

Rigorous Geodetic Positioning in the Americas

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SUMMARY

NOAA's National Geodetic Survey developed and has operated the Online Positioning User Service (OPUS) since March 2001. This web-based tool provides accurate, reliable and consistent geodetic-quality coordinates in a global reference frame from GNSS data collected by a single, multi-frequency receiver. The original version of OPUS was primarily optimized to accept datasets from two to 48 hours in duration that were observed from any location in the continental United States, Alaska, Hawaii and the Caribbean. The solution reports for datasets collected in these regions lists NAD83 as well as ITRF/IGS coordinates. The current version of OPUS has been modified to accept and process GNSS data from any part of the world. For datasets collected outside the United States and its territories, the solution reports will only list coordinates at the average epoch of the observation window in the latest realization of the global reference frame which is currently referred to as IGS08. Today OPUS is used extensively by the surveying, engineering and GIS/LIS communities to support numerous applications in forestry, land administration, photogrammetry, construction, shipping and resource management. Specific applications of OPUS to the Americas are described.

RESUMEN

El Servicio Geodésico Nacional de los EE UU ha desarrollado y operado OPUS (Online Positioning User Service) desde marzo del 2001. Es este un servicio accesible a través de la Web que proporciona de forma consistente coordenadas geodésicas de gran exactitud referidas a un marco de referencia global usando los datos archivados por un receptor GNSS de varias frecuencias. La versión original de OPUS se ha optimizado para procesar archivos de GPS de dos a 48 horas de duración observados en cualquier lugar del territorio continental de los Estados Unidos, Alaska, Hawai y el Caribe. La solución que recibe el usuario de estas áreas geográficas está expresada en coordenadas referidas a los marcos de referencia ITRF/IGS y NAD83. La versión actual de OPUS ha sido modificada y acepta el procesamiento de datos GNSS de cualquier parte del mundo. Cuando se procesan datos observados fuera de los Estados Unidos o sus territorios, el usuario recibe un listado de coordenadas referidas al marco geocéntrico de referencia más actual, que en estos momentos es el IGS08. La época de estas coordenadas corresponde al tiempo medio de la ventana de observación. En la actualidad OPUS es empleado extensivamente por agrimensores, ingenieros y otros usuarios en numerosas aplicaciones como catastro, fotogrametría, construcción, explotación de recursos naturales, etc. Su aplicación a las Américas se detalla.

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1. INTRODUCTION

The National Geodetic Survey (NGS), an Office of the U.S. National Oceanic and Atmospheric Administration (NOAA), released in May, 2001 a web-based utility called the Online Positioning Users Service (OPUS). OPUS has revolutionized how accurate positional coordinates are obtained (Weston et al. 2007; Stone, 2006; Soler et al., 2011).

The idea behind this development was to accomplish NGS' mission: the provision of accurate positioning for the establishment and development of the basic framework defining the U.S. National Spatial Reference System (NSRS). As part of this effort, scientists at NGS brought to fruition two major ideas based on the innovative Global Positioning System (GPS) technology. First, the Continuously Operating Reference Stations (CORS) network of permanent GPS receivers (currently about 1,800) was established to consolidate an accurate and reliable geodetic reference frame (Snay and Soler, 2008). Subsequently, the CORS stations were used to efficiently disseminate accurate positioning referred to NSRS thanks to OPUS software (Mader et al., 2003; Soler et al., 2006). The success of these two projects has surpassed NGS' original expectations as measured by the compliments received from GPS users such as surveyors, engineers and GIS/LIS professionals who frequently use CORS and OPUS in their day-to-day work.

The processing algorithms in all OPUS utilities use satellite orbits from the International GNSS Service (IGS), GPS data from a number of reference stations belonging to regional and global networks (CORS, IGS), and a set of servers located at NGS headquarters in Silver Spring, Maryland that process the submitted GPS data. The advantage of OPUS is that even a single user can establish geodetic control using only one receiver-antenna in combination with the CORS, therefore, reducing the investment in multiple GPS instruments and the engagement of extra field personnel.

In particular, OPUS enables its users to submit a GPS data file to NGS via the Web; whereby the data will be processed using NGS computers and software to determine the positional coordinates associated with the location where the data was observed. The original version of OPUS focused on GPS static mathematical models, thus, it is now known as OPUS-S ("S" for static). NGS also introduced other flavors of OPUS including: OPUS-RS (rapid static), and OPUS-DB (data base). However, these other versions of OPUS were expressly developed for GPS observations recorded in the U.S., and thus are not described in this paper. In the following sections after an outline of OPUS-S is discussed, the specific applications of this service to the Americas will be explained. A practical procedure will be detailed allowing any user in the Americas to transform OPUS-S results to the frame SIRGAS2000.

2. OPUS-S

The OPUS submittal main Web page is www.geodesy.noaa.gov/OPUS/. The submittal page requires the user to enter the following basic information through a straightforward interface that contains supplementary explanations:

- 1.- observation file(s) in RINEX or most receiver raw formats, optionally compressed
- 2.- antenna type, chosen from dropdown menu (over 300 currently listed)
- 3.- vertical antenna height, in meters, from mark to Antenna Reference Point (ARP)
- 4.- the user's email address (to receive the results)
- 5.- the following information can be entered by clicking the "Options" button, but are not required:
 - 5a- Select whether extended output information or XML is desired
 - 5b- Select specific CORS to include or exclude in the solution

Finally, the user needs to choose the specific OPUS processor, clicking, for international solutions:

Static (OPUS-S) for observing sessions > 2 hrs. and < 48 hrs. (it can only cross UTC midnight once)

In either case, OPUS only accepts GPS observations. In the future, NGS plans to include GLONASS observation data that will be processed in combination with GPS data. This addition will increment the number of visible satellites above the horizon and improve the results in areas obstructed by buildings and high surrounding mountains. OPUS only accepts data epochs at intervals which are an integer divisor of 30 seconds (1, 2, 3, 5, 6, 10, 15, 30 seconds). Large 1 or 2 second files may have to be converted to 30 seconds in order to prevent time-out problems during the data upload process via the Web portal.

3. INTERNATIONAL OPUS-S REPORT

The international OPUS-S report is different to the one obtained for North American users. Due to the multitude of local geodetic datums adopted around the world, the coordinates of the international OPUS-S report are only given with respect to the most current accurately determined geocentric Cartesian frame, IGS08 (a realization of ITRF2000 by the IGS), given at the mean epoch of the GPS observation span. The X, Y, Z coordinates are also presented as curvilinear coordinates (latitude, longitude, and ellipsoid height using the standard GRS80 ellipsoid). For mapping applications, the UTM coordinates are also reported.

The actual format of the OPUS-S report available for international users is given in Fig. 1.

FILE: brft2370.12o OP1348760626205

1008 NOTE: Antenna offsets supplied by the user were zero. Coordinates
1008 returned will be for the antenna reference point (ARP).
1008

NGS OPUS SOLUTION REPORT
=====

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: <http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy>

USER: rick.foote@noaa.gov
RINEX FILE: brft2370.12o

DATE: September 27, 2012
TIME: 15:48:21 UTC

SOFTWARE: page5 1106.16 master53.pl 082112
EPHEMERIS: igs17025.eph [precise]
NAV FILE: brdc2370.12n
ANT NAME: LEIAX1202 NONE
ARP HEIGHT: 0.00

START: 2012/08/24 00:00:00
STOP: 2012/08/25 00:00:00
OBS USED: 45659 / 46216 : 99%
FIXED AMB: 125/162 : 77%
OVERALL RMS: 0.017 (m)

REF FRAME: IGS08 (EPOCH:2012.6463)

X: 4985393.477 (m) 0.011 (m)
Y: -3954993.421 (m) 0.023 (m)
Z: -428426.608 (m) 0.010 (m)

LAT: -3 52 38.80531 0.009 (m)
E LON: 321 34 28.06472 0.023 (m)
W LON: 38 25 31.93528 0.023 (m)
EL HGT: 21.627 (m) 0.007 (m)

UTM COORDINATES

UTM (Zone 24)
Northing (Y) [meters] 9571397.538
Easting (X) [meters] 563779.005
Convergence [degrees] -0.03884794
Point Scale 0.99965035
Combined Factor 0.99964695

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE (m)
DH8854	PMB1 PARAMARIBO CORS ARP			2136143.0
DH8856	SRZN ZANDERIJ CORS ARP			2121939.7
CHPI				2187099.5

Figure 1. OPUS-S report for international users

The values tabulated in Fig. 1 are self-explanatory except the statistics attached to each coordinate, Cartesian as well as curvilinear. OPUS-S does not provide, as it is usually done, standard deviations but rather peak-to-peak statistics. The peak-to-peak statistic, also called the “range” of the solutions, is defined as the difference between the maximum and minimum numbers from the three baseline solutions reached by each coordinate component. This statistic was selected in OPUS-S because is more pessimistic (more realistic) than the GPS-derived standard deviations, generally called “formal errors” in the geodetic-surveying literature and which are known to be excessively optimistic.

The mathematical relationship between peak-to-peak (range) errors and the sample standard deviation (σ) was investigated by Schwarz (2006) arriving at the following equation:

$$\text{Peak-to-peak} \approx 1.6929 \times \sigma$$

Therefore, once an OPUS-S report is available, the immediate subsequent question is how the data obtained in a typical international OPUS-S solution could be used, for example, in South America. Fig. 1 reproduces a GPS 24 h observation span at station Fortaleza in Brazil (BRFT) which happens to be a CORS station. The results give the coordinates referred to the frame IGS08 at the mean epoch of observation 2012.6463. Let's assume that we want to transform these coordinates to the SIRGAS2000 frame which is the adopted datum in South America. Two steps should be taken into consideration to accomplish this transformation as accurate as possible:

- 1) Determine the velocities of the tectonic plate where the point is located.
- 2) Transform the coordinates from the IGS08 reference frame, epoch of date to the ITRF2000, epoch 2000.4 (SIRGAS2000).

4. DETERMINE THE VELOCITIES OF THE TECTONIC PLATE AT THE POINT

The velocities due to tectonic plate rotations at any point on the Earth could be determined using the Internet utility available at the University NAVSTAR Consortium (UNAVCO) Web portal under the heading "Plate Motion Calculator." To take advantage of this software, we need to start by assuming a geophysical tectonic plate model. There are several geophysical models available in the literature, but let us assume that we select the one introduced in the International Earth Rotation and Reference Systems Service (IERS) Conventions of 1996, the so-called no-net-rotation NNR-NUVEL-1A, which specifies the plate angular rotations for each plate as tabulated in McCarthy (1996, p.14). Using UNAVCO's plate calculator, which is available at the following URL:

http://www.unavco.org/community_science/science-support/crustal_motion/dxdt/model.html

One should be able to easily determine the plate velocity at any point on the Earth's surface in general and South America in particular.

Furthermore, this Web page is very informative and complete and contains the references to all important scientific papers that, over the years, have introduced different geophysical tectonic plate models. Additionally, if desired, the user can select other versions of Internet plate motion calculators cited at the bottom of the above mentioned URL.

To obtain the velocity components along the local East and North directions, the user will introduce into the appropriate input field of the UNAVCO calculator the (X, Y, Z) values

from the OPUS-S output referred to the IGS08, epoch of date (in Fig. 1, 2012.6463). It is recommended to use X, Y, and Z coordinates, as opposed to curvilinear coordinates, to avoid the possible confusion between E and W longitudes. For the plate model selection, the authors as stated previously, recommend users to select “NUVEL 1A” in the window ‘Model’; “Auto” in the window ‘Tectonic Plate of Attributed Motion’; and “NNR no-net-rotation” in the window ‘Reference’. Finally, in the ‘Output format’ window, one can select ‘ASCII table w/local E&N plate velocities’. After clicking the ‘Submit’ button, the program will return the values of the velocities at the point in question expressed along the local east (E) and north (N) directions in units of mm/yr due to the rotation of the tectonic plate where the point is located. The plate motion calculator assumes a spherical Earth, thus the velocity along the vertical (Up) component should be assumed equal to zero. If we substitute the input data described above into the plate motion calculator, we will get the following components of the velocities of the South American plate at station BRFT:

$$\begin{aligned}
 \text{Velocity along the E component} &= -5.48 \text{ mm/yr} \\
 \text{Velocity along the N component} &= 11.68 \text{ mm/yr} \\
 \text{Velocity along the height component} &= 0.00 \text{ mm/yr}
 \end{aligned}
 \tag{1}$$

To check the accuracy of the UNAVCO plate model calculator, recalling that station BRFT belongs to the CORS network, we can actually compare the values in (1) with the real observed results. These are available at the following link:

ftp://www.geodesy.noaa.gov/cors/coord/coord_08/brft_08.coord.txt

	Differences between “true” and modeled	
Velocity along the E component =	-4.70 mm/yr	0.78 mm/yr
Velocity along the N component =	12.30 mm/yr	0.62 mm/yr
Velocity along the height component =	1.90 mm/yr	1.90 mm/yr

(2)

It is clear that the values of the velocities obtained from the model agree reasonable well with the results determined through a multiyear solution of GPS data processed between the years 1994 and 2011. However, the “true” observed velocity values are not known except at a very few CORS-type permanent stations, nonetheless, the plate velocities computed at any other point in the field through the velocity model are clearly adequate, as seen from the comparison in (2), for any type of surveying, photogrammetric control and GIS work.

Thus, knowing the modeled values of the plate velocity components we proceed to complete the final step of the transformation to the SIRGAS2000 which is described in the next section.

5. CONVERSION FORM IGS08, MEAN EPOCH OF OBSERVATION TO ITRF00, EPOCH 2000.4 (SIRGAS2000)

To transform coordinates between the IGS08 and ITRF2000 frames, the 14 transformation parameters between the two frames are required. However, this transformation could be efficiently done using the NGS utility, also available through Internet, called Horizontal Time Dependent Positioning (HTDP). HTDP was introduced by NGS in 1991 (Snay, 1998). It was primarily devised for correcting NAD 83 positional coordinates and/or geodetic observations for the effect of crustal deformations but also for transforming positional coordinates and velocities between reference frames (Pearson et al., 2010). Nonetheless, the program only predicts angular plate velocities at points in the North American, Pacific, and Mariana tectonic plates, the only plates affecting NAD 83 positional coordinates. The geophysical model used by HTDP is also NNR-NUVEL-1A. That is precisely the reason why UNAVCO's plate motion calculator to compute velocity plate rotations in South America was invoked. The HTDP utility, explanatory material and instructions are available at the following NGS Web page location:

<http://www.geodesy.noaa.gov/TOOLS/Htdp/Htdp.shtml>

Conceptually, the procedure to be followed for using HTDP requires knowledge of the following parameters:

Initial (starting) frame: IGS08 = ITRF2008

Final (ending) frame: ITRF2000

Starting (epoch) date, in decimal of year, of the input position: 2012.6463

Final (epoch) date, in decimal year, of the output position: 2000.4 (The epoch of the datum SIRGAS2000)

X, Y, Z, coordinates of the point in question in meters

Velocities along the local components north (N = 11.68 mm/yr) and east (E = -5.48 mm/yr). (Up = 0.00 mm/yr).

These parameters are inserted in the corresponding window of HTDP so that an accurate transformation between OPUS-S results and SIRGAS2000 could be obtained. It should be noted that in the example of Fig.1, it was assumed that the measured height from the point on the ground to the antenna reference point (ARP) was zero. This is not the general case when GPS surveys are performed in the field. Typically, the surveyor needs to measure the height from the mark on the ground to the ARP and include this value as one of the input values in OPUS-S. The location of the ARP varies from antenna model to antenna model depending on the design adopted by the manufactures. If uncertain about the location of the ARP, one should check the diagrams specific for each antenna model available at the NGS Web page:

<http://www.ngs.noaa.gov/ANTCAL/>

6. PRACTICAL EXAMPLE

Assume that a survey point was observed using a GPS receiver and the data submitted to OPUS-S resulting in the output report is depicted in Fig. 1. Although some information should be already known from the field measurements (instrument type; antenna name; height of the ARP above the mark on the ground; etc.), the OPUS-RS report also archives some of this information to facilitate the detection of blunders. Then, if we want to transform the X, Y, Z coordinates referred to the IGS08 frame at epoch 2012.6463 to SIRGAS2000 (ITRF2000, epoch 2000.4), first we need to compute the South American plate velocity at the point. These values were already obtained in section 4 and are given in equation (1).

The final step will be to invoke HTDP by linking to its Web page. Among all the options available written on the page we should select:

1) "Interactively transform positions between reference frames and/or dates."

This step should be followed by clicking on:

2) "Individual points entered interactively."

Finally a set of windows will appear under the page titled: "Horizontal Time-Dependent Positioning." These blank spaces should be filled with the pertinent data corresponding to the OPUS-S solution (Fig. 1) complemented by the velocities of the South American plate computed using UNAVCO's plate motion calculator and given in (1). For clarity, the completed form, including the values used in the example described in this paper, is reproduced verbatim in the Appendix.

After clicking the 'Submit Query', the results shown in Fig. 2 are obtained.

HTDP Output

```
*****
HTDP (version 3.2.3) OUTPUT

TRANSFORMING POSITIONS FROM ITRF2008 or IGS08      (EPOCH = 08-24-2012
(2012.647))
                                TO ITRF2000 or IGS00/IGb00 (EPOCH = 05-26-2000
(2000.400))

                INPUT COORDINATES      OUTPUT COORDINATES      INPUT VELOCITY

BRFT
LATITUDE        3 52 38.80531 S        3 52 38.81033 S        11.68 mm/yr north
LONGITUDE       38 25 31.93528 W        38 25 31.93318 W        -5.48 mm/yr east
ELLIP. HT.                21.627                21.636 m        0.00 mm/yr up
X                  4985393.477                4985393.516 m        -2.79 mm/yr
Y                  -3954993.421                -3954993.369 m        -4.78 mm/yr
Z                  -428426.608                -428426.763 m        11.65 mm/yr
```

Figure 2. Results referred to SIRGAS2000 from HTDP using UNAVCO's plate model

Fig. 2. illustrates the final transformation of the OPUS-S results from GPS measurements in South America, given in the SIRGAS2000 frame (ITRF2000, epoch 2000.4). Notice that the entire procedure is easy to implement and the results are accurate for most types of surveying (even geodetic) applications.

It was mentioned above that HTDP was not designed to predict the velocities for the South American plate. However, HTDP can transform between many popular geodetic frames if the plate velocities are known. Therefore, to corroborate that the velocity plate model selected in this example provides accurate results, we again use HTDP to do a corroboratory test. Re-using all the data described before, except that now we are going to replace UNAVCO's plate model velocities by the known "true" ones determined by a multiyear solution and tabulated in equation (2). Thus, using the same input to HTDP as shown in the Appendix after replacing the plate velocities by the "true" 3D velocity values (N = 12.30 mm/yr; E = -4.70 mm/yr; Up=1.90 mm/yr), we get the results of Fig. 3.

HTDP Output

```
HTDP (version 3.2.3) OUTPUT

TRANSFORMING POSITIONS FROM ITRF2008 or IGS08          (EPOCH = 08-24-2012
(2012.647) )
                                TO ITRF2000 or IGS00/IGb00 (EPOCH = 05-26-2000
(2000.400) )

                INPUT COORDINATES      OUTPUT COORDINATES      INPUT VELOCITY

BRFT
LATITUDE        3 52 38.80531 S        3 52 38.81058 S        12.30 mm/yr north
LONGITUDE       38 25 31.93528 W        38 25 31.93349 W        -4.70 mm/yr east
ELLIP. HT.      21.627                    21.612 m              1.90 mm/yr up
X                4985393.477              4985393.492 m          -0.78 mm/yr
Y               -3954993.421              -3954993.362 m          -5.38 mm/yr
Z                -428426.608              -428426.769 m          12.14 mm/yr
```

Figure 3. Results from HTDP using the "true" plate velocities

The differences between the position of the transformed OPUS-S coordinates using the modeled velocities and the "true" velocities given in the sense model minus "true" are:

Latitude difference = 7.6 mm
 Longitude difference = 9.4 mm
 Ellipsoid height difference = 2.27 cm

These differences were computed from the original X, Y, Z coordinates in Figs. 2 and 3, after projecting into a local geodetic frame at the assumed "true" ARP of point BRFT. No

assumption about a spherical Earth was made for these computations. The results are the experimental confirmation that the modeled velocities for all practical purposes (surveying, cadastral work, GIS, etc.) are equivalent to the observed “true” plate velocities.

7. CONCLUDING REMARKS

It has been empirically demonstrated that fairly accurate transformations of geocentric coordinates are possible between the OPUS-S output report and the SIRGAS2000 frame (ITRF2000, epoch 2000.4). The approach described herein facilitates the use of OPUS-S solutions anywhere in the world as long as a velocity plate model is selected. In this particular investigation, UNAVCO’s “Plate Motion Calculator” and the NNR-NUVEL-1A geophysical tectonic plate model were chosen to easily determine the plate velocities at any point on the South American tectonic plate. However, the same approach can be implemented at any other location in the world. Once the plate velocities are known, a rigorous transformation amid a selection of mostly used reference frames is feasible by relying on NGS’ utility HTDP. It was evidently demonstrated that, at least, for a period time span of 12 years, the results from UNAVCO’s plate motion calculator in South America are, for all practical purposes, equivalent to knowing the best set of “true” tectonic plate velocities.

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APPENDIX

Horizontal Time-Dependent Positioning

Transforming Positions Between Two Reference Frames

Specify the reference frame for the input values:

ITRF96	▲
ITRF97 or IGS97	
ITRF2000 or IGS00/IGb00	
ITRF2005 or IGS05	
ITRF2008 or IGS08	▼

Specify the reference frame for the output values:

ITRF93	▲
ITRF94	
ITRF96	
ITRF97 or IGS97	
ITRF2000 or IGS00/IGb00	▼

Dates may be entered either in the month-day-year format or in the decimal-year format. For the month-day-year format, the month is a number between 1 and 12 and a four-character year is required. The month, day, and year may be separated by spaces or by commas.

Valid examples are:

5, 4, 1998 for May 4, 1998

5 4 1998 for May 4, 1998

For the decimal-year format, enter yyyy.xxx where yyyy denotes the year and xxx denotes the fraction of the year.

Valid examples are:

2010.0 for January 1, 2010

1979.359 for May 12, 1979

1991.35 for May 8, 1991

The decimal point is required but the precision of the fractional year is optional.

The fractional year is obtained by subtracting one from the day-of-year and then dividing the result by 365 (or 366 if it is a leap year).

Thus, the fractional year corresponds to UTC midnight at the beginning of the day.

HTDP models are not valid for dates before the 1906 San Francisco earthquake.

month-day-year decimal year

Specify the reference date of the input position(s):

Specify the reference date of the output position(s):

Input the site's position either in terms of latitude, longitude, and ellipsoidal height or in terms of geocentric Cartesian coordinates -X,Y,Z- but not both. For latitude (positive north) and longitude (positive west), use the form degrees, minutes, and seconds and use either commas or spaces to separate the individual values. The field for seconds must include a decimal point. To denote negative values, use negative degrees, minutes, and seconds.

Valid examples for latitude are:

37, 34, 35.67

37 34 35.67

-37 -34 -35.67 denotes a point in the southern hemisphere.

Values for ellipsoidal height or for X, Y, and Z must be specified in meters and must be entered with a decimal point (but without commas).

Select the type of coordinates to be entered:

Latitude, Longitude, Height X, Y, Z

Latitude or X:

Longitude or Y:

Height or Z:

Station Name (optional):

Select how the required velocity (relative to the input frame) is to be entered:

Use the velocity predicted by this program (ignore the input boxes below)

Specify the velocity in terms of north-east-up components (use the input boxes below)

Specify the velocity in terms of global X-Y-Z components (use the input boxes below)

North or X (mm/yr):

East or Y (mm/yr):

Up or Z (mm/yr):

Biographical Notes

Dr. Neil D. Weston is the Chief of the Spatial Reference System Division at the National Geodetic Survey. His team is responsible for defining and maintaining the National Spatial Reference System in the United States. His other interests are in GNSS software development, 3-D imaging and motion analysis.

Dr. Tomás Soler has served as an NGS scientist since 1979. Tom supervised the GPS Branch from 1990 – 2003 and currently serves as the Chief Technical Officer in the Spatial Reference System Division of the National Geodetic Survey.

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