Satellite and receiver chamber calibrated antenna pattern for TRF scale determination

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A. Villiger[1], L. Prange[1], R. Dach[1], F. Zimmermann[2], H. Kuhlmann[2], A, Jäggi[1]

[1] Astronomical Institute, University of Bern, Bern, Switzerland
[2] Institut für Geodäsie und Geoinformation, Universität Bonn

Introduction

An important part of the ITRF realization is the determination of the scale. So far the ITRF scale has been determind by Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI), GNSS did not contribute to it due to missing satellite antenna calibrations. Even though in theory the estimation of satellite z-component of the Phase Center Offsets (z-PCO) and scale parameters is possible, the numerical stability is weak because the scale and z-PCOs are connected by the cosine of the zenith angle (up to 14 degrees for the satellite antenna) which are close to one (Bruni 2017; Rebischung 2014). According to Zhu et al. (2003) the relation between the up-component on the ground and the z-PCO can be empirically extracted and is about 7.8 ppb (parts per billion). A change of $+1\,\mathrm{cm}$ to the height of each station, corresponding to a scale change of 1.6 ppb, would be to a substantial part absorbed by the satellite antenna offsets (an offset of $-20\,\mathrm{cm}$ in the z-component).

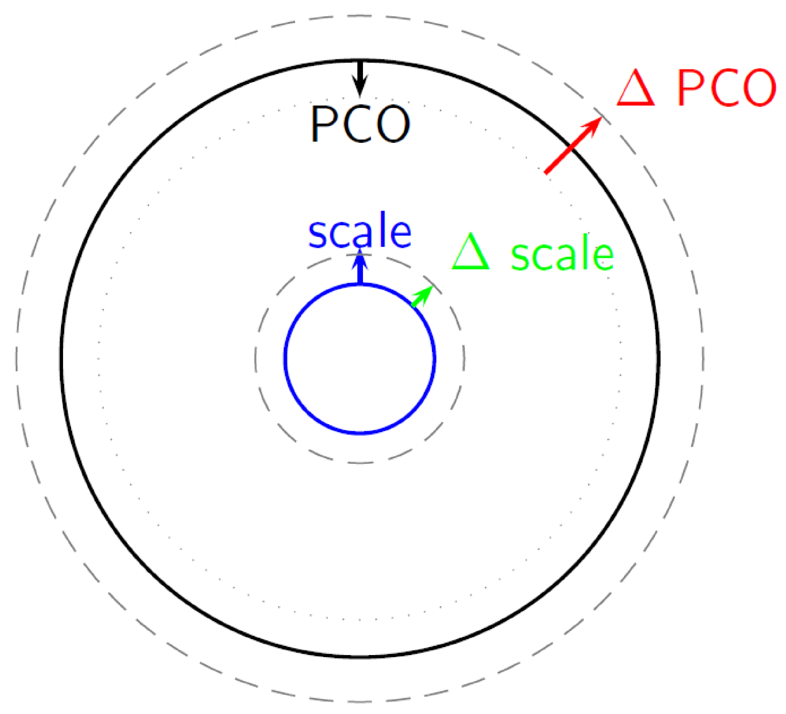

Figure 1: A scale change of $+1\,\mathrm{cm}$ on the ground will have an effect of $-20\,\mathrm{cm}$ on the satellite antenna z-offsets.

Antenna calibrations

With the disclosure of the pre-launch satellite antenna calibration results for the remaining eight Full Orbit Capability (FOC) satellites this year the European Global Navigation Satellite System Agency (GSA) released as the first global system provider those values (GSA 2019). This opens the potential to estimate a GNSS scale using Galileo and contribute to the scale determination of the next ITRF.
A first brief comparison can be made by using the z-PCO values published by Steigenberger et al. (2016) who estimated them using the ITRF scale and GPS L1/L2 for E1/E5 antenna pattern for the ground stations due to the lack of available calibrations. The comparison reveals a systematic offset of about 16 cm for the ionosphere-free linear combination (IF) of E1 and E5.

Table 1: Difference between estimated (Steigenberger et al. 2016) and released satellite antenna offsets (z-component) in cm.

Satellite	Estim.	Cal.	Diff
E101 (IOV)	95	83.7	11.3
E102 (IOV)	95	92.4	2.6
E103 (IOV)	95	82.4	12.6
E201 (FOC)	105	90.7	14.3
E202 (FOC)	105	86.4	18.6
E203 (FOC)	110	92.6	17.4
E204 (FOC)	110	75.3	34.7
Average	-	-	15.9

With the availability of the satellite antenna calibrations for Galileo the situation for the ground segment became critical because up to now the International GNSS Service (IGS) ANTEX file only contains calibrations for GPS and GLONASS L1/L2. A potential source of fully calibrated antenna patterns are chamber calibrated PCO and phase variations (PV). With a data set of more than 250 individual chamber calibrated antenna pattern we were able to create a set of chamber calibrated type-mean antenna pattern covering more than 35 antenna/radom combinations.
In preparation of the next IGS contribution to the ITRF 2020 Geo++ released a first set of robot calibrations which also include Galileo. The main focus of this study is the potential of having ground and space calibrated antenna for the scale determination and is based on the created type-mean chamber calibrations.

Network development

With the available data set of more than 35 chamber calibrated type-mean antenna/radom pattern we were able to compute a global GNSS network solution (based on CODE's MGEX solution (Prange et al. 2017)) to study a possible GNSS contribution to the determination of the TRF scale. For GPS and GLONASS L1 and L2 were used to create the IF, for Galileo E1 and E5. Over the two years, 2017 and 2018, the sites tracking Galileo sites used in our processing increased from about 100 to 140 stations (out of 180 in total). Out of the 100 sites at the beginning of 2017 40 were ITRF 2014 reference sites. This number increased to 60 by the end of 2018 (compared to 80 in case of GPS). Note that Galileo was not used for the ITRF 2014 generation.

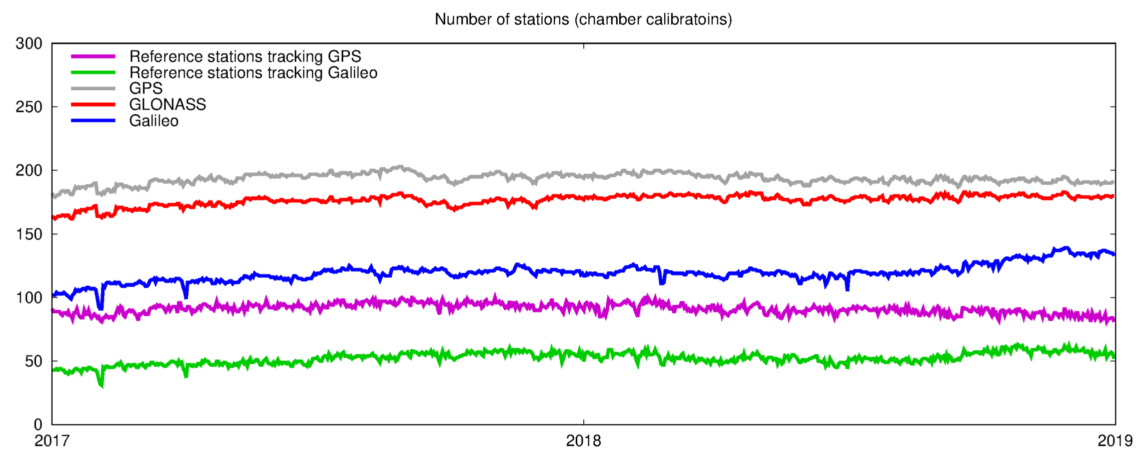

Figure 2: Number of stations processed per day. Note that all stations have tracked GPS.

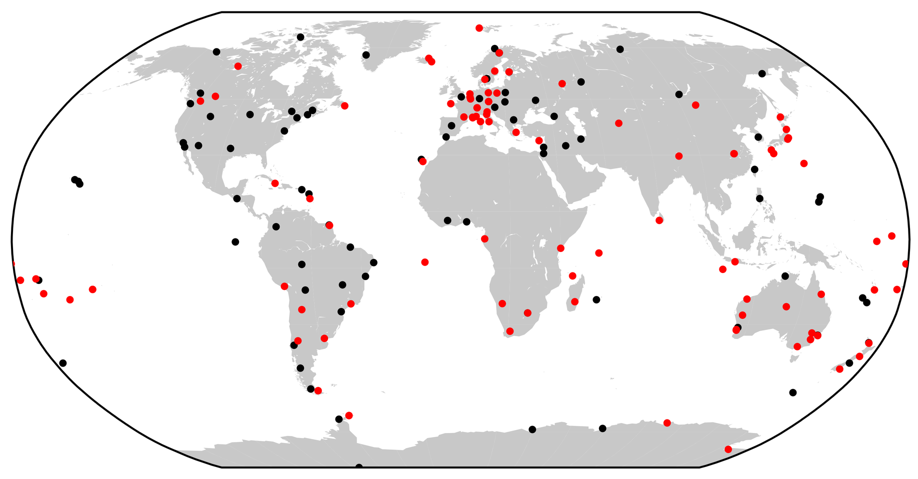

Figure 3: Network for the test campaign (1. January 2017). Sites tracking Galileo are red and the remaining sites black.

Scale determination

The processing of the two years of data led to a set of Normal Equations (NEQ) including Earth Orientation Parameters, Orbits, Station coordinates, Troposphere parameters, and the satellite antenna z-PCOs. With this set of NEQs we were able to run different tests to address the feasibility of using Galileo for the scale determination. Due to high correlations between the mean station heights and satellite antenna z-PCOs (Zhu et al. 2003; Rebischung 2014; Bruni 2017) the potential to estimate both parameters is limited.
We introduced a system-wise z-PCO offset, using the IGS14 ANTEX file as the a priori z-PCO values for GPS and GLONASS and the disclosed chamber calibrated pattern for Galileo, and estimated the z-PCO changes introducing different scale sources. The first three solutions are based on the individual GNSS. One system was constrained, which leads to the scale corresponding to that GNSS, and estimated system-wise z-PCO offsets for the two other systems. In a second step we introduced the scale by constraining the ITRF 2014 scale and opened the z-PCO offsets for all three systems.

Table 2: GNSS-wise PCO (z-component) z-offset estimation (w.r.t. IGS14 ANTEX values) inducing scale by each GNSS and ITRF2014. All values are give in cm

Scale System	GPS	GLO	GAL
GPS	-	-6.1	25.8
GLONASS	4.0	-	31.6
Galileo	-22.1	-25.8	-
ITRF 2014	-9.7	-14.4	15.3

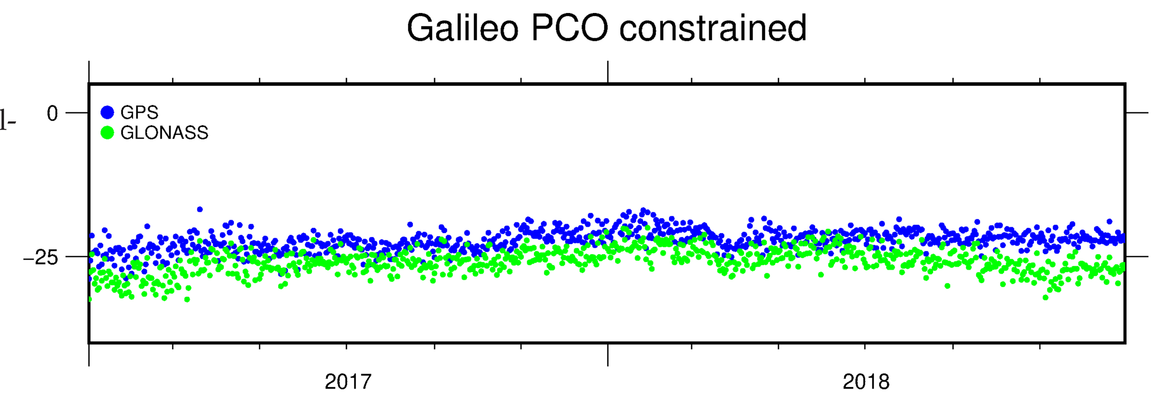

Figure 4: Estimated daily system-wise z-offsets for GPS (blue) and GLONASS (green). The Galileo PCOs are constrained and the corresponding scale change transferred over the ground antennas to the other GNSS.

The results showed the expected behavior. Because the GPS and GLONASS z-PCO values were originally estimated during the ITRF 2014 realization, we expect that constraining one of the two system would leads only to a small offset to the other system. When constraining Galileo the change to the GPS and GLONASS z-PCOs are, as expected, quite close together. The last experiment, listed in the table above, estimated z-PCOs for all three systems by introducing the scale from ITRF 2014 directly (constraining the scale to the reference frame). The daily scattering is for the z-PCO estimation when introducing the scale trough Galileo is below 3 cm.
The extracted scale using Galileo is 1 ppb which corresponds to a height difference of 6.6 mm on the Earth surface. Comparing the scale to the values from International VLBI Service (IVS), International Laser Ranging Services (ILRS), and International DORIS Services (IDS) published by Altamimi et al. (2016) we note that the Galileo defined scale is closer to the VLBI than to the SLR scale.

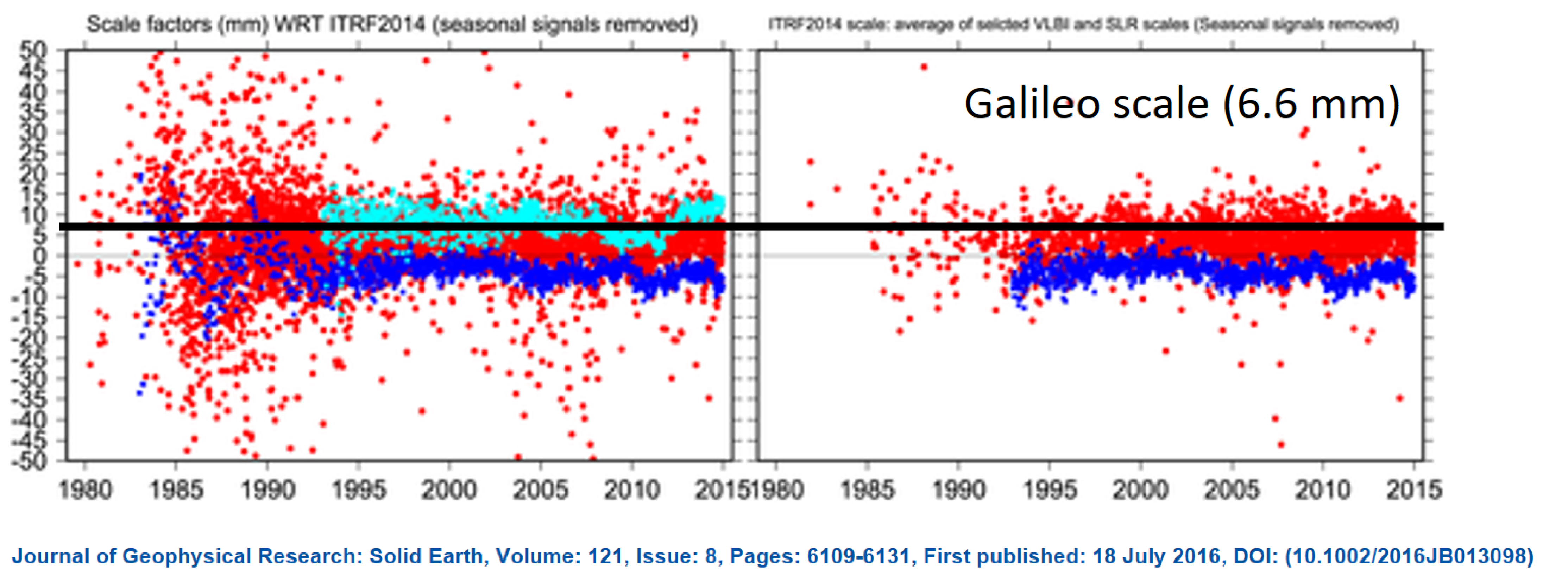

Figure 5: Comparison of the scale derived by the individual techniques (IVS (red), SLR (blue), DORIS (light blue), and GNSS (black)). The GNSS scale is based on two years 2017-2018 and added ontop of the figure published by Altamimi (2016).

Summary

GSA disclosed as the first global GNSS provider the chamber calibrated satellite antenna pattern. With the release of the pattern the main obstacle for a fully calibrated system, including the ground and space segment, was the lack of calibrated receiver antenna pattern for the E5 frequency. With a data set of more than 250 individual chamber calibrated antennas it was possible to derive type-mean calibrations for more than 35 receiver/radome combinations covering 49 % of the IGS network. In addition to them, Geo++ released the first multi-GNSS robot calibrated antenna pattern during the preparation of the IGS contribution for the ITRF 2020.
With the chamber calibrated type-mean receiver and satellite antenna calibrations available, we were able to run test solutions including GPS, GLONASS, and Galileo. Using a consistent reprocessed two year data period (2017 and 2018) we were able to estimate a reliable scale by constraining the Galileo satellite z-PCO and estimating a system-wise GPS and GLONASS shift in the z-PCOs. The shift allows to transfer the scale introduced by Galileo to the other systems. The estimated Galileo scale of 1 ppb is closer to the one obtained by VLBI than SLR .

Outlook

For the two year test campaign from 2017 to 2018 we could show that a scale contribution using the released Galileo satellite antenna pattern is possible. We used in our test chamber calibrated receiver antenna pattern because the robot calibrations were released during the ITRF preparation this summer (too late to be considered for this study). The final IGS contribution will rely mostly on those robot calibrations due to consistency reasons as most for most of the older antennas only pattern from robot calibrations are available.
The main question which is currently under investigation is the potential to transfer the scale backwards until 1994. For most of the time Galileo was not yet available, the first In Orbit Validation satellites were launched in 2011, and later the constellation was filled up until it reached its full constellation in 2018. Transferring the Galileo scale to GPS and GLONASS based on data of 2017 and 2018 might be sufficient to transfer the scale backward in time. However, this question is still open and has to be addressed during the preparation of the ITRF 2020.

Contact address

Arturo Villiger
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)
arturo.villiger@aiub.unibe.ch

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