ISSN 0735-2727, Radioelectronics and Communications Systems, 2019, Vol. 62, No. 10, pp. 530–540. © Allerton Press, Inc., 2019.
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Testing Static and Kinematic Modes of Precise Point Positioning Service in Ukraine

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Received March 29, 2019
Revised September 16, 2019
Accepted October 10, 2019

Abstract—The article presents the results of experimental studies of the TerraStar service, which implements autonomous real-time PPP (Precise Point Positioning) technology. The service provides high-speed orbital and clock data of GPS, GLONASS, GALILEO, BeiDou navigation satellites received from more than 100 global navigation satellite system (GNSS) ground stations. These data, together with the algorithms of the NovAtel dual-frequency (multi-system) navigation receiver with integrated TerraStar PPP technology provide solutions for high-precision (4–40 cm) position determination. The data is transmitted to the navigation receiver via radio channels of geostationary satellites.

The authors have evaluated the claimed positioning accuracy for Ukraine in difficult radio navigation conditions (urban canyon, the city of Kyiv and Kyiv region), which complements a number of existing studies on the accuracy of TerraStar service in different regions of the world.

An experimental technique is described that contains the procedures for initializing, recording, and storing data from a navigation receiver for subsequent comparison with a reference trajectory generated using GrafNav/GrafNet 8.70 software.

It was determined that the accuracy of estimating coordinates obtained in post-processing by PPP using GrafNav/GrafNet 8.70 software is comparable with the accuracy of coordinates calculated by the NovAtel OEM 719 receiver in real time using information from TerraStar.

It was experimentally confirmed that the positioning accuracy in the studied area corresponds to the accuracy declared by the TerraStar providers, which remains for 5 min even in the absence of TerraStar data.

DOI: 10.3103/S0735272719100054

INTRODUCTION

The modern world is characterized by the rapid introduction of global navigation satellite systems (GNSS) technologies in various areas of life. This is reported by the European GNSS Space Agency (GSA) [1].

The recent marketing researches [1] indicate that the global revenue of services using GNSS will increase by 150 billion euros from 2015 to 2025. At the same time, the number of GNSS receiving units (chips) will increase by more than two and a half times, and will amount to about 9 billion units in 2025. Thus, for each person there will be more than one product using GNSS technology.

This broad spread of GNSS is caused by the creation and development of GPS, WAAS (USA), GLONASS, SDCM (Russia), EGNOS, GALILEO (European Union), BEIDOU (China), QZSS (Japan), NAVIC (India), multi-system and multi-frequency navigation receivers, augmentation systems, improvement of measurement information processing methods.

Considerable attention is paid to the problems of improving satellite navigation technologies. The article [2] provided theoretical information on refining the ephemeris of navigation satellites, articles [3, 4] published data on improving the models of the ionosphere and troposphere, article [5] presented materials on improving the noise immunity of satellite navigation systems due to spatial filtering of interference by a microstrip antenna array, article [6] presented methods for estimating satellite navigation in the geostationary orbit; article [7] presented theoretical questions of forming corrections for high-precision

ACKNOWLEDGMENTS

The authors express their sincere gratitude to NovAtel. Inc. (Canada) and EPS (Kharkiv, Ukraine) for the opportunity to conduct experimental research of the high-precision positioning service TerraStar.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ADDITIONAL INFORMATION

The initial version of this paper in Russian is published in the journal "Izvestiya Vysshikh Uchebnykh Zavedenii. Radioelektronika," ISSN 2307-6011 (Online), ISSN 0021-3470 (Print) on the link http://radio.kpi.ua/article/view/S0021347019100054 with DOI: 10.20535/S0021347019100054.

REFERENCES

1. European GNSS Agency, *GNSS Market Report*, Issue 5 (2017). URI: https://www.gsa.europa.eu/system/files/reports/gnss_market_report_2017_-_surveying.pdf.
2. S. V. Sokolov, V. V. Kamenskij, S. M. Kovalev, "Stochastic estimation of ephemerides of navigation satellites in perturbed orbits," *Radioelectron. Commun. Syst*. **61**, No. 8, 350 (2018). DOI: 10.3103/S0735272718080034.
3. Q. J. Mohd, D. S. Achanta, V. K. R. Nalam, T. K. Pant, "Comparison of TEC estimation techniques using S1 and L5 signals of IRNSS," *Radioelectron. Commun. Syst*. **61**, No. 7, 306 (2018). DOI: 10.3103/S0735272718070038.
4. O. Kutsenko, S. Ilnytska, V. Konin, "Investigation of the residual tropospheric error influence on the coordinate determination accuracy in a satellite landing system," *Aviation* **22**, No. 4, 156 (Dec. 2018). DOI: 10.3846/aviation.2018.7082.
5. S. Ye. Martynyuk, D. O. Vasylenko, F. F. Dubrovka, A. G. Laush, "Novel microstrip antenna array for anti-jam satellite navigation system," *Radioelectron. Commun. Syst*. **58**, No. 3, 97 (2015). DOI: 10.3103/S0735272715030012.
6. V. V. Konin, F. O. Shyshkov, "Autonomous navigation of service spacecrafts on geostationary orbit using GNSS signals," *Radioelectron. Commun. Syst.* **59**, No. 12, 562 (2016). DOI: 10.3103/S0735272716120049.
7. K. Gunning, J. Blanch, T. Walter, "SBAS corrections for PPP integrity with solution separation," *Proc. of 2019 Int. Tech. Meeting of The Institute of Navigation*, 28-31 Jan. 2019, Virginia, USA (2019), pp. 707-719. DOI: 10.33012/2019.16739.
8. Z. Nie, P. Zhou, F. Liu, Z. Wang, Y. Gao, "Evaluation of orbit, clock and ionospheric corrections from five currently available SBAS L1 services: Methodology and analysis," *Remote Sensing* **11**, No. 4, 411 (2019). DOI: 10.3390/rs11040411.
9. N. S. Kuzmenko, I. V. Ostroumov, K. Marais, "An accuracy and availability estimation of aircraft positioning by navigational aids," *Proc. of 2018 IEEE 5th Int. Conf. on Methods and Systems of Navigation and Motion Control*, *MSNMC*, 16-18 Oct. 2018, Kyiv, Ukraine (IEEE, 2018), pp. 36-41. DOI: 10.1109/MSNMC.2018.8576276.
10. I. V. Ostroumov, N. S. Kuzmenko, "Accuracy assessment of aircraft positioning by multiple radio navigational aids," *Telecommun. Radio Engineering* **77**, No. 8, 705 (2018). DOI: 10.1615/telecomradeng.v77.i8.40.
11. V. Kharchenko, M. Mukhina, "Correlation-extreme visual navigation of unmanned aircraft systems based on speed-up robust features," *Aviation* **18**, No. 2, 80 (2014). DOI: 10.3846/16487788.2014.926645.
12. M. P. Mukhina, D. M. Demchenko, "Analysis of visual correlation-extreme methods of UAV navigation," *2013 IEEE 2nd Int. Conf. Actual Problems of Unmanned Air Vehicles Developments Proc.*, *APUAVD*, 15-17 Oct. 2013, Kyiv, Ukraine (IEEE, 2013), pp. 213-216. DOI: 10.1109/APUAVD.2013.6705329.
13. NovAtel CORRECT with PPP using TerraStar Corrections. *APN-061 Rev K* (2019). URI: https://www.novatel.com/assets/Documents/Bulletins/APN061-NovAtelCORRECT-withTerraStar.pdf.
14. "Precise Positioning with NovAtel CORRECT Including Performance Analysis," *NovAtel White Paper* (Apr. 2015). URI: https://www.novatel.com/assets/Documents/Papers/NovAtel-CORRECT-PPP.pdf.
15. A. Jokinen, C. Ellum, I. Webster, S. Shanmugam, K. Sheridan, "NovAtel CORRECT with precise point positioning (PPP): Recent developments," *Proc. of 31st Int. Tech. Meeting of the Satellite Division of the Institute of Navigation*, ION GNSS + 2018, Sept. 2018, Miami, USA (IEEE, 2018), pp. 1866-1882. DOI: 10.33012/2018.15824.
16. A. Zhalilo, A. Yakovchenko, "Development of PPP-method realization for low Earth orbit satellite trajectory determination using on-board GPS-observations," *Eastern-European J. Enterprise Technol.* **5**, No. 9, 33 (2016). DOI: 10.15587/1729-4061.2016.81026.
17. C. Cai, Y. Gao, L. Pan, J. Zhu, "Precise point positioning with quad-constellations: GPS, BeiDou, GLONASS and GALILEO," *Advances Space Res.* **56**, No. 1, 133 (2015). DOI: 10.1016/j.asr.2015.04.001.
18. L. Pan, X. Zhang, X. Li, X. Li, C. Lu, J. Liu, Q. Wang, "Satellite availability and point positioning accuracy evaluation on a global scale for integration of GPS, GLONASS, BeiDou and GALILEO," *Advances Space Res.* **63**, No. 9, 2696 (2019). DOI: 10.1016/j.asr.2017.07.029.
19. J. Guo, X. Li, Z. Li, L. Hu, G. Yang, C. Zhao, D. Fairbairn, D. Watson, M. Ge, "Multi-GNSS precise point positioning for precision agriculture," *Precision Agriculture* **19**, No. 5, 895 (2018). DOI: 10.1007/s11119-018-9563-8.
20. K. Kazmierski, "Performance of absolute real-time multi-GNSS kinematic positioning," *Artificial Satellites* **53**, No. 2, 75 (2018). DOI: 10.2478/arsa-2018-0007.
21. F. Xia, S. Ye, P. Xia, L. Zhao, N. Jiang, D. Chen, G. Hu, "Assessing the latest performance of GALILEO-only PPP and the contribution of GALILEO to multi-GNSS PPP," *Advances Space Res.* **63**, No. 9, 2784 (2019). DOI: 10.1016/j.asr.2018.06.008.

22. A. Jokinen, C. Ellum, I. Webster, S. Masterson, T. Morley, "NovAtel CORRECT with precise point positioning (PPP) for high accuracy kinematic applications," *Proc. of 28th Int. Tech. Meeting of the Satellite Division of the Institute of Navigation*, ION GNSS + 2015, Sept. 2015, Florida, USA (2015), pp. 1123-1152. URI: https://www.ion.org/publications/abstract.cfm?articleID=12846.
23. J. B. DeSanto, C. D. Chadwell, D. T. Sandwell, "Kinematic post-processing of ship navigation data using precise point positioning," *J. Navigation* **72**, No. 3, 795 (2019). DOI: 10.1017/S0373463318000887.
24. R. Romero-Andrade, A. Zamora-Maciel, J. D. J. Uriarte-Adrián, F. Pivot, M. E. Trejo-Soto, "Comparative analysis of precise point positioning processing technique with GPS low-cost in different technologies with academic software," *Measurement* **136**, 337 (2019). DOI: 10.1016/j.measurement.2018.12.100.
25. L. De Groot, E. Infante, A. Jokinen, B. Kruger, L. Norman, "Precise positioning for automotive with mass market GNSS chipsets," *Proc. of 31st Int. Tech. Meeting of the Satellite Division of the Institute of Navigation*, ION GNSS + 2018, Sept. 2018, Miami, USA (2018), pp. 596-610. DOI: 10.33012/2018.16003.
26. D. Laurichesse, S. Banville, "Innovation: Instantaneous centimeter-level multi-frequency precise point positioning," *GPS World J.* **29**, No. 4 (Apr. 2018). URI: https://www.gpsworld.com/innovation-instantaneous-centimeter-level-multi-frequency- precise-point-positioning/.
27. V. Kharchenko, A. Zhalilo, V. Kondratyuk, V. Konin, O. Kutsenko, V. Sushko, D. Shelkovenkov, V. Shokalo, "GPS navigation and surveying, the results of experimental verification of OmniSTAR technology," *Proc. GosNII GA Aeronavigation*, No. 7, 28 (2007). URI: http://er.nau.edu.ua:8080/handle/NAU/25602.
28. V. V. Konin, O. V. Kutsenko, E. O. Lukianenko, S. I. Ilnytska, "Experimental investigation of multi-GNSS in static mode," *Proc. of 2018 IEEE 5th Int. Conf. on Methods and Systems of Navigation and Motion Control*, *MSNMC*, 16-18 Oct. 2018, Kyiv, Ukraine (IEEE, 2018), pp. 179-182. DOI: 10.1109/MSNMC.2018.8576274.
29. V. P. Kharchenko, V. M. Kondratyuk, S. I. Ilnytska, O. V. Kutsenko, "Recommendations to UAV navigation system test validation and some practical results," *Proc. of 2014 IEEE 3rd Int. Conf. on Methods and Systems of Navigation and Motion Control*, *MSNMC*, 14-17 Oct. 2014, Kyiv, Ukraine (IEEE, 2014), pp. 31-34. DOI: 10.1109/MSNMC.2014.6979723.
30. O. V. Kutsenko, S. I. Ilnytska, V. M. Kondratyuk, V. V. Konin, "Unmanned aerial vehicle position determination in GNSS landing system," *Proc. of 2017 IEEE 4th Int. Conf. Actual Problems of Unmanned Aerial Vehicles Developments*, APUAVD, 17-19 Oct. 2017, Kyiv, Ukraine (IEEE, 2017), pp. 79-83. DOI: 10.1109/APUAVD.2017.8308781.
31. *TerraStar® Correction Services*. URI: https://www.novatel.com/products/terrastar-gnss-corrections/#contentTab1.
32. *Introducing NovAtel Connect™*. URI: https://www.novatel.com/assets/documents/papers/introducing_novatel_connect.pdf.
33. Waypoint products group, A NovAtel Precise Positioning Product, *GrafNav/GrafNet*, *GrafNav Static. User Manual*, OM-20000165, Rev. 4 (2018). URI: https://www.novatel.com/assets/Documents/Waypoint/Downloads/GrafNav-GrafNet-User-Manual-870.pdf.
34. M. S. Grewal, L. R. Weill, A. P. Andrews, *Global Positioning Systems*, *Inertial Navigation and Integration* (Wiley, NY, 2001). DOI: 10.1002/0471200719.
35. S. V. Bulashev, *Statistics for Traders* [in Russian] (Sputnik+, Moscow, 2003).