Does the Inclusion of Regional Navigation Satellite Systems Help or Harm Global Solutions?

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R. Dach[1], L. Prange[1], A. Villiger[1], D. Arnold[1], M. Kalarus[1], S. Schaer[1,2], P. Stebler[1], A. Jäggi[1]

(1) Astronomical Institute, University of Bern, Bern, Switzerland
(2) Swiss Federal Office of Topography, swisstopo, Wabern, Switzerland

Introduction

The IGS (International GNSS Service, where GNSS stands for Global Navigation Satellite Systems, Johnston et al., 2017) recently finished its third reprocessing campaign as a contribution to the ITRF2020. It considers GPS, GLONASS, and, for the first time, Galileo. As reported in Dach et al. (2021), CODE (Center for Orbit Determination in Europe) contributed with a solution that incooperates with three GNSS, namely

- GPS: orbits since 1994; satellite clock corrections with 30 s sampling since the year 2000 and exclusively with 5 s sampling starting in the year 2003.
- GLONASS: orbits since 2002; satellite clock corrections since 2008 with 30 s and 2011 with 5 s sampling (since year 2012 nearly every day complete).
- Galileo: orbits since 2013; satellite clock corrections since 2014 with 30 s sampling (not further densified because of the excellent Galileo clock stability; linear interpolation is perfectly sufficient).

Besides ambiguity-fixed satellite clock corrections, a fully consistent set of phase biases was generated, enabling PPP with ambiguity resolution (PPP-AR) following the approach described in Schaer et al. (2021) .
CODE already generates a triple system solution (GPS+GLONASS+Galileo) for its rapid and ultra-rapid series. Once ITRF2020 is introduced for the operational product generation, CODE plans the include at least these three systems also for the reference frame relevant product line, specifically for the final series.
The question is whether the regional Japanese QZSS (Quasi-Zenith Satellite System) should be included or not.

Why to include QZSS?

There are several formal arguments that support the inclusion of QZSS in a reference frame relevant processing chain in an IGS-style processing:

1. the QZSS constellation is complete and operational,
2. complete and consistent products covering four satellite systems can be provided to the user community,
3. the satellite meta data have been published by the system provider (as complete as for Galileo),
4. the receiver antenna calibration values are available; consistent to GPS, Galileo (and GLONASS).

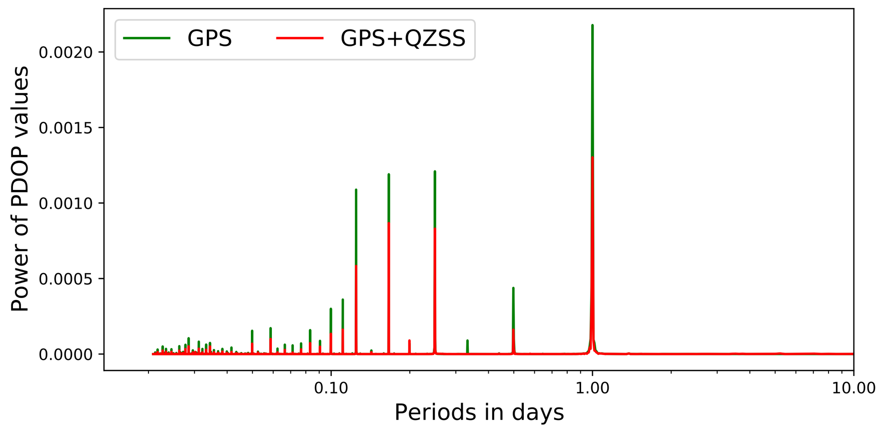

Figure 1: Power spectrum of PDOP values computed for IGS station Tsukuba, Japan using the GPS- and QZSS-constellations from day 200 to 320 of year 2021.

As shown in Dach et al. (2009) for combining GPS and GLONASS and supported by numerous other studies, the combination of different GNSS constellations may improve the observation geometry at GNSS tracking sites (indicated by the PDOP, position of dilution of precision) and reduce the impact of system specific, satellite-type related, or orbit type specific error signals of GNSS-derived parameters (e.g., Earth rotation).
The example of the IGS station Tsukuba, Japan (see Figure 1) shows that favorably located ground stations (i.e., stations located close to the satellites ground track) are benefiting from additional satellites: Adding just 3 QZSS satellites to the 32 GPS satellites can considerably reduce the magnitude of periodic PDOP values. This is in particular remarkable because the GPS satellites have exact twice the revolution period as the QZSS ones.

Why not include QZSS?

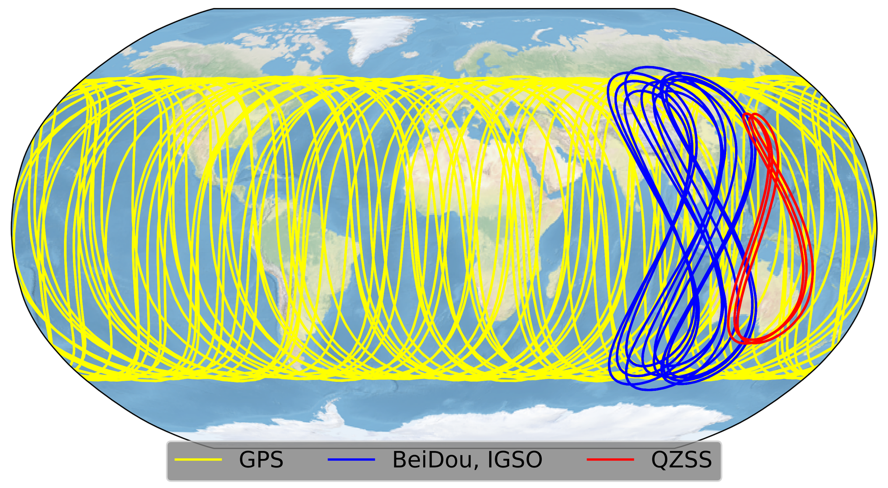

Figure 2: Ground tracks of selected satellite navigation systems (situation in October 2021).

The regional navigation satellites systems (RNSS, such as QZSS or the regional component of the Chinese BeiDou) have also disadvantages: They have a stronger impact on those stations located relatively close to the satellite's ground track, i.e., stations that can observe the additional satellites with high elevation, while stations on the opposite side of the globe are not effected at all. The situation is illustrated in two elevation azimuth diagrams in Figure 3 .

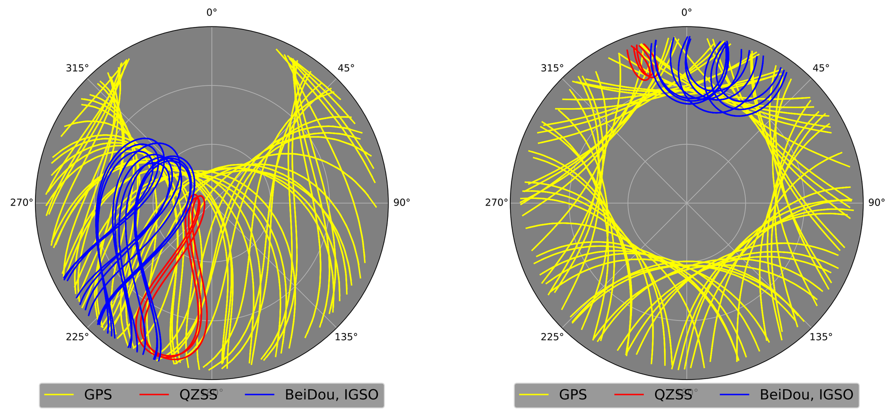

Figure 3: Elevation azimuth diagram for IGS-stations Tsukuba (Japan) on the left and Thule (Greenland) on the right hand plot.

Such a non-global tracking scenario does not really seem worth striving for in order to estimate global parameters, like Earth rotation parameters, geocenter coordinates or related datum parameters for determination of station coordinates.

Description of the test setup

Although several RNSS exist, we focus on QZSS in this study for the above mentioned reasons. On the other hand, the GNSS part is only represented by GPS due to the good interoperability with QZSS (both support the same frequencies L1 and L2).
Other GNSS are disregarded in order to keep a reasonable balance between GNSS and RNSS: the QZSS-constellation is consisting of 3 satellites in IGSO. Their impact on a solution with 32 GPS-satellites is expected to be more pronounced than their influence on the triple-system solution with GPS, GLONASS, and Galileo with a total of up to 80 satellites in MEO.

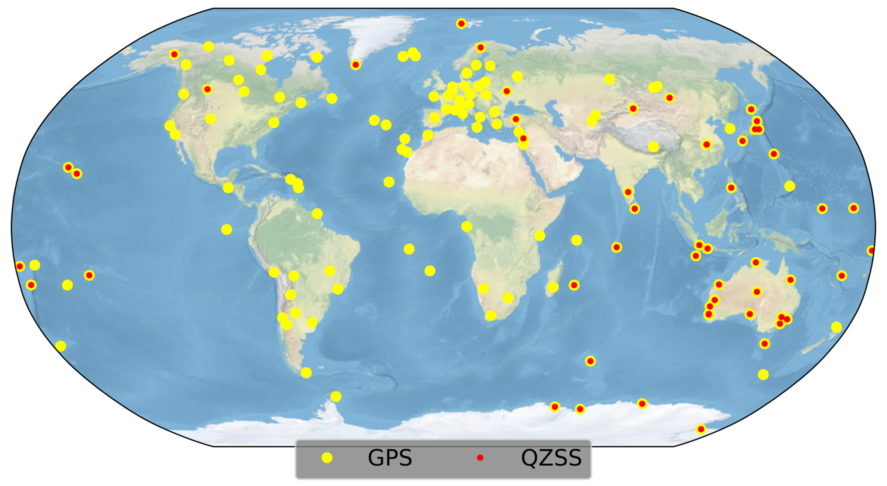

Figure 4: Network for CODEs MGEX-solution indicating the stations tracking GPS and QZSS satellites (situation in October 2021).

CODE's MGEX solution serves as basis for the experiments. Each of the 140 globally distributed GNSS stations (see Figure 4) provides GPS measurements. Sites also sampling QZSS are indicated with an extra red dot.
Apart from the selection of the systems, the processing follows the standard procedure for the CODE's MGEX solution strategy as described in Prange et al. (2020) . Three-day long-arc solutions are generated starting from day 200 of year 2018 (when all three QZSS satellites in IGSO became active) for 1200 days (until day 303 of year 2021).

Solution statistics

Adding QZSS increases the number of observations by about 10% compared to the GPS-only case (in a network as shown in Figure 4). Typically two ambiguity parameters per station are estimated for MEO satellites, whereas it is usually only one ambiguity per station per day for the high flying IGSO satellites (illustrated in Figure 3). On the other hand, the ambiguity resolution is not that successful for QZSS (about two third of the ambiguities can be resolved) as for GPS (success rate is nearly 90%).
This changes the overall degree of freedom from a GPS-only to the combined GPS+QZSS solution also explaining the increase of the a posteriori formal errors as shown in Figure 5 .

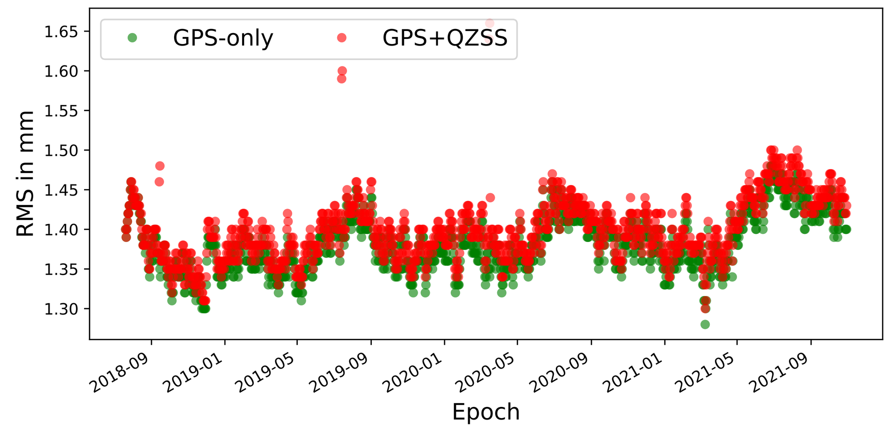

Figure 5: Time series of the a posteriori formal error from the GPS-only and GPS+QZSS three-day solutions.

Earth rotation parameters

In Figure 6 the estimates for the Earth rotation parameters from the two solution series (GPS-only and GPS+QZSS) are directly compared. The X-component shows some periodic pattern. A spectral analysis indicates mainly a semi-annual period (at 170 days and an amplitude of 5 μas); other periods have amplitudes below 1 μas in X- and Y-components.

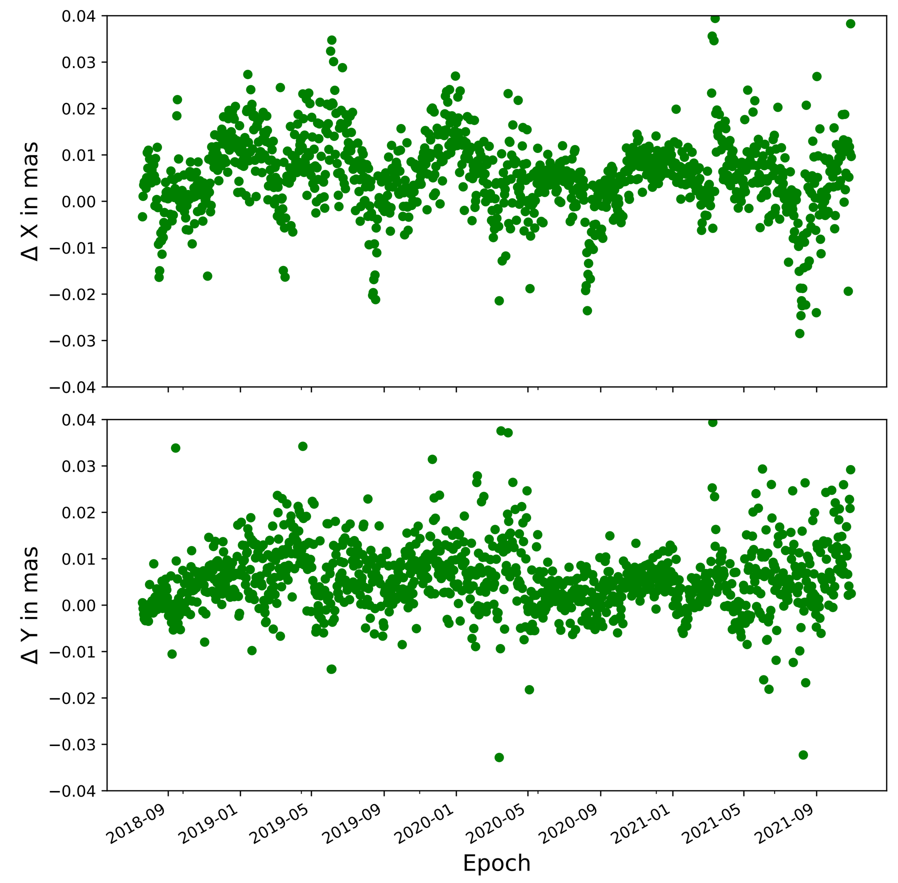

Figure 6: Daily differences in the pole coordinates between the GPS-only and GPS+QZSS daily solutions.

Both components show a systematic offset of +5 μas towards the direction where the ground tracks of the QZSS-satellites are located. This indicates that there is an impact on the estimated Earth rotation parameters when adding the QZSS to the GPS measurements. These systematic differences are by the way not reflected in the formal errors of the obtained Earth rotation parameters (difference below 1 μas). This means that the asymmetric distribution of measurements with respect to the location of the pole does not degrade the capability of the GPS-constellation in estimating the polar motion parameters.
Even though there are systematic differences detectable between these two solutions their magnitude is neglectable regarding the general uncertainty of the GNSS-based estimated Earth rotation parameters. The +5 μas difference in the Earth rotation corresponds to about 0.05 mm on the Earth surface; 0.2 mm at the height of the GPS-constellation or 0.3 mm on the height of the QZSS-satellites.

Geocenter coordinates

The estimated geocenter X- and Y-coordinates and their formal errors agree within 1 mm between the GPS-only and the GPS+QZSS solutions. Here, the conclusion is the same as for the Earth rotation parameters: there is no significant systematic impact due to the additional regional system.

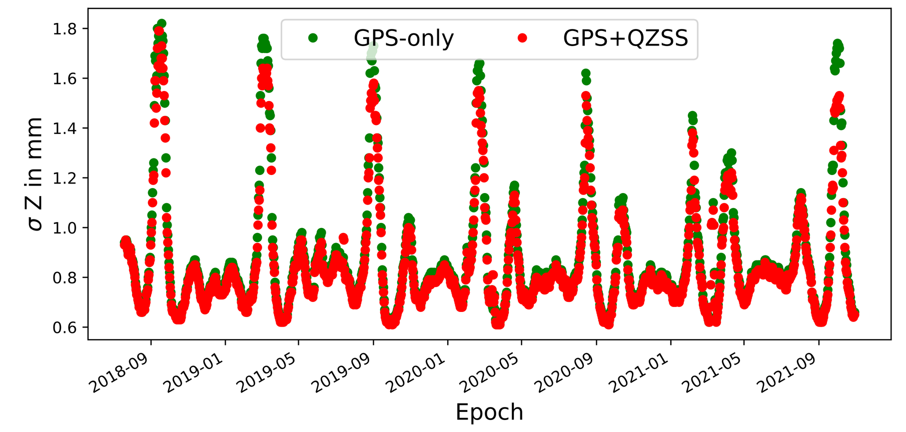

Figure 7: Formal errors of the Z-component of the geocenter coordinates for the two solution types studied.

As the Z-component is more related to the orbit modelling than the location of the center of mass (see Meindl et al., 2013) the difference between the GPS-only and GPS+QZSS solution is on average 2 mm with a standard deviation of 3 mm . The formal errors (plotted in Figure 7) confirm the influence of the satellite constellation on the Z-component of the geocenter coordinates obtained by GNSS.

Station coordinates

The repeatability of the station coordinates changes by less than 0.1 mm for the horizontal and 0.2 mm for the vertical components when adding QZSS to the GPS-solution. Regarding daily repeatability of the station coordinates there is no significant impact between the two solution; there are approximately as many improvements as degradations.

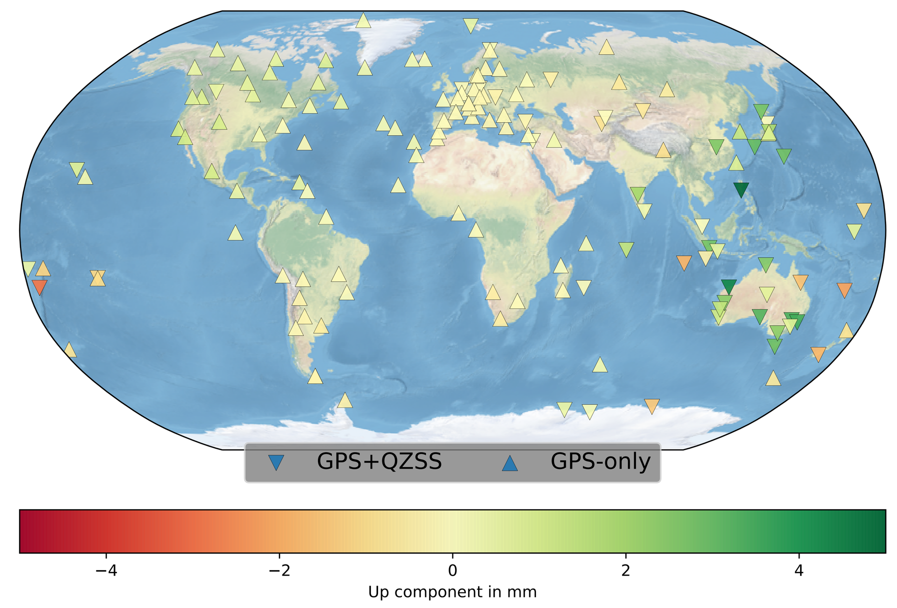

Figure 8: Difference in station coordinates (without Helmert transformation) between GPS and GPS+QZSS solutions, up component (day 350 of year 2019).

The two types of coordinate sets can be either directly compared by their differences or indirectly after computing a Helmert transformation over the whole network. The difference between these two comparisons shows that there is no systematic effect that is absorbed by the transformation parameters (they are also below 0.1 mm on the Earth surface for all seven components). We may thus conclude that the datum definition is also not degraded by adding the measurements from the regional satellite system. Surprisingly some stations show differences of up to 5 mm between the GPS-only and GPS+QZSS solution. They are all related to sites located in the vicinity of the ground tracks of the QZSS satellites and they are limited to receivers providing QZSS-measurements. As nearby stations (such as, e.g., two GNSS-receivers in Tsukuba, Japan) may show opposite behavior, orbit errors are probably not the cause. One possible explanation could be: differently effective receiver antenna patterns for satellite systems that transmit on the same frequency (which would be in disagreement with the assumptions and processing standards applied within the IGS). Another possible explanation could be near-field multipath effects in the station' environment affecting GPS and QZSS signals in different ways. A repetition of the experiment using the signals on the L5 frequencies from QZSS, the modernized part of the GPS constellation, and Galileo might help to clarify this particular phenomenon.

Summary - short answer to the question

Adding a Regional Navigation Satellites System (e.g., QZSS to GPS) does not degrade global parameters derived in a GNSS solution, given that the orbit modelling, the antenna calibrations and receiver behavior is sufficiently understood.

Contact address

Rolf Dach
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)
Email rolf.dach@aiub.unibe.ch

Poster compiled by Rolf Dach, December 2021
Astronomical Institute, University of Bern, Bern
Email rolf.dach@aiub.unibe.ch