Assessment of alternative calibration methods

S1. Introduction

Two alternative calibration methods were considered for the Jason-2 receiver calibration. Both methods were adapted from ground-based GPS receiver calibrations and have been used extensively in that context. The Minimum Standard Deviation (MSD) method (Valladares et al., 2009) determines a receiver bias that minimizes the difference among equivalent vertical TEC values, after initial bias corrections associated with the individual GPS satellites are applied. The SCORE (Self Calibration Of Range Error) method uses consistency conditions for calculated Equivalent Vertical Total Electron Content values at common penetration points to determine the combined GPS receiver and GPS satellite biases (Bishop et al., 1994). The results described here are primarily for simulated data, generated using the Parameterized Ionosphere Model (PIM) (Daniell et al., 1995) with the Gallagher (1988) plasmasphere model (Gallagher et al., 1988). This simulation is expected to provide a plasmasphere representation that is sufficiently characteristic of the plasmasphere for an assessment of the calibration methods.

S2. Minimum Standard Deviation method

The implementation of the MSD method used here is based on the recognition that the unknown receiver bias appears in the minimization expression in a quadratic form, so that, ideally, only three standard deviation evaluations are required to determine the associated parabola, whose minimum determines the receiver bias. (Note that a closed-form solution for the minimization also exists, but the standard deviation calculation had already been developed for other evaluations.) However, because this implementation used the GMTmath utility from the Generic Mapping Tools (Wessel and Smith, 1998), with limited reported precision for the derived parabola coefficients, the determination of the minimum can be somewhat imprecise. This limitation was resolved by evaluating additional samples for the parabola and fitting this larger set (typically no more than four samples) to derive the parabola coefficients and the associated minimum.

For the ground-based receiver calibrations, the MSD method uses a restricted range of Local Time [2:00,6:00] to evaluate the standard deviation of equivalent vertical TEC measurements (Valladares et al., 2009). For Jason-2 on day 2011-205 (24 July 2011), this local time period corresponds to high northern latitudes, which are in daylight, rather than during nighttime. A similar daylight circumstance occurs for high southern latitudes for the Local Time range [15:00,19:00]. An additional consideration is that, for a fixed ground-based receiver, an interval of Local Time corresponds to a similar interval of Universal Time, while for Jason-2 an interval of Local Time can contain a large range in Universal Time, in groups separated by multiples of the orbital period.

For this simulation calibration study, no relative GPS satellite biases were added to the simulated data, SimPEC (because these are presumed to be accurately removed for the actual data calibrations), and no receiver bias was added to the simulated data, so the expected derived bias would be zero. Also, no residual error initially was assumed for the alignment of the receiver dispersive phase measurements to the dispersive group delay measurements. The slant plasmasphere electron content, SPEC (= SimPEC - Bias), values are converted to equivalent vertical plasmasphere electron content (VPEC) values using the standard "thin-shell" formula

$$VPEC = SPEC \cdot \cos\left(\arcsin\left(\frac{R_J \cdot \cos(\varepsilon)}{R_e + H_s}\right)\right) \tag{S1}$$

for line-of-sight elevation ε, Jason-2 orbital radius R_J, and Earth radius R_e, with a shell altitude H_s = 2537 km. The shell altitude was derived from the PIM model ratios for SPEC to VPEC, by inverting the "thin-shell" formula for ratios calculated during the first full orbit for day 2011-205, and selecting the median shell altitude. Data were restricted to elevations of 60° and above, to avoid the larger errors expected for the conversion from SPEC to VPEC at lower elevations.

Table S1. Simulation data subsets for the first Minimum Standard Deviation bias determination evaluation, with results. Day and Night are designated based on the geometrical eclipse of the Jason-2 satellite.

Latitude	Day/Night	#Samples	Derived Bias	%Change of StdDev from Bias=0 Case
[-75,-45]	Day	2120	1.723	-0.9498
[-75,-45]	Night	251	2.185	-0.8043
[-45,-15]	Day	1129	-3.124	-0.0858
[-45,-15]	Night	851	-1.327	-0.0504
[-15,15]	Day	314	0.075 *	-0.0021
[-15,15]	Night	389	-2.316 *	-0.1632
[15,45]	Day	1168	-0.337	-0.0013
[15,45]	Night	634	1.894 *	-0.0697
[45,75]	Day	2245	1.769 *	-0.9220

For the cases marked with an asterisk, the standard deviation associated with the derived bias is larger than the original standard deviation for the PIM VPEC values (determined directly from the model, rather than using a slant factor).

A global standard deviation minimization for the data set, over all times and locations, was considered invalid, because the VPEC varies considerably with latitude (see Mazzella and Yizengaw, Fig. 5) and also between day and night. Therefore, the simulated data were calibrated in subsets, designated by the first two columns of Table S1. The "Day" and "Night" conditions are determined by the presence or absence of solar illumination of the Jason-2 satellite, as calculated using the solar zenith angle and the geometrical eclipse of the sun by the Earth (neglecting refraction effects). This criterion is different from a selection by Local Time. Because the date studied corresponds to Northern hemisphere summer, there are no nighttime data for the high latitude Northern hemisphere region.

The source of the variability of the derived bias values was investigated using displays for VPEC versus Local Time for each of the data sets. For most of the data sets, small differences for the VPEC profiles could be distinguished as arising solely from the slant factor function (SPEC/VPEC) utilization, compared to the VPEC calculated using PIM. This could be a contributor to the derived bias variability, especially because small standard deviation changes are associated with significant bias differences.

The sensitivity of the bias determinations with respect to the data set selections was examined further, for "Day" and "Night" specifications using nominal Local Time ranges, rather than actual solar illumination, with the Local Time for each data sample evaluated at the median altitude along the line-of-sight to the GPS satellite. The "Day" Local Time range is [07,13] hours, while the "Night" Local Time range is [19,25] hours, but the polar regions were not subdivided by day and night, because of the substantial daylight coverage. The results of these calibrations are presented in Table S2. Note that the data sets for latitude ranges [-45,-15], [-15,15], and [45,75] are the same as those for Table S1, and the corresponding derived bias values agree.

Table S2. Simulation data subsets for the second Minimum Standard Deviation bias determination evaluation, with results. Day and Night are designated based on the Local Time ranges [07,13] and [19,25].

Latitude	Day/Night	#Samples	Derived Bias	Table S1 Bias
[-75,-45]	All	2371	2.406	1.723 (D),2.185 (N)
[-45,-15]	Day	1129	-3.124	-3.124
[-45,-15]	Night	851	-1.327	-1.327
[-15,15]	Day	314	0.075	0.075
[-15,15]	Night	389	-2.316	-2.316
[15,45]	Day	759	11.255	-0.337
[15,45]	Night	1043	-6.257	1.894
[45,75]	Day	2245	1.769	1.769

The sensitivity of the bias determination to the reference altitude (H_s) used for the slant factor function was examined by utilizing a median altitude for each data set, derived from the line-of-sight median altitudes for the associated data samples. These line-of-sight median altitudes are only available for the simulated model data, so a similar model reference would be required for processing actual data. The results of this evaluation are summarized in Table S3, for the same data sets used for Table S1, with the biases from Table S1 also displayed, for comparison. The bias differences tend to be smaller when the reference altitude is close to the nominal reference altitude (2537 km) used for the derivations in Table S1.

Table S3. Simulation data subsets for the third Minimum Standard Deviation bias determination evaluation, with results. Reference altitudes (Hs) are determined separately for each subset.

Latitude	Day/Night	#Samples	H_s	Derived Bias	Table S1 Bias
[-75,-45]	Day	2120	1904	1.499	1.723
[-75,-45]	Night	251	2355	2.137	2.185
[-45,-15]	Day	1129	2330	-2.871	-3.124
[-45,-15]	Night	851	2796	-1.514	-1.327
[-15,15]	Day	314	3325	-1.040	0.075
[-15,15]	Night	389	3809	-4.668	-2.316
[15,45]	Day	1168	2506	-0.289	-0.337
[15,45]	Night	634	3349	1.709	1.894
[45,75]	Day	2245	1746	1.513	1.769

The simulation results presented above are for "ideal" data sets, with no intrinsic noise for the data, although the approximation using a reference altitude and associated formula for the conversion from SPEC to VPEC is employed. However, a distinct feature of processing actual data is the need to align the relative dispersive phase profiles to the absolute (but biased) dispersive group delay profiles. For ground-based GPS measurements, the duration of the data segments used in the alignment process can be several hours, with the shortest usable segments being at least three-quarters of an hour, but for the Jason-2 data, the largest duration for such data segments is only about 50 minutes. Thus, the associated alignment errors can be significant.

Based on comparisons for SPEC cumulative distributions between actual Jason-2 data and simulated data with Gaussian noise (Mazzella and Yizengaw, Fig. 4), the standard deviation for the noise contribution was estimated to be about 0.75 TEC units (1 TEC unit = 10^{16} electrons m^{-2}). To model this level of noise as alignment error, a random Gaussian value, for a standard deviation of 0.75, was assigned to each Jason-2 data segment, designated by a continuous time sequence for a single GPS satellite, to shift the SPEC values. Calibrations using the MSD method were then performed, for the same data subsets designated in Table S1, using the same (global) slant factor reference altitude of 2537 km. These results are summarized in Table S4.

Table S4. Simulation data subsets for the fourth Minimum Standard Deviation bias determination evaluation, for simulated alignment noise, with results.

Latitude	Day/Night	#Samples	Derived Bias	Table S1 Bias
[-75,-45]	Day	2120	1.641	1.723
[-75,-45]	Night	251	4.781	2.185
[-45,-15]	Day	1129	-1.892	-3.124
[-45,-15]	Night	851	-3.644	-1.327
[-15,15]	Day	314	8.880	0.075
[-15,15]	Night	389	7.507	-2.316
[15,45]	Day	1168	0.018	-0.337
[15,45]	Night	634	4.765	1.894
[45,75]	Day	2245	3.960	1.769

Because the data are restricted to elevations above 60°, the maximum slant factor is only about 1.1, for the designated reference altitude of 2537 km. For elevations above 75°, the maximum slant factor is only about 1.03. Thus, the ability to compensate for VPEC offsets produced by noise is significantly restricted, especially if the receiver bias is the only adjustable parameter. (As noted for the Jason-2 PEC analysis (Mazzella and Yizengaw), the ground-based multipath consistency criterion (Andreasen et al., 2002) could not be used for the Jason-2 satellite, because the potential variability of the solar panel orientation invalidates the consistency condition.)

The small derived bias for the latitude = [-15°,15°]/Day case in Table S1 and Table S2 is regarded as fortuitous, especially from consideration of the small number of samples (314). The small derived bias for the latitude = [15°,45°]/Day case in Tables S1, S3, and S4 is somewhat surprising, considering the significant VPEC gradients for this region, but is also regarded as fortuitous, especially in comparison to the results derived for the alternative "Day" selection in Table S2 for this latitude range and the discrepant bias results for the similar selection case for latitude = [-45°,-15°]/Day in Tables S1, S2, S3, and S4. Consequently, the MSD method was not regarded as suitable for the Jason-2 receiver calibration.

S3. SCORE method

For the SCORE method, consistency conditions between pairs of derived Equivalent Vertical Total Electron Content (VPEC) values at common penetration points are applied, in a weighted least squares formulation, to determine the combined GPS receiver and GPS satellite biases (Bishop et al., 1994). In the same manner as the MSD method, the slant plasmasphere electron content, SPEC (= SimPEC - Bias), values are converted to equivalent vertical plasmasphere electron content (VPEC) values using the standard "thin-shell" formula (Eq. (S1)). In addition to a (possibly identical) altitude for the penetration points, H_p, other significant parameters associated with the SCORE calibration are the scale lengths for latitude ($\Delta\theta$), local time ($\Delta\tau$), and Universal Time (ΔT) (Mazzella et. al, 2002), designating the weighting in latitude (θ), local time (τ), and measurement time (T) differences for "common" penetration points for distinct (different GPS satellites) line-of-sight measurements (also described as "conjunctions"). For this study, $\Delta\theta$ = 1.0 degree, $\Delta\tau$ = 0.1 hour, and ΔT = 0.4 hour. Associated with these weightings are strict difference limits of θ_{lim} = 3.0 degrees for latitude, τ_{lim} = 0.3 hour for local time, and T_{lim} = 1.5 hours for Universal Time. The last limit prevents measurements from different Jason-2 orbits from being compared. (The Jason-2 orbital period is approximately 112 minutes, or 1.87 hours (Dumont et al., 2011).) The conjunction restrictions for SCORE are somewhat different from those described by Zhong et al. (2016) using a separation angle.

The SCORPION (SCORE for Plasmasphere and IONosphere) method extends SCORE for the additional determination of the plasmasphere electron content (PEC) for a ground-based receiver, to improve the receiver calibration accuracy. Because of the extended technical features of SCORPION, including full SCORE emulation capabilities, and associated data analysis and display capabilities, SCORPION was used for this study, treating the plasmasphere in the manner that SCORE treats the ionosphere, with no additional parameterized representation of the plasmasphere.

The initial reference altitude for the slant factor formula was chosen to be H_s = 2536.6493 km, which was derived from the PIM model ratios for SPEC to VPEC, by inverting the slant factor formula for PEC ratios calculated during the first full orbit for day 2011-205, and selecting the median slant factor altitude. The same altitude was initially chosen to define the penetration point locations. To accommodate the reduced reliability of a simple slant factor function for the plasmasphere, an elevation threshold of 60° was imposed (in contrast to the 35° elevation threshold typically used for ground-based calibrations).

For evaluation, the data samples associated with conjunctions were plotted separately, and produced a set of disjoint segments in time and latitude in the vicinity of the Jason-2 orbit. Only 501 samples were selected, which produce 551 unique conjunction pairs, associated with only 26 of the available 31 GPS satellites.

Although the standard calibration mode for SCORE/SCORPION is to determine the combined satellite and receiver biases for each of the GPS satellites, the small number of samples and conjunction pairs, and the incomplete satellite inclusion, favored the receiver-only calibration mode (initially described by Andreasen et al., 1998), for which the relative satellite biases are removed from the raw slant PEC measurements. This mode also more closely resembles the Minimum Standard Deviation method. Geographic coordinates were used in the implementation of SCORE, and are optional for SCORPION, but geomagnetic coordinates were used for this SCORPION calibration, because they are more suitable for the plasmasphere.

For simulated data from the PIM/Gallagher model, the derived bias was -0.585 TEC units, which is close to the expected value of zero. Because the relative GPS satellite biases are generally known, and in this simulation are known exactly (as zero), the full PEC profile (above the 60° elevation threshold) can be generated, and is displayed in Fig. S1.

The correspondence in equivalent vertical PEC between the samples of each conjunction pair was also examined. The TEC differences between corresponding samples lie in the range [-1.61,1.17] TEC units, with a mean difference of 0.03 TEC units and a standard deviation of 0.32 TEC units. Thus, for the most favorable conditions, the SCORE-emulation method appears to produce reasonable results.

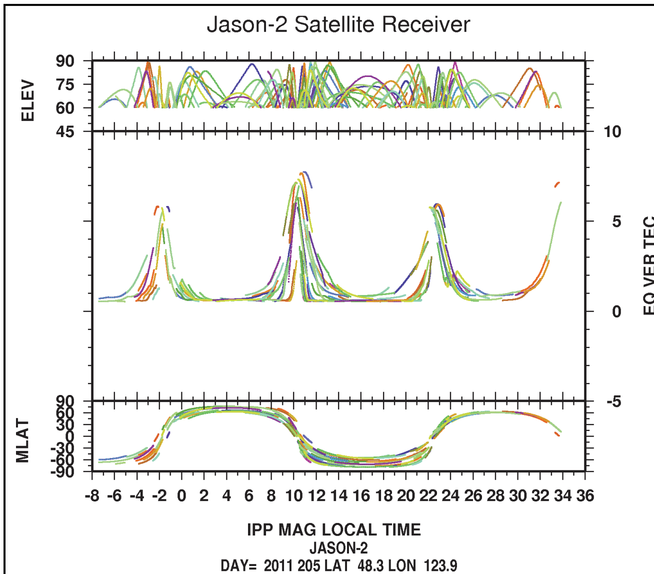

Figure S1. Full vertical PEC profile, for derived bias from simulated data, applied to all PRNs and all data samples (not solely conjunction samples) versus magnetic local time at the penetration point, with magnetic latitude for the penetration point in the bottom panel, equivalent vertical TEC for the plasmasphere in the middle panel, and elevation angle for the line-of-sight in the top panel. (The local time spans more than 24 hours because of contiguous continuity conditions for the data segments.)

For a more realistic simulation, data segments with alignment error noise were used. These are the same data that were prepared for the MSD method simulation displayed in Table S4, with a noise standard deviation of 0.75 TEC units. The derived receiver bias was 3.80 TEC units, so a significant fraction (>80%) of the derived VTEC values are negative. (See Fig. S2.) The TEC differences between corresponding samples are significantly larger than for the noise-free case, lying in the range [-2.28,1.97] TEC units, with a mean difference of -0.06 TEC units and a standard deviation of 1.07 TEC units.

Because SCORE/SCORPION can determine biases associated with the individual GPS satellites (but combined with the receiver bias), that mode of operation was applied to the noise-added Jason-2 simulation case. For ground-based GPS data, this can be advantageous, especially when each GPS satellite appears only once per day, because then the residual alignment errors are incorporated into the bias determinations. However, for satellites that appear twice, in different regions of the sky, the residual alignment errors can be different for the two occurrences, and the resulting diurnal VTEC profile can be slightly distorted. For Jason-2, with multiple occurrences for each GPS satellite during the day, the distortions could be more frequent but also more localized, because the continuous data segments are relatively short (the longest segment is less than 52 minutes). The initial application of this alternative calibration produced bias values in the range [-1.149,17.407] TEC units, with the biases occurring in three disjoint clusters, [-1.149,1.963], [2.996,3.738], and [16.565,17.407], having a mean value of 4.155 TEC units, which was used for all of the GPS satellites without conjunction pairs. The largest biases produce significantly negative VTEC values, distinctly separated from the remainder of the data (Fig. S3). This separation of VTEC values arises from the absence of common conjunction pairs between at least two groups of GPS satellites. (In this case, there are five distinct groups of conjunction pairs, with only one having distinctly different biases and associated VTEC values.) Because SCORPION can accommodate a subset of relative bias assignments, it is possible to somewhat alleviate this large separation of VTEC values by assigning a relative bias difference between a pair of GPS satellites, for one in each group. In this case, the relative bias association was defined for PRN 2 and PRN 6, which had overlapping segments in local time, but these occurred on successive orbits. For the simulation, the assigned bias difference was zero. The resulting local time variation for VTEC (Fig. S4) showed at least three profiles with separations of about 4 TEC units, but not completely disjoint. The range of VTEC values was [-7.962,6.271] TEC units, essentially as a uniform distribution, with fluctuations, over the range [-8,1] TEC units and a tail extending to 6.27 TEC units. Approximately 80% of all VTEC values were negative. The associated bias range was [-1.149,7.914] TEC units, with an average value of 4.709 TEC units for the derived biases. (This average bias was used for the five GPS satellites without any conjunctions.)

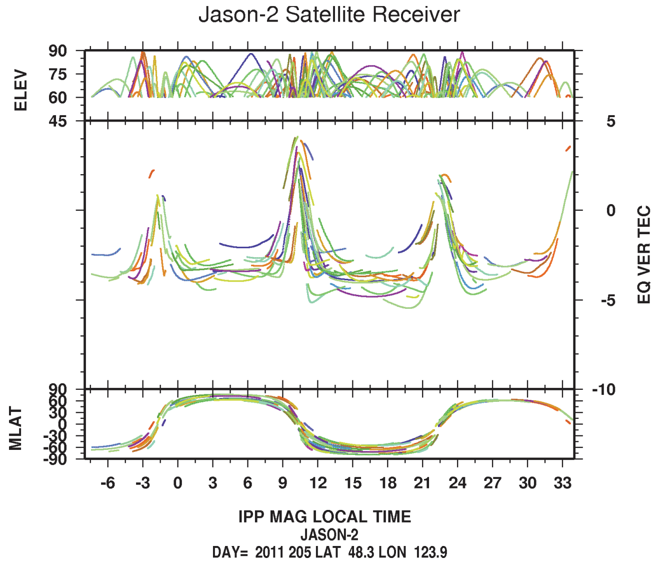

Figure S2. Full vertical PEC profile, for derived bias from simulated data segments with added alignment error noise.

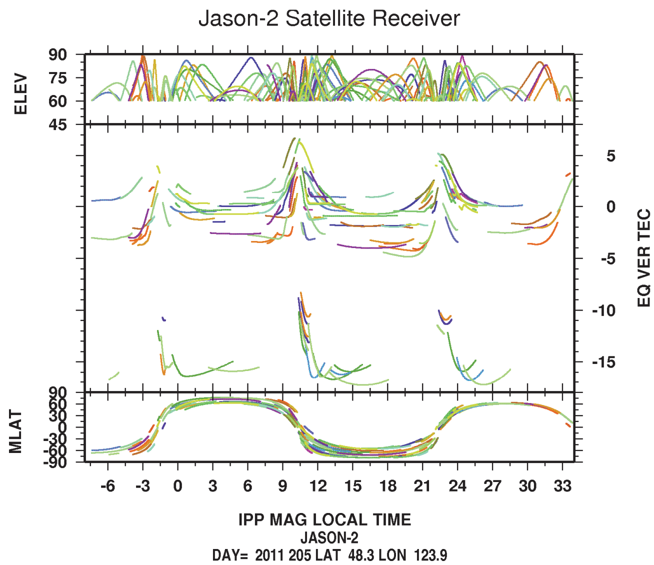

Figure S3. Full vertical PEC profile, for derived individual GPS satellite biases from simulated data segments with alignment error noise, indicating disjoint clusters of conjunctions.

For the actual data, a set of SCORE/SCORPION receiver-only calibrations was performed, for various combinations of the slant factor altitude H_s and the penetration point altitude H_p. As described by Mazzella and Yizengaw (accompanying paper), the minimum raw slant PEC for the data was 16.949 TEC units, with a model PEC correction (not applied) of 0.021 TEC units and an additional correction (not applied) estimated as 2.962 TEC units arising from the tail of a Gaussian noise distribution, so the SCORE/SCORPION bias estimates, if accurate, should fall approximately within the range 17-20 TEC units, with the percentage of negative slant PEC values ranging up to about 17%. The results are summarized in Table S5, arranged in order of increasing receiver bias values.

These results are somewhat better than expected from the simulated receiver-only calibration for noisy data, which had a derived receiver bias (error) of 3.80 TEC units. However, the statistically derived bias value (19.890 = 16.949 - 0.021 + 2.962, for actual data) was still considered as a better determination.

Table S5. Summary of results for SCORE/SCORPION receiver-only calibrations of actual Jason-2 data.

PPAlt (km)	H_s (km)	Bias	#Samples	#Pairs
2536.6493	2536.6493	17.263	502	548
2668.	2668.	17.272	454	491
2800.	2800.	17.310	429	431
2855.	2855.	17.556	410	415
2427.	2427.	17.596	540	602
2318.	2318.	17.866	565	642
2100.	2536.6493	17.930	672	759
3173.	3173.	17.993	336	332
2100.	2100.	18.252	672	759
5591.25	2536.6493	19.170*	323	571
5591.25	2536.6493	21.235	103	161

*Used θ_{lim} = 5.34 degrees, τ_{lim} = 0.53 hour, $\Delta\theta$ = 1.78 degrees, $\Delta\tau$ = 0.18 hour.

Except as noted, the parameter values associated with the conjunction comparisons were:

θ_{lim} = 3.0 degrees, τ_{lim} = 0.3 hour, T_{lim} = 1.5 hours, $\Delta\theta$ = 1.0 degree, $\Delta\tau$ = 0.1 hour, ΔT = 0.4 hour.

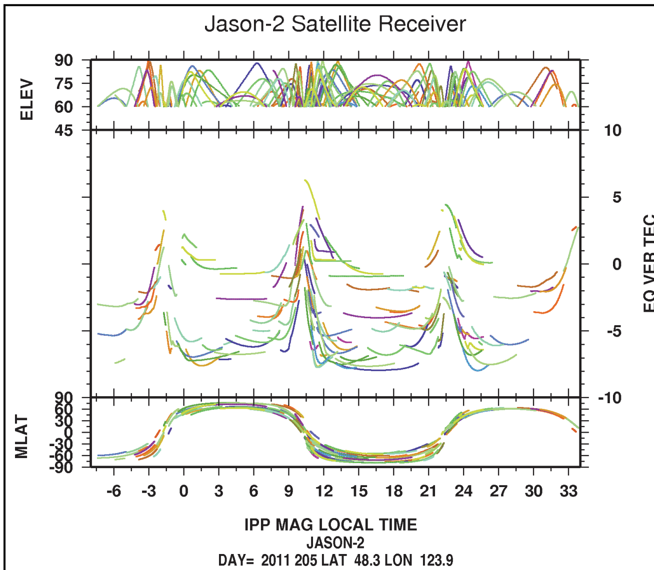

Figure S4. Full vertical PEC profile, for derived individual GPS satellite biases from simulated data segments with added alignment error noise, after defining bias relation between PRN 2 and PRN 6.

References

Andreasen, A. M., Holland, E. A., Fremouw, E. J., Mazzella, A. J., Rao, G. S., and Secan, J. A.: Investigations of the nature and behavior of plasma-density disturbances that may impact GPS and other transionospheric systems, AFRL-VS-TR-2003–1540, Air Force Res. Lab., Hanscom Air Force Base, Mass., 2002.

Andreasen, C. C., E. J. Fremouw, A. J. Mazzella, Jr., G. S. Rao, and J. A. Secan, Further Investigations of Ionospheric Total Electron Content and Scintillation Effects on Transionospheric Radiowave Propagation, AFRL-VS-HA-TR-98-0037, Air Force Res. Lab., Hanscom Air Force Base, Mass., 1998.

Bishop, G., D. Walsh, P. Daly, A. Mazzella, and E. Holland, Analysis of the temporal stability of GPS and GLONASS group delay correction terms seen in various sets of ionospheric delay data, Rep. ION GPS-94, Inst. of Navig., Washington, D.C., 1994.

Daniell, R. E., Brown, L. D., Anderson, D. N., Fox, M. W., Doherty, P. H., Decker, D. T., Sojka, J. J., and Schunk, R. W.: PIM: A global ionospheric parameterization based on first principles models, Radio Sci., 30, 1499–1510, 1995.

Dumont, J.P., Rosmorduc, V., Picot, N., Bronner, E., et al.: OSTM/Jason-2 Products Handbook, OSTM-29-1237, JPL, 2011.

Gallagher, D. L., Craven, P. D., and Comfort, R. H.: An empirical model of the Earth’s plasmasphere, Adv. Space Res., 8(8), 15–24, 1988.

Mazzella, A. J. and Yizengaw, E.: A Comparison of Jason-2 Plasmasphere Electron Content Measurements to Ground-based Measurements, (accompanying paper)

Mazzella, A. J., Holland, E. A., Andreasen, A. M., Andreasen, C. C., Rao, G. S., and Bishop, G. J.: Autonomous estimation of plasmasphere content using GPS measurements, Radio Sci., 37, 1092–1095, doi:10.1029/2001RS002520, 2002.

Valladares, C. E., Villalobos, J., Hei, M. A., Sheehan, R., Basu, Su., MacKenzie, E., Doherty, P. H., and Rios, V. H., Simultaneous observation of travelling ionospheric disturbances in the Northern and Southern Hemispheres, Ann. Geophys., 27, 1501–1508, doi:10.5194/angeo-27-1501-2009, 2009.

Wessel, P., and Smith, W. H. F.: New, improved version of Generic Mapping Tools released, Eos Trans. AGU, 79(47), 579, doi:10.1029/98EO00426, 1998.

Zhong, J., Lei, J., Yue, X., and Dou, X.: Determination of Differential Code Bias of GNSS Receiver Onboard Low Earth Orbit Satellite, IEEE Transactions on Geoscience and Remote Sensing, 54(8), 4896-4905, doi:10.1109/TGRS.2016.2552542, 2016.