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A simple, interactive GIS tool for transforming assumed total station surveys to real world coordinates – the CHaMP transformation tool

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ABSTRACT

Increasingly, geoscientists and biologists are monitoring the natural environment with total station and terrestrial laser scanning surveys. Due to the remote nature of many of the sites monitored (e.g., streams, rivers, glaciers, etc.) the surveys are often done in unprojected, Cartesian, local, assumed coordinate systems. However, without the survey data projected in real world coordinates the range of possible analyses is limited and the contextual power of existing imagery, elevation models, and hydrologic layers can not be exploited. This requires a transformation from the local assumed to the real world coordinate systems. We present a simple interactive interface, as an ArcGIS Add-In, that allows a user to transform unprojected total station data into real-world coordinates using three benchmark coordinates, which can be collected from a hand-held GPS (available at http://ctt.joewheaton.org/). Unlike most transformations built into GIS programs, our tool uses an affine transformation (simple shift and rotate) to preserve the precision and relative accuracy of the total station survey, while leveraging the absolute positional accuracy of the hand-held GPS to place one's data approximately in real world coordinates for GIS overlay purposes. The user can quickly visually inspect between six and twelve transformation options, while comparing the residual error estimates to interactively choose the most reasonable transformation. The tool provides an easy-to-use, cost-effective workflow, which facilitates the sharing and visualization of precise total station survey data in real world coordinates through a webGIS or virtual globes (e.g., Google Earth, NASA Whirlwind). The tool has been tested and was used by 12 crews to transform topographic total station surveys of 364 sites into real world coordinates as part of the Columbian Habitat Monitoring Program (CHaMP).

1. Introduction

Total station surveys are a widely used method to survey topography (USACE, 2007), with applications ranging from traditional land surveying (Kizil and Tisor, 2011) to landform evolution monitoring (Lane and Chandler, 2003). In the geosciences, repeat total station surveys have proved useful in monitoring morphodynamic evolution (i.e., geomorphic change detection) of rivers (Lane et al., 1994; Fuller et al., 2003; Merz et al., 2006), glaciers (Nainwal et al., 2008), beaches (Delgado and Lloyd, 2004; Baptista et al., 2011) and mass wasting of hillslopes (de Sanjose-Blasco et al., 2007; Mackey et al., 2009). Similarly, in the biological sciences total stations are now becoming standard tools in monitoring streams and rivers by fisheries biologists (Bouwes et al., 2011), riparian ecologists (Marquardt et al., 2010) and

stream ecologists (e.g., Walters et al., 2003). Both in the geosciences (Tooth, 2006; Chien and Keat Tan, 2011) and biological sciences (Butler, 2006), there is increasing demand to collect spatially explicit data that can be visualized in GIS and shared in any of a number of common webGIS platforms (e.g., Google Earth, Google Maps, Bing Maps, Mapquest, etc.). Even though the vast majority of these new geoscience and biology practitioners lack formal training in surveying and may only have basic training in GIS, their appreciation for and need to make their own data spatially explicit is increasing (Brown, 2006; Udell, 2008).

Unfortunately, most such practitioners lack the abilities and/or tools to transform their precise total station data (and terrestrial laser scanning data) to an accurate real world location, without degrading the high relative accuracy and precision of the survey data (Sheppard and Cizek, 2009). Since many total station surveys are now undertaken in remote and/or undeveloped localities (e.g., deep canyon gorges, alpine glacial valleys), there is often not an established local control network tied to a projected real world coordinate system (PRWCS). Thus, many of these surveys

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are done from an unprojected Cartesian local assumed coordinate system (UCLACS). For the generally short (i.e., < 1–2 km) spatial extents of total station surveys, using a UCLACS will often suffice for applications like change detection monitoring where the most important things are that the control network and same coordinate

system (UCLACS or PRWCS) are used consistently. However, as GIS has become more of an everyday tool in the geosciences for visualization, contextualization, modeling and analysis of topographic data (Lane and Chandler, 2003), there is an increasing demand for such surveys to be in PRWCS (e.g., biodiversity
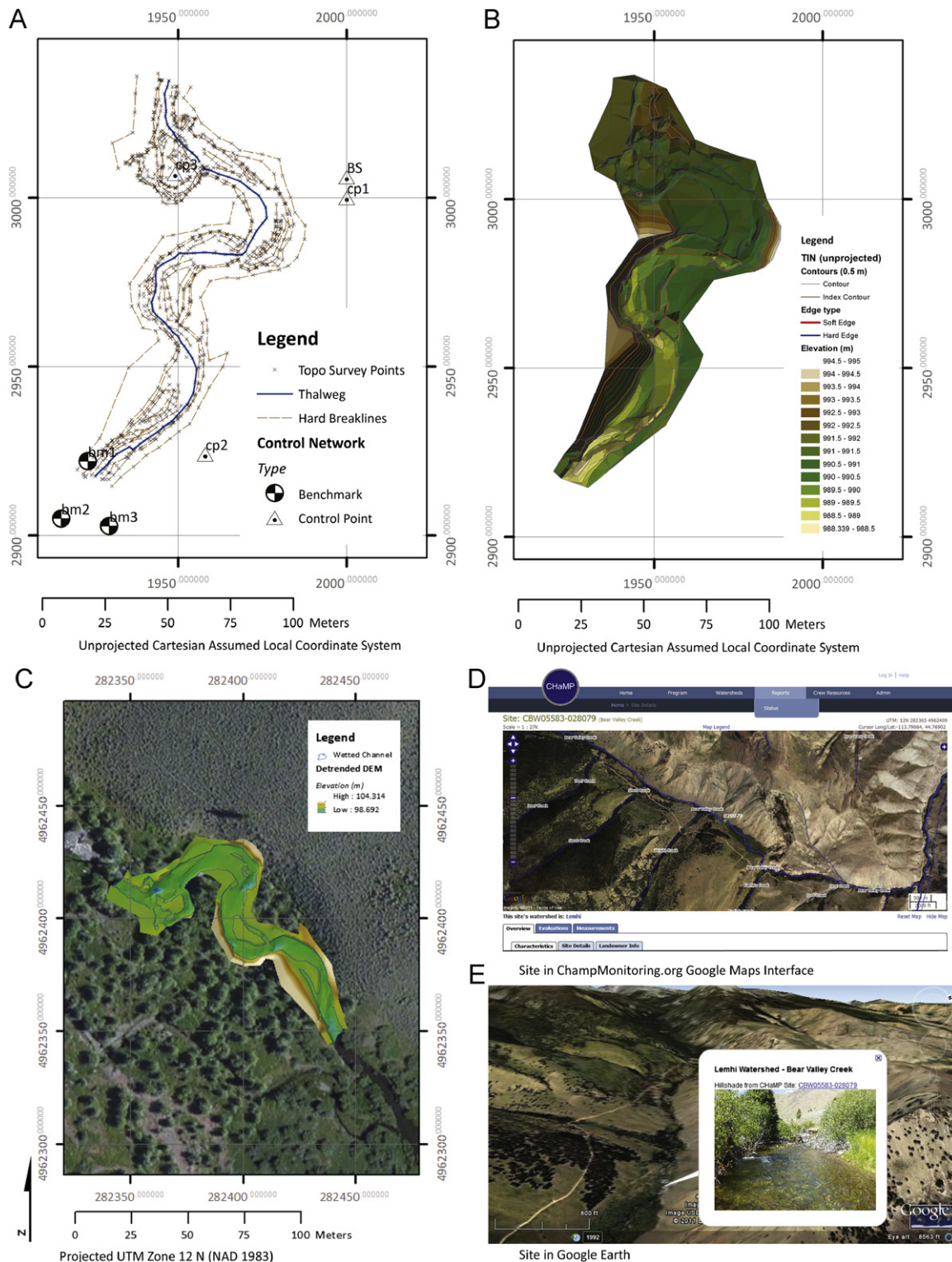

Fig. 1. The value of total station data being projected in real world coordinates. (A) Raw total station data in an assumed coordinate system is not that informative as there is little context to accompany it. (B) A derived product, like this TIN, may be recognizable and useful, but still lacks basic context. (C) When the data is transformed into real world coordinates, we can overlay it with other layers in a GIS enabling spatial associations to be made by visual inspection as well as facilitating a broader range of spatial analyses. (D) and (E) finally, projected data can be easily shared as KML for visibility in webGIS applications (D) or Google Earth (E). Data from CHaMP site CBW05583-028079 on Bear Valley Creek in the Lemhi Watershed (available at: http://www.champmonitoring.org/Site/Details/3592).

community, see: Butler, 2006). Although most GIS programs can handle data from UCLACS, without real world coordinates the contextual power of overlaying that data with other datasets ;(e.g., aerial imagery, vector datasets of roads, physiographic features, political boundaries, etc.) and certain analyses are not possible. For the overlay in GIS to be useful, high absolute accuracy is not essential and locational accuracies on the order of 5–10 m will more than suffice. The more important factors for later change detection of total station data are internal consistency between surveys, and preservation of high relative accuracy and precision of the survey data. Although, survey software, CAD software, scientific applications and GIS can all generally work with data in UCLACS, there is much more one can do (particularly in GIS) with data in PRWCS (Fig. 1). It is thus critical that practitioners understand what is required to use total station surveys to project data into PRWCS for use in GIS (Tiede and Lang, 2010).

Traditionally, to transform coordinate data (x,y,z) from a UCLACS into a PRWCS requires (a) using survey-grade rtkGPS to obtain accurate coordinates for the same control points acquired by the total station, or (b) occupying a known pre-existing control network surveyed in PRWCS (USACE, 1994; USACE, 2007). Both methods are straight-forward for the trained surveyor with access to the right equipment and/or post-processing software. The problems are that many practitioners who might use total stations, (a) may not have access to the necessary post-processing software, (b) often do not also have access to rtkGPS, and/or (c) may work in areas where an existing control network tied into a PRWCS may not exist within a practically feasible distance from the survey area. In other situations, tree cover, canyon walls and/or steep terrain may limit the visibility of satellites and/or produce GPS multi-pathing errors, rendering survey-grade GPS useless. Thus, it becomes cost prohibitive and/or infeasible to transform this survey data into PRWCS.

One practical application where only having data in UCLACS can be problematic is repeat topographic surveys as part of monitoring campaigns (Fig. 1). Even if a transformation from UCLACS to PRWCS is possible, what is the best practice for using the PRWCS during subsequent repeat visits? For example, we have been involved in the development of a new monitoring program called CHaMP (Columiba Habitat Monitoring Program, http://champmonitoring.org) for tracking the status and trend of anadromous salmonid fisheries habitat throughout the Columbia Basin (Bouwes et al., 2011). In CHaMP, physical habitat is largely quantified through topographic surveys undertaken with total stations. In its pilot implementation year in 2011, twelve CHaMP crews from seven different agencies established 364 monitoring sites within eight sub-basins, of the interior Columbia River Basin that will be revisited at one to three year intervals. Crews are comprised of 3–4 people with two dedicated to total station surveying. Over the next three years, 25 crews will extend this effort to a total of 800 sites throughout the Columbia River Basin, many of which are in remote areas. The extensive implementation effort across many sub-basins and crews requires data collection efforts use durable, cost-effective tools that have manageable weights for remote use. Total stations were chosen as the best tradeoff between meeting the topographic survey needs of CHaMP across a wide range of conditions and being economical (total stations can be purchased for c. \$10 K whereas rtkGPS with base-station costs a minimum of \$30 K to \$50 K).

The purpose of this paper is to present a simple new ArcGIS Add-In that helps practitioners transform their total station data in UCLACS to a PRWCS, while maintaining the high relative accuracy of the total station data. We demonstrate the utility of the Add-In, which we call the CHaMP Transformation Tool (CTT), with a common application of transforming a topographic survey of a stream using an assumed coordinate system (i.e., UCLACS) in

to real world coordinates (i.e., PRWCS). The CTT can be used to transform any ground-based survey using assumed coordinate systems (e.g., total station or ground-based LiDaR) into a real world coordinate system.

2. The CHaMP transformation tool

We developed the CTT to assist CHaMP survey crews in establishing PRWCS when they first established a monitoring site. However, the tool is applicable beyond CHaMP, particularly where users wish to transform precise data from an UCLACS to a PRWCS. Here we review the field data requirements, the pre-processing steps necessary to use the CTT, the transformation method we employ, and a basic description of the tool interface.

2.1. Field data required

Two types of field data are required to use the CTT. The first is a total station survey (or terrestrial laser scanner survey) in an UCLACS (Fig. 2(A) and (E)). Using an assumed coordinate system is a common practice in total station surveys where a pre-existing control network or survey-grade GPS is unavailable. An assumed coordinate system is set up during the user's first total station setup, by occupying a 'known' point, which they assign assumed coordinates to (Fig. 2(A)). It is customary when using assumed coordinates to define a coordinate system with an initial, 'known' point that will (a) not be confused with a real projected coordinate system, (b) does not contain elevations that could be confused with real elevations at the site, (c) will not result in measured x–y coordinates with negative values (e.g., −100, −200) during the course of the survey (i.e., do not start with an origin of 0,0), and (d) has clearly distinguishable eastings, northings and elevations (e.g., 10,000, 20,000, 30,000) when working in UTM projections. They then set up the total station with a 'Backsight by Direction' setup, which uses a bearing (commonly set to be zero degrees) to a backsight point (typically another control point or benchmark), to orient the instrument (e.g., Fig. 2(E)). Once the survey is begun on this assumed coordinate system, all additional station setups use a 'backsight to known point' or 'resectioning' setup with control established within this consistent UCLACS. This results in all data, including the control, collected in a single UCLACS. At some point during the course of the survey at UCLACS coordinates for three benchmarks need to be acquired (Bouwes et al., 2011; Rentmeester, 2011).

The second type of data required for the CTT are coordinates in a PRWCS for the three benchmark points common to the total station survey (e.g., Fig. 2(C) and (D)). These 'common points' are typically control points or benchmarks, which were established and used in the total station survey (e.g., rebar and cap, 60 penny nail, rebar and brass moment, X etched in bedrock). The coordinate transformation and residual error check will work best if the three benchmarks are:

1. Located at least two to three times farther apart than the average positional imprecision of the hand-held GPS used to capture Benchmark location (e.g., > 30 m).
2. Spread out across the extent of the area to be surveyed such that the survey is roughly encompassed in an equilateral triangle formed by the points. This will ensure that rotation angles for the transformation are large enough to be significantly different from each other.
3. Inter-visible between each other (this means that if there is a line-of-sight between each, such that if one point is lost in the future, the other two can be used to occupy the network and begin a survey).
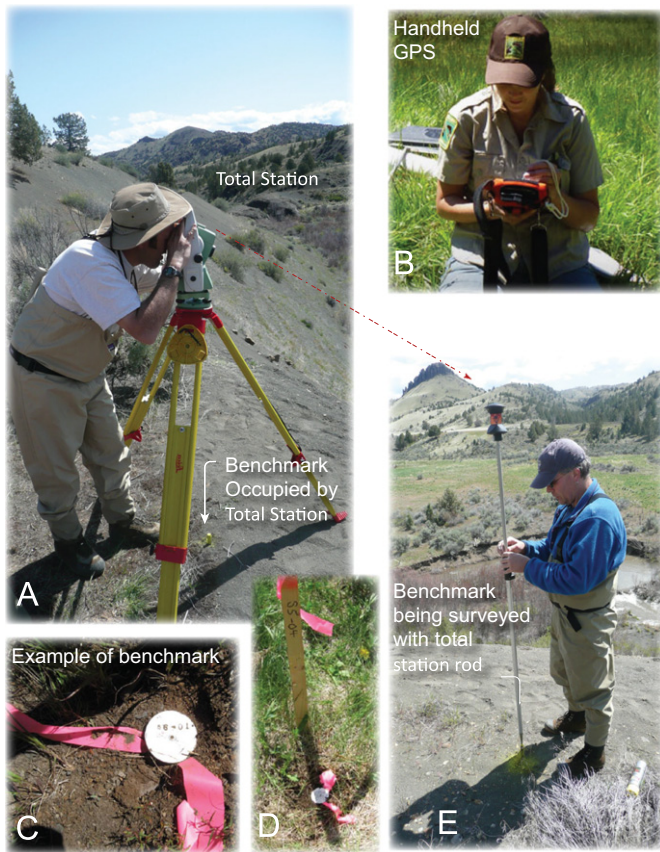
Fig. 2. Data Collection Components – (A) A total station being used to survey in an UCLACS, occupying a known benchmark. (B) Example of hand-held GPS, which can be used to collect approximate ($+/-2$ to 5 m) coordinates at a benchmark in PRWCS. (C) and (D) Examples of installed benchmarks (5/8" × 30" rebar with a 2" aluminum cap set flush with the ground). (E) Example of a benchmark being surveyed in with a total station.

In practice, site constraints (e.g., trees, roads, etc.) may limit the feasibility of achieving the first two goals listed above (e.g., goal two not achieved in Fig. 1), but these are good rules of thumb to strive for in practice. The third goal is essential.

There are multiple methods to acquire the PRWCS coordinates of these three benchmark points. The most common is to use a simple, inexpensive, consumer-grade GPS (e.g., Garmin handheld, Smart-Phone, GPS card in field data collector: e.g., Fig. 2(B)). Such devices typically yield a horizontal positional dilution of precision (PDOP) of 2 to 5 m and a vertical dilution of precision of 3–10 m. For purposes of GIS overlay at scales of 1:1000 or coarser, positional accuracies of ± 5–10 m is more than adequate for context and many analyses. In rare instances where high resolution (e.g., ≥ 25 cm) aerial imagery is present, it may be possible to derive sufficient quality (i.e., ± 10–20 m) photo control points if ground features visible in the photo (e.g., fence corner, rock edge, etc.) can be accurately located in the field and on the photo.

2.2. Pre-processing

The CTT requires both the total station data to be transformed (in UCLACS) and the benchmark coordinates (in PRWCS). The user enters the coordinates for three benchmarks in either geographic coordinates or the desired post-transformation PRWCS. The CHaMP protocol (Bouwes et al., 2011) requires that GPS coordinates of three benchmarks are recorded using a handheld data logger, which automatically formats the GPS coordinates for upload to CTT

precluding the need to type coordinates in manually. Such users will also be using the CHaMP GIS Processing Workflow Tools (Whitehead, 2011). The Tools are a series of Python scripts and Geoprocessing Models packaged in a Arc Toolbox, which help take the raw total-station data (from SurveyPro field acquisition software), and exported from the ForeSight software as a ∗.dxf file containing point coordinates, 3D polylines and polygons, and put them into a file geodatabase using the 'Import Data from.DXF File Tool'. Based on feature codes in the survey data, the "Import Data from.DXF File Tool' automatically separates out the data into functional groups (e.g., Topo Points, Control Points, vs. Breaklines, etc.). Using the CHaMP GIS Processing Workflow Tools is a very easy and useful option for the user to manage their files and pre-process their data, but this is not necessary to use the CTT. Both CHaMP and non-CHaMP users need to have their untransformed data in ArcGIS compatible feature class formats (i.e., a feature class in a file geodatabase, or a shapefile). Additionally, the benchmarks need to be labeled correctly and consistently in an attribute field in the UCLACS control point file.

2.3. Transformation method

There are numerous transformation methods for transforming between coordinate systems ranging from simple to sophisticated. The choice of appropriate method depends on the specifics of the application and is generally one that should be made by someone with proper training in surveying and geomatics as well as a solid understanding of the source data and how it was collected. In this paper, we focus upon the special case of how to transform data into PRWCS, which was collected with a precise instrument (e.g., total station or terrestrial laser scanner) on an UCLACS, and for which PRWCS coordinates at control points are acquired with minimal precision (e.g., handheld GPS).

We used an 'affine' transformation because it preserves straight lines in the original data when calculating the transformation (Berger, 1987; Vuilleumier, 2011). An affine transformation is a simple mathematical operation of a translation (shift in space) followed by a linear transformation (a rotation). We want to preserve the relative positional accuracy and precision of the total station survey in UCLACS, but take advantage of the absolute accuracy of the low-precision PRWCS coordinates at our benchmarks (Sprinsky, 2002). Fig. 3 illustrates the process conceptually. Essentially, a single GPS coordinate will ultimately be used as the basis for the horizontal shift and datum adjustment, and a bearing based on a second GPS coordinate will be used to define the rotation. Note that the use of an affine transformation is not a typical transformation in GIS; usually, UCLACS to PRWCS transformations assume the geometry of destination courses is both more accurate (in the right location) and more precise (repeatable) than the original UCLACS. Most transformations preserve the relative geometry of the destination coordinates. In other words, the PRWCS destination coordinates are the master and the UCLACS source coordinates act as the slave. The result is that such transformations stretch and warp the source data to fit the geometry of the destination coordinates and straight lines in source are not preserved. By contrast, with the affine transformation used here shifts and rotates the total station data into PRWCS in a rather approximate and imprecise fashion (i.e., $+/-2$–20 m), but which has sufficient absolute positional accuracy for overlay purposes in a GIS (i.e., in the right $+/-10$–20 m neighborhood). More importantly, the high relative accuracy of the precise total station survey ($+/-0.5$–2.0 cm typically) is maintained in the transformation to a PRWCS.

The simple affine transformation our tool implements can be calculated with simple linear algebra in many CAD and survey software applications. However, as previously mentioned, these tools and techniques are not widely accessible to practitioners in the geophysical and biological sciences. Although some of the Georectification tools (e.g., rubbersheeting) in GIS can be parameterized to do
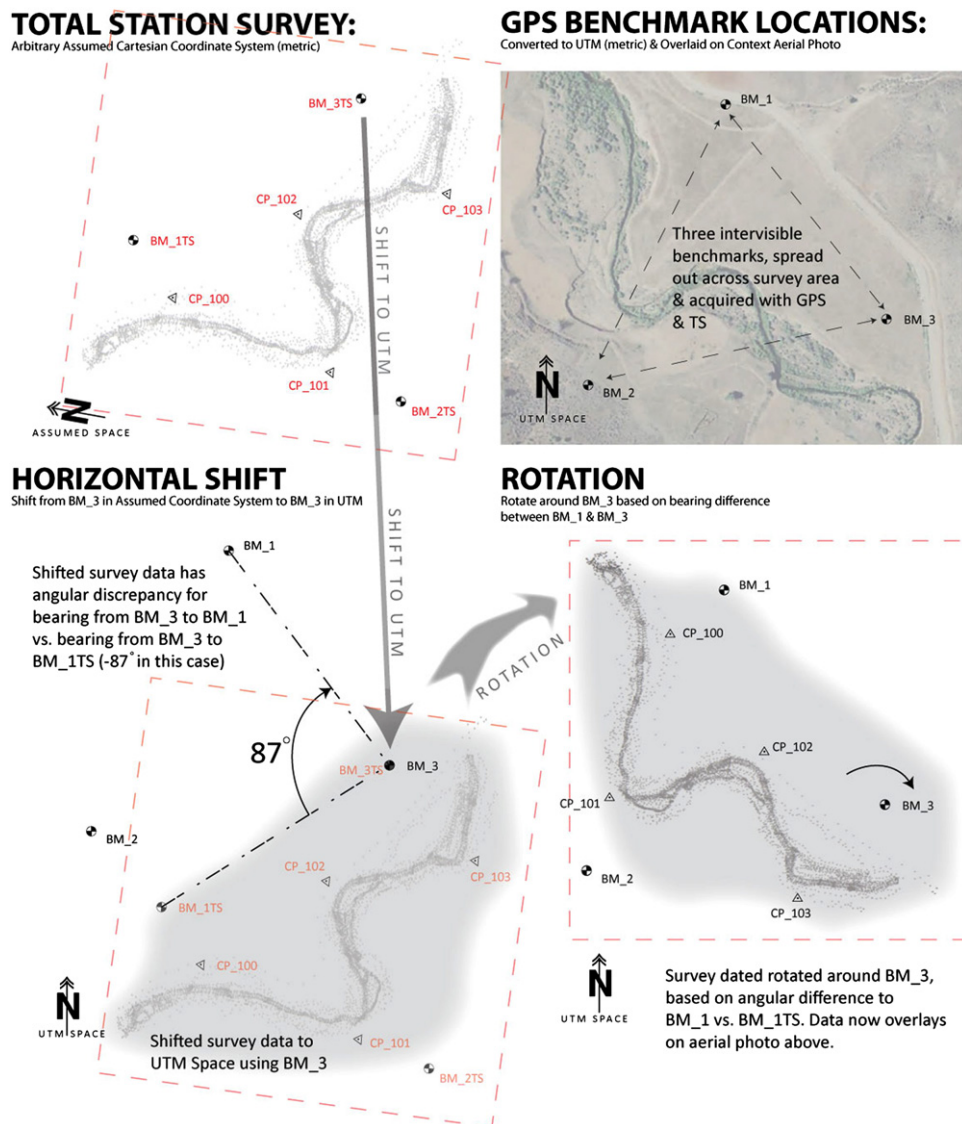
Fig. 3. An illustration of the affine transformation process used here. The top left shows total station data in an UCLACS, whereas the top right figure shows three common benchmarks collected with GPS in real coordinates and overlaid on an aerial photo. The two steps in the affine transformation process used here are the horizontal shift (bottom left) using BM_3 as a base point, and rotation (bottom right), based on bearing difference between BM_1 and BM_3.

affine transformations, these generally only apply to raster data and can not be used on vector data (i.e., points, polylines and polygons). Moreover, as there are several options to choose how to undertake an affine transformation, a workflow that allows the user to make an informed and documented choice through an interactive process is essential to promoting good survey practice. Thus, we suspect the simple and pragmatic workflow the CTT facilitates will prove useful to many practitioners and researchers using total station data and assumed coordinate systems.

2.4. The CHaMP transformation tool interface and example

The CTT was designed to be easy and intuitive enough so that field crews with limited GIS experience could use it, but flexible and powerful enough that it would be of use to experienced surveyors. The CTT Add-In appears as a small toolbar when installed and activated in ArcGIS. The toolbar consists of two buttons, the *Transformation Tool* button, and an *About Information* button. When the *Transformation Tool* button is clicked, it brings up a dockable panel in ArcGIS, which consists of three sequential steps (instances of the panel). We will illustrate the user

application of this tool with a 2011 CHaMP survey from a site on Bear Valley Creek (Lat. 44.7859°, Long. −113.76377; see also interactive map in online supplement) in the Lemhi watershed of the Columbia Basin (reference site: CBW05583-028079; data available from http://champmonitoring.org).

Before starting, the user should review their raw, untransformed UCLACS data by visualizing this in survey software, CAD, GIS or even MS Excel to check for and correct obvious busts or blunders (e.g., rod height errors, mislabeled points, incorrect control point or benchmarks locations). Next, the user should create a new empty Map Document (*.mxd) in ArcMap, and change the display properties of the data frame to the real coordinate system the user wishes to project and transform data into. The user should not add their UCLACS data prior to setting the coordinates of the data frame because it is best to have the map focused in the area of the survey within the destination PRWCS. By default, a data frame in ArcGIS takes on the coordinate system of the layer first added to it (assuming one exists). Next, the user adds some aerial imagery for context (Fig. 4(A)). This can be imagery the user already has or a basemap layer, such as Bing Imagery that is available in ArcGIS as an online basemap layer.
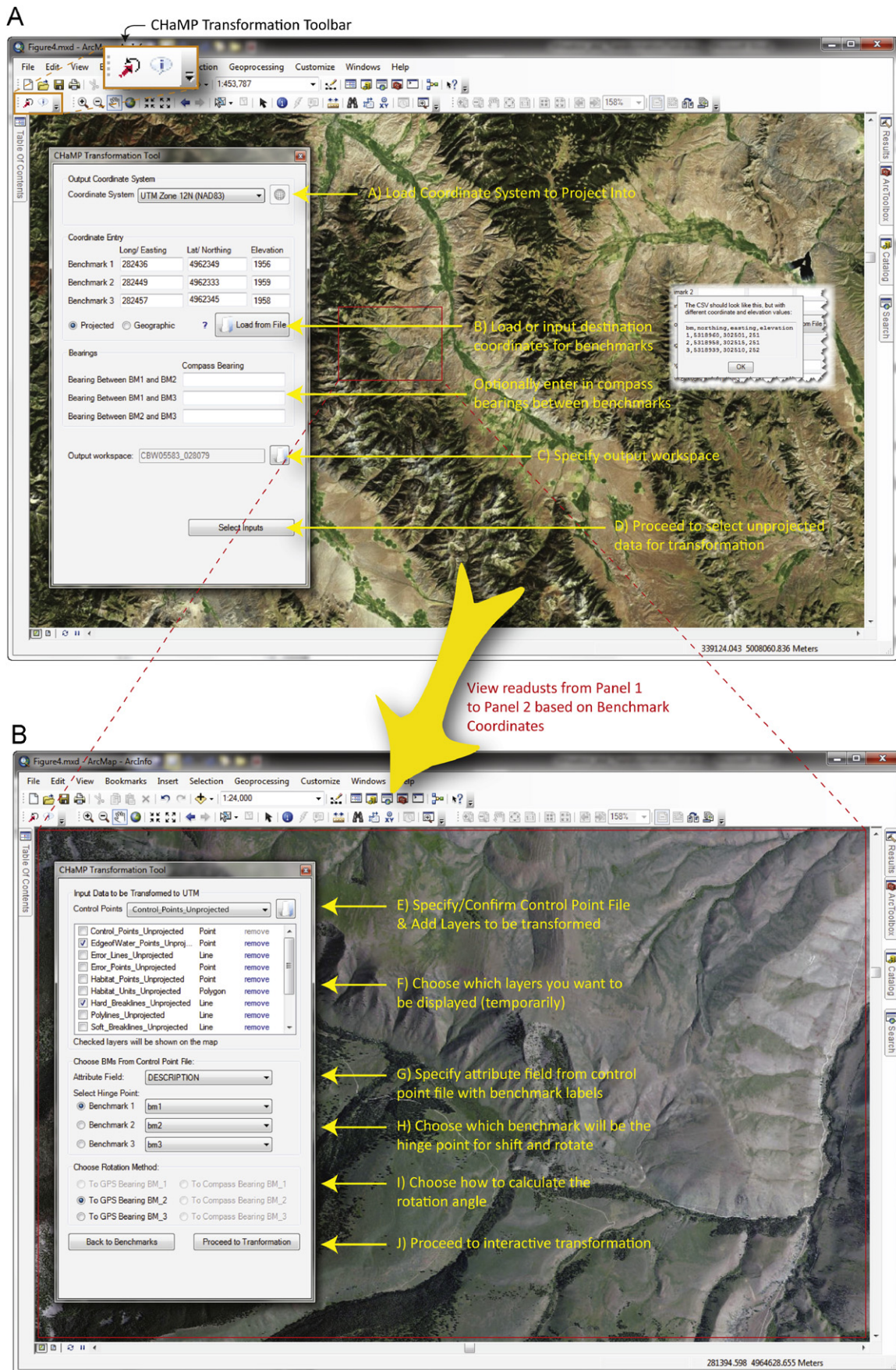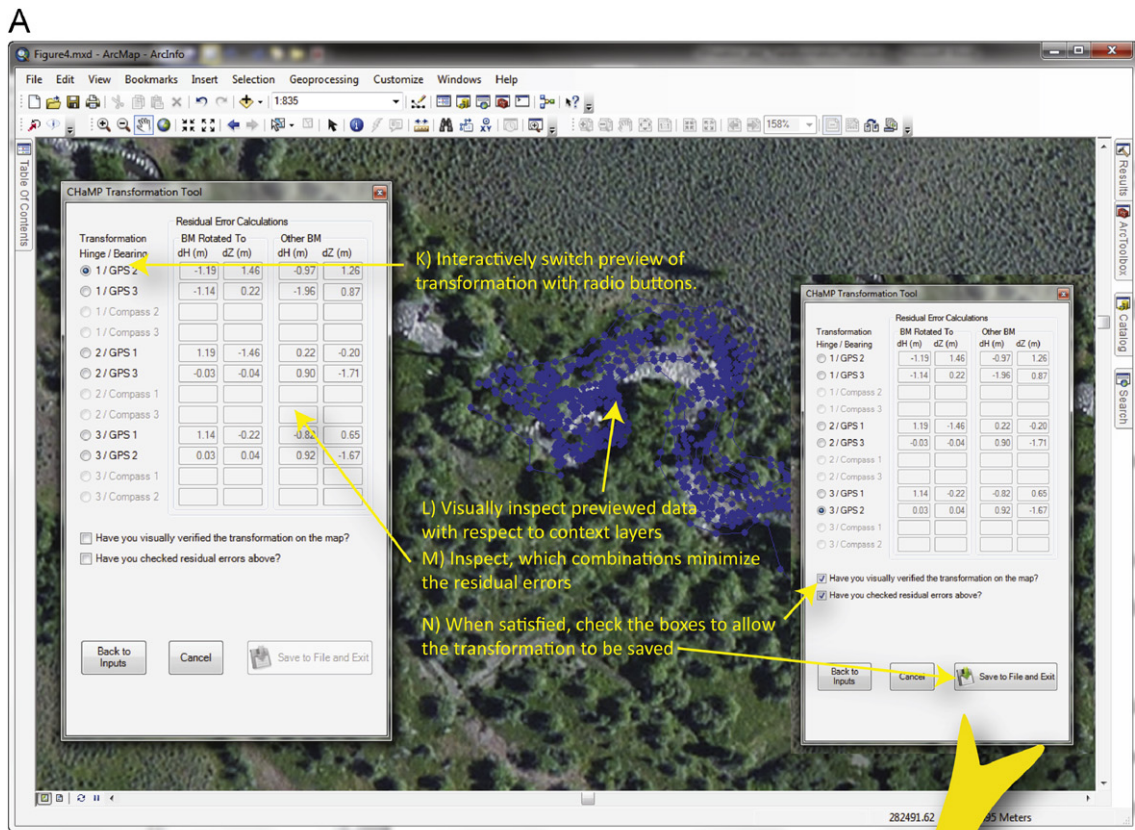
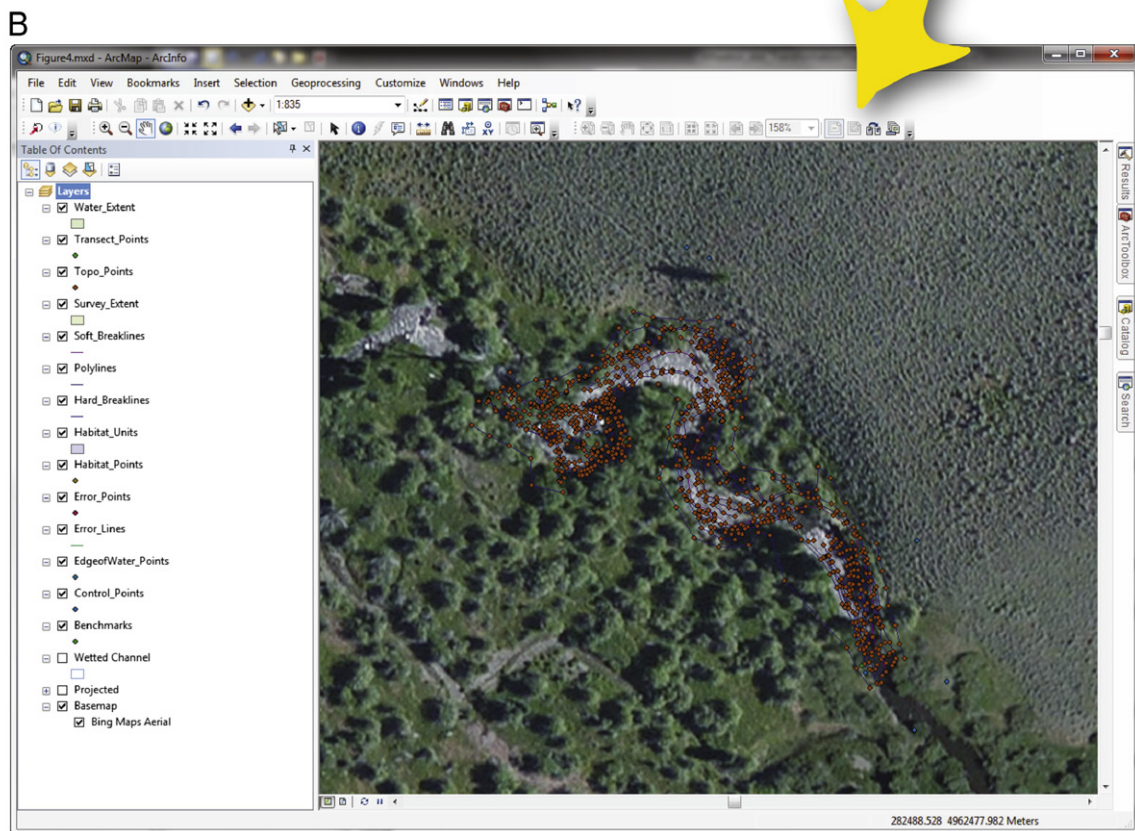**Fig. 4.** Steps 1 and 2 in the CHaMP Transformation tool.

Fig. 5. Step 3 and Output of CHaMP Transformation tool.

Once the data frame coordinates and imagery are set, the user starts the CTT and enters the parameters from the destination PRWCS (Fig. 4(A)). Namely, in the first panel the user chooses (A) the coordinate system they wish to transform into (e.g., UTM Zone X?), (B) the coordinates of the three benchmarks used in either the PRWCS or geographic coordinates (i.e., latitude and longitude). The coordinates are used to define potential rotation angles for the transformation. For (B), users also have the option of manually entering the coordinates or loading them from a file. If users are using the CHaMP GIS Processing Toolbox (Whitehead, 2011), they can simply load the 'Benchmark_Coordinates.csv' file, which is automatically generated from 'Import Data Tool'. Option-ally, a user can utilize bearings measured with a compass between the benchmarks to establish rotation angles (typically less accurate). Next, (C) the Output Workspace for where to save the transformed data is specified. CHaMP users can simply specify the survey geodatabase as the output workspace (also automati-cally created by 'Import Data Tool'), and the CTT knows to look in the 'unprojected' feature dataset for data to transform and output it to a 'projected' feature dataset.

In the second panel, the user chooses the source UCLACS data to be transformed and the initial parameters for the transformation (Fig. 4(B)). More specifically, this is a matter of (E) choosing the control points/benchmarks to use, (F) selecting the input vector data layers to transform and preview (unwanted layers can be removed from the list, and checked ones are shown in the preview), (G) specifying which attribute field in the control file contains the benchmark labels, (H) choosing the initial hinge point for the shift and rotation, and (I) choosing the rotation angle method. If the user is using the CHaMP GIS Processing Toolbox, steps E and G are automatic. In F, it is typically helpful for the user to display enough points and linework so they can visually compare these features to the context layers (e.g., aerial photographs). Note that the selection of a hinge point and rotation method is simply a first guess that can be changed interactively in the final step.

The most important part of the CTT is the ability to interactively preview the multiple transformation options. There are six possible transformation combinations typically, and up to twelve combina-tions if compass bearings were entered in the first panel. This interactive step takes place in the third and final panel, where the user is able to quickly preview the differences between the different transformation parameters until the best combination is found (Fig. 5(A)). This is typically a matter of choosing the transformation option that has the most accurate overlay on the context imagery and minimizes the residual errors. Once the user has arrived at their final choice, they click on the 'Save to File and Exit' button and the outputs will be saved to the specified output workspace (step C in first Panel: Fig. 4(A)) and added to the map document's table of contents (Fig. 5(B)). A table is also produced which records the residual error values of the different transformation options as well as the trans-formation parameters used. The whole process typically takes less than five minutes, and the output control file provides new coordi-nates for use in all subsequent resurveys of the site.

This Add-In was programmed in Visual Studio.Net using C# and ArcObjects and is compiled to work with ArcGIS 10.X. The Add-In is freeware and the source code is OpenSource and is available from: ⟨http://ctt.joewheaton.org/⟩.

3. Summary

The CHaMP Transformation Tool is a simple ArcGIS Add-In that allows the user to transform assumed total station data into real world coordinates through an easy to use and interactive interface. The input requirements are simple and only require unprojected coordinate survey data (typically from a total station) and GPS coordinates for three benchmarks from the original survey. The GPS coordinates can be collected with a simple handheld GPS. The tool uses a simple affine transformation to preserve the precision and relative accuracy of the total station survey, while leveraging the absolute positional accuracy of the hand-held GPS to 'get one's data in the ballpark' for GIS overlay purposes. In simple terms, this involves a shift and rotate operation, without any scaling, warping or distortion of the original total station data typically introduced by other transformation methods. The user interactively chooses the 'best' transformation parameters through a combination of visual inspec-tion of the overlay of the data as well as inspecting residual error calculations. The tool has been tested and successfully implemented on over 364 sites by 12 different crews over the past six months as part of the Columbia Habitat Monitoring Program (CHaMP). The tool provides practitioners using total stations for monitoring a cost effective and simple means of transforming assumed total station data into real world coordinates and leveraging the overlay and contextual power of GIS.

Online supplemental information

- Link to CHaMP Transformation Tool Website: ⟨http://ctt.joewheaton.org⟩.
- Youtube Video Tutorials: ⟨http://ctt.joewheaton.org/home/how-to-use-the-ctt⟩.
- GoogleEarth *.kmz of transformed data.
- Raw data used in Example Application *.zip.
- PlugIn Software: ⟨http://www.gis.usu.edu/~jwheaton/et_al/CHAMP_TransformationTool/CHAMP.esriAddIn⟩.

Acknowledgments

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2012.02.003.

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