



DIFFERENTIAL GNSS AND CORRECTION SERVICES

GNSS Under Attack course

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BME



FACULTY OF
CIVIL ENGINEERING

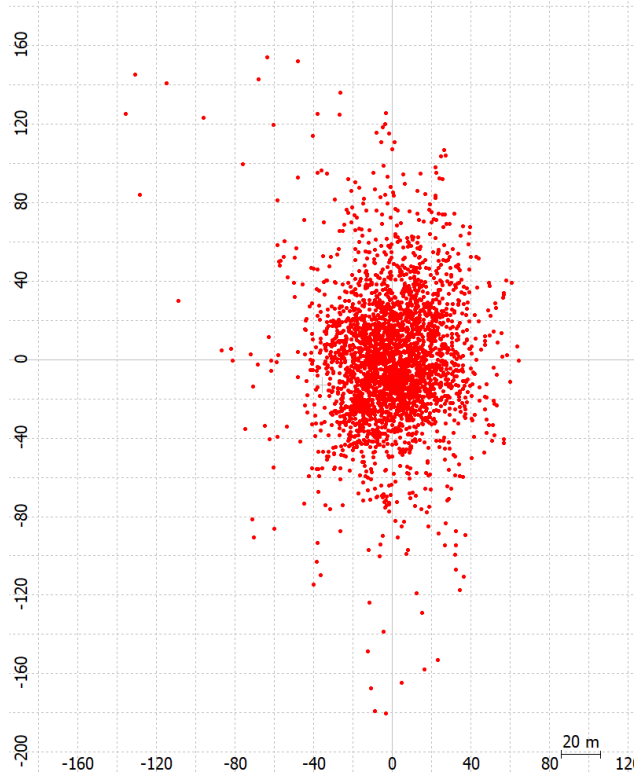


DEPARTMENT OF GEODESY AND
SURVEYING

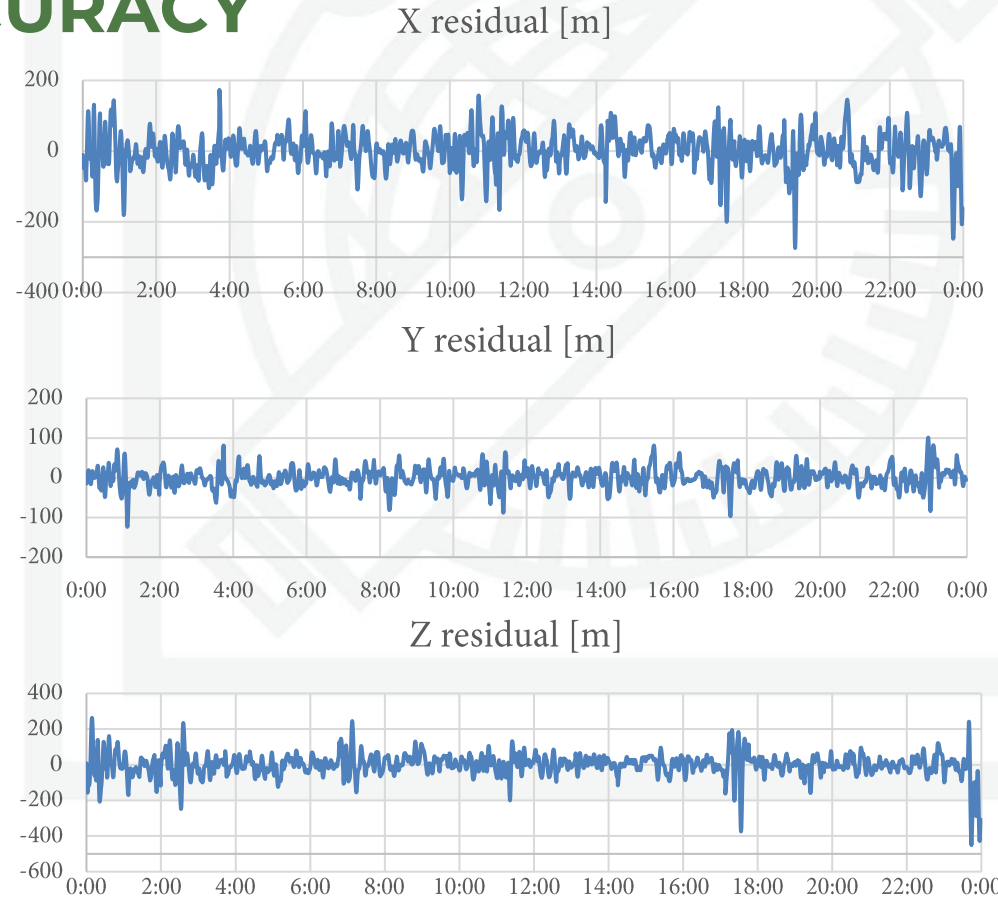
CONTENT

- 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



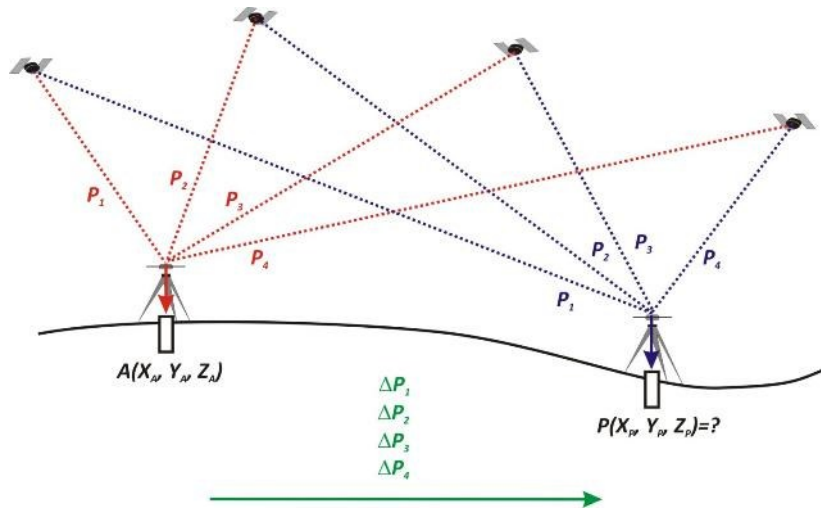
GPS SPP under Selective Availability
(PENC, April 30, 2000)



HANDLING SYSTEMATIC ERROR

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

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



Principle of DGNSS Positioning

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

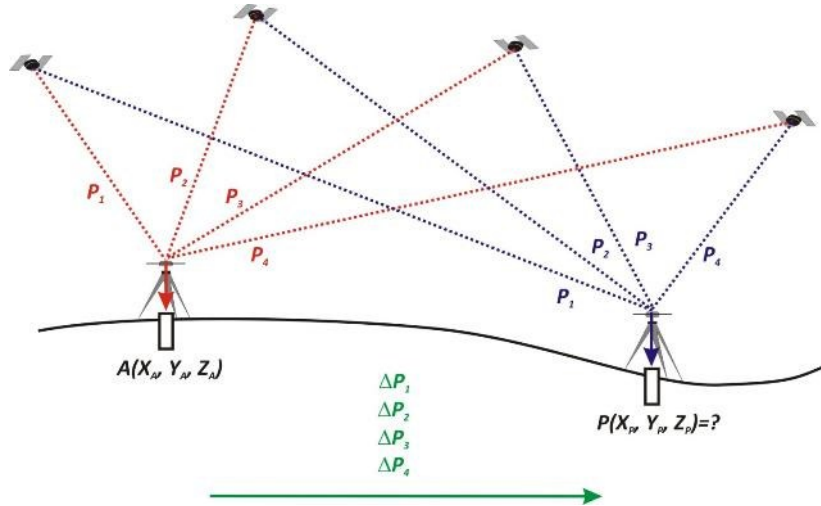
$$\Delta R^S = \rho_A^S - R_A^S = -c\delta^S + c\delta_A - T - I$$



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

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

DIFFERENTIAL GNSS METHOD (DGNSS/DGPS)

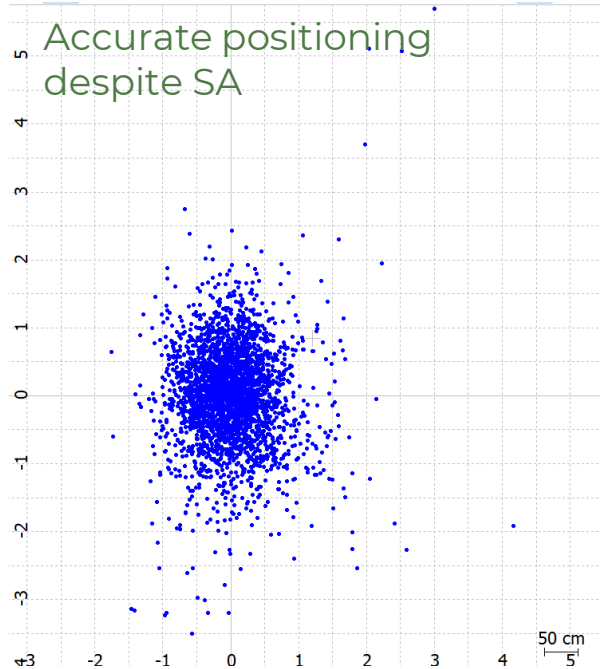


Principle of DGNSS Positioning

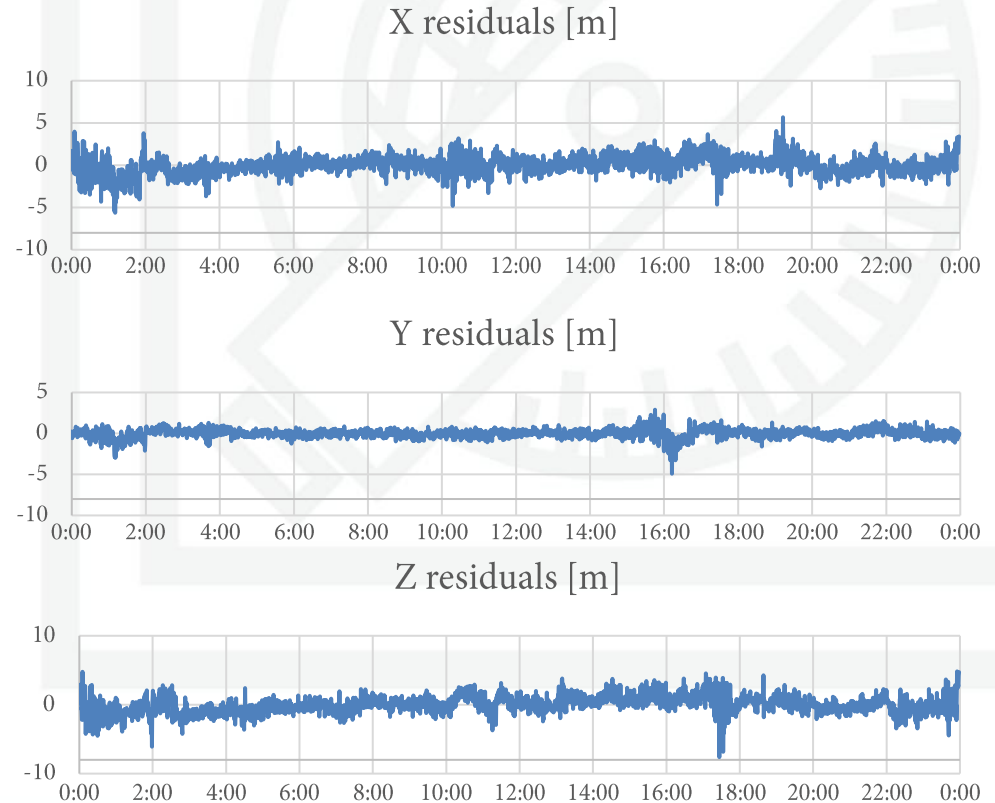
Differential corrections:

- 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)

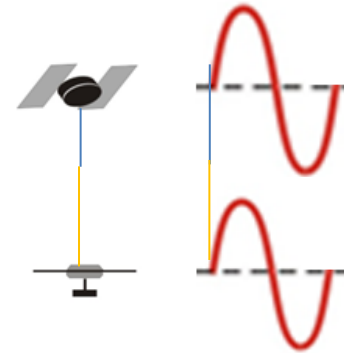
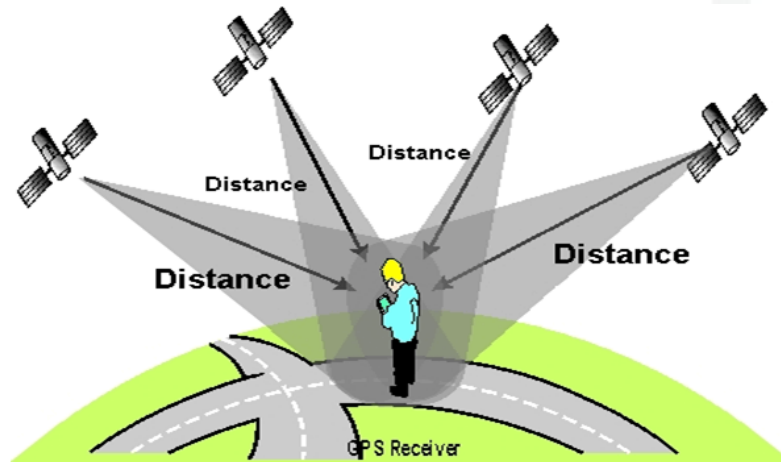


DGPS under Selective Availability
(**GRAZ** -> **PENC**, April 30, 2000)



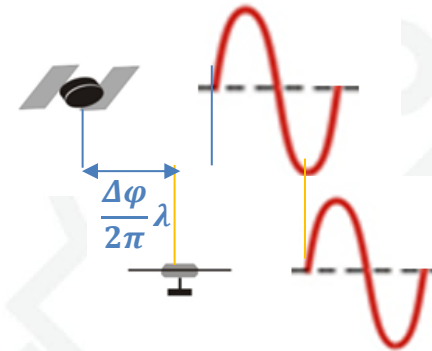
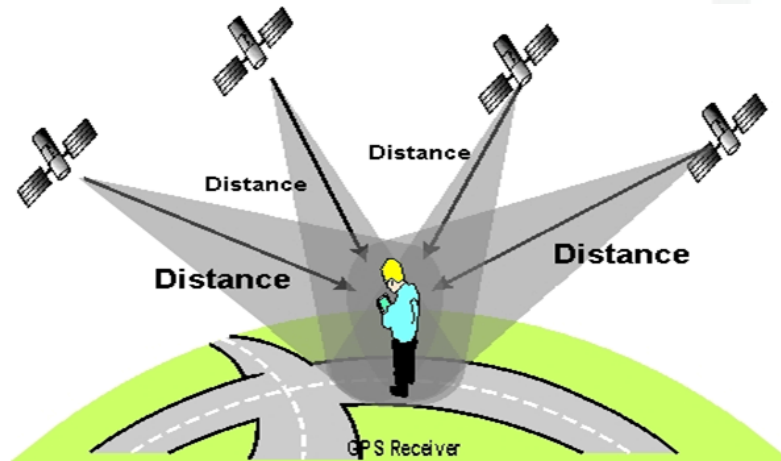
RANGING WITH CARRIER WAVES

Carrier waves → phase ranges



RANGING WITH CARRIER WAVES

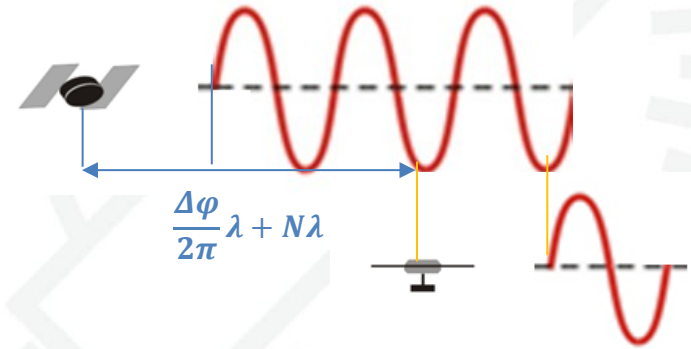
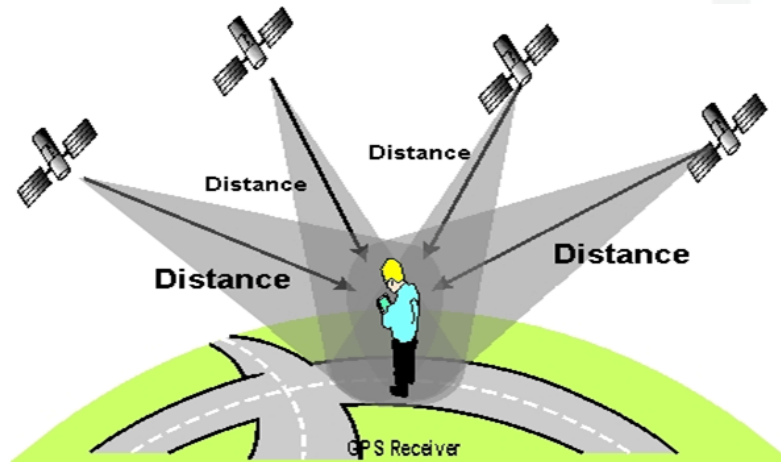
Carrier waves → phase ranges



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:

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

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

δ^S satellite clock bias N phase ambiguity (integer) T troposphere

δ_R receiver clock bias λ wavelength I ionosphere

time dependent

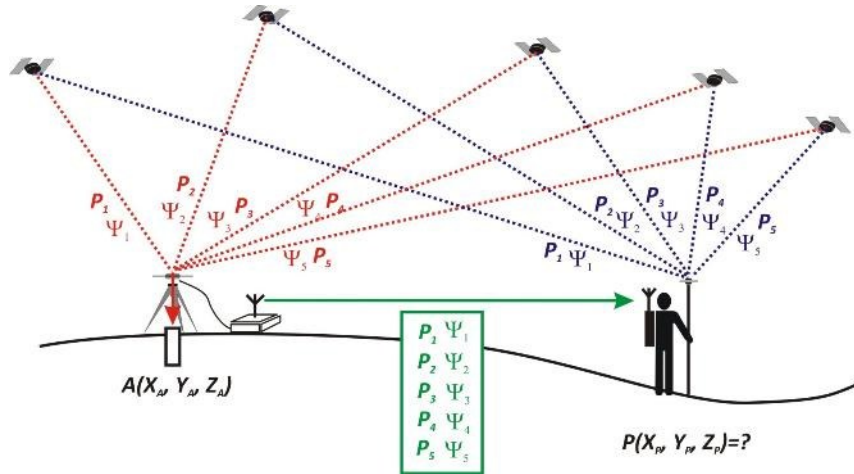
time independent

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):

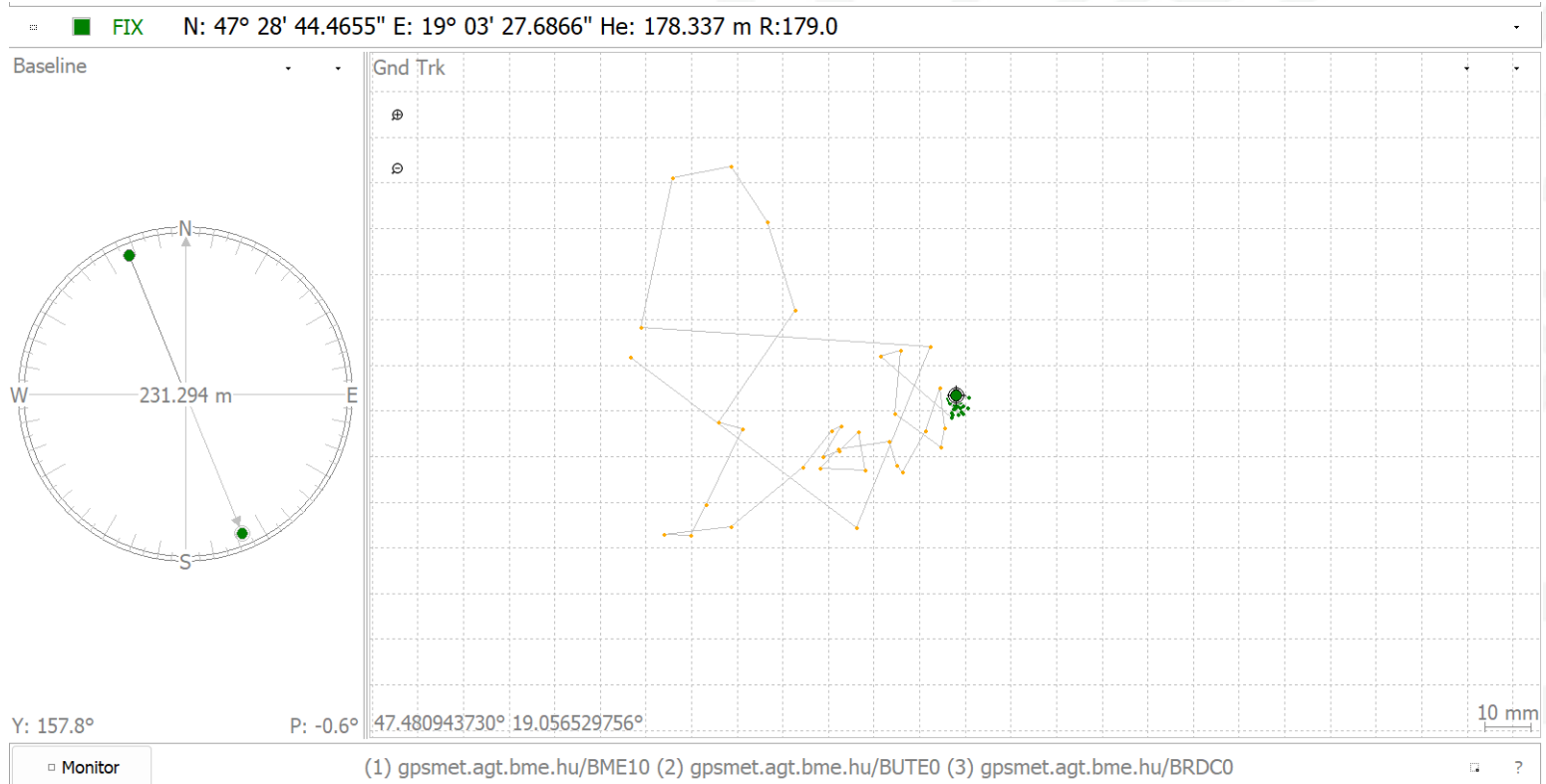
$$\Delta\Delta\Psi_{AP}^{SQ} = \Delta\Psi_{AP}^S - \Delta\Psi_{AP}^Q$$

eliminates receiver clock bias



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

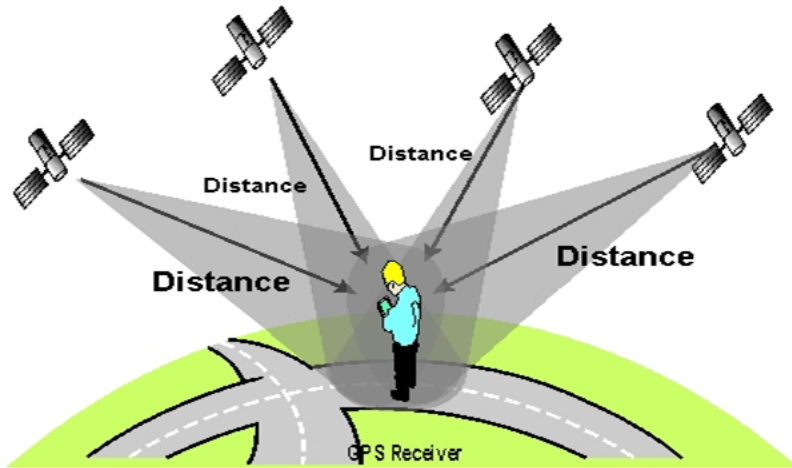
RELATIVE POSITIONING - DIFFERENCING



ANOTHER WAY OF HANDLING SYSTEMATIC ERROR

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

State Space Representation (absolute positioning with corrections):

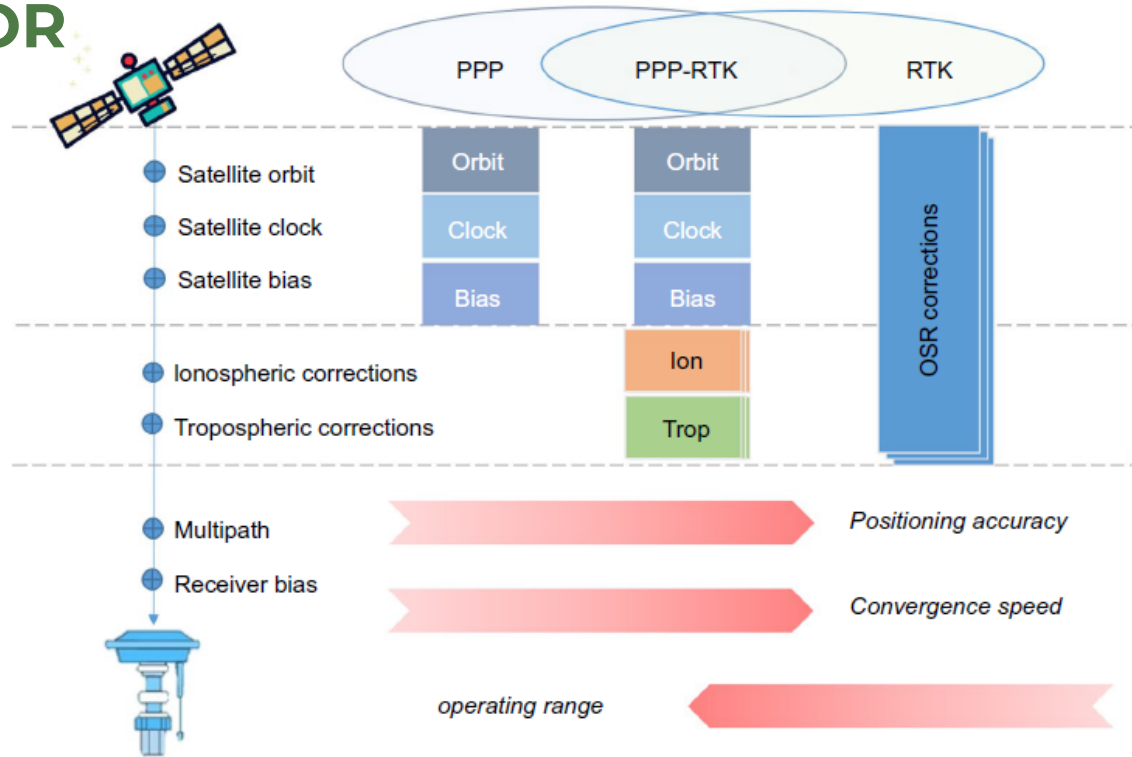


Principle of Absolute Positioning

$$\begin{array}{l} \text{model} \\ \downarrow \\ R_B^S = \rho_B^S + c\delta^S - c\delta_B + T + I \quad \text{SPP} \\ \\ \text{model model} \\ \downarrow \downarrow \\ \Psi_B^S = \rho_B^S + c\delta^S - c\delta_B + \lambda N + T - I \quad \text{PPP} \end{array}$$

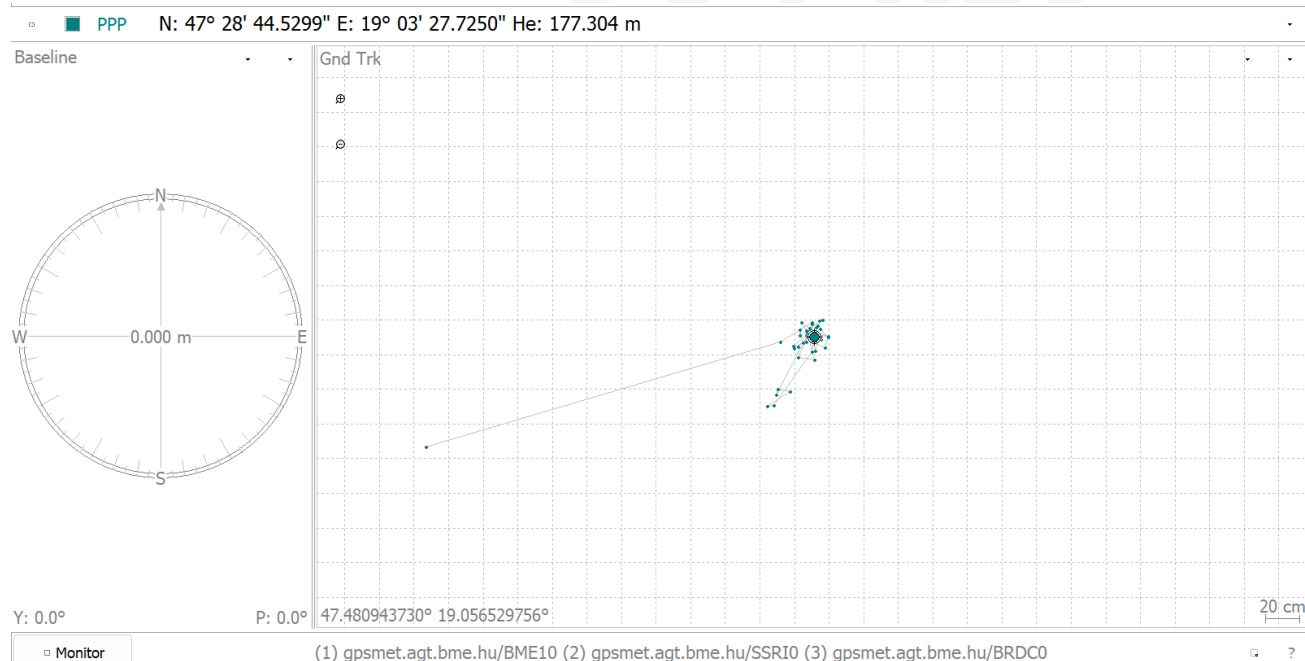
How to derive the models?

ANOTHER WAY OF HANDLING SYSTEMATIC ERROR



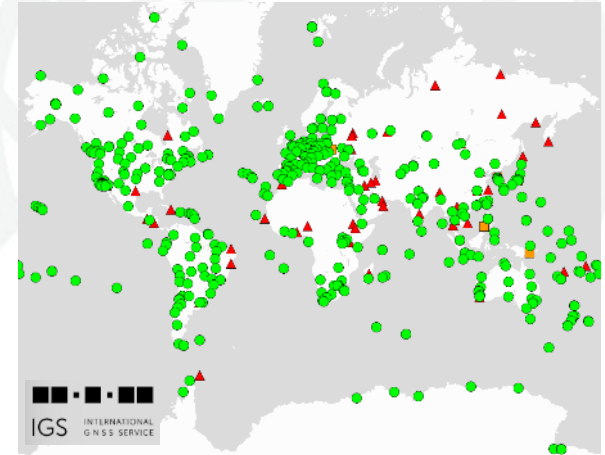
Source Li, X., Huang, J., Li, X. et al. Review of PPP-RTK: achievements, challenges, and opportunities. *Satell Navig* 3, 28 (2022). <https://doi.org/10.1186/s43020-022-00089-9>

ANOTHER WAY OF HANDLING SYSTEMATIC ERROR



How to derive the models?

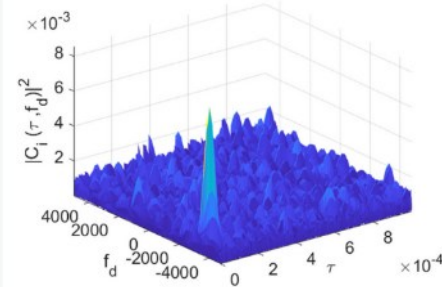
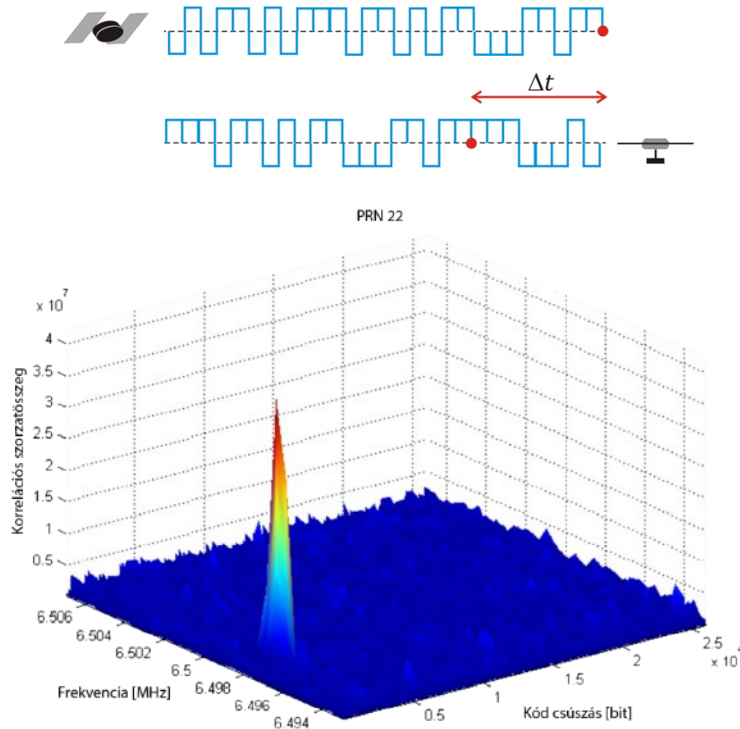
GNSS INFRASTRUCTURE



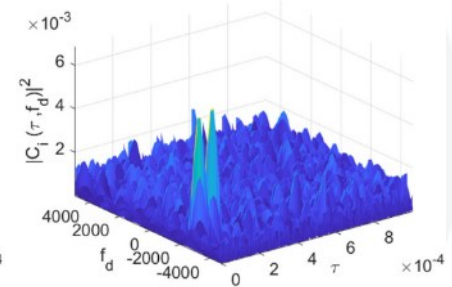
National → Continental → Global



MOTIVATION 2 : RELIABILITY



(a) Legitimate signal, \mathcal{H}_0



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

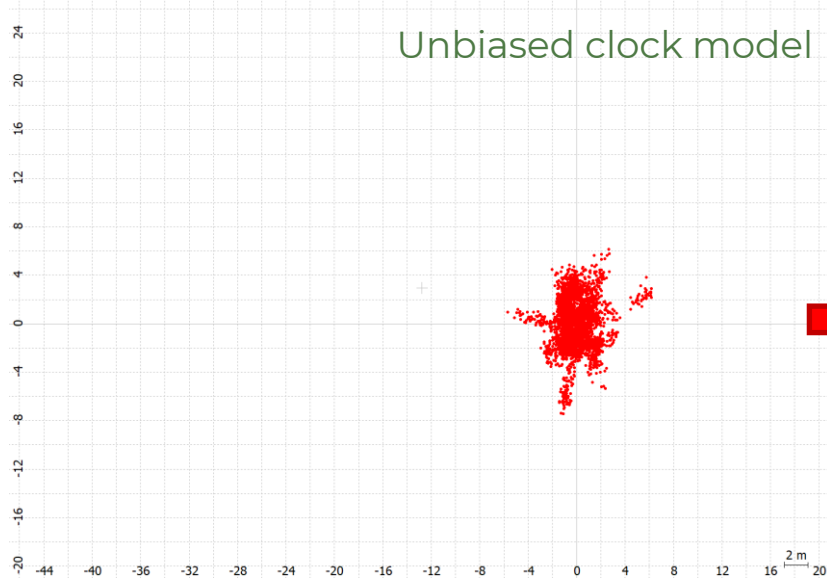
Borhani-Darian, P., Li, H., Wu, P. et al. Detecting GNSS spoofing using deep learning. *EURASIP J. Adv. Signal Process.* **2024**, 14 (2024). <https://doi.org/10.1186/s13634-023-01103-1>

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

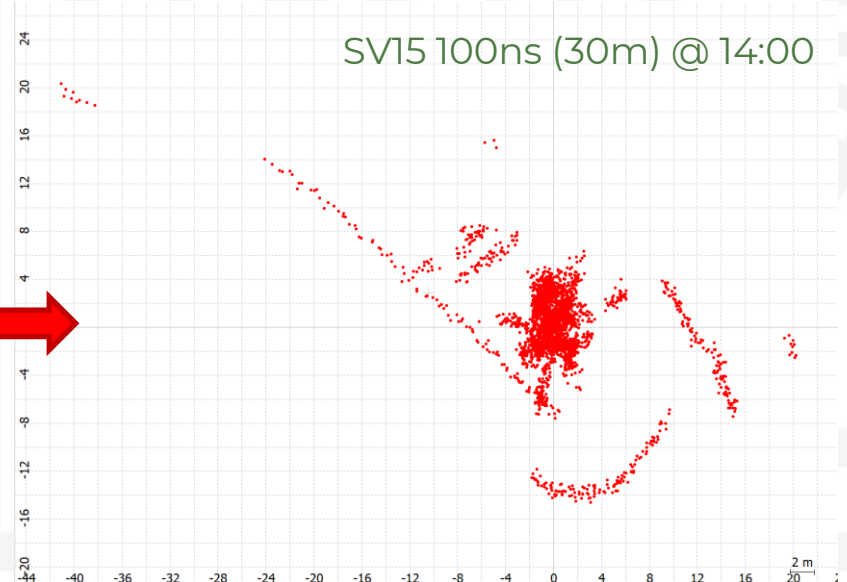
MOTIVATION 2 : RELIABILITY

Example: wrong satellite clock model

Unbiased clock model

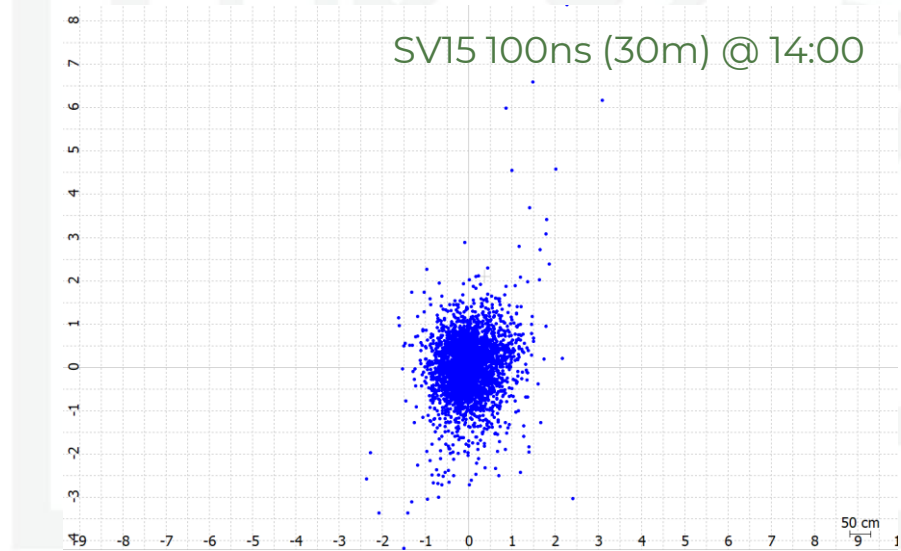
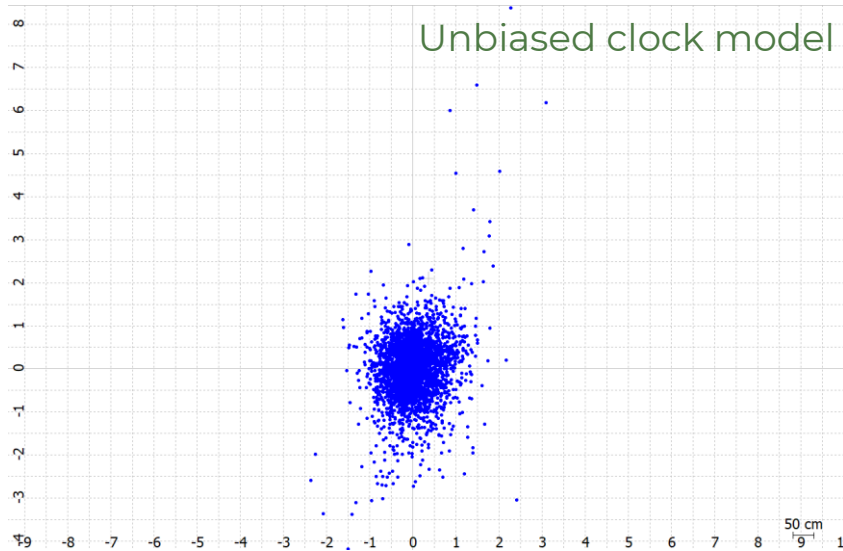


SV15 100ns (30m) @ 14:00



MOTIVATION 2 : RELIABILITY

Example: wrong satellite clock model



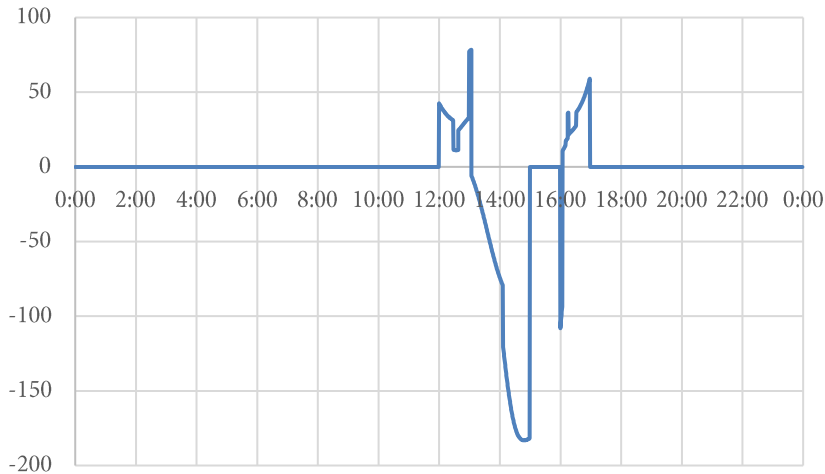
With DGPS corrections (GRAZ → PENC)

MOTIVATION 2 : RELIABILITY

Example: wrong satellite clock model

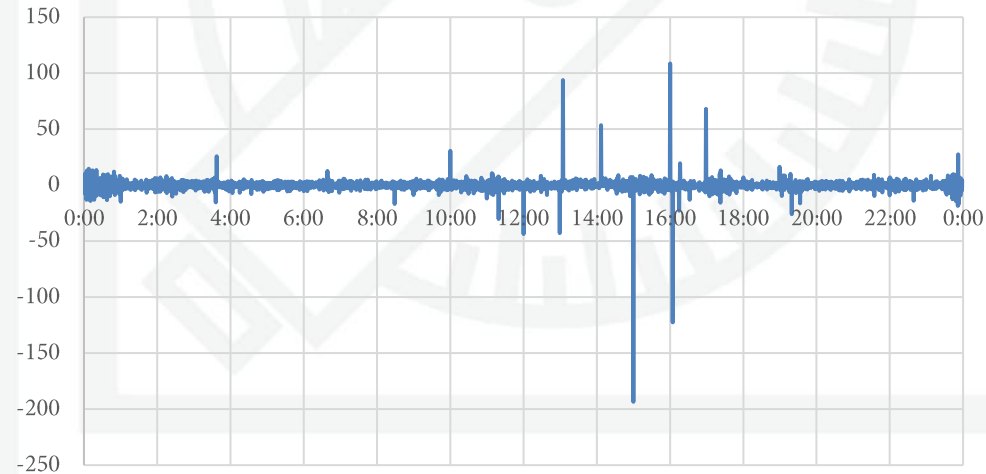
SV15 100ns (30m) @ 14:00

Residual receiver clock error [m]



Without differential correction

Residual receiver clock error [m]

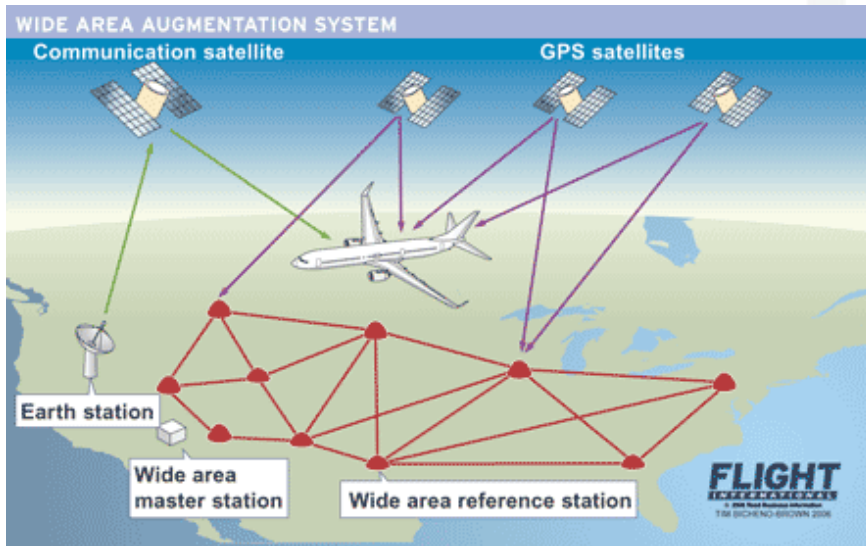


With differential correction

Timing application

MOTIVATION 2 : RELIABILITY

Safety-of-Life applications

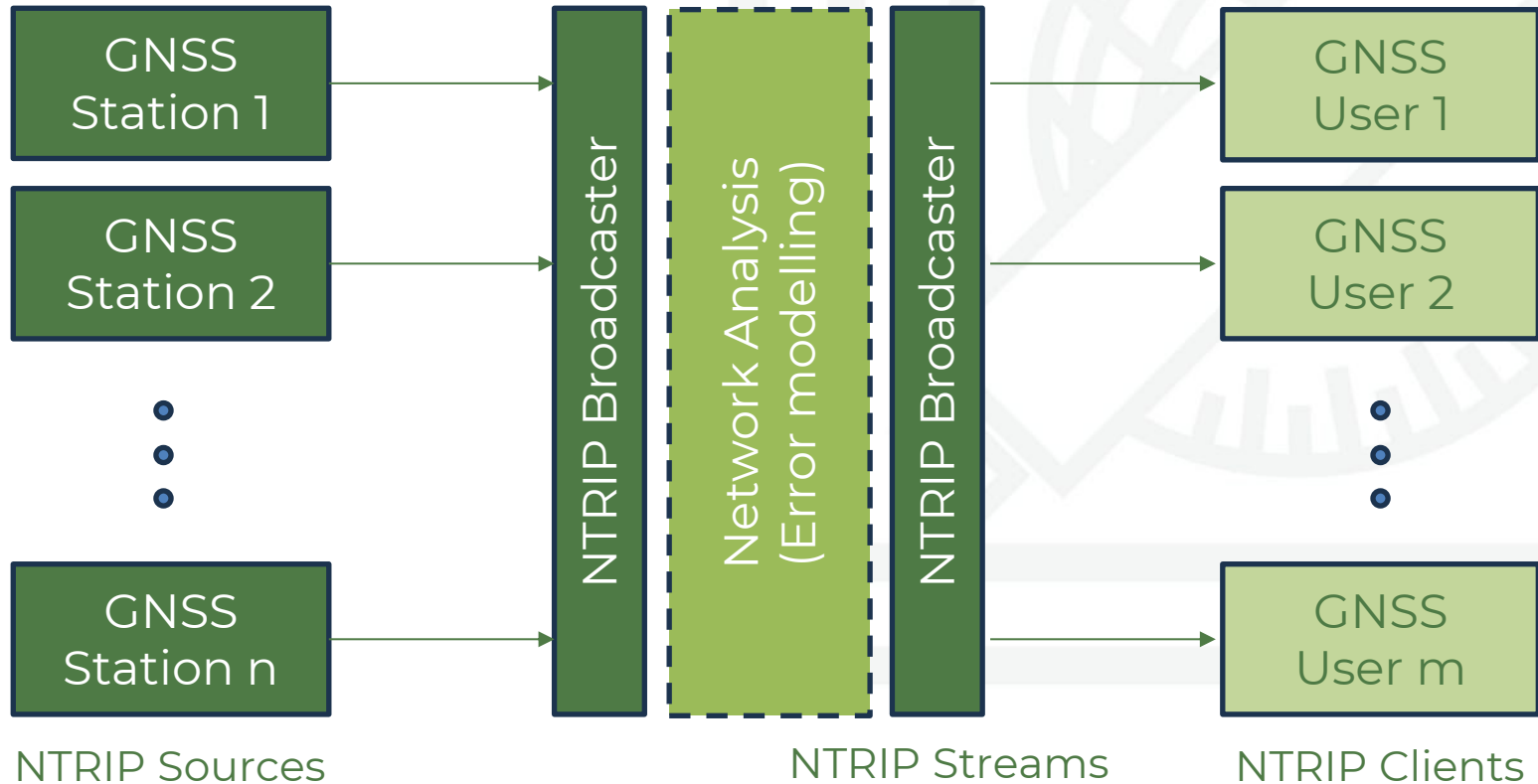


- improved accuracy (error model)
- improved reliability (residual error model, malfunction detection and alerting)

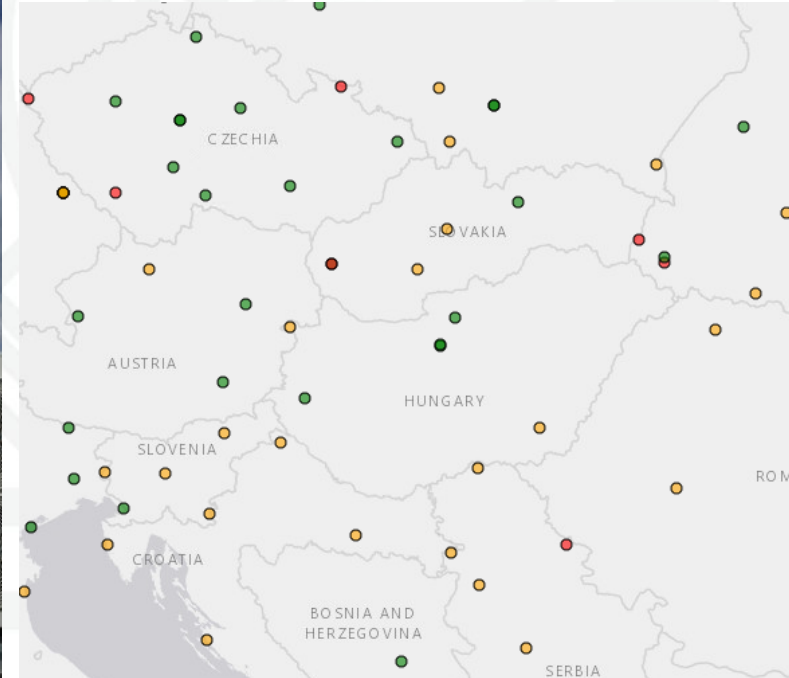
GNSS CORRECTION SERVICES

- 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

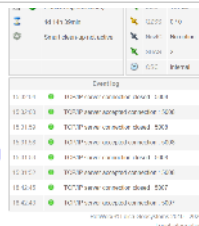
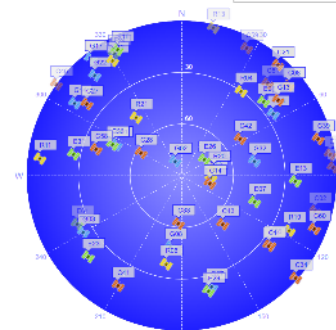
TYPICAL STRUCTURE



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	TCPIP 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 (ZZON1)
●	RTCM 3 x GPS/GLO extended and ephemeris	1 sec	0.21 s	Ntrip server (source): 2101 (ZZON2)
●	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	TCPIP server: 5007

NMEA	Message	Connection: port
No item configured		

BINEX	Message	Connection: port
No item configured		



Mountpoint Id	Host	Source Agent	Time of contact	IP	Clients	KBytes read	KBytes written	Client connections	Connected for
/BME11	6	152.66.5.195	NTRIP NtripServerCMD1.0.0	02/Dec/2025:12:38:26	152.66.5.195	0	19756636	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	152.66.6.49	0	3062587	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	22 days, 16 hours, 16 minutes and 31 seconds
/BUTE1	30110	152.66.6.49	NTRIP Leica Viva	13/Jan/2026:03:25:09	152.66.6.49	0	689543	0	22 days, 16 hours, 16 minutes and 30 seconds
/BUTE1	31296	152.66.5.195	NTRIP NtripServerPOSIX1.5.1	13/Jan/2026:03:25:19	152.66.6.49	1	3702818	3760092	22 days, 16 hours, 16 minutes and 20 seconds
/BME10	31296	152.66.5.195	NTRIP NtripServerPOSIX1.5.1	28/Jan/2026:09:11:06	152.66.5.195	2	659797	1316075	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	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	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	4 days, 0 hours, 36 minutes and 41 seconds
/UBASE2	31767	151.0.80.190	NTRIP RTKLIB/dcm05_b34i	31/Jan/2026:19:05:17	151.0.80.190	0	570556	22	4 days, 0 hours, 36 minutes and 22 seconds
/BRDC0	31775	157.90.249.44	NTRIP Caster2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	813206	0	4 days, 0 hours, 34 minutes and 32 seconds
/SSRU1	31776	157.90.249.44	NTRIP Caster2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	136616	0	4 days, 0 hours, 34 minutes and 32 seconds
/SSRU0	31777	157.90.249.44	NTRIP Caster2.0.21 (relay)	31/Jan/2026:19:07:07	157.90.249.44	0	206984	0	4 days, 0 hours, 34 minutes and 32 seconds
/BME10	31296	152.66.5.195	NTRIP NtripServerPOSIX1.5.1	28/Jan/2026:09:11:06	152.66.5.195	2	659797	1316075	2 days, 8 hours, 22 minutes and 4

ZZON NTRIP Source

NTRIP Broadcaster
@ BME DGS

EXAMPLE – STANDALONE CORRECTION SERVICE

Mountpoint Id	Host	Source Agent	Time of connect	IP	Clients	KBytes read	KBytes written	Client connections	Connected for
DBME11	6	152.66.5.193	NTRIP StripServerCMD1.0.0	02/Dec/2025:12:38:26	152.66.5.193	0	19758636	0	61 days, 7 hours, 3 minutes and 12 seconds
DBUTE2	30108	152.66.5.193	NTRIP Leica Viva	13/Jan/2026:03:25:06	152.66.6.18	0	2062587	0	22 days, 16 hours, 15 minutes and 23 seconds
DGNSS	30108	152.66.5.193	NTRIP Leica Viva	13/Jan/2026:03:25:06	152.66.6.18	0	1306189	23	1 22 days, 16 hours, 15 minutes and 21 seconds
DBUTE1	30110	152.66.5.193	NTRIP Leica Viva	13/Jan/2026:03:25:08	152.66.6.18	0	689513	0	22 days, 16 hours, 15 minutes and 20 seconds
DBUTE9	30112	152.66.5.193	NTRIP Leica Viva	13/Jan/2026:03:25:15	152.66.6.18	1	3702818	3760092	13 22 days, 16 hours, 15 minutes and 20 seconds
DBME10	31296	152.66.5.193	NTRIP StripServerCMD1.0.0	28/Jan/2026:09:11:06	152.66.5.193	2	659797	1316075	10 7 days, 16 hours, 30 minutes and 23 seconds
ZZCON0	31763	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:09:58	84.1.97.62	2	605814	1232894	43 1 days, 6 hours, 26 minutes and 41 seconds
ZZCON1	31761	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:09:58	84.1.97.62	0	120773	211	7 1 days, 6 hours, 26 minutes and 41 seconds
ZZCON2	31763	84.1.97.62	NTRIP Leica Viva	31/Jan/2026:19:09:58	84.1.97.62	0	501075	90806	29 1 days, 6 hours, 26 minutes and 41 seconds
DBNBS2	31767	157.90.249.14	NTRIP Casco2.0.21 (delay)	31/Jan/2026:19:07:07	157.90.249.14	0	813206	0	0 1 days, 6 hours, 24 minutes and 32 seconds
DBRDC0	31775	157.90.249.14	NTRIP Casco2.0.21 (delay)	31/Jan/2026:19:07:07	157.90.249.14	0	135616	0	0 1 days, 6 hours, 24 minutes and 32 seconds
SSRI1	31776	157.90.249.14	NTRIP Casco2.0.21 (delay)	31/Jan/2026:19:07:07	157.90.249.14	0	206984	0	0 1 days, 6 hours, 24 minutes and 32 seconds
SSRI2	31777	157.90.249.14	NTRIP Casco2.0.21 (delay)	31/Jan/2026:19:07:07	157.90.249.14	0	206984	0	0 1 days, 6 hours, 24 minutes and 32 seconds
DBNBS1	31778	157.90.249.14	NTRIP Casco2.0.21 (delay)	31/Jan/2026:19:07:07	157.90.249.14	0	206984	0	0 2 days, 8 hours, 22 minutes and 41 seconds

NTRIP Broadcaster
@ BME DGS

Serial Port Debug 4.0(20140103) DecoderGNSS 03.03.20140102.20140103

Type: Ntrip Client
IP: 152.66.5.152
PORT: 2101
Close Port
Send
File
Clear
Save
Break

SSRI1
BUTE0
BUTE1
BUTE2
ZZON0
ZZON1
ZZON2
PKS20
PKS21
PKS22
DGNSS
UBASE2

20 47 114.42
GGA List Stream

33.3030.06000,N,11425.68000,E,1.09,1.0,0.00,M,0.0,M,0.0,*78

Hex Cmd checksum Hex Text

Auto Send
1000 ms
Display Error
Data Parse
Enter/Newline
Text

G22 24733405.622 129974917.875 1802240 40.1 -475.611 24733404.488 101279151.520 18
G27 24071229.170 126495284.795 20447232 41.9 3823.470 24071230.467 98567826.973 20
G28 25837445.977 135776702.931 120832 34.5 -2898.602 25837446.274 105800026.038 9
G32 21886615.509 115014963.663 8257536 52.8 726.733 21886615.523 89622062.193 82
RTCM3 1087 0100 03 82029.000 SatelliteNum=08 SignalNum=03 GLO[L1C L2C L2P] contain obs
R04 22019343.831 117912656.116 13369344 44.1 3754.909 22019343.850 91709861.327 12
R05 19348267.658 103427660.722 9437184 54.6 443.260 19348268.506 80443771.547 94
R06 20782585.661 110899941.582 4718592 51.5 -3454.047 20782588.122 86255544.788 47
R11 24235188.615 129505441.025 10485760 36.7 3333.992 24235191.850 100726447.018 11
R12 23473127.423 125389241.221 4587520 41.8 728.894 23473130.017 97524967.433 41

pseudoranges

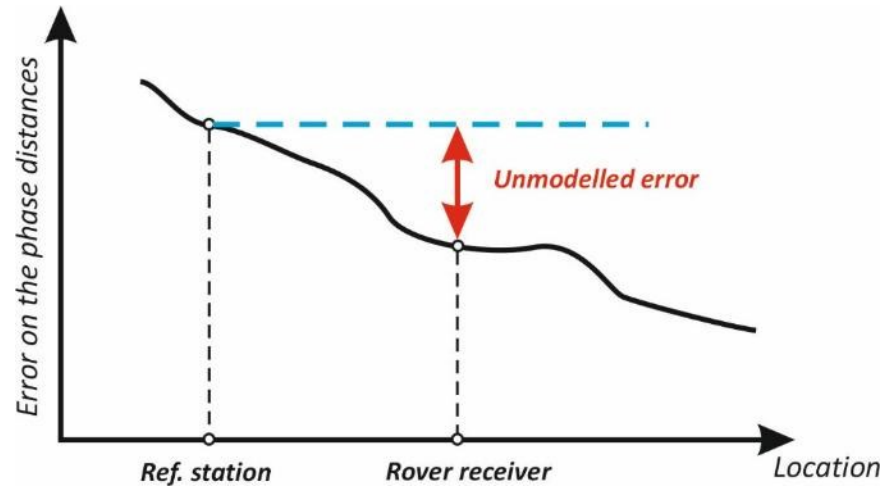
phase ranges

NTRIP Client

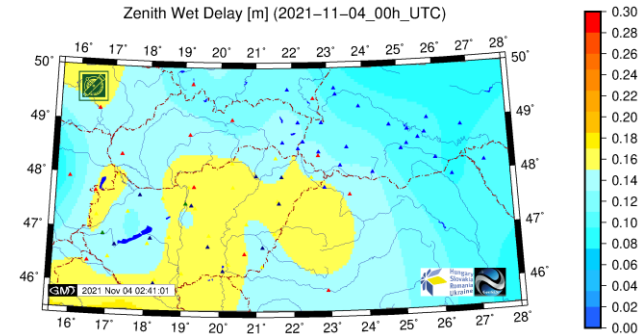
FORMAT: presentation tomorrow

STANDALONE CORRECTION SERVICE

Limitation of standalone correction services:

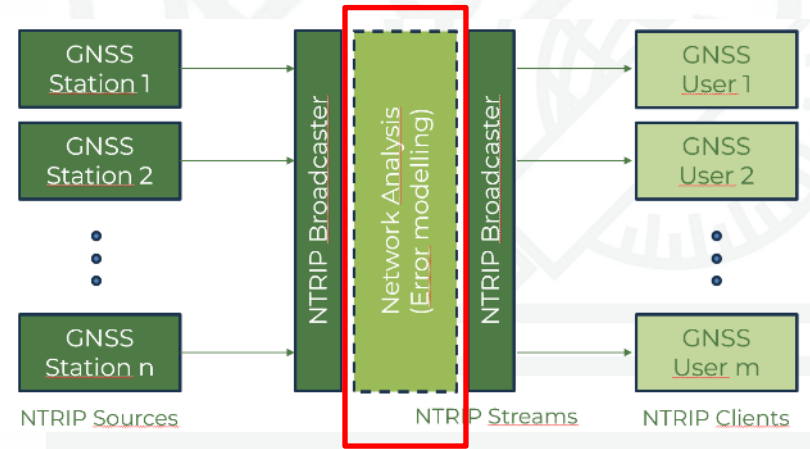
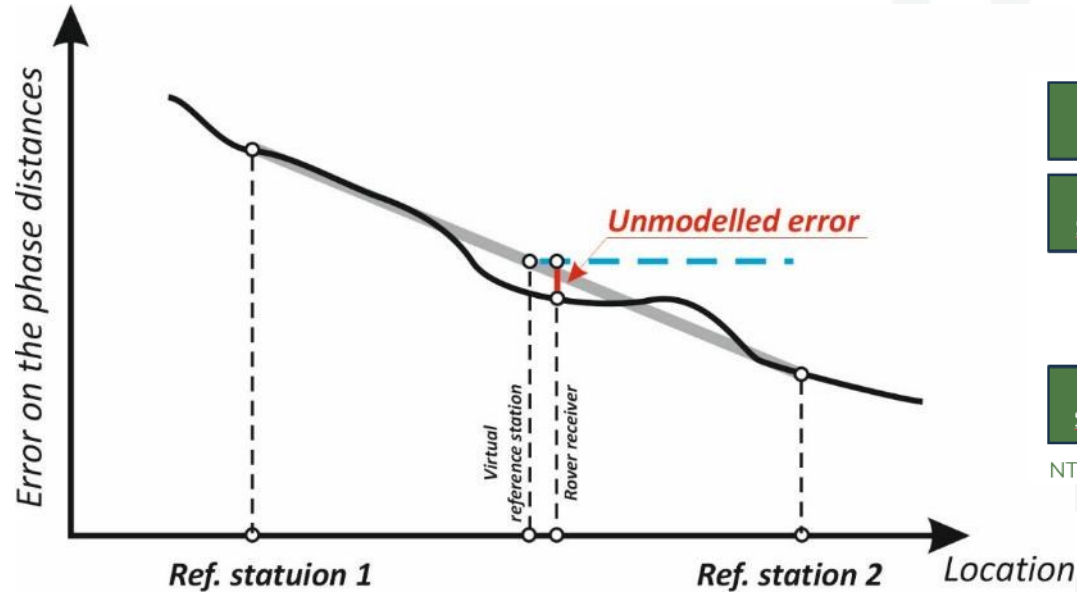


Precipitation radar

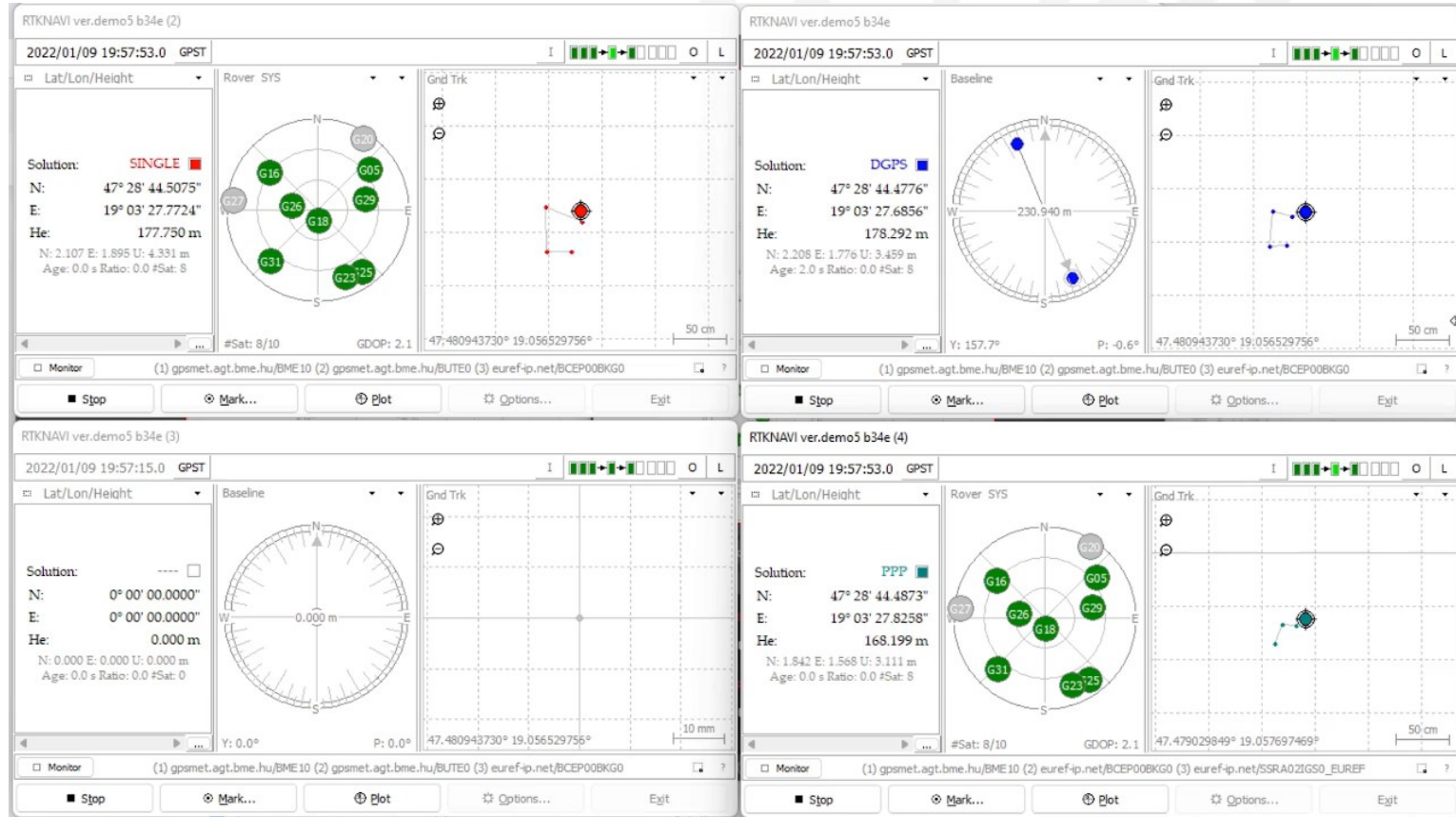


Zenith Tropospheric Delay

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