Current State of Multi-constellation and multi-frequency Precise Point positioning

Fernando Chacón[1], Antonio Herrera[1], M. Clara de Lacy[1, 2]

[1] Dpto. Ing. Cartográfica, Geodesia y Fotogrametría, Universidad de Jaén, Campus de las Lagunillas, 23071 Jaén, Spain, (fchacon@ujaen.es; aherreraolmo@gmail.com)
[2] Centro de Estudios Avanzados en Ciencias de la Tierra, Energía y Medio Ambiente (CEACTEMA), Universidad de Jaén, Campus de las Lagunillas, 23071 Jaén, Spain, (mclacy@ujaen.es)

Key words: *precise point positioning; GPS; galileo; multi-GNSS*

ABSTRACT

Precise Point Positioning is a standalone method to estimate the coordinates of a single GNSS receiver based on undifferenced observations and modelling all the effects present during the observation session by precise products. The reference system of the coordinates estimated will be the same as the satellite orbits used in GNSS data processing. Due to its accuracy, PPP satisfies all most of applications where GPS observations are used. In recent years, the interoperability of new global navigation satellite systems (referred to as multi-GNSS) has driven the combination of observations coming from different satellite constellations. Multi-GNSS consists of the interoperability of at least two satellite constellations with some of their frequencies working in common. In this context, it has been essential to implement effective PPP algorithms to take advantage of the novelties presented by the different satellite navigation systems. As a consequence, some scientific software has been updated to support multi-frequency and multi-constellation GNSS data in PPP mode. Some of them are Bernese 5.2, RTKLIB, goGPS and PCUBE. The last one is being developed by the authors. This program implements two techniques for multi-GNSS data processing. One of them is based on a sequential filter and the other one is based on the Least Squares Approach. The purpose of this work is to study the capability and evaluation of multi-GNSS PPP performance along a whole day comparig the solutions estimated by different GNSS processing software. Special attention will be paid to the benefits introduced by new frequencies and services provided by the European System Galileo.

I. INTRODUCTION

PPP is a method for obtaining precise positioning using GNSS observations. This approach estimates the coordinates of a single GNSS receiver, modeling all the effects present during the observation session. The reference system of these coordinates will be the same as the satellite orbits used in GNSS data processing. At this moment, this method is a useful tool for estimating station positions due to the fact that its accuracy satisfies the requirements of most applications where GPS observations are used. Currently there are several free online PPP processing resources, all of these support GPS and Glonass dual-frequency observations in static and kinematic mode. However, some of them is no able to process Galileo data. Furthermore, the scientific Bernese software version 5.2 (Dach *et al.*, 2015) has been updated to support dual frequency and multi-constellation GNSS data (GPS, Glonass and Galileo) in PPP mode.

In recent years the interoperability of new global navigation systems (hereafter referred to as multi-GNSS) has driven the combination of observations coming from different satellite constellations. As a result, a remarkable improvement in precision, reliability and convergence time is expected. Several authors have studied these expected benefits in Precise Point Positioning PPP (Hernández-Pajares *et al.*, 2010; Cai and Gao, 2013; Paziewski and Wielgosz, 2014; Chen *et al.*, 2015; Fan *et al.*, 2017; Liu *et al.*, 2017; 2019; Montenbruck *et al.*, 2017; Pan. Z *et al.*, 2017; Zhao *et al.*, 2017). As a consequence, MGNSS PPP programs have been developed. For example, Moreno *et al.* (2014) developed and implemented PCUBE software; Bahadur and Nohutcu (2018) implemented PPPH program and GAMP software based on RTKLIB was developed by Zhou *et al.* (2018). The improvements achieved in MGNSS PPP are mainly studied using GPS, Glonass and Beidou observations (Liu *et al.*, 2017; Pan *et al.*, 2017; Marques *et al.*, 2018; Pan *et al.*, 2019). The evaluation of Galileo PPP performance throughout a whole day is still rare, (Xia *et al.*, 2019; Zhang *et al.*, 2019) since the Galileo constellation is not yet completed. The Galileo system has provided initial services since 2016. The aim of this paper is to study the possible benefits added by Galileo's initial services and the current GPS constellation in PPP. Not all satellites of the Galileo constellation can be used: E22 is not usable; E20 is unavailable from 2015/05/27 until further notice;

E18 and E14 may be used only for testing purposes. The satellites transmit the signals E1, E6, E5a/b/ab. The current GPS constellation is a mix of old and new satellites. It is composed of four blocks. Blocks IIR and IIR-M are formed of 10 and 7 satellites respectively. Block IIF is formed of 12 satellites and finally three satellites belonging to the GPSIIIA Block were launched in 2018, 2019 and 2020. The last two blocks transmit L1 C/A, L1/L2 P (Y), L2C, L1/L2 M, L1 C/A, L1/L2 P (Y), L2C, L1/L2 M, L5 signals. A significant aspect to consider in July 2020 is the Official U.S. government information about the Global Positioning System (GPS) and related topics ("GPS.gov: New Civil Signals" 2020) which underlines: "until further notice, the L2C and L5 signals are considered pre-operational. A pre-operational signal means the availability and other characteristics of the broadcast signal may not comply with all requirements of the relevant interface specifications and should be employed at the users' own risk".

In this paper, GPS and Galileo data from ZIM3, MGNSS station for one month in 2019 (February 1 to 28, 2019) and for another month in 2021 (November 1 to 30, 2021) are considered. The data sets are processed using different algorithms implemented in the PCUBE program. The reason why the authors use this software is that this program implements different PPP algorithms and its performance was checked with other software such as the online services CSRS-PPP, magicGNSS, and APPS and Bernese (Moreno *et al.*, 2014). One of these algorithms, called MAP3, is able to perform static PPP from multi-frequency and multi-GNSS constellations.

II. MGNSS Positioning

MGNSS consists of the interoperability of at least two satellite constellations with some of their frequencies working in common, and this is achieved considering the biases due to the presence of different systems and frequencies. Montenbruck *et al.* (2017) defined the term ''bias" in the context of GNSS observations: "deviations of the measured value from an idealized reference or a priori model. Biases are commonly treated as additive terms in the functional model of pseudorange and carrier phase observations, and are typically (but not necessarily always) considered as constant values during a given processing arc." The biases play a very important role when different constellations and signals are involved in GNSS precise point positioning. In this context, the most important ones are: Differential Code Bias (DCB), Inter-system Bias (ISB) and Inter-frequency Bias (IFB).

DCBs represent the variation in travel time for two signals in a constellation, which are independent of ionospheric dispersion but are related to the hardware-dependent group delay differences in a pair of satellite receivers. The term Inter-system bias is the difference of at least two different interoperable GNSS constellation signals. The objective of ISB is to correct the pseudorange (and carrier phase) model in order to align the measurements of a constellation (*e.g.* Galileo) with that of a reference constellation (*e.g.*, GPS), (Montenbruck *et al.*, 2017). ISBs can be modelled by known values provided by MGEX, available at an internet repository online of two different Data Centers, one being the Crustal Dynamics Data Information System ("CDDIS, products" 2019) and the second one GeoForschungsZentrum Potsdam ("GFZ, products" 2019). They can estimate as additional parameters as well.

III. GNSS Data Description and Processing Strategies

A. *Data set from MGEX*

In recent years MGEX or the multi-GNSS Experiment, created by the International GNSS Service (IGS), distributes products and observations coming from multi-GNSS constellations. The analysis centers (ACs) generate the necessary products such as orbits and clocks for the different GNSS constellations. Precise orbit intervals are 5 or 15 minutes and the corrections for the clocks are sampled at 30 seconds or 5 minutes.

MGEX products (orbits and clocks) are computed based on GNSS observations of the MGEX network and, optionally, other proprietary stations. To study the performance of the current Galileo and GPS data in PPP, a GNSS station belonging to MGEX network was selected: ZIM3. The main characteristics of the receiver and antennae of this station are summarized in Table 1. GPS and Galileo data from DOY 32 to 59, 2019 (February 1 to 28, 2019) were processed using precise products from CODE AC. In the same way, we process the dates corresponding to the month of November 2021, DOY 305 to 334 (days 1 to 30).

Table 1. Characteristics of the receivers and antennae involved in the tests

Site	ZIM3
Country	Switzerland
Receiver	TRIMBLE NETR9
Antenna	TRM59800.00
Sat. System	GPS+GLO+GAL+BDS+QZSS+SBAS

Nowadays the Galileo constellation is formed of 28 satellites but not all of them can be used: E22 is not usable; E20 is unavailable from 2015/05/27 until further notice; E18 and E14 could only be used for testing purposes in 2019 but are not available at the date of writing of this document.

A significant aspect to consider in July 2020 is the Official U.S. government information about the Global Positioning System (GPS) and related topics ("GPS.gov: New Civil Signals" 2020) which underlines: "until further notice, the L2C and L5 signals are considered pre-operational. A pre-operational signal means the availability and other characteristics of the broadcast signal may not comply with all requirements of the relevant interface specifications and should be employed at the users' own risk".

PCUBE implements different PPP algorithms and its performance was checked with other software such as the online services CSRS-PPP, magicGNSS, and APPS and Bernese (Moreno *et al.*, 2014). One of these algorithms, called MAP3, is able to perform static PPP from multi-frequency and multi-GNSS constellations. To compare the processed daily solution, we subsequently used RTKLib and Bernese 5.2. In order to compare the processed daily solution, we subsequently used RTKLib and Bernese 5.2, including new dates corresponding to the full month of November 2021 (days 1 to 30).

B. *PCUBE software*

PCUBE is a PPP program implemented in MATLAB. This software is able to estimate PPP solutions using two methods: one of them is a sequential filter based on the classical iono-free combination, therefore this algorithm process only dual frequency GNSS data; the other method is named MAP3 and is based on the Least Squares (LS) approach. MAP3 allows us to perform static PPP from multi-frequency and multi-system GNSS observations. The MAP3 algorithm was designed with two parts, and in each part the LS theory is applied. According to Moreno *et al.* (2014). The mathematical formulation used in PCUBE can be seen in (Moreno *et al.*, 2014) and the PCUBE software flowchart is shown in Figure 1.

Table 2 summarizes the main characteristics of the computed solutions. Table 3 summarizes the different models, input files and set-up strategies used in MGNSS PPP. The estimated coordinates were compared with the IGS14 coordinates in the weekly observation period, since they are considered as the "true" coordinates. When GPS + Galileo are processed, ISBs are known from MGEX precise products.

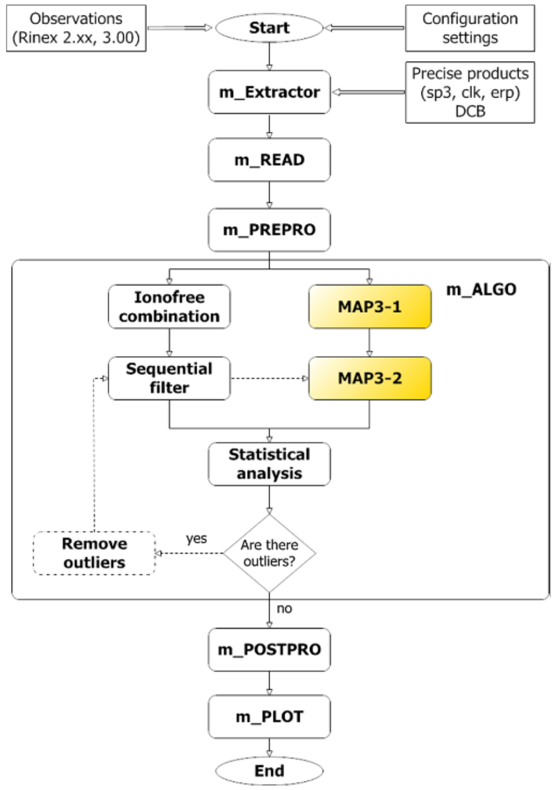

Figure 1. PCUBE software flowchart (Moreno *et al.*, 2014).

Table 2. Main characteristics of the solutions estimated with PCUBE

Solution	Const.	Method	Freq.	Observation
MAP3	GPS + GAL	LSA	3 if L5 available	L1 L2 L5 E1 E5b E5a
MAP3-GPS	GPS	LSA	3 if L5 available	L1 L2 L5
MAP3-GAL	GAL	LSA	3	E1 E5b E5a

Table 3. Models and data processing strategies used

	LSA
Constellations	GPS only, Galileo only, GPS + Galileo
Observations	L1, L2, L5; E1, E5a; E5b
Processing mode	Static
Precise products	Precise ephemeris and clocks from CODE with 5 minutes and 30 seconds sampling rate, respectively ("CDDIS, products" 2019)
Satellite PCO and PCV corrections	IGS absolute antenna model from IGS14.atx
Receiver PCO and PCV corrections	IGS absolute antenna model from IGS14.atx GPS PCO/V L5 are assumed the same with GPS L2 Galileo corrections are assumed the same with GPS
Observables	Undifferenced dual and triple frequency raw observations when 3rd frequency available
Sampling rate	30 and 1 seconds for long and short periods, respectively
Elevation mask	8º
Observation	Elevation dependent weighting
STD observables	0.003 m for phases 0.3 for pseudoranges
Phase ambiguities	Estimated as float for each arc
ISB	Known from precise products from CDDIS (MGEX)
Troposphere modelling	Dry model Saastamoinen and Wet model estimated every two hours
Relativistic effects	Applied (Kouba and Street, 2009)
Phase wind-up correction	Applied (Wu *et al.*, 1992)
Site displacement	Solid Earth tides and ocean loading applied (Petit and Luzum, 2010)

C. *RTKLiB*

RTKLiB is a free software with different GUIS created by Tomoji Takasu (2008). It allows both GNSS data post-processing and real-time positioning (RTK), enabling and disabling different corrections on the processing, modification of parameters to obtain the solution and its presentation. The output file provides the geocentric XYZ coordinates and the covariance matrix of the solution in each epoch, the number of satellites in each epoch and the type of solution.

D. *Bernese*

Bernese is a high-precision, scientific GNSS software capable of performing multi-GNSS data processing. Developed at the Astronomical Institute of the University of Bern (AIUB), it has spread through the scientific community over time, used by CODE (Centre for Orbit Determination in Europe) in its international (IGS) and European (EUREF/EPN) activities.

E. *goGPS*

goGPS is software created for GNSS raw data processing. Developed to work with low-cost single-frequency GPS receivers, it is adapted to multi-constellation, multi-frequency and multi-track observations. Furthermore, implements multiple algorithms that allow data analysis, and least squares (LS) processing. It can calculate accurate PPP and network adjustments (NET).

IV. MGNSS PCUBE RESULTS

Table 4 shows the statistics of PPP accuracy of the North, East and Upwards components in terms of RMSE for February 2019 results. The magnitude of the RMSE agrees with those obtained by Hadas et al (2019) when they estimate static PPP coordinates using MGEX data and products at 2019 precision level. From these results, we can observe that Upward RMSE is in general slightly better than 2D. This fact is not normal in GNSS processing, and is probably due to the assimilation of PCO/V used for L5, E5a and E5b and the mismodelling of inter-frequency bias in PCUBE. The positioning error at cm-level is slightly high. Next future, more research will be done processing current data and adding inter-frequency bias model in PCUBE.

V. MGNSS GOGPS, BERNESE AND RTKLIB RESULTS

Modern data (1-30 november, 2021) coming from the same has been processed using similar modelling options. Tables 4-7 shows the statistics of the PPP accuracy of the North, East and Up components in terms of RMSE processing only Galileo data, only GPS data and GAL+GPS data. In this case for the November 2021 results for GPS; GPS+GAL; GAL respectively.

Table 5 shows the GPS results for each software. It can be seen that goGPS and Bernese are at the same level of results. RTKLiB is slightly worse.

Table 4. ZIM3 positioning results in North (N), East (E) and Upward (U) components in cm. PCUBE

Solution	RMS error [cm]			2D positioning error [cm]	3D positioning error [cm]
	N	E	U		
MAP3 GPS +GAL	1.92	2.55	1.70	3.19	3.62
MAP3-GPS	1.47	1.56	1.28	2.14	2.50
MAP3-GAL	1.96	2.76	1.98	3.38	3.92

Table 5. GPS ZIM3 positioning results in North (N), East (E) and Upward (U) components in cm. GOGPS, BERNESE AND RTKLIB

Solution GPS	RMS error [cm]			2D positioning error [cm]	3D positioning error [cm]
	N	E	U		
goGPS	0.15	0.15	0.58	0.21	0.62
Bernese	0.31	0.14	0.53	0.34	0.63
RTKLiB	0.32	0.27	1.18	0.42	1.25

Table 6. GPS+GAL ZIM3 positioning results in North (N), East (E) and Upward (U) components in cm. GOGPS, BERNESE AND RTKLIB

Solution GPS+GAL	RMS error [cm]			2D positioning error [cm]	3D positioning error [cm]
	N	E	U		
goGPS	0.24	0.18	0.82	0.31	0.88
Bernese	0.24	0.27	0.91	0.36	0.98
RTKLiB	0.38	0.26	1.24	0.55	1.35

Table 7. GAL ZIM3 positioning results in North (N), East (E) and Upward (U) components in cm. GOGPS, BERNESE AND RTKLIB

Solution GAL	RMS error [cm]			2D positioning error [cm]	3D positioning error [cm]
	N	E	U		
goGPS	0.16	0.15	1.13	0.60	1.28
Bernese	0.44	0.17	1.91	0.76	2.05
RTKLiB	N.S	N.S	N.S	N.S	N.S

These tables show accuracy at few mm level is achieved. Next months, PCube will be used with these data set. Comparing only GPS solutions, only Galileo solutions and GPS+GALILEO solutions, we can say the best solution corresponds to the results obtained processing GPS data only.

Table 7 contains the GAL results. In it goGPS is minimally better than Bernese. For RTKLiB there is no estimated solution (N.S.=No Solution). This may be due to the number of unknowns influencing each processing mode of the respective software.

VI. CONCLUSIONS

In this paper, a first test to analyse the performance of current Galileo and GPS systems in Precise Point Positioning has been carried out. In particular, data coming from ZIM3 will be process with goGPS, Bernese and RTKLiB. Accuracy at mm level has been achieved with 24 hours' session. The best results are obtained when GPS data only are processed. Next months, the same data set will be processed with PCUBE to compare the results. More research will be done to verify the achieved solutions.

VII. Acknowledgements

This research has been funded by: University of Jaén: Programa Operativo FEDER Andalucía 2014-2020 - Project 1263446 - call made by UJA 2018. POAIUJA 2021-2022 and CEACTEMA. Junta de Andalucía: Plan Andaluz de Investigación. Desarrollo e Innovación PAIDI2020 – Project PY20_00897. Project P07-RNM-03087 and Research Group RNM282. MINECO of Spain: Project CGL2016-78577-P.

References

Bahadur, B., and Nohutcu, M. (2018). PPPH: a MATLAB-based software for multi-GNSS precise point positioning analysis. *GPS Solutions*, 22(4), 113.

BKG, data. (2019). Available in: ftp://igs.bkg.bund.de/MGEX, (Aug. 5, 2019).

CDDIS, data. (2019). Available in: ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex, (Aug. 5, 2019).

CDDIS, high rate data. (2019). Available in: ftp://ftp.cddis.eosdis.nasa.gov/pub/gnss/data/highrate, (Aug. 5, 2019).

CDDIS, products. (2019). Available in: ftp://ftp.cddis.eosdis.nasa.gov/pub/gnss/products/, (Aug. 5, 2019).

Cai, C., and Gao, Y. (2013). Modeling and assessment of combined GPS/GLONASS precise point positioning. GPS Solutions, 17(2), pp. 223–236.

Chen, J., Zhang, Y., Wang, J., Yang, S., Dong, D., Wang, J., Qu, W., and Wu, B. (2015). A simplified and unified model of multi-GNSS precise point positioning. *Advances in Space Research*, 55(1), pp. 125–134.

Dach. R.. Fridez. P.. Lutz. S., and Walser. P. (2015). Bernese GNSS Software Version 5.2

Fan, L., Li, M., Wang, C., and Shi, C. (2017). BeiDou satellite's differential code biases estimation based on uncombined precise point positioning with triple-frequency observable. *Advances in Space Research*, 59(3), pp. 804–814.

GPS.gov: New Civil Signals. (2020). Available in: https://www.gps.gov/systems/gps/modernization/civilsignals/, (Feb. 13, 2020).

GPS.gov: Space Segment. (2020). Available in: https://www.gps.gov/systems/gps/space/, (Feb. 13, 2020).

Hadas, T., Kazmierski, K., and Sośnica, K. (2019). Performance of Galileo-only dual-frequency absolute positioning using the fully serviceable Galileo constellation. *GPS Solutions*, 23(4), 108.

Hernández-Pajares, M., Juan, J. M., Sanz, J., Ramos-Bosch, P., Rovira-García, A., Salazar, D., Ventura-Traveset, J., López-Echazarreta, C., and Hein, G. (2010). The ESA/UPC GNSS-Lab tool (gLAB): An advanced multipurpose package for GNSS data processing. 2010 5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS *Signals and Signal Processing (NAVITEC),* IEEE, Netherlands, pp. 1–8.

Liu, T., Yuan, Y., Zhang, B., Wang, N., Tan, B., and Chen, Y. (2017). Multi-GNSS precise point positioning (MGPPP) using raw observations. *Journal of Geodesy*, 91(3), pp. 253–268.

Liu, T., Zhang, B., Yuan, Y., Li, Z., and Wang, N. (2019). Multi-GNSS triple-frequency differential code bias (DCB) determination with precise point positioning (PPP). *Journal of Geodesy*, 93(5), pp. 765–784.

Marques, H. A., Aquino, M., Veettil, S. V., and Monico, J. F. G. (2018). Accuracy assessment of Precise Point Positioning with multi-constellation GNSS data under ionospheric scintillation effects. *Journal of Space Weather and Space Climate*, 8, A15.

Montenbruck, O., Steigenberger, P., Prange, L., Deng, Z., Zhao, Q., Perosanz, F., Romero, I., Noll, C., Stürze, A., Weber, G., Schmid, R., MacLeod, K., and Schaer, S. (2017). The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges. *Advances in Space Research*, 59(7), pp. 1671–1697.

Moreno, B., Rodríguez-Caderot, G., and de Lacy, M. C. (2014). Multifrequency algorithms for precise point positioning: MAP3. *GPS Solutions*.

Pan. L, Zhang, X., Guo, F., and Liu, J. (2019). GPS inter-frequency clock bias estimation for both uncombined and ionospheric-free combined triple-frequency precise point positioning. *Journal of Geodesy*, 93(4), pp. 473–487.

Pan. Z, Chai, H., and Kong, Y. (2017). Integrating multi-GNSS to improve the performance of precise point positioning. *Advances in Space Research*, 60(12), pp. 2596–2606.

Paziewski, J., and Wielgosz, P. (2014). Assessment of GPS + Galileo and multi-frequency Galileo single-epoch precise positioning with network corrections. *GPS Solutions*, 18(4), pp. 571–579.

Petit, G., and Luzum, B. (2010). (IERS Technical Note; No. 36). (36), 179.

Xia, F., Ye, S., Xia, P., Zhao, L., Jiang, N., Chen, D., and Hu, G. (2019). Assessing the latest performance of Galileo-only PPP and the contribution of Galileo to Multi-GNSS PPP. *Advances in Space Research*, 63(9), pp. 2784–2795.

Zhang, R., Tu, R., Liu, J., Hong, J., Fan, L., Zhang, P., and Lu, X. (2019). Performance of Galileo: Global coverage, precise orbit determination, and precise positioning. *Advances in Space Research*, 64(2), pp. 299–313.

Zhao, L., Ye, S., and Song, J. (2017). Handling the satellite inter-frequency biases in triple-frequency observations. *Advances in Space Research*, 59(8), pp. 2048–2057.

Zhou, F., Dong, D., Li, W., Jiang, X., Wickert, J., and Schuh, H. (2018). GAMP: An open-source software of multi-GNSS precise point positioning using undifferenced and uncombined observations. *GPS Solutions*, 22(2), 33.

Zhou, F., Dong, D., Li, P., Li, X., and Schuh, H. (2019). Influence of stochastic modeling for inter-system biases on multi-GNSS undifferenced and uncombined precise point positioning. *GPS Solutions*, 23(3), 59.