Real-time Retrievals of ZTD and PWV from GNSS Precise Point Positioning

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RMIT UNIVERSITY

IGS Workshop 2016
Feb 8-12, Sydney, Australia

Abstract

This study investigates the retrievals of zenith total delay (ZTD) and precipitable water vapour (PWV) using the real-time precise point positioning (PPP) approach, based on the BKG NTRIP Client (BNC) and its modifications. Results are validated using GPS observations at 20 globally distributed stations in a period of one month. The derived ZTDs agree well with the tropospheric products from the International GNSS Service (IGS) and the root mean square (RMS) of the discrepancies is <13 mm. The RMS errors of the PWV in comparison with radiosonde data are ≤3 mm. The theoretical accuracy of PWV in various conditions is also analysed. The RMS error of PWV is proved to be a strictly increasing function of zenith wet delay (ZWD) and weighted mean temperature T_m. Hence the retrieval of PWV is more challenging in higher temperature and humidity conditions. This research proves that even in "unfavorable" retrieval conditions (e.g. ZWD is 0.6 m and T_m is 294K respectively), an accuracy of at 3 mm level for PWV is still achievable using the real-time ZTD from PPP and the empirical models for T_m. Preliminary studies of ZTD retrievals using multi-GNSS data are also conducted. The addition of GLONASS observations significantly increases the number of visible satellites and improves the Dilution of Precision (DOP) indices. However, a test at 12 global IGS stations shows that adding GLONASS data slightly degrades the accuracies of ZTDs. This is potentially caused by the lower accuracy of real-time GLONASS orbit and clock products currently available.

Processing Strategy

- Data is processed in real time with a 30s interval
- GPT2 rather than the more accurate VMF1-FC is implemented in BNC to provide the *a priori* ZHD and mapping functions. This simplifies the PPP data processing at a large number of stations
- BNC is used to provide ZTD rather than ZWD directly as any errors in the *a priori* ZHD derived from GPT2 will be absorbed into the ZWD estimates. In addition, ZTD rather than ZWD is typically used in meteorological data assimilations. Thirdly, it can provide a long term pressure reference, in particular for dry and polar regions where ZWD is small.
- GPT2 also provides the surface pressure for the calculation of weighted mean temperature

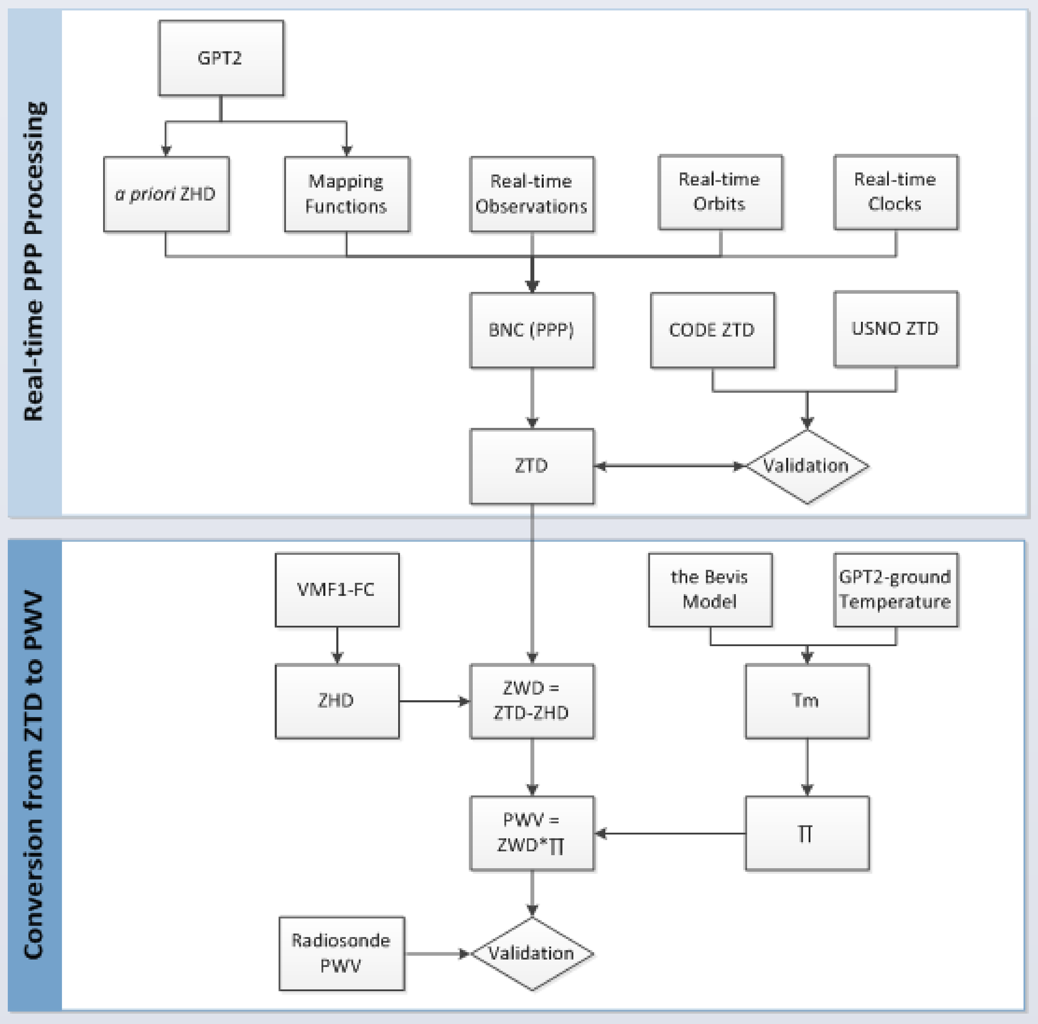

Fig. 1: Flow chart of real-time retrieval of ZTD and PWV using the PPP technique

BKG Ntrip Client – Modifications

BNC Version 2.8 runs under RHEL 6, based on the following modifications to cater for the real-time retrievals of ZTD

- GPT2 has been implemented to provide the *a priori* ZHD and mapping functions
- Antenna-related corrections: 1) The satellite phase center offset (PCO) correction is not necessary as the real-time orbit and clock products from BKG are referred to the same phase centre; 2) The satellite phase center variation (PCV), receiver PCO and PCV have been calibrated using the IGS absolute antenna models
- Error corrections for solid Earth tide and ocean tide loading have been implemented using the latest IERS conventions (2010)

GPS-only ZTD

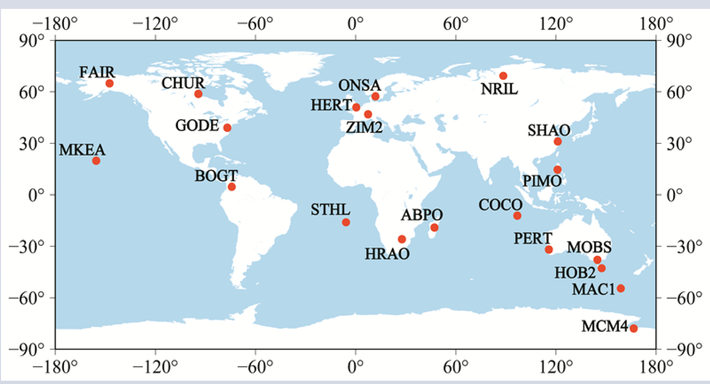

Fig. 2: Distribution of stations selected for the tests. The collected data includes real-time GPS measurements, IGS ZTD and radiosonde (radiosonde sites are within 60 km distance)

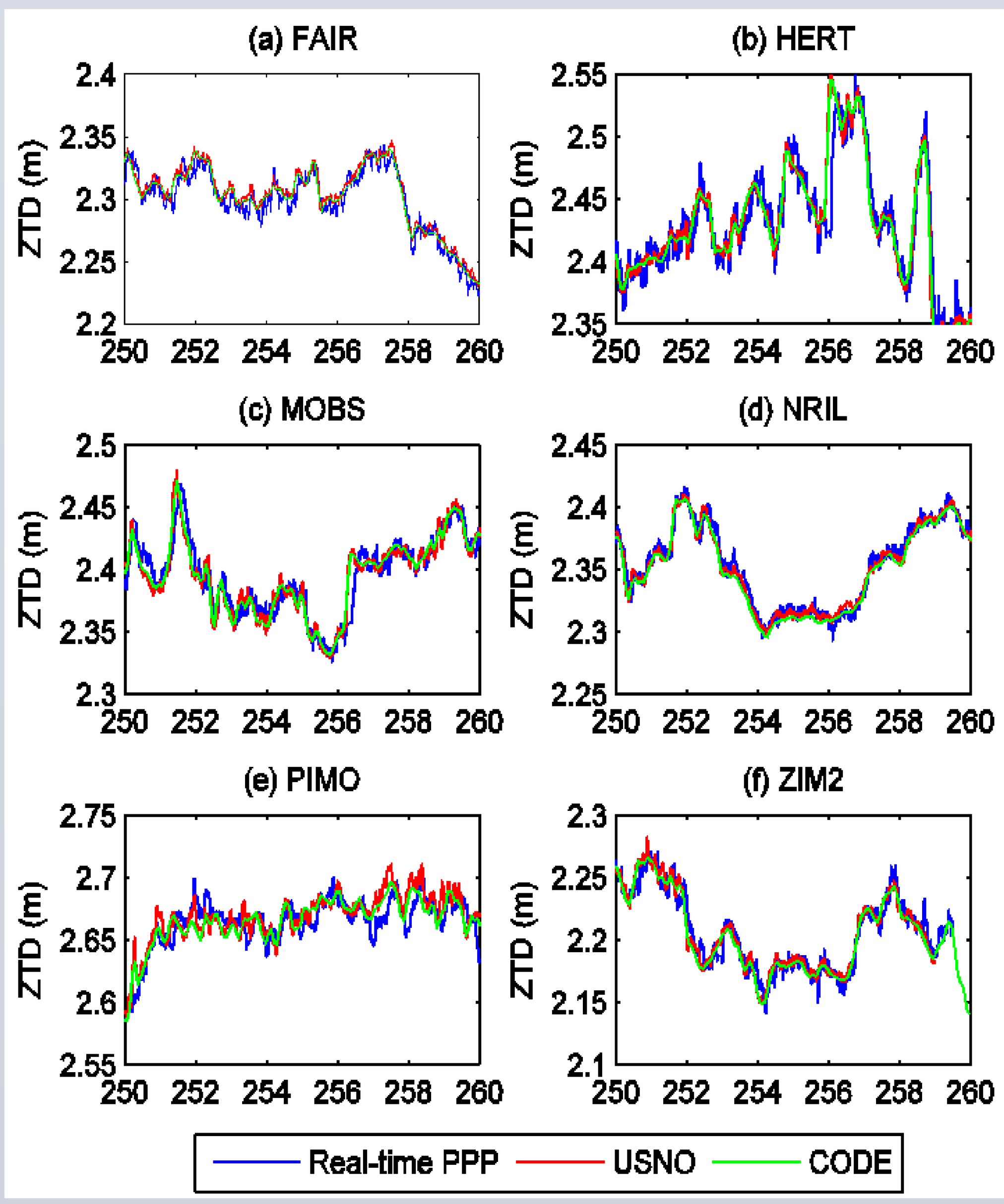

Fig. 3: ZTD from real-time PPP, USNO and CODE at six IGS stations during DOY 250-260, 2013. PIMO is a station where PPP-ZTDs show poorer agreement with the reference data. HERT is a station where real-time GPS data suffers from internet instability at the end of DOY 255. The other four stations are presented here for comparisons

Sites	PPP – CODE bias	STD	RMS	<20	PPP – USNO bias	STD	RMS	<20	USNO – CODE bias	STD	RMS	<20
ABPO	-2.6	7.9	8.3	97	-2.8	8.8	9.2	96	1.0	4.4	4.5	100
BOGT	0.1	9	9	97	-1.2	9.6	9.6	95	1.3	5.8	5.9	99
CHUR	0.7	8.8	8.8	96	1.4	9.4	9.5	95	-1.0	3.3	3.4	99
COCO	3.4	10.4	11	94	3.2	11.1	11.5	91	0.1	4.7	4.7	99
FAIR	1.7	7.1	7.3	98	4.4	7.4	8.6	97	-2.3	3.4	4.1	99
GODE	0.6	11.5	11.6	95	1.2	11.6	11.7	92	0.1	4.3	4.3	99
HERT	0.8	10.5	10.5	95	1.1	11.8	11.8	94	-0.3	4.6	4.6	100
HOB2	1.2	9.5	9.6	95	1.1	10.6	10.7	93	-0.7	4.3	4.4	100
HRAO	2.3	9	9.3	95	1.8	8.9	9.1	96	0.6	4.8	4.9	99
MAC1	-0.1	7.2	7.2	99	0.8	7.5	7.6	98	-2.0	3.5	4.1	100
MCM4	-1.2	5.5	5.6	99	4.3	5.2	6.8	99	-6.2	2.8	6.8	100
MKEA	5.1	6.4	8.1	98	5.5	6.5	8.5	98	-0.9	5.0	5.0	99
MOBS	-0.3	9.6	9.6	94	-1	10.8	10.9	93	-0.1	4.3	4.3	100
NRIL	-2.8	5	5.7	99	-0.4	5.7	5.7	99	-2.7	2.7	3.8	100
ONSA	1.3	8.4	8.5	97	1.4	9.1	9.2	96	0	4.1	4.1	100
PERT	-1.2	10.2	10.2	94	0.3	11.4	11.4	92	-1.0	4.3	4.4	100
PIMO	0.8	11.6	11.6	90	2.5	12.5	12.7	88	-2.2	7.2	7.5	98
SHAO	-1.3	11.1	11.2	92	-0.4	11.4	11.4	93	-1.5	4.7	4.9	99
STHL	9.8	6.8	11.9	92	6.4	7.9	10.2	95	1.9	4.6	5.0	100
ZIM2	-1.1	8.1	8.1	96	0.3	8.4	8.4	97	-1.3	4.1	4.3	100

Tab. 1: Mean bias, STD, RMS and percentage of values below 20 mm (the threshold value for weather nowcasting) of the differences between the RT PPP-ZTD and IGS products from USNO and CODE during Sept 2013

Column USNO-CODE shows that the RMS errors between the CODE and USNO ZTDs vary from 3.4mmto 7.5 mm. Columns PPP-CODE and PPP-USNO show that the STD and RMS of PPP-ZTD are <12mm with respect to the CODE ZTD and <13mm with respect to the USNO ZTD. This shows that the retrieved ZTD is accurate enough as inputs to NWP models as 15 mm is the threshold as is suggested by *De Haan* (2006).

The three stations located in the tropics or subtropics, i.e., COCO, PIMO, and SHAO, tend to show larger RMS in ZTD with respect to the reference data

GPS+GLONASS ZTD

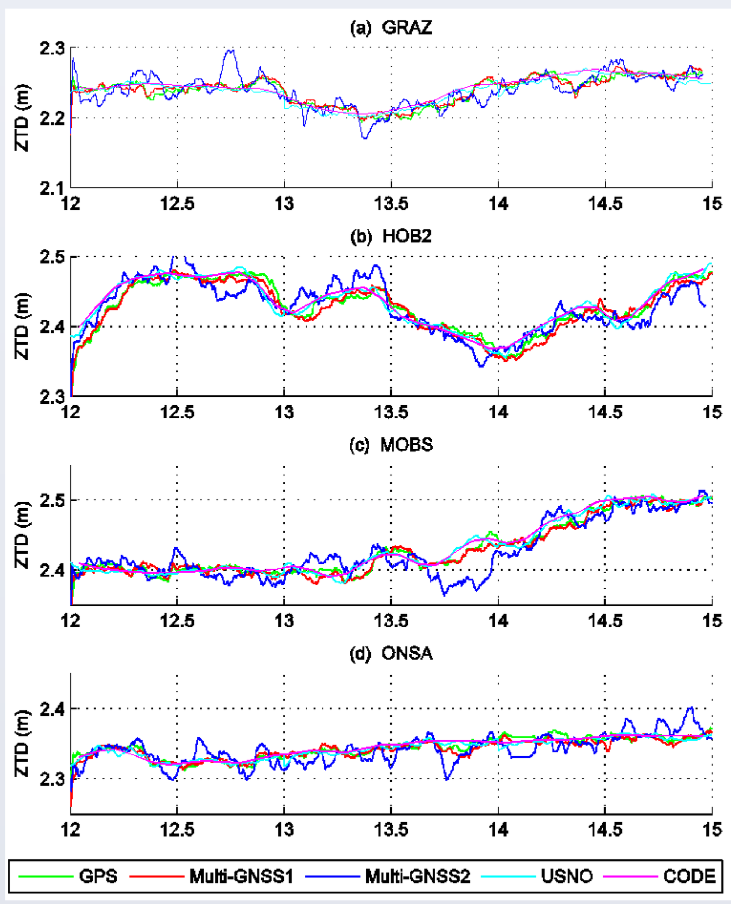

Fig. 4: ZTD derived using RT observations from GPS only and GPS+GLONASS during DOY 012-014, 2014. Multi-GNSS1 represent the results using weighing 5:1 while Multi-GNSS2 represent the results using weighing 1:1.

Tab. 2: Mean bias, STD and RMS of the differences between RT PPP-ZTD and CODE ZTD during DOY 012-014, 2014

Sites	1) GPS only[a] Bias	STD	RMS	2) Multi-GNSS[b] Bias	STD	RMS	3) Multi-GNSS[c] Bias	STD	RMS
ALIC	1.6	7.8	8	2.5	8	8.4	-1.8	15	15.1
COCO	3.1	7.4	8	1	8.8	8.9	1	8.8	8.9
DAV1	1.5	6.1	6.3	2.6	6.3	6.9	-2	11.6	11.8
GRAZ	2.9	8.7	9.2	2.2	10.5	10.8	2.9	13.8	14.1
HERT	1.6	9.8	9.9	0.5	9.7	9.7	1.4	11.9	11.9
HOB2	2.5	9.5	9.8	6.2	10.8	12.5	5.3	18	18.8
MOBS	4	7.4	8.4	6.5	7.6	10	7.6	19.2	20.6
NTUS	3.1	7.5	8.1	-1.5	7.6	7.7	1.8	10.5	10.6
ONSA	1.5	5.5	5.7	3.2	6.2	7	2.6	13.9	14.1
PERT	-7.4	10.9	13.2	-1.8	9.5	9.7	5.1	15.7	16.5
STHL	-0.8	9.6	9.6	-1.1	9.8	9.8	-3.5	15.2	15.6
TOW2	2	11.4	11.6	-1.1	10.5	10.6	-2	15.7	15.8

[a]PPP algorithms are implemented using GPS-only observations

[b]PPP algorithms are implemented using GPS+GLONASS observations with weighting 5:1

[c]PPP algorithms are implemented using GPS+GLONASS observations with weighting 1:1

PWV Results

Tab. 3: Mean Bias, STD and RMS of the differences of RT PWV and radiosonde data during September 2013. The weighted mean temperature T_m is derived from model T_m=70.2+0.72T_0 by *Bevis et. al.* (1992) where T_0 is surface pressure provided by GPT2

The height difference has a substantial impact on the comparisons: 1) Radiosonde stations at high altitudes (i.e., ABPO, BOGT, HRAO and MKEA) tend to provide insufficient information; 2) If the GPS station is located much lower than that of the radiosonde, i.e., PIMO, there would be a significant data gap between the two stations. These radiosonde stations with height issues are regarded as "dubious" and listed in the bottom part of the table

The STD and RMS values at all other 15 stations without height issues are ≤3 mm which meets the accuracy requirement of weather nowcasting as is suggested by *De Haan* (2006).

IGS Site	GPS Ht(m)	RS. Ht(m)	Dista-ce(m)	PWV (mm) Bias	STD	RMS
CHUR	-19	-10	1	0.0	1.5	1.5
COCO	-35	-40	2	0.4	1.9	2.0
FAIR	319	140	25	-0.7	1.4	1.6
GODE	14	41	56	1.0	1.9	2.2
HERT	83	102	4	0.5	1.8	1.8
HOB2	41	22	4	-0.8	2.1	2.3
MAC1	-7	-22	2	-0.4	1.5	1.5
MCM4	98	-22	1	-2.2	0.8	2.4
MOBS	41	143	22	0.2	1.8	1.8
NRIL	48	43	11	-1.4	0.8	1.6
ONSA	46	193	38	-0.6	1.7	1.8
PERT	13	-6	15	-0.1	2.0	2.0
SHAO	22	11	42	-0.6	2.9	3.0
STHL	453	447	5	0.2	1.2	1.2
ZIM2	956	534	40	-1.9	2.1	2.8
ABPO	1553	1263	36	-2.5	3	3.9
BOGT	2576	2549	9	-2.3	1.7	2.8
HRAO	1414	1519	54	-2.1	2.6	3.3
MKEA	3755	11	41	-4.7	2.1	5.1
PIMO	96	651	33	3.6	2.9	4.7

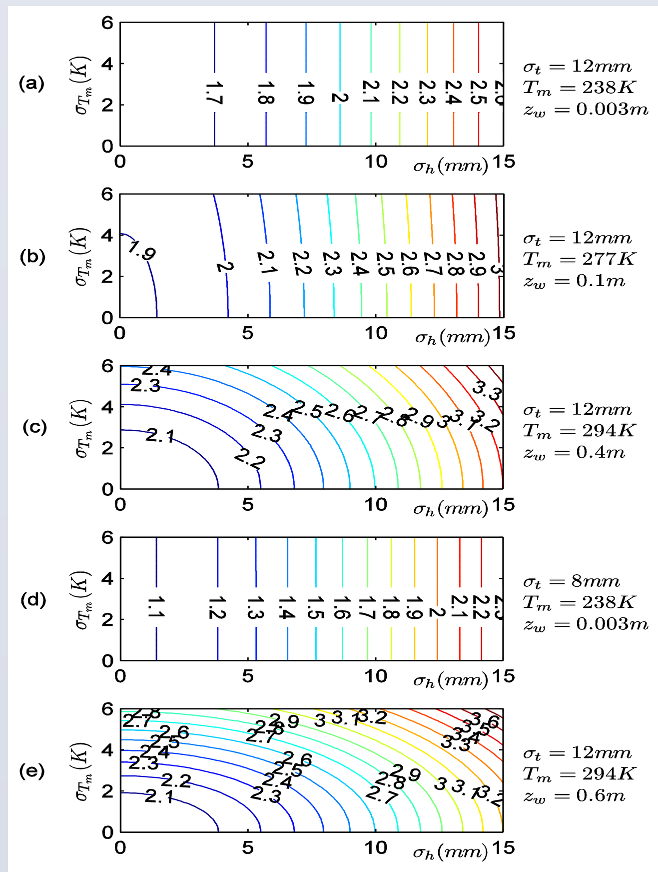

Fig. 5: The achievable accuracies of PWV in different climatic conditions defined by σ_t (RMS of PPP-ZTD), T_m and z_w (ZWD): (a & d) represent polar regions; (c & e) represent tropical or subtropical regions; and (b) represents the moderate conditions. Fig. 5d differs from Fig. 5a assuming PPP-ZTD is more accurate (smaller σ_t), while Fig. 5e differs from Fig. 5c assuming higher relative humidity (larger z_w).

The contour lines also show the accuracy requirements of T_m and ZHD for different accuracy levels of PWV. Apparently PWV of 3 mm accuracy is achievable in all climatic conditions providing the ZTD obtained from real-time PPP is used.

In polar regions where the air is extremely dry, the accuracy of ZHD dominates the accuracy of PWV. With the increase of T_m, the error component introduced by T_m increases accordingly. In tropical or subtropical scenarios (Fig. 5c), T_m accounts for more than the ZHD component does. In polar conditions (Fig. 5a & Fig. 5d) and moderate conditions (Fig. 5b), it is not challenging to obtain accurate PWV even if coarse T_m is used. Most of the selected 20 stations in this investigation belong to these scenarios. In high temperature and humidity conditions (Figs. 5c & 5e), all the three components PPP-ZTD, ZHD and T_m need to be computed accurately.

Conclusions

This study investigates the real-time retrievals of ZTD and PWV using BNC and the PPP technique. The tests show that this technique is able to provide ZTD of 13 mm accuracy. This meets the input requirement for NWP models. If these ZTD products are converted into PWV, the retrieved PWV can be better than 3 mm and meets the accuracy requirement for weather nowcasting, as validated using radiosonde data. The 3 mm accuracy of PWV is also theoretically proved achievable in "unfavorable" retrieval conditions even if empirical models are used for the conversion from PPP-ZTD.

References

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