



Research Paper / Makale

**Assessing the Contribution of Galileo to GPS+GLONASS
Single Point Positioning Navigation**

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Received/Geliş: 17.06.2020

Accepted/Kabul: 09.09.2020

Abstract: In addition to the legacy GPS and GLONASS, a new global emerging system, European Galileo became operational for positioning, timing, and navigation purposes. In this study, the contribution of the Galileo constellation to GPS+GLONASS combined single point positioning (SPP) is investigated. A one-week of data in 2019 (DOY: 274-280) and 25 IGS-MGEX stations are chosen to conduct GPS+GLONASS and GPS+GLONASS+Galileo SPP. The results indicate that average Root Mean Square Errors (RMSE) of northing, easting and, up components are improved by 11%, 16%, and 4%, respectively. It is also observed that maximum errors of GPS+GLONASS SPP are significantly reduced when adding Galileo constellation.

Keywords: Galileo, GLONASS, GPS, SPP

**Galileo'nun GPS+GLONASS Tek Nokta Konum Belirlemeye
Katkısının Değerlendirilmesi**

Öz: İlk olarak ortaya çıkan küresel GPS ve GLONASS'a ek olarak, Avrupa Galileo uydu sistemi konumlandırma, zamanlama ve navigasyon amacıyla faaliyete geçmiştir. Bu makalede, Galileo navigasyon uydularının GPS + GLONASS kombine tek nokta konumlandırmasına (SPP) katkısı incelenmiştir. GPS + GLONASS ve GPS + GLONASS + Galileo SPP değerlendirmeleri için 2019'daki bir haftalık veri (DOY: 274-280) ve 25 IGS-MGEX istasyonu seçilmiştir. Sonuçlar, kuzey, doğu ve yukarı bileşenlerin ortalama Karasal Ortalama Hatalarının (RMSE) sırasıyla %11,%16 ve %4 oranında iyileştirildiğini göstermektedir. Ayrıca, GPS+GLONASS SPP değerlendirmelerine ait maksimum hataların, Galileo uyduları eklendikten sonra ciddi oranda azaldığı gözlemlenmiştir.

Anahtar kelimeler: Galileo, GLONASS, GPS, SPP

1. Introduction

With the modernization of GPS and GLONASS, some global constellations are under construction. These are BeiDou and Galileo, built by China and Europe, respectively (Guo et al., 2017; Montenbruck et al., 2017; Li et al., 2018). For a long time, satellite-based navigation technology mainly relied on GPS and GLONASS systems, which are operating at full capability. The European Galileo is the first civilian-based global satellite navigation system in the world aiming to offer precise positioning service on a global scale (Li et al., 2015). It is cooperatively operated and held by the European Union (EU) and the European Space Agency (Xia et al., 2019). BeiDou-2 satellites are mainly operating the Asia-Pacific region. BDS-3 satellites provide global coverage but due to the hardware and software issues, a few International GNSS Service-multi-Global Navigation Satellite System (IGS-MGEX) stations can record BeiDou-3 signals. Most of the GNSS stations

How to cite this article

Öğütçü S., Farhan H. T., "Assessing the Contribution of Galileo to GPS+GLONASS Single Point Positioning Navigation" El-Cezeri Journal of Science and Engineering, 2020, 7 (3); 1377-1383.

Bu makaleye atıf yapmak için

Öğütçü S., Farhan H. T., "Galileo'nun GPS+GLONASS Tek Nokta Konum Belirlemeye Katkısının Değerlendirilmesi" El-Cezeri Fen ve Mühendislik Dergisi 2020, 7 (3); 1377-1383.

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need to be updated for firmware and hardware for working BDS-3 signals consistently (Private communication with CSNO-TARC).

Galileo launched four in-orbit validation (IOV) satellites from 2011 and 2012. After that, 22 full operational capability (FOC) satellites were launched from August 2014 to July 2018, out of which two were placed at highly elliptical orbits. The last reinforcement was done on July 26, 2018, and four additional FOC Galileo satellites were launched. Upcoming launches are planned from late 2020 onward [6]. First launches will re-enforce the constellation with the deployment of spare satellites. After this, subsequent launches will be used for constellation replenishment purposes (personal communication with the European GNSS Service Centre). The full operational capability Galileo constellation is composed of 30 satellites out of which six are active spare satellites in three orbital planes.

The single point positioning (SPP) technique has been widely used in many fields such as vehicle and aircraft navigation, Geographic Information System (GIS) and land surveying. Single-frequency code measurements are generally used in SPP, contrary to the precise relative [7] and PPP techniques [8;9], therefore, positioning accuracy is around at meter-level. For a long period, the SPP technique mainly relies on GPS and GLONASS systems. With the rapid development of Galileo constellation, it is now feasible to conduct triple-constellation (GPS+GLONASS+Galileo) SPP for anywhere in the earth. Some smartphone manufacturers start to integrate Galileo signals in addition to GPS+GLONASS on hardware and software [10].

There are several research studies addressing the SPP using MGEX. Ryan et al. (1998) first conducted the multi-constellation integrated SPP but only GPS and GLONASS systems were available at that time [11]. Santerre et al. (2014) [12] conducted triple-constellation (GPS+GLONASS+BeiDou) SPP in Changsha, Hunan province, China. They found 20% in horizontal and 50% in vertical component improvement using GPS+GLONASS+BeiDou SPP compared with GPS+GLONASS SPP. Pan et al. (2016) [13] investigated quad-constellation (GPS+GLONASS+Galileo+BeiDou) SPP. The results show that %29, %17 and 23% improvements in north, east, and up components are achieved using quad-constellation over GPS-only SPP. KwaĹniak (2018) [14] conducted GPS and GPS+Galileo SPP using two GNSS stations. It is found that three-dimensional accuracy was improved when adding Galileo to GPS-only SPP, but the overall improvement was not significant.

The above-mentioned studies were mainly conducted with the limited number of Galileo satellites and some above-mentioned studies were conducted in regional areas. Therefore, the purpose of this study is to assess the current contribution of Galileo to GPS+GLONASS over the global scale.

2. Single Frequency SPP Model

In general single frequency code measurements are used for SPP due to the nature of navigation. The equation can be written as follows:

$$P_r^s = \rho + c * (dt_r - dt^s) + d_{TROP} + d_{IONO} + \epsilon_P \quad (1)$$

where the superscript s represents satellite, the subscript r represents receiver, P_r^s is the pseudo-range measurement, ρ is the geometric range in meters, c is the speed of light in meters per second, dt_r is the receiver clock error in seconds, dt^s is the satellite clock error in seconds, d_{TROP} is the tropospheric delay, d_{IONO} is the ionospheric delay, and ϵ_P contains the other unmodeled errors. Satellite clock error (dt^s) and ionospheric delay (d_{IONO}) can be mitigated using broadcast ephemerides. Therefore, the unknown parameters are receiver three-dimensional earth-centered-earth-fixed (ECEF) coordinates and the receiver clock error (dt_r). If more than one navigation

constellation is used, Inter- System Bias (ISB) needs to be added in the equation. ISB can be explained as the sum of receiver-dependent hardware delay differences occurring among different GNSSs and the receiver-independent time differences caused by different clock datum constraints among external GNSS satellite clock products [15]. Using the above equation and considering GPS time as a reference time system, GPS, GLONASS, and Galileo observations can be written as;

$$P_r^G = \rho_G + c * (dt_r - dt^G) + d_{TROP}^G + d_{IONO}^G + \epsilon_P^G \tag{2}$$

$$P_r^R = \rho_R + c * (dt_r - dt^R + ISB^R) + d_{TROP}^R + d_{IONO}^R + \epsilon_P^R \tag{3}$$

$$P_r^E = \rho_E + c * (dt_r - dt^E + ISB^E) + d_{TROP}^E + d_{IONO}^E + \epsilon_P^E \tag{4}$$

where G, R, and E refer to GPS, GLONASS, and Galileo systems observations respectively; ISB denotes Inter-System Bias with respect to reference GPS time. The unknown parameters can be expressed for multi-GNSS SPP as;

$$\bar{X} = [X_r, Y_r, Z_r, dt_r, ISB^{s,i}] \tag{5}$$

where X_r, Y_r, Z_r are the receiver coordinates and $ISB^{s,i}$ refer the ISB parameter of each GNSS with respect to GPS.

3. Data Processing

25 IGS-MGEX stations are chosen to investigate the Galileo contribution to GPS+GLONASS SPP. Figure 1 shows the location of the stations. SPP processes were conducted as GPS+GLONASS and GPS+GLONASS+Galileo over the one-week of data in 2019 (DOY: 274-280). When choosing the stations, it was ensured that each station could track the GPS/GLONASS/Galileo data and these stations were also available in the IGS weekly combined solution. The frequency and epoch availability were also checked using in-house software. It was assured that each RINEX files contain more than 90% of the data.

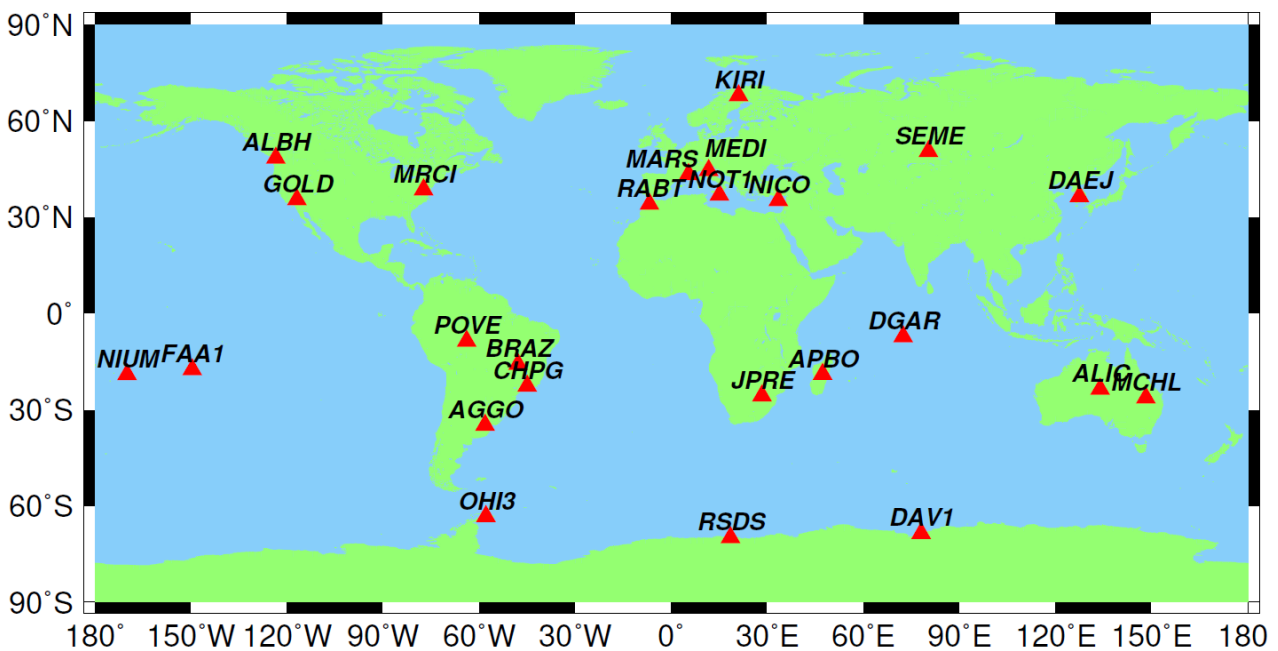


Figure 1. Location of the used MGEX stations

Processes were conducted as epoch-wise and each epoch coordinate was included for the statistical analysis. The reference coordinates of the stations were taken from the IGS weekly solutions in

Solution Independent Exchange (SINEX) format with an accuracy of within a few millimeters. RTKLIB open-source software [16] was used for SPP processes. 7° elevation cutoff angle was chosen for each process. Klobuchar ionospheric model [17] and Saastamoinen tropospheric model [18] were used to mitigate the ionospheric and tropospheric effects, respectively. Data sampling was chosen 30 s for each process.

3. Results

For the convenient visualization, Root Mean Square Errors (RMSEs) of topocentric coordinates, north, east and, up from GPS+GLONASS and GPS+GLONASS+GALILEO SPP are shown in Table 1 and Table 2. Table 1-2 also include maximum absolute errors of north, east and, up components obtained from GPS+GLONASS SPP. Galileo contribution is computed as the RMSEs and maximum error differences between GPS+GLONASS and GPS+GLONASS+Galileo SPP. The positive value of contribution refers that adding Galileo to GPS+GLONASS SPP reduces RMSEs and maximum errors. Figure 2 and figure 3 show the Galileo contribution to RMSEs and maximum errors, respectively, for each component.

Table 1. RMSEs and maximum absolute errors of GPS+GLONASS SPP (Units: meter)

STATIONS	N	E	U	Max_N	Max_E	Max_U
SEME	1.21	0.75	3.36	3.56	2.33	7.77
NIUM	2.31	0.82	2.79	5.79	3.59	8.26
NOT1	1.00	0.69	2.81	3.09	2.22	8.51
DAV1	0.79	0.58	3.03	3.53	2.67	8.51
RSDS	1.11	0.57	1.93	3.89	2.00	5.96
APBO	0.83	0.52	4.14	2.24	1.67	8.51
RABT	1.26	0.69	3.37	3.90	1.85	8.12
POVE	0.80	0.76	1.91	2.36	2.62	6.78
OHI3	1.03	0.67	3.61	3.90	2.62	9.15
CHPG	1.14	0.75	3.30	3.54	2.76	8.83
JPRE	0.87	0.69	4.32	2.43	2.22	8.91
NICO	1.01	0.64	2.95	2.91	1.65	6.80
MRCI	0.92	0.59	2.57	2.86	2.23	7.62
MEDI	1.04	0.68	2.68	3.01	1.97	7.33
MCHL	0.75	0.61	4.40	3.19	2.38	8.86
MARS	1.04	0.70	2.53	3.07	1.88	6.49
DGAR	1.02	0.65	3.28	2.66	1.81	7.38
DAEJ	0.83	0.68	3.24	2.96	2.07	8.60
BRAZ	1.27	1.00	2.92	3.57	3.39	8.70
ALIC	0.91	0.69	4.55	3.12	2.06	10.40
ALBH	0.87	0.55	3.03	2.43	1.74	6.83
AGGO	1.39	0.78	4.06	5.07	3.64	10.85
GOLD	0.94	0.68	3.14	3.47	2.99	8.79
KIRI	0.68	0.64	2.19	2.81	2.40	6.53
FAA1	1.76	0.79	3.06	4.92	3.02	8.23

As can be seen from Figure 2 and Figure 3, contribution of Galileo to RMSEs is at the dm-level. The biggest contribution in RMSEs is seen for the vertical component compared with the horizontal component. The maximum computed errors from GPS+GLONASS SPP are also reduced significantly when adding Galileo to GPS+GLONASS SPP. The biggest (0.40 m) and smallest

(0.10 m) RMSE contributions obtained from Galileo are observed for the vertical component of RABT and DGAR stations, respectively.

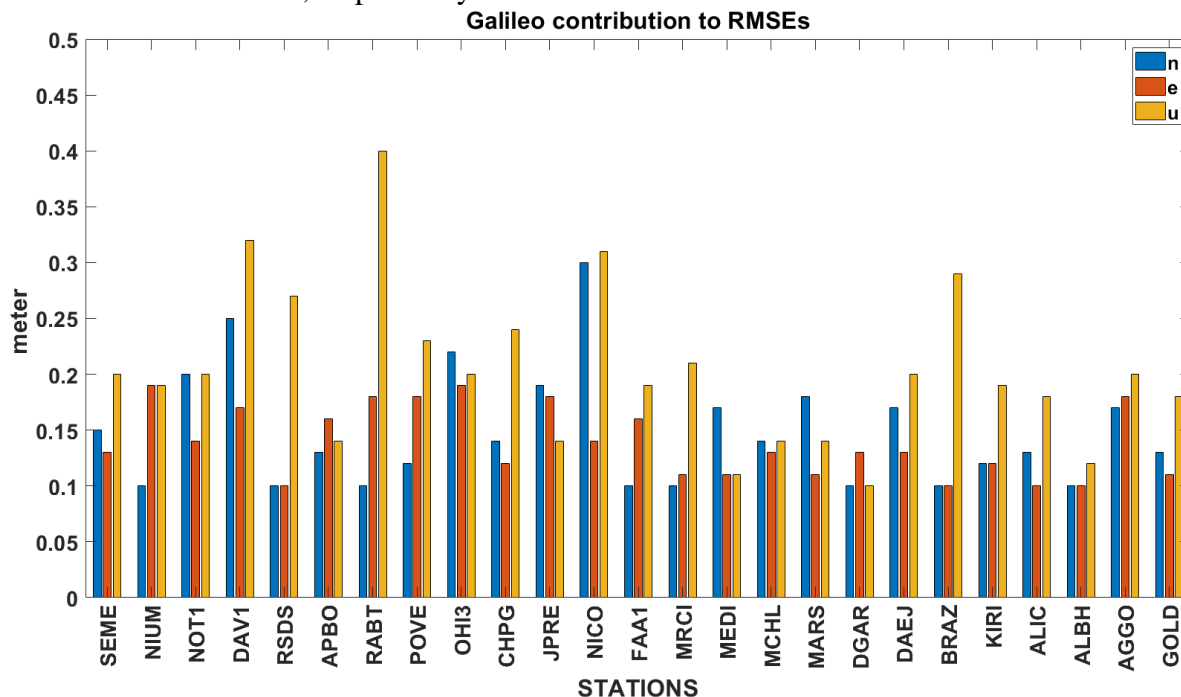


Figure 2. Galileo contribution to RMSEs

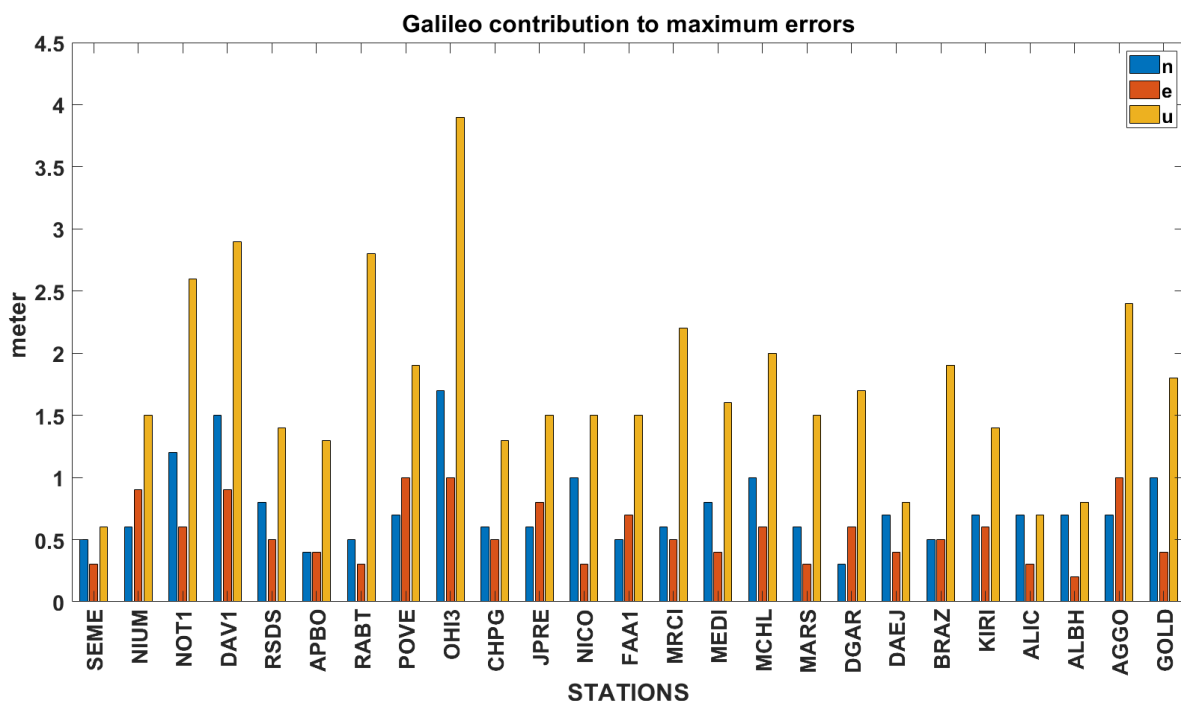


Figure 3. Galileo contribution to maximum errors

As can be seen from Figure 2 and Figure 3, contribution of Galileo to RMSEs is at the dm-level. The biggest contribution in RMSEs is seen for the vertical component compared with the horizontal component. The maximum computed errors from GPS+GLONASS SPP are also reduced significantly when adding Galileo to GPS+GLONASS SPP. The biggest (0.40 m) and smallest (0.10 m) RMSE contributions obtained from Galileo are observed for the vertical component of RABT and DGAR stations, respectively. Meter-level error decreasing is observed for the up component for most of the stations. The biggest (3.80 m) and smallest (0.47 m) maximum absolute

errors contributions obtained from Galileo are observed for the vertical component of OHI3 and SEME stations, respectively.

4. Conclusion

In this study, Galileo contribution to GPS+GLONASS SPP was investigated in terms of RMSE and maximum computed error based on the one-week observations in 2019 (DOY: 274-280). 26 IGS-MGEX stations distributed around the world were chosen for this experiment. Two different SPP processing were conducted as GPS+GLONASS and GPS+GLONASS+Galileo using the RTKLIB open-source software. The results showed that Galileo contribution to GPS+GLONASS SPP is at the dm-level for RMSEs. The reduction of the maximum computed errors from GPS+GLONASS was also estimated. It was observed that meter-level decreasing in the maximum errors was observed for most of the stations. The results also showed that the maximum contributions of Galileo to GPS+GLONASS SPP was seen in the vertical component for RMSEs and maximum errors. It should be emphasized that each SPP was conducted using a 7° elevation cutoff angle to simulate the unconstrained environment. It is evident that Galileo contribution to GPS+GLONASS SPP is much larger for the constrained environment such as forest and urban canyon where the GNSS cutoff angle would be much higher than 7° due to the decreasing the GNSS visibility.

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