# NATIONAL VDATUM -- THE IMPLEMENTATION OF A NATIONAL VERTICAL DATUM TRANSFORMATION DATABASE

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The National Ocean Service (NOS) in NOAA has developed a vertical datum transformation tool, VDatum, which allows transformation of bathymetric and/or topographic elevation data among 28 different orthometric, ellipsoid/3-D, and tidal datums. Expansion of VDatum to nationwide coverage, that is, the development and population of *national vertical datum transformation database* ("National VDatum"), will enable NOAA and other agencies and institutions collecting coastal and offshore spatial data to seamlessly integrate that data despite different vertical datums used. National VDatum will also allow full advantage to be taken of the power of new technologies such as real-time kinematic (RTK) GPS and topographic and bathymetric LIDAR. With VDatum, RTK-GPS hydrographic surveys will not need water level stations installed during the survey, settlement and squat corrections for the survey vessel, or post-survey data processing. With VDatum, topographic LIDAR data can be transformed to the mean high water (MHW) datum to produce a consistently defined MHW shoreline. Bathymetric LIDAR data can be transformed to produce a consistently defined mean lower low water line. National VDatum is also a requirement for producing a true National Bathymetric Database. The use of VDatum will be a cornerstone of the new way that NOS will acquire, handle and process bathymetric and shoreline data and efficiently use these data to produce NOAA nautical chart and electronic vector products and to support coastal resource managers.

## THE NEED FOR A VERTICAL DATUM TRANSFORMATION TOOL

With 95,000 miles of coastline to cover, the mapping and charting agencies of the U.S. are always searching for ways to apply new technologies in order to increase the efficiency of their data acquisition operations and the accuracy of their mapping and charting products and services. At the same time they are also looking for ways to make use of high quality data acquired by other federal and state agencies and universities. Sometimes, however, there can be roadblocks to taking full advantage of the latest technologies, as well as roadblocks to being able to make use of data acquired by 3$^{rd}$-parties. In this case the roadblock is the missing capability to easily and accurately transform elevation data from one vertical datum to another, and what is needed is a National Vertical Datum Transformation Tool database (National VDatum).

Elevation data, such as bathymetry and topography, must be referenced to a vertical datum, as must shoreline data. Such elevation data cannot be seamlessly blended (or even compared) unless these data are referenced to the same vertical datum. Unfortunately the huge variety of ellipsoid, orthometric, and tidal datums in use around the nation has made it difficult to integrate elevation data from different agencies and institutions. For example, data referenced to different vertical datums has kept NOAA and the U.S. Geological Survey (USGS) from integrating their bathymetric and topographic data sets for a variety of important applications (such as storm surge modeling, hurricane evacuation planning, and the permitting activities of coastal resource managers). It has also led to different shorelines being depicted on the charting products of NOAA and the mapping products of USGS, a fact which has caused confusion among the coastal resource managers who rely on both sets of products. Differences in vertical datums have also limited the ability to share elevation and shoreline data among NOAA, USGS, FEMA, NIMA, MMS, and the numerous state mapping agencies.

Many agencies and institutions are using newer technologies for their data gathering operations, such as acoustic multibeam systems and side scan sonar for hydrographic surveys, topographic LIDAR to measure land elevations, water-penetrating LIDAR to measure bathymetry, and other airborne and satellite systems. Most of these systems use kinematic GPS positioning with the resulting elevation data vertically referenced to an ellipsoid datum. Yet, in the products derived from these data the elevations must usually be referenced to an orthometric or a tidal datum, often for legal reasons.

Sometimes the agency has had to go to great lengths to reference their data to the correct datum. The National Ocean Service (NOS) in NOAA carries out hydrographic surveys to measure bathymetry and to identify underwater obstructions that might be a safety hazard to navigation. In order to produce depth sounding data that are referenced to mean lower low water (MLLW), the legal chart datum for the U.S., NOS has traditionally operated an array of water level stations during the hydrographic survey, so that the water surface height above MLLW (due mainly to the astronomical tide and to water level changes due to the wind) can be subtracted from the total water level depths measured by the multibeam. Interpolation of water level values between the stations was typically calculated using a discrete tidal zoning technique, which has known limitations and error sources. In addition, as the survey vessel moves through the water, it sinks into the water to a degree determined by its speed (settlement and squat), and this change in vertical position, which affects the depths measurements, must also be corrected. However, since survey vessels now use real-time kinematic (RTK) GPS, the bathymetric data will already be referenced to an ellipsoid datum, so all that is really required is to transform these data to the MLLW datum. To do such a transformation one must know the geographic distribution of the ellipsoid datum and the MLLW datum for the survey area. If that were known, then one could avoid installing water level stations during survey operations, avoid settlement and squat calculations for the survey vessel, and avoid hours of post-survey data processing. A case study of this approach is found in Riley, Milbert, and Mader (2003).

The measurement of shoreline presents its own special problems (Parker, 2001; Parker, submitted). The legal shoreline for the U.S. is the mean high water (MHW) shoreline depicted on the nautical charts produced by NOAA. Yet it is extremely difficult to measure shoreline where every point on that shoreline truly represents the horizontal position of the land-water interface when the water level is exactly at the MHW value for that exact position. Most airborne and satellite images from which shoreline is determined capture a shoreline at a moment in time, during which it is very unlikely that the water level will be exactly at a true MHW value at each point along the entire coast line, since tide regimes change over distance (most quickly in shallow waters). It may not even be MHW anywhere in the image, since high water values vary throughout the month and year, and because the wind, atmospheric pressure, river discharge, and thermal expansion of the water column can all change the water level and thus shift the horizontal location of the shoreline in the image. Such imagery cannot be corrected to reflect a true MHW shoreline. A much more consistent and thus more accurate method is to produce a digital elevation model (DEM) covering the intertidal zone (using topographic LIDAR data flown near the time of low water) referenced to the ellipsoid, and transforming those data to the MHW datum. The zero elevation line would then be the MHW shoreline. Similarly, producing an inter-tidal DEM, referenced to the ellipsoid, using water-penetrating (bathymetric) LIDAR flown near the time of high water, and transforming those data to the MLLW datum, is a very accurate way to determine a true MLLW line. Examples of MHW shorelines derived from transformed topgraphic LIDAR data can be found in Parker (2002), Parker (submitted), and Woolard, Aslaksen, Longenecker, and Ryerson (2003). The latter reference also includes an example of MLLW shoreline derived from transformed bathymetric LIDAR data.

Thus, to solve all these problems, to be able to effectively use new measurement technologies and to be able to share and blend elevation data sets, one must have a vertical datum transformation tool.

## VDATUM, A VERTICAL DATUM TRANSFORMATION TOOL

A vertical datum transformation tool, VDatum, has been developed by NOS (Milbert, 2002), which allows the easy transformation of elevation data between any two vertical datums, among a choice of 28 vertical datums, which can be categorized as three general types: (1) orthometric, (2) tidal, and (3) 3-D or ellipsoid datums.

VDatum was first used for the NOAA-USGS Tampa Bay BathyTopo Demonstration project, to create a digital elevation model (DEM) by transforming NOAA's bathymetric data and USGS's topographic data to the same vertical datum and blending them together. (Parker, 2002; Gesch and Wilson, 2001; and see also http://chartmaker.ncd.noaa.gov/bathytopo/ ) A fully calibrated hydrodynamic model of Tampa Bay was used to determine the geographic distribution of the tidal datums. VDatum was programmed as a Java application, with both interactive and batch modes. The source code and algorithms are open, and VDatum is being made available to the coastal user community. (see also http://chartmaker.ncd.noaa.gov/bathytopo/vdatum.htm)

### Types of Vertical Datums

Vertical datums have traditionally come in two categories: those based on a form of mean sea level (MSL), called *orthometric datums*, and those based on tidally-derived surfaces of high or low water, called *tidal datums*. In addition, there is a recently added third category, consisting of *3-dimensional* or *ellipsoid datums* realized through space-based systems such as the Global Positioning System (GPS). Topographic maps (e.g., from USGS) generally have elevations referenced to orthometric datums, either the North American Vertical Datum 1988 (NAVD 88) or to the older National Geodetic Vertical Datum 1929 (NGVD 29). All GPS positioning data are referenced to one of many 3-D/ellipsoid datums. NOAA's nautical charts have depths referenced to mean lower low water (MLLW), and bridge clearances are referenced to mean high water (MHW). The legal shoreline in the U.S., which is the shoreline represented on NOAA's nautical charts, is the MHW shoreline, that is, the land-water interface when the water level is at an elevation equal to the MHW datum.  The MLLW line is also depicted on NOAA's charts.

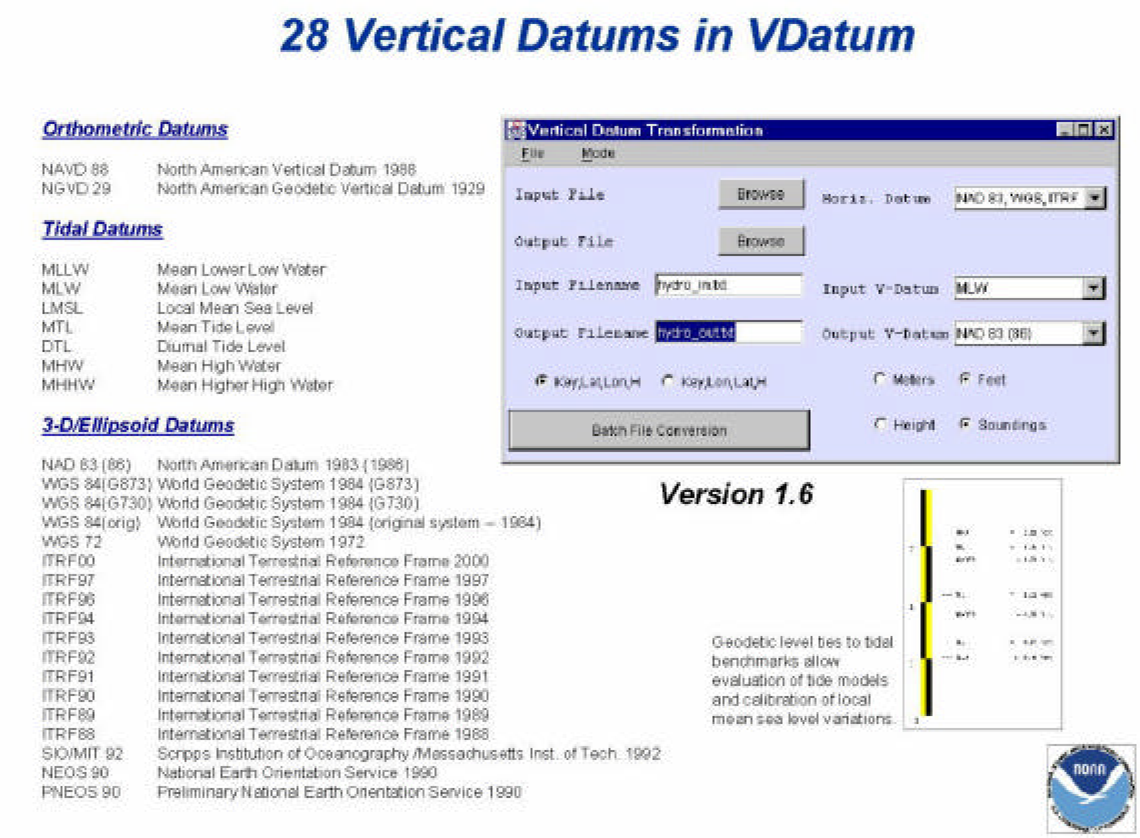



**Figure 1.  The 28 vertical datums included in VDatum.**

*Orthometric datums* are essentially equipotential (gravitational) surfaces of the Earth with one or more tide stations used as control points.  They have often been viewed as being based on a form of MSL.  The National Geodetic Vertical Datum of 1929 (NGVD 29), which was originally called the "Sea Level Datum of 1929", has 21 tide station control points in the U.S. and 5 in Canada.  MSL, however, departs from an equipotential surface through the effects of winds, atmospheric pressure, water temperature, salinity, and currents.  (Local MSL also changed from 1929 due to vertical land movement.)  Unacceptable inconsistencies in NGVD 29 led to the establishment of a new national orthometric datum, the North American Vertical Datum of 1988 (NAVD 88), which has only one control point (Father Point, Quebec, Canada).  The differences between these two orthometric datums can be up to 2.2 meters.

*3-D or ellipsoid datums*, which have become so important since the development of GPS, are based on a geometric model, an ellipsoid that approximates the earth's surface (without the topography).  There can be many different 3-D datums depending on how the origin of the ellipsoid is defined.  For example, there is a 2 meter difference between two of the most frequently used 3-D datums, the North American Datum of 1983 (NAD 83) and the World Geodetic System of 1984 (WGS 84).  VDatum uses only the vertical component of the 3-D datum, which, as the name implies, is a complete 3-dimensional coordinate system.

The *geoid* is a specific gravitational equipotential surface which best fits (in the least squares sense) global sea level. Since this equipotential surface includes the effects of topography, it will differ significantly (by as much as 100 meters) from a geocentric ellipsoid because of the Earth's irregular mass distribution, being higher than the ellipsoid where there is a greater mass. GEOID99, the latest geoid model developed by NOS, specifically relates NAD83 ellipsoid heights to NAVD 88 orthometric heights. It was calibrated against GPS ellipsoid heights on leveled benchmarks throughout the conterminous United States.

*Tidal datums* are based on averaged stages of the tide, such as MHW and MLLW. To minimize all the significant tidal daily, monthly, and yearly variations, a tidal datum such as MHW is defined as the average of all the high water elevations over an 18.6-year period (often rounded to 19 years). This also averages out most meteorological effects on water level, which could bias a tidal datum computed from a shorter length data time series. Tidal datum elevations vary significantly with horizontal (geographic) distance, especially in shallower waters, and they usually vary more rapidly than the horizontal variation in orthometric or 3-D/ellipsoid vertical datums. In Tampa Bay the separations between the tidal surfaces and the NAD 83 (and other 3-D/ellipsoid datums) are in excess of 24 meters. The relationship of NAVD 88 to local mean sea level is calibrated from tide model comparisons with leveled tidal benchmarks, and is approximately a constant 0.163 meters in Tampa Bay.

**Geographic Distribution of Tidal Datums**

Tidal datum transformation fields for VDatum in a bay or port are generated using a numerical hydrodynamic model that has been accurately calibrated to all local water level stations. For Tampa Bay a version of the Princeton Ocean Model that had been was previously developed in NOS was used. It is a three-dimensional, free-surface, sigma-coordinate baroclinic hydrodynamic model using a curvilinear grid with typical grid spacing from 1000 to 100 meters. For calibration purposes the model was forced with coastal water levels, inputs from seven rivers, winds and air temperature, and coastal salinity and temperature. The typical standard deviation of the differences between model predictions and data was approximately 2.7 cm. For the purpose of determining the geographic distribution of tidal datums the model was forced at the Bay entrance with accepted tidal harmonic constants and run for one year, with the various stages of the tide picked off and averaged for every grid point of the model. The one-year averages were corrected for the 18.6-year lunar nodal cycle by comparison to the St. Petersburg water level station. The hydrodynamic model was used to generate a set of fields representing the difference between MLLW and: mean low water (MLW), diurnal tide level (DTL), mean tide level (MTL), mean sea level (MSL), mean high water (MHW), and mean higher high water (MHHW).

For bays or estuaries where a fully calibrated hydrodynamic model is not available, a technique for spatial interpolation among locations with water level station data has been developed (Hess, 2002). This method, the tidal constituent and residual interpolation (TCARI) method, uses a set of weighting functions (generated by solving numerically Laplace's Equation) to quantify the local contributions from each of the water level stations. TCARI does this in a manner that considers distances between stations by over-water paths only, and thus includes the effects of islands and bending shoreline.

When using a numerical hydrodynamic model (the preferred way to produce the distribution of tidal datums in a waterway), it is necessary that the model values at the locations of water level stations match exactly the values derived from the long time series of data at those water level stations. To assure this, TCARI is used to interpolate the errors for each tidal datum between the tide stations, and then the resulting error correction fields are used to correct the tidal datum fields.

## NATIONAL COVERAGE FOR VDATUM

In addition to the Tampa Bay Demonstration Project, several other projects have taken place which have resulted in a populated VDatum for those regions. These include: another NOAA-USGS BathyTopo project, for a section of Louisiana near Port Fourchon; the creation of a blended bathymetric elevation surface off the coast of California for a marine sanctuaries application; a blended bathymetric elevation surface for the New Jersey coast for an interagency offshore aggregates study; a VDatum implementation for a special hydrographic survey in Delaware Bay with RTK-GPS vertical referencing (see Hess, Milbert, Gill, and Roman, 2003; and Riley, Milbert, and Mader, 2003); and several areas for determining MHW shoreline from transformed LIDAR data (see Woolard, Aslaksen, Longenecker, and Ryerson, 2003; Parker, 2002; and Parker, submitted).

However, there is a strong need for a National VDatum, so that vertical datum transformation can be carried out on elevation data sets anywhere in the U.S. Many coastal users have requested VDatum for their area, and NOAA has a number of important applications that will benefit greatly from a National VDatum (see below). In fact, the use of a vertical datum transformation tool should become a cornerstone of the new way that NOAA will acquire, handle, and process bathymetric and shoreline data and efficiently use these data to produce NOAA nautical charts and electronic navigation products. This need for a National VDatum was recently supported by the *Committee on National Needs for Coastal Mapping and Charting* of the *Ocean Studies Board* of the *National Academies of Science*. It was also supported by the *RTK GPS Navigation for Hydrographic Surveys and Seamless Vertical Datums Workshop*, as well as by user groups represented at numerous conferences over the last two years.

Some very important applications for which National VDatum is critical include (Parker, 2002):

(1) the implementation of a seamless National Bathymetric Database. VDatum will transform all the historical data sets to a common datum (MLLW). This database will be the source of bathymetric data for the Vector Product Database from which electronic navigational chart (ENCs) products will be produced or updated;

(2) the improved efficiency and accuracy of hydrographic surveys with vertical referencing from RTK-GPS by eliminating the need for time-consuming water level corrections (requiring water level stations installed during the survey) and vessel settlement and squat corrections. The bathymetric data will be measured "on the fly" relative to chart datum (MLLW) using VDatum to transform the RTK-GPS-referenced data to MLLW.;

(3) the measurement of *consistently* defined MHW shoreline from RTK-GPS-referenced

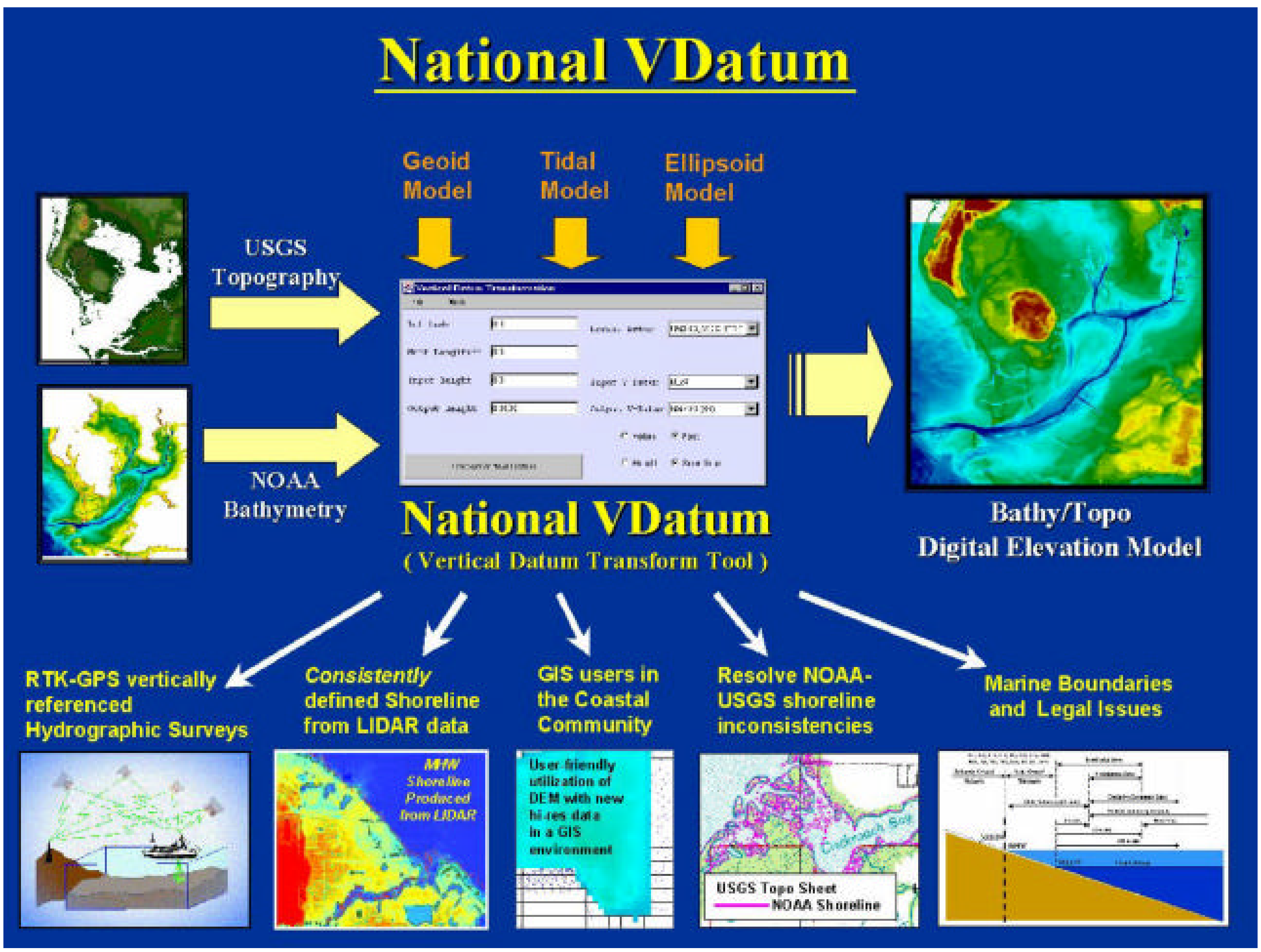
LIDAR elevation data from the intertidal zone transformed with VDatum to the MHW datum, with the zero line then being the shoreline; a consistently defined MLLW line can also be produced from transformed bathymetric LIDAR data;

(4) the ability to use high-quality 3rd-party bathymetric data (from universities, companies, and state, county, and city agencies) in NOAA nautical chart products, with VDatum solving the vertical datum incompatibility problems that have prevented this;

(5) meeting local coastal user needs for being able to blend their bathymetric data with that obtained by other groups;

(6) the implementation of a full National Bathy/Topo/Shoreline Program with the U.S. Geological Survey, VDatum being required for the blending of USGS's topographic data with NOAA's bathymetric data after their transformation to a common datum; and

(7) marine boundary applications.



## THE DEVELOPMENT OF A NATIONAL VDATUM

The development of a National VDatum has two major activities. First, is the design and implementation of the data transformation database, taking into consideration all future applications and user-friendly access requirements via the Internet, including the ability to handle multiple grids with different resolutions (a problem still being worked on). Second, is the population of this database with datum transformation fields for all U.S. coastal areas.

This second activity is a huge undertaking considering the 95,000 miles of coastline to be covered. The largest part of this effort is producing the geographic distribution of the various tidal datums (using hydrodynamic tidal models and TCARI) for all the shallow bays, estuaries, and tidal rivers of the U.S. Building these tools and models requires sufficient baseline information of tidal datum and geodetic datum relationships established at water level stations. In some areas additional water level stations will need to be installed for short time periods and additional GPS measurements made at these and other stations to fill gaps in knowledge or to verify model output at critical locations. Ellipsoid models are available for producing the geographic distribution of the various ellipsoid datums. Geoid models are available for the entire U.S., but more advanced geoid modeling work still needs to be done for Alaska and Hawaii before they can be included in National VDatum.

A major budget FY05 initiative has been submitted to populate the National VDatum database for the entire continental U.S. in five years, with Alaska and Hawaii accomplished the following year. Until that initiative is successful, or some other support is obtained, the National VDatum database will be populated area by area, based on available resources, with priorities based on a number of considerations, including: areas with high quality LIDAR data from which shoreline is to be derived; planned hydrographic surveys; high priority areas to be added to the National Bathymetric Database; future joint NOAA-USGS Bathy/Topo/Shoreline projects; areas with high-quality 3rd-party data; user requests from the coastal zone community; and homeland security needs.

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