Estimation of River Width with Fully-Focused SAR Altimetry Data

by

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Student number:	4812034	
Project duration:	May 6, 2019 – August 1, 2019	
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1 Introduction

Rivers are very important surface water, they supply drinking water for people, offer irrigation water for farms and sustain freshwater organisms. However, they can also cause damages, like flooding in high precipitation and serious environmental damage areas, drought in high temperature areas. [5] The variation of surface water storage accompanied by width changes can be monitored by morphologic characters, including river extend and river width. [7]

Traditional way to measure river width is doing fieldwork which is labor- and time-consuming. With the development of remote sensing technology in recent years, hydraulic variables can be measured easily, however, new problems arise in resolution and the path of signal propagation. For example, visible band sensors, such as MODIS and Landsat, the short repeat intervals give modest spatial resolution, if the rivers are narrower than it, they can't be detected by the satellites. And the problems with cloud cover which would stop the signal to reach water surface can't be ignored. Moreover, optical sensors encountered with challenges when the water surface is below vegetation canopies, especially for areas where there are forests like Amazon, the signal reflected by water on the leaves would be mistaken for rivers and then contaminate the results. For SAR-based estimation, accuracy is further limited by the roughness over water surface caused by wind. [1]

The objects of study are rivers which are relatively narrow when compared with lakes and oceans. Because higher spatial resolution is more important for small targets, in the trade-of between temporal resolution and spatial resolution, we decide to sacrifice temporal resolution and use CryoSat-2 data. CryoSat-2 was launched in April 2010 with Synthetic Aperture Radar (SAR) altimetry on broad, runs in polar orbit with 92 degree's inclination and 717 km altitude. The 369 days' repeat cycle with a 30 days' sub-cycle permit geographically complete observations of land, as a cost of it, the ground track patterns are dense with 7.5 km inter-track distance at equator and along-track resolution is about 300 meters. [2]

Fully-focused SAR (FF-SAR) processing can further improve the along-track resolution to the theoretical limit which is equal to half of the antenna length when compared with SAR imaging system. [4] The CryoSat-2 mission is operated in a closed burst mode with 64 echoes each burst, this narrows the footprint in along-track direction to about 300 meters. When apply FF-SAR technique directly to SAR altimetry on CryoSat-2, the along-track resolution is improved to 0.56 meter in our case. This high along-track resolution allows to measure small scale features which are not parallel to the track. FF-SAR technique also improves the effective number of looks, which can result in a better geophysical parameter estimation. [4]

This is the first time when altimetry is used for estimating river width, normally it is only used for measuring water height. We interested in how accuracy can we determine river width using satellite radar altimetry. The main approach is using FF-SAR altimetry data and computing river width based on the power of waveform. We develop the method over the Netherland to see the performance, and then apply it to a more complicated area, Vietnam. Based on the results, give suggestions for future study.

2
Methodology

Because of special characteristics of FF-SAR altimetry, we choose the Netherlands as the start area and select waterbodies over it to develop the method. The main idea of the method is computing river width based on the differences of waveform power over land and water, and the computed widths are filtered based on 3- σ criterion to get better accuracy.

2.1. Data description

The Synthetic aperture radar Interferometric Radar Altimeter (SIRAL) carried by CryoSat-2 allows to operate in three different modes: Low Resolution Mode (LRM), Synthetic Aperture Radar mode (SAR) and SAR Interferometric mode (SARIn). LRM uses conventional pulse-limited radar altimeter on the left side of figure 2.1, while the processing in SAR and SARIn modes is the delay/Doppler on the right side of figure 2.1. For both techniques, the illuminated area has two independent components, along-track and cross-track. Footprint of FF-SAR is a narrow strip on the surface, with pulse limited cross-track and SAR focused along-track. [4] The component we use is along-track, so the along-track positions of points over earth surface can be estimated relatively to the altimeter position with delay/Doppler beam. [5] Moreover, the along-track resolution is improved to 0.56 meter which allows to measure narrow rivers, while the temporal resolution doesn't change.

The dataset of one track can be 3D visualized with positions along track, waveform bins and power in top image of figure 2.2. The waveform is measured for each along track position, so distance between adjacent waveforms is equal to along-track resolution 0.56 m. And for each waveform, it contains 256 bins with 23.4 cm bin width. Turn around the image to position-power plane as shown in bottom image of figure 2.2, the position can be blocked into three parts based on the power: part 1 (position 0-3000), part 2 (position 3001-5500) and part 3 (position 5500-end). Each part, the signal replicates a couple of times along-track with the maximum power position as the axis of symmetry and the magnitude of power decrease with the increase of distance from the maximum value. This is caused by the pulsing into bursts of CryoSat-2 which is known as alias effect and occurs every 170 waveforms, so only the highest middle one is the real signal.

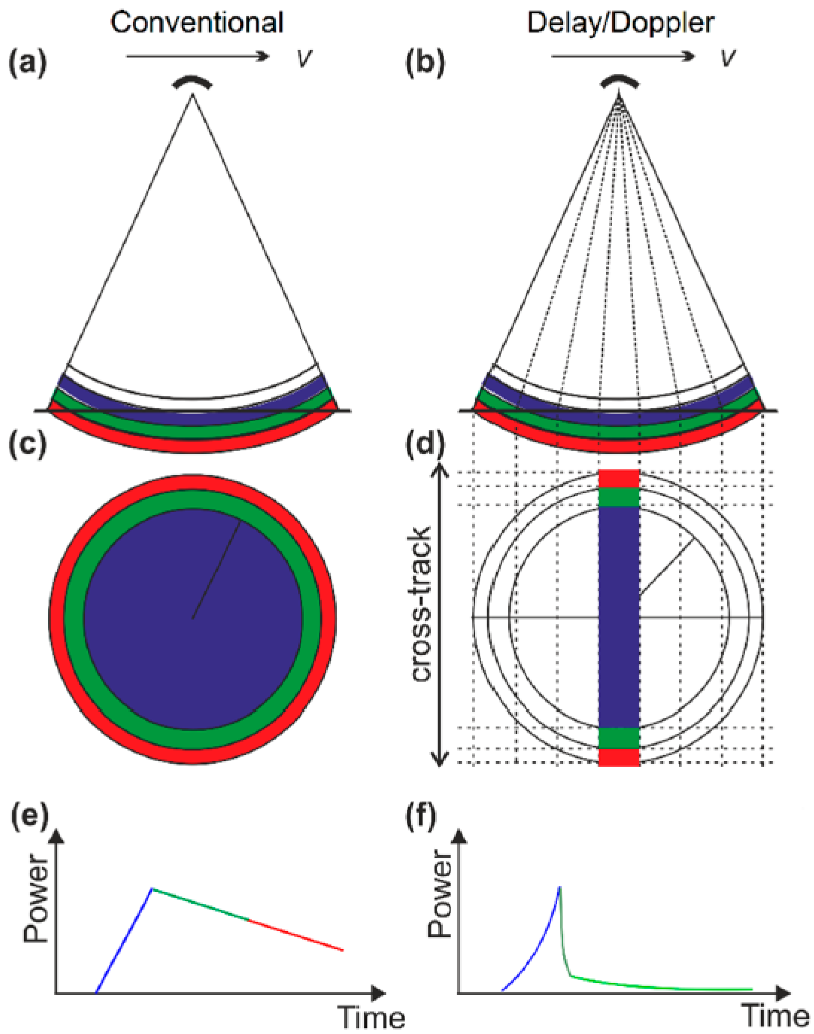
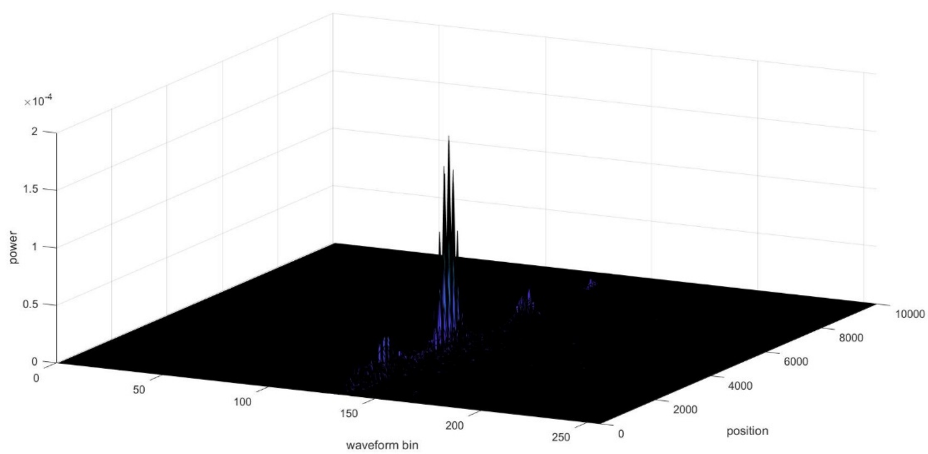


Figure 2.1: Comparison of a conventional pulse-limited radar altimeter (left) and a SAR altimeter (right): **(a,b)** footprint side view; **(c,d)** footprint plan view; **(e,f)** wavefrom [6]



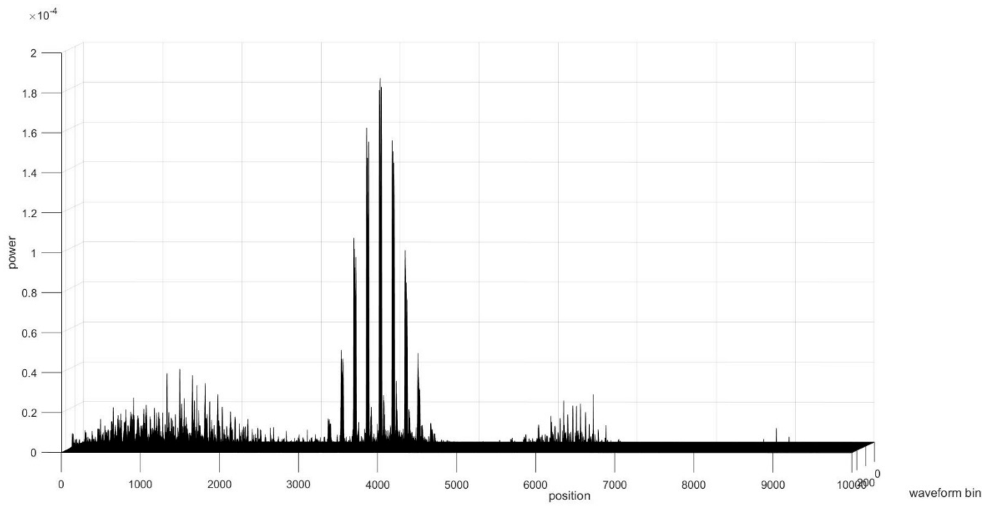


Figure 2.2: Top: 3D visualization of dataset of one track; Bottom: alias effect, there are three clear parts (part 1: position 0-3000, part 2: position 3001-5500 and part 3: position 5500-end), for each part only the highest middle signal is the real signal, others are alias

The power of waveform from water is at least five times larger than that from land, so these two features can be distinguished from each other. To show the power differences more obvious, we choose two waveforms. One is from land, another is from water, and the magnitude of power from land is two orders of magnitude smaller than that from water. The image on the left of figure [2.3] is waveform over land with 10-6 power magnitude. There is extreme value of power, but it doesn't represent waterbody, because on both sides of it there are clearly other peaks which are not much smaller than maximum power. The image on the right of figure 2.3 is waveform over waterbody with 10-4 power magnitude, the extreme power is obvious. In the middle of figure 2.3, we put both waveforms together, water waveform power is extremely large, while the land waveform can only be seen at the bottom of the image.

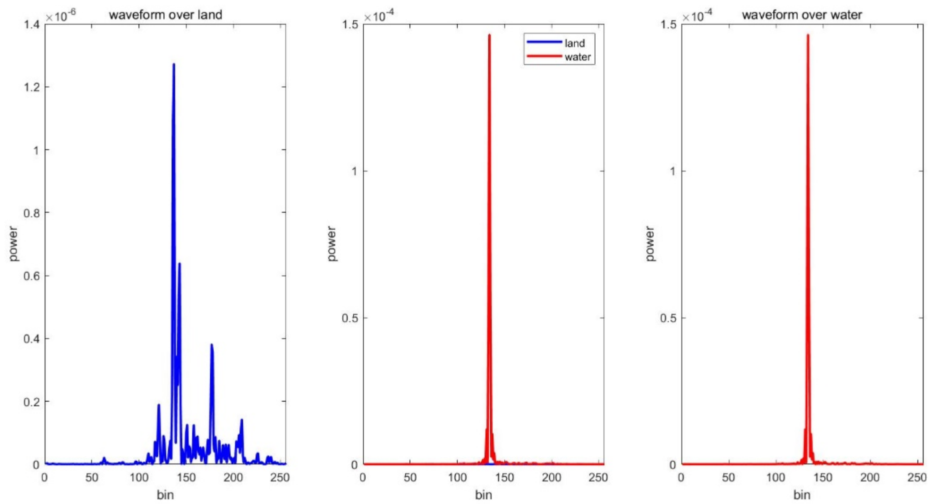


Figure 2.3: Waveforms over land and water. Left: waveform over land; Middle: comparison between over land and over water waveforms; Right: waveform over water

Because of the great power differences, the sum up power of 256 bins for each waveform would still discriminate waterbody and land. Based on that we can identify whether a reflection point along track is located at waterbody or not. And then the width can be determined by the distance between the continuous first and last waterbody reflection points.

2.2. Research area

To start with an easy case, we choose the area around the city of Zwolle in the Northeast of the Netherlands, shown in figure 2.4, as research area to develop the method. Based on the characteristics of FF-SAR altimetry, the advantages of this area are clear. On the one hand, there are lots of canals, which show similar morphologic characteristics as rivers, so rivers and canals are interchangeably in this report. They would give enough number of results for statistic computation. Even if just one canal in some places, the length of the canal is long enough to give enough amount of observations. On the other hand, the potential outliers caused by alias effect are much less, because the width of each canal over this area is much smaller than the width which the results begin to be contaminated by aliasing. The critical value is about 95.2 m, it is given by the products of the number of waveforms which we begin to see alias effect and the along-track resolution.

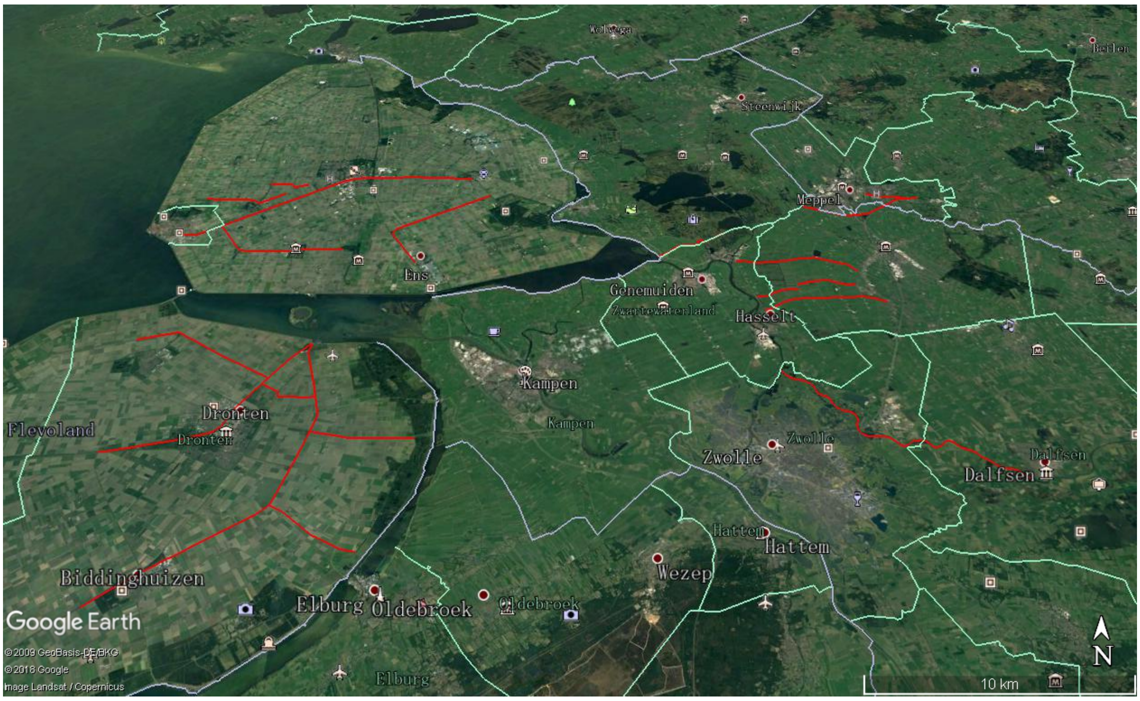


Figure 2.4: Research area in the Netherlands and selected canals (red lines)

Google earth offers coordinates of points, 19 canals are picked up by using this tool and their relative positions are depicted by red lines in figure 2.4. These canals are selected based on three basic criterions. Firstly, the direction of canals should be roughly east-west. Because the satellite travels with 92 degree's inclination, east-west direction target can be seen clearly by the altimeter and the width would be evaluated with high accuracy. Secondly, to avoid the alias effect, the widths of canals should be as narrow as possible, but not narrower than along-track resolution, or it can't be detected by altimeter. Thirdly, the distance between canals should be at least 300 m, because their signals would contaminate each other. For example, if two canals are very close, the altimeter would take them as one. Besides, enough number of points over each canal is crucial, because in the following processes, some points would be filtered out for variety of reasons and we want to get as many width results for each canal as possible to do statistic computation. Generally, for each canal we pick more than 50 points with roughly same distance interval. In the case of short canals where we can't pick that much points, the number is at least 15.

2.3. River width

In order to compute the river width, the signal for each google earth derived point should be found first. For each canal, we find the corresponding signal for each point in three steps. Firstly, find the corresponding track for each river point based on the perpendicular distance, the closest track is the corresponding one.

Secondly, each track may pass more than one waterbody, find all the segments of a track which represent waterbody based on the power of waveform mention in section 2.1. Each segment contains a set of successive waveforms with high power value. Thirdly, find the corresponding segment for each point by filtering out the segments which are 100 m away from it. In this step, the distance is on the earth's surface, the altitudes are not considered. The result after these processes is each point finds its corresponding set of waveforms.

The distance between two adjacent tracks is much larger than the distance between two successive canal points, so the corresponding track segment for different river points can be the same and this would contaminate statistic results. We solve this by keeping the point which is closest to the segment and filtering out other points which share the same segments. Then the correspondence between points and segments is one to one.

With the distance between two successive waveforms is 0.56 meter, the width w can be calculated:

$$w = 0.56 \times (N - 1) \tag{2.1}$$

Where N is the number of waveforms in each segment for each canal point, N-1 is the number of intervals. Because we record the number of waveforms from one, when there are two waveforms, there is just one interval.

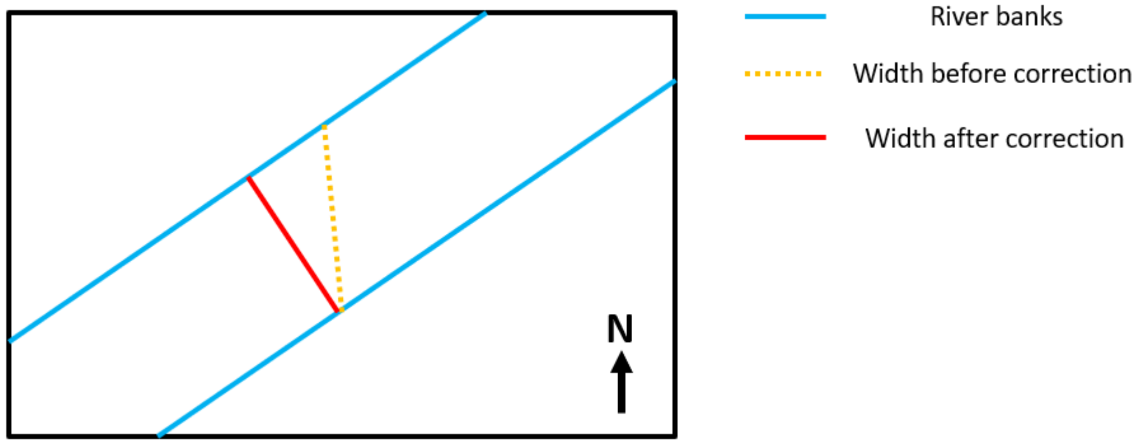


Figure 2.5: Angle correction. River width before (yellow dots) and after (red line) angle correction. River width before angle correction is along the track.

Although we choose the canals carefully, not all of them are perfectly perpendicular to the track, angle correction is needed. We compute the azimuth differences between track and canal segment, then apply trigonometric function (sin) to do the correction. The direction of river is defined from west to east, while the pass directions of track include descending and ascending, we convert all descending tracks direction to ascending, travel from south to north, by getting the supplementary angle of their azimuth. Then the azimuth difference is defined as rivers' azimuth minus ascending tracks' azimuth and its value is smaller than 180 degree. Finally, we can get the estimated width which is perpendicular to river banks like red line in figure 2.5.

2.4. Data Filtering

Data filtering is indispensable for high accuracy results. Before that, two datasets should be prepared. One is the differences between computed width and truth width measured from google earth. It is defined as computed width minus truth width. Another is the absolute value of azimuth differences in section 2.3 minus 90 degree, for simplicity we call it angle.

The outliers in the estimated widths are caused by variety of reasons and they can't be avoided completely. For example, environmental effects including large waterbodies which can be found in interpretation column in Appendix A and B and figures about them are shown in section 3, would result in obvious outliers. In order to get rid of them, the filtering approach based on 3- σ criterion is used, which can filter out majority of the outliers and gives results with higher accuracy.

The progresses include three steps. Firstly, fit a linear trend of width differences as a function of angle. Secondly, compute the standard deviation of the differences between width differences and fitted lines. The value we got in this step is σ. Thirdly, set interval $[-3\sigma, 3\sigma]$, points outside of this interval are filtered out. Then we repeat the whole procedure until there is no point outside of the interval.

3

Results and discussion

Area in the Netherlands is selected for developing the method and inspecting its performance. Then, we apply this method to area in Vietnam, where canals' characteristics are similar to that in the Netherlands, but they situate in a more complicated environmental condition. The results from different areas are discussed in details to find out the factors which contaminate the results.

3.1. The Netherlands

Area around the city of Zwolle in the Northeast of the Netherlands is chosen. The coordinates of points over 19 canals are obtained from Google earth and stored as text file for each canal respectively. We got 144 tracks' FF-SAR altimetry data and all the tracks pass this area. Because of the low temporal resolution, the period of the data is from the year 2010 to 2018.

The widths are computed based on theory in section 2.3 and the computed results are listed in Appendix A computed width column. Before filtering, we plot a histogram for width differences on the right of figure 3.1, it contains 41 bins with 5 m bin size. From horizontal axis, the range of width differences is almost from -100 m to 100m. This indicates for both cases, computer width is larger than truth width and converse, the outliers exist. For further inspect these outliers, we take the angle into consideration and plot scatter diagram with width differences and angle on the left of figure 3.1. Majority of the points with smaller than 10 degree angles concentrate around zero width differences, but the overall distribution of points is loose, typical large width differences about 80 m are reached when the angle is 0.7, 7.3 and 66.8 degree respectively. With information recorded in Appendix A when take points from Google Earth, these deviations can be explained. The first point even with almost perpendicular position relation between river and track, the large difference is large which is caused large waterbody, lake. The second large width difference measured with moderate angle is caused by wider unparallel bank lines. Because the bank lines on both side of a measure point are generally parallel to each other, unparallel bank lines would result in errors mainly in angle correction step. The last point with big angle is recorded with waterway cross, both factors can contribute error in width. We will inspect the effect for each later.

To do the outlier removal, we first apply linear fit to original data, the fitted result is represented by a red line on the right of figure 3.1. At the start of the line, it is supposed to be almost parallel to the zero width differences line because of the good points concentration. But the large width differences caused by lake pulls the line slightly up and the intercept with vertical axis, 4.9826 m, is slightly more than zero. With the increase of angle, the points are more dispersive and the effect of negative width differences are dominant because of their large magnitude, so the line is pulled down by these values and the slope decreases to -0.6909 m/degree. This also indicates with the increase of angle, the computed width become smaller and smaller than truth width.

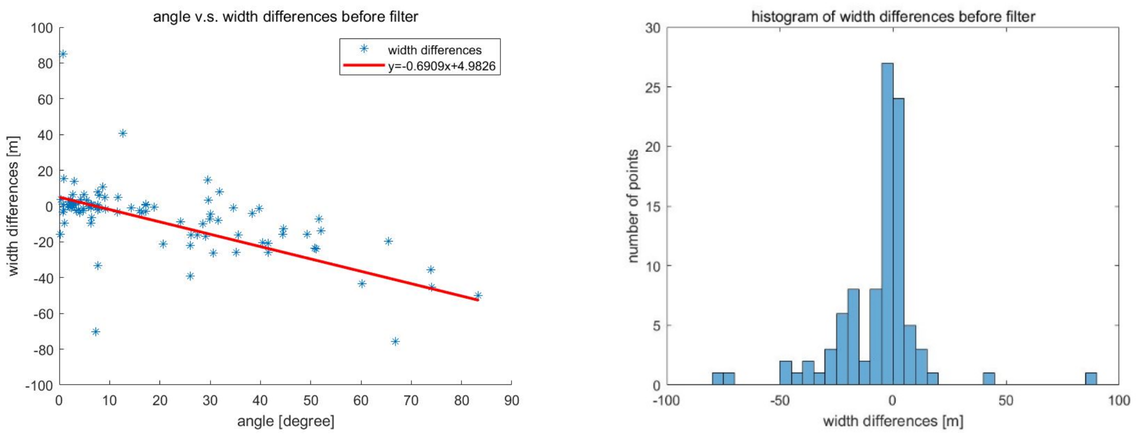


Figure 3.1: Before 3- σ filtering. Left: scatter diagram of width differences and angle, red line is linear fitted: $y = -0.6909x + 4.9826$; Right: histogram of width differences with 41 bins and 5 m bin size.

3- σ criterion is applied to do data filtering following the process in section 2.4. after filtering, we plot the histogram again on the right of figure 3.2. The number of bins is still 41 and the bin size is 5 m. Compared with right of figure 3.1, the range is narrowed to around -20 m to 20 m, because a large number of outliers are filtered out. The performance of filtering is clearer shown in scatter diagram of width differences and angle on the left of figure 3.2. Not only the range of width differences is smaller, the upper boundary of angle is reduced to about 55 degree. Although the filtering is done, we still fitted a line for the survived points to better describe the results. Without the pull of large width difference points, the line is flatter with -0.2471 m/degree slope. And the advantage of smaller than 10 degree angles' concentration around zero width difference is shown by the smaller intercept with vertical axis, 1.7626 m.

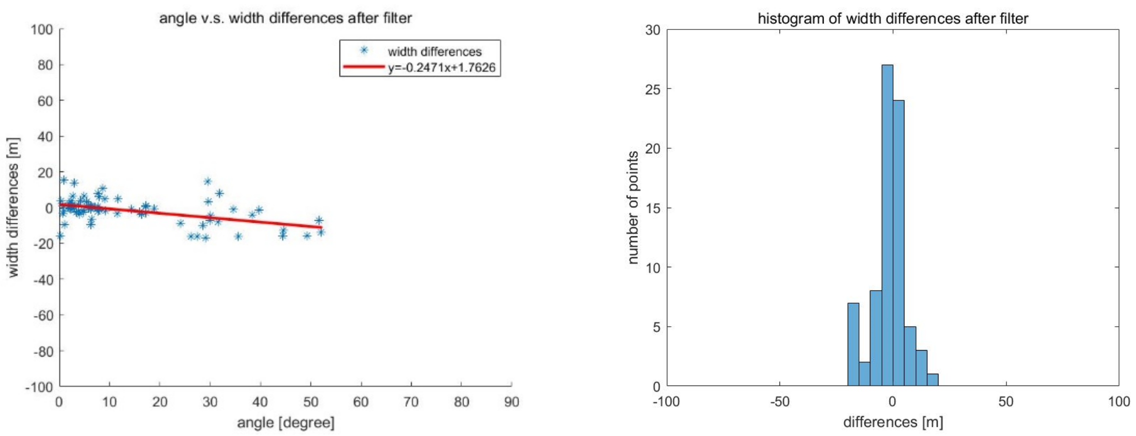


Figure 3.2: After 3- σ filtering. Left: scatter diagram of width differences and angle, red line is linear fitted: $y = -0.2471x + 1.7626$; Right: histogram of width differences with 41 bins and 5 m bin size.

Statistics are computed to inspect the performance of this method over this area. Three statistics are used: mean of width differences, standard deviation of width difference and accuracy. The accuracy here is defined as $\left(1 - \frac{\text{meanof standard deviation}}{\text{meanof truth width}}\right) \times 100\%$ The statistic values together with other parameters are listed in figure 3.3. Still 18 canals survived after filtering, from the number of survived points for each canal, only canal 1 and 2 has more than 10 points left. The dataset for each canal is too small to compute statistics, so we compute them over all survived points. Mean of width differences reflects the computed width is 1.63 m smaller than truth width, it also indicates that the factors like wider unparallel bank lines contribute more to the error than other factors which would result in a larger computed width. The standard deviation, 7.06 m, is too large and the distribution of width differences is too dispersive for rivers narrower than 15 m. Although the accuracy, 69.36%, seems nice, we can't ignore the problem reflected by the standard deviation, the dataset is divided into two groups. These two groups represent canals' truth width narrower 15 m and canals' width wider than

15 m, respectively.

canal ID	mean of computed width [m]	mean of truth width [m]	number of points for each canal
1	37.97	36.93	11
2	21.12	21.03	12
3	29.47	26.67	3
4	21.74	21.58	4
6	38.78	39.71	2
7	37.73	41.36	3
8	15.11	28.02	4
9	26.52	23.34	6
11	9.06	8.24	5
12	10.91	27.16	2
13	21.74	21.60	6
14	9.92	20.09	3
15	11.45	13.68	5
16	5.59	4.89	1
17	6.10	6.72	1
18	10.33	7.73	2
19	14.74	29.56	2
20	9.12	10.78	5
mean of width differences: -1.63 m			
standard deviation of width differences: 7.06 m			
accuracy: 69.36%			

Figure 3.3: Statistics of the Netherlands area

Statistics and characteristics of narrow canal group are listed in figure 3.4. Mean of width differences is only -0.01 m, the negative and positive width differences are balanced. The standard deviation, 3.01 m, is smaller than the narrowest canal, so this value is more acceptable than value in figure 3.3. The accuracy is slightly lower than the whole dataset estimation, because small dataset gives a better chance for errors to exist.

canal ID	mean of computed width [m]	mean of truth width [m]	number of points for each canal
11	9.063058043	8.244	5
15	11.44794017	13.684	5
16	5.592575325	4.89	1
17	6.104228427	6.72	1
18	10.33218018	7.73	2
20	7.590275584	7.165	4
mean of width differences: -0.01m (computed width is smaller)			
std of width differences: 3.01 m			
accuracy: 67.29%			

Figure 3.4: Statistics of group of width smaller than 15 meters

Statistics and characteristics of wide canal group are listed in figure 3.5. Mean of width differences is largest among three datasets. Based on that we can conclude in our case the factors contribute for smaller computed width occur more often in wide group. Evidence can be found from Appendix A, the wider canals are more likely to encounter with waterway crosses. Standard deviation in this group is also largest, but compared with the truth width of each canal, it is about half of the narrowest canal width. That said, the standard deviation is more acceptable than that in narrow group. Moreover, with larger dataset than narrower group, the accuracy is also higher.

canal ID	mean of computed width [m]	mean of truth width [m]	number of points for each canal
1	35.69	36.44	12
2	21.12	21.03	12
3	29.47	26.67	3
4	21.74	21.58	4
6	34.06	41.80	3
7	35.70	47.94	6
8	15.11	28.02	4
9	26.52	23.34	6
12	10.91	27.16	2
13	21.74	21.60	6
14	9.92	20.09	3
19	14.74	29.56	2
mean of width differences: -3.49 m (computed width is smaller)			
std of width differences: 9.12 m			
accuracy: 68.51%			

Figure 3.5: Statistics of group of width larger than 15 meters

3.2. Vietnam

Move to a more complicated case, we apply this method to South Vietnam shown in figure 3.6, where the distances between canals are smaller and intersections among canals are more. We only choose ten canals over this area, because except canal 5, we pick up 22 points, other canals are long enough and more than 50 points can be picked up for each. These canals are depicted by red lines in figure 3.6. We got 40 tracks' FF-SAR altimetry data and the time period is from year 2011 to 2013.

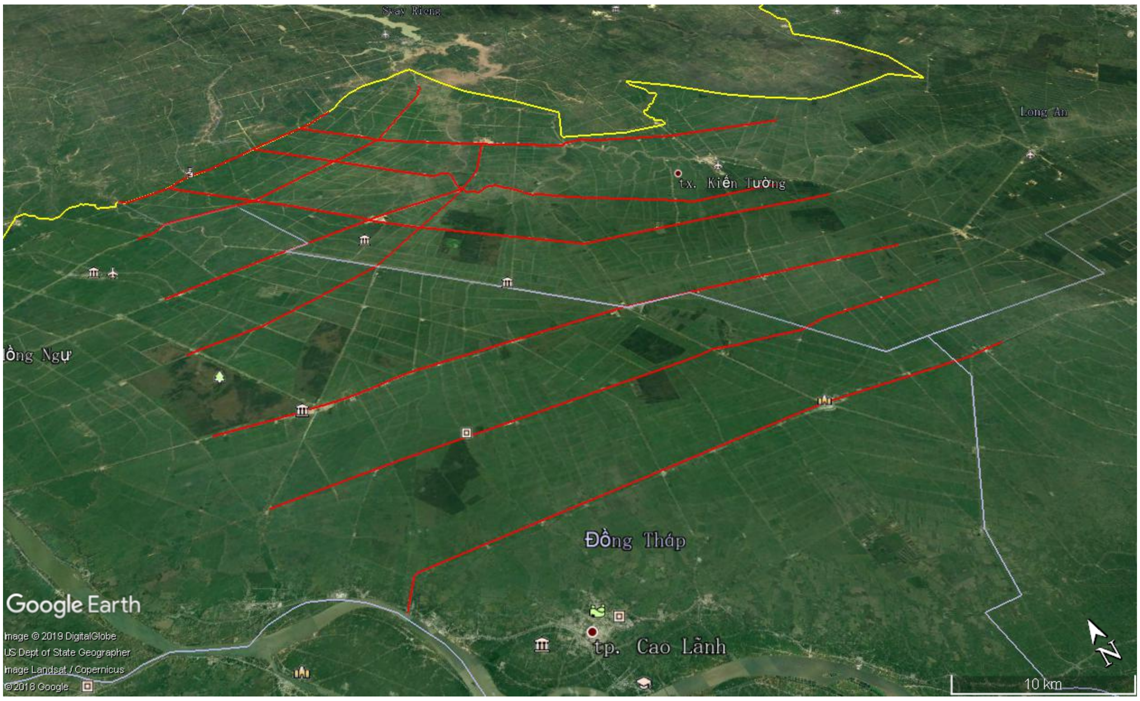


Figure 3.6: Research area in South Vietnam and selected canals (red lines)

The widths are computed based on theory in section 2.3 and the computed results are listed in Appendix B computed width column. Before filtering, we plot a histogram for width differences on the right of figure 3.7, it contains 81 bins with 5 m bin size. The number of bins is about twice larger than that in the Netherlands, because the limit of horizontal axis is from -200 m to 200m and the width differences distributed between -50 m and 170 m. Majority of the width differences concentrate between -50 m and 50 m, the rest of them are distributed between 70 m and 170 m. This indicates the factors denote larger computed width happens more often in this area. Including the angles, we plot scatter diagram on the left of figure 3.7. From the horizontal axis, the upper limit of angles is about 40 degree which is even smaller than filtered dataset in the Netherlands and it illustrates the direction condition of canals is much better in this area. Majority of the points are distributed around the zero width differences, and all the larger outliers represent positive width differences. Together with small data size, they result in large magnitude of slope, -0.7350 m/degree, and large intercept with vertical axis, 39.5371 m. With information recorded in Appendix B, these large outliers are mainly caused by large waterbody, flood complex waterway network.

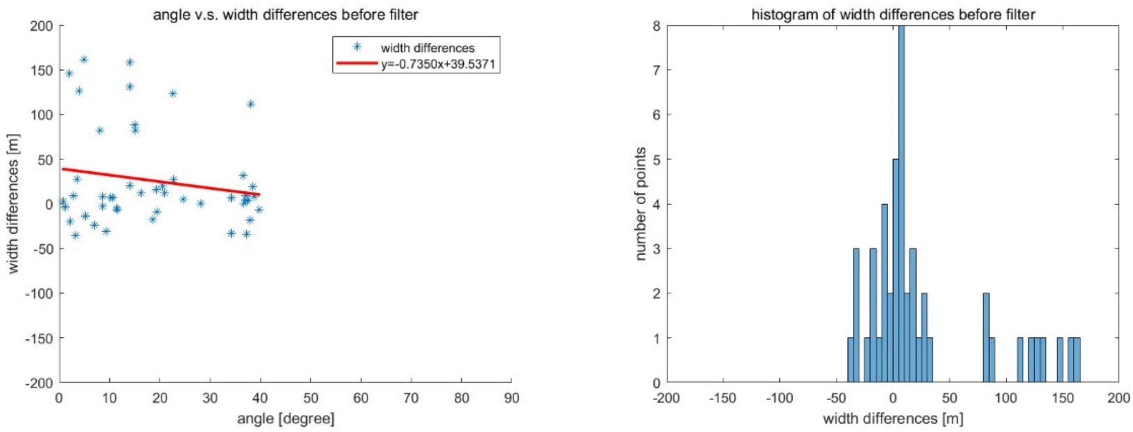


Figure 3.7: After 3- σ filtering. Left: scatter diagram of width differences and angle, red line is linear fitted: $y = -0.2471x + 1.7626$; Right: histogram of width differences with 41 bins and 5 m bin size.

After filtering based on 3- σ criterion in section 2.4, the histogram of width differences is plotted again on the right of figure 3.8. The number of bins remains 81 with 5 m bin size. Compared with right of figure 3.7, the outliers which is larger than 50 m are all filtered out. Scatter diagram of filtered dataset is plotted with fitted line on the left of figure 3.8, the upper limit of angle remains unchanged, but the fitted line is much flatter than that in figure 3.7 because the removal of outliers. The magnitude of slope is strongly decrease and now positive with small magnitude, 0.1482 m/degree. The intercept with width differences axis is negative, -3.0956 m, because more negative width differences when the angle is close to zero.

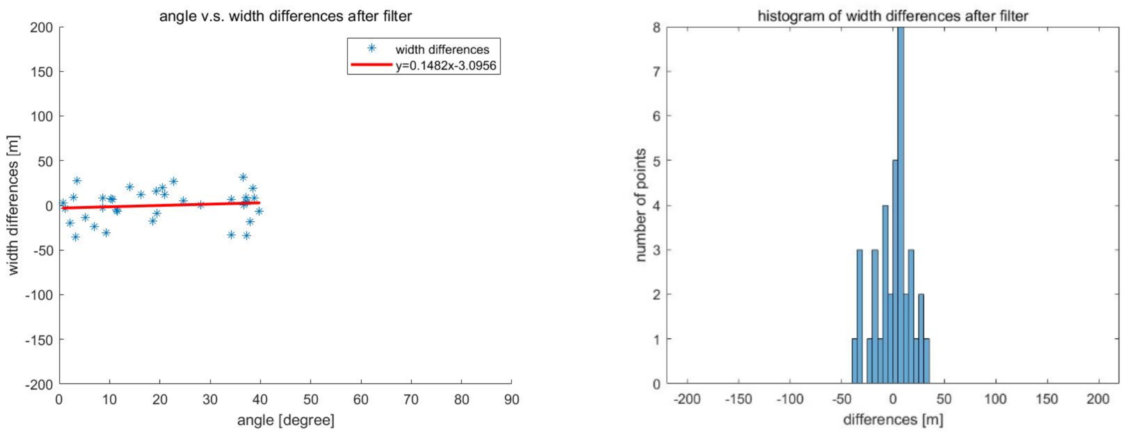


Figure 3.8: After 3- σ filtering. Left: scatter diagram of width differences and angle, red line is linear fitted: $y = 0.1482x - 3.0956$; Right: histogram of width differences with 81 bins and 5 m bin size.

Same statistics are computed for this area and listed in figure 3.9 with other parameters. Eight canals survive from filtering, but the survived points for each canal is less than 10. The dataset for each canal is too small to compute statistics, so we compute them over all survived points. From mean of width differences, the computed width is 0.1 m smaller than truth width, this value is ten times smaller than that in the Netherlands. The standard deviation, 17.56 m, illustrate very large width differences variation, especially for canals narrower than 35 m because the standard deviation exceeds half of the width. The estimation accuracy in this case is much smaller than that in the Netherlands, it is only 50.40%. Based on the main differences between the Netherlands and Vietnam, the complex environmental condition and small dataset do have effect on the results.

canal ID	mean of computed width [m]	mean of truth width [m]	number of points for each canal
1	55.37	55.00	2
2	31.00	31.18	8
3	32.99	51.56	2
4	28.65	42.46	4
6	37.20	39.94	3
8	32.49	37.08	2
9	32.85	26.62	9
10	42.00	34.79	7
mean of total differences: -0.10 m (computed width is smaller)			
std of total differences: 17.56 m			
accuracy: 50.40%			

Figure 3.9: Statistics of Vietnam area

3.3. Results comparison

There are two main differences between the Netherlands and Vietnam. Firstly, the size of data is larger in the Netherlands. Secondly, the environmental condition is more complicated in Vietnam, details information of it can be found in Appendix B. As we already mention the first difference above, only effects of environment are discussed in this section. The number of larger than 100 m outliers is larger in Vietnam, from Appendix B marked with red color, some of them are caused by flood and lakes, others are effect by crosses and nearby canals. Luckily, they are all filtered out and don't contaminant the statistics. Inspecting the interpretation for survived points, the two main different special conditions survive in Vietnam are flood and crosses.

For flood condition, because the selected area in Vietnam is included in the Vietnamese Mekong Delta, which suffer from annual (fluvial) flood.[9] Especially from June 2011, long periods of heavy rainfall along the Mekong river cause the worst flooding in 50 years in South Vietnam, which is exactly the time period of our data. Another evidence can be found by comparing Appendix A and B, there are more points shifted to the ground near the canals in Vietnam, inspect these points in Google Earth's 2019 image when there is no flood, most of them cause much larger width than truth width. And these shift to ground points takes part 51.35% of the survived points.

There are three points locate at crosses are survived from filtering in Vietnam. From Appendix C, where the target canals are depicted by red lines while two yellow points represent the computed width, it is clear that the crosses cause the points deviate from where they should be. The deviation largely based on the target canal position. From the first two images in Appendix C, the two canals which form the cross are not perpendicular to each other, the width points deviate to the ground and usually give a smaller computed width. From the last image where the target canal perpendicular to another, the points remain in the canal but give a wider width.

4 Conclusions

Above all, the method works best for canal which satisfies two conditions. One is the angle deviation from 90 degree is less than 10. Another is the width of canal is smaller than15 meters. When the deviation angle increases, the width differences would become larger and larger. When the width of canal increases to 95.2 m, the alias effect would take a role and result in larger computed width.

There are three noticeable factors which contribute noise to results. Firstly, large waterbody like lakes connect or near the canals make the computed differences much larger. Secondly, crosses have different effect on the river width which is depended on the relative location of two canals. In general, perpendicular canals would give larger computed width and verse vice. Finally, the truth width of flooded area should be measured as the same time when we compute width, in order to get more accurate width differences. If we don't and measure the truth width during no flood period, the value would be much smaller than it should be.

Improvement can be made from three different parts when works with CryoSat-2 data. Firstly, get a larger area with more waterways and use more tracks in order to get more observation points. The more the observations, the more reliable of the statistic results. Secondly, eliminate the nearby waterways' effect, because they may make the computed width extremely large and deducing their influence is essential. Lastly, expand this method to measure larger than 95.2 m rivers, eliminate the alias effect for it.

For future expectation, the Sentinel-3 and Sentinal-6 with much shorter repeat cycle, 27 days and 10 days respectively, allows to monitor the temporal dynamics of waterbody. Sentinel-3 SRAL, which inherits SAR altimetry technologies from CyoSat and Jason altimeter missions, can also provide high spatial resolution (300 m along-track) and a global coverage with inclination 98.65 degree. [3] Another advantage of Sentinel-3 over CryoSat-2 is it always passes the same point every time so we don't need to do interpolation. In this way, we get rid of interpolation error. Sentinel-6 will be launched in 2020 with 66 degree's inclination. [8] Although it doesn't have a larger global coverage, it can completely avoid alias effect because it won't work in burst mode.

A
appendix

Information table for canals in the Netherlands

Canal ID	Truth width [m]	Computed Width [m]	Width differences [m] (C-T)	Angle Differences [°]	Angle Dif with 90 [°]	Latitude [°N]	Longitude [°E]	Latitude [°N]	Longitude[°E]	Interpretation
1	64.44	78.29828508	13.85828508	87.0811022	2.9188978	52.6578129	5.630006211	52.65710291	5.629889025	a house over the canal
1	48.88	23.05278525	-25.82721475	48.45776325	41.54223675	52.6595672	5.640145085	52.65928866	5.640099001	
1	49.68	45.04658265	-4.633417355	120.1230329	30.12303288	52.6620032	5.646771815	52.66247263	5.646694565	
1	46.42	49.6085669	3.188566899	119.7155149	29.71551486	52.6631724	5.649392412	52.66368821	5.649307588	
1	31.15	10.6466815	-20.5033185	49.5062893	40.4937107	52.6839136	5.697571418	52.68378845	5.697550748	
1	32.99	47.73867228	14.74867228	119.5560264	29.55602639	52.6861269	5.703478008	52.68661461	5.70339757	
1	28.97	12.22791806	-16.74208194	119.1411491	29.14114905	52.6932023	5.719785064	52.69332697	5.719764544	
1	28.88	26.2293703	-2.650629697	85.24385977	4.756140227	52.7076918	5.771915458	52.70792711	5.77187659	trees' shadow, truth width is not accurate
1	29.51	29.97346145	0.463461453	82.38716776	7.612832245	52.7079973	5.776029919	52.70772401	5.775984757	
1	29.93	37.73894288	7.808942881	82.32590106	7.674098936	52.7081062	5.819401129	52.7084502	5.819344197	
1	31.41	29.06815867	-2.341841332	86.5806428	3.419357197	52.7081314	5.827193207	52.70787152	5.827150371	
1	31.78	31.33730237	-0.442697626	87.81995217	2.180047828	52.7079542	5.833911382	52.70767047	5.833864548	
1	32.17	30.4003648	-1.769635203	80.76015154	9.239848458	52.7075423	5.837894203	52.70782073	5.837848258	
2	10.89	14.52014794	3.630147941	85.7598479	4.240152105	52.6448962	5.724496486	52.64502536	5.724475256	
2	22.5	21.20711465	-1.292885354	94.74346815	4.743468148	52.6448962	5.710273726	52.64508537	5.71024257	
2	22.17	21.1509373	-1.019062696	96.31352535	6.313525349	52.6449014	5.707743879	52.64508988	5.707712811	
2	23.58	23.37991604	-0.200083963	96.25646429	6.256464292	52.6448877	5.706518958	52.6450999	5.706483961	
2	21.63	22.25657035	0.62657035	263.5126833	6.487316688	52.6451011	5.702137011	52.64490009	5.702103896	
2	22.02	19.97952902	-2.040470984	262.3277884	7.67221163	52.6450999	5.700584293	52.64491918	5.700554433	
2	21.65	19.55568478	-2.094315218	266.1463888	3.853611235	52.6451187	5.698362941	52.64494234	5.698333954	
2	19.77	20.59566887	0.825668872	96.27986195	6.279861953	52.6449362	5.696273368	52.64512346	5.696242432	
2	20.09	18.85697267	-1.233027332	262.0492034	7.950796642	52.6451292	5.695688111	52.64495943	5.695660082	
2	19.87	23.50045099	3.630450987	267.6637922	2.336207803	52.6451592	5.69483114	52.64494866	5.694796533	
2	22.9	22.83731855	-0.06268145	264.0743676	5.925632414	52.6451663	5.691176046	52.64496098	5.691142182	a little bit shift to north
2	25.23	25.56148697	0.331486972	262.8823193	7.117680685	52.645184	5.684604698	52.64495267	5.684566527	
3	4.96	6.146525954	1.186525954	86.2096834	3.7903166	52.6891112	6.240195462	52.68916691	6.240186259	not the width of canal, but a ditch
3	36.18	44.2612302	8.081230197	58.19753393	31.80246607	52.6869225	6.230341284	52.68739266	6.23026347	
3	38.86	37.98994635	-0.870053649	104.2731708	14.27317079	52.674206	6.18746672	52.67455449	6.187409242	
4	23.89	21.83711275	-2.052887245	269.068339	0.931661045	52.6904484	6.238353825	52.69025194	6.238321395	
4	23.8	39.19463495	15.39463495	269.0520481	0.947951878	52.6906413	6.234558108	52.69029146	6.23450053	
4	19.5	10.01848356	-9.481516443	96.33321289	6.333212889	52.6907088	6.229714558	52.69079984	6.229699496	
4	105.35	190.3853413	85.03534134	269.2890254	0.710974648	52.691512	6.228887034	52.68980701	6.228605767	lake
4	19.13	15.90865322	-3.221346781	101.5938369	11.59383692	52.6908293	6.22447135	52.69097642	6.224446996	
6	53.69	18.25859616	-35.43140384	16.04012512	73.95987488	52.5365864	5.714151043	52.53718351	5.714052668	
6	45.99	24.61567767	-21.37432233	249.2679425	20.73205748	52.5222002	5.681921159	52.52196405	5.681882376	not parallel bank lines
6	44.74	41.72914042	-3.010859579	252.8114551	17.18854487	52.5217798	5.678120028	52.52138685	5.678055643	wired place can't figure out water or shadow for truth width abstraction
6	34.68	35.84049794	1.160497941	252.792017	17.207983	52.5199541	5.670555242	52.5196186	5.670500089	two water ways
6	44.18	11.0979353	-33.0820647	82.25900562	7.740994384	52.5194505	5.664065614	52.51955021	5.664049216	one obstacle between water
6	75.27	4.99945032	-70.27054968	82.72709881	7.272901186	52.5186471	5.65740767	52.51869244	5.657400222	not parallel bank lines
7	49.43	28.50736773	-20.92263227	311.5292068	41.52920678	52.5049165	6.244385507	52.50457185	6.244329104	
7	50.93	7.523052891	-43.40694711	150.1615355	60.16153548	52.5144325	6.221581812	52.51456699	6.221559774	on the ground
7	50.67	26.70121451	-23.96878549	321.1430482	51.14304822	52.5167369	6.218124929	52.51635572	6.218062426	fork
7	15.94	16.58151225	0.641512247	287.2236473	17.22364725	52.5163721	6.217840587	52.5162163	6.217814938	fork
7	45.98	19.76479654	-26.21520346	120.5894114	30.58941139	52.5188853	6.191336593	52.51909268	6.19130247	turn,on the ground
7	52.8	50.07890826	-2.721091741	285.9344153	15.93441534	52.5250915	6.15144502	52.52462751	6.151368747	
7	186.67	62.69477031	-123.9752297	298.9966534	28.99665336	52.5258168	6.149854689	52.5251798	6.149749942	lake
7	53.38	33.76266744	-19.61733256	155.4305206	65.43052059	52.5256682	6.147370424	52.52639507	6.14725117	
7	51.18	6.006959893	-45.17304011	344.0353666	74.03536662	52.5277793	6.144983236	52.52758562	6.144951446	
7	54.11	4.125427451	-49.98457255	173.2848188	83.28481884	52.5364051	6.145608517	52.53672085	6.145556688	
7	55.33	46.515029	-8.814971002	114.108261	24.10826095	52.5386567	6.138602514	52.53911507	6.138527292	
7	58.91	35.35313701	-23.55686299	140.853456	50.85345596	52.5409015	6.13285463	52.54140434	6.132772007	
7	60.77	38.74303964	-22.02696036	116.0392545	26.03925454	52.5477427	6.12825731	52.54812911	6.128193794	on the ground
7	60.81	21.63456956	-39.17543044	116.0455081	26.04550808	52.5471309	6.124198542	52.547348	6.124162808	lake,on the ground
7	130.15	8.606803887	-121.5431961	337.4039102	67.40391021	52.5629316	6.101389827	52.56273228	6.101357062	fork
8	85.06	9.27306565	-75.78693435	156.7799831	66.77998311	52.5736721	5.756880103	52.57346273	5.756845716	on the ground, cross
8	28.04	20.87025553	-7.169744473	60.07796373	29.92203627	52.479417	5.737472119	52.47963107	5.73743702	
8	38.7	12.8152255	-25.8847745	54.8151755	35.1848245	52.4557008	5.683414168	52.45584237	5.683391013	
8	28.34	15.56860562	-12.77139438	225.4671312	44.53286876	52.4474283	5.668006399	52.44723256	5.667974222	
8	28.19	12.42928793	-15.76071207	220.7529484	49.24705158	52.4463531	5.665773897	52.44618184	5.665745889	a lot of trees
8	27.5	11.58418508	-15.91581492	225.5050226	44.49497738	52.4454762	5.662813008	52.44533141	5.662789229	on the ground, no river point
9	23.43	26.75836329	3.328363293	264.5472042	5.452795772	52.5236734	5.812527119	52.52343462	5.812487946	
9	24.33	25.62617178	1.296171782	95.84287705	5.842877046	52.5233574	5.805608467	52.52358786	5.805570757	
9	23.29	29.64609123	6.356091233	267.2609306	2.7390694	52.5236009	5.803559705	52.52333228	5.803515598	
9	22.52	27.41703388	4.897033881	101.7121513	11.71215129	52.5233773	5.800977026	52.52362892	5.800935792	near cross
9	23.76	27.4395701	3.679570098	270.3207237	0.320723658	52.5240332	5.796927589	52.52378827	5.796887423	
9	22.73	22.26084047	-0.469159532	108.8328555	18.83285549	52.5241281	5.794115648	52.52433924	5.794080883	
11	7.64	7.833040849	0.193040849	267.5857077	2.414292322	52.5463201	5.756804782	52.5462504	5.756793336	
11	7.8	8.390692391	0.590692391	267.3025267	2.697473332	52.5464316	5.753398171	52.5463557	5.753385668	
11	8.53	9.511005691	0.981005691	267.5092092	2.490790771	52.5464802	5.752415592	52.54639541	5.752401684	
11	8.8	9.511103973	0.711103973	267.5228573	2.477142742	52.5465412	5.750622842	52.54645652	5.750608983	
11	8.45	10.06944731	1.619447311	267.3780353	2.621964663	52.5465866	5.749410644	52.54649551	5.749395655	
12	26.73	10.43829202	-16.29170798	117.4255766	27.42557657	52.5737848	5.686647088	52.57367897	5.686629729	
12	27.58	11.38747134	-16.19252866	54.42855814	35.57144186	52.5598157	5.72427293	52.55994011	5.724252479	on the ground
13	22.92	13.43793316	-9.482066835	88.99516099	1.004839013	52.6361144	6.103645939	52.63623495	6.103626046	
13	24.22	20.71812204	-3.501877955	89.228584	0.771415995	52.636462	6.109480075	52.63664889	6.109449253	
13	23.73	24.6378031	0.907803103	89.23488735	0.765112651	52.6360791	6.113718823	52.63629992	6.113682442	on the ground, ditch
13	22.63	18.99242597	-3.637574028	94.05116181	4.051161812	52.6373447	6.122386154	52.63751593	6.122357975	
13	20.92	31.5560988	10.6360988	98.65987045	8.659870451	52.6374057	6.129009238	52.63769141	6.128962219	on the ground, ditch
13	15.18	21.0773647	5.8973647	97.91324476	7.913244758	52.6356942	6.167949483	52.63550512	6.167918295	
14	16.19	9.040225374	-7.149774626	38.38149236	51.61850764	52.6115461	6.105491867	52.61141636	6.105470525	on the ground, ditch
14	20.68	12.8768509	-7.803149097	58.39088654	31.60911346	52.6148537	6.109930305	52.61471915	6.109908157	ditch effect
14	23.41	7.839931295	-15.5700687	89.76013158	0.239868417	52.6166271	6.125794049	52.61669759	6.125782453	
15	10.77	6.591515456	-4.178484544	51.69333059	38.30666941	52.604349	6.104926456	52.60427428	6.104914166	on the ground, fork
15	12.65	11.2008565	-1.449143503	50.29013786	39.70986214	52.6047673	6.108270296	52.60463777	6.108248974	
15	17.68	13.96615926	-3.713840736	106.4202281	16.42022806	52.6088076	6.12086077	52.60893775	6.120839332	near a bridge
15	13.8	7.23436542	-6.56563458	96.41868544	6.418685444	52.6095953	6.1269503	52.60966074	6.126939533	
15	13.52	18.24680419	4.72680419	80.88818762	9.11181238	52.6105818	6.157720466	52.61041468	6.157692967	
16	9.75	50.2642054	40.5142054	102.6763766	12.67637663	52.6202634	6.131829749	52.62072451	6.131753893	ditch effect
16	4.89	5.592575325	0.702575325	92.95073586	2.950735857	52.6198893	6.16727865	52.61983859	6.167270275	river point doesn't along river because the river too narrow and the turns effect
17	6.72	6.104228427	-0.615771573	277.7158173	7.715817303	52.6888809	5.632055571	52.6888261	5.632046547	
18	8.42	7.273572615	-1.146427385	92.40780365	2.407803646	52.7014245	5.715200465	52.70148908	5.715189834	
18	7.04	13.39078775	6.350787749	265.0953591	4.90464093	52.7017826	5.700523012	52.70166245	5.700503159	
19	32.57	18.9187346	-13.6512654	322.1029458	52.10294576	52.6373069	5.82226225	52.63702825	5.822216339	on the ground
19	26.55	10.55603815	-15.99396185	116.152733	26.15273296	52.6780941	5.842751572	52.67820043	5.842734043	
20	13.5	12.45133315	-1.048666854	55.43679549	34.56320451	52.6538743	6.064678523	52.65401126	6.064656026	on the ground, ditch effect
20	25.24	15.24670813	-9.993291867	61.43396588	28.56603412	52.652505	6.062758554	52.65266174	6.062732792	on the ground, ditch effect
20	4.98	5.596963797	0.616963797	91.886812	1.886812004	52.6500294	6.050713877	52.65008014	6.050705528	irregular river bank
20	4.8	7.2762729	2.4762729	91.83347921	1.833479206	52.6497663	6.044507843	52.64983088	6.044497177	
20	5.38	5.036532494	-0.343467506	92.12547447	2.125474474	52.6495738	6.03913116	52.6496186	6.039123753	

B

appendix

Information table for canals in Vietnam

Canal ID	Truth width [m]	Computed Width [m]	Width differences [m] (C-T)	Angle Differences [°]	Angle Dif with 90 [°]	Latitude [°N]	Longitude [°E]	Latitude [°N]	Longitude[°E]	Interpretation
1	39.81	166.4843651	126.6743651	86.05389517	3.946104834	10.533544	105.6047509	10.532044	105.604593	
1	60.7	143.0198253	82.31982534	81.84727843	8.152721574	10.523715	105.7948072	10.525013	105.794671	on the ground
1	55.42	76.04459003	20.62459003	75.91988497	14.08011503	10.52042	105.8640681	10.521125	105.863994	
1	54.57	34.6948922	-19.8751078	92.17910574	2.179105737	10.51694	105.8974421	10.516628	105.897409	on the ground
2	29.63	27.12378205	-2.506217947	81.29323577	8.706764235	10.612774	105.5188759	10.613017	105.51885	trees' shadow effect the truth width measurement
2	45.34	72.66034386	27.32034386	86.45046549	3.549534511	10.612221	105.5507001	10.611575	105.550632	cross
2	46.19	10.62316193	-35.56683807	86.77618401	3.223815994	10.610444	105.5814277	10.610349	105.581418	a small lake
2	21.83	29.90211518	8.072115182	81.42693163	8.573068373	10.610104	105.5840744	10.610372	105.584046	
2	27.15	34.12324962	6.973249615	79.36180046	10.63819954	10.600739	105.7130917	10.601053	105.713059	
2	31.13	39.7100264	8.580026395	87.12703536	2.872964638	10.597621	105.7771152	10.597264	105.777078	on the ground
2	27.96	189.6824365	161.7224365	94.97589039	4.975890385	10.591184	105.8375611	10.589498	105.837384	near a cross, two canals very close, one point is on the ground
2	28.17	19.02039047	-9.149609529	70.64301264	19.35698736	10.584851	105.8601163	10.58503	105.860098	
2	20	14.81843306	-5.181566941	78.53753338	11.46246662	10.581799	105.9175423	10.581935	105.917528	
3	53.71	184.7072497	130.9972497	75.95397992	14.04602008	10.678714	105.5164731	10.6804	105.516296	
3	49.34	18.79023353	-30.54976647	80.70932797	9.290672033	10.673024	105.5768619	10.673196	105.576844	on the ground
3	53.78	47.18897193	-6.591028069	78.47495308	11.52504692	10.665881	105.7062348	10.666316	105.706189	
4	58.75	25.47974609	-33.27025391	55.81875124	34.18124876	10.852446	105.7612409	10.85272	105.761212	on the ground
4	37.07	42.22550354	5.155503541	65.29422886	24.70577114	10.81342	105.7015918	10.813831	105.701549	
4	39.93	16.12016786	-23.80983214	83.03535974	6.964640255	10.763261	105.5680062	10.763404	105.567991	on the ground
4	34.07	30.79276312	-3.27723688	88.75792892	1.242071085	10.757626	105.5036616	10.757899	105.503633	on the ground
6	49.61	56.73957217	7.129572166	79.63952701	10.36047299	10.92683	105.6787562	10.927351	105.678701	
6	52.59	175.6997327	123.1097327	247.3378341	22.66216588	10.91011	105.6121778	10.908399	105.611998	irrigation lakes, one point on the ground
6	21.68	24.07789151	2.397891509	269.2417744	0.758225612	10.90305	105.5811639	10.902836	105.581142	fork, width of another narrower canal
6	44.25	190.2869909	146.0369909	268.0258402	1.97415981	10.907776	105.5263249	10.906091	105.526148	
6	48.54	30.79296828	-17.74703172	251.4523369	18.54766314	10.905774	105.5231137	10.905481	105.523083	near cross
7	34.85	123.3443192	88.49431921	75.02587253	14.97412747	10.995186	105.6825363	10.996315	105.682418	
7	26.12	184.7662729	158.6462729	76.02735009	13.97264991	10.972578	105.6097147	10.974275	105.609537	near cross
8	34.59	21.19306798	-13.39693202	275.1807146	5.180714592	10.732891	105.7913287	10.7327	105.791309	near cross, on the ground
8	39.56	43.79529123	4.235291231	307.0586402	37.05864024	10.9135	105.5822589	10.913012	105.582208	near fork, on the ground
9	26.32	38.69750628	12.37750628	110.9616425	20.96164247	10.810443	105.9723177	10.810814	105.972279	
9	18.63	34.35288271	15.72288271	109.3070088	19.30700878	10.813781	105.9615115	10.814107	105.961477	on the ground
9	14.97	26.87423575	11.90423575	286.3022776	16.30227764	10.831308	105.9056548	10.831061	105.905629	
9	16.97	17.28170629	0.311706293	118.1494882	28.14948822	10.837085	105.8906555	10.837262	105.890637	on the ground
9	20.91	40.90304655	19.99304655	290.5403938	20.54039385	10.849307	105.8646789	10.84892	105.864638	on the ground
9	21.46	48.04448029	26.58448029	292.7037155	22.70371551	10.849942	105.8634868	10.84948	105.863438	on the ground, a small lake
9	45.61	12.0341306	-33.5758694	127.2588869	37.25888687	10.85795	105.831434	10.858085	105.83142	in the lake
9	38.45	47.76764797	9.317647969	127.1373645	37.13736454	10.859831	105.8280588	10.86037	105.828002	on the ground
9	36.25	29.71013558	-6.539864416	129.7451597	39.74515972	10.904669	105.7557586	10.905012	105.755722	flood area
9	38.21	149.7412288	111.5312288	128.1444552	38.14445516	10.906748	105.752478	10.908437	105.7523	flood area
10	30.7	112.9545312	82.25453125	105.1831854	15.18318542	10.734509	105.9014609	10.735566	105.90135	on the ground
10	27.28	8.833710754	-18.44628925	127.933557	37.93355704	10.769946	105.8378742	10.770046	105.837864	on the ground
10	31.2	31.84812423	0.648124232	306.7734215	36.77342155	10.797565	105.7981259	10.797208	105.798088	
10	32.68	63.88323578	31.20323578	306.5477739	36.5477739	10.800776	105.7955168	10.800064	105.795442	on the ground
10	45.81	52.29959614	6.489596136	304.261265	34.26126501	10.821315	105.7728958	10.820751	105.772837	on the ground, ditch
10	47.04	54.97826109	7.938261086	128.8153224	38.81532239	10.828868	105.7637159	10.829496	105.76365	on the ground, ditch
10	36.92	40.49205665	3.572056646	307.3839152	37.38391524	10.942065	105.6476685	10.941608	105.64762	on the ground, ditch
10	22.58	41.66342158	19.08342158	308.4503762	38.45037621	10.968765	105.6191838	10.968286	105.619133	

C

appendix

Google Earth screenshot of Vietnam canal crosses

Figure C.1: Red lines are selected canals, yellow points are the computed width along track before angle correction.

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