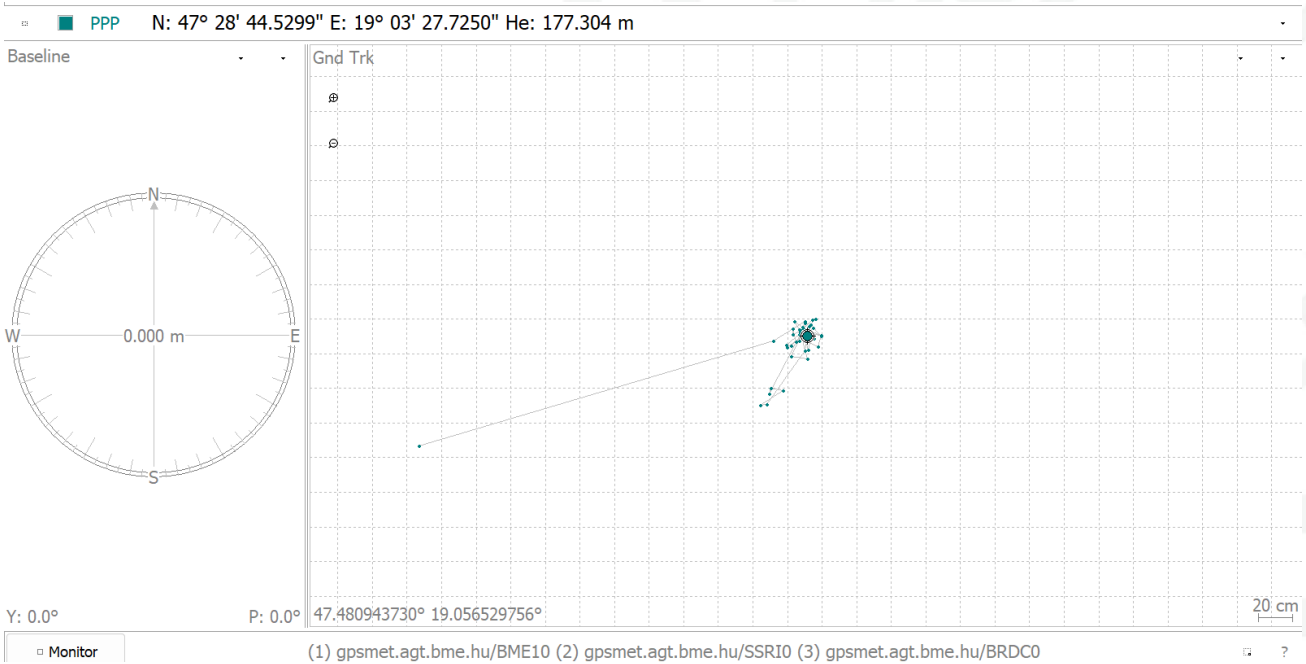
How to derive the models?

Another Way of Handling Systematic Error



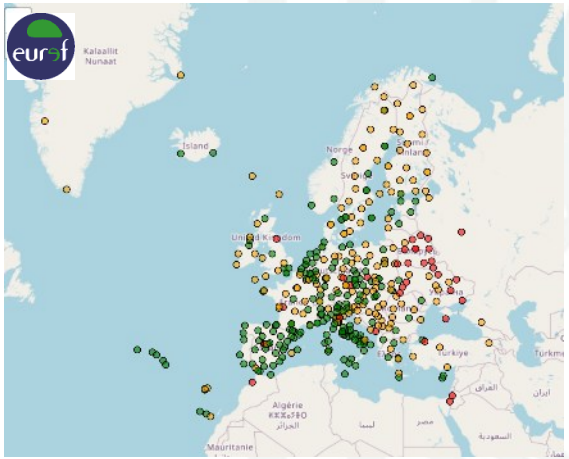
Source Li, X., Huang, J., Li, X. et al. Review of PPP–RTK: achievements, challenges, and opportunities. Satell Navig 3, 28 (2022). https://doi.org/10.1186/s43020-022-00089-9

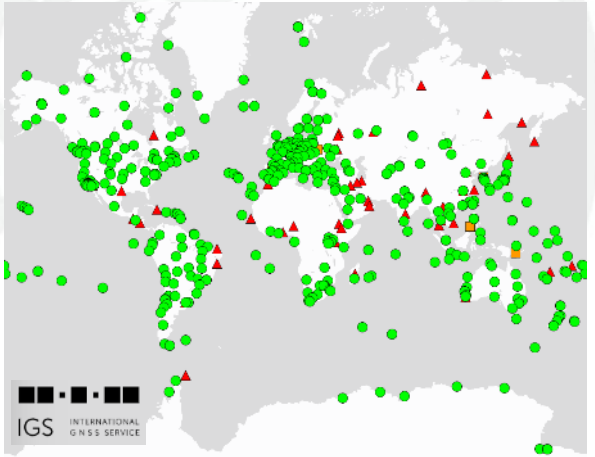
Another Way of Handling Systematic Error



How to derive the models?

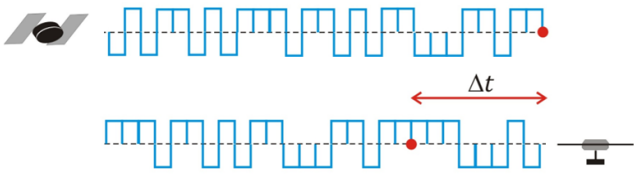
GNSS Infrastructure

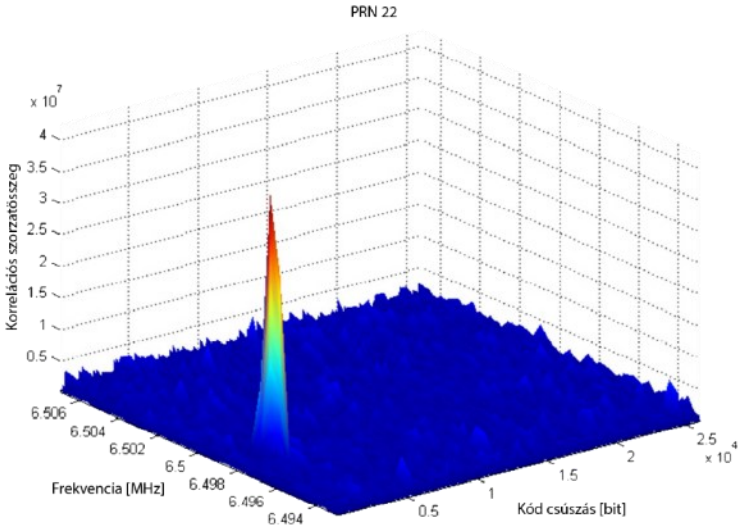


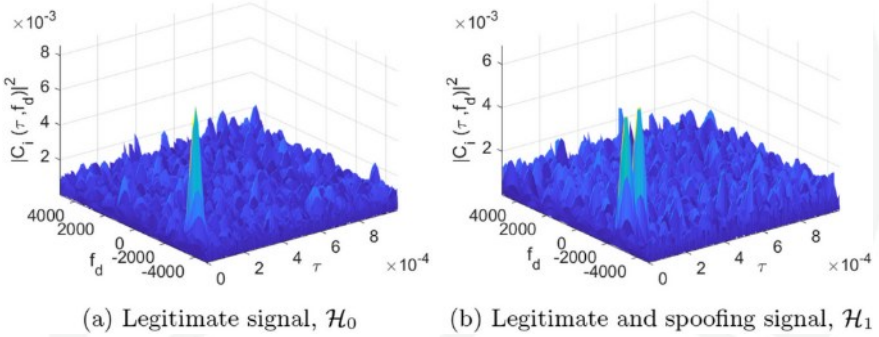


National → Continental → Global

Motivation 2 : Reliability







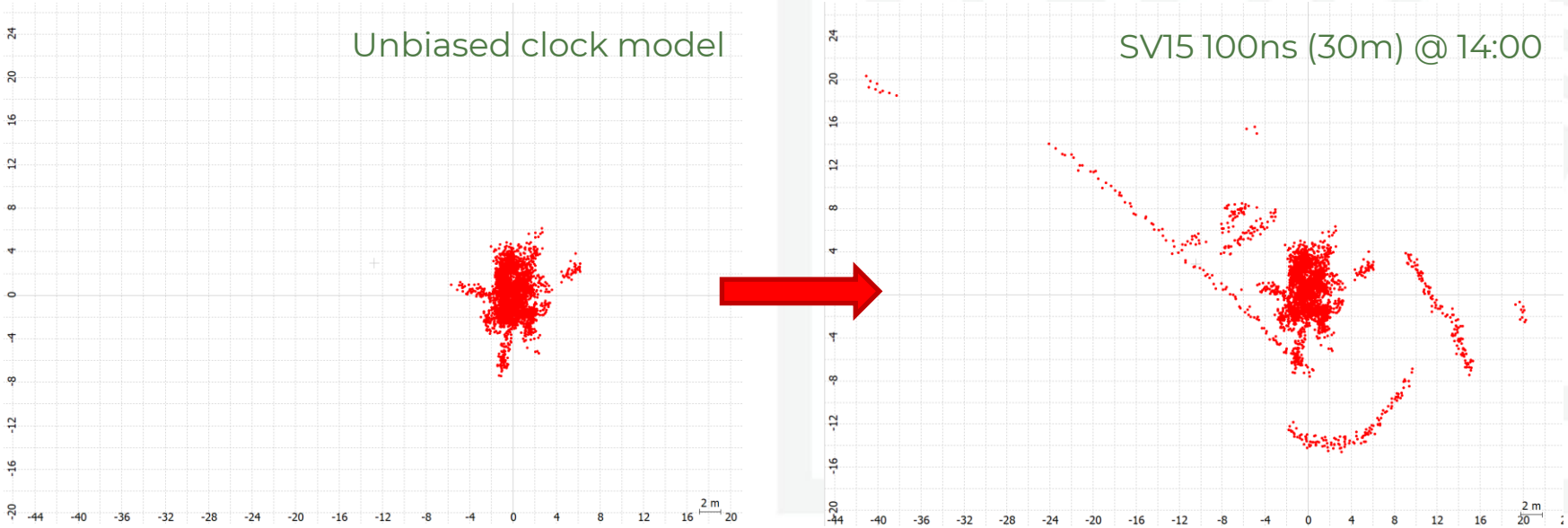
(a) Legitimate signal, $\mathcal{H}_0$ (b) Legitimate and spoofing signal, $\mathcal{H}_1$

Borhani-Darian, P., Li, H., Wu, P. et al. Detecting GNSS spoofing using deep learning. EURASIP J. Adv. Signal Process. ***2024****, 14 (2024). https://doi.org/10.1186/s13634-023-01103-1*

Which signal is used?
What will be the delay (and the pseudorange)?
How does it affect timing?

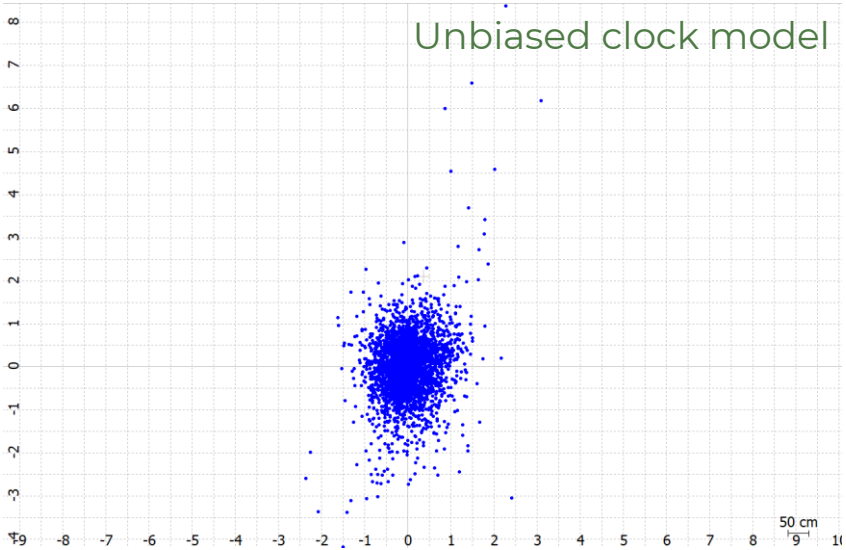
Motivation 2 : Reliability

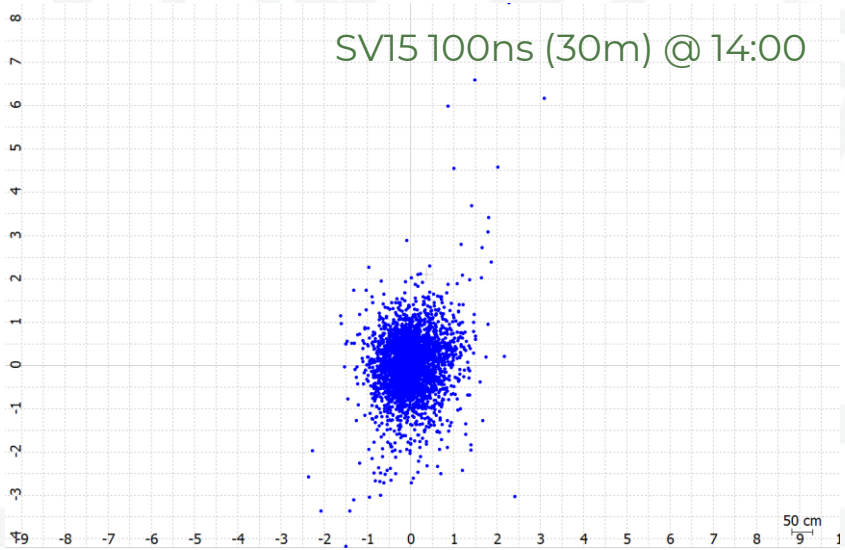
Example: wrong satellite clock model



Motivation 2 : Reliability

Example: wrong satellite clock model



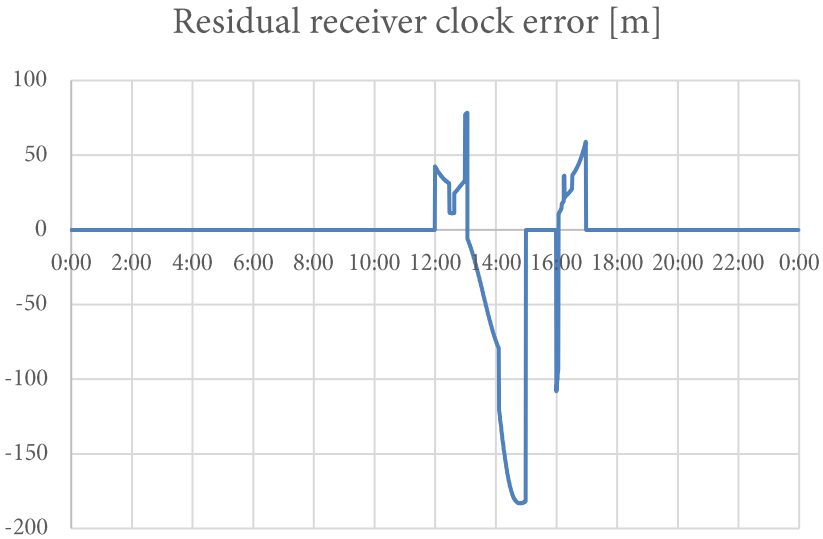


With DGPS corrections (GRAZ → PENC)

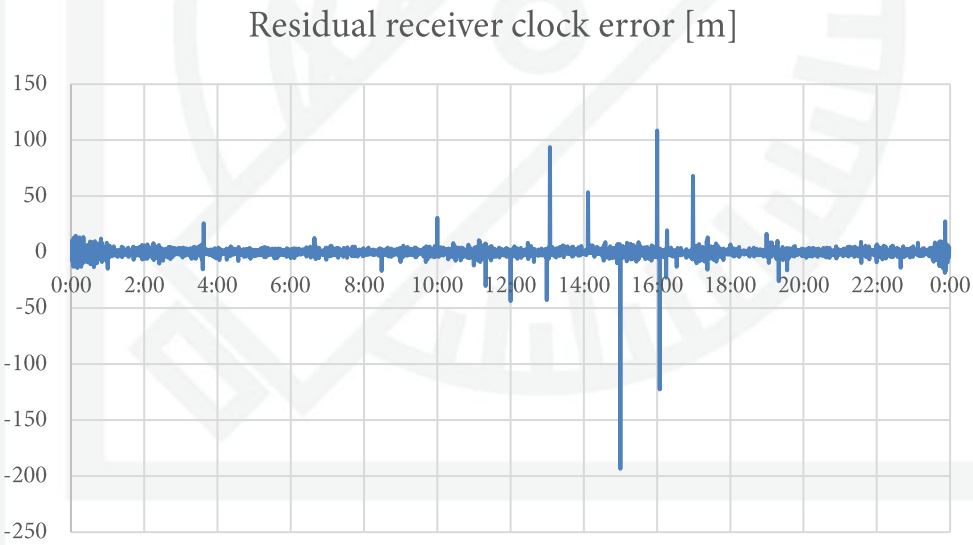
Motivation 2 : Reliability

Example: wrong satellite clock model

SV15 100ns (30m) @ 14:00



Without differential correction

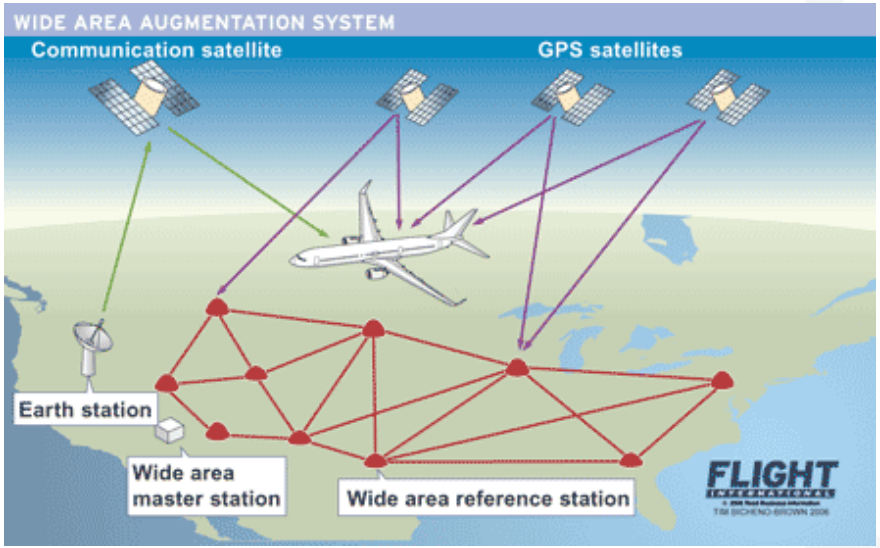


With differential correction

Timing application

Motivation 2 : Reliability

Safety-of-Life applications



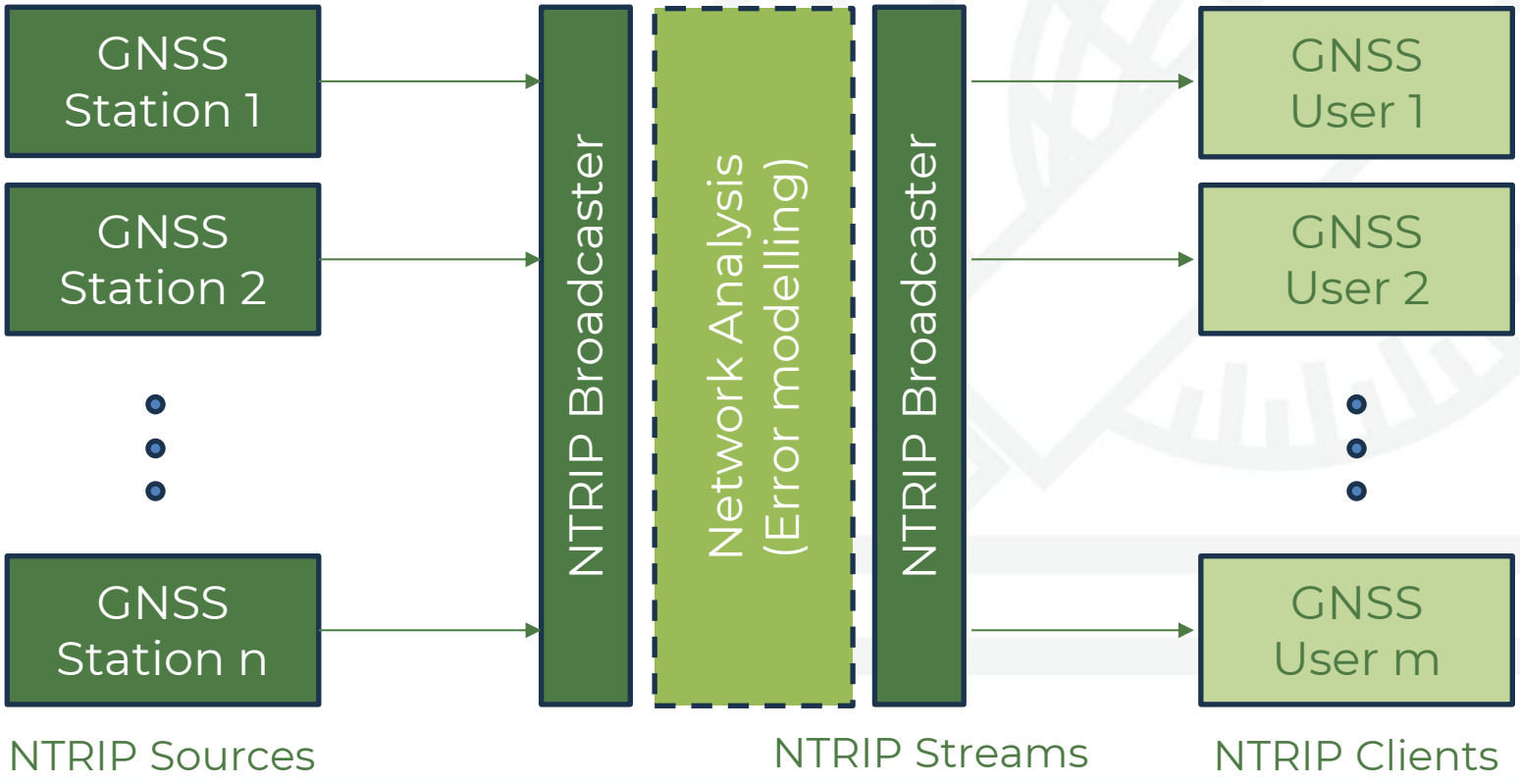
WAAS EGNOS JCAB JAPAN CIVIL AVIATION BUREAU

- improved accuracy (error model)
- improved reliability (residual error model, malfunction detection and alerting)

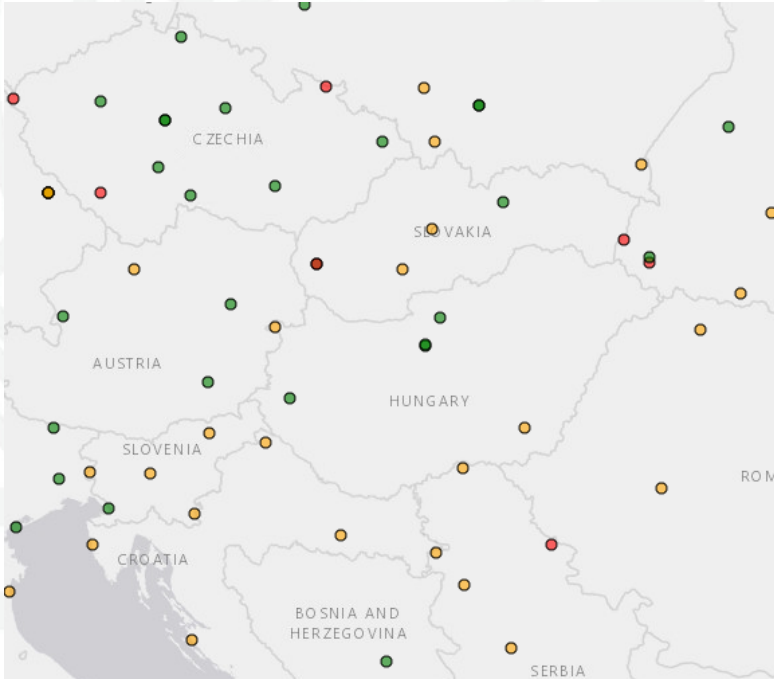
GNSS Correction Services

- Improved positioning accuracy (cm – dm – m)
- Different techniques (RTK / DGNSS / PPP)
- Service area (local / regional / global)
- Integrity information (error detection, alerting)
- SBAS vs GBAS
- Media: radio signal vs Internet

Typical Structure



Example – Standalone Correction Service



Example – Standalone Correction Service

Data streams

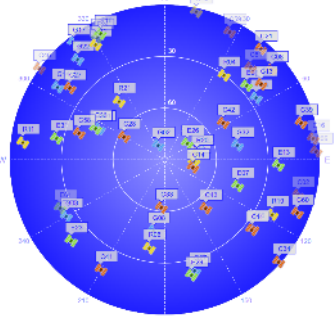
Outgoing data streams | Incoming data streams

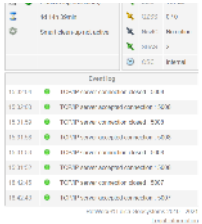
Real time	Type / message	Data rate	Last sent	Connection: port
●	RTCM 3.x GNSS MSM7 and ephemeris	1 sec	0.28 s	Ntrip server (source): 2101 (ZZON0)
●	RTCM 3.x GPS/GLO extended and ephemeris	1 sec	0.28 s	Ntrip server (source): 2101 (ZZON1)
●	RTCM 3.x GNSS MSM5 and ephemeris	1 sec	0.25 s	Ntrip server (source): 2101 (ZZON2)
●	RTCM 3.x GNSS MSM5 and ephemeris	1 sec	0.23 s	TCP/IP server: 5008
■	RTCM 3.x GNSS MSM3 and ephemeris	1 sec	–	Ntrip server (source): 2101 (ZZON3)
●	RTCM 3.x GNSS MSM7 and ephemeris	1 sec	0.21 s	Ntrip server (source): 2101 (ZZON0)
●	RTCM 3.x GPS/GLO extended and ephemeris	1 sec	0.21 s	Ntrip server (source): 2101 (ZZON1)
●	RTCM 3.x GNSS MSM5 and ephemeris	1 sec	0.19 s	Ntrip server (source): 2101 (ZZON2)

LB2	Data	Message	Data rate	Connection: port
●	Meas.Data Set.Data	Message E	1 sec	TCP/IP server: 5007

NMEA	Message	Connection: port
No item configured		

BINEX	Message	Connection: port
No item configured		





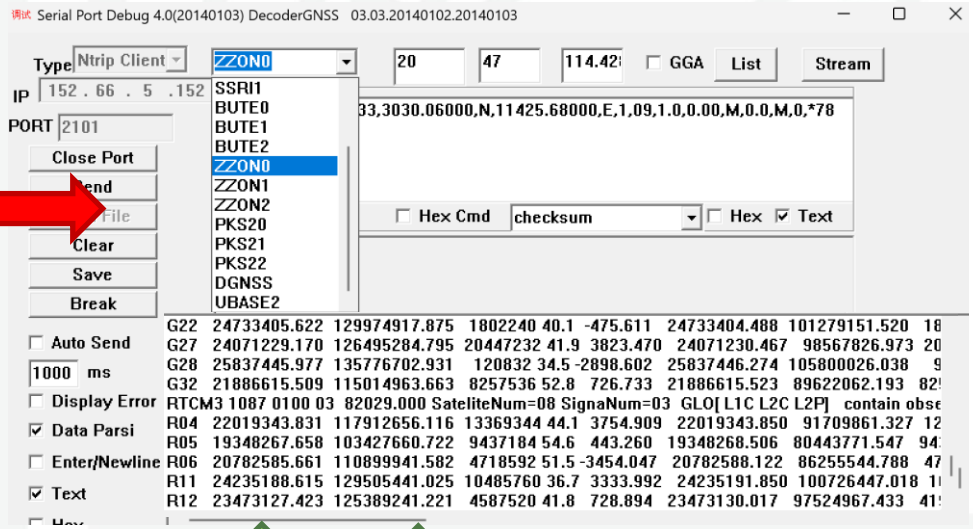
ZZON NTRIP Source

Mountpoint	Id	Host	Source Agent	Time of connect	IP	Clients	KBytes read	KBytes written	Client connections	Connected for
/BME11	6	152.66.5.195	NTRIP NtripServerCMD/1.0.0	02/Dec/2025:12:38:26	152.66.5.195	0	19756636	0	0	64 days, 7 hours, 3 minutes and 13 seconds
/BUTL2	30108	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:06	152.66.6.49	0	3062587	0	0	22 days, 16 hours, 16 minutes and 33 seconds
/DGNSS	30109	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:08	152.66.6.49	0	1306169	23	1	22 days, 16 hours, 16 minutes and 31 seconds
/BUTL1	30110	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:09	152.66.6.49	0	689543	0	0	22 days, 16 hours, 16 minutes and 30 seconds
/[illegible]	[illegible]	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:19	152.66.6.49	1	3702818	3760092	15	22 days, 16 hours, 16 minutes and 20 seconds
/BME10	31296	152.66.5.195	NTRIP NtripServerPOSIX/1.51	28/Jan/2026:09:11:06	152.66.5.195	2	659797	1316075	10	7 days, 10 hours, 30 minutes and 33 seconds
/ZZON0	31763	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:04:58	84.1.97.62	2	605814	1232894	43	4 days, 0 hours, 36 minutes and 41 seconds
/ZZON1	31764	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:04:58	84.1.97.62	0	120773	211	7	4 days, 0 hours, 36 minutes and 41 seconds
/ZZON2	31765	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:04:58	84.1.97.62	0	504075	90906	29	4 days, 0 hours, 36 minutes and 41 seconds
/UBASE2	31767	151.0.80.190	NTRIP RTKLIB/demo5_b34i	31/Jan/2026:19:05:17	151.0.80.190	0	570556	22	1	4 days, 0 hours, 36 minutes and 22 seconds
/BRDC0	31775	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	813206	0	0	4 days, 0 hours, 34 minutes and 32 seconds
/SSRI1	31776	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	136616	0	0	4 days, 0 hours, 34 minutes and 32 seconds
/SSRI0	31777	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	206984	0	0	4 days, 0 hours, 34 minutes and 32 seconds
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2 days, 8 hours, 22 minutes and 4

NTRIP Broadcaster @ BME DGS

Example – Standalone Correction Service

Mountpoint	Id	Host	Source Agent	Time of connect	IP	Clients	KBytes send	KBytes written	Client connections	Connected for
/BME11	6	152.66.5.195	NTRIP NtripServerCMD/1.0.0	02/Dec/2025:12:38:26	152.66.5.195	0	19756656	0	0	64 days, 7 hours, 3 minutes and 13 seconds
/BUTE2	30108	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:06	152.66.6.48	0	3062587	0	0	22 days, 16 hours, 16 minutes and 33 seconds
/DGNSS	30108	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:08	152.66.6.48	0	1306169	23	1	22 days, 16 hours, 16 minutes and 31 seconds
/BUTE1	30110	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:09	152.66.6.48	0	689563	0	0	22 days, 16 hours, 16 minutes and 30 seconds
/BUTE0	30112	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:18	152.66.6.48	1	3702818	3760092	15	22 days, 16 hours, 16 minutes and 20 seconds
/BME10	31296	152.66.5.195	NTRIP	28/Jan/2026:09:11:06	152.66.5.195	2	659797	1316075	10	7 days, 10 hours, 30 minutes and 33
/ZZON0	31763	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:07:58	84.1.97.62	2	605814	1232894	43	1 days, 0 hours, 36 minutes and 41 seconds
/ZZON1	31761	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:07:58	84.1.97.62	0	120773	211	7	1 days, 0 hours, 36 minutes and 41 seconds
/ZZON2	31763	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:07:58	84.1.97.62	0	504075	90806	29	1 days, 0 hours, 36 minutes and 41 seconds
/CBASE2	31767	151.0.80.190	NTRIP RTKLIB/demo5_b34i	31/Jan/2026:19:08:17	151.0.80.190	0	370338	22	1	seconds
/DRDC0	31775	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	813206	0	0	1 days, 0 hours, 34 minutes and 32 seconds
/SSRI1	31776	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	136616	0	0	1 days, 0 hours, 34 minutes and 32 seconds
/SSRI0	31777	157.90.249.44	NTRIP Caster/2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	206981	0	0	1 days, 0 hours, 34 minutes and 32 seconds
										2 days, 8 hours, 22 minutes and 4



NTRIP Broadcaster
@ BME DGS

pseudoranges

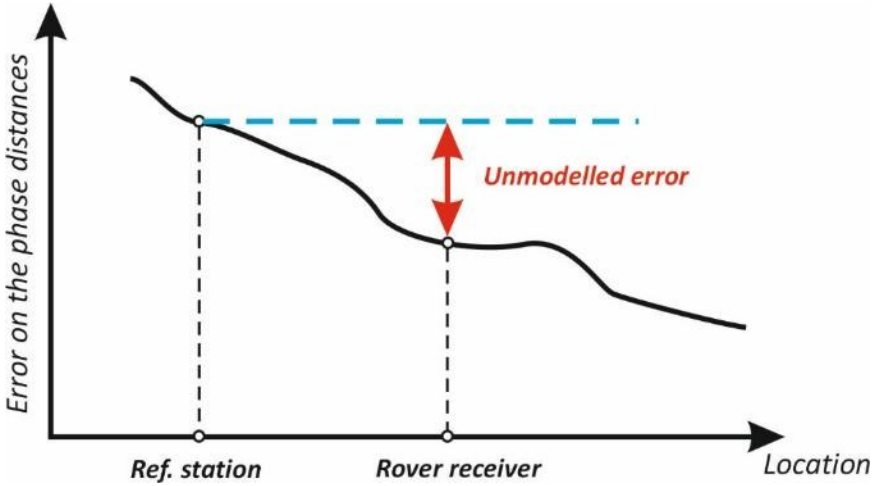
phase ranges

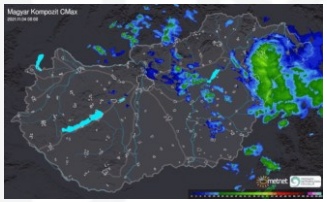
NTRIP Client

FORMAT: presentation tomorrow

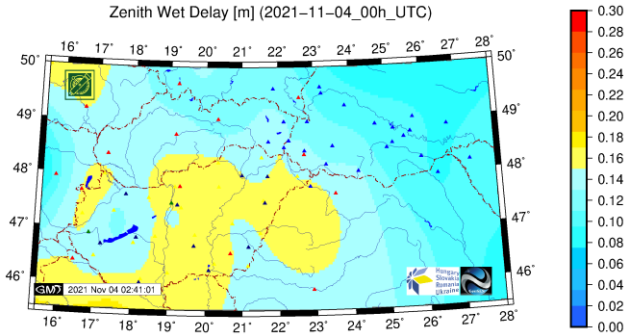
Standalone Correction Service

Limitation of standalone correction services:



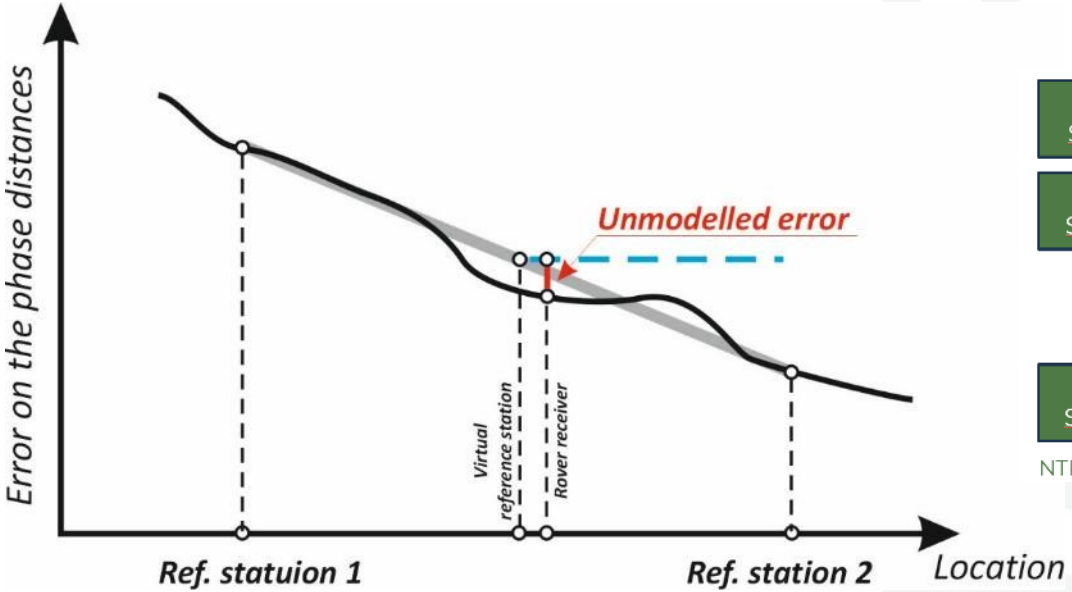


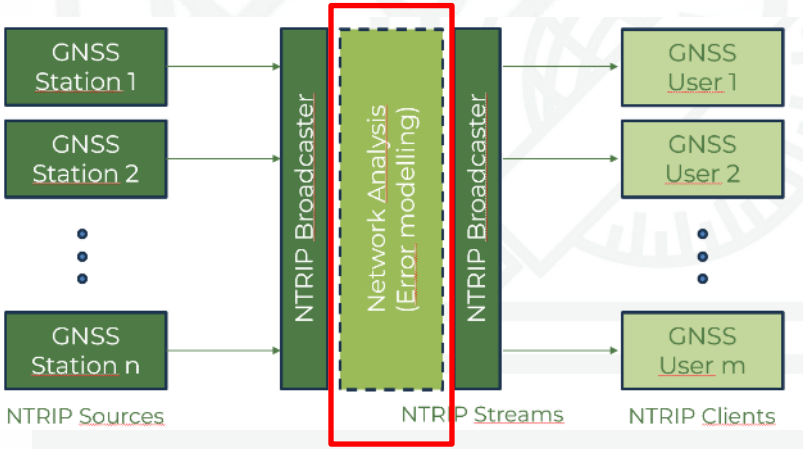
Precipitation radar



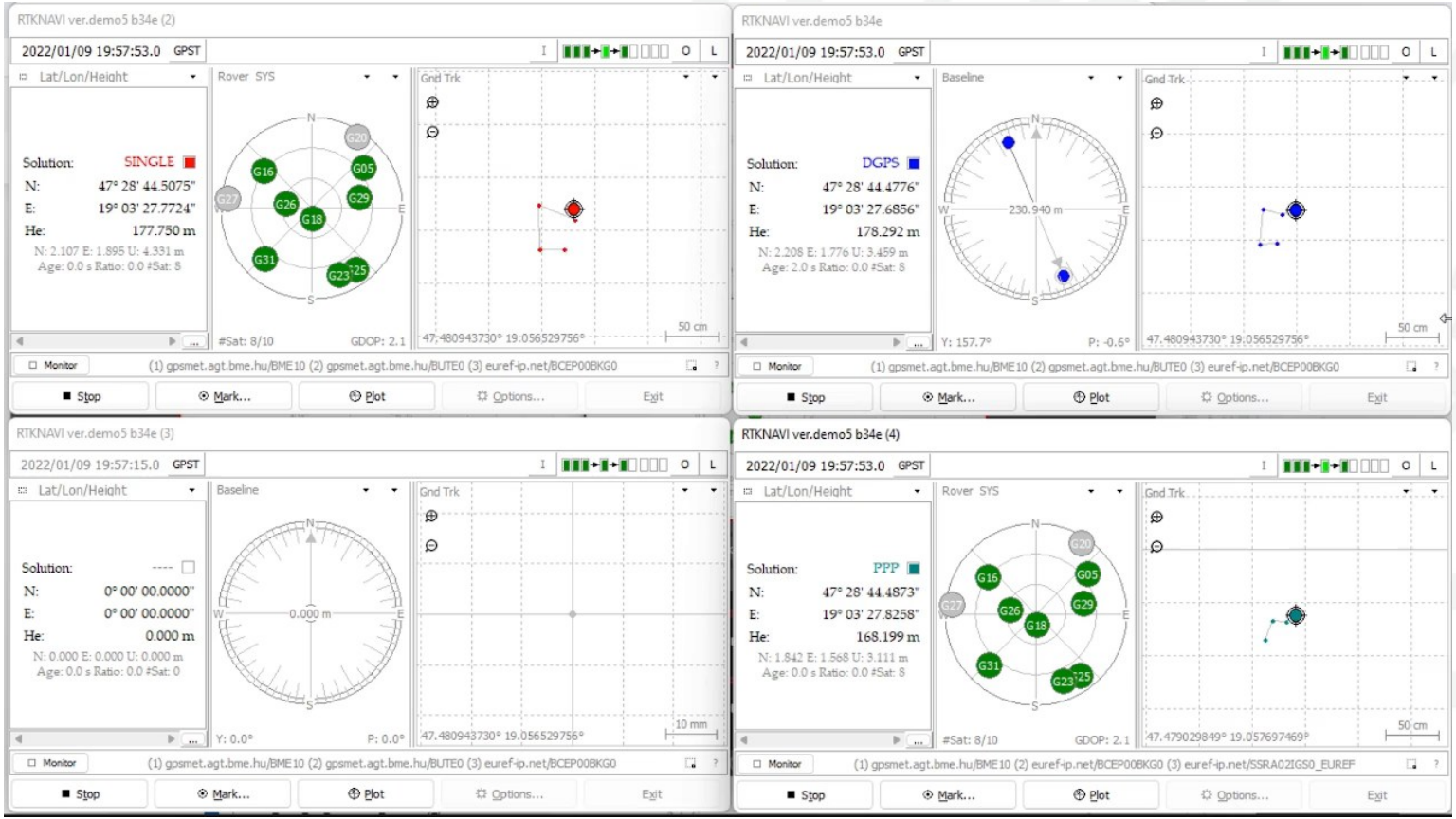
Zenith Tropospheric Delay

Networked Correction Services





Comparison of positioning techniques



Take-away Messages

- Differential corrections are useful for error mitigation and detection but not a universal solution
- Various positioning techniques – various accuracies
- Differential correction services – critical national infrastructure: accuracy - integrity