



NOAA Technical Memorandum NMFS-AFSC-249

Smooth Sheets: How to Work with Them in a GIS to Derive Bathymetry, Features and Substrates

by
M. Zimmermann and J. L. Benson

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Alaska Fisheries Science Center

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by
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ABSTRACT

There is a wealth of bathymetry, feature, and substrate information available to natural resource scientists in the form of smooth sheets, which are paper maps that serve as final records of detailed, original National Ocean Service (NOS) hydrographic surveys. The paper smooth sheets have been scanned into electronic image files, the image files georeferenced, and the bathymetry and some of the geographic feature information (e.g., kelp beds) has been digitized into text files. These image and text files are available to the public from the National Geophysical Data Center (NGDC: <http://www.ngdc.noaa.gov/>), along with the descriptive report documents, containing the hydrographic survey metadata (year, vessel, hydrographic methods). Although numerous researchers are using these valuable bathymetry, feature, and substrate resources for a variety of purposes, there is little information about how to utilize or interpret the available data; therefore, there is a risk of users misunderstanding or misinterpreting the data. This guide is written to provide the user with enough information to understand and properly utilize the smooth sheets and their associated data.

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INTRODUCTION

What are Smooth Sheets?

Physically, a paper smooth sheet with muslin backing was the final product of a hydrographic survey (Hawley 1931). According to the Hydrographic Manual published by the National Ocean Service (NOS), a smooth sheet "is ultimately archived as the official permanent record of the survey and is the principal source and authority for charted hydrographic data" (p. 1-5, Umbach 1981). The concept of creating a smooth sheet rather than a data file of the soundings dates back to 1837 (for the United States). Hydrographers on surveying vessels would collect soundings with lead lines while recording visually determined sextant angles to shore-based navigation stations (Hawley 1931), rather than recording positions with latitudes and longitudes. Thus, the angles needed to be translated into latitude and longitude coordinates. As part of this process, the soundings were drawn on a smooth sheet, along with the shoreline, geographic features (e.g., kelp beds, rocky reefs, islets, rocks), seafloor substrates (e.g., gravel, sand, mud), and the navigational signals, in order to provide a visual record of the hydrographic survey, which could be annotated as new information became available. After completion of several smooth sheets in an area, the information from the smooth sheets was used to create or update navigational charts, which typically cover a larger area and thus are drawn at a smaller scale. Though more detailed than navigational charts, smooth sheets are not intended for use in navigation. Instead the smooth sheets were used as internal documents by the hydrographic agency. Only after they were scanned, digitized, and posted to National Geophysical Data Center (NGDC: (<http://www.ngdc.noaa.gov/>) (Wong et al. 2007) did they become widely used by non-hydrographers.

The NOS navigational charts are the legal standard for safe navigation on the ocean (Title 33 Code of Federal Regulations 164). Most people using these navigational charts are probably unaware that the charts might only display a small fraction of the smooth sheet information. Detailed hydrographic data typically are recorded on smooth sheets at a scale of 1:20,000, but are reduced in complexity at smaller scale 1:100,000 or 1:1,000,000 navigational charts. All scientists who conduct research on the ocean have probably used the small scale navigational charts for a variety of cruise planning and data analysis tasks without knowing that perhaps ten times as much information was available from the precursor hydrographic surveys, represented by the smooth sheets. Others who are aware of the smooth sheet resource might not understand some of the details about successfully using this rich data resource. Therefore, now that electronic copies of the smooth sheets are readily available, it is worthwhile for non-hydrographers to understand how to use them.

Thousands of the paper smooth sheets were converted into electronic data files (Wong et al. 2007) through a process which involved 1) scanning the paper smooth sheets into electronic TIF files, 2) georeferencing the smooth sheet images, and 3) digitizing the soundings from the smooth sheets into text files. The smooth sheets also were converted into proprietary SID files (formally called MrSID or multiresolution seamless image database).

The georeferencing information, which provided the latitude and longitude equivalent to selected locations on the TIF or SID image, must have been created for the digitization process mentioned in Wong et al. (2007) but is not available now. Therefore, the georeferencing information needs to be recreated before these digitized smooth sheet data can be used. Additionally, the text file of soundings needs minor formatting to separate the text into columns along with the addition of five column headers: hydrographic survey name, latitude, longitude,

depth in meters, type of observation, and cartographic feature code (formatting and codes described at; <http://www.ngdc.noaa.gov/mgg/dat/geodas/docs/hyd93.htm>). By far the most common cartographic features are bathymetric soundings (code = 711), but there are other features which might be of interest to natural resource scientists such as rocks (code = 89), kelp patches (code = 103), tide rips (code = 146), ledges or reefs (code = 530), and islets (code = 988). Hand-written or typed documents containing the hydrographic survey metadata (year, vessel, hydrographic methods), called descriptive reports, are also available.

Due to the vast amount of information digitized (often exceeding 10,000 soundings per smooth sheet) from thousands of smooth sheets, there was little possibility of proofing and editing the results (Wong et al. 2007) without funding a project of a similar magnitude. Thus, it is expected that the user will encounter some digitization errors (Wong et al. 2007) and yet, without the georeferencing information, the user has no immediate method of comparing the text file of soundings to the smooth sheet from which the text file was derived. The central importance of this document are the instructions informing users how to georeference the smooth sheets and how to compare the digitized data to the smooth sheet.

Standard Georeferencing

Georeferencing is the process of converting the coordinates of a map image from pixel locations to geographic locations. For example, a location that is 494 pixels from the left edge of an image and 12,004 pixels from the bottom edge of the image might be equivalent to a longitude of W153° 13' and a latitude of N57° 22'. These instructions are specific to georeferencing the smooth sheets in ArcMap v. 10.0 (ESRI: Environmental Systems Research Institute, Redlands, CA), but the same general steps should be comparable to other geographic information system (GIS) packages.

Digital copies of most smooth sheets produced by the NOS and its precursor agencies are available free of charge at the NGDC. Both SID and TIF image files are available as zipped files (*.SID.gz or *.TIF.gz), which need to be downloaded and unzipped prior to any processing. Once unzipped, the SID or TIF image of a smooth sheet can be brought into a GIS. Because the smooth sheets do not come with any associated datum or projection information, in ArcMap the smooth sheets are automatically assigned a scale based on the pixels which compose the image (SID), or on the size of the image in inches (TIF), such that the lower left or southwest corner plots at coordinate 0,0.

The georeferencing process involves selecting a minimum of six locations scattered around the periphery of the smooth sheet image where the latitude and longitude are clearly defined - such as at graticule intersections - and translating the image space (pixels or inches) into geographic space (latitude and longitude). If the graticules are square then this translation process is straightforward. If the graticules are not square, as is the case in some polyconic projections, then a minimum of 10 locations must be selected and these must be converted into latitude and longitude coordinates using a rubber sheet (variable shift) type of adjustment, called *Spline* in ArcMap. If the smooth sheet was not created in a current datum such as NAD83 HARN (North American Datum of 1983, High Accuracy Resolution Network), as is the case with most of the digitized smooth sheets, then it must be datum-shifted as part of the georeferencing process. Only after this georeferencing process is complete, including any rubber-sheeting and datum-shifting, can the user proof and edit the bathymetry data, and use it for analyses.

As an example, these instructions will detail the steps for georeferencing the smooth sheet H05152, covering Kiliuda Bay on Kodiak Island, Alaska. Within the remainder of this document, *italicized* words will reference menu options within ArcMap.

1. Start a new project in ArcMap.

2. Add the H05152.sid or H05152.tif smooth sheet image. SID files are smaller than TIF files due to their internal compression and therefore SID files take less memory and draw more quickly. Any time a SID image file is loaded into ArcMap, the software automatically creates a *.sid.aux.xml file - so if the file has been opened in ArcMap before it will already have one of these files. The georeferencing process will create a new *.sid.aux.xml file along with a "world file" (*.sidw), and together these two files will contain the information that instructs ArcMap how to stretch, contort, or twist the smooth sheet and plot it correctly. If the georeferencing needs to be changed, it is often easiest to exit ArcMap, delete the old *.sid.aux.xml and *.sidw files, and start fresh in ArcMap.

Smooth sheet H05152 shows Kiliuda Bay running roughly 20 km east and west across the center of the image, with the southeast end of the bay having a 5 km opening to the Gulf of Alaska (Fig. 1). The bay is dotted with thousands of soundings and numerous features such as rocks, islets, kelp patches, rocky reefs, and substrate samples, all of which are too small to see clearly. Within the confines of the bay there are 30 times as many soundings (7,531 vs. 255) and 17 times as many substrate observations (313 vs. 18) as the best navigational chart for this location (Zimmermann et al. in review). Significant place names have been added with large block letters and important map elements indicated. The land surrounding the bay is largely blank except for some place names, a legend, and georeferencing information.

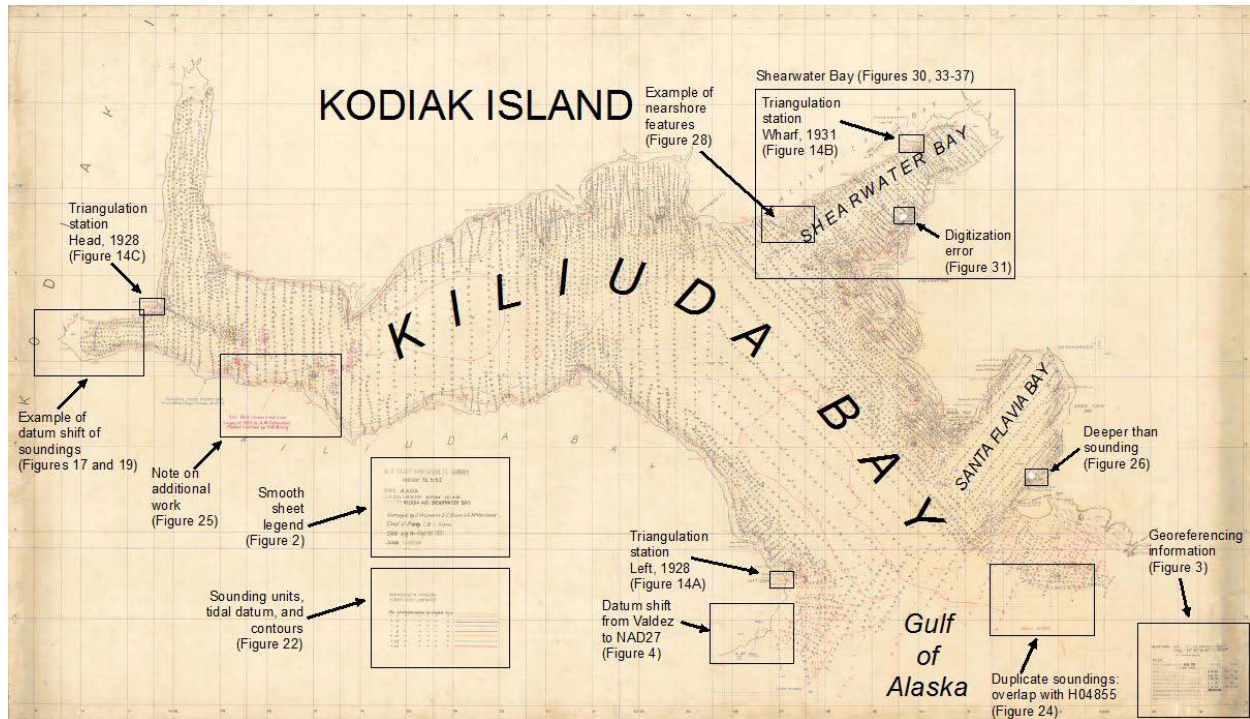


Figure 1. -- Smooth sheet H05152 with significant place names shown in block letters and important features indicated.

The legend (Fig. 2) gives the H-number of the survey, location, key personnel involved, date, and scale. It might be surprising to many readers that this survey is from 1931, but it is the most recent survey of this area, and, more importantly, is the *only* survey of this location. Therefore, it is the primary source of information for current navigational charts, even if they are editions from the present year.

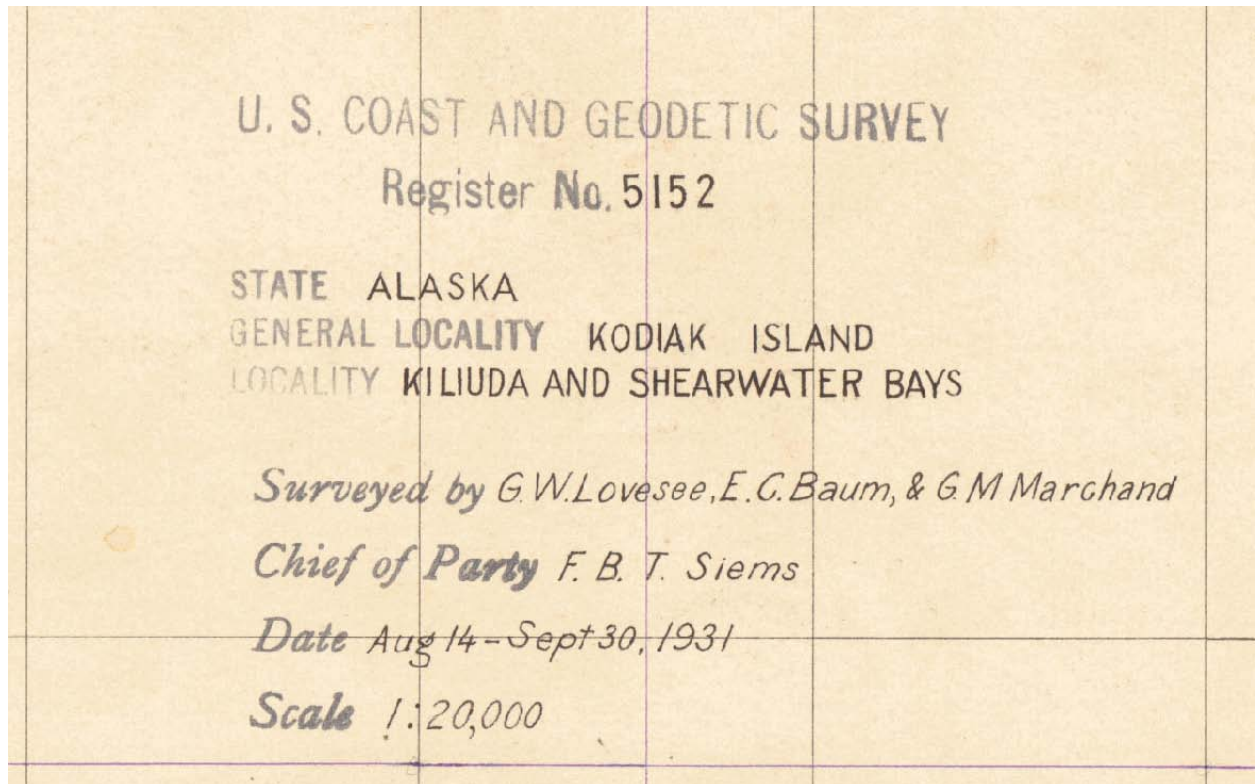


Figure 2. -- Legend of smooth sheet H05152.

The georeferencing information (Fig. 3) for a smooth sheet typically states the horizontal datum and a triangulation station. For the older Alaska datums, such as Valdez in this example, there are no existing algorithms for converting them to modern datums, so there is some extra work involved. The triangulation station "Left, 1928" in this example is given in degrees, minutes, and seconds, along with seconds expressed in the equivalent amount of meters. This station is the key to bringing this smooth sheet into a modern datum because the difference between the modern interpretation of the station's position and the original position is the amount of horizontal shifting required. If this station position is not written on the map, it can sometimes be found in the descriptive report, or derived less accurately from georeferencing the smooth sheet in the old datum.

Δ Left, 1928, Lat: 57° 15' 28.406" - 878.7m Long: 152° 56' 46.997" - 787.9m VALDEZ DATUM		
No. 26		
Hydrographic Sheet: NO. 26	Initials	Date
Scale 1 - 20,000		
Projection by	G M M	11-7-31
Projection verified by	M G R	DO
Triangulation stations plotted by	G M M	11-9-31
Triangulation stations verified by	C J B	DO
Topographic stations transferred by	G M M	11-11-31
Topographic stations verified by	TRACING	
Hydrographic stations plotted by		
Hydrographic stations verified by		

Figure 3. -- Datum and scale information on smooth sheet H05152.

The smooth sheet also has a set of black graticule lines representing the original datum (Valdez), a second set of purple graticule lines representing a more modern datum (North American Datum of 1927: NAD27), and partial third set of blue graticule lines representing Port Hobron datum, another archaic datum (Fig. 4). In addition, there is a small reference mark added in 1948 also drawn in purple indicating the datum shift from Valdez to NAD27. Users need to understand that just because a newer datum name is drawn on the smooth sheet does not mean that the smooth sheet, or any data derived from the smooth sheet, is in that newer datum. When selecting graticules for georeferencing, it sometimes can be difficult to distinguish the original, black, complete set of graticules from newer, colored, and often incomplete graticules. This example will work through using the original, black Valdez datum graticules so that it can be demonstrated how to shift the image from the arcane Valdez datum to NAD83 HARN.

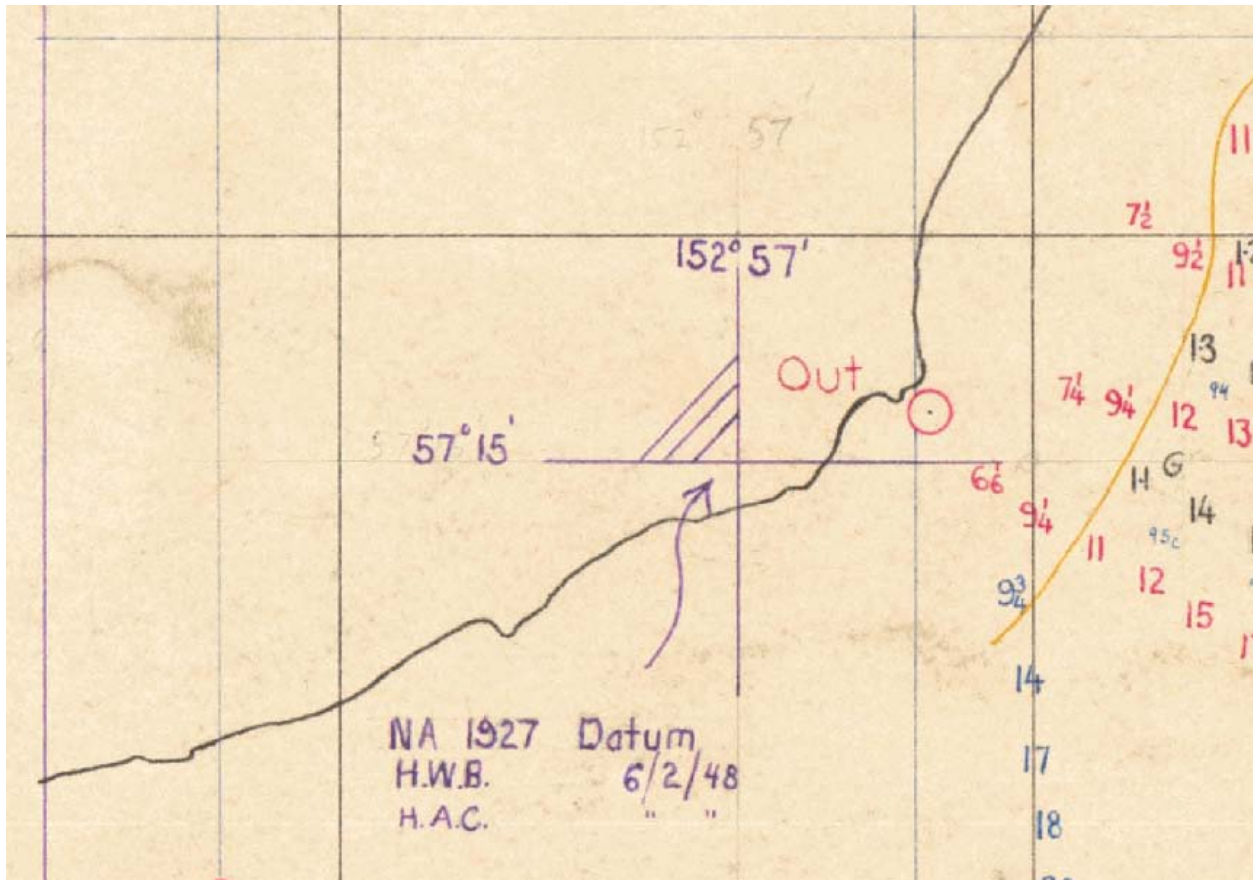


Figure 4. -- Latitude and longitude shift from original Valdez datum to NAD27.

3. Add the free *Georeferencing* toolbar (Fig. 5) in ArcMap by going to the *Customize* tab, selecting *Toolbars*, and then placing a check next to *Georeferencing*. Then the *Georeferencing* toolbar should appear.

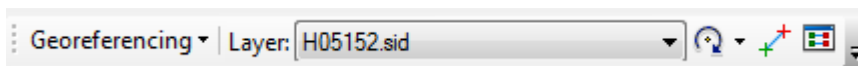


Figure 5. -- Georeferencing toolbar available in ArcMap.

4. Using the *magnifying glass* from the *Standard* toolbar, zoom into and select (left click with the mouse) on six locations for georeferencing on the periphery of the smooth sheet where the original black latitude and longitude graticules cross (Fig. 6). It is important to select

georeferencing locations that encompass the soundings, stations, shoreline, and any other features that the user wishes to georeference, as long as they were not distorted or smeared during the image scanning process, which commonly occurred along the edge of the smooth sheet image. Record the coordinates at these locations for future reference because it can be easy to get lost zooming in, zooming out, and panning around the image. Convert the coordinate degrees, minutes, and seconds into decimal degrees (divide the minutes by 60, divide the seconds by 3600, and add both to the degrees).

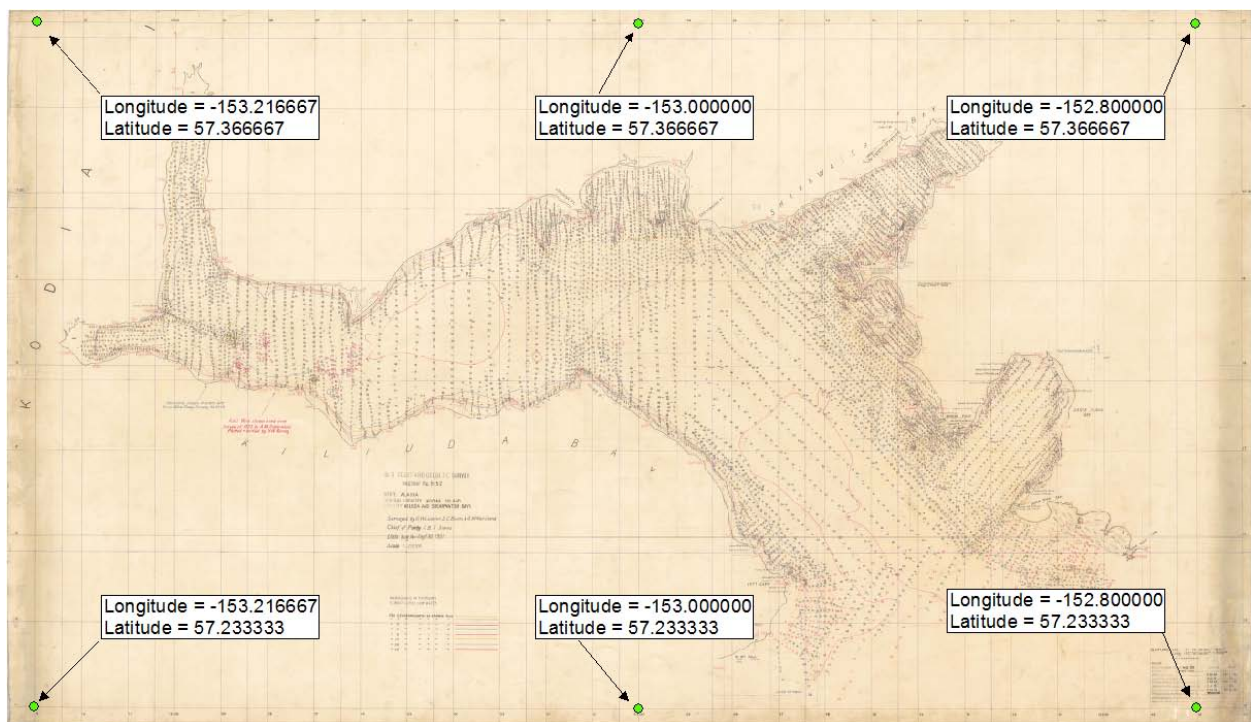



Figure 6. -- Location of six points for georeferencing smooth sheet H05152.

5. Zoom into one of the preselected georeferencing locations. Click on the *Add Control*

Points button  on the *Georeferencing* toolbar (Fig. 5), left click to select the intersection of the graticules, and then right click to input the longitude for the X-coordinate and the latitude for the Y-coordinate (Fig. 7).

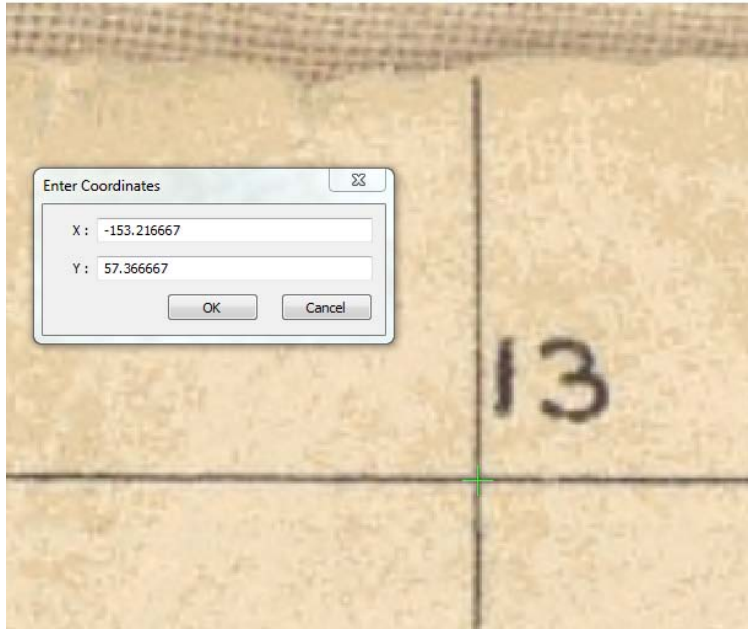


Figure 7. -- Selecting a georeferencing position and entering the coordinates.

Zoom back out and create the other five georeference points (Fig. 8). Note how the shape of the image has changed from Figures 6 to 8. The smooth sheet image has been converted from image space into coordinate space, but the transformation is not yet finalized. Each georeference point is represented by a red and a green plus symbol. The green plus symbol is the original location that was selected for georegistration, the red plus symbol is the offset due in part to small errors in the selection of the six locations, distortion of the image, and polygonal shape of the smooth sheet image due to polyconic projection. In Alaska, many of the smooth sheets were drawn in a polyconic projection where the northern portion of the longitude graticules are closer together than the southern portion, causing a typical distortion of the image (see Fig. 1, Reynolds 1930). If the distortion is small, then a simple georeferencing transformation can be used to convert the smooth sheet from image space to coordinate space. If the distortion is significant, then a minimum of 10 georeferencing positions coupled with a stronger transformation must be used. The error can be assessed in the Link table.

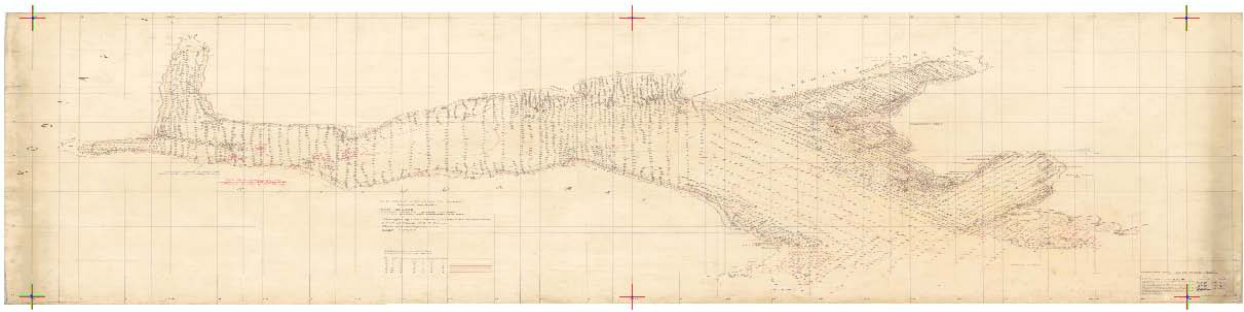

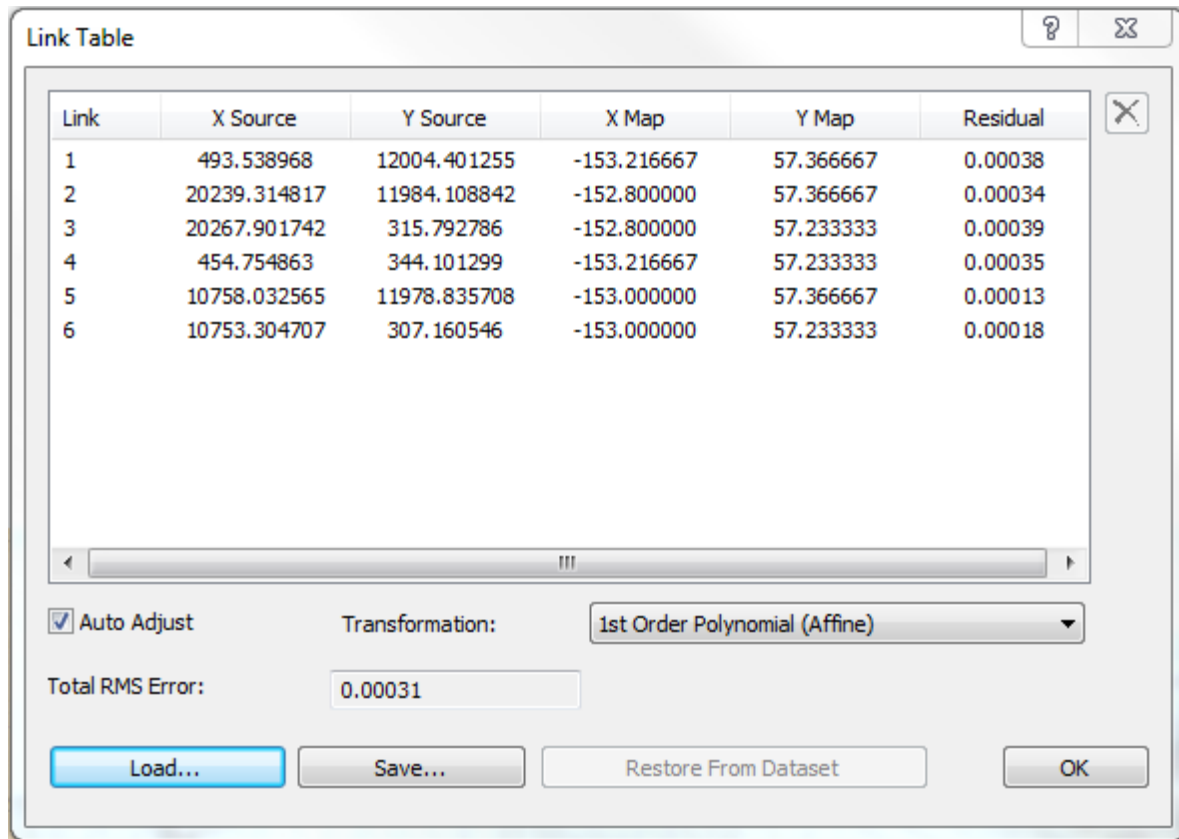


Figure 8. -- Six georeferencing locations for H05152.

6. Open the *Link Table* by clicking on the *View Link Table* button  (Fig. 5). The *X Source* and *Y Source* columns are the image space coordinates and the *X Map* and *Y Map* columns are the corresponding longitude and latitude coordinates (Fig. 9). The *Residual* column is the individual error associated with each *Link*. Check to make sure that the *Residual* for each *Link* is small and that the *Total Root Mean Square (RMS) Error* is small. Large values indicate errors in data entry or image distortion. If there are bad *Links*, select and delete them. As a rule of thumb, if the total $RMS \leq 0.00040$ then the distortion is not significant and the default Transformation of *1st Order Polynomial (Affine)* can be used. If the distortion is ≥ 0.00040 , then a minimum of 10 georeferencing locations must be used along with a *Spline* transformation, which acts like rubber sheeting.



Link	X Source	Y Source	X Map	Y Map	Residual
1	493.538968	12004.401255	-153.216667	57.366667	0.00038
2	20239.314817	11984.108842	-152.800000	57.366667	0.00034
3	20267.901742	315.792786	-152.800000	57.233333	0.00039
4	454.754863	344.101299	-153.216667	57.233333	0.00035
5	10758.032565	11978.835708	-153.000000	57.366667	0.00013
6	10753.304707	307.160546	-153.000000	57.233333	0.00018

☒ Auto Adjust Transformation: 1st Order Polynomial (Affine)

Total RMS Error: 0.00031

Load... Save... Restore From Dataset OK

Figure 9. -- Link table of georeferencing coordinates for H05152.

When satisfied that the georeferencing *Links* are good and the polyconic distortion is minimal or accounted for, click the *Save...* button and create a text file of *Links* in order to save your work. Thus, if the *.aux.xml and *.sdw files are deleted or lost, the georeferencing work can be recreated quickly by importing these saved *Links* with the *Load...* button.

7. If the smooth sheet was in a modern datum, then the next step would be to select the *Georeferencing* button from the *Georeferencing* toolbar, and select *Update Georeferencing*, which creates the *.aux.xml and *.sdw files (Fig. 10). Then the final step would be to use *ArcToolbox* to access the *Data Management Tools, Projections and Transformations, Raster*, and *Define projection*, where the appropriate datum of NAD83 HARN can be selected from a list of supported datums.

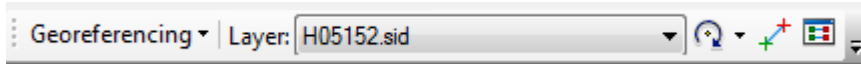


Figure 10. -- Georeferencing toolbar.

However, in this example and in many Alaskan smooth sheets, additional steps are required prior to these final Georeferencing and Projection steps.

Custom Georeferencing (Datum Shifting)

8. Creating a custom datum shift for a smooth sheet involves calculating the difference between a triangulation station in the original datum (Valdez) and a modern datum (NAD83 HARN). As noted above, the Valdez position for station "Left, 1928" is written on the smooth sheet. The NAD83 HARN position can be obtained by downloading a Shape file for a selected state from the National Geodetic Survey (NGS) web page (Dave Doyle, National Geodetic Survey, pers. comm.) (Fig. 11); http://www.ngs.noaa.gov/cgi-bin/sf_archive.prl .

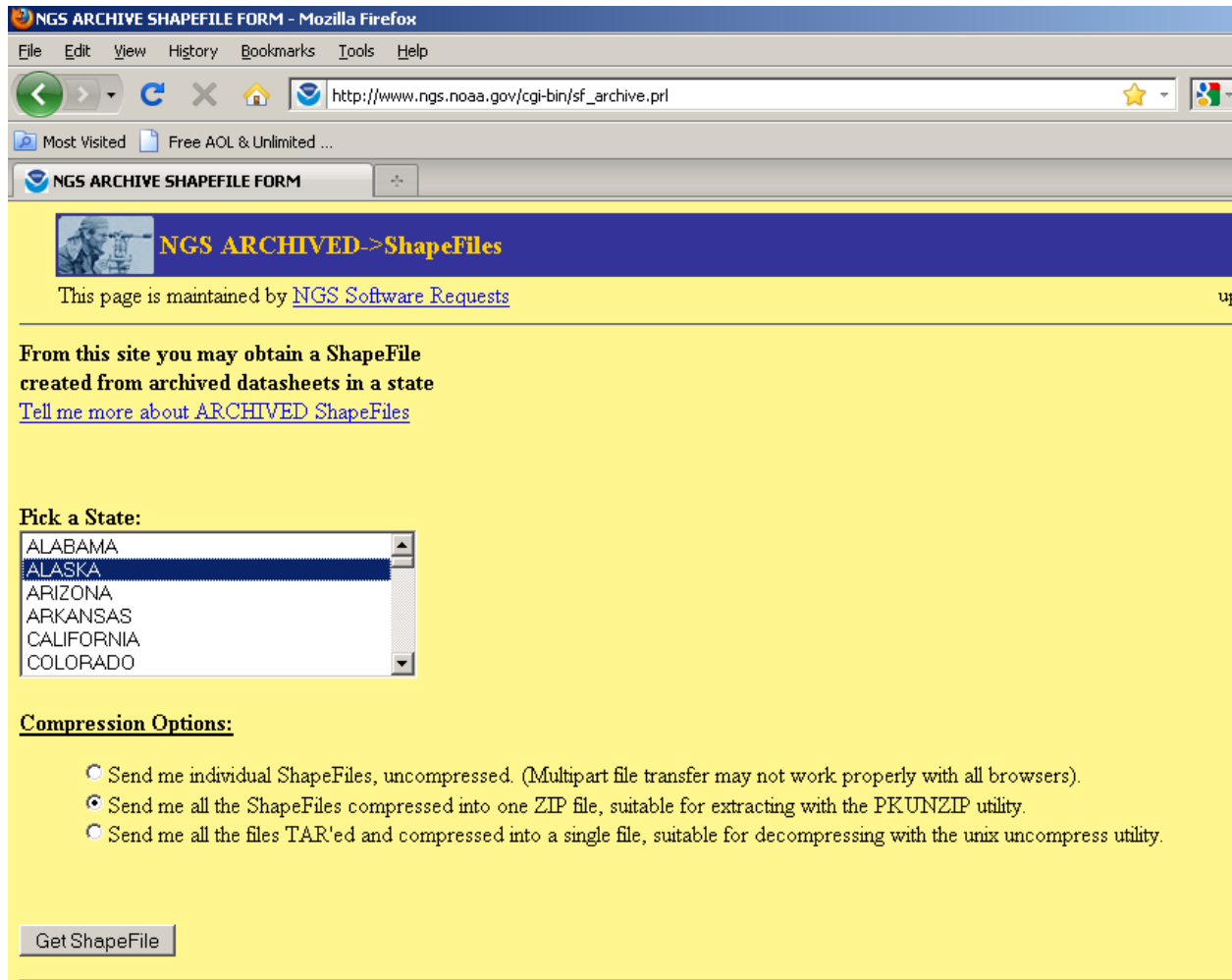


Figure 11. -- Web page which provides state-wide file of triangulation stations.

When plotted on top of the georeferenced smooth sheet, the offset caused by the datum shift is quite noticeable (Fig. 12). The NAD83 HARN location of station Left plots to the north and to the east of its position on the smooth sheet.

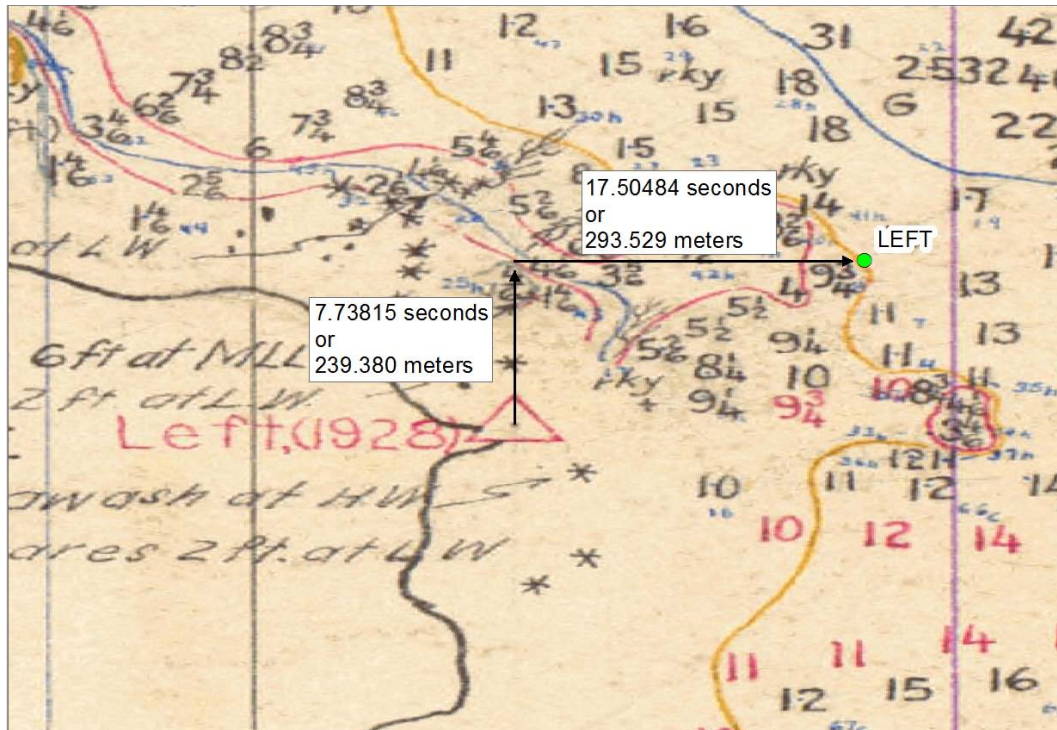


Figure 12. -- Horizontal datum offset at triangulation station Left, drawn as a red triangle with a black dot in the middle, for smooth sheet H05152.

The Valdez position of triangulation station Left calculated from the smooth sheet is

$$57 + (15/60) + (28.406/3600) = 57.257891$$

$$-(152 + (56/60) + (46.997/3600)) = -152.946388.$$

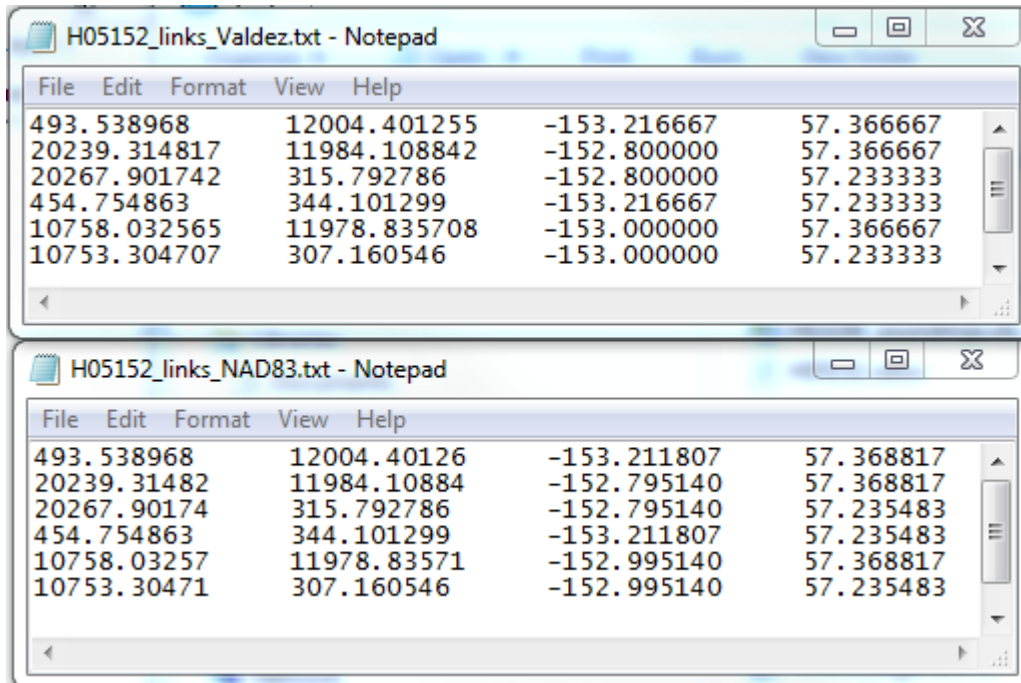
The NAD83 HARN position of Left calculated from the NGS Shape file is

$$57 + (15/60) + (36.14415/3600) = 57.26004$$

$$-(152 + (56/60) + (29.49216/3600)) = -152.94153.$$

Thus the coordinates of triangulation station Left have shifted to the north by 0.002149 degrees or (degrees \times 3600 = seconds) by 7.73815 seconds, and to the east by 0.004862 degrees or by 17.50484 seconds (Dave Doyle, National Geodetic Survey, pers. comm.). The links file needs to be edited to reflect this change in position by adding 7.73815 seconds to the Valdez

latitude (make more northern), and adding 17.50484 seconds to the Valdez longitude (make more eastern) of the original georegistration links file in order to create a NAD83 HARN georegistration links file (Fig. 13). Then use the NAD83 HARN links to georegister the smooth sheet (see step 7).



H05152_links_Valdez.txt - Notepad			
File	Edit	Format	View Help
493.538968	12004.401255	-153.216667	57.366667
20239.314817	11984.108842	-152.800000	57.366667
20267.901742	315.792786	-152.800000	57.233333
454.754863	344.101299	-153.216667	57.233333
10758.032565	11978.835708	-153.000000	57.366667
10753.304707	307.160546	-153.000000	57.233333

H05152_links_NAD83.txt - Notepad			
File	Edit	Format	View Help
493.538968	12004.40126	-153.211807	57.368817
20239.31482	11984.10884	-152.795140	57.368817
20267.90174	315.792786	-152.795140	57.235483
454.754863	344.101299	-153.211807	57.235483
10758.03257	11978.83571	-152.995140	57.368817
10753.30471	307.160546	-152.995140	57.235483

Figure 13. -- Valdez datum (above) and NAD83 HARN links (below) files for georegistering smooth sheet H05152.

Once georegistered, define the projection by using *ArcToolbox* to access the *Data Management Tools, Projections and Transformations, Raster, and Define projection*. Select "NAD 1983 HARN" as the projection. This process creates and stores the georegistration and projection information into the companion H05152.sid.aux.xml and H05152.sidw files. These files must accompany the *.SID file in order for it to plot properly.

Test the georeferencing work by plotting the triangulation stations on top of the smooth sheet, so that the station alignment can be assessed (Fig. 14). This step is important in order to

prove that the georeferencing work, which was independently conducted on the graticules and adjusted by the primary triangulation station, can be confirmed by the plotting of the triangulation stations. In this example with H05152, the primary station Left, as drawn on the smooth sheet, plots about 15 m to the south of its true position (Fig. 14A). In the northeast section of the smooth sheet, station Wharf is drawn about 6 m to the southwest of its correct location (Fig. 14B). In the west end of the smooth sheet, station Head is drawn about 10 m to the southeast of its correct position (Fig. 14C). Thus all the placement errors are minor and this georegistration and datum-shifting were accomplished successfully.



Figure 14. -- After georegistration and datum-shifting, triangulation stations Left (A), Wharf (B) and Head (C), all show close alignment with the independent file of NAD83 HARN triangulation stations.

There are instances where the "seconds" portion of the original datum triangulation station position is reported only as meters instead of seconds. In order to convert the meters into seconds, use the Inverse computation software http://www.ngs.noaa.gov/PC_PROD/Inv_Fwd/ (Vincenty 1975);

1. Select the Clarke 1866 (NAD27) ellipsoid.
2. Round down the position of the triangulation station to whole minutes (57 15 00 and - 152 56 00).
3. Enter this as the first station.
4. Then add 1 minute to the latitude and enter that as the second station.

The answer is 1856.1033 m/min of latitude at this location (Fig. 15).

```

Program Inverse - Version 3.0

Ellipsoid options :

1> GRS80 / WGS84  <NAD83>
2> Clarke 1866   <NAD27>
3> Any other ellipsoid

Enter choice :
2

Enter First Station
                (Separate D,M,S by blanks or commas)
hDD MM SS.sssss Latitude :      <h default = N >
N57 15 00
hDDD MM SS.sssss Longitude :    <h default = W >
W152 56 00

Enter Second Station
                (Separate D,M,S by blanks or commas)
hDD MM SS.sssss Latitude :      <h default = N >
N57 16 00
hDDD MM SS.sssss Longitude :    <h default = W >
W152 56 00

Ellipsoid : Clarke 1866      <NAD27>
Equatorial axis,  a  =      6378206.4000
Polar axis,      b  =      6356583.8000
Inverse flattening, 1/f = 294.97869821380

First Station :
-----
LAT = 57 15 0.00000 North
LON = 152 56 0.00000 West

Second Station :
-----
LAT = 57 16 0.00000 North
LON = 152 56 0.00000 West

Forward azimuth      FAZ = 0 0 0.0000 From North
Back azimuth         BAZ = 180 0 0.0000 From North
Ellipsoidal distance S =      1856.1033 m

Do you want to save this output into a file <y/n>?

```

Figure 15. -- Inverse distance estimate for a minute of latitude at station Left.

5. Then run the software again to determine the distance of a minute in longitude at this location. This time, keep the latitude constant (From 57 15 00 To 57 15 00) and add 1 minute to the longitude (From 152 56 00 To 152 57 00). The answer is 1006.1057 meters (Fig. 16).

```

Program Inverse - Version 3.0

Ellipsoid options :

1> GRS80 / WGS84  <NAD83>
2> Clarke 1866   <NAD27>
3> Any other ellipsoid

Enter choice :
2

Enter First Station
      (Separate D,M,S by blanks or commas)
hDD MM SS.sssss Latitude :      <h default = N >
N57 15 00
hDDD MM SS.sssss Longitude :    <h default = W >
W152 56 00

Enter Second Station
      (Separate D,M,S by blanks or commas)
hDD MM SS.sssss Latitude :      <h default = N >
N57 15 00
hDDD MM SS.sssss Longitude :    <h default = W >
W152 57 00

Ellipsoid : Clarke 1866      <NAD27>
Equatorial axis,  a  =  6378206.4000
Polar axis,      b  =  6356583.8000
Inverse flattening, 1/f = 294.97869821380

First Station :
-----
LAT = 57 15 0.00000 North
LON = 152 56 0.00000 West

Second Station :
-----
LAT = 57 15 0.00000 North
LON = 152 57 0.00000 West

Forward azimuth      FAZ = 270 0 25.2312 From North
Back azimuth         BAZ = 89 59 34.7688 From North
Ellipsoidal distance S = 1006.1057 m

Do you want to save this output into a file <y/n>?

```

Figure 16. -- Inverse distance estimate for a minute of longitude at station Left.

In this example of using triangulation station Left from H05152, divide the fraction of a second in meters by the distance of the whole second in meters, then multiply by 60 to convert to seconds. For latitude, divide 878.7 by 1856.1033, then multiply by 60, and the result of 28.404669" is very close to the conversion on the smooth sheet (28.406"). Similarly, for longitude ($60 \times (787.9 / 1006.1057)$), the estimated seconds of 46.987111" from the Inverse software is very close to what is written on the smooth sheet (46.997").

The datum shift in meters also can be calculated by using this translation between meters and seconds. Divide the difference in latitude or longitude seconds by 60 and multiply by the distance of a second in meters in the latitude or longitude direction. For example, the latitude difference of 7.73815" is divided by 60 and then multiplied by 1855.9827 m/s, resulting in 239.380 m. Similarly, the longitude difference of 17.50484" is divided by 60 and then multiplied by 1006.1057 m/s, resulting in 293.529 m.

The methods of using a single triangulation station for each smooth sheet differ slightly from the datum-shifting conducted by Dave Doyle for the Dutch Harbor, Unalaska Island, Alaska tsunami inundation grid (see Appendix A in Taylor et al. 2006), where a regional datum-shift was calculated for a group of smooth sheets in the area of interest. Similarly, an average datum-shift could be calculated from all of triangulation stations within each smooth sheet, or the links in different sections of the smooth sheet could be pro-rated by the nearest triangulation stations.

Shifting the Soundings

Simple Soundings Shift

The text file of digitized soundings from NGDC needs to be checked for accuracy once the smooth sheet is properly georeferenced into NAD83 HARN datum. As noted previously, the file

of soundings for a smooth sheet can be downloaded from NGDC and converted from the original format (after unzipping) into a text file, and plotted by the longitudes and latitudes. If the smooth sheet was digitized properly, then soundings from the text file should correctly align with their corresponding locations on the smooth sheet.

The digitized soundings for H05152 plot with an error of about 330 m to the south and about 420 m to the west of the smooth sheet locations, which means that there was an issue with the digitizing (Fig. 17). Since these errors are larger than the datum shift, it is difficult to interpret what might have happened during the digitization process to cause this.

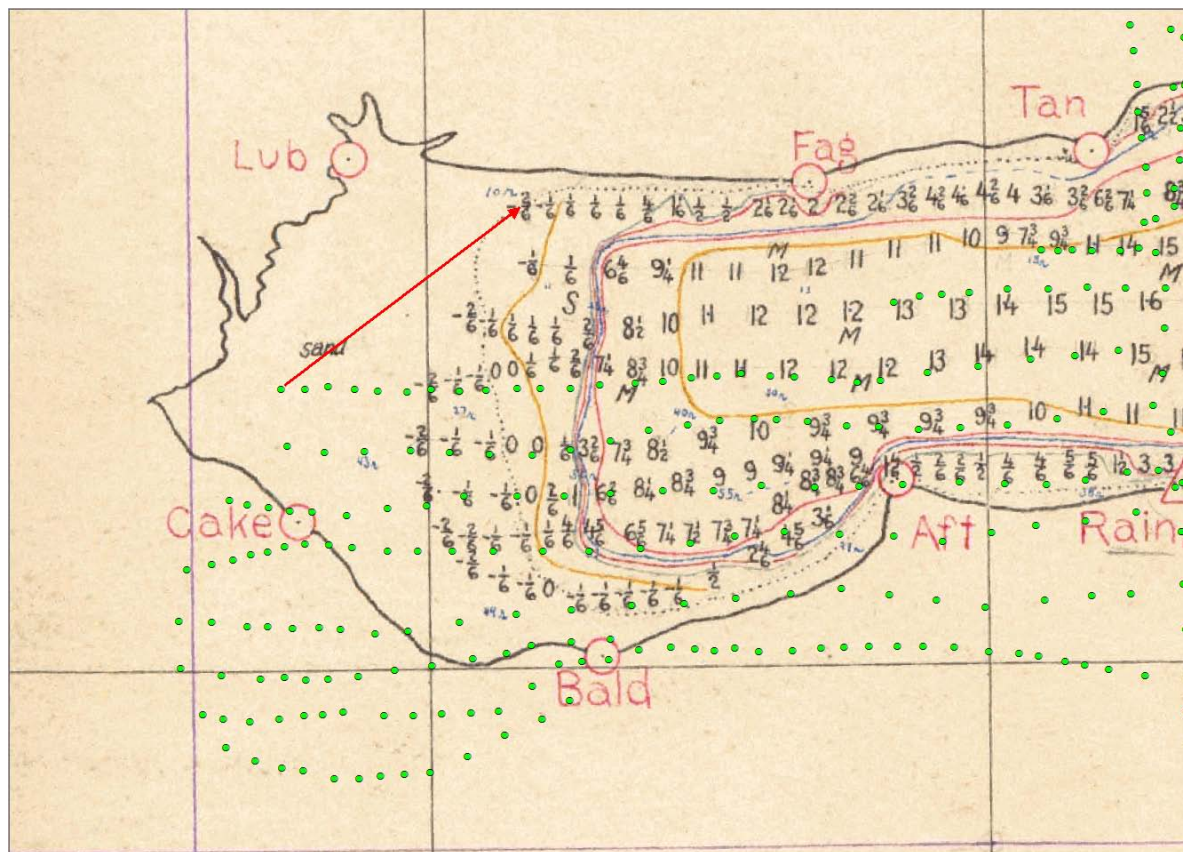


Figure 17. -- Horizontal shift required in order to convert the downloaded soundings file into NAD83 HARN datum.

The simplest fix for this error is to select all of the soundings as a group and manually shift them a constant amount. To implement this in ArcMap;

1. Start a new project
2. Add the georeferenced and datum-shifted smooth sheet. Add the soundings as a Shape file with the same projection (NAD83 HARN).
3. Under the *Customize* tab, select *Toolbars*, and place a check by *Editor*. Under the *Editor* toolbar, select *Start Editing*, choose the soundings shape file, and select the *black arrowhead* (Fig. 18).



Figure 18. -- Editor toolbar with select tool (black arrowhead) shown.

4. Zoom out beyond the full extent of the soundings shape file and select the entire soundings file by clicking and dragging with the *arrowhead tool*. Zoom in on a location where it is relatively easy to see how to shift the soundings, and then drag them into place while they are still selected as a group (generally indicated by light blue coloring) (Fig. 19).

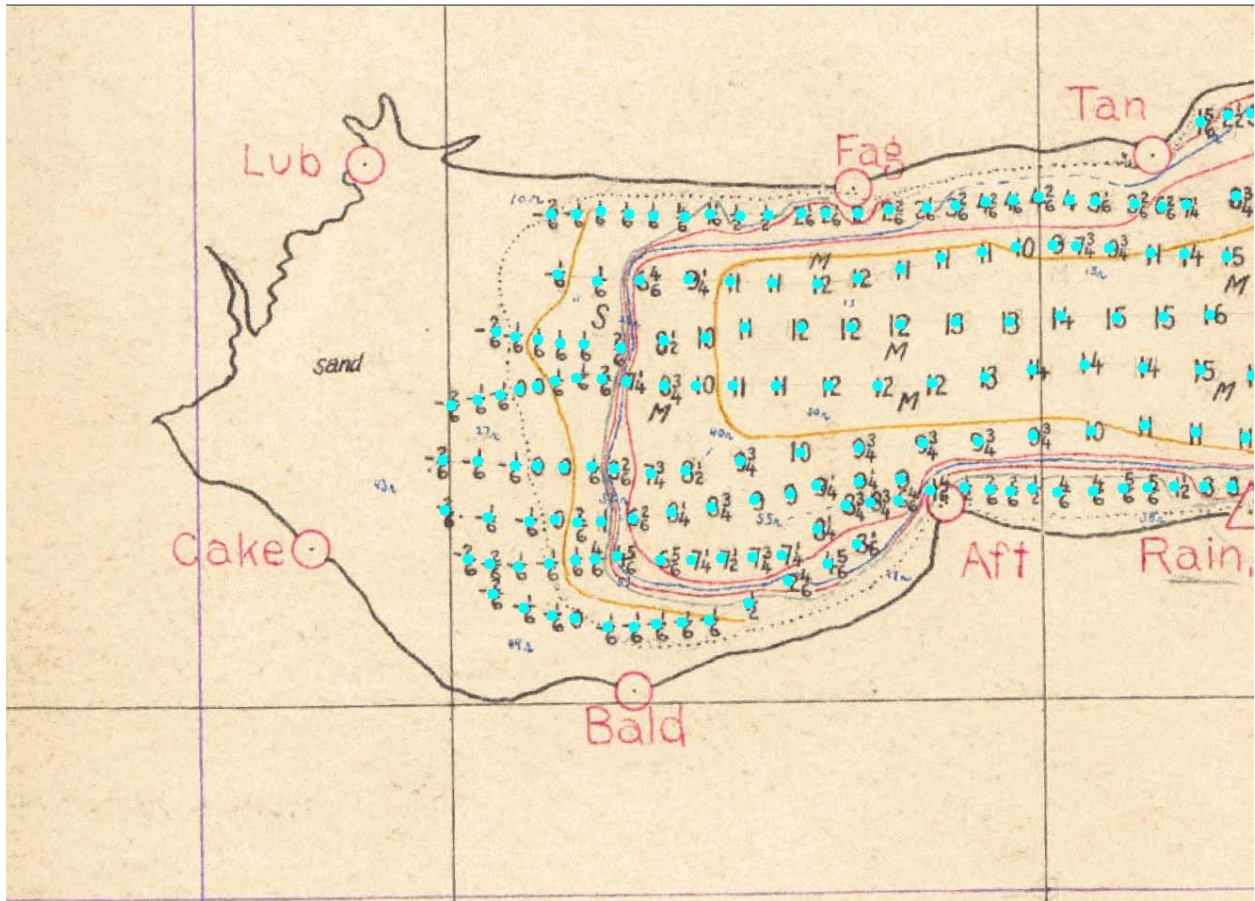


Figure 19. -- Horizontal shift of soundings completed using Editor in ArcMap.

5. Under the *Editor* Toolbar, select *Save Edits* and then select *Stop Editing*. Pan around the smooth sheet to determine if shifting all the soundings a fixed amount as a group was appropriate for the entire smooth sheet. If this was the case, then the soundings can be checked for digitization errors against the smooth sheet. If this was not the case, then a more complicated shift of the soundings is required.

Complicated Soundings Shift

The soundings for some smooth sheets need a complicated or variable shift. An example of the need for a variable shift is survey H09128 in Hanus Bay, Catherine Island off of Peril Strait in

southeast Alaska. The southern portion of the smooth sheet must have been georeferenced close to its correct location, but the northern portion must have been georeferenced accidentally too far to the north (green soundings original and incorrect, red soundings shifted and correct: Fig. 20). In H09128 it appears that only the latitudes, and not the longitudes, are in error. As a result, most of these soundings of Hanus Bay span the deep waters of Peril Strait, whereas some of the soundings incorrectly plot on the opposite shore of Chichagof Island. The gap in soundings of Dead Tree Island creates a phantom island in the middle of Peril Strait. The southern soundings are approximately 870 m too far north, but the northern soundings are approximately 4,200 m too far north. The problem cannot be fixed with a simple, mass shift (Fig. 20).

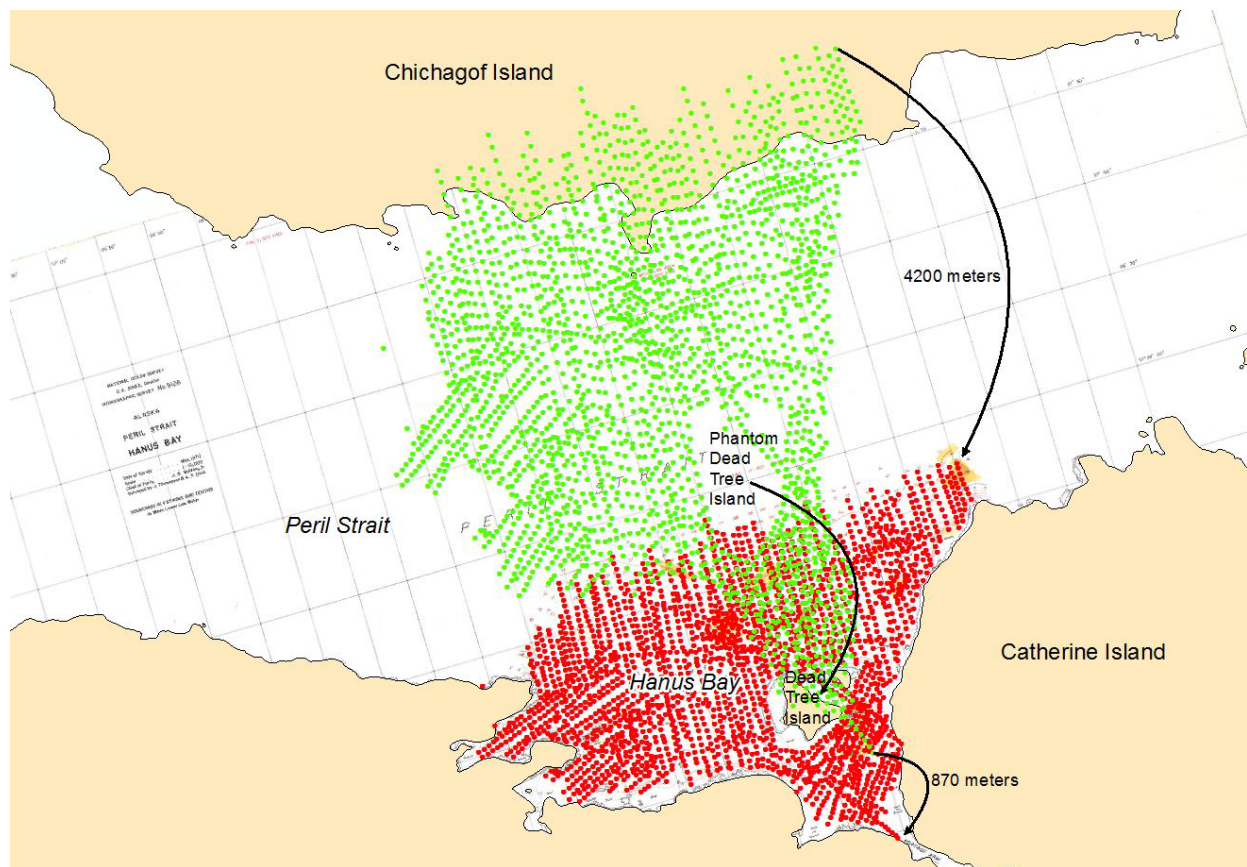



Figure 20. -- Complicated horizontal shift of soundings from H09128, where the northern soundings are approximately 4,200 m too far north and the southern soundings are approximately 870 m too far north.

1. Start a new project
2. Add the georeferenced and datum-shifted smooth sheet. Add the soundings as a Shape file with the same projection (NAD83 HARN).
3. Under the *Customize* tab, select *Toolbars*, and place a check by *Editor*, *Snapping*, and *Spatial Adjustment* toolbars (Fig. 21).



Figure 21. -- Spatial adjustment toolbar to use for variable shifts of soundings.

4. Under the *Snapping* toolbar select (place a check by) *Use Snapping*
5. Under the *Editor* toolbar select *Start Editing*.
6. Under the *Spatial Adjustment* toolbar, select *Set Adjust Data* and then *All features in these layers*.
7. Use *links* button  to A) click on a misplaced point, and then B) click on the location that it should be. Make numerous *links* surrounding the point file. Then click *Adjust* under the *Spatial Adjustment* toolbar and the point data should shift.
8. *Save changes* and quit *Editor*.

Proofing and Editing the Soundings

The soundings need to be proofed and edited by comparing them to the georeferenced and datum-shifted smooth sheet. Aside from the typical horizontal-shifting issue associated with

older datums, there are some characteristic digitization errors that should be investigated and fixed. There are also some random errors that can be found in a general review of the soundings.

Characteristic Errors

Unit errors in the bathymetric soundings are very important to correct, but often hard to detect when working on a single data set. These errors are quite apparent when assembling a regional bathymetry data set. Nearly all older smooth sheet bathymetry was recorded in fathoms and in sixths of a fathom (a sixth of a fathom is a foot; six feet equals a fathom). Some of the smooth sheet soundings were recorded in feet, especially in shallower waters. It is important to read the smooth sheet legend or the descriptive report to make sure that the correct units are used. The lower section of the H05152 legend states the soundings units (fathoms) and vertical datum (MLLW) (Fig. 22). Smooth sheet H02669 was created with a combination of feet and fathoms (Fig. 23).

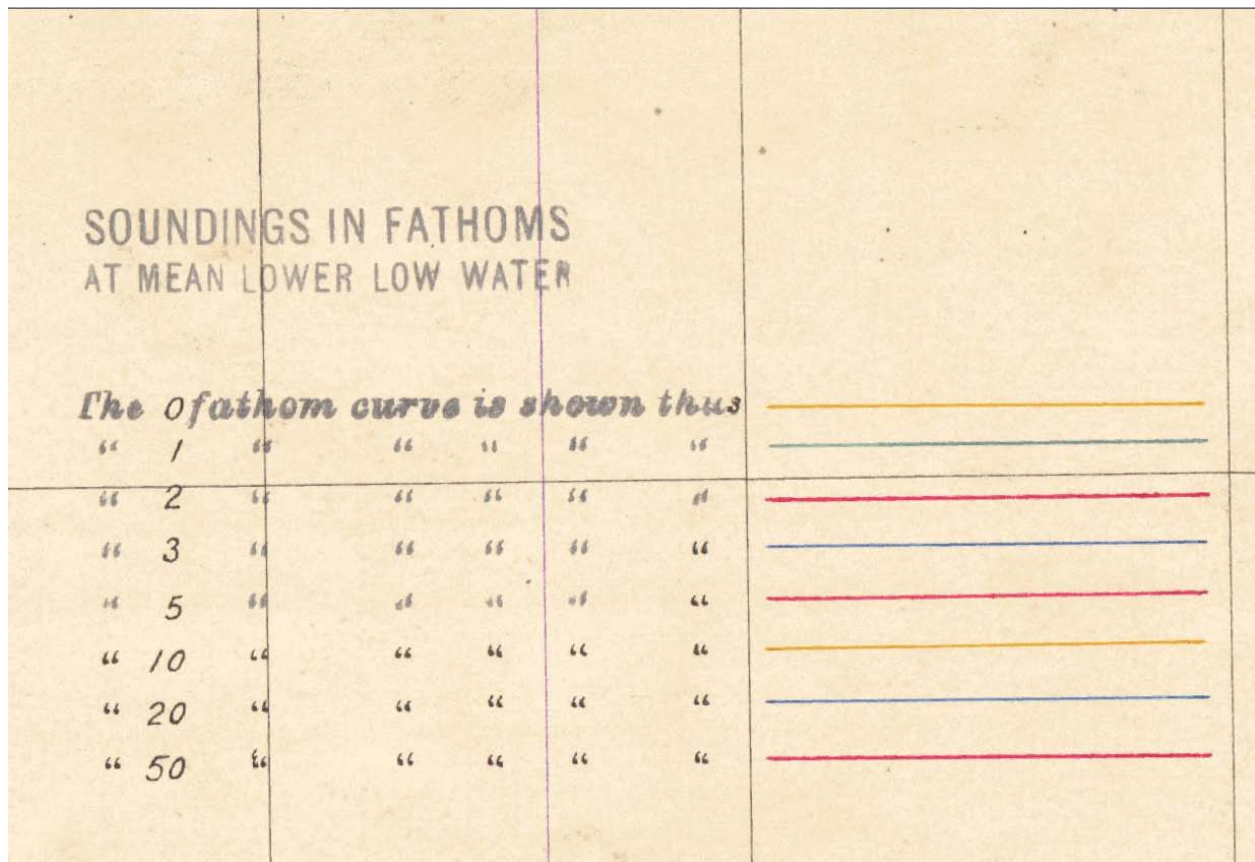


Figure 22. -- Sounding units, bathymetric curves, and vertical datum for smooth sheet H05152.

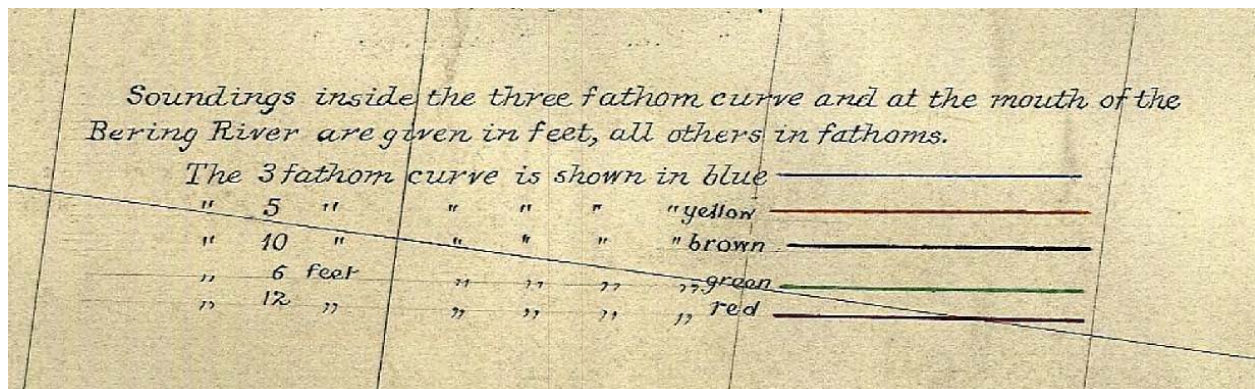


Figure 23. -- Sounding units for H02669 area mix of feet and fathoms.

Smooth sheet H04842, located at the southern tip of Kruzof Island, outside of Sitka in southeast Alaska, was digitized as if the soundings were in feet, rather than fathoms, resulting in depths that are one-sixth of their true depth.

Duplicate soundings are perhaps the most common characteristic error. Soundings from neighboring surveys were often drawn in different colors on the smooth sheet in order to show the continuity among soundings in the overlapping area. Unfortunately, these were typically digitized twice, at slightly different spatial offsets, resulting in a step or bench-like feature where none exists. These duplicate soundings from neighboring surveys should be deleted from any neighboring surveys, but retained in their original survey. For example, where the Kiliuda Bay (H05152) survey meets the Gulf of Alaska, it overlaps with neighboring survey H04855 such that some of the H04855 soundings are duplicated in slightly different positions (Fig. 24). Similarly, there are soundings in H04855 that are duplicates of H05152 soundings (not shown) and these would also need to be deleted.

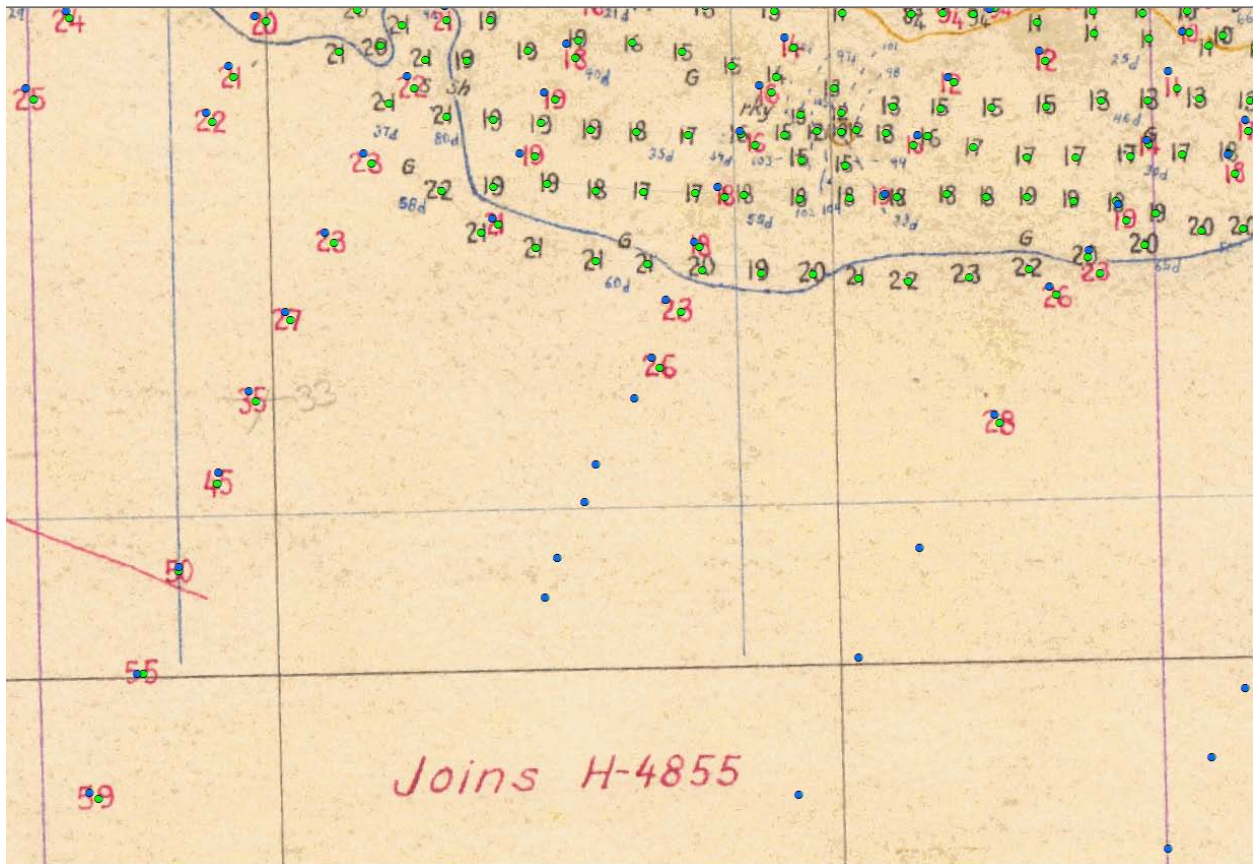


Figure 24. -- Overlap of H05152 and H04855 with duplicated soundings.

Users should also be aware that some of these smooth sheets were supplemented with soundings from what was termed "Additional work" (Fig. 25). Though typically drawn in a different color than the main body of the smooth sheet, these soundings are not duplicates of neighboring surveys, but important supplements to the original smooth sheet work, which was deemed inadequate. These "Additional" soundings should be retained. If these "Additional" soundings are not in the digitized file of soundings, the user should digitize them.

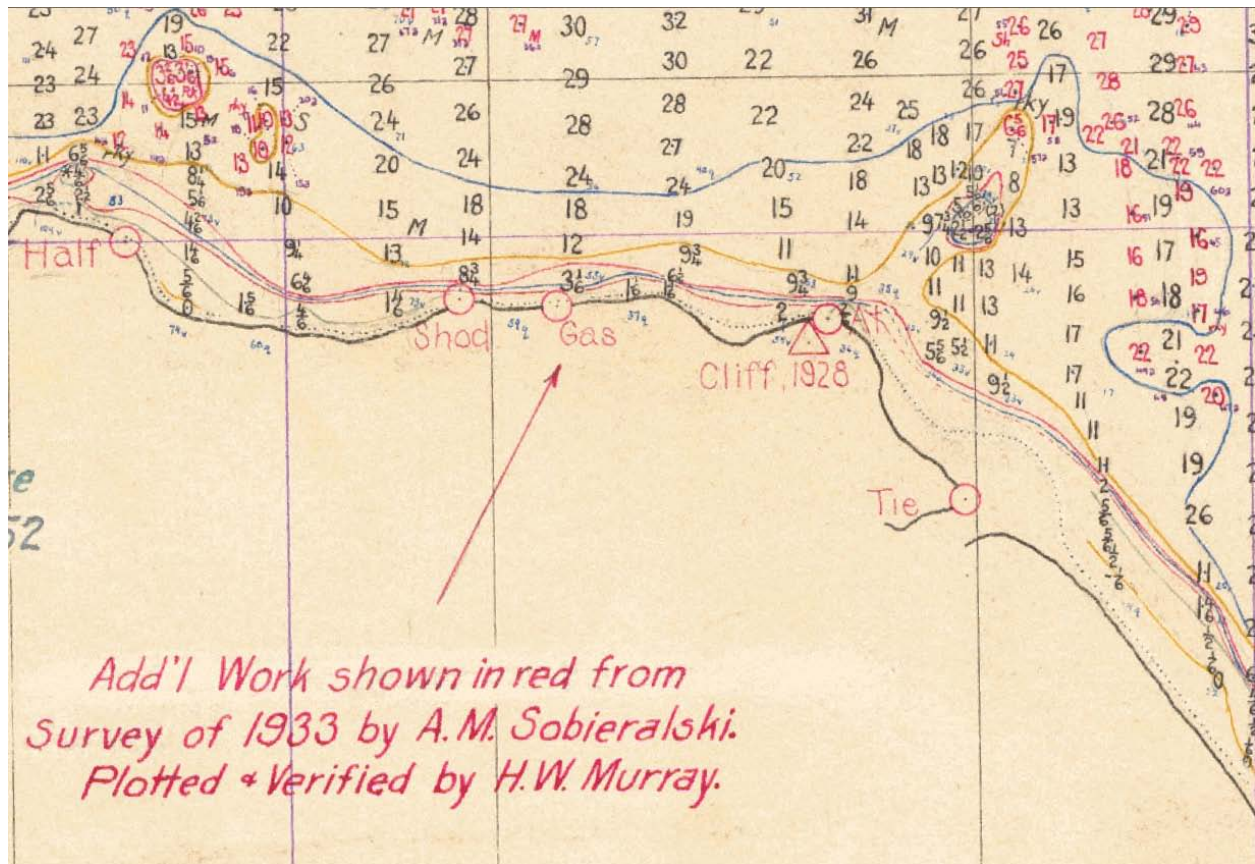


Figure 25. -- Additional soundings added to H05152 two years after its completion.

Soundings that are written on the smooth sheet as a fraction, with zero in the numerator and a depth in the denominator, are termed "deeper than" (Fig. 26). These notations indicate soundings which did not hit the seafloor because the lead line was too short. However these are typically digitized as if the depth in the denominator is the correct depth. Users may want to delete these soundings because the true depth at these locations is not known.

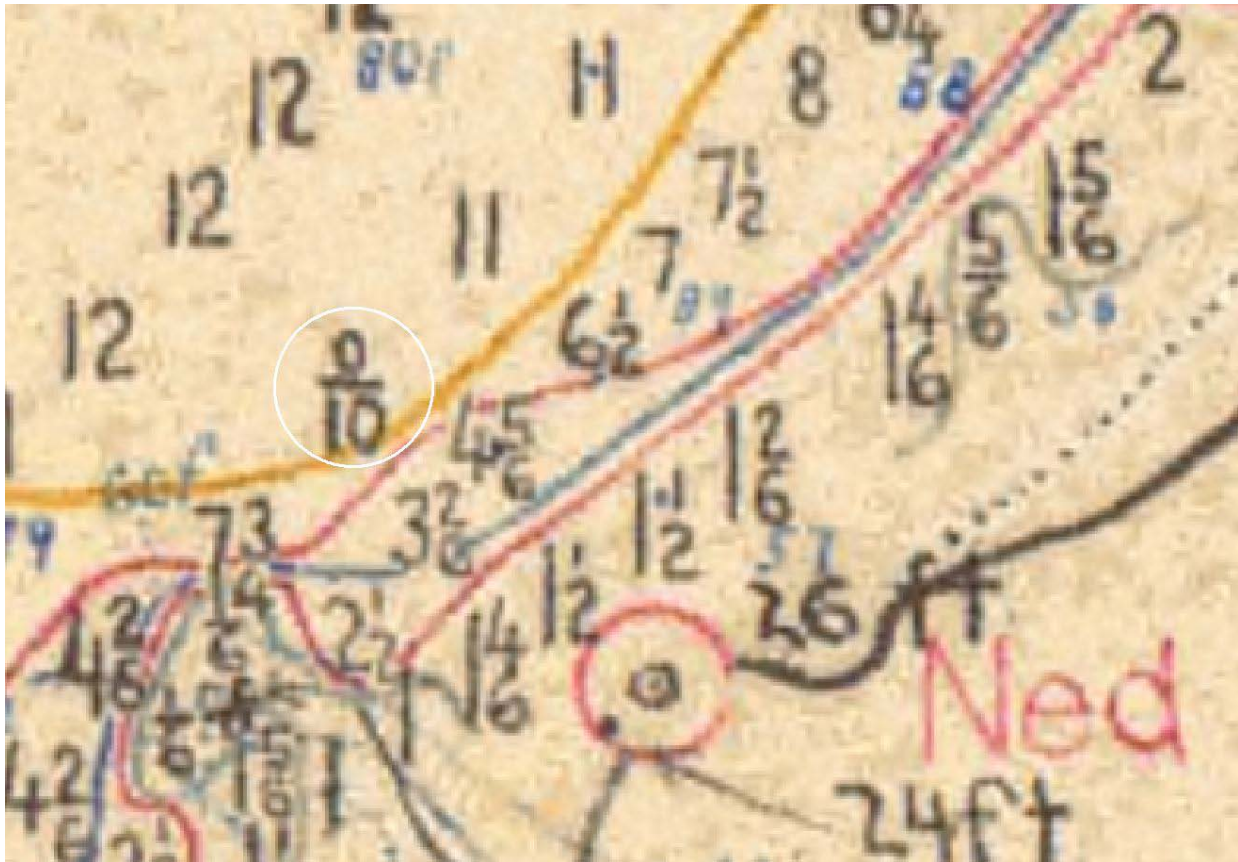


Figure 26. -- Example of "deeper than" sounding from H05152, where the lead line was not long enough to reach the seafloor.

Rocky reefs were sometimes digitized along their edge in tenths of meter increments, starting at 0.1 meters until the end of the reef (Fig. 27). While these might be reasonable estimates of the reef depth (0.1 m, 0.2 m, 0.3 m...), they are not depth measurements, and users only wanting true depths might not want to retain them as depths. The reef in Figure 27 was digitized in a clockwise direction, starting in the north at 0.1 m and ending at the same position with a duplicate value of 1.5 m.

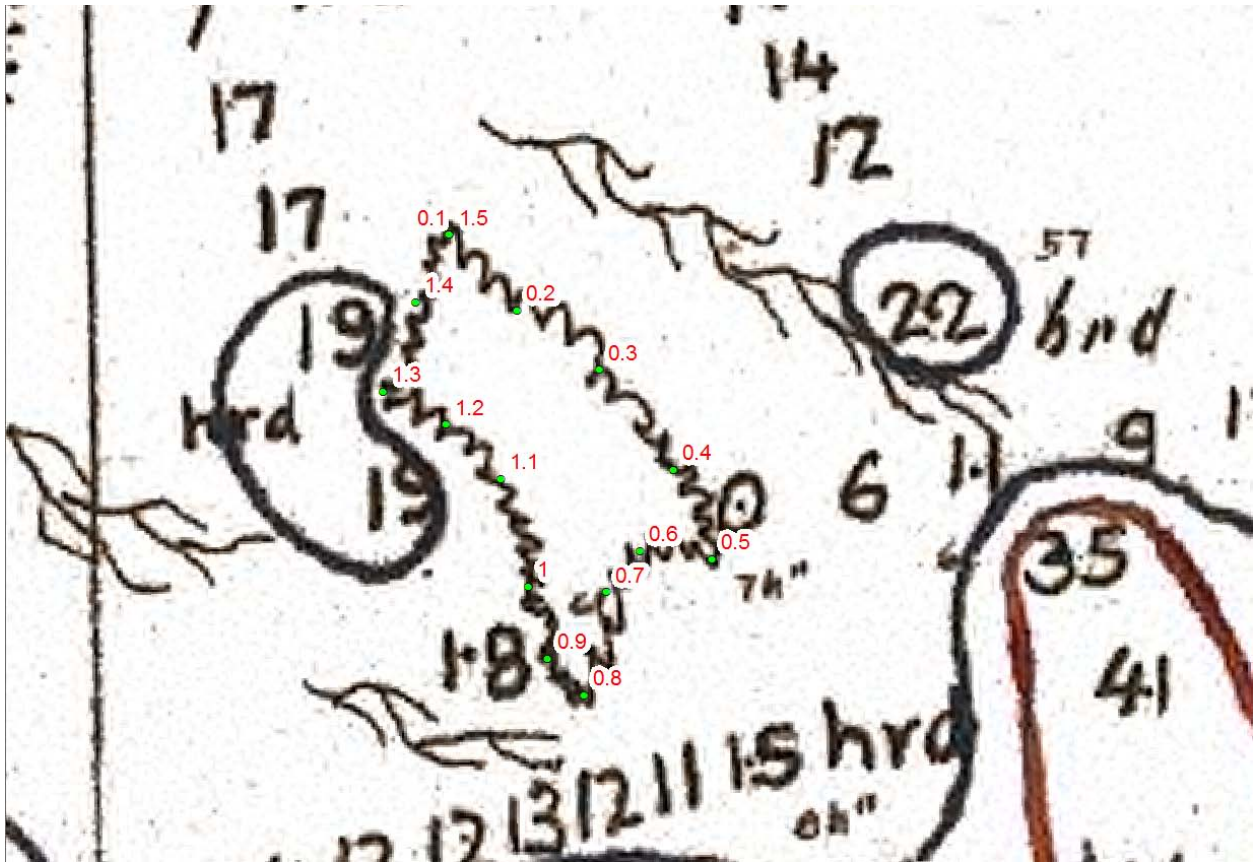


Figure 27. -- False depth soundings ranging from 0.1 to 1.5 m along the edge of a rocky reef in H02926_1.

Features such as kelp patches, rocky reefs, rocks, and islets are sometimes not digitized as frequently as the soundings, and users may want to add these elements for a more complete representation of the smooth sheet. Kelp patches are represented by wavy, forking lines (Hawley 1931) and are digitized as cartographic code 103 (Figs. 27 and 28) with a null depth of 99999.9 m. Rocky reefs (code = 530) are sometimes digitized as false depths, as mentioned above, and sometimes not digitized at all. Rocks (code = 89) are represented as asterisks (sometimes awash) or plus signs (always underwater) on the smooth sheets (Hawley 1931). Islets (code = 988) are represented by a shoreline encircling a small, water-bound piece of land. Rocky reefs, rocks, and islets may also have a depth or elevation associated with their symbology, typically in feet. If the

data value is in parentheses or in a phrase such as "bares 3 ft at MLLW" then it is an elevation, and will be a negative value, while most of the bathymetry soundings are positive values.

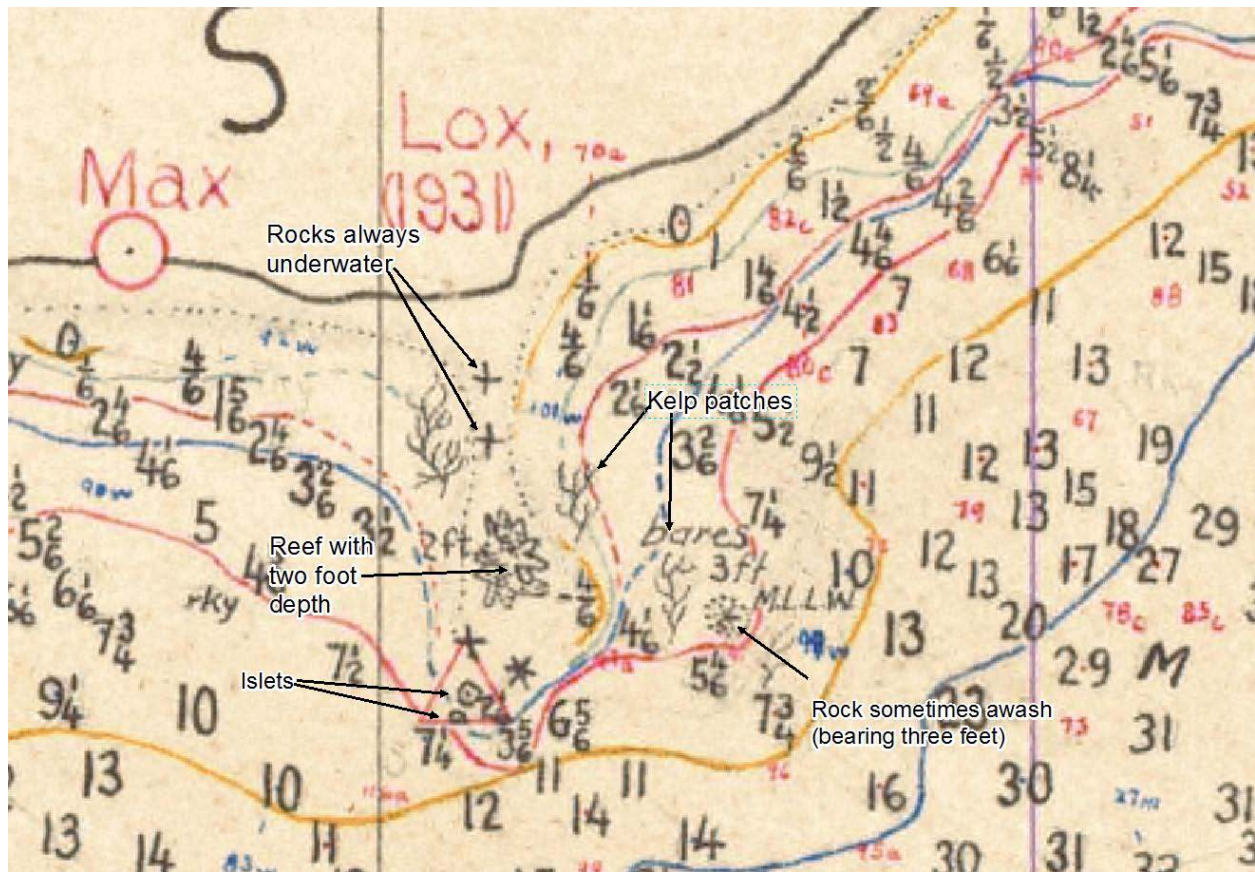


Figure 28. -- Features of rocks, reefs, kelp patches, and islets from H05152.

Tide rips, whirlpools (Fig. 29A), eddies (Fig. 29B), and overfalls are represented by a variety of symbols including triangular peaks (Fig. 29C) and small spirals (Hawley 1931), (code = 146), also with a null depth. None occurred in H05152.

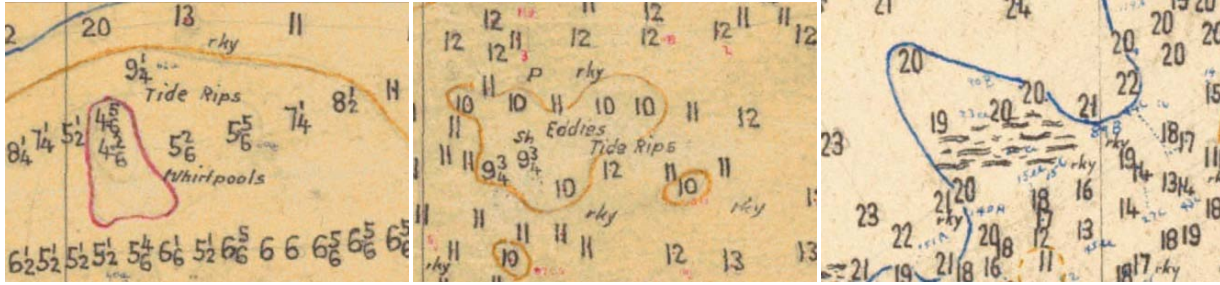


Figure 29. -- Notation of (A) tide rips and whirlpools from H05080, (B) eddies and tide rips from H05080, and (C) triangular peaks from H05051.

Random Errors

Missing soundings are easily created through digitizing them as additional records onto the original soundings file by using the *Editor* in ArcMap. It is fastest to digitize the soundings in their original units (eg., fathoms) and then to convert them as a group into meters.

Wrong depths are most easily discovered by creating a TIN (triangulated irregular network) surface from all of the non-null soundings, plotting the TIN surface as slope, and searching for individual triangles with a steep slope (Fig. 30). Steep slopes can be indicated by a bright color such as red and flat slopes can be indicated by a dim color such as blue - in this example there is a small patch of red and orange triangles on the eastern side of Shearwater Bay within Kiliuda Bay (Fig. 30).

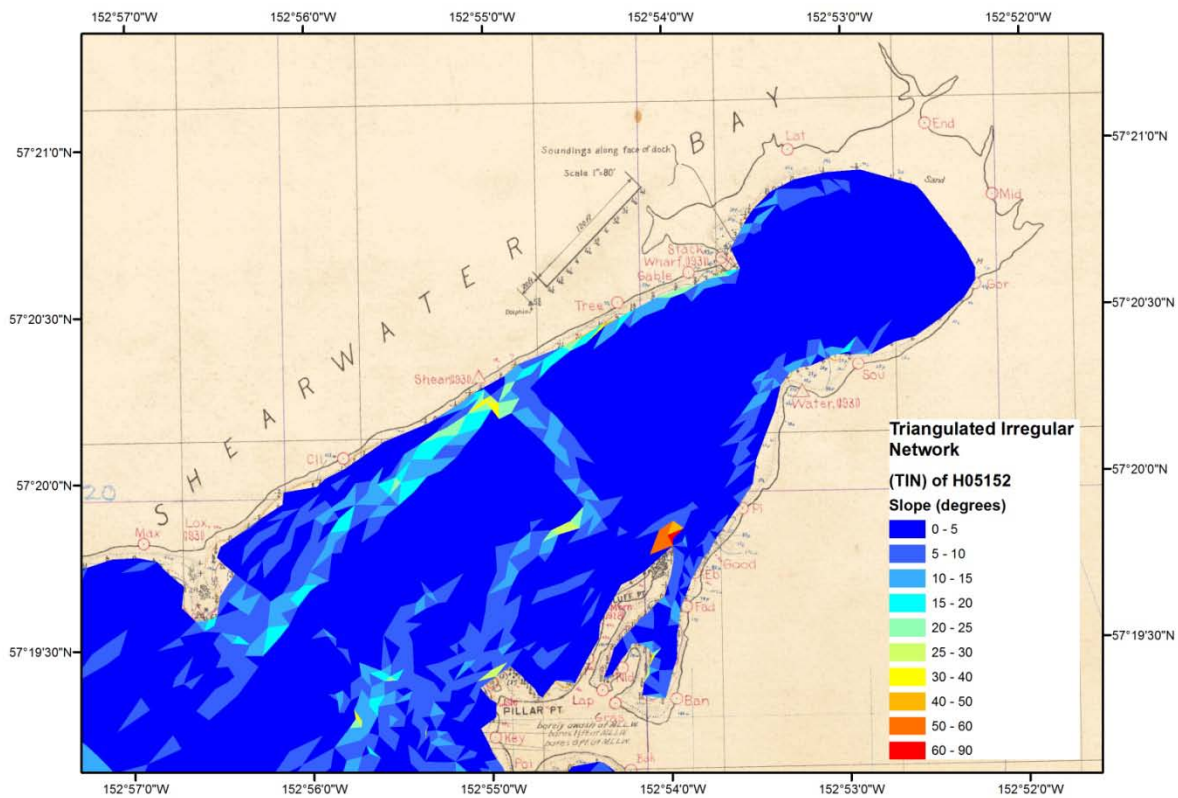


Figure 30. -- Triangulated irregular network (TIN) continuous surface showing steepness or slope in degrees, with flat areas blue and steep areas red.

Investigating the digitized soundings in this area (Fig. 31) of steep slope reveals that there is a sounding of 4/6 fathoms on the smooth sheet that got digitized as 46 fathoms (84.1 m).

Alternatively, it is possible to compare each sounding in meters (or converted to fathoms) to each fathom sounding drawn on the smooth sheet, but this is a tedious process.

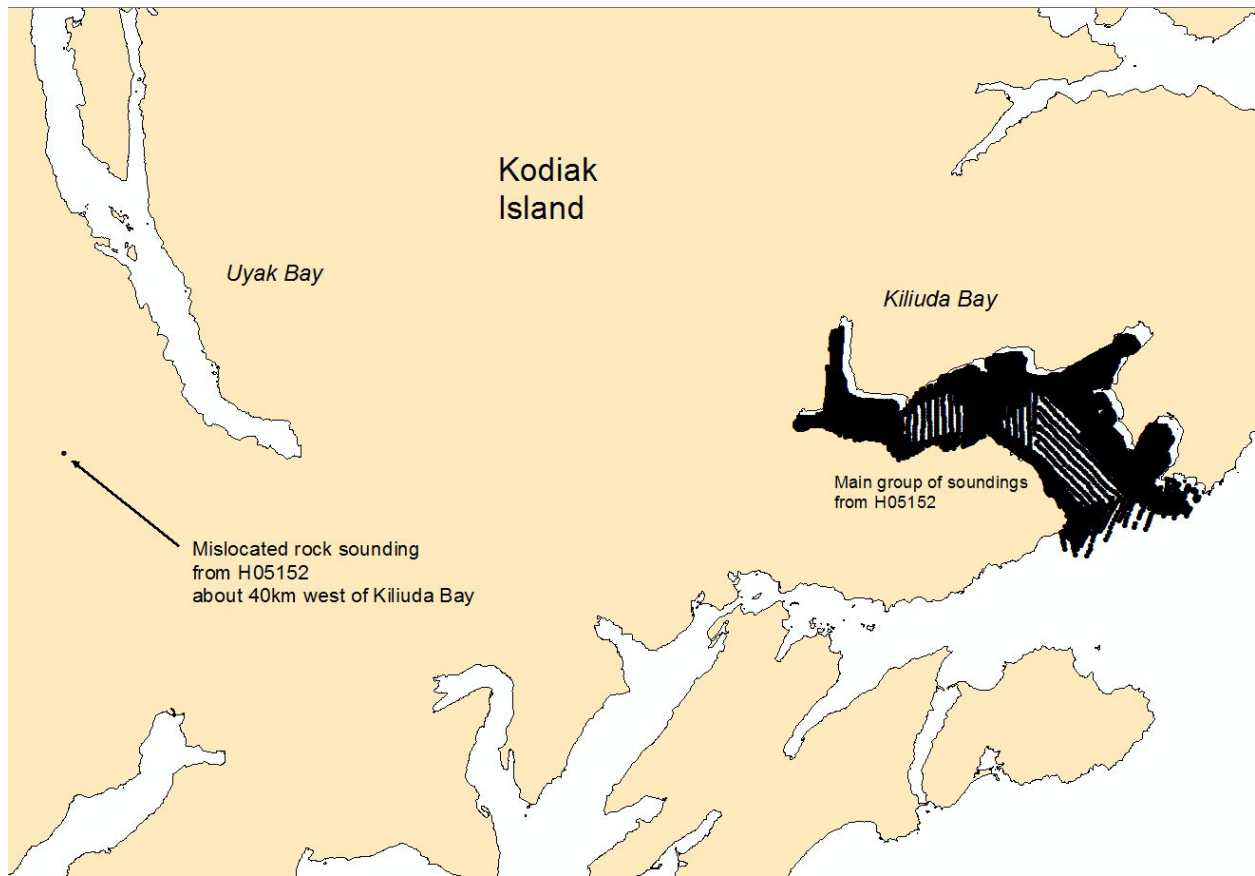


Figure 32. -- Rock sounding in H05152 accidentally digitized 40 km to the west of Kiliuda Bay.

Additional Work

Shorelines and substrates can also be digitized from the smooth sheet as complements to the soundings available from NGDC. Shore lines are drawn on the smooth sheets at the location of mean high water (MHW; high tide line in Alaska waters), which is typically defined as an elevation on the smooth sheet or in the descriptive report. Substrates are seafloor characteristics described in terms of color, grain size, and other characteristics such as composition (e.g., broken shells), or hardness or softness.

Shoreline

The shoreline from the smooth sheet can be digitized in a GIS and added to the bathymetry - in ArcMap this process is termed vectorization. In general, the shallowest bathymetric sounding is zero depth, which is the low tide line, formally defined as mean lower low water (MLLW) in Alaska waters. That means that the area extending from the MLLW line to the MHW is often blank. According to the descriptive report for H05152, the MHW shore line is 7.9 feet above MLLW in Kiliuda Bay.

The vectorization process is fairly difficult, with several complicated and time-consuming steps, so the details are not reported here. In summary, vectorization involves isolating the dark shoreline pixels from the TIF smooth sheet, guiding the ArcMap software on a path through an automated bisecting of the dark pixels, and converting the path traveled through the dark pixels into a polyline. The polyline is drawn as a series of connected straight lines with each new segment progressing straight along the shore line until a turn is required, and then a new segment is drawn. Each change of direction at the start of a new segment is termed a vertex, and these vertices can be converted into a shape file of points with the bathymetric depth of MHW, which was -7.9 feet according to the H05152 descriptive report. For example, in Shearwater Bay within Kiliuda Bay, there is a gap, sometimes termed the "white space," between the shallowest soundings and the shoreline (Figs. 30 and 33). Length of shoreline segments vectorized from H05152 are short, averaging about 4 m in length for H05152, and these segments are easily converted into points, which can be defined as a depth of -7.9 feet and added to the bathymetry (Fig. 33).

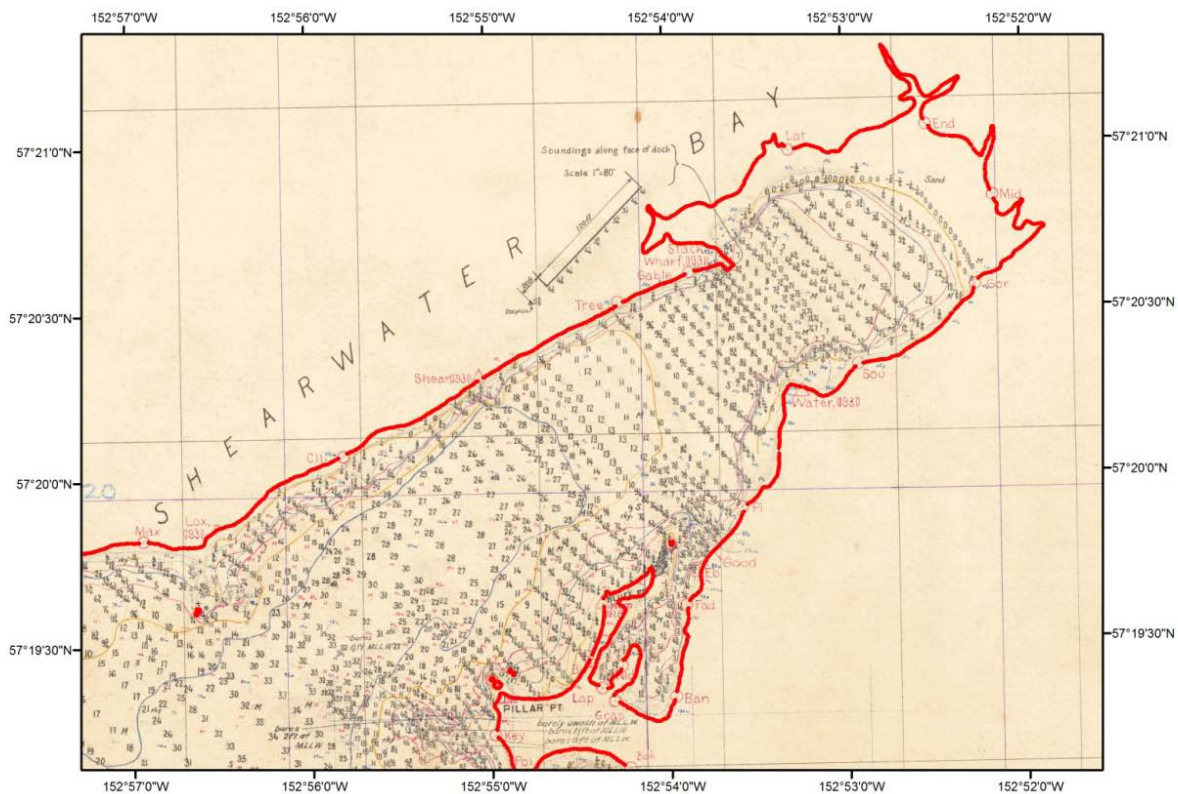


Figure 33. -- Shoreline, defined as MHW (mean high water), converted into bathymetry points, so that the inshore "white space" can be covered.

When added to the original smooth sheet bathymetry, the digitized shore line bathymetry allows creating an interpolated surface, such as a raster surface or grid, up to the shore line, eliminating the "white space" between the shallowest soundings and the shore line (Fig. 34). This complete bathymetric surface can be divided horizontally or vertically into areas or volumes such that numerous calculations can be made.

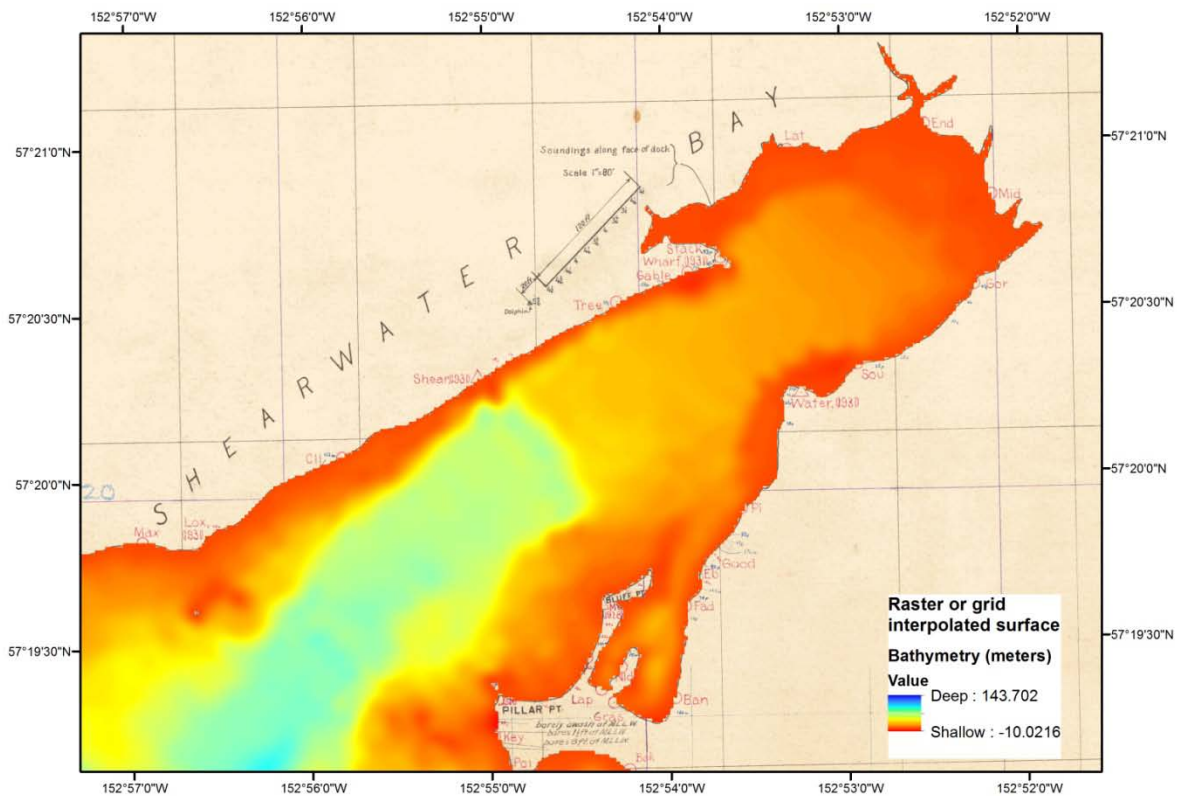


Figure 34. -- Raster or grid bathymetric surface of H05152 in the Shearwater Bay portion of Kiliuda Bay, showing elimination of the inshore "white space" by adding the shoreline points to the bathymetry points.

This interpolated bathymetric surface can be added to other imagery, such as USGS topographic maps (available in ArcMap v. 10.0, ESRI, Redlands, CA), along with digitized streams and rivers (Alaska Department of Natural Resources:

ftp://ftp.dnr.state.ak.us/asgdc/adnr/hydro_63360.zip). The connection of streams and rivers to the bathymetric surface are the pour points of freshwater runoff from the surrounding landscape. The watershed for Kiliuda Bay can be derived by following the topographic contours.

Boundaries of the watershed can be intersected to regional precipitation estimates (for example,

<http://agdc.usgs.gov/data/usgs/water>; Jones and Fahl, 1994) for calculating freshwater runoff (Fig. 35).

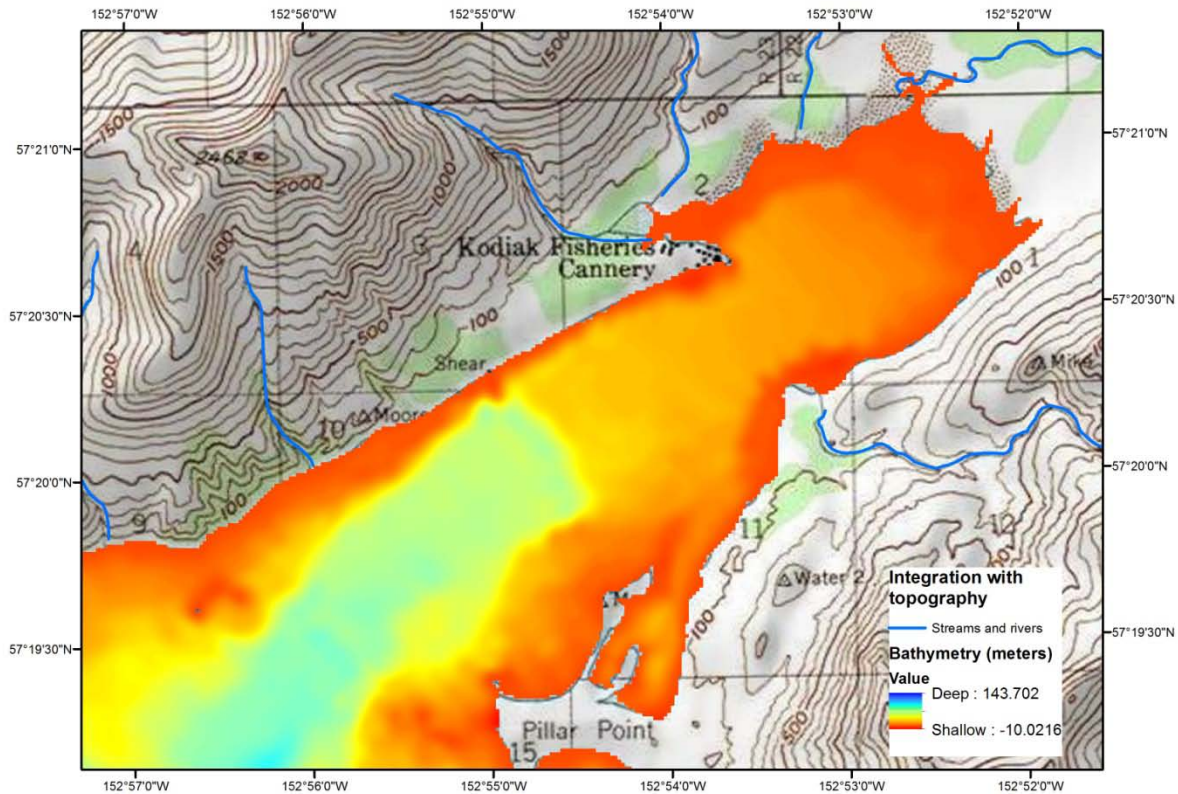


Figure 35. -- Plotting the completed bathymetric surface on top of a georeferenced U.S. Geological Survey topographic map, available within ArcMap, along with digitized streams and rivers (Alaska Department of Natural Resources: ftp://ftp.dnr.state.ak.us/asgdc/adnr/hydro_63360.zip).

The smooth sheet bathymetric surface can also be plotted on top of satellite or airplane orthographic imagery (supplied to ESRI courtesy of Bing Map Imagery© Microsoft Corporation and its data suppliers) (Fig. 36). Efforts such as the Alaska Statewide Digital Mapping Initiative (SDMI: <http://www.alaskamapped.org/sdmi>), which is creating seamless, ortho-rectified, true color imagery with a resolution of 2.5 m in pixel size for the entire state of Alaska, will make it

possible to link seafloor bathymetry directly to the land. As a reference, the bathymetry grid shown has a pixel size of 20 m. In this instance it appears that the stream entering the head of Shearwater Bay in the northeast corner of Figure 36 has changed course since the USGS topographic map was created.

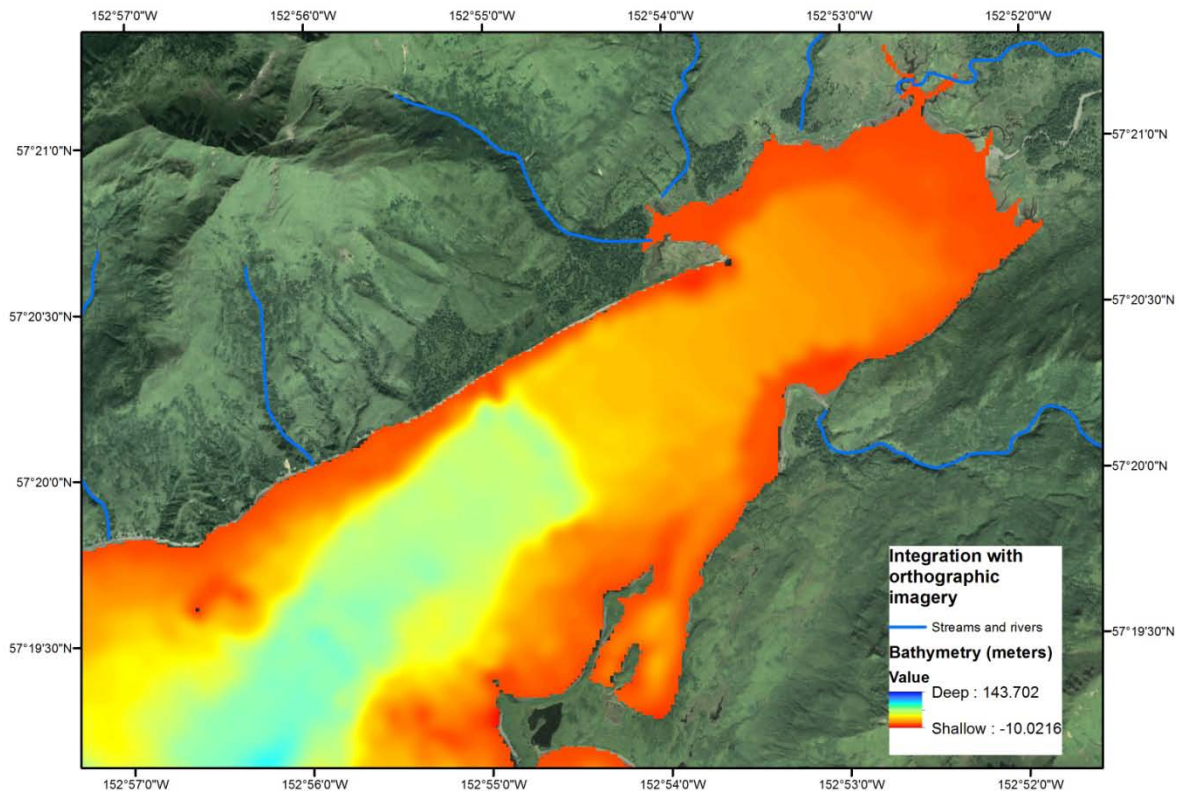


Figure 36. -- Plotting the completed bathymetric surface on top of orthographic imagery (supplied to ESRI courtesy of Bing Map Imagery© Microsoft Corporation and its data suppliers), along with digitized streams and rivers (Alaska Department of Natural Resources:
ftp://ftp.dnr.state.ak.us/asgdc/adnr/hydro_63360.zip).

Substrates

Substrate, or sediment type, observations were made from the same equipment used to collect hydrographic soundings: the heaving lead or deep-sea sounding apparatus, such as the Belknap-

Sigsbee specimen cylinder (Hawley 1931). A hollow in the end of the lead line weight was filled with tallow or soap and the observer noted what grains stuck to it. A person carefully heaving and lowering the lead could feel the difference between hard and soft substrate as the lead impacting the seafloor telegraphed a signal up the taut rope. The purpose of collecting this information was primarily for characterizing anchorages, but also as a navigational aid in foggy weather (Hawley 1931). Verbal sediment observation such as Mud, Sand, and Gravel can be translated into numerical grain size diameters, or phi values, on the Wentworth scale, using established conventions (Jenkins 1997). Unfortunately, many of the smooth sheet substrate observations are not directly translatable because Hard, Soft, and Sticky observations could mean numerous different grain sizes. Similarly, Rocky substrate observations, which probably indicate rock larger than boulders (-8 phi or 256 mm), fall off the Wentworth scale and are not translated into grain size diameters. Bathymetric features such as rocks, islets, rocky reefs, and kelp patches also all probably indicate some sort of bedrock or rock larger than boulders and are not directly translatable into grain sizes. Therefore, in order to include the non-traditional substrate observations in the numerical phi size output, Rock, Rocky and allied observations were translated as -9 phi, a size larger than boulders. The substrate observation of Hard was translated as 0 phi (the border between very coarse and coarse Sand), Soft was translated as 6 phi (same as Silt), and Sticky was translated as 9 phi (same as Clay) (Zimmermann et al. in review). The resulting surface has dramatic differences from the traditional sediment surface in Shearwater Bay (Fig. 37), where the smallest grain size diameter of Sticky or Clay is allowed to dominate in the middle of the bay and Rock or rock allies dominate some of the nearshore areas near Bluff Point, Pillar Point, and the unnamed point opposite Pillar (see Fig. 28). Without the Sticky or

Rock observations, the entire bay would have been mud and sand with two patches of gravel representing the largest grain size.

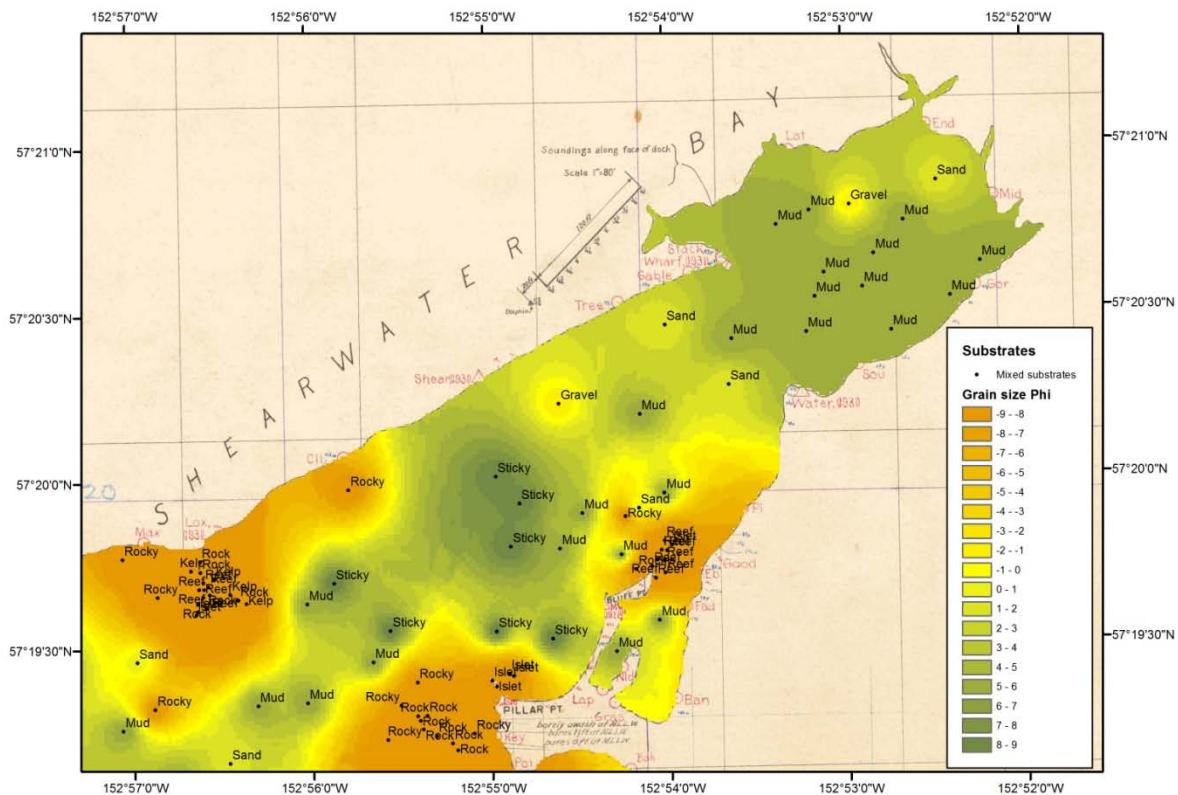


Figure 37. -- Substrate surface of estimated mean phi grain size plotted underneath verbal sediment and feature observations within the Shearwater Bay portion of Kiliuda Bay, from smooth sheet H05152.

SUMMARY AND CONCLUSIONS

There is a large amount of information available on the smooth sheets, but they require some understanding and interpretation before use. Without the numerous processing steps described here, the bathymetry and sediment surfaces might not align properly, or contain significant errors, such that basic calculations are incorrect. To start, the user should read the legend and

georeferencing information, noting any potentially misleading datum shifts drawn on the smooth sheet so that the proper graticule lines can be located. Georeferencing the smooth sheet with six links (or 10 links, if needed) on the graticules around the periphery and datum-shifting the smooth sheet by calculating the difference in the position of a triangulation station into NAD83 HARN is critical for proper alignment. Afterwards the user should check that the triangulation stations align properly and determine if the digitized soundings from NGDC also align properly. The soundings may need to be shifted hundreds of meters for proper alignment with the smooth sheet. Sounding units should be checked. Duplicate soundings that overlap with neighboring surveys need to be deleted, but soundings added to the smooth sheet after the survey date should be retained. "Deeper than" soundings should be deleted and features should be digitized with depths added for them, if available. Missing soundings should be added and misdigitized and mislocated soundings need to be corrected. The shoreline can also be digitized and added to the bathymetry data in order to create a more complete depth surface. The user may also wish to digitize the substrates, adding to them features (e.g., rocks, islets, kelp patches) from the bathymetry with some potentially useful substrate information.

After all this processing, the user should have a correct bathymetric surface, a correct sediment surface, and feature maps. The bathymetry surface can be used to calculate related surfaces such as slope, rugosity, aspect, local minima/maxima, and other surfaces - all of which might have some importance in determining ecological value. The sediment information can be used to calculate individual surfaces for mud, sand, and gravel if needed. Bathymetric and sediment surfaces should align with each other, topographic maps, and satellite imagery to facilitate relating the bay to land-based observations, such as streams and rivers, watersheds, and vegetation types, if known. A digitized shoreline can be used to estimate length of shore, length

of island and islet shores, and exposure to the Gulf of Alaska (Zimmermann et al. in review). Correcting the bathymetry, sediment, and feature inputs and properly aligning them in a GIS allows all sorts of complicated ecological questions to be answered. For example, if the user wanted to select kelp areas within x distance of mainland shore, within y distance of certain sediment type, farther than z distance of a stream outlet, with less than 50% exposure to the ocean, and then estimate the percentage of water volume exchanged between high and low tides, it's all possible with GIS queries. (Zimmermann et al. in review).

ACKNOWLEDGMENTS

B. McMahon, G. Nelson (retired) and especially C. Barry (Pacific Hydrographic Branch of the NOS) provided assistance with interpreting smooth sheets, bathymetric sounding files, and descriptive reports. D. Doyle from the National Geodetic Survey provided invaluable assistance with triangulation stations and datum shifts. D. Fischman, G. Glover, J.A. Bunn, J. Campagnoli, M. Frydrych, and M. Cole from the National Geophysical Data Center helped with accessing smooth sheets on the NGDC web site. We also thank K. Rand and M. Lander for their reviews.

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