Looking for optimal ways to combine global ionospheric maps in real-time

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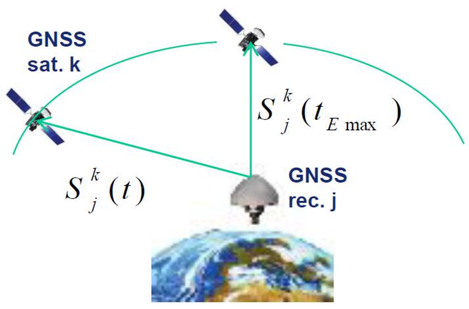
Summary: The goal of this poster is to summarise the study, definition, implementation and continuous operation of a first version of the real-time combination of Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC) in the context of the International GNSS Service (IGS). In this way we fulfill the corresponding Action Item committed during the previous IGS WS 2017 in Paris *(Hernández-Pajares et al. 2017).*

1. Real-time assessment based on GNSS-dSTEC

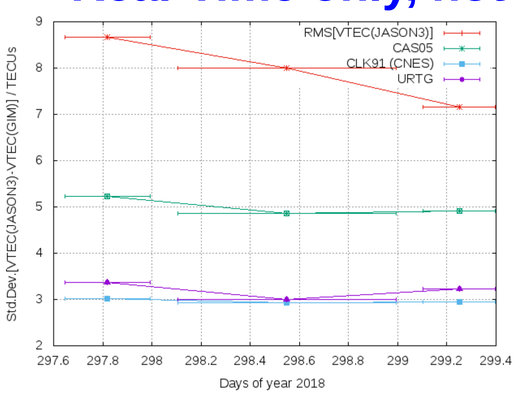
RT Weighting scheme	PROS	CONS
[A] "Self-consistency" (reference: L1-L2 at the same elevation in the same phase continuous arc...)	The same which is being already applied for final and rapid combination with common mapping	We have to wait to the second (elevation-decreasing) half of each arc, i.e. half number of performance estimations...
[B] "dSTEC" (reference: L1-L2 at max. elev. ....)	Well characterized (e.g. recent paper); it only demands to store the reference LI, which is less affected by mapping errors	Same than [A] "Self-consistency"
[C] "RT-dSTEC" (The first L1-L2 measurement in the arc is taken as reference)	Full data availability, only one data stored per arc	The low elev. Ref. STEC is typically the (or one of the) very bad estimated ones, affecting all the time series.
[D] = [C] (during the ascending arc part) + [A] (during the descending part)	Full data availability, only one memory record per arc (updated at max. elevation).	Potential "overweight" of the first low-elevation reference ray (potentially mitigated with elev. mask).

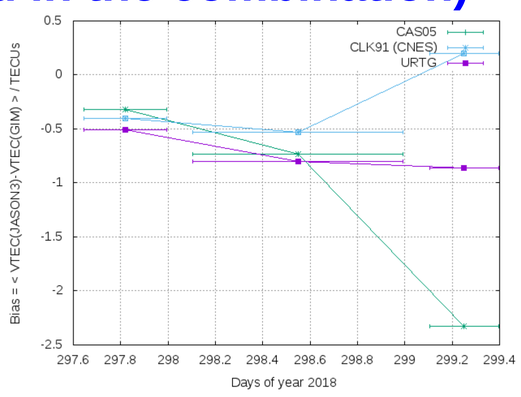


$$\Delta S_O \equiv S_j^k(t) - S_j^k(t_{E\,max}) \approx M \cdot V(t) - M_{E\,max} \cdot V(t_{E\,max})$$

- We take as reference the first available dual-frequency phase-based ionospheric meas when the elevation is >10º (an optimal approach, following *Hernández-Pajares et al. 2018*).

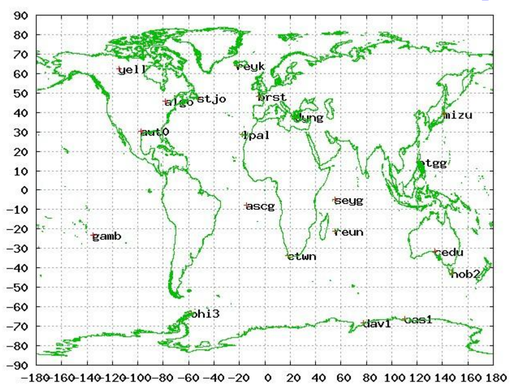
2. Standard Deviation and Bias of GIM VTEC vs JASON3 VTEC observations (external & near Real-Time only, not used in the combination)

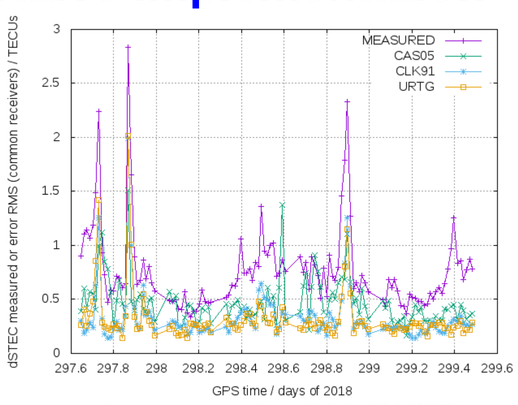




- CNES (CLK91) and UPC (URTG) RT-GIMs show a very similar performance: Standard Deviation around 3 - 3.5 TECUs, in front of a RMS of less than 7-9 TECU for the measured TEC (days 297.6 to 299.4, 24-26 October 2018).
- The bias appears a bit more stable for URTG during this recent short period and such very first RTcomparisons.

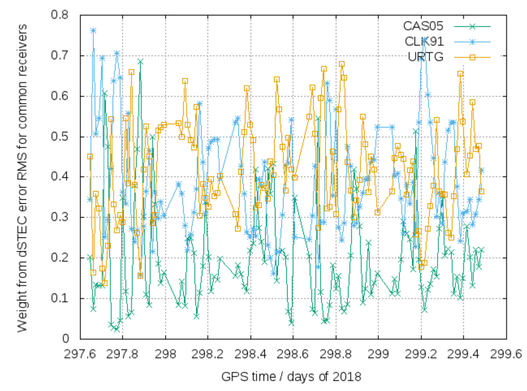
3. dSTEC RMS of common worldwide receivers in the first Real-Time operative implementation





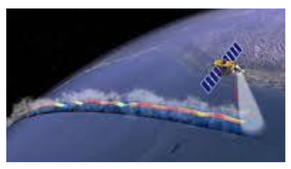
- The common receivers (presently 20, see map) among the ones used by CAS (CAS05), CNES (CLK91) and UPC (URTG) are used to estimate the corresponding dSTEC RMS. The inverse of the squared RMS is used as the global time-varying weight for each RT-GIM (see next plot).
- In this very first common RT runs CLK91 and URTG show similar results, slightly better than CAS05, similarly to the external assessment vs JASON3 VTEC (see section 2 above).

4. RT-GIM weights in the first Real-Time operative implementation



- The weights, derived from the normalized inverse of the dSTEC RMS over the same measurements of the common receivers, each 20 minutes, are shown in the left-hand plot.
- CLK91 show typically a similar weight than URTG during these very first common RT results.

5. External JASON-3 VTEC assessment of the RT-dSTEC-error-weighted IGS GIM (IRTG, 25/10/18)



jason3.ionex.cas0.18298 **RT-CAS**

Validation with JASON: <TEC_JASON - TEC_GPS> [TECU] (reference day of year: 298)

Bias	Sigma	RMS	VTEC	%ERR	#OBS
-0.73	4.86	4.92	8.00	61.5	41085

UT(hours)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
2.00	-3.29	4.37	5.47	4.62	118.2	227
4.00	-1.20	6.53	6.64	8.90	74.6	4075
6.00	-1.24	5.21	5.35	8.01	66.9	4232
8.00	-2.59	4.18	4.92	6.45	76.2	3765
10.00	-0.86	4.31	4.39	7.05	62.3	3893
12.00	0.29	3.57	3.58	7.94	45.1	3427
14.00	-0.64	2.41	2.49	6.52	38.2	3520
16.00	-0.94	3.84	3.95	7.43	53.2	4460
18.00	0.87	4.62	4.70	9.88	47.5	3558
20.00	1.24	4.85	5.01	10.13	49.4	3612
22.00	-0.35	5.76	5.77	8.51	67.8	4605
24.00	-3.77	4.64	5.98	6.68	89.6	1711

Lat(deg)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
-60.00	1.12	2.48	2.72	4.99	54.6	7138
-40.00	-0.89	3.12	3.24	6.06	53.5	8439
-20.00	-1.83	5.24	5.55	8.91	62.3	6567
0.00	-0.56	7.05	7.07	12.58	56.2	6222
20.00	-0.50	6.52	6.54	10.29	63.5	5524
40.00	-1.30	3.57	3.80	7.26	52.4	4422
60.00	-2.29	2.87	3.67	5.81	63.1	2773

jason3.ionex.clk9.18298 **RT-CNES**

Validation with JASON: <TEC_JASON - TEC_GPS> [TECU] (reference day of year: 298)

Bias	Sigma	RMS	VTEC	%ERR	#OBS
-0.53	2.93	2.98	8.00	37.3	41085

UT(hours)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
2.00	-3.21	2.73	4.22	4.62	91.2	227
4.00	-0.42	3.82	3.85	8.90	43.2	4075
6.00	-0.23	2.95	2.96	8.01	36.9	4232
8.00	0.37	2.55	2.57	6.45	39.9	3765
10.00	-0.11	2.97	2.97	7.05	42.2	3893
12.00	-1.35	2.12	2.51	7.94	31.6	3427
14.00	-1.81	3.35	3.80	6.52	58.4	3520
16.00	-1.09	2.47	2.70	7.43	36.3	4460
18.00	0.48	3.23	3.26	9.88	33.0	3558
20.00	-0.04	2.68	2.68	10.13	26.5	3612
22.00	-0.54	2.17	2.24	8.51	26.3	4605
24.00	-1.50	2.19	2.65	6.68	39.7	1711

Lat(deg)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
-60.00	1.41	2.19	2.61	4.99	52.3	7138
-40.00	-0.31	2.24	2.26	6.06	37.4	8439
-20.00	-0.35	2.29	2.32	8.91	26.0	6567
0.00	-1.24	3.53	3.74	12.58	29.7	6222
20.00	-2.48	3.83	4.56	10.29	44.3	5524
40.00	-1.12	2.29	2.55	7.26	35.1	4422
60.00	-0.23	1.53	1.55	5.81	26.6	2773

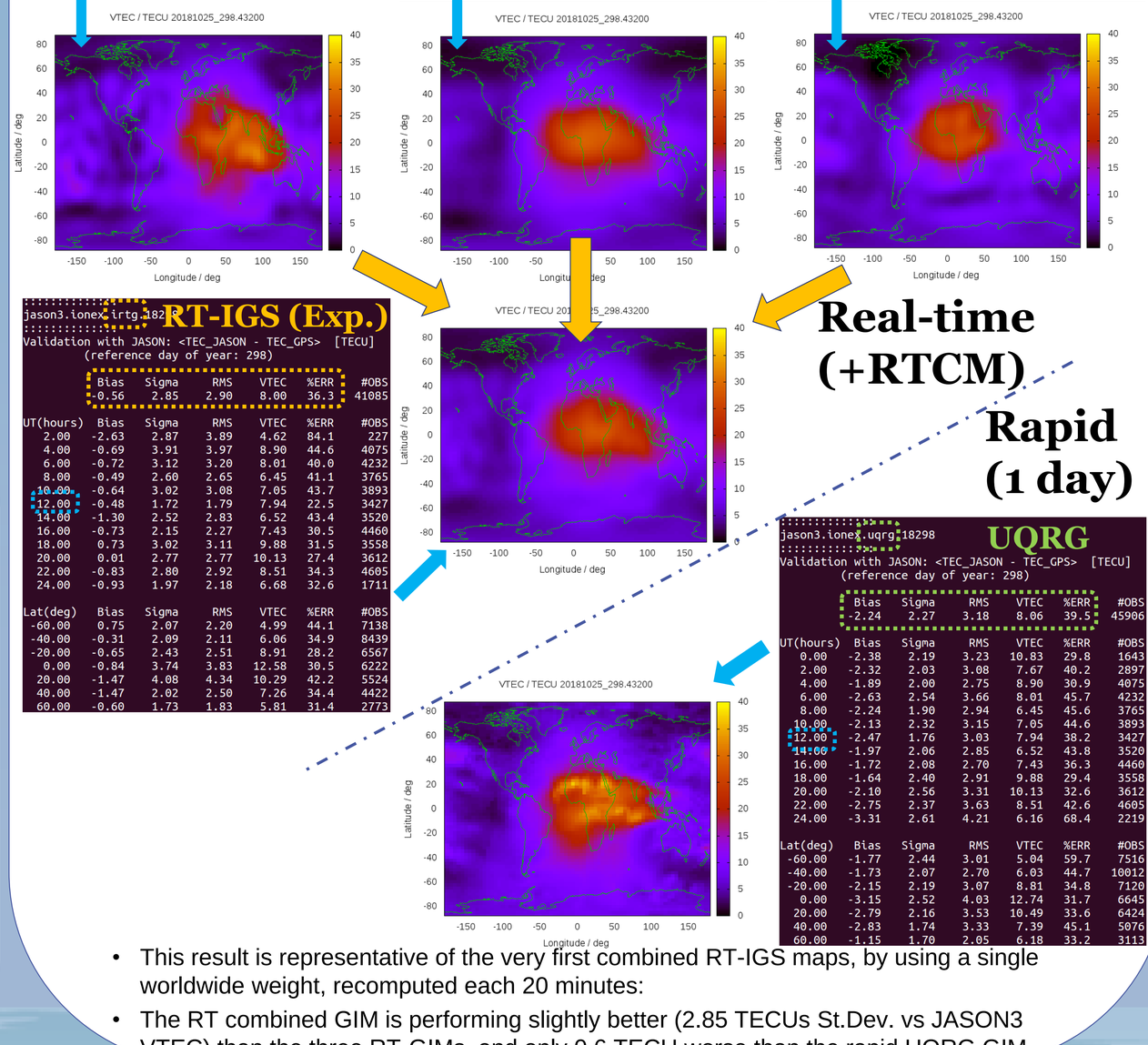
jason3.ionex.urtg.18298 **RT-UPC**

Validation with JASON: <TEC_JASON - TEC_GPS> [TECU] (reference day of year: 298)

Bias	Sigma	RMS	VTEC	%ERR	#OBS
-0.80	3.00	3.10	8.00	38.8	41085

UT(hours)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
2.00	-1.00	2.03	2.26	4.62	48.9	227
4.00	-0.56	3.55	3.59	8.90	40.3	4075
6.00	-1.12	3.51	3.68	8.01	46.0	4232
8.00	-0.73	3.31	3.39	6.45	52.6	3765
10.00	-1.01	3.51	3.66	7.05	51.9	3893
12.00	-0.99	2.33	2.53	7.94	31.9	3427
14.00	-1.36	2.29	2.66	6.52	40.8	3520
16.00	-0.49	2.88	2.92	7.43	39.3	4460
18.00	-0.22	2.85	2.86	9.88	28.9	3558
20.00	-0.79	2.71	2.82	10.13	27.8	3612
22.00	-1.21	2.53	2.81	8.51	33.0	4605
24.00	0.34	2.46	2.49	6.68	37.2	1711

Lat(deg)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
-60.00	-0.25	2.47	2.49	4.99	49.8	7138
-40.00	-0.10	2.49	2.50	6.06	41.2	8439
-20.00	-1.01	2.66	2.85	8.91	32.0	6567
0.00	-1.17	3.80	3.98	12.58	31.6	6222
20.00	-1.37	4.03	4.26	10.29	41.3	5524
40.00	-2.01	2.09	2.90	7.26	40.0	4422
60.00	0.05	1.91	1.91	5.81	32.8	2773



jason3.ionex.irtg.182 **RT-IGS (Exp.)**

Validation with JASON: <TEC_JASON - TEC_GPS> [TECU] (reference day of year: 298)

Bias	Sigma	RMS	VTEC	%ERR	#OBS
-0.56	2.85	2.90	8.00	36.3	41085

UT(hours)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
2.00	-2.63	2.87	3.89	4.62	84.1	227
4.00	-0.69	3.91	3.97	8.90	44.6	4075
6.00	-0.72	3.12	3.20	8.01	40.0	4232
8.00	-0.49	2.60	2.65	6.45	41.1	3765
10.00	-0.64	3.02	3.08	7.05	43.7	3893
12.00	-0.48	1.72	1.79	7.94	22.5	3427
14.00	-1.30	2.52	2.83	6.52	43.4	3520
16.00	-0.73	2.15	2.27	7.43	30.5	4460
18.00	0.73	3.02	3.11	9.88	31.5	3558
20.00	0.01	2.77	2.77	10.13	27.4	3612
22.00	-0.83	2.80	2.92	8.51	34.3	4605
24.00	-0.93	1.97	2.18	6.68	32.6	1711

Lat(deg)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
-60.00	0.75	2.07	2.20	4.99	44.1	7138
-40.00	-0.31	2.09	2.11	6.06	34.9	8439
-20.00	-0.65	2.43	2.51	8.91	28.2	6567
0.00	-0.84	3.74	3.83	12.58	30.5	6222
20.00	-1.47	4.08	4.34	10.29	42.2	5524
40.00	-1.47	2.02	2.50	7.26	34.4	4422
60.00	-0.60	1.73	1.83	5.81	31.4	2773

Real-time (+RTCM)

Rapid (1 day)

jason3.ionex.uqrg.18298 **UQRG**

Validation with JASON: <TEC_JASON - TEC_GPS> [TECU] (reference day of year: 298)

Bias	Sigma	RMS	VTEC	%ERR	#OBS
-2.24	2.27	3.18	8.06	39.5	45906

UT(hours)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
0.00	-2.38	2.19	3.23	10.83	29.8	1643
2.00	-2.32	2.03	3.08	7.67	40.2	2897
4.00	-1.89	2.00	2.75	8.90	30.9	4075
6.00	-2.63	2.54	3.66	8.01	45.7	4232
8.00	-2.24	1.90	2.94	6.45	45.6	3765
10.00	-2.13	2.32	3.15	7.05	44.6	3893
12.00	-2.47	1.76	3.03	7.94	38.2	3427
14.00	-1.97	2.06	2.85	6.52	43.8	3520
16.00	-1.72	2.08	2.70	7.43	36.3	4460
18.00	-1.64	2.40	2.91	9.88	29.4	3558
20.00	-2.10	2.56	3.31	10.13	32.6	3612
22.00	-2.75	2.37	3.63	8.51	42.6	4605
24.00	-3.31	2.61	4.21	6.16	68.4	2219

Lat(deg)	Bias	Sigma	RMS	VTEC	%ERR	#OBS
-60.00	-1.77	2.44	3.01	5.04	59.7	7516
-40.00	-1.73	2.07	2.70	6.03	44.7	10012
-20.00	-2.15	2.19	3.07	8.81	34.8	7120
0.00	-3.15	2.52	4.03	12.74	31.7	6645
20.00	-2.79	2.16	3.53	10.49	33.6	6424
40.00	-2.83	1.74	3.33	7.39	45.1	5076
60.00	-1.15	1.70	2.05	6.18	33.2	3113

- This result is representative of the very first combined RT-IGS maps, by using a single worldwide weight, recomputed each 20 minutes:
- The RT combined GIM is performing slightly better (2.85 TECUs St.Dev. vs JASON3 VTEC) than the three RT-GIMs, and only 0.6 TECU worse than the rapid UQRG GIM.

Conclusions and Future Work

- A first combination of RT GIMs (IRTG) is continuously and consistently working at UPC facilities, fulfilling the commitment from previous IGS WS 2017.
- IRTG is being obtained by computing, each 20 minutes, a new global weight for each one of the three independent RT-GIMs: from CAS (CAS05), CNES (CLK91) and UPC (URTG).
- The weights are given by the inverse of the squared RMS of the dSTEC error, taking as reference observation the first one of each given phase-continuous-transmitter-receiver arc during the last hour with elevation higher than 10º, and with a difference of at least 25º with the first one, and a minimum of 50 observations per arc.
- The performance of the first RT combinations, compared with the external JASON-3 VTEC, seems slightly better than the one of the combined RT-GIMs.
- The potential performance improvement after double checking the RTCM encoding of all the GIMs and after adding a geographical variability in the weight, including the spectral domain, can be studied in the future.

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