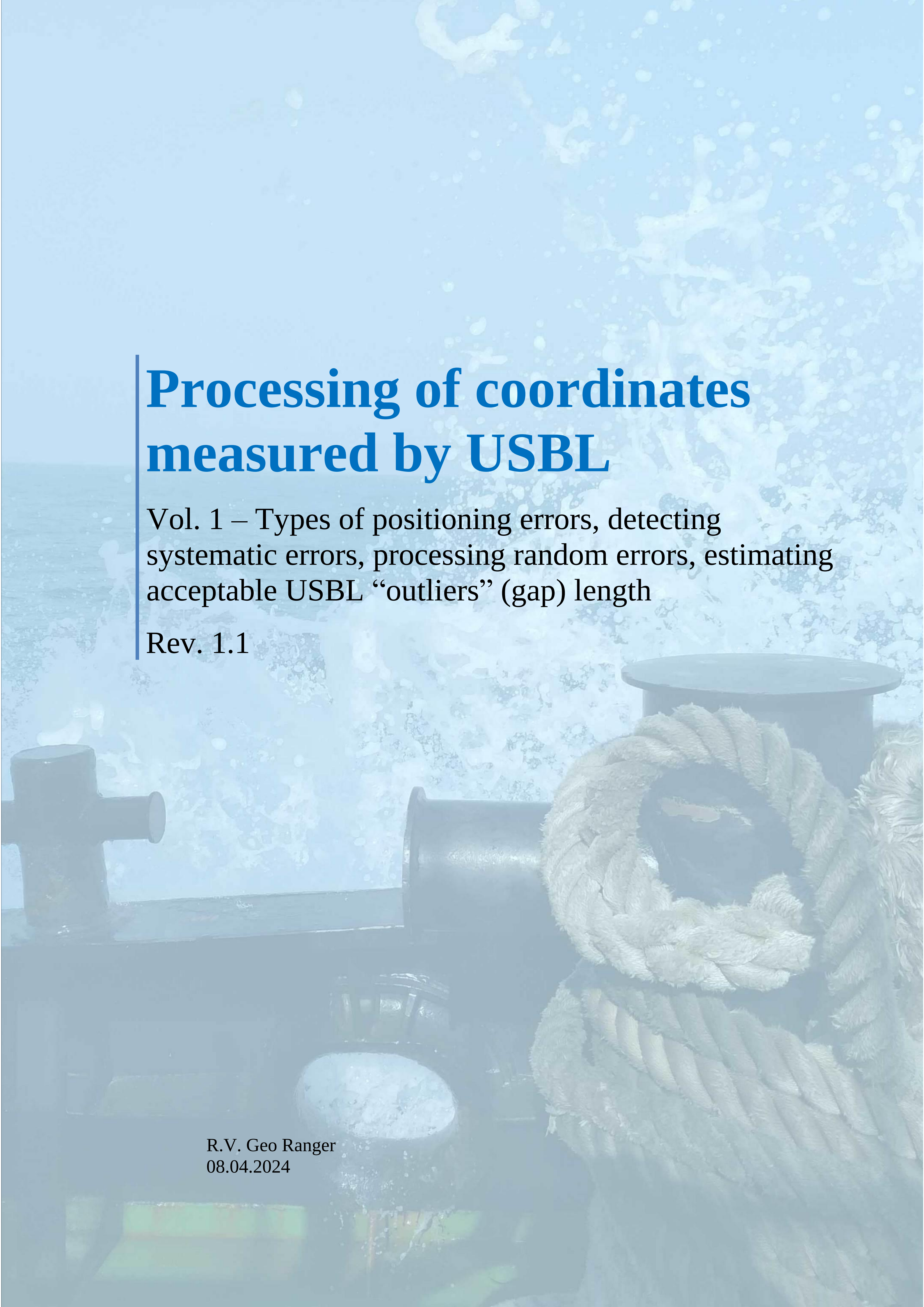

Processing of coordinates measured by USBL

Vol. 1 – Types of positioning errors, detecting systematic errors, processing random errors, estimating acceptable USBL “outliers” (gap) length

Rev. 1.1

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Content

History of changes

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List of Figures

Introduction

Initial conditions. The magnetic survey is performed using ScanFish, which has two rows of 4 G-882 magnetometers installed. Positioning is done using USBL (Kongsberg HiPAP 502) with disabled averaging, Kalman filtering and prediction.

Problem description. The coordinates output from USBL contain ***outliers*** (spikes). These outliers differ sharply from other coordinates or do not fit into the "regular variation" of coordinates. Such values are "rejected". They are removed from the coordinate measurements, and a "hole" is formed at the place of the outliers. This hole represents the measurements with undefined coordinates. The term ***"outlier"*** will be used to imply that the measured coordinates related to the outlier are false and should be removed. In general, the coordinates obtained by calculations are substituted instead of those removed. The following calculations are referred to as "interpolation." This term must be understood broadly. It can refer to linear interpolation or interpolation performed by mathematical modeling using predictive mathematical methods.

Problem to be solved. It is necessary to estimate the maximum acceptable outlier length at which interpolation of values within the outlier is permissible. Interpolation should be performed under the condition that the positioning error does not exceed the ***acceptable deviation*** (in our case – 2 meters) from the true coordinates of the towed device. If the outlier length exceeds the maximum acceptable deviation, the measurements within the outlier are “rejected” (completely excluded from the measurement results).

Solution Method. A ScanFish track is complicated by a ***simulated outlier*** of a given length that is moved sequentially along the entire track. Each time the track is processed, it is interpolated inside the outlier. The difference between the measured coordinates inside the outlier and the processed (interpolated) ones is calculated. If the difference does not exceed the acceptable deviation, the outlier length is considered as acceptable for the analyzed track, including “real” (not simulated) outliers present on it.

1 Types of positioning errors with USBL

1.1 Types of positioning errors

Several types of errors can be distinguished for the coordinates received from USBL.

Systematic errors, which are related, e.g., to the USBL set angles (such an error may occur when changing the rotation angle of the USBL rod after calibration and set angles determination) or other incorrect settings. Systematic errors are most often manifested as an offset of the coordinates output by the USBL by some angle and/or distance.

When positioning SSS, systematic USBL errors can be detected by comparing sonograms with MBES data (which is installed on board and USBL is not used for its positioning). Also, systematic errors can be detected by comparing target coordinates on adjacent sonograms. It is to determine the stability of the target position that the “counter courses on adjacent lines” technique is used. It is assumed that the systematic error, which is referenced to the vessel's coordinate system, will “change its sign” in the survey area coordinate system on the counter courses, resulting in the target displacement.

Systematic errors can also be detected on magnetic survey data by comparison with the position of local objects or cables on SSS and MBES data. In most cases, such objects are relatively rare and the magnetic anomalies are integral: (1) the anomaly area is several times larger than the object area; (2) it is not so easy to correlate the position of the object and its “position within the anomaly”; (3) there may be a buried part of the object that is not visible on the SSS and MBES data, but which also produces the part of the magnetic anomaly. Therefore, the “counter- courses on adjacent lines” technique is mainly used in magnetic survey: the anomaly outlines overlap on counter-courses assumes the absence of systematic positioning errors by USBL.

It should be noted that the cause of a systematic error in determining the position of the towed device by USBL may not be “the presence of an error directly in the USBL system”, but the presence of an error in the auxiliary system whose data is used for the position calculation. For example, an error in the MRU set angles will result in an error while determining the bearing angle from the USBL, and an incorrect sound speed will result in an error when determining the distance to the towed object.

A common type of systematic USBL error caused by the auxiliary system is an incomplete vessel roll compensation. In this case, there are oscillations in the towed device track that correlate with Roll, Pitch or Yaw. With a tow cable length of about 200 meters and a tow point position on the vessel's diametrical plane, the vessel's Roll cannot be mechanically transmitted to the towed object, nor can it result in the appearance of Yaw on the towed device (followed by the appearance of oscillations in the track of the towed device). The presence of such “oscillations” indirectly indicates that the USBL system settings need to be checked.

Let us list the main possible sources of systematic error: incorrect sound speed; USBL misalignment angles; MRU / Gyro misalignment angles; errors in offsets (GPS, MRU, USBL transducer); difference between vessel metacenter coordinates and vessel CoG coordinates, as well as the change of metacenter coordinates depending on tank fullness and model error for intensive vessel roll.

Random errors associated with random noise in USBL operation; in the field data, this appears as “scattering” of the towed device track points relative to a straight line, when the towed device is moving in a straight line. Random noise can be characterized using statistical parameters (modal values, arithmetic mean, standard deviation). In general, random noise is assumed to be the sum of many small and independent errors, so the noise is considered to be normally distributed in terms of mathematical statistics. The causes of random noise on the USBL are the hardware error and, possibly, the intensive high-frequency constant vibration in the receiver or transmitter area (caused, for example, by the operation of the vessel's engines). As with the systematic error, the cause of noise in the USBL position determination of the towed device may not be “USBL system noise”, but noise from an auxiliary system whose data is used in the position calculation (e.g., MRU).

Outliers and single spikes related to the temporary impact of external factors on the USBL system. In general, such an impact is strong enough to produce a measurement that breaks out of the general pattern. The USBL transponder short-term “shielding” can cause a single spike in the USBL data. Such shielding can be achieved by:

(1) parts of the towed device when it is in motion – a ROV turn or ScanFish motion with any of the structural elements on the USBL transducer-transponder line;

(2) bottom relief peculiarities – the USBL transponder mounted on the ScanFish is “covered” by the sand wave as it rounds the relief;

(3) relative position of multiple towed devices – the “near” device is on the transducer-transponder USBL line for the “far” device.

In general, in the situations described above, there is an impact on the USBL acoustic pulse (diffraction, over-reflection, shielding), which leads to an incorrect determination of the towed device coordinates.

As well as for the systematic error, the cause of the outlier may not be the “USBL system”, but the auxiliary system data, e.g. – spike of the GPS position when satellite or base station correction is lost.

An example of outlier cause analysis is discussed in the following section.

Two other types of errors that are “borderline” to those listed above are less common.

Extended exposure is associated with repeated (or extended over time) exposure to external factors. In this case, the line between single outliers and random errors is blurred. Examples of “extended exposure”:

(1) Suppose for a DP vessel that when a certain thruster is turned on, the vibration starts to affect the USBL transducer, then at the moments of turning on, the "random error rate" will increase dramatically. We will get a recording section that, depending on the duration and strength of the thruster impact, can be considered both a "continuous outlier" section and a "section with a large random error";

(2) Let the device is positioned near the DP vessel, and “one of the vessel's keel jets” appears periodically on the USBL transducer-transponder line, at these moments the “random error rate” will increase. We will get a recording section, that, depending on the duration and strength of the keel jet turbulence

effect, can be considered both a "continuous outlier section" and a "section with a high random error rate".

In a way, "extended exposure" may include work in or near the blind acoustic zones of the USBL transducer.

Variable systematic errors. While "extended exposure" is associated with the appearance and disappearance of external factors, variable systematic errors are associated with relatively smooth changes in conditions. Examples are changes in local hydrology – anomalies in the water column associated with changes in the acoustic velocity (thermocline, river confluences). If there is a smooth change in water column properties along the geophysical survey line, we will get a smooth increase and decrease in the towed device positioning error. If there is a repeated abrupt change, we will get the analog of "extended exposure" (in the limit – with outliers and changes in noise level). The described type of errors is related to the anomalous condition of the water environment in the work area and occurs quite rarely.

In fact, each of the discussed error types requires its own processing method. The following is a method for processing outliers when there is a temporary loss of USBL position, associated with the impact of external factors. Namely, the method of calculating the length of the "USBL position loss area" for which the interpolation of the towed device position within the outlier is acceptable (the specified positioning accuracy of the towed device for performing the magnetic survey is taken as the criterion of the interpolation acceptability).

1.2 Analyzing the causes of USBL outliers (ScanFish survey example)

Initial conditions. Magnetic survey is performed using ScanFish with two rows of 4 G-882 magnetometers installed. Positioning is performed using USBL (Kongsberg HiPAP 502) with disabled averaging, Kalman filters and prediction.

Let us assume that from the analysis of tracks of towed devices positioned by USBL, there are no interference types such as "extended exposure" and "variable systematic errors" type on them. Also, there are no explicit systematic errors in the tracks (which can be checked by comparing magnetic survey results on adjacent lines on opposite courses). The ScanFish track contains only random errors and outliers. The random errors are mainly caused by hardware noise and are close to a statistical normal distribution.

When working with ScanFish, there are two possible mounting positions for the USBL transponder: (1) on a special mounting location on the ScanFish body, (2) on the tow cable in front of the ScanFish (typically at a distance of 2-2.5 meters from the ScanFish COG). In the example below, the transponder is mounted on the ScanFish body (***Figure 1.1***).

When analyzing the coordinates, no definite cause for the outliers has been identified:

-- Outliers are present in both sandy wave and flat bottom areas. This rules out "bottom topography shielding", although, some profiles show a direct correlation between the presence of sand waves and outliers;

-- Outliers are present with both two and one towed ScanFish, which eliminates acoustic interference from the transponder of the second ScanFish;

-- With two ScanFish towed, outliers may occur on both the near-ship and far-ship ScanFish, i.e., the "near-ship unit is on the USBL transducer-transponder line of the far-ship unit" mechanism does not work;

-- The outliers do not depend on the drift of the ScanFish with the current relative to the vessel. This may be an indirect indication that the outliers are independent of the current speed and tilt angle of the ScanFish body on which the USBL transponder is mounted.

Figure 1.1 USBL transponder mounting position on the ScanFish body

The cause of outliers is unlikely to be a single factor discussed above, but a combination of several ones; therefore, it is difficult to correlate outliers directly with any of the factors described. From the general analysis, we can assume that the outliers are related to ScanFish body roll and pitch. The following situations of outlier occurrence can be distinguished:

1) Given the front part of the ScanFish body goes up, the USBL transponder is lifted and shielded by the ScanFish body from the USBL transducer, and its acoustic pulse is "lost" to the USBL. (***Figure 1.2***, ***Figure 1.3***);

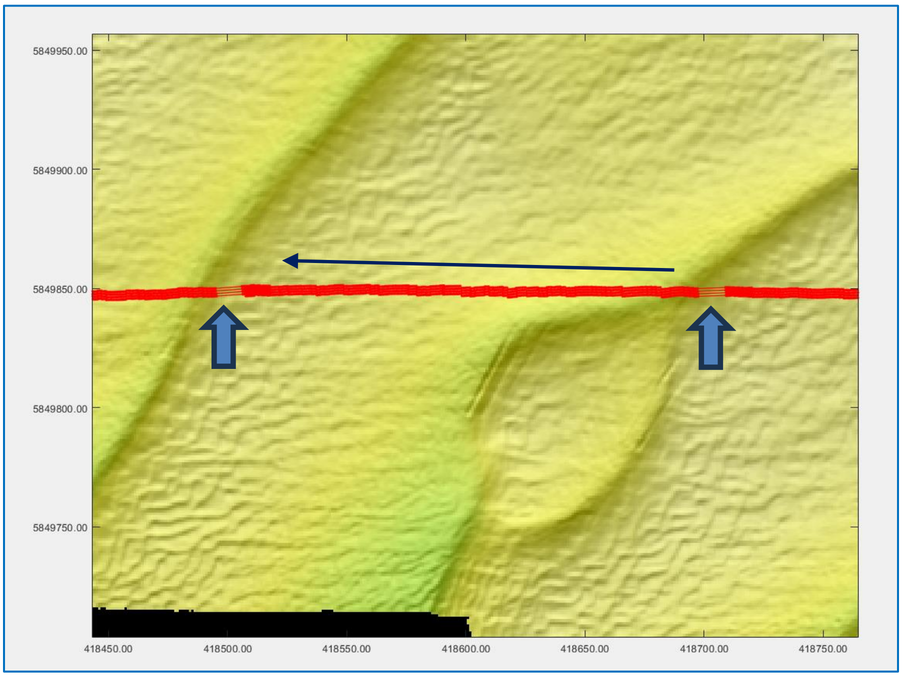

Figure 1.2 Outliers when the ScanFish is “lifted” on a sand wave

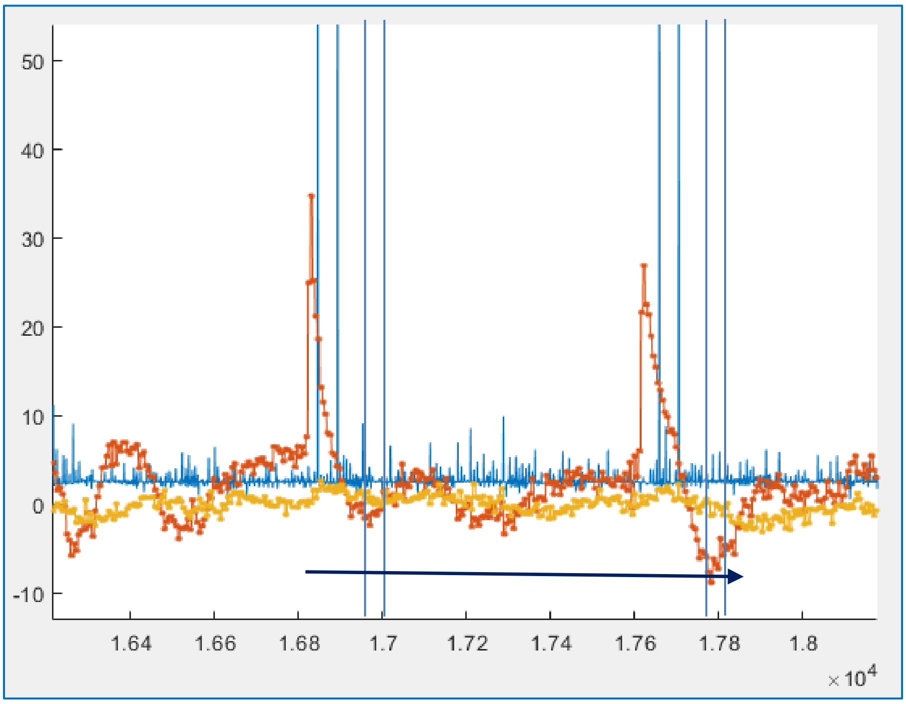

Figure 1.3 Comparison of the outlier position when the ScanFish is “lifted” on a sand wave (blue vertical lines), Pitch (orange) and Roll (yellow).

2) When the front of the ScanFish body is lowered, the USBL transponder is pointed down at the bottom. The USBL transponder signal is "absorbed" by the bottom, resulting in an outlier in the coordinates. An example is shown in ***Figure 1.4*** and ***Figure 1.5*** – after passing a sand wave, the ScanFish body front part goes down (to bury the ScanFish), the transponder is directed towards the bottom and its acoustic pulse for USBL is “lost”;

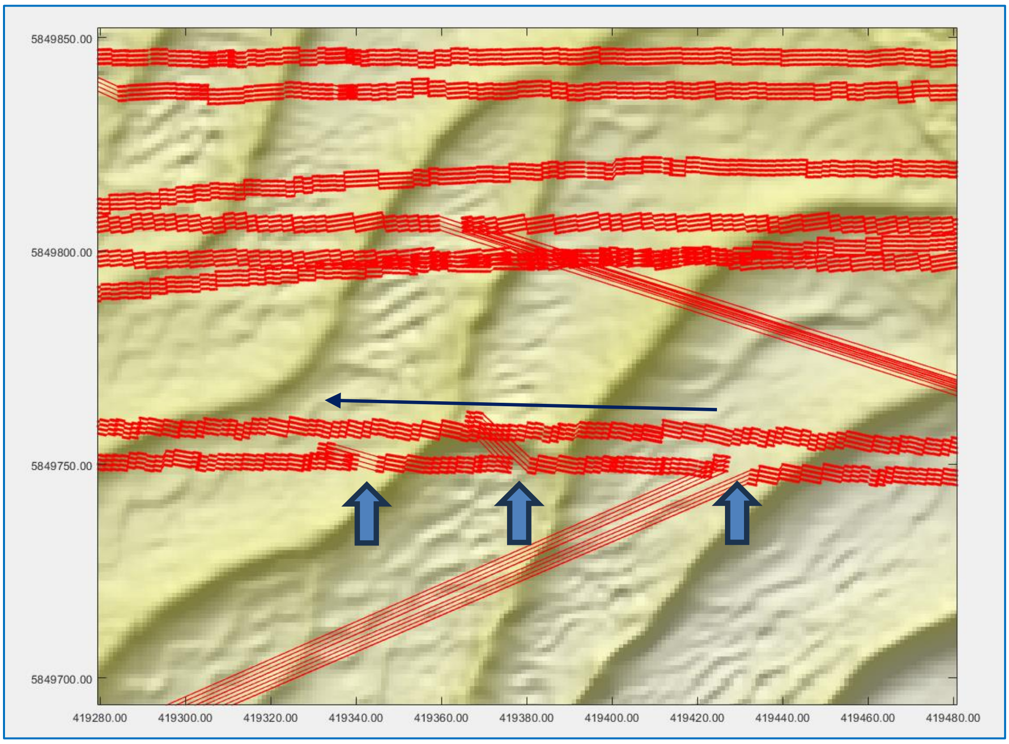

Figure 1.4 Outliers when ScanFish “slips” from a sand wave

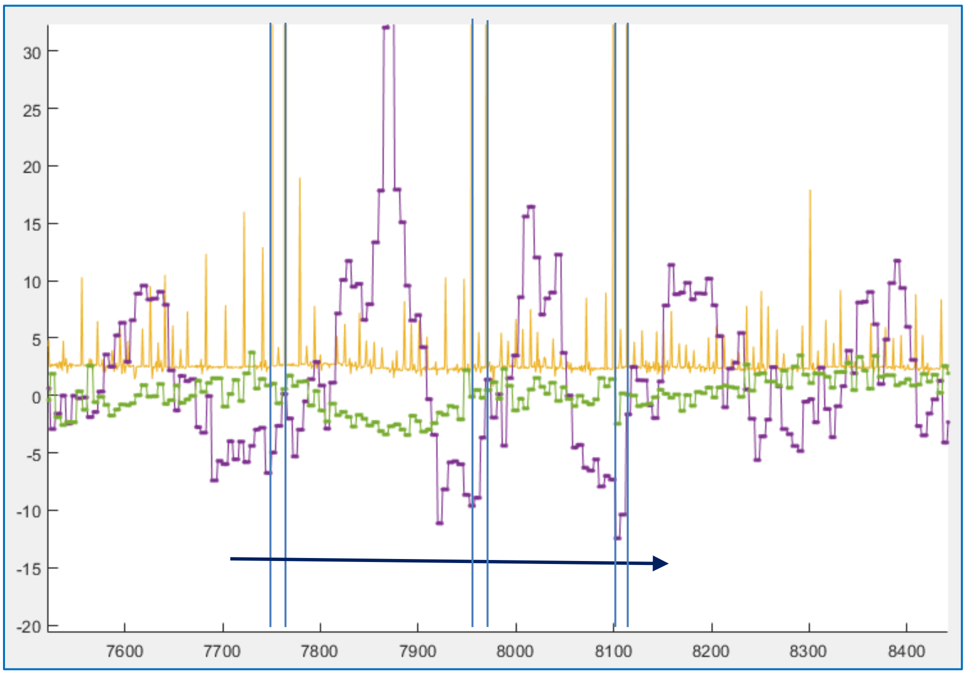

Figure 1.5 Comparison of outlier position when ScanFish “slips” from a sand wave (blue vertical lines), Pitch (purple) and Roll (green)

3) Let the front part of the ScanFish body go slightly down, then the USBL transponder is pointed towards the bottom at a slight angle. Due to the bottom peculiarities, the USBL transponder signal is “reflected” from it and the USBL transducer “recognizes” exactly the reflected part of the sweep signal. In this case, the path of the reflected signal to the USBL transducer is lengthened, which results in ScanFish coordinates “bounce back”. An example is shown in ***Figure 1.6***.

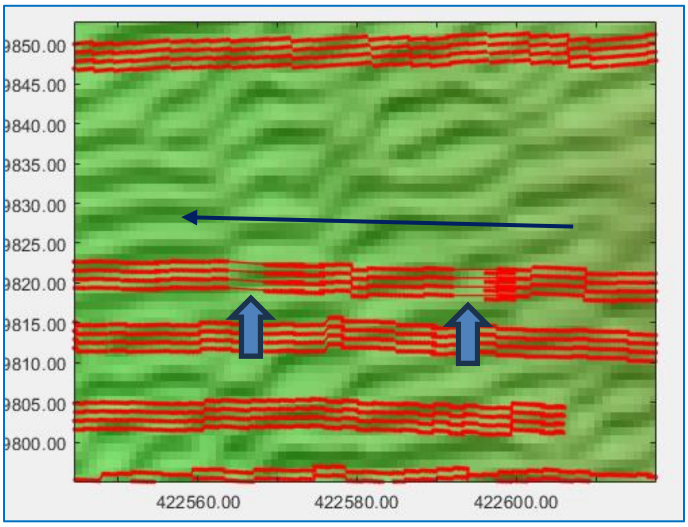

Figure 1.6 “ScanFish bounces” back when moving over a flat bottom (outlier at about 10 meters, ScanFish altitude 3.5 meters)

Thus, in the case considered (the transponder is mounted on the ScanFish body), the presence of outliers could possibly be caused by a number of reasons (current, relief), which makes the ScanFish body roll and pitch. Superimposed on this is the frequency of USBL acoustic pulses (QINSy extrapolates the USBL transponder coordinates after receiving the USBL acoustic pulse or until new data is received from the USBL system or until time-out) and probably the extrapolation of the single sample either by USBL or QINSy (***Figure 1.3*** – USBL coordinates outlier occurs already after passing the wave crest and Pitch output closer to ten degrees). It is also possible that the “ScanFish bounce” is a result of the bottom surface nature, leading to the reflection of the USBL transponder sweep signal from it.

Due to the impact of a large "complex of causes" for the example considered:

1) it is impossible to precisely correlate the outlier occurrence with any single sensor measurement (therefore, it is not possible to find a trivial cause and a "simple and straightforward solution" to eliminate it);
2) the occurrence of outliers in the first approximation can be considered as “random” (the result of joint impact of many independent causes).

In this case, eliminating outliers lies in the plane of “strong change of measurement conditions”, e.g., moving the USBL transponder from the ScanFish body to the tow cable.

2 Terminology and an overview of the coordinate processing graph

Before discussing quality control methodology, it would be important to clarify the meaning of certain terms to be used in the following:

-- ***True values*** are those referred to as the values of a physical quantity measured by "ideal" instruments with zero error under "ideal conditions" (i.e., without external interference or disturbance);

-- ***Measured values*** are those which belong to a physical quantity measured by real instruments with a measurement error; moreover, the measurements may be subject to various external factors that reduce their accuracy;

-- ***Raw data*** will be considered as a set of measured results that have not been subject to any additional processing. Partially, "raw data" is synonymous with "measured values" but for two differences (1) the former emphasizes the absence of additional processing, while the latter focuses on the "physical" implementation of the measurements; (2) the term "data" (e.g., coordinates derived from USBL data) is not directly analogous to the term "measurements". However, for coordinates received by USBL the measurements are the transponder response time and bearing angles from the USBL transducer to the transponder, which are converted into "raw data" – the coordinates of the towed device, using MRU measurements and other additional systems. In general, the data remain "raw" if simple mathematical formulas are used for recalculations that combine measured values for several measurement systems; if the data are processed with elements of integration, interpolation or prediction (e.g., Kalman filters), they are defined as "processed data";

-- ***Processed data*** are the same raw data with additional mathematical processing procedures;

-- ***Real outliers*** are defined as the absence in a series of measurement for some time (absence means performing measurements with a very large error, which does not allow obtaining information about the measured value). The distance corresponding to the outlier in coordinates is referred to as the ***outlier length***;

-- ***Modeled outliers*** are referred to as artificially created outliers in a series of measurements;

-- ***Interpolation or interpolation procedures*** are referred to as mathematical processing procedures that fill the outliers (in our case, the coordinates of the towed device at the outlier position) with the results of mathematical processing (linear interpolation, spline interpolation through splines or regression methods and also interpolation by means of mathematical modeling);

-- ***Processed data approximated to the true values*** are referred to as raw data subjected to mathematical processing procedures that reduce measurement error and approximate the raw data to the true values. For example, the ScanFish track raw coordinates necessarily include random normally distributed noise; then it is not raw measurements complicated by random noise (scatter), but processed coordinates with reduced level of random noise (e.g., by averaging) that will be closer to the true values. Actually, we will use these processed coordinate values as "approximated to the true values" in mapping and interpreting the magnetic field. In part, "processed data" and "data approximated to the true values" are synonymous, but not all processing procedures are aimed at "reducing measurement error” (in a narrow sense); e.g., processing procedures that perform interpolation within an outlier are aimed at “recovering missing raw data”;

-- ***Measurement error reduction procedures*** are those mathematical processing procedures by means of which data approximated to the true values are obtained from raw data;

-- ***Deviation*** (distance, difference) are what we'll call the difference between the data approximated to the true values and the raw data. The maximum deviation determined by the survey based on technical specifications will be called the ***maximum acceptable deviation*** or ***acceptable deviation***.

In a first approximation, the coordinate processing could be represented as consisting of the following steps:

-- random noise reduction,

-- outliers' (false values) removal,

-- values' interpolation in the outlier’s position.

A detailed description of the coordinate processing graph can be found in Part 5:

“Coordinates’ processing obtained by USBL, Vol.2 – Program implementation: functions gMapPickHandleNan2, gFieldsDespike1D, gFieldsDespike2D”. The functions of the ge0mlib library are used to process coordinates and measurements of auxiliary systems.

It would be convenient to consider positioning quality control “for random noise” and “for outliers” separately.

3 Positioning quality control by random noise level

According to statistics, if a random value is normally distributed, its standard deviation decreases with the number of measurements in proportion to the square root of the number of measurements. That is, if the USBL coordinates change only slightly inside the sliding window (by an amount much smaller than the standard deviation), then averaging within the sliding window will reduce the random variation for the USBL coordinates. In practice, this case never occurs, because it implies a near-stop state of the towed device. ***However, the same rule can be extended to a linearly varying value.*** At the same time, “the increments in the left part of the window” compensate for “the increments in the right part of the window”; averaging the linear function results in a value equal to the value in the center of the window. The random standard deviation also decreases proportionally to the square root of the number of samples within the window.

Therefore, the best sliding window width is the one that contains enough measurements to reduce the random error ***while keeping the variation of the averaged value close to linear***. If the window size is significantly increased, the statistical component of the positioning error begins to decrease more slowly, but the error caused by the nonlinearity of the averaged value increases and begins to exceed the random error. Thus, the optimal size of the averaging sliding window also depends on the ***the survey line pass-mode*** (proximity of the coordinate variation to linear-uniformal at a small distance).

Based on the data processed close to the true values (with reduced random noise) and the raw data, we can perform a first approximation ***positioning quality control at the random noise level***. The calculations are as follows:

-- perform raw coordinate processing to obtain processed coordinates that approximate the true values (e.g., with random normally distributed noise removed);

-- compare the raw coordinates with the coordinates approximated to the true values – the distance between them should not exceed acceptable deviation.

If the distance exceeds the acceptable deviation, the random noise level along the profile is considered to be unacceptably high; and the impact of the noise sources should be reduced to continue the survey.

4 Positioning quality control by outlier length

A towed device with no active controls will change its position very smoothly. If there are no local currents and jets as well as the tow cable is long enough, it moves the device in a very stable, smooth and uniform way due to the inertia caused by the towed device dynamics and the tow cable dynamics in the water column. Short-term displacement of the tow point from the tow line (roll, displacement of the vessel's stern during a slight change in the vessel's course) will have little effect on the towed device position. If there is a significant displacement, the towed device displacement will be very smooth. The effect of changes in vessel speed, current strength and the unevenness on the towed device will make the towed device to deviate from a straight line; let us call the effect of these features ***the survey line pass-mode***.

In fact, the problem of determining the maximum length of outliers that can be interpolated is to establish to what extent *the survey line pass-mode* allows interpolation to be performed. The interpolation acceptability criterion will be the deviation of the interpolated values from the measured ones by a value not exceeding the threshold level.

Given the concepts discussed above, it is possible to estimate the acceptable USBL outlier length for the survey line pass-mode using the following method:

-- create a modeled outlier of the specified length on the ScanFish track;

-- perform raw coordinates' processing complicated by the outlier; processing includes procedures to reduce measurement error (e.g., procedures of averaging as a way to reduce random noise level) and procedures to interpolate values at the outlier position;

-- find the difference between the processed interpolated coordinate values and the raw coordinate values at the outlier position;

-- if the calculated difference does not exceed the acceptable deviation, the outlier value is considered acceptable;

-- repeat the procedures described above, moving the modeled outlier along the ScanFish track to check its acceptability at any of the survey line sections.

By repeating the procedure for different outlier lengths, it is possible to find the length at which the interpolation error starts to exceed the acceptable deviation. In practice, it is preferable to use a value that is obviously smaller than the value at which the acceptable deviation is exceeded.

In the method described above, the “deviation of the interpolated coordinate values at the modeled outlier position from the raw coordinates” is calculated. However, in this case the error is the sum of a random error and an outlier interpolation error. To estimate the outlier interpolation error, it is necessary to calculate the “deviation of the interpolated coordinate values at the modeled outlier position from the coordinates approximated to the true ones”.

4.1 Systematic error effect on the acceptable outlier length estimation

The presence of systematic error or slowly varying systematic errors will not affect the calculation results for the acceptable outlier length and random noise level. For the described procedure, in the presence of a systematic error the processed coordinates approximated to the true ones will not correspond to the physical towed device track, but to the "physical towed device track complicated by a systematic error". It is possible to check the presence of the systematic error using the method described above – by comparing the position of magnetic field anomalies obtained for counter courses on adjacent ScanFish survey lines.

4.2 The towed device active controls effect on the acceptable outlier length estimation

The procedure described above for estimating the acceptable USBL outlier length works well for a passive towed device. However, for a 3D-ScanFish, equipped with active controls, the towing conditions' invariability is disrupted (at any moment the operator can "intervene" and disrupt the "towing patterns" by changing the nature of the ScanFish controls):

-- For modeled outliers, the raw 3D-ScanFish coordinates are obtained when the towed device is held on the survey line in a controlled manner (i.e., offset across the tow line);

-- For real outliers, the raw 3D-ScanFish coordinates will be obtained when the towed device is uncontrolled (or "miscontrolled"). This means that the controls which define the offset across the tow line will be locked after the USBL signal is lost. 3D-ScanFish will continue the "offset" defined before the USBL signal was lost, and once the USBL operation is recovered, 3D-ScanFish algorithms will begin to correct the "accumulated deviation from the motion line given to the autopilot".

-- In general, 3D-ScanFish motion patterns are more complex to analyze. E.g., if there is a "low offset outlier for USBL coordinates", the 3D-ScanFish controls will be moved to the "wrong position" to eliminate the "false offset defined by the outlier".

To be able to use the method described, the offsets performed by the 3D-ScanFish controls in the horizontal plane must be "relatively slow" to avoid a significant offset during the outlier time (time of USBL signal loss or small USBL coordinates' failure). This condition can be estimated by checking the amount of 3D-ScanFish deviation from the planned track (motion line given to the autopilot) at the beginning and at the end of the real outlier. If this deviation has not significantly changed, the error "caused by control loss" can be neglected.

4.3 The winch operation effect on the acceptable outlier length estimation

For a passive towed device, there is a change of position when the tow cable is pulled up/pulled out with a winch by the operator (while for ScanFish and 3D-ScanFish a constant length of cable is usually used during the survey, for SSS, for example, the control of the tow altitude above the bottom is done exactly by pulling up/pulling out the tow cable).

To obtain the coordinates close to the true ones, **when averaging the coordinates in a sliding window**, the window size should be quite small because there will be coordinates "smearing" for the sections in the area of start and stop of winch operation. That is, on the one hand, by averaging we remove random noise, but on the other hand, we add an error due to the “coordinate shift” (an error caused by the towed device irregular movement on the section entering the sliding window, if a section of the winch operation enters the sliding window. Indeed, while for “passive movement” the track change will be quite slow and the change of position within the sliding window can be assumed to “occur according to a linear law”, the impact of winch operation will change the track relatively quickly.

When interpolating within the outlier, if the start or end of the winch operation is inside the outlier, there will also be a “smearing” of coordinates along the entire length of the outlier. As a result, the interpolated coordinates inside the outlier will have large deviations from the true values.

Unlike the active controls impact, the winch operation can be considered more as a “part of the survey line pass-mode”. If at the winch operation moments, the deviation between raw and processed coordinates is large, it will mean that it is necessary to add the etched cable length to the procedure of “interpolation of values inside the outlier” to reduce the modeled error of this procedure.

5 The acceptable USBL outlier length estimation example

5.1 Calculations

Let us consider the described regularities on the survey data example. ***Figure 5.1*** shows an example of random noise on the ScanFish track section: the red line shows the original track, the blue one represents the processed coordinates (the data with random noise removed). The deviations take the form of "line segments with approximately equal deviation", which then changes relatively abruptly. This shape is due to the extrapolation of QINSy measurements from two specific data sources:

- data received from USBL coordinates of the USBL transponder that is mounted on the towed device (updates approximately every 3 seconds, "large offsets");
- data received from MRU that is mounted on ScanFish as a result of magnetometer coordinates calculation relative to the USBL transponder (updates approximately every second, "small offsets").

[Note: to calculate the most accurate magnetometer coordinates calculation it is preferable to have raw USBL and MRU data rather than extrapolated QINSy coordinates; it is then possible to carry out outlier removal and averaging (to remove random noise) on primary measured values which have not been a subject to mathematical processing. Also, when using extrapolated QINSy coordinates, the averaging in the sliding window takes place "towards the middle of the line segments", while the measured values are positioned "at the beginning of the line segments".]

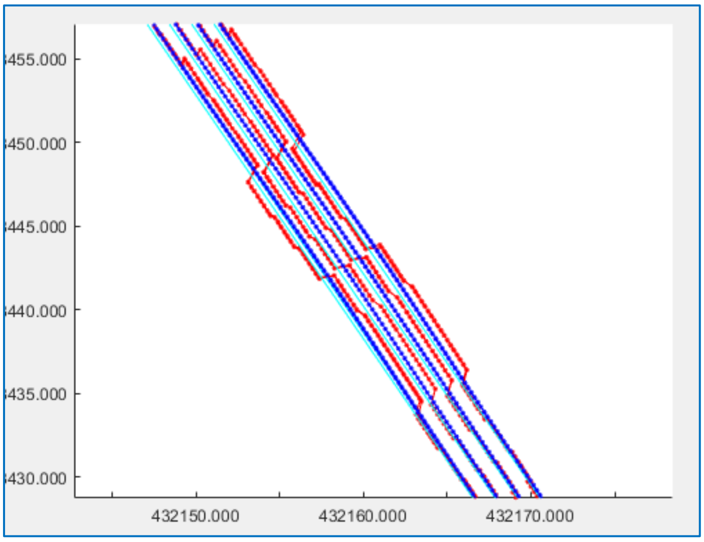

Figure 5.1 Raw coordinates (red) and "processed coordinates approximated to the true values" (blue)

Figure 5.2 shows the difference (distance) between the coordinates of the processed and raw tracks; hereinafter we will refer to these values as ***deviations***. In our case, the deviations are formed mainly by random noise, and the value of deviations on the entire track does not exceed one meter, except for three sections where deviations slightly exceed 1 meter.

In this figure and the figures below, the outliers are not represented by points, but by line segments generated by QINSy interpolation, as described in ***Figure 5.1***.

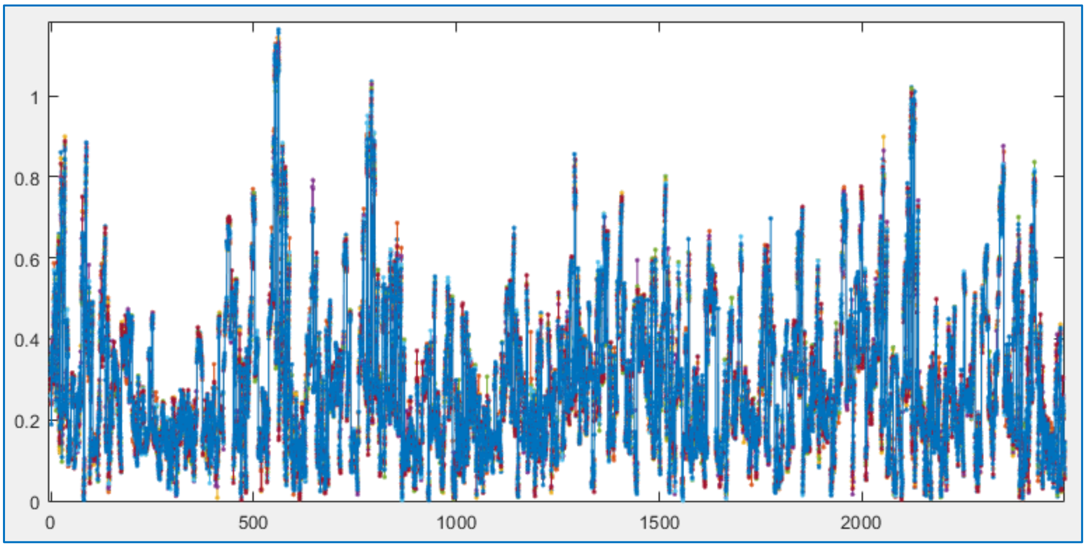

Figure 5.2 Distance between raw and processed coordinates is random noise quality control (plots for 8 magnetometers are shown in different colors)

There are three figures (***Figure 5.3***, ***Figure 5.4***, ***Figure 5.5***) below showing calculations for modeled outliers of 25, 50 and 150 meters. The deviations due to random noise were calculated beforehand (similar to ***Figure 5.2***); this value is given in blue lines for all 8 magnetometers installed on ScanFish. After adding the modeled outliers ("holes"), the track was reprocessed and the deviations were recalculated. The amplitude of the deviations for tracks with modeled outliers is shown as red lines for all 8 magnetometers. The boundaries of modeled outliers are indicated by vertical green lines.

As can be seen from the figures, the 25-meter outlier causes only insignificant track deviations when interpolating (***Figure 5.3***). These deviations do not exceed those caused by random noise. The deviations remain insignificant even at the outlier length of 50 meters (***Figure 5.4***). It is only when the outlier length reaches 150 meters (***Figure 5.5***) that the contribution to the deviations made by interpolation within the outlier begins to significantly exceed the ones caused by random noise

Sequentially, modeled outlier shifting along the entire track gives similar results; only at the outlier length of 80 meters does the deviation due to interpolation begin to exceed the deviation due to random noise. At the same time, nowhere does the deviation value exceed the threshold of 2 meters. Consequently, the real outlier of 15 meters on the track can be interpolated during the track processing (its value is obviously small to cause significant deviations exceeding the acceptable one).

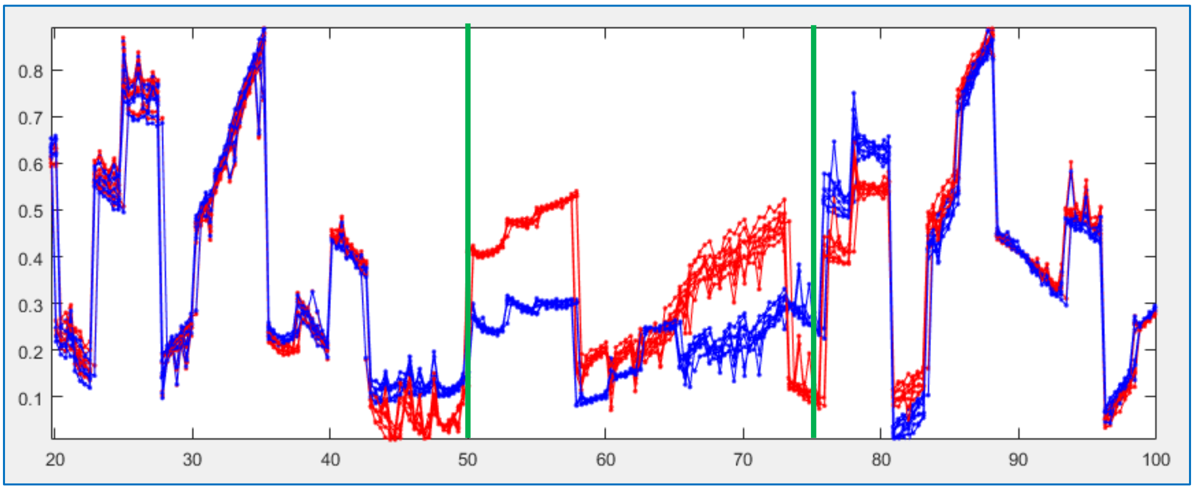

Figure 5.3 Distance between raw and processed data (blue), the same distance with a modeled outlier of 25 m (red)

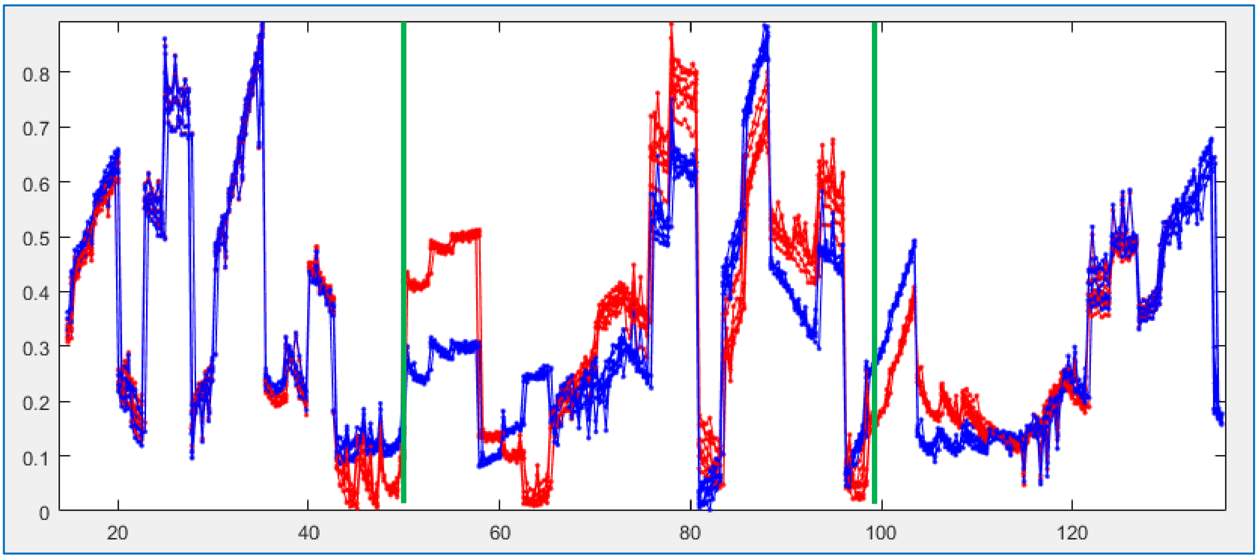

Figure 5.4 Distance between raw and processed data (blue), the same distance with a modeled outlier of 50 m (red)

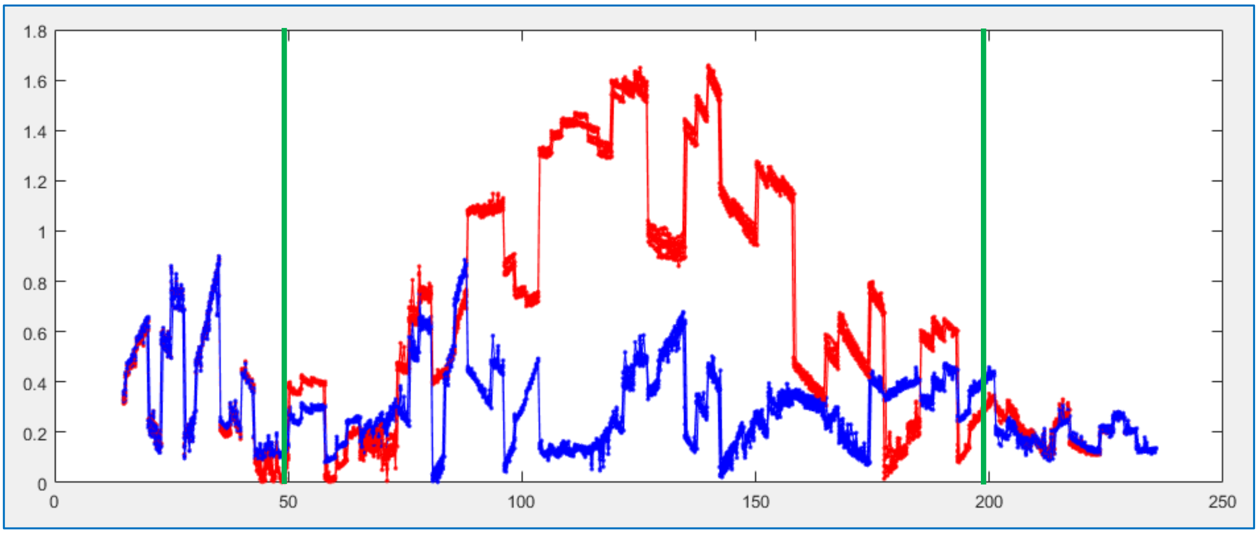

Figure 5.5 Distance between raw and processed data (blue), the same distance with a modeled outlier of 150 m (red)

Qualitatively, the plots in *Figure 5.3*, *Figure 5.4* and *Figure 5.5* can be interpreted as follows:

-- As the towed device passes the survey line, there are long-period offset-oscillations in the towed device track relative to the straight survey line. These offsets will characterize the "survey line pass-mode" (for a passive device, it is an offset from the straight survey line by the current; for a controlled 3D-ScanFish, it is an offset from the straight survey line by the current and the thruster flap-ailerons operation to bring the ScanFish back);

-- By creating a modeled outlier and filling it with interpolation results, we obtain coordinates that differ from the measured ones by the absence of the described "long-period offset-oscillations". Indeed, processing and interpolation methods can make the track visually smooth and uniform, but there will be no artifacts created by local hydrogeology or thruster flap-ailerons operation;

-- By calculating the difference between the "interpolated values" inside the outlier and the "measured values", we determine the outlier length at which the long-period offset-oscillations affect the towed device coordinates "not significantly". That is, the deviation of the measured track coordinates from the interpolated ones does not exceed the acceptable deviation.

For practical calculations, there is no need to go through many different lengths of "modeled outlier". It is enough to do calculations for one length, obviously exceeding the length of real outliers present on the track, to make sure that the "acceptable deviation" is not exceeded for this length. Also, it is not necessary to go through the coordinates of all the magnetometers installed on ScanFish, it is enough to perform calculations for one of them. *Figure 5.6* shows the results of calculations for multiple displacement of the modeled outlier with the length of 50 m, the step along the track is 25 m, the calculations were done for 8 magnetometers. The areas beyond the figure boundaries correspond to outliers up to 6 meters in length.

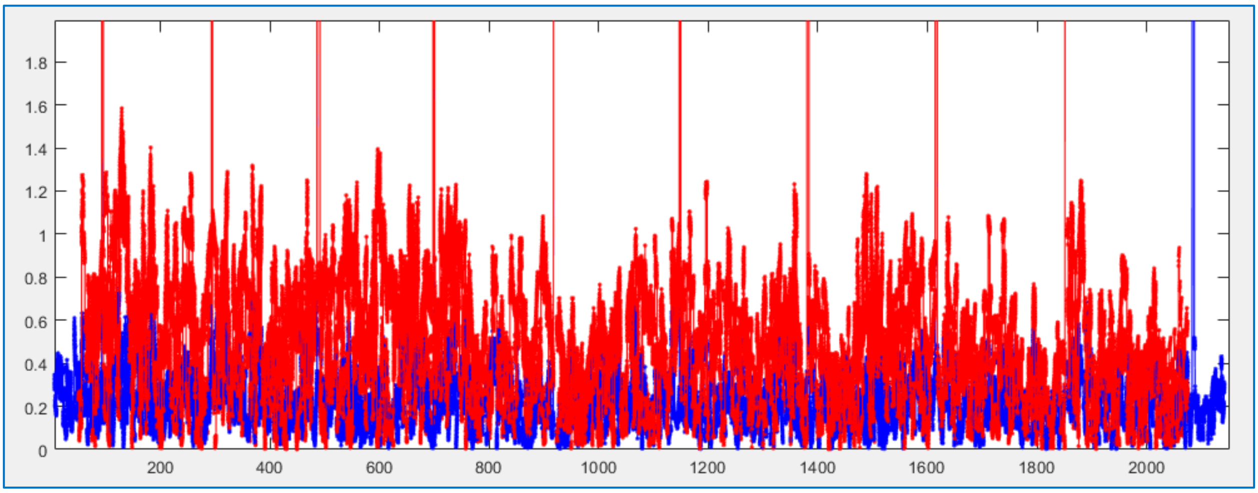

Figure 5.6 Distance between raw and processed coordinates (blue); the same distance with repeatedly applied modeled outlier of 50 m (red)

5.2 Matlab code and calculation algorithm

To check the acceptable outlier length, the following sequence of steps is recommended:

-- To estimate the outlier lengths on the survey profile and select the value of L to be used for estimation and calculation. This value must be greater than the length of the outliers for which we want to check the acceptability;

-- To perform data processing with an applied outlier of length L. To estimate the distance between "raw data without outlier" and "processed data with modeled outlier", by plotting graphs similar to those shown in ***Figure 5.3***, ***Figure 5.4*** and ***Figure 5.5***. The calculated deviation must not exceed the acceptable deviation (survey error) for positioning;

-- To add repeatedly the modeled outlier of length L to the initial data. Probably an acceptable option is to offset the outlier not by one sample along the profile, but by a value multiple of the outlier length (1/2, 1/4, etc.);

-- To conveniently display the processing results in a graphical form, as shown in ***Figure 5.6***. At the same time, while performing calculations for each outlier, ***the distance between raw and processed coordinates*** is drawn only inside the outlier (not for the whole profile). In this case, you can see in which part of the profile the acceptable deviation for a given outlier length is exceeded. The graphical information may probably be supplemented with a count number that corresponds to the first point of the modeled outlier;

-- Points corresponding to real (not modeled) outliers will show a significant deviation. It would be desirable to highlight these areas on the plots with a different color.

Thus, as a result of checking the acceptable outlier length for a survey profile, we will have the following data set:

-- The value of the outlier length L that exceeds the length of the outliers for which we are checking "acceptability";

-- Plots of the distance between raw and processed coordinates, drawn inside the modeled outlier for a set of modeled outlier positions (offset along the profile by a multiple of the modeled outlier value – 1/2, 1/4, etc.). The points corresponding to real outliers are marked with a different color (these points will deviate significantly from the processed coordinates) and are not factored in the calculations. If the distance between the raw and processed coordinates within the modeled outlier exceeds an acceptable value, this will be displayed in plots (such as those shown in ***Figure 5.6***);

-- The graphical information can be supplemented with the written text indicating the number of the first measurement within the modeled outlier for which the distance between raw and processed coordinates exceeded the acceptable deviation, and the distance from the profile origin to the first measurement of the modeled outlier (calculated from the data processed without modeled outliers).

The MatLab code function targeted to perform calculations on the acceptable outlier length is provided in Appendix 1.

Conclusions

The paper addresses the following issues:

1) Types and sources of errors in the coordinates of a towed device positioned by USBL are explained. They are as follows:
   -- systematic errors;
   -- random noise;
   -- spikes (outliers) or gaps;
   -- "extended exposure" and "varying systematic errors", rare error types, have been also discussed.
2) Possible causes of the outliers that led to this particular survey have been analyzed. The outliers are assumed to occur in conjunction with two conditions: the roll-pitch of the ScanFish body (on which the USBL transponder is mounted) and the character of seabed in the area of ScanFish movement.
3) Practical methods for estimating various types of errors are described:
   -- The “counter-courses on adjacent lines” technique used to determine the presence of systematic errors has been examined;
   -- The method of measuring the random noise level by calculating the distance between “raw coordinates” of the towed device and “processed coordinates approximated to the true values” (e.g., coordinates smoothed to remove random noise) is examined. The presence of deviations exceeding the acceptable deviation may serve as an indicator of insufficient positioning accuracy of the towed device;
   -- The method of estimating the acceptable outlier distance in coordinates is also studied. For this purpose, the distance deviation between the processed coordinates of the towed device (coordinates smoothed to remove random noise) and “processed coordinates with modeled outlier” of a certain length is calculated. The calculations are performed many times, with the modeled outlier moving sequentially along the track of the towed device. If the distance-deviation value exceeds the acceptable positioning error, it is an indication that coordinates' interpolation within a given outlier length is cannot be performed. Calculations are performed for different outlier lengths to find the maximum acceptable length (at which interpolation within the outlier can be done) for the given track.
4) For a device with horizontal motion control (3D-ScanFish), the “degree of control impact” can be assessed by estimating the deviation value of the device from the planned track at the beginning and at the end of the outlier. If the deviation exceeds the acceptable value, this impact may be regarded as “significant”.

Appendix 1. MatLab code

```
if strcmp(gKey{1},'GapSize') %
  %{'GapSize',50};MagToolR06;
  try gS=gKey{2};catch,gS=input('Gap size=');end;
  for n=1:SU.MagN,
    a=[0 cumsum(sqrt(diff(M1{n}.Es).^2+diff(M1{n}.Ns).^2))];plot(a,sqrt((M1{n}.E-M1{n}.Es).^2+(M1{n}.N-M1{n}.Ns).^2),'.-b');hold on;
    for nd=gS:round(gS./2):a(end)-gS*2,
      [~,x1]=min(abs(a-nd));[~,x2]=min(abs(a-nd-gS));
      %plot(a(x1-SU.sWin:x2+SU.sWin),sqrt((M1{n}.E(x1-SU.sWin:x2+SU.sWin)-M1{n}.Es(x1-SU.sWin:x2+SU.sWin)).^2+(M1{n}.N(x1-SU.sWin:x2+SU.sWin)-M1{n}.Ns(x1-SU.sWin:x2+SU.sWin)).^2),'.-b');hold on;
      M1m=M1;tmp=M1m{n}.QMask;tmp(x1:x2)=1;
      [M1m{n}.Es,M1m{n}.Ns,M1m{n}.QMask]=gNavDespike2D(M1m{n}.ti,M1m{n}.E,M1m{n}.N,tmp,SU.QBitEN,0,{'poly',2},{'linear','extrap'},{SU.sWin,'loess'},[],'',1,'%.3f',0);
      %plot(a(x1-SU.sWin:x2+SU.sWin),sqrt((M1{n}.E(x1-SU.sWin:x2+SU.sWin)-M1m{n}.Es(x1-SU.sWin:x2+SU.sWin)).^2+(M1{n}.N(x1-SU.sWin:x2+SU.sWin)-M1m{n}.Ns(x1-SU.sWin:x2+SU.sWin)).^2),'.-r');hold on;
      plot(a(x1:x2),sqrt((M1{n}.E(x1:x2)-M1m{n}.Es(x1:x2)).^2+(M1{n}.N(x1:x2)-M1m{n}.Ns(x1:x2)).^2),'.-r');hold on;
    end;
  end;
  hold off;
end;
```