Experience from inclusion of GLONASS into Precise Point Positioning algorithms

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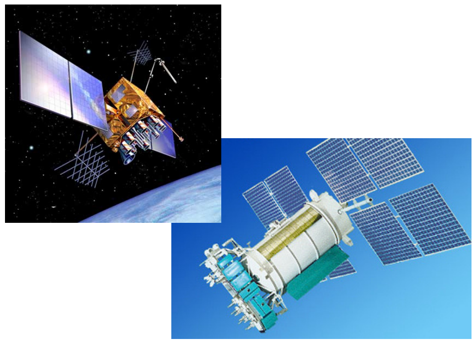

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Outline

- The Precise Point Positioning (PPP) technique using the un-differenced GPS observations and the precise IGS orbits and satellite clock products is nowadays a frequently used approach for geocentric coordinate determination without using reference stations.
- Recently for the PPP are predominantly used the GPS observations, mainly due to fact, that for the other GNSS the precise satellite clocks were not generally available and due to GLONASS incomplete error modeling.
- The ESOC GLONASS Data Analysis Centre besides the GLONASS orbits provides regularly also the GLONASS satellite clocks estimates in 5-minute intervals.
- We will examine the model for computing real-valued ambiguities from code and phase GPS and GLONASS un-differenced observations, the procedures for reduction of observed GPS and GLONASS ranges, and finally the individual GNSS solutions and well as the combination of GLONASS and GPS un-differenced data.
- All the procedures are demonstrated by using the software package ABSOLUTE which is developed for the PPP GNSS processing at the Slovak University of Technology in Bratislava.

Content

- Basic information about PPP analysis in post-processing mode
- Applied modeling of GNSS range corrections
- Differences in PPP processing of GPS and GLONASS
- Results of individual and combined GNSS PPP
- Perspectives

Principles of PPP based on double frequency code and phase observables

Combination of code R and phase Ψ undifferenced GNSS observations

$$R_A^j(t) = \rho_A^j(t) + c\left[\delta^j(t) - \delta_A(t)\right] + I_A^j(t)$$
$$\lambda \Psi_A^j(t) = \rho_A^j(t) + c\left[\delta^j(t) - \delta_A(t)\right] + \lambda N_A^j - I_A^j(t)$$

- Continuos tracking of satellite j allows to obtain ionofree pseudoranges at centimeter level.

$$P_A^j(t) = \rho_A^j(t) + c\left[\delta^j(t) - \delta_A(t)\right]$$

Linearized observation equation

$$\Delta P_A^j(t) = P_A^j(t) - \rho_{A0}^j(t) - c\delta^j(t) = a_{XA}^j \Delta X_A(t) + a_{YA}^j \Delta Y_A(t) + a_{ZA}^j \Delta Z_A(t) - c\delta_A(t) + \varepsilon_A^j$$

- Precise orbits and satellite clocks produced by IGS analysis centers (or their combination) have to be used.
- Parameters to be estimated: static site coordinates and receiver clock corrections estimated for every observation epoch.

Model corrections necessary to obtain subcentimeter range accuracy

- Pseudoranges inferred from combination of double frequency code and phase observations have to corrected for all effects influencing the instantaneous satellite – receiver distance at millimeter level (Zumberge et al., 1997, Kouba et al., 2001).
- Majority of such effects is eliminated when double difference are applied in relative positioning mode.
- Ionosphere effects were eliminated in *P* due to double frequency combination

$$\begin{aligned}\Delta P_A^j(t) &= P_A^j(t) - \rho_{A0}^j(t) - c\delta^j(t) + \Delta\rho_{Exc}^j + \Delta\rho_{Cod}^j + \Delta\rho_{Win}^j(t) + \\ &\quad + \Delta\rho_{Rel}^j(t) + \Delta\rho_{Sag}^j(t) + \Delta\rho_{Tid}^j(t) + \Delta\rho_{Tro}^j(t) + \Delta\rho_{Dpm}^j(t) \\ &= a_{XA}^j \Delta X_A(t) + a_{YA}^j \Delta Y_A(t) + a_{ZA}^j \Delta Z_A(t) - c\delta_A(t) + \varepsilon_A^j\end{aligned}$$

Model corrections necessary to obtain subcentimeter range accuracy

- *Ecc* – satellite antenna offsets
- *Cod* – satellite and receiver code biases
- *Win* – phase wind-up effect
- *Rel* – special relativity corrections
- *Sag* – correction of the Sagnac effect due to Earth rotation
- *Tid* – solid Earth tidal effects and ocean loading
- *Tro* – dry and wet components of troposphere delay
- *Dpm* – effect of diurnal polar motion and earth rotation variation

$$
\begin{aligned}
\Delta P_A^j(t) = P_A^j(t) - \rho_{A0}^j(t) - c\delta^j(t) + \Delta\rho_{Exc}^j + \Delta\rho_{Cod}^j + \Delta\rho_{Win}^j(t) + \\
+ \Delta\rho_{Rel}^j(t) + \Delta\rho_{Sag}^j(t) + \Delta\rho_{Tid}^j(t) + \Delta\rho_{Tro}^j(t) + \Delta\rho_{Dpm}^j(t) \\
= a_{XA}^j \Delta X_A(t) + a_{YA}^j \Delta Y_A(t) + a_{ZA}^j \Delta Z_A(t) - c\delta_A(t) + \varepsilon_A^j
\end{aligned}
$$

Processing algorithm

- Assembling of necessary input data – RINEX observations, satellite orbits and clocks, differential code biases, satellite and receiver antenna parameters.
- Cycle slip detection, resolution of real valued ambiguities, phase and code ionofree pseudorange evaluation.
- Precise satellite orbits and clock interpolation using Lagrange polynomials.
- Application of range corrections using modeled biases, o-c values computations.
- Parameter estimation using least-square approach in first approximation individually for each observation epoch.
- Second approximation of epoch adjustments and unique adjustment for all available epochs.
- The final adjustment using code and phase data. The estimated parameters include site coordinates, receiver clocks, ambiguity improvements, troposphere delays and other relevant parameters.

Preprocessing of observed code and phase observations, ambiguity estimation

- The preprocessing model depends on availability of observation data – C/A, P1, P2, L2C code, L1 and L2 phase observables.
- System of equations for P1, P2, L1 and L2 :

$$\begin{bmatrix} R_1 - \Delta R_1^{sat} - \Delta R_1^{rec} \\ R_2 - \Delta R_2^{sat} - \Delta R_2^{rec} \\ \lambda_1 \Psi_1 \\ \lambda_2 \Psi_2 \end{bmatrix}_{GNSS} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & \alpha_f & 1 \\ 1 & 0 & -1 & 1 \\ 0 & 1 & -\alpha_f & 1 \end{bmatrix} \begin{bmatrix} \lambda_1 N_1 \\ \lambda_2 N_2 \\ I_P \\ P \end{bmatrix}_{GNSS}$$

- Parameters solved – initial real valued ambiguities N1 and N2, epoch ionofree pseudoranges *P* and ionosphere effect Ip
- Such system is solved for each sufficiently long continuous interval of GPS and GLONASS satellite tracking.
- The satellite and receiver code biases *ΔR* are generally not available, some of them are known in form of their differences (DCB) or they have to be partly estimated in further analysis.

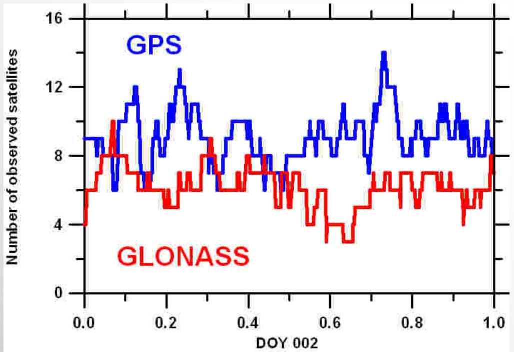
Some differences in GPS and GLONASS PPP analysis

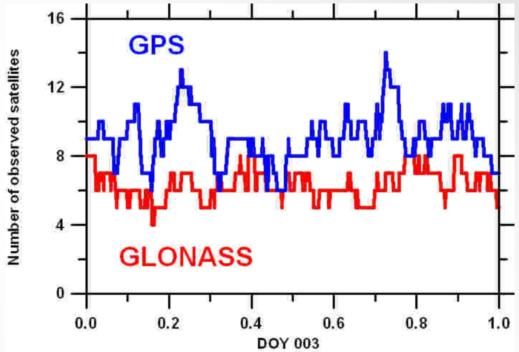
- Different orbits: GPS a=26 560 km, P=11h 58m, i=55 deg, GLONASS: a=25 510 km, P=11h 16m, i=65 deg.
- Configuration repeatability: GPS 23h 56m, GLONASS 8 sidereal days.
- Available number of operational satellites (January 2010) GPS – 30, GLONASS - 16
- Different code modulations – CDMA for GPS and FDMA for GLONASS, different receiver code biases – unknown inter-channel biases.
- Availability P1 for all GLONASS satellites, availability of L2C for new generation of GPS satellites.
- Code observations from GPS receivers used in this study (Trimble NetR5 and NetR8) – GPS: C1 + P2 + L2C, GLONASS: C1+P1+P2
- Precise GPS and GLONASS orbits and satellite clocks in 15 min intervals are produced by more IGS ACs, GLONASS clocks in 5 min intervals are available from ESOC AC Darmstadt.

Demonstration of PPP using GPS and GLONASS – EPN stations MOP2 and GANP

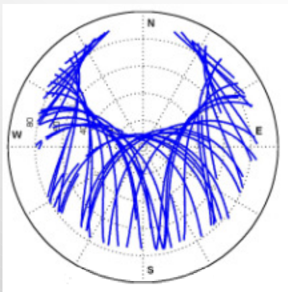
- Post-processing of 24-hour static observations: MOP2 – receiver Trimble NetR5, antenna TRM55971.00 with TZGD radome, GANP – receiver Trimble NetR8, antenna TRM55971.00
- Used code observations: GPS - C1 and P2, GLONASS - P1 and P2
- The GLONASS satellite configurations usually allows positioning (at least 4 satellites) during whole 24 h interval, however some short gaps may occur.

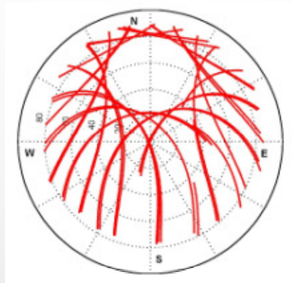
Satellite availability at MOP2 – DOY 002 and 003 of 2010





- Sky plot during 24 h session – GPS and GLONASS satellites

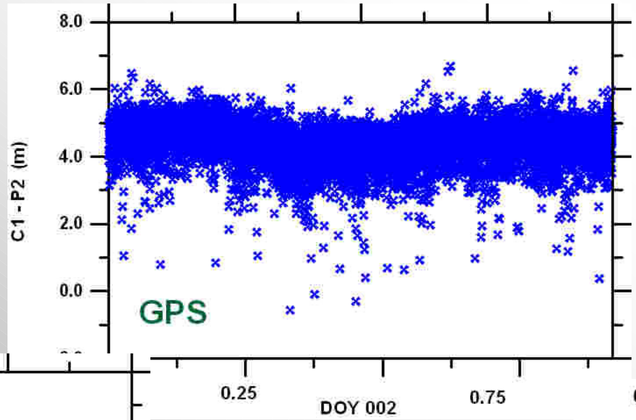


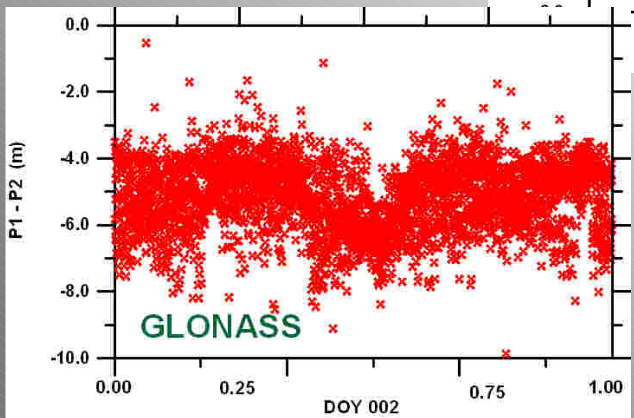


Demonstration of PPP using GPS and GLONASS – effect of inter-channel biases

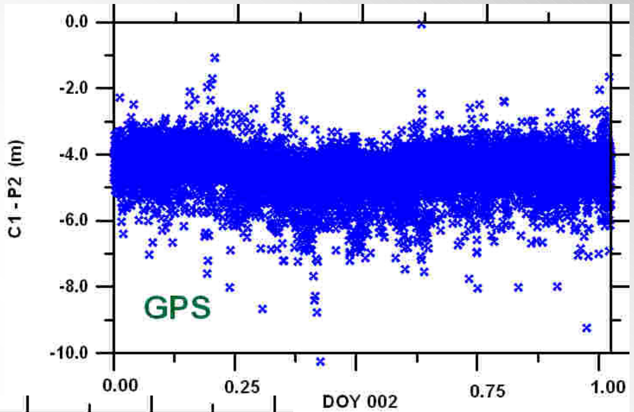
- Differences between C1 and P2 codes (GPS) and P1 and P2 codes (GLONASS)
- Scatter of data is due to ionosphere, varying satellite elevation, and satellite and receiver DCBs.
- The GPS and GLONASS code differences are significantly biased at MOP2 due to receiver inter-channel bieses (not so visible at GANP). GLONASS is more dispersed than GPS.
- The pattern of GLONASS P1-P2 is similar at MOP2 and GANP.

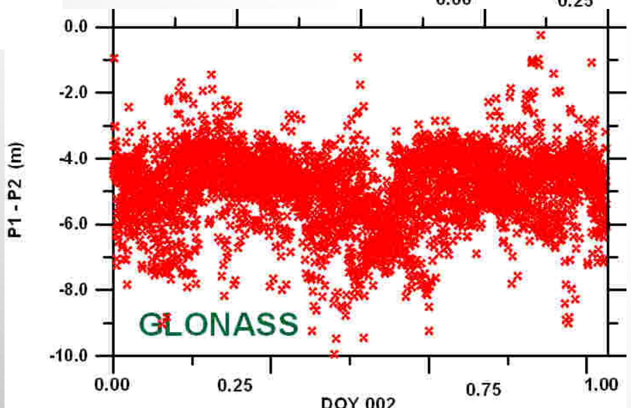
MOP2





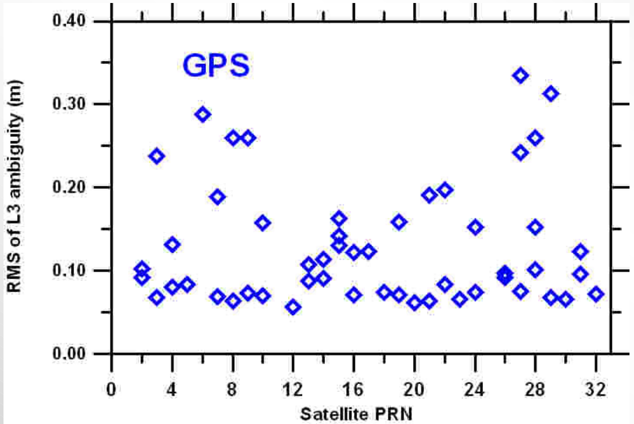
GANP

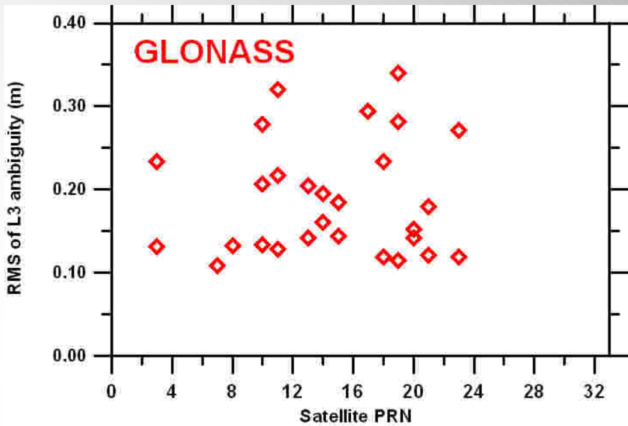




Demonstration of PPP using GPS and GLONASS – combination of code and phase data

- RMS of real valued L3 ambiguities – MOP2 DOY 002





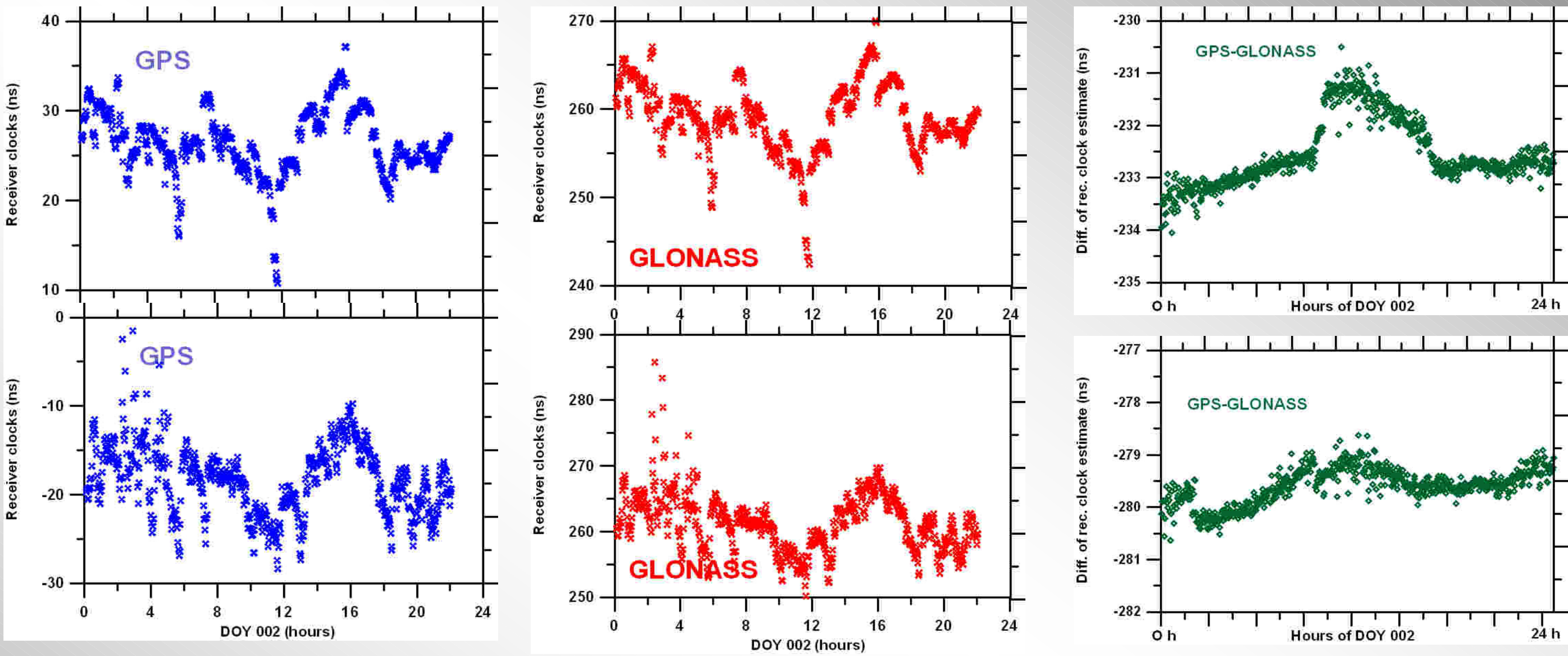
- The lower limit for RMS error of L3 ambiguity evaluation using combination of code and phase observations is 0.07 m for GPS and 0.11 m for GLONASS. This is achieved for ~ 5 hour continuous observations. For shorter intervals the accuracy of ambiguities is decreasing.
- The internal consistence of code and phase observations of single satellites is about 30% lower for GLONASS when comparing to GPS.
- We assume that the main reason for lower GLONASS accuracy are the less stable observed GLONASS code data.

Demonstration of PPP features using GPS and GLONASS – satellite clocks

- Receiver clock adjustment from separate GPS and GLONASS solutions and the difference between the clock estimates

MOP2

GANP

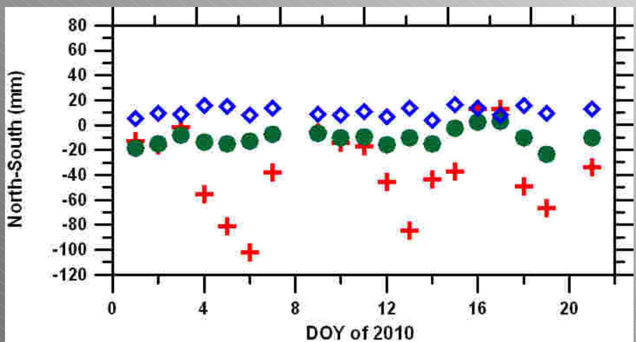


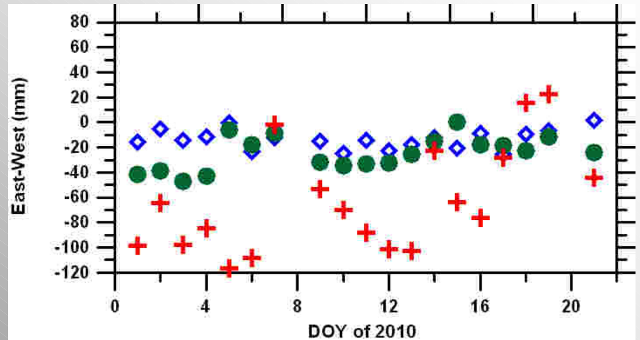
- There is general agreement of receiver clocks behavior inferred from separate GPS and GLONASS adjustment at the 1-2 ns level. The not known receiver code biases between C1-P2 of GPS and P1-P2 of GLONASS lead to hundreds ns clock estimation biases for both examined Trimble NetR receivers.
- The detailed comparison shows that this apparent clock differences are time depended and they should be modeled in the GNSS combination algorithms.

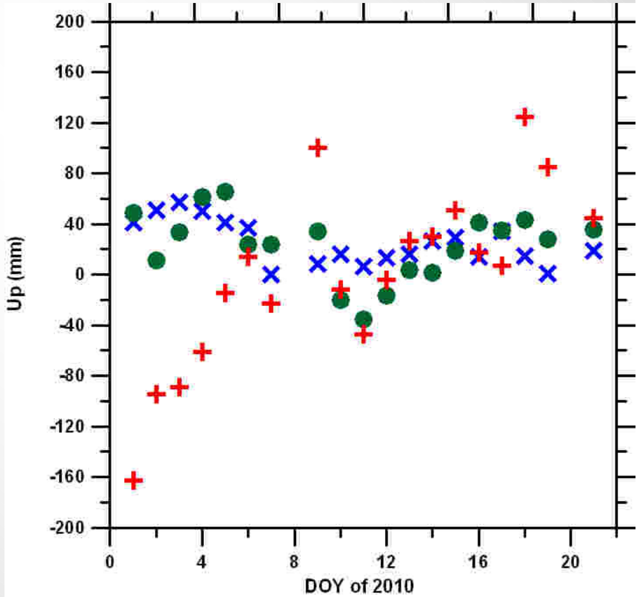
Demonstration of PPP using GPS and GLONASS - combined solution

- Combined adjustment of parameters: coordinates, receiver clocks, troposphere for 2h intervals, quadratic receiver code biases model.

- Three weeks of 24-hour observations at MOP2 and GANP were used for GPS-only, GLONASS-only and GPS+GLONASS combined solution.
- The formal errors using ABSOLUTE software (mm):
- o GPS-only: σ(n)=1.5, σ(e)=3.0, σ(up)=5.4
- + GLONASS-only: σ(n)=5.9, σ(e)=10.1, σ(up)=11.1
- o GPS+GLONASS: σ(n)=1.8, σ(e)=3.1, σ(up)=4.8
- The inclusion of GLONASS does not change the precision of coordinate estimates even though the number of satellites was enlarged.







Repeatability of GPS, GLONASS and combined daily coordinate estimates

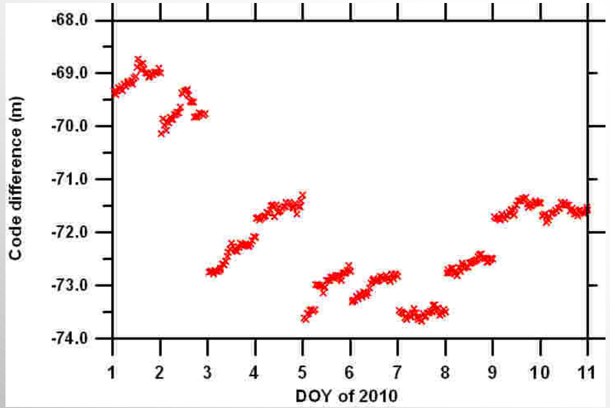
Statistics from 3 weeks of 24-hour coordinate adjustments

	Solution	n-s(mm)	e-w(mm)	up(mm)
MOP2	GPS	4	8	18
	GLONASS	32	49	71
	COMBINED	7	13	27
GANP	GPS	5	8	13
	GLONASS	26	75	99
	COMBINED	9	14	21

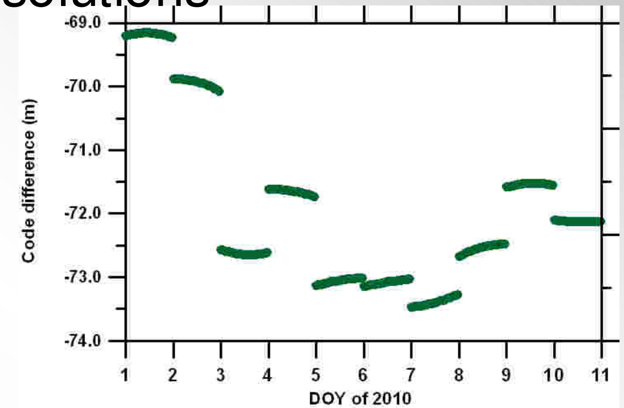
- The inclusion of GLONASS into PPP GPS-based coordinate adjustment does not improve the repeatability of 24-hour coordinates.
- The combined solution is biased from GPS-only from 10 to 20 mm in all 3 coordinates.
- The daily solutions of GLONASS-only have significantly larger scatter if compared to GPS-only estimates.

Demonstration of PPP using GPS and GLONASS - differences in the receiver clock estimates

- Differences between receiver clock estimates obtained from separate GPS and GLONASS 24-hour based adjustments during 10 days



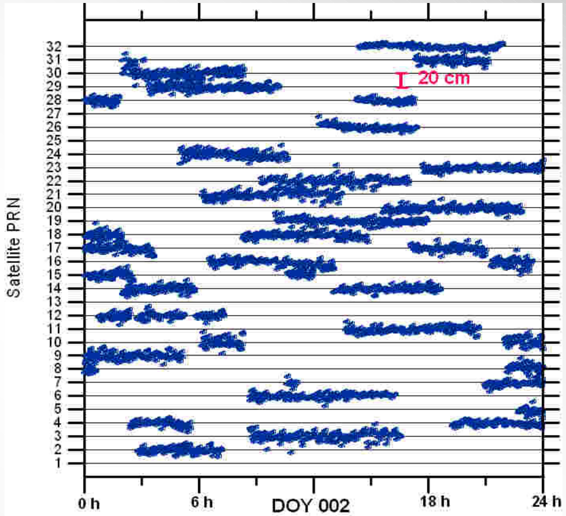
- Modeled receiver inter-channel bias between GPS and GLONASS codes from the combined 24-hour solutions

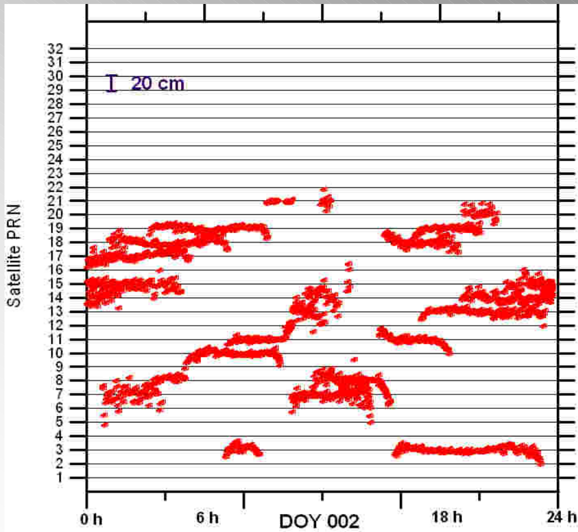


- The main feature of estimated differences in separate GPS and GLONASS receiver clock estimates is their day-to-day variability.
- The modeled receiver code biases in combined solution agree with the difference between the GPS and GLONASS clock estimates at ~2 ns level.

Demonstration of PPP using GPS and GLONASS - phase residuals

- Phase residuals for individual GPS and GLONASS satellites - MOP2 solution.





- There are significant differences in behavior of GPS and GLONASS phase residuals.
- GPS phase residuals behave as stationary in time, their RMS is ~ 40 mm.
- GLONASS residuals are partially time-dependent with specific pattern, their RMS is ~ 60 mm.
- For some GLONASS satellites the RMS of phase residuals are constantly larger than 80 mm (particularly satellite No. **7**, but also No. 14, 15).
- The phase observations of GLONASS should be de-weighted in the combination procedure in futire.

Conclusions

- We demonstrated the capability of separate and combined GPS and GLONASS PPP coordinate estimation using the precise ESOC satellite orbits and clocks products in post-processing mode.
- For examined processing steps are not observed fundamental differences between GPS and GLONASS derived results, however for majority of GLONASS outputs the lower consistency is observed.
- The most pronounced discrepancy in the code observations is the bias between the C1-P2 data (GPS) and P1-P2 data (GLONASS) resulting to differences in receiver clock estimation. This bias has to be modelled in the combined adjustment process.
- We observed also discrepancies in stability of phase observations resulting to larger scatter of GLONASS residuals than of GPS, especially for some satellites. Origin of less stabile GLONASS phase data is complex, including the quality of observations, uncertainties of GLONASS orbits and clocks parameters, etc.
- Due to phenomena mentioned, the inclusion of GLONASS into PPP algorithms recently does not recently contribute to improvement of GNSS absolute positioning even the larger number of satellites is available. The future investigations will be concerned on quality evaluation of GLONASS individual satellites parameters and to more detailed bias modelling before combination with GPS.

Thanks for your attention！