Vertical Control in a Tidally Influenced Complex River System
With a Fixed Low Water Datum

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Introduction

The Center for Operational Oceanographic Products and Services (CO-OPS) of the National Ocean Service (NOS) is responsible for providing vertical control and tidal zoning specifications for all hydrographic and photogrammetric in-house and contract surveys. Normally CO-OPS is tasked with providing tidal zoning and vertical control in a marine environment where tidal datums are referenced to provide tidal correctors. However, in the case of Columbia River, OR/WA this was only partially true because in the upper Columbia River, chart datum is a fixed datum known as the Columbia River Datum (CRD), established by the Army Corp of Engineers in 1911. CO-OPS was tasked with providing tides control for a river that is tied to a fixed vertical datum that was established during a specific river flow period. At the beginning of this project, no prior tidal zoning scheme had been established and CRD datum ties to existing tide station datums had not been definitively accepted.

This paper shows some of the procedures that were required for CO-OPS to establish a tidal datum link to the CRD so that a reasonable tidal zoning scheme could be generated to vertically control a photogrammetric survey in defining shoreline boundaries of the Columbia River. In addition, new software will be discussed that should help to define optimal windows of time for flying photogrammetry surveys based on predicted tide station data.

Figure 1. Geographic Overview of the Columbia River Estuary and River
Data Collection, Processing, and Datum Computation

The Columbia River is a unique case study because it uses a fixed low water datum specific to the river, called Columbia River Datum, or CRD, as reference for most of the river upstream of the entrance estuary. CRD was established in 1911 by the US Army Corps of Engineers (USACE). Columbia River was noted to be an exceptional case because of the considerable variation in the low water elevation from year to year. The Columbia River has a significant seasonal variation in water level due to seasonal run-off in the watershed and has variability from year-to-year depending on the snow mass accumulated each winter. In order to account for this, the river datum “zero” was set at a point below the average low water, but not as low as the lowest record for a long period, as defined by the combination of circumstance, which seldom would occur in unison. At the time this reference plane was called “low water,” except at Astoria, which remained at Mean Lower Low Water (MLLW). At the time CRD was developed, the lowest recorded water level record occurred at Portland October 6, 1886, and became the “zero” of the gauge operating there at that time. The reference was set at the low water of October 6, 1886 and was never changed. Prior to 1911, short term gauges had been used along the river for hydrographic survey, but they were only approximate in accuracy of their zeros. A station had been operational at Astoria for over a year, and was used to establish the MLLW reference there. During the 1911 study to establish a new low water datum, gauges were set at Astoria and Portland, as brackets for the area in question. Several staff gauges were placed in the middle. Where benchmarks existed from previous hydrographic study, elevations were used to set the gauges as close to CRD as possible, and where benchmarks were not available, the elevation was estimated. Benchmarks were set for each station, and the elevation above the gauge zero recorded. The gauges were left in from May through October, 1911, at which point it was assumed the lowest stage had been reached, during which time several measurements were taken at all daytime high and low tides. Most of the gauges were removed in October, 1911. However, on November 2, 1911, the river fell to zero at Portland, and read very low at the other remaining gauges, which Army Corps recognized as an extreme low water and a possible complication to the low water datum calculation. Further complicating the calculations, it was understood that a true low water reference for the lower portion of the river cannot be established from the readings of any one day’s low water, even when the water level falls to zero in the upper reaches. Levels were run at Astoria and Portland to US Geological Survey (USGS) benchmarks to connect zeros of the gauges with the benchmark elevations. It was thought in 1911 that the mean range of tide of the river decreased in a linear trend moving from Astoria to Portland, and water level data showed that there was a gradual slope in mean sea level moving downstream, with Portland 5.35 feet higher than Astoria. The theory was that with the slight slope of water level differences and uniform changes in range of tide, that using CRD would provide a linear low water profile throughout the river. While it is noted in the original publication regarding CRD that the values at each station may be approximate, and may not include all possible contributions to water level, it is stated that the values used in this reference datum were “sufficiently accurate” and further work not required. Columbia River Datum has existed as a fixed datum ever since. (Hickson, 1912)

CRD is now primarily maintained by USACE Portland District and is tied to National Geodetic Vertical Datum of 1929 (NGVD29). Elevations of CRD are held at bench marks along the river basin and tide gauges can be set to these elevations during survey operations. Shortly after the establishment of NGVD29, geodetic ties were made at all possible benchmarks where a
The presence of a geodetic tie at a CRD benchmark allows a reference point to level tidal datums to. For recent hydrographic and photogrammetric surveys, the relationships between CRD, NGVD29, North American Vertical Datum of 1988 (NAVD88), and tidal datums were reconciled at all installed subordinate tide gauges to provide to the Office of Coast Survey and to the National Geodetic Survey. An extensive research effort was needed at two of the eight locations since leveling connections were not made to old NGS level lines in Oregon. Destroyed or lack of CRD referenced benchmarks make this relationship difficult to establish in some areas, such as the Multinomah Channel.

Examining the relationships between tidal datums and CRD, it is apparent the assumption of linearity on which CRD was founded is not entirely accurate. This is especially evident moving from the estuary influence near Astoria to the river influence upstream of Wauna, OR. The relationship between MLLW and CRD is not constant throughout the river system, as MLLW is based on tabulation of the tides and changes elevation relative to the bathymetry and the land depending upon the range of tide and the mean sea level (or mean river level) relative to specific 19-year periods (National Tidal Datum Epochs- currently 1983-2001). CRD is a fixed datum based on low river stages and not on tidal elevations. Cross sectional diagrams have been developed to examine the relationship between MLLW and CRD and the changes in the difference moving up the river. Figure 2 illustrates all tidal and geodetic reference datums calculated for Columbia River with reference to CRD. In order to plot all stations together, including Astoria, the only station not on CRD, a constant of -0.681 meters was applied to datums for comparison purposes. Geodetic relationships have a roughly linear trend decreasing in elevation relative to CRD moving upstream. NGVD29 is higher than CRD at some stations near the mouth, from Astoria to Longview. Further upstream the geodetic reference is below CRD, with a greater difference upstream. NAVD88 follows the same trend, with NAVD88 close to CRD at Astoria, decreasing in relation to CRD further upstream. All tidal datums are above CRD for the entire river, in keeping with the original premise of the low water reference datum. Trends of Mean Sea Level (MSL) reveal a slight downward slope from the entrance to upstream, but with a net decrease of only 1.094 meters, or 3.59 feet, less than the 5.35 feet measured in 1911, and not entirely linear. There is a notable drop in MSL near Longview, between the sections of the system under basin influence and those under river influence. The differences between high water tidal datums (MHHW and MHW) and low water tidal datums (MLW and MLLW) also change very drastically near Longview, with a much larger difference in the estuary entrance than the upper reaches of the river basin. This is reflective of the significant decrease in mean range of tide upstream, which explains why both the high and low water tidal datums level off to the south of Longview with reference to CRD.

While computation of CRD is relatively straightforward in places in which the ties still exist and corrections can be made, complications arise in the production of CO-OPS products such as predictions available via the internet (www.co-ops.nos.noaa.gov). For each station used in the hydrographic survey and photogrammetry projects, CRD, NAVD88, NGVD29, and tidal datums were computed, and the relationship established. However, CO-OPS products utilize accepted MLLW datums as the low water reference datum, and generate predictions based on this. Observed water levels are available through the CO-OPS website because the staff for the subordinate gauges was set to CRD for each station, and the data collected using CRD as station datum. While this is not inherent on the website, notice of this nuance was provided in the project instructions for hydrographic survey and photogrammetry. Predictions using CRD as the low water datum had to be manually produced, while predictions using MLLW as the low water
datum are readily available via the website. This is a very important distinction for project planning, especially given the inconsistent relationship between MLLW and CRD throughout the river system.

**Figure 2.** Tidal and Geodetic Datums Referred to Columbia River Datum

### Old Zoning Scheme

The method of discrete tidal zoning currently utilized by the National Ocean Service (NOS) develops co-tidal charts of co-range and co-phase lines using analyses of tide observations, as well as hydrodynamic and other tidal models, and other research. Co-phase lines are constructed by interpolating between historical and operational stations based on Greenwich high water interval (HWI) lines and low water interval (LWI) lines, and overlaying them on a nautical chart. Co-range lines are drawn similarly, but use either Mean Range of Tide (Mn) or Great Diurnal Range (GT), depending on geographic area and tide type. Polygons, or “zones”, are drawn from these lines, with the restriction that adjacent zones should not vary more than 0.2 feet in range, or 0.3 hours in Greenwich intervals. Each zone has a correction value based on the variation of time and range of tide from an operational reference station, which can be used to eliminate tidal influence from soundings in hydrographic survey, and assist in planning of flight windows for photogrammetry. (Wong, 2001) Co-tidal lines for estuaries, bays, and rivers rely mainly on shore-based water level data analysis, and in these shallow water areas, it is quite common to find complex tide characteristics (Tronvig and Gill, 2001). The more complex an area, and the more available historical water level data, the more detailed a co-tidal chart can become. Tide characteristics can change over time, not only from shoaling, and natural
changes in bathymetry, but particularly in areas with engineered changes, such as shoreline manipulation, damming of rivers and streams, or dredging. It is vital to an accurate zoning scheme to have recent data to correct for any outdated historical data.

Prior to 2002, Columbia River as a whole had not been zoned. A hydrographic survey project done in 1996 was limited to the lower Columbia River where chart datum is based solely on tidal datums. Tide control included water level stations at Astoria and a subordinate gauge at Jetty “A” close to the estuary entrance, near Cape Disappointment. Astoria was used for water level control for the entire survey, and the vertical reference datums used were Mean High Water (MHW) and MLLW. Figure 3 shows the tidal zoning created for this 1996 project. A water level corrector value was provided for each polygon in relation to Astoria, in order to remove the tide from soundings collected during the survey. In 2002, a multiyear hydrographic survey of the entire Columbia River, from the mouth through the upper reaches of the river past Portland, was begun. A large number of historical stations along the river extent allowed preliminary zoning to be developed for the entire survey area. But because the most recent data sets for these stations were from the mid 1980’s or older (except for Astoria), interpolation for accurate zoning was impossible. A hydrographic survey requires tighter control than was available using only Astoria as control for the entire river. Using Astoria as the only control station, a corrector of more than 400 minutes would have to be added to the predicted tide for zones up river of Portland, and the tidal range decreased to 20% of that at Astoria. This is far outside the range of acceptable control for tidal zoning correctors. In addition, river influence significantly distorts the tidal signature of the upper reaches of the Columbia River, making it inappropriate to use Astoria as sole tide control for the entire survey. In order to gain better vertical control and produce more accurate tidal zoning throughout the river system, subordinate gauges needed to be installed. Typically at least 30 days of continuous water level data is needed to calculate tidal datums at subordinate gauges. Because the seasonal flow has such a great impact on water levels in the Columbia River, the subordinate gauges remained operational for at least a year, in order to capture the seasonal effects, and obtain accurate tidal datums based on the lowest three months of river flow that was used to generate CRD in the 1911 Army Corp of Engineers datum survey.
New Zoning Scheme

While the 1996 hydrography project used MHW and MLLW as reference datums for the project instructions, the instructions changed slightly for the 2002 project. Soundings at the mouth of the Columbia River still use MLLW as the low water reference datum, but all soundings east (and south) of Chart 18521, the edge of which is just east of Harrington Pt., use CRD as the low water reference datum. The river has been zoned in its entirety and has undergone several iterations as more tidal data were collected. Subordinate gauges, and accurate, up to date, tidal datums at these subordinate gauges have been fundamental to the zoning and project planning processes. It is especially important, not only because Astoria provides poor control for upper reaches of the river, but also because frequent dredging occurs along the Columbia River. Astoria, OR (944-9040) is the only long-term control gauge in the river system, so it acts as control for the rest of the subordinate gauges for the purpose of tidal datums calculations, as well the tidal reference station for the survey area near the river entrance.

Six subordinate gauges: Wauna, OR (943-9099), St. Helens, OR (943-9201), Morrison St. Bridge, OR (943-9221), Vancouver, WA (944-0083), Longview, WA (944-0422), and Skamokawa, WA (944-0569), were first installed in accordance with the Port of Portland in March 2002 for the multiyear hydrography project begun in the 2002 field season for a Homeland Security baseline project. A photogrammetry project first proposed for the 2003 field season is scheduled to take place this spring. These gauges will provide important tidal control during the photogrammetric flights. While a few of the stations were new stations, most of them were historically operated in 1985-86. Data for the subordinate stations were collected on CRD, and datums were calculated on three months of lowest river flow. It should be noted that depending on river flow, water levels may significantly differ from published datums. Challenges in selection of subordinate gauge locations included finding sites with at least one geodetic tie to CRD, and finding sites that would not be destroyed before hydrography was
completed. The stations were left in for a year in order to take seasonal effects into consideration during tidal datum computation, and three of the six (Wauna, OR, Morrison St. Bridge, OR, and Skamokawa, WA) were removed in April 2003. Those three gauges were reinstalled from March to November 2004 for the planned NGS photogrammetry project, but were again removed due to project delays. Prior to flight time, proposed for July 2005, those gauges will be reinstalled for control along the river. The last survey work for hydrography was finished during the 2003 field season, and the photogrammetry project is planned for summer 2005. Partnerships are in place to continue operations of some of these gauges for real time water level data throughout the river for navigational purposes.

The original preliminary tidal zoning for the Columbia River, based solely on Astoria water levels and historical station data, is illustrated in Figure 4. The zoning has been refined from the 1996 iteration, as evidenced by more detail and smaller tide zones, especially upstream of Astoria. All of the zones west of the chart division, at Harrington Pt., in this figure used MLLW as reference, while in the river east, and all points up river, used CRD as its low water reference.

![Figure 4. Preliminary Tidal Zoning provided for 2002 Hydrographic Survey Project Instructions](image)

The project area was increased in 2003, to include several tributaries and channels, such as the Lewis River, east of Saint Helens, and the Multnomah Channel, running parallel to the west of the Columbia River, south of Saint Helens and north of Portland. In order to obtain accurate information for tidal zoning in the Lewis River in preparation of the 2003 remote sensing project instructions, water levels at a National Weather Service (NWS) gauge at Woodland were used. The OR/WA0301 instructions recommended confirming predictions with the NWS Forecast Office hydrology prediction model for this section of the Columbia River. Subordinate stations Multnomah Channel, OR (943-8125) and Rocky Point, OR (943-9189) were installed and datums computed on one month of data from November 2003 in order to fill in the remaining gap in tidal zoning, along the Multnomah Channel. Complications arose in the Multnomah Channel stations due to an insufficient number of benchmarks with CRD connections. Through interpolation methods between stations with CRD connections nearby, the connections were eventually reconciled. Predictions for these stations could not be given.
without an accepted tie between tide station derived tidal datums and CRD, and difficulties existed in the predictions generation process and referring predictions to the correct reference datum.

**Figure 5** illustrates the current tidal zoning, using the most recently accepted tidal datums for all subordinate stations, including Rocky Point and Multnomah Channel. It can be seen that much more detail exists in the zoning. For instance, whereas there used to only be 8 zones from the entrance of the Columbia River to the point at which it changes to using CRD as a reference datum, there are now 18 zones in the most current set of zoning. The increase in detail is attributed mostly to the more accurate information on Greenwich Intervals provided by subordinate gauges. The zones are smaller, and now include Youngs Bay, near Astoria. This is the final zoning scheme which was used for the most recent parts of the multiyear hydrographic survey project, and was provided to the National Geodetic Survey (NGS) for flight planning in the 2005 photogrammetry project.

![Figure 5. Tidal Zoning provided for 2004 Photogrammetry Project Instructions](image)

A look at the 2002 zoning alongside the 2004 current zoning scheme for the entire river, in **Figures 6A and 6B** makes the level of refinement more obvious. As more water level data were collected, and more accurate tidal datums were calculated for subordinate gauges throughout the river, the zoning became much more detailed, and was extended into more areas. **Figure 6B** illustrates the entire river as it is currently tidally zoned, using all available subordinate data and computed tidal datums.
Figure 6A. 2002 Columbia River Zoning: First Iteration

Figure 6B. 2004 Columbia River Zoning: Current Iteration
Shoreline Imagery in Conjunction with Columbia River Datum

Shoreline mapping has involves the acquisition of remotely sensed data used to determine the boundaries between private, state, and federal lands at the land-water interface. Due to the nature of most shorelines, this acquisition must adhere to specific standards so that shoreline coverages can mesh seamlessly to produce high accuracy charts and photographic renderings. One of these standards, tidal datum determination (in conjunction with tidal zoning), can often be the largest single source of error to the remotely sensed data set if not accurately calculated. Typically shoreline mapping has used the tidal datums of Mean High Water (MHW) to define the shoreline on nautical charts and Mean Lower Low Water (MLLW) to delineate the boundaries between private and public lands.

As the tide rises and falls it scours the shoreline of most visible vestiges of the previous tidal cycle, so the use of debris line on a beach or land-water interface to determine MHW is not acceptable due to the landward intrusion of the most recent highest high tide or storm surge (Attachment J, 2004). Equally as difficult to delineate, MLLW tide levels are nearly impossible to recognize through the surf zone and may expose rocks, sandbars, and other hazards to navigation that may not be visible at any other higher water elevations. Therefore it is critical to coordinate remotely sensed data acquisition with these two datums to be able to delineate the two required tide lines of MHW and MLLW.

Columbia River is heavily influenced by the tides of the Pacific and has typical tidal curvature to its tidal signature. Figure 7 shows the tidal signature of Astoria, OR at a time period (in this case August 2003) in which shoreline acquisition could occur with good results. Take note of the symmetry of the tidal curve with the slope of the rising and falling tide being nearly identical.

Figure 7. Tidal signature from a CO-OPS water level station at Astoria, OR for August 15-18, 2003.
The addition of water via terrestrial inputs gives the tidal signature of up river tide stations an asymmetrical skewing of outgoing high tides. This asymmetry can be seen in the form of a slant in Figure 8. In applications of remote sensing this unique tidal signature tends to reduce the time of data collection due to the sharp slope of the outgoing high tide.

Figure 8. Tidal signature from a CO-OPS water level station at Vancouver, WA for August 15-18, 2003.

However, because CRD was purposely developed as a fixed low water datum, this elevation is too conservative for a low water tide to be reached at regular intervals. Therefore, remote sensing aircraft must coordinate flight times with MLLW relative to CRD, a tidal datum that occurs with much more frequency, to obtain correct shoreline data. The difference of MLLW to chart datum (CRD) for these specific charts is overcome by a best fit line relation between the two datums, or ‘datum offset’. Further complicating the application of MLLW to shoreline data collection in up river areas is that the datum offset between CRD and MLLW changes as one moves from tide station to tide station from the headwaters to the mouth of the Columbia River. Figures 2 and 9 shows the relationship of MLLW to CRD as it progresses up the river.
To help Remote Sensing survey platforms produce higher quality data while making the data collection more efficient, NGS and CO-OPS have introduced several unique techniques. Borrowed from standard hydrography, discrete tidal zoning uses time and range correctors to relate areas with no current tidal data to water level stations that are operating during the time of the shoreline data acquisition. The zoning has been enhanced to give both times of high and low water as an output over the standard averaged time corrector used in hydrography. This allows easier manipulation of flight times for collection points at both MHW and MLLW, the desired datums of interest. Also, because shoreline collection platforms are moving at a much faster rate than typical hydrographic ships (250 knots versus 5 knots respectively) it has been found that the zones are too small in size and complicate flight window patterns. A tendency for the remote sensing aircraft to over fly numerous zones in a single flight line has lead to inefficiencies and resultant complications for shoreline data collection. By applying requirements set out solely for remote sensing instead of standard hydrography, CO-OPS will work towards combining several small “hydrographic discrete tidal zones” into large “photogrammetric” tidal zones” better suited for shoreline data acquisition. This zoning technique will help in the planning of flight time windows for the remote sensing aircraft by giving predictions of tide heights and time several days to weeks in advance of a survey.

Another tool being created by CO-OPS (with the assistance of NGS) to better predict times and heights of tides for remote sensing data collection is a program called PHOTO Windows. This software currently uses tidal predictions in conjunction with discrete tidal zoning values to help remote sensing aircraft plan survey routes for optimum collection. The software obtains high and low water time correctors from the discrete tidal zoning in the survey area of interest and applies this information to predicted astronomical tides. Developments in the software will soon utilize tidal zone range differences so that remote sensing tolerance values will be calculated and applied to the tidal signature of controlling tide gauges for the survey. Figure 10 shows the basis for this program by applying MHW and MLLW tidal datums to the

**Figure 9.** Relationship of MLLW to Columbia River Datum from the mouth of the river at Astoria, OR to the head waters at Vancouver, WA and Portland, OR.
tidal curve at Vancouver, WA during the dates of August 16-18, 2003 and overlaying the shoreline data collection tolerances.

Figure 10. Remotely sensed data acquisition tolerances overlaid on the Vancouver, WA tidal data.

These flight window tolerances at MHW and MLLW are determined by tide type and mean range of the area where shoreline data will be collected. In a diurnal or semi-diurnal tide regime, where the inequalities of tides are very low, a mean range of 5 ft or less produces a window tolerance that will be +/- 0.3 ft of the sought after datum. While Mean Ranges greater than 5ft in these areas will have a tolerance equivalent to 10% of the entire range. For example, a location with 6.2 ft of mean range in a diurnal tide regime would produce flight window tolerances of +/- 0.62ft for MHW and MLLW datums. This flight window calculation for MHW on August 16, 2003 at Vancouver, WA can be seen in Figure 11.
To more efficiently collect remotely sensed shoreline data these flight windows must be compiled over several zones in order to mesh the time window into one single flight line which the aircraft can fly. In Figure 12, the tidal zoning has been applied to the control station at Vancouver to produce six distinct tidal signatures for areas in which the zones encompass. These signatures have used time and range correctors from the Vancouver tide station to show the tide as it progresses up the river.
It is anticipated that the PHOTO Windows software will be able to recognize the neighboring zone information and produce start and stop times for several adjacent zones. In the case of zones CR86 through CR91, the most optimum data collection time for shoreline at MHW would be on the receding high water because most of the zones pass through the window tolerance at close to the same time. The only drawback to data collection at this point would be the limited time of an open flight window. Figure 13 shows how the zones are adjacent to one another and how the flight path of the shoreline data collection is oriented. (Keep in mind that the entire zoning scheme for this project is not present, but merely a few zones to pass on the concept.)

![Figure 13. Tidal Zoning in the area of Vancouver, WA showing applicable time and range correctors to be used on the highlighted aircraft trajectory.](image)

Future editions of the PHOTO Windows software will look to include an automatic tolerance calculator by deriving certain range and tide level values from accepted datums as well as the creation of metadata files to describe the process by which values were obtained so that users of the software understand how their data is being applied. In addition to incorporating water levels and time of tide, other factors must come together for shoreline imagery to be acquired. One such phenomenon that must be determined for specific types of shoreline imagery is the angle of the sun relative to the land surface. CO-OPS and NGS are currently in the process of addressing the sun angle in conjunction with the Flight Windows software so as to mesh the two to specify when imagery can be obtained using passive sensor systems like digital and orthophotography. This will calculate when the sun is higher than 30 degrees relative to the land azimuth but lower than 90 degrees when a sun spot actually prevents delineation of the water-land intersection. When incorporated into the Flight Windows program this sun angle ‘layer’ would be overlaid on the tidal signature and flight window tolerances to produce a single high accuracy plot of the optimum remotely sensed shoreline data collection.
Conclusion

The ultimate goal of hydrographic and photogrammetric surveying in the Columbia River was to update the nautical charts of the area. In order to provide vertical control and tidal zoning in the Columbia River to support these surveys, detailed knowledge of the established local chart datum and current tidal regime is required. Considerable effort was expended to gather necessary data to properly characterize the hydrodynamics of Columbia River and integrate the additional data to fit the locally established datum. In addition, an example of how this complex vertical control will be applied to an upcoming photogrammetric survey has been presented with a look at future tools to enhance Remote Sensing support products.

Sources


