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Chapter 10

ADVANCES USING DIVER-TOWED GPS RECEIVERS

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ABSTRACT

The quality of scientific sampling, monitoring or underwater mapping depends more and more on the exact allocation of place and time to the object of interest. This might be the sample itself or the visual documentation of the object of interest by high resolution images, video sequences or underwater mapping. Ideally, these data are accompanied by other geo-referenced physical and chemical datasets. In this chapter we used diving depth and CTD data as additional information. Georeferencing is not a problem for terrestrial work. Accuracy and precision will become even better at low cost with the implementation of new satellite positioning systems like Galileo, which can be used in combination with GPS thus receiving a better satellite coverage. For underwater field work very few low cost resolutions are available. It is not possible to take the GPS receiver without an external antenna below water, because high frequency Radio waves (L1 1.575,42 MHz; L2 1.227,60 MHz) that transmit the GPS signal are not able to penetrate the water column more than a few centimeters. A gateway is required between the GPS receiver and a surface buoy containing the GPS antenna; this can be a cable or an acoustic signal linking both units.

Here, we focus on cable towed solutions but discuss other promising alternatives that might be on the market within the near future. Cable-towed GPS receivers have been recently used by the authors in biodiversity studies in the Antarctic as well as in monitoring studies in the Baltic Sea. The diver used maps for orientation, followed tracks and marked objects below water. However, the deviation between the GPS receiver and the surface buoy caused an increase of the positioning error. A special situation was given when the divers used a scooter for locomotion. This error term was corrected quantitatively using specific algorithms and information about heading and additional cable length in relation to water depth. We used a Garmin 76csx handheld connected to a surface buoy with GPS antenna for our studies. Images and video sequences were georeferenced using interpolated positions from the tracks, which were recorded every 5

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seconds. The method used turned out to be straight forward and loss of signal was hardly observed.

Keywords: Underwater GPS, position correction, error discussion, scientific diving, georeferenced monitoring, underwater photography, underwater videography

10.1. INTRODUCTION

No matter how good satellite signal strength and accuracy of positioning at the water surface are how to get the signal below water without diluting it too much. The problem is that electro-magnetic waves used by Global Navigation Satellite Systems are filtered effectively during the first cm of the water column [1]. How did researchers handle this problem in the past? Which additional mistakes must be considered for exact positioning and error calculation? Why did we still present a diver-towed cable system, while other systems have been used for years? What can we expect to come in future and what will be the advantages and disadvantages of each system?

Originally, GPS was created by the U.S. department of defense and became fully operational in the year 1995. However, only in the year 2000 the United States made a more accurate GPS signal available for civilian use. Consequently, GPS was hardly used within environmental research studies before this date. Several monitoring designs were developed in the 1990s, but positioning depended on the availability of local maps. Close to the coast landmarks were used to hold a straight line. Two pairs of landmarks allowed defining a specific monitoring spot, where the two lines intersected. Several studies were based on transect lines [2, 3] where only start and end points of each transect were marked. Bass & Miller [4] used the manta tow technique for describing the abundance and distribution of organisms in large areas of coral reefs. A snorkel diver was towed with a constant speed behind a boat. Heidelbaugh & Nelson [1] used quadrates to assess changes in sea grass cover. In other studies the factor “distance” was replaced by the factor “time” used during the underwater survey [5].

After the year 2000 most researchers provided GPS data to describe sampling locations, but often did not mention data accuracy, although there is a general agreement that surveys conducted without the accuracy of GPS locations are of significantly less value. Only the usage of permanent markers might have allowed a posteriori determination of the exact monitoring positions of data taken before 2000. Only a few researches mentioned that the sampling localities or transects were recorded by GPS, but the problem of positioning was undertaken from the surface or below water remained unclear [6, 7]. In another case GPS reference was taken from the boat only and the direction of each transect noted [8]. A detailed review of standards and protocols for seabed habitat mapping is given by Coggan et al. [9] within the European MESH Program, but the authors did not discuss specific error sources for geographic positioning.

The supra and intertidal positions can be registered accurately because signal reception does not differ from other terrestrial research. GPS signal can be received directly from sea kayaks or boats when stationary in very shallow water (1-3m) like back reefs, lagoons or rivers without increasing the error term [10]. In other studies snorkel divers used a floating device for positioning or georeferencing images they took in shallow water [11, 12]. Mueller et al. marked start and end points of transects by positioning a GPS antenna over the exhaust bubbles of divers [13]. Above mentioned studies probable horizontal deviation caused by currents is still not mentioned.

The U.S. Environmental Protection Agency Region 10 Dive Team used the same method for georeferencing which we discuss in this chapter with reference to its accuracy and limitation [14, 15]. They used an inexpensive recreational Wide Area Augmentation System (WAAS) enabled Global Positioning System (GPS) device which was diver-towed in a raft above the dive team and recorded positions throughout the dive [14]. The method itself has been known for several years [16] and has already been used by recreational divers. It has been widely discussed in Internet Forums, often questioning the accuracy of the system. Schipek et al. [17] mentioned that they used additional weight to prevent buoyancy and drift of a diver-towed floating device. However, it is not possible to maintain a floating device vertically above a diver if current velocity is too high or the divers move with a certain velocity through the water. The floating device will be pulled down below water. Cunha et al. [18] placed a GPS unit in a housing attached to a buoy, vertically positioned over the diver. Again no error terms of possible deviation of the GPS unit in relation to the diver were presented.

10.2. Technical Realization

Out of all eligible underwater GPS facilities, the wired one has been chosen as being the most convenient for scientific diving. It has consistently been developed further and complemented for its achievements, because it is the only method offering options for errors and corrections. This system consists of a surface buoy with a GPS antenna attached in addition to the diver-operated handheld (Figure 10.1). The GPS antenna is connected to a GPS-handheld via a cable. The handheld is located in an underwater housing and is carried by the diver. Our housing is manufactured from an aluminum block by the German company Sealux, Ltd., and it allows the GPS handheld to be handled and the data and information shown on the GPS display to be read clearly.

The cable length S, which corresponds at least to the diving depth WD, should be variable and capable of being adapted. Any extension is not possible because the signal strength decreases with increasing cable length and leads to ever rising errors in position determination. Garmin-GPS-76(csx)-handhelds have been used for the practical dives under the responsibility of the authors so far. The maximum cable length has been to 50 m defined the maximum diving depth. The cable lengths can be exchanged by adapters or underwater plugs according to the operating depth. Connectors and antenna cable must be suitable for the transmission of high-frequency signals. The advantages of this configuration are low weight, small dimensions. The underwater GPS can be transported in the aircraft without precautions. Here low purchase cost that means reserve equipment offers high flexible capability and simple technology. No special energy supply is required and commercial batteries are sufficient.

The use of underwater GPS while diving is possible at any time without any additional risk for teams of divers when relevant safety regulations are followed. The divers can do their work in areas that are unknown without previous marking or tagging.

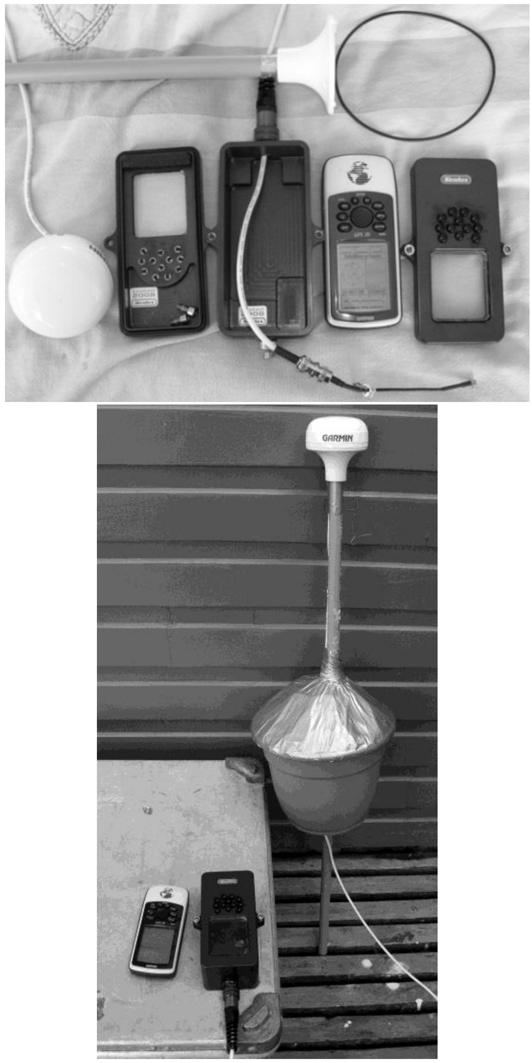


Figure 10.1. Complete underwater GPS system.

The length of the divers' tracks is limited only by the storage capacity of the handhelds used or by the capacity of its battery power concerning the underwater GPS. From a practical point of view the accuracy of position detection is sufficient for most dives. The vast majority of scientific diving operations take place in shallow water (WD < 20 m) anyway. The system is suitable both for underwater navigation as well as for georeferencing of underwater photos, videos, and measurement data. The security and efficiency of dive operations has significantly been increased due to a much better underwater navigation in comparison to traditional methods (compass, natural circumstances etc.).

However, there are some problems which might cause adverse effects that cannot be ignored. If the GPS antenna cable length exceeds the diving depth, then the GPS buoy may not be located directly above the diver. There is a more or less large difference (horizontal share of the vector) between the current position of the diver and the position of the GPS antenna at the same moment. Various velocities and directions of flow at various levels of water depth make it almost impossible to correct the buoy's offset accurately. Additional and appropriate measures are required to either keep small or to correct the positions measured. The diver must tow a cable and a marker buoy while swimming, which may increase the air consumption to overcome the additional hydrodynamic resistance. In some conditions the movements are too fast and the cable lengths are not sufficient or if seaway is too heavy the GPS antenna can be towed under water hindering in this way GPS signal reception. To avoid these problems, a mathematical physical modeling has been developed for the underwater GPS in this chapter.

10.3. Modeling to Quantify the Error in Position Determination due to Cable Connection and for Calculating Buoyancy of GPS Buoy

10.3.1. Sources of Error

While recording the positioning locations by means of a commercial GPS handheld, a measurement error R_{GPS} is declared normally. The amount of the error is not always evident, and the limited accuracy is mainly due to the following sources of error. Multi-path / signal corruption low number of satellites / poor satellite geometry erratic ionospheric activity artificially generated inaccuracies like clock and ephemeris errors. Without using special techniques (activation of WAAS [wide area augmentation system] or additional stationary terrestrial reference stations for differential GPS) the achievable accuracies R_{GPS} for the Garmin GPS 76csx are at least ±3...10 m. For this purpose, a simple practical test demonstrates the achievable accuracy in praxis that is a GARMIN GPS 76csx was positioned at a fixed place for 24 hours with an unobstructed view to the sky.

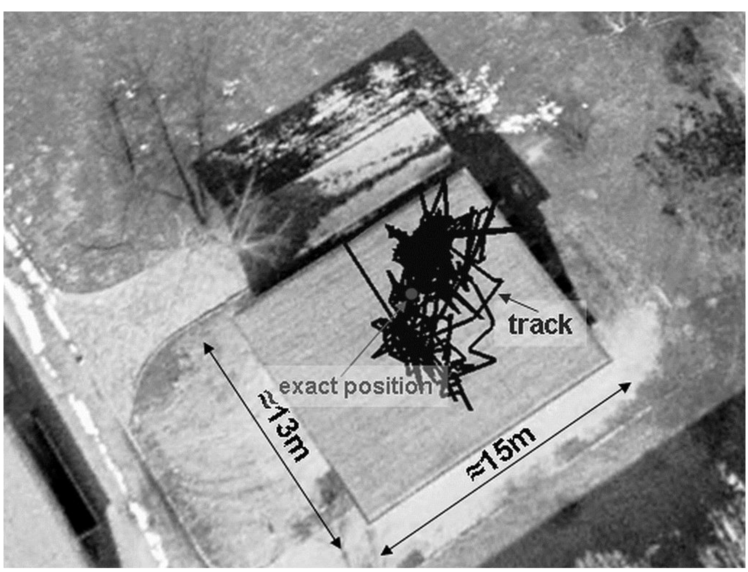


Figure 10.2. Track recorded by a GPS-handheld, which worked for 24 hours without changing the position.

In this way, every 2 minutes a track point was written. Ideally, all track points should have been saved as a track consisting of all congruent track points. The result, however, was not a point, and the image shown in Figure 10.2, confirming the error of ±3m identified by the handheld When using a cable-connected GPS handheld under water another error might occur, this may be much more important under certain circumstances (Figure 10.3).

The geographical position of the GPS buoy can differ from the diver's position by the amount with the components (Cx,Cy). This discrepancy is particularly dependent on the cable length S and the diving depth WD. It was the aim of the mathematical modeling to determine how important the influence of hydro-dynamic forces due to the relative motion between cables buoys and water. Here, parameters such as cable diameter d, cable weight in water Q and velocity v must be taken into account. The hydro-dynamic form exposed heavy cable was not straight instead of parabola-shaped. A special situation occurs when an underwater scooter and an underwater GPS are used in combination. Here, a certain offset of the buoy to the scooter cannot be avoided. This must be corrected afterwards: another possible source of errors in georeferencing of underwater shots is the offset between the camera diver and the diver with the GPS handheld. Under ideal circumstances the diver with the GPS dives above the camera diver only with vertical offset.

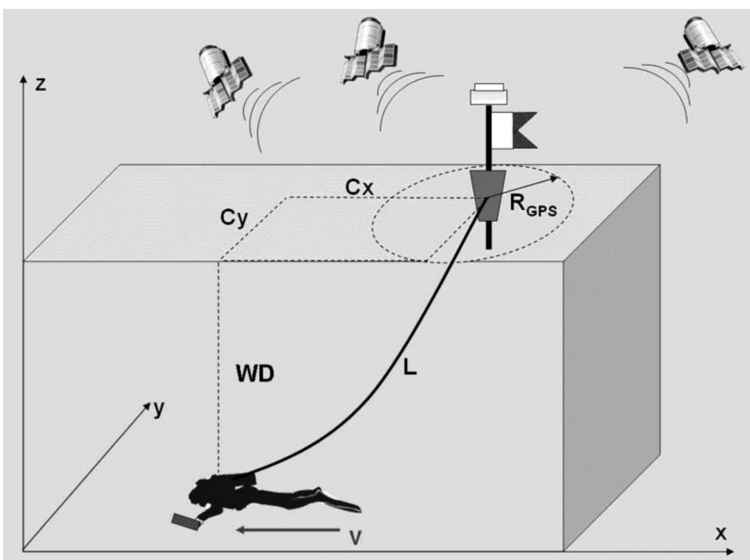


Figure 10.3. Positioning error occurring with cable-connected underwater GPS.

10.3.2. Modeling

A theoretical approach was used to determine the cable form, which was developed at the Rostock University in the mid-80s for the calculation of fishing trawls [19-22]. The method can be applied to tension rope systems, consisting both of individual ropes and meshes. For the calculation the ropes are discretized, i.e. divided into single elements with an articulated connection at their ends. Transferring this to the GPS cable, the model shown in Figure 10.4 is obtained.

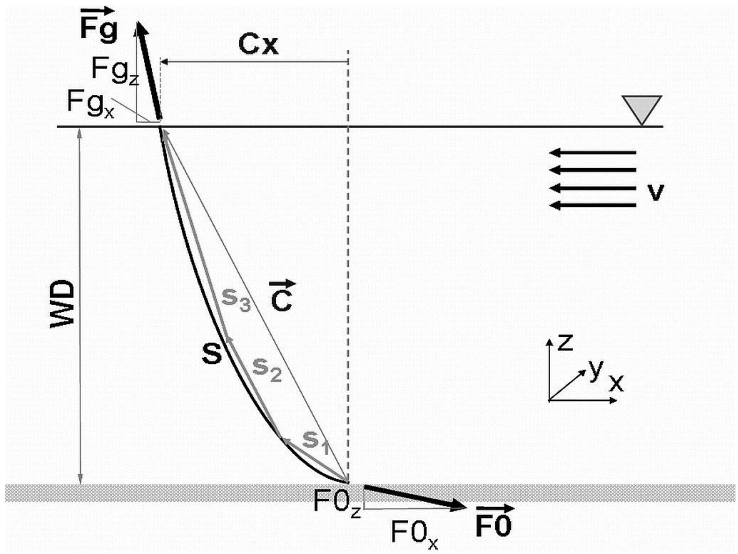


Figure 10.4. Sketch of model for calculating the GPS cable.

Regarding the model the following assumptions and specifications are made.

- The GPS cable of the length S is divided into individual inflexible elements with the lengths s*i*.

$$S = \sum_{i=1}^{n} s_i \tag{1}$$

- The length of the individual elements s_i is determined automatically. The elements are shorter, if the cable has a greater curvature; they are longer with lower curvature.
- This method much better helps to reproduce the cable form, and the shape-dependent hydrodynamic forces acting on the individual elements remain small compared to the tension. This in turn positively influences the ability of the procedure to approximate.
- All single elements have the diameter d, but the diameter can also be different for each element.
- The weight of an element in water is $Q_i=s_i*q_i$.
- Each element can only be exposed to tension.
- The 2 ends of each element have an articulated moment-free connection with the neighboring element.
- The same velocity of motion v in amount and direction (stationary flow) is given over the entire water depth.

The vector describes the distance between the lower endpoint of the cable and its upper endpoint; it consists of the components

$$\vec{C} = (Cx, Cy, WD) \tag{2}$$

The upper cable end is always located on the water surface. To meet this demand, the z-component of the buoyancy force Fg of buoy is changed step by step. The x-component of the buoyancy force Fg is the hydrodynamic resistance of the buoy, depending on the velocity v of the diver through calm water. The simulation calculations are limited to the x-z plane, because the main deviations are expected there and the essential influencing parameters (v) is known. If Cy is to be determined as well, which can be done with the mathematical model without problems, then the lateral forces (crosswind, transverse flows) must be known, which are also temporally variable.

The program KABKURR (Niedzwiedz, G. 1991-2010) was used to determine of the cable forms and the required buoyancy force of the buoy. In the mid-90's it has specially been developed at the Rostock University for calculating single ropes and has successfully been employed for various tasks ever since [23, 24].

The simulation calculations have been made for the following cable parameters:

Cable diameter: d=5mm
Weight per 1 m of cable in water: q=-0,1N/m
Cable lengths: S=WD+(0,5;1;2;3;4;5;6;7;8;9;10)m
Diving depth: WD=(5;10;20;30;40)m
Water current: v =(0,1;0,2;0,3;0,4;0,5;0,6;0,7;0,8;0,9;1,0)m/s

The hydrodynamic resistance of the surface buoy is Fgx=-1/25[kg/m]*v^2.

A total of 550 variants have been determined for the above parameter range, and in addition for each cable form the required buoyancy Fgz of the GPS buoy in order to span the predetermined diving depth WD.

10.3.3. Results from the Calculation of Cable Forms and Offset Cx

For each diving depth the cable forms can be represented graphically, such as given in Figure 10.5 as an example for WD= 30m and 11 different cable lengths. In addition, in Figure 10.5, the cable forms can be compared at different velocities v. The continuous lines make the cable form at v= 0.2m/s, the marked lines are cable forms with identical cable length but at v=1m/s. In Table 10.1, some of the calculated position differences between GPS buoy and diver Cx are listed for WD=30m.

Table 10.1. Buoy offset Cx at WD=30m, different cable lengths and 4 different velocities

S-WD[m]	0,5	1	2	3	4	5	6	7	8	9	10
Cx1 (v=0,1m/s) [m]	3,9	6,5	9,0	10,8	12,3	13,6	14,7	15,7	16,6	17,5	18,3
Cx2 (v=0,2m/s) [m]	5,4	6,8	10,0	12,3	14,3	16,0	17,5	19,0	20,4	21,7	23,0
Cx3 (v=0,5m/s) [m]	5,6	6,8	10,3	12,7	14,8	16,8	18,5	20,2	21,7	23,2	24,6
Cx4(v=1m/s) [m]	5,6	6,8	10,3	12,8	14,9	16,9	18,7	20,3	21,9	23,4	24,9
ΔCx=Cx4 - Cx1 [m]	1,7	0,3	1,3	2,0	2,6	3,3	4,0	4,6	5,3	5,9	6,6
ΔCx=Cx3 - Cx2 [m]	0,2	0	0,3	0,4	0,5	0,8	1,0	1,2	1,3	1,5	1,6

The calculation results for the other diving depths are similar, where the offset Cx decreases with lower water depth generally.

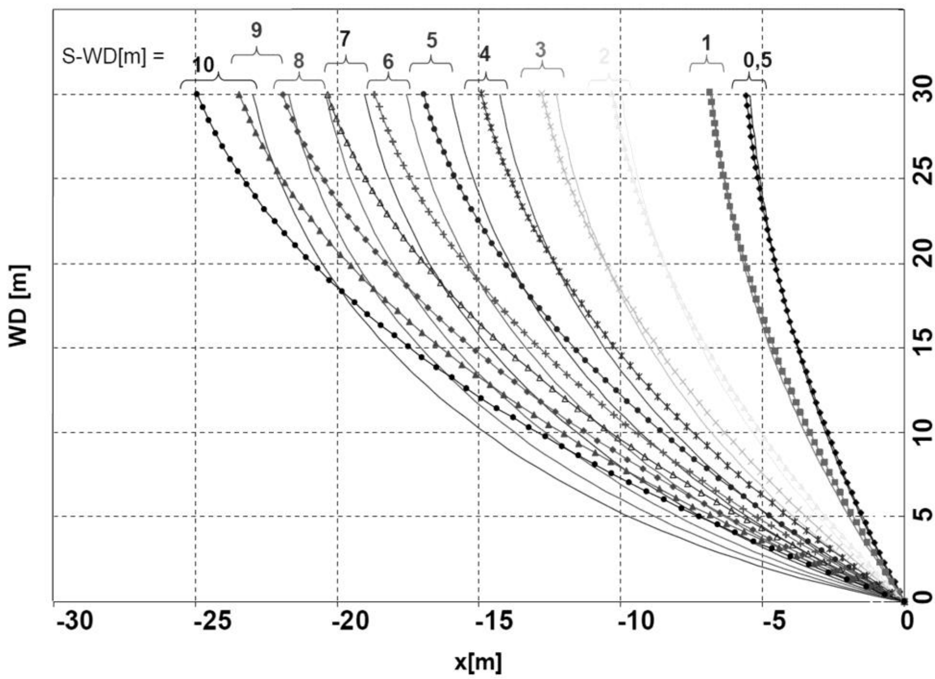


Figure 10.5. Cable forms for WD=30m, S=30,5m …40m and v=0.2 and 1m/s.

Table 10.2. Buoy offset Cx at WD = 10 m, 20 m and 40 m, 2 cable lengths (low (S + 1 m) and maximum (S + 10m)) and 4 different velocities

WD [m]	10m		20m		40m	
S-WD[m]	1	10	1	10	1	10
Cx1 (v=0,1m/s) [m]	2,9	11,7	3,9	15,3	6,2	21,0
Cx2 (v=0,2m/s) [m]	3,1	15,5	4,3	19,6	6,7	25,9
Cx3 (v=0,5m/s) [m]	3,2	16,9	4,4	21,2	6,8	27,6
Cx4(v=1m/s) [m]	3,2	17.0	4,4	21,4	6,9	27,9
ΔCx=Cx4-Cx1 [m]	0,3	5,3	0,5	6,1	0,7	6,9
ΔCx=Cx3-Cx2 [m]	0,1	2,4	0,1	1,6	0,1	1,7

10.3.4. Determination of the Required Buoyancy of Buoy

The buoyancy of the buoy is required, on the one hand, to carry the weight of the cable, which spans the water depth. On the other hand, there is a resultant hydrodynamic force downward. There is certainly no need to discuss in more detail why the required buoyancy force of buoys Fgz increases with increasing diving depth (thus cable length) and increasing inflow velocity. The calculated values shown in the diagrams are interesting (Figure 10.6.1-Figure 10.6.4). Sometimes, very large hydrostatic buoyancy is necessary to ensure that the buoy remains at the water surface. These forces are required by the diver and cannot always be applied. A compromise is necessary, which is discussed in the next section.

10.3.5. Conclusion According to the Cable Calculations

The difference Cx between the diver’s position and GPS antenna (= recorded position) can be significant, if the cable length is longer than the diving depth. Despite the buoy’s large buoyancy forces and very small differences between cable length and diving depth, this discrepancy is zero only in exceptional cases. To make georeferencing of underwater objects as accurate as possible, the following diving tactics and measures are applied.

1. The assignment of a measured geographical location to an underwater measuring value (= photo, video, sediment or water sample, etc.) is done after the dive. This requires that the time of sampling is recorded exactly, and the watch applied for this must be compared and synchronized with the GPS time immediately before or after the dive.

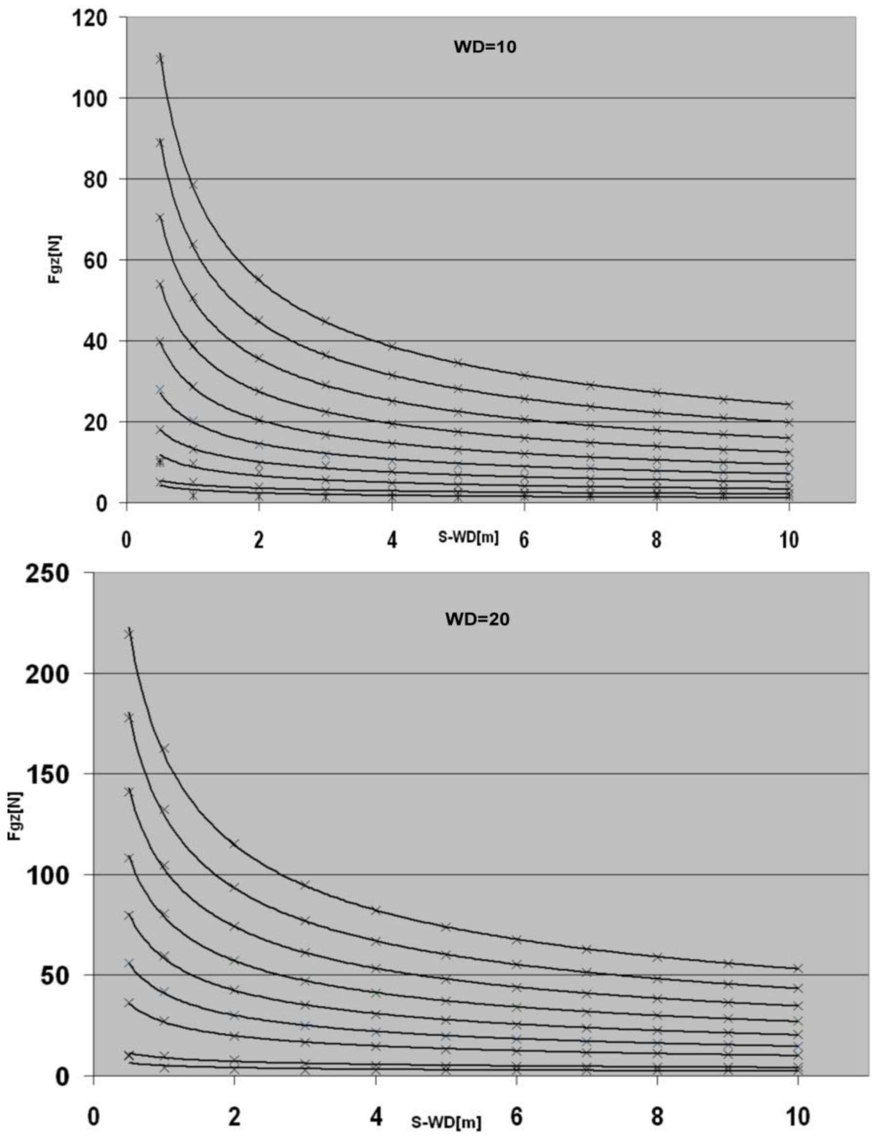
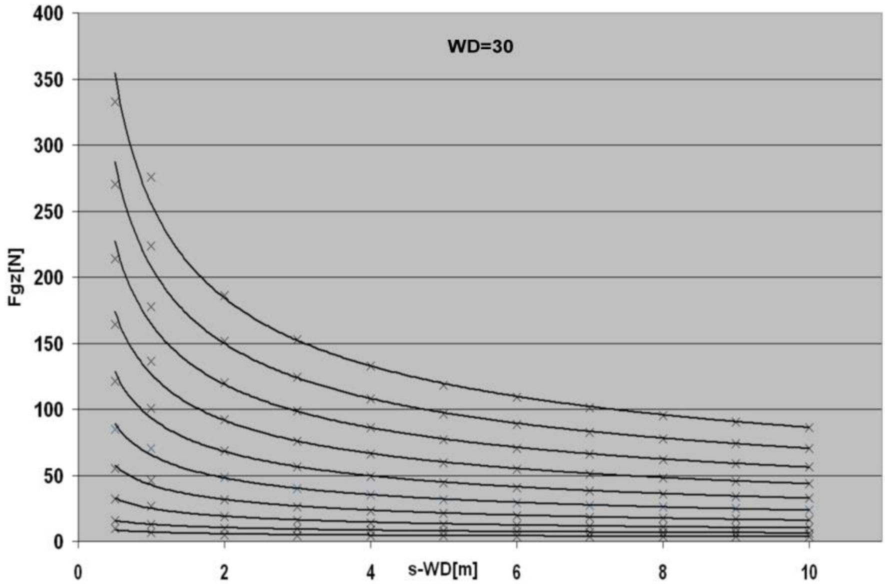


Figure 10.6.1. – 10.6.4. (Continued).



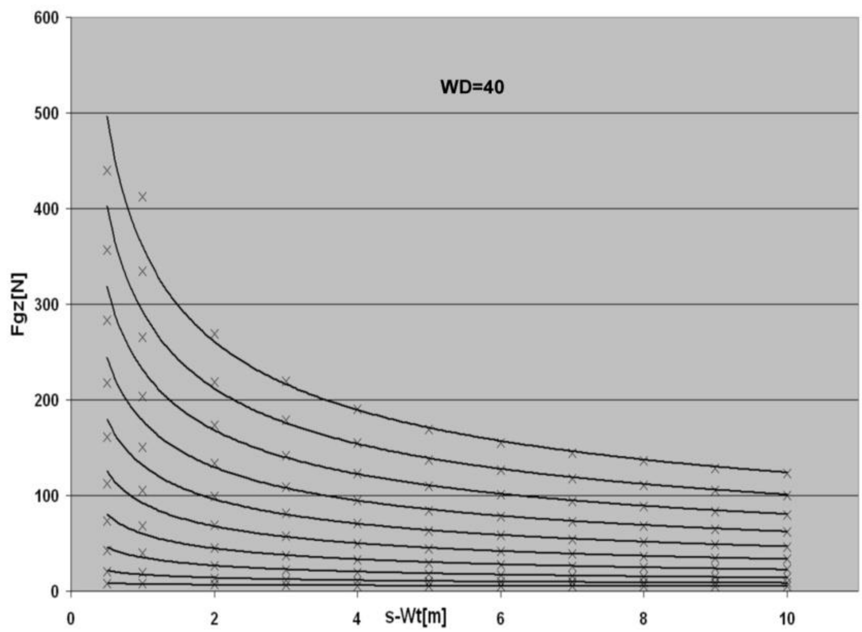


Figure 10.6.1.- 10.6.4. Necessary buoyancy of buoy for an antenna cable exposed to flow at different diving depths, cable lengths and inflow velocities.

Today's underwater photo, video systems and also gauges have internal clocks, and the time difference of which must in any case be indicated promptly after the dive. Meanwhile, there are a number of software tools available which are used to geocode photos afterwards (e.g. open source:geosetter.de). The relative precision can be enhanced, if values for positioning are averaged over a longer time period.

2. While taking selective samples from an underwater location the swimming speed (= inflow velocity) should be reduced to the greatest possible extent and at the same time the cable should be kept taut. In underwater photography, this is common practice for producing

sharp images. Here a team of at least two dive buddies is recommendable, with a special division of tasks.

3. During continuous motion it is hardly possible to take photos or videos while at the same time keeping the cable always taut. The hydrodynamic resistance hinders the forward motion and requires harder efforts to be made by the diver. Depending on the diving depth, even at relatively short cable lengths (S-WD=0.5) an offset Cx of several meters is possible (Figure 10.5, Table 10.1, Table 10.2). Apart from this, buoys with a strong buoyancy force should be used, which in turn can significantly affect the cable in heavy seaway at the water surface. What makes matters worse is that the diving depth can change (e.g. when swimming a course from the shallow shore into deeper water or vice versa as part of underwater monitoring). Here arises the need to continuously correct the geo-position measured by the GPS antenna with respect to the diver's position.

To correct the measured geo-position, a simple algorithm is required. It is not feasible to perform the above calculations constantly for every recorded track point or to pick any special result for the changing spectrum of parameters from the example calculations done before (here 550). Taking a closer look at the calculated results of Cx it seems that within the normal speed range of divers (v<0.5m/s) changes of Cx remain relatively small (ΔCx=Cx3-Cx2). The change of Cx is even less than the inaccuracy of the GPS signal reception R_{GPS}. Therefore in further procedures it is assumed, that in the interval of v=0.2…0.5m/s the speed does not depend on Cx. For each 10 calculated speeds v_i per diving depth and cable length, a medium offset of Cx_m has been calculated (Formula (3)).

$$C_{x\_m} = \frac{1}{10}\sum_{i=1}^{10} Cx(v_i) \tag{3}$$

Thus, the cable length S and the diving depth WD remain as the main parameters influencing Cx. Analogous to the theory of the catenary curve or parabola, it would now be possible to have a correlation between prescribed opening conditions and certain span width.

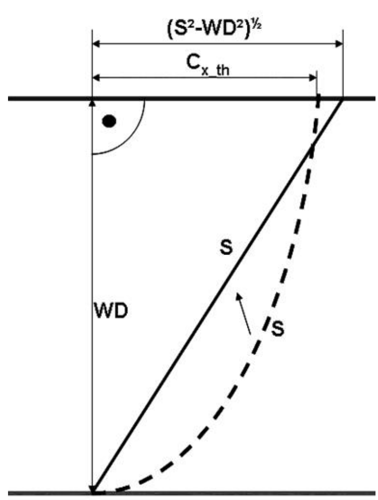


Figure 10.7. Simplified model for determining Cx on the basis of simulation calculations.

Because the cable curvature remains small in most cases, it is possible to apply a modified form of the theorem of Pythagoras as follows (Figure 10.7).

$$C_{x\_th} = K * \sqrt{S^2 - WD^2} \tag{4}$$

Applying formula (4) and with K=0.9 the theoretically calculated values of Cx could be approximated in such a way as to ensure that a very good agreement be achieved, as shown in diagram (Figure 10.8). In Figure 10.8 the average deviations are shown additionally. At S-WD=const. an average value C_{x_m} has been formed for Cx over all 10 speeds considered. The error indicator seen in the diagram corresponds to the mean deviation. The mean values of C_{x_m} were then compared to the values C_{x_th} determined according to formula 3. The results prove that, in this way, a very simple determination of values for Cx is possible. However, it is expected that at least the parameter K will be different for another antenna cable; possibly the argumentation on the admissibility of the procedure should then be renewed. This means the cable forms for the entire parameter spectrum considered must be recalculated.

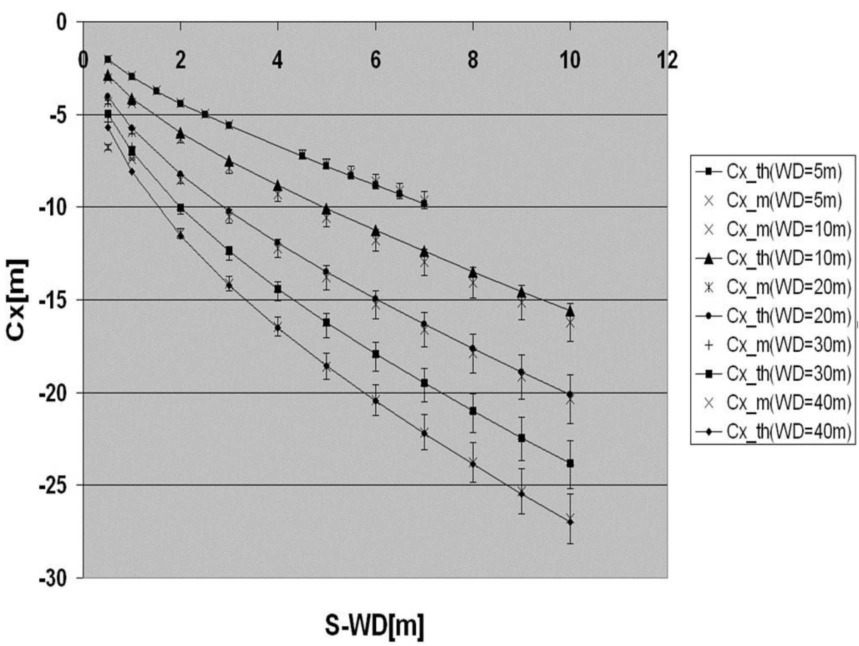


Figure 10.8. Comparison of C_{x_m} and C_{x_th}.

Figures 10.6 shows that the necessary buoyancy of the buoy in particular for larger water depths and short cable lengths can be significant and can amount up to 500N. However, the calculation results also show that already with a slight extension of the buoy cable and at a moderate speed of motion this required buoyancy quickly decreases. A buoy of about 100N buoyancy represents an optimal solution in the authors' opinion: it is manageable, has a lower hydrodynamic resistance in small water displacement and leads to less (dynamic) cable load (in the case of waves on the water surface).

10.4. Correction of the Geo-location

10.4.1. Further Theoretical Fundamentals

From nautical science, methods and algorithms are known to determine how a specific target location B is reached when launched from a position A and travelling a distance E under a prescribed course angle ω (Figure 10.9). Transferred to the application of a towed underwater GPS the start position A would be the position of the GPS antenna at the water surface and the target position B would be the diver's place. The distance E corresponds to the theoretically calculated offset Cx. The course angle (bearing) ω can be determined either from 2 adjacent track points of the recorded course or e.g. with the help of the program Map Source used to read out the GARMIN-GPS-76csx. Because the distance E≈Cx is extremely small compared to the radius of the curvature of the earth R_E=6.371.01km, the problem can be solved simply in the plane without the application of spherical trigonometry:

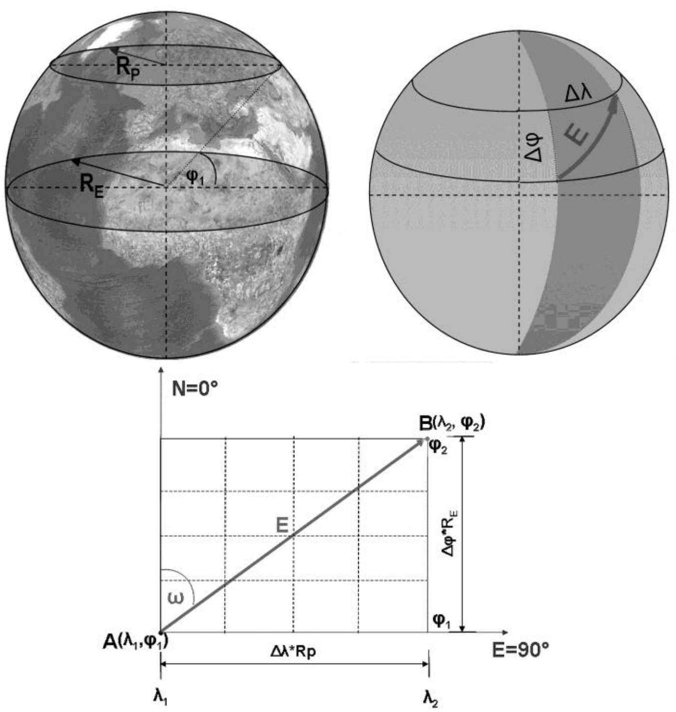


Figure 10.9. Sketches for the calculation of the target location B with the help of the start point A, the course angle ω and the distance E.

$$\varphi_2 = \varphi_1 + \Delta\varphi \quad and \quad \lambda_2 = \lambda_1 + \Delta\lambda \tag{5.1}$$

with

$$\Delta\lambda = \frac{E}{R_P} * \sin\omega \tag{5.2}$$

$$\Delta\varphi = \frac{E}{R_E} * \cos\omega \tag{5.3}$$

$$Rp = R_E * \cos\varphi_1 \tag{5.4}$$

The calculative correction of the geo-position according to the formulas (5) requires the geographical coordinates of latitude φ_1 and longitude λ_1 and the course angle ω. On the other hand, the main parameters influence the offset Cx, which means that the cable length S and the current diving depth WD must be known. A recommendation from the viewpoint of diving practice would be to keep the cable length constant over the entire dive. The diving depth WD can be read out from the diving computer at any time of the dive, provided that it has been synchronized with the GPS time before the dive.

10.4.2. Calculatory Transformation

a) Accuracy of the Target Point Calculation

The destination coordinates were calculated with our own program GEO_KOORD (Figure 10.10) beginning with a starting point, the course angle and the distance. Alternatively, there are numerous "bearing and distance calculators" on the Internet which can make such calculations.

Figure 10.10. Worksheet of the program GEO_KOORD as hardcopy.

GEO_KOORD primarily served to check and compare the results of the calculated target coordinates. In addition to the simplified method another method was programmed for this purpose (Equs. 5). It was developed by the geodesist Thaddeus Vincenty [25]. Briefly summarized, even at distances of several kilometers the target point can be determined by means of the simplified procedure (5) with very high accuracy, as can be shown by example calculations and comparisons (Table 10.3).

Table 10.3. Comparison of calculations of the target point B by given distance E and Bearing ω using different methods

	Starting point A	given Distance E	Course angle / Bearing ω	End point B
1a) Position calculator with Vincenty (direct)	54°09’54,44“N; 11°56’46,09“E	30m	0°	54°09′55,4103″N, 011°56′46,0900″E
1b) GEO_KOORD with Vincenty formula	54°09’54,44“N; 11°56’46,09“E	30m	0°	54°09’55,41“N; 11°56’46,09“
1c) GEO_KOORD with formula (5)	54°09’54,44“N; 11°56’46,09“E	30m	0°	54°09'55,41"N; 11°56'46,09"E
2a) Position calculator with Vincenty (direct)	54°09’54,44“N; 11°56’46,09“E	111.317m = 60nm	0°	55°09′54,4290″N, 011°56′46,0900″E
2b) GEO_KOORD with Vincenty-formula	54°09’54,44“N; 11°56’46,09“E	60nm	0°	55°09’54,43“N; 11°56’46,09“E
2c) GEO_KOORD with formula (5)	54°09’54,44“N; 11°56’46,09“E	60nm	0°	55°09’58,39“N; 11°56’46,09“E
3a) Position calculator with Vincenty (direct)	54°09’54,44“N; 11°56’46,09“E	30m	45°	54°09′55,1261″N, 011°56′47,2592″E
3b) GEO_KOORD with Vincenty formula	54°09’54,44“N; 11°56’46,09“E	30m	45°	54°09’55,12“N; 011°56'47,26"E
3c) GEO_KOORD with formula (5)	54°09’54,44“N; 11°56’46,09“E	30m	45°	54°09'55,13"N; 011°56'47,26"E
4a) Position calculator with Vincenty (direct)	54°09’54,44“N; 11°56’46,09“E	60nm	45°	54°51′57,9347″N, 013°10′19,5304″E
4b) GEO_KOORD with Vincenty-formula	54°09’54,44“N; 11°56’46,09“E	60nm	45°	54°51'57,93"N; 013°10'19,53"E
4c) GEO_KOORD with formula (5)	54°09’54,44“N; 11°56’46,09”E“	60nm	45°	54°52'22,81"N; 013°09'18,92"E

b) Geo-coding of Videos

Different from digital photos, videos do not have a file scope, where metadata of images (EXIF, IPTC, XMP) can be stored as additional important information. Metadata of digital images may not only contain camera data but also the geographical coordinates of the location where the photo was taken. Displaying subtitles as an overlay would be a possibility to provide videos with geodata. Looking in more detail at the format of those subtitle files, it is straight forward to create one’s own subtitles with a text editor for videos in the DV format. Numerous professional programs, as well as efficient freeware, are available. However, time-consuming manual work would be needed for transferring geographical positions in such subtitle files. The need for automating this procedure was arising. At the same time the aim was to upgrade the program and to equip it with the following options- time synchronization of the devices providing data for the subtitles.

Reading out of logged data in device-specific format from various pieces of equipment, optional arrangement of the subtitle, not all available data, must always be displayed. Sometimes, a comment in the right place can be useful. Possibility of interpolation of data those are available in larger time intervals for continuous correction of the geodata according to (5) with an optional calculation method. If a file of the dive profile is available, the current diving depth may be assigned to the geo-position. This can be written in the corresponding gpx (GPS Exchange format) file as negative geographical height. In a following step, a 3 dimensional representation of the dive profile would be possible. Writing a results file in an easily readable format with the possibility of further processing. Meanwhile, a programming result named SUBTITLE (version 4) is available. The program can be obtained from the first mentioned author. The flowchart (Figure 10.11) clearly shows how the program basically works.

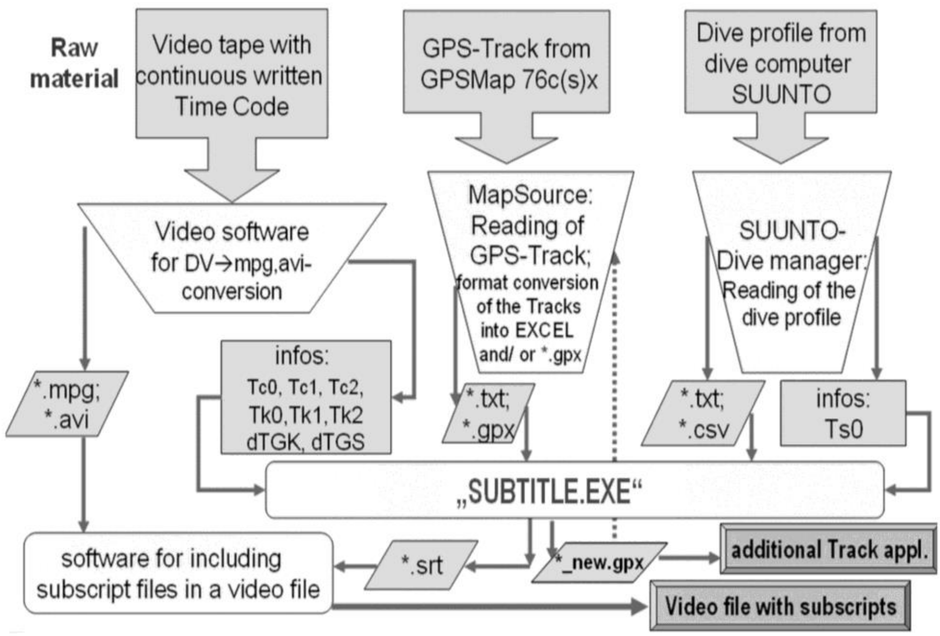


Figure 10.11. Flowchart of the SUBTITLE-program.

Initial data for SUBTITLE are

- the recorded GPS track e.g. in gpx format (output by Map Source).
- Underwater video in DV format (as mpg- or avi-file)
- Dive profile (data from a dive computer)
- Recently, data from a CTD probe (C=conductivity, T=temperature, D=depth) can also be read and associated with the geographical position.

The most important step for acceptable results is the time synchronization of all devices used. First the deviations from GPS time of all internal clocks in the devices (the underwater camera, the dive computer, CTD probe) must be detected:

dTGK = time difference between GPS and camera time
dTGS = time difference between GPS and dive computer (or CTD probe)

It must be decided whether to write subtitles for the whole video or just for a part of it. For this purpose information on the Time Code Tc and on the camera time Tk are required.

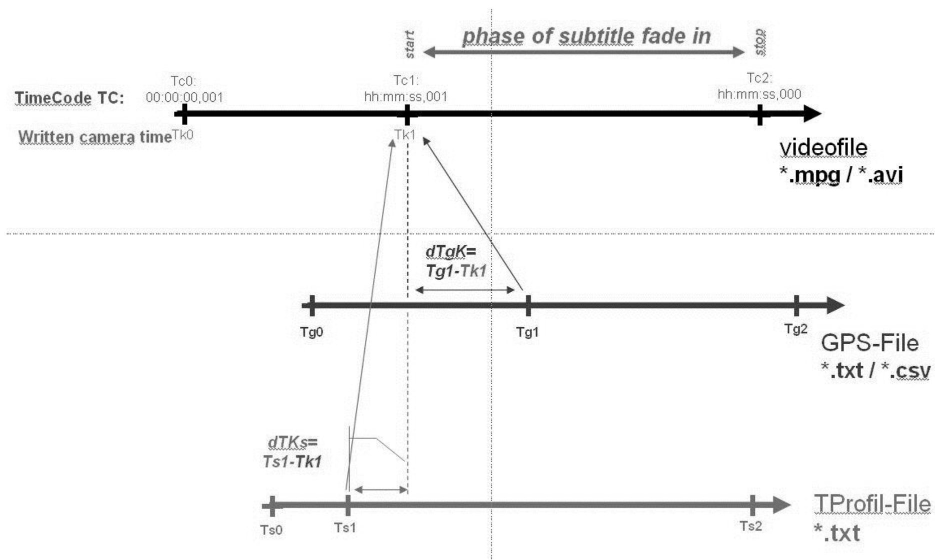


Figure 10.12. Time synchronization.

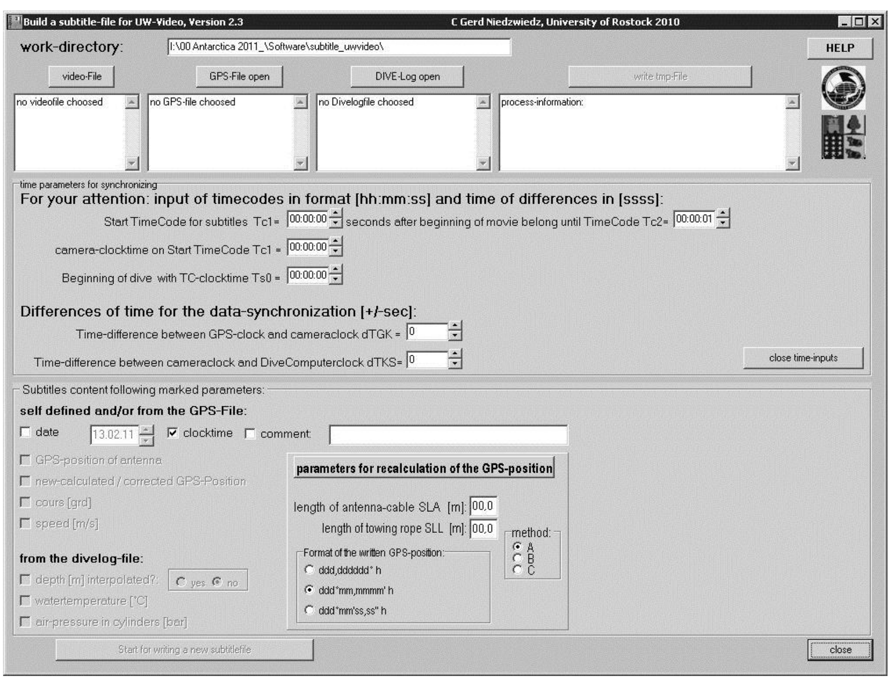


Figure10.13. Worksheet of the program SUBTITLE as hardcopy.

The dive computer applied always starts recording the dive profile at the time 00:00:00, so the information Ts0 must be recorded apart as the beginning of the dive. It starts to become tricky, if the start of the dive Ts0, the beginning of the video recording Tc0 (Tk0) or Tc1(Tk1), and switch-on of the GPS handhelds take place at different times and in addition there are time differences between the device-internal clocks. At least in this situation the manual creation of a subtitle file is very time-consuming and increases the risk of errors. The principle process of time synchronization is shown in Figure 10.12.

Results of the application of the program SUBTITLE (Figure 10.13) are:

- Sub-title file in the *.srt-format
- ASCII file (*.tmp), which includes all data from *.srt too, but is more easily readable
- Modified *.gpx file that, in addition, contains the diving depth, assigned to the geographical position.

10.5. Field Experiments and Applications

10.5.1. Underwater Monitoring on Artificial Reefs of the Baltic Sea

Near the Ostseebad Nienhagen, approx. 10 km west of Warnemünde/Germany, an artificial reef has been subject to scientific investigations since 2003. The reef consists of concrete elements with different weights and shapes, natural stones and netlike structures, which have been arranged in a particular configuration in an area of 200x200m at a water depth of 12 m (Figure 10.14).

The investigation of the impact of fishing on artificial structures was one of the major scientific tasks in the past. The investigations were linked to flow physical and biological data collections. The area was and still is regularly visited by research divers documenting the reef recovery by means of underwater photo and video recording (more information: http://www.riff-nienhagen.de/). In 2004, the artificial reef was surveyed by applying side-scan sonar for the first time. Five years later, these measurements were repeated with a special multi-beam echo sounder. Results from both methods are suitable to give an optical impression of the arrangement of the underwater structures.

After these numerous dives, it is now relatively easy for the scientists involved to identify where an underwater photo has been taken in the reef area. Nevertheless, the precise georeferencing of these photos is of interest for photo archiving and a later evaluation by other colleagues. In Figure 10.15, a dive course is shown which was swum by a research diver within the artificial reef, Nienhagen.

The representation of the track and the photo was done using Google Earth (version 6.2), although the suitability of the program for scientific purposes is restricted only. Today, professional GIS software is available (e.g. ARCVIEW), which also offers a popular option of Google Earth: the overlay of a recorded course on a background image with known projection. This is the case with side-scan and echo sounder images of the artificial reef Nienhagen. Figure 10.15 was created in this way.

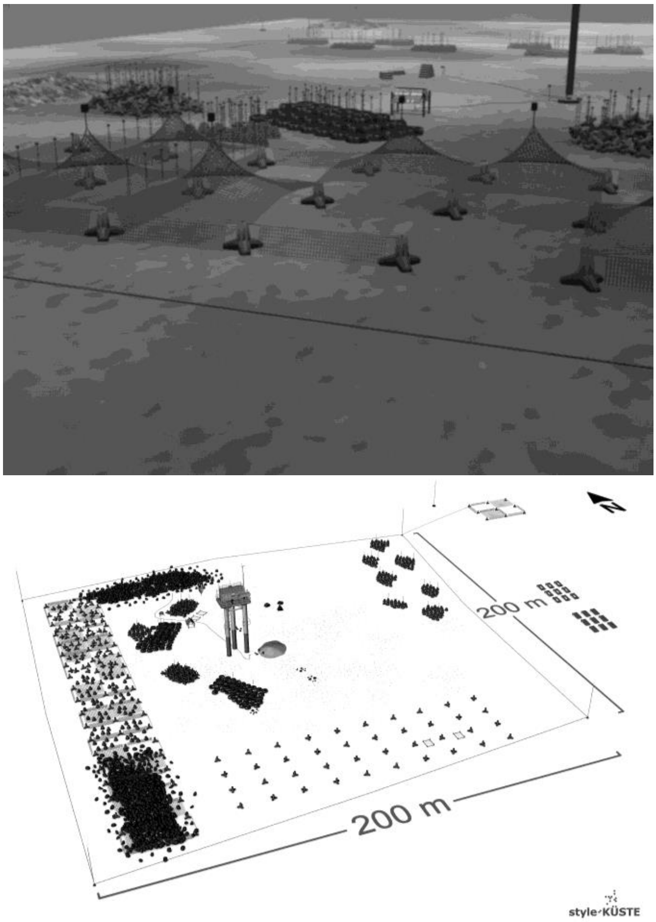


Figure 10.14. Impressions of the artificial reef, Nienhagen (Source: style-kueste.de).

Figure 10.15. Track of a dive in the artificial Baltic Sea reef Nienhagen and associated georeferenced underwater photo.

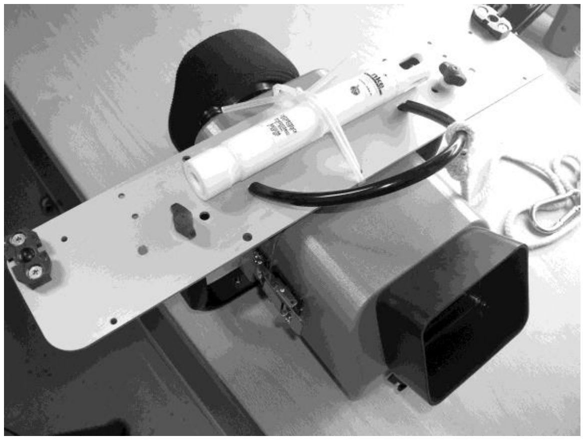


Figure 10.16. CTD probe attached to the underwater video camera.

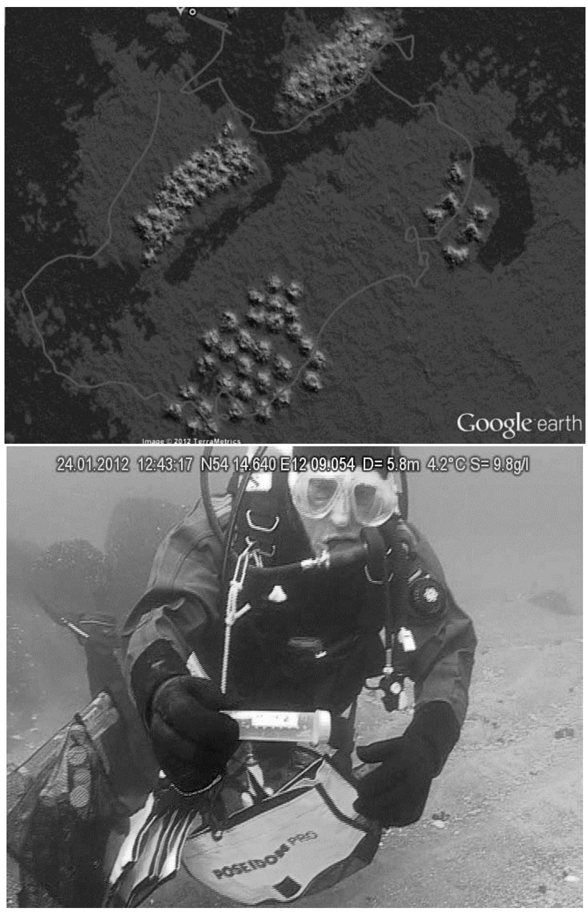


Figure 10.17. Video tracks in the reef area Rosenort with frozen image.

In 2009 a further artificial reef was built northeast of Warnemünde, 7 km off the coast section of Rosenort. Similar investigations as in the Nienhagen reef have taken place here. However, the built-up area is much smaller (30x40m) and the water depth is only 6-7m. Here, a geo-referenced underwater video monitoring with a CTD probe was carried out in January 2012 for the first time. A diver was operating an underwater video camera with a CTD probe attached to it (Figure 10.16).

Values of temperature, salinity and water depth were measured at intervals of 1 second and stored. Due to the additional use of the underwater GPS, it is now possible to associate not only the video image but also the CTD measurements to the geographical position. During the monitoring a diver took sediment samples at specific points. Figure 10.17 shows the video track leading through the reef area of Rosenort complemented by a frozen video image. In the subtitle of the frozen image the following information can be recognized date and time, geographical current position (GPS), depth, temperature, salinity (CTD probe).

10.5.2. Underwater Monitoring in the Antarctic

Georeferencing of habitats is a standard method in the field of terrestrial and nautical research, but a diver-towed GPS buoy was never used before under the harsh conditions of the Antarctic. Within the frame of a Chilean Biodiversity project at Fildes Bay, King George Island (South Shetlands), we used a diver-towed GPS along predefined transects from 2.5 to 30m depths during a two month stay in the Antarctic. Although the GPS signal of the Garmin 76csx handheld often was not perfect due to weather conditions, only a maximal horizontal error of up to 10m was shown on the display and all transects were realized as previously planned.

We recorded up to 10 photo quadrants (40x 60 cm) every 2,5 m depth and estimated the coverage and diversity of the marine benthos using the software CPCe 3.6 [26] (Figure 10.18). Quadrants were photographed perpendicular to the substratum using an aluminum rack on which the camera was fixed.

Such a photogrammetric, nondestructive assessment technique is commonly used to monitor changes of marine habitats due to anthropogenic factors over long time periods but the method requires ground-truthing. The advantage of this method is that the same study sites can be used without their excessive manipulations and quantitative information on species cover, density, and frequency can be analyzed [27]. The renunciation of bottom lines and additional markers excluded the risk that floating drift algae became entangled along transect.

Using a diver-towed GPS permitted us to locate even small communities over three subsequent years and to observe the development of huge sponges like Mycale tylotornota, Koltun 1964 (Figure 10.19). We included both hard bottom and soft bottom communities and identified more than 200 macro-fauna organisms by ground-truthing [28]

Additionally, the possibility to mark geographic positions below water allowed us to install cameras for longer time periods underwater without the need to mark the position with a buoy on the surface and risk its displacement by floating icebergs. Time lapse recording of movement of the limpet Nacella concinna (Strebel 1908) and the sea urchin Sterechinus neumayeri (Meissner 1900) was realized in shallow water and the camera position was recorded with the GPS (www.youtube.com/ watch?v=rKV8s00SFL8).

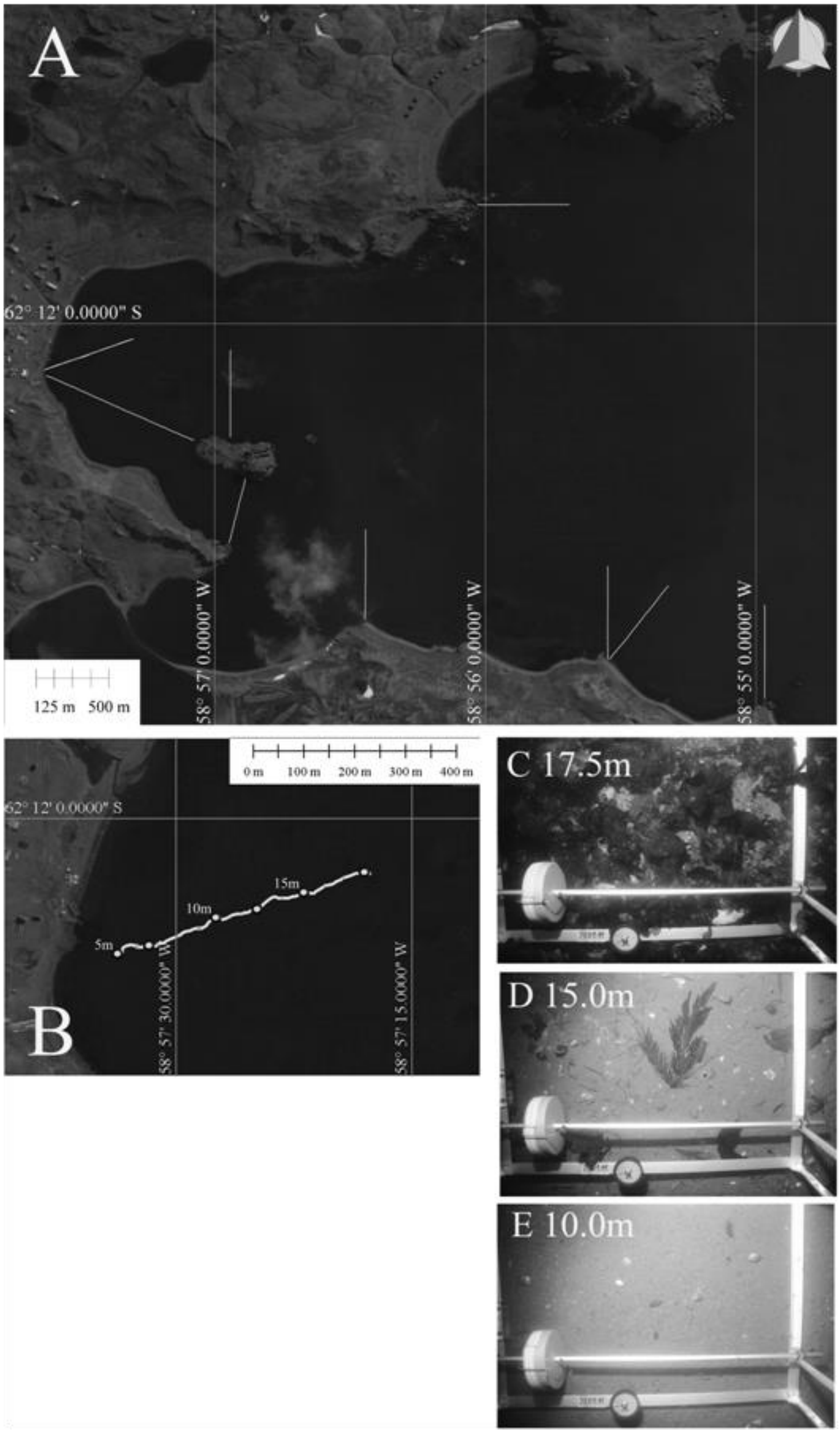


Figure 10.18. A) Monitoring transects realized in the inner part of Fildes Bay, Antarctic in 2012. B) High resolution crop of a single transect at the eastern part of the bay. Circles indicate the positions where images were taken. C-E) images of the bottom at 17.5, 15.0 and 10.0m depth, frame size 60x40cm.

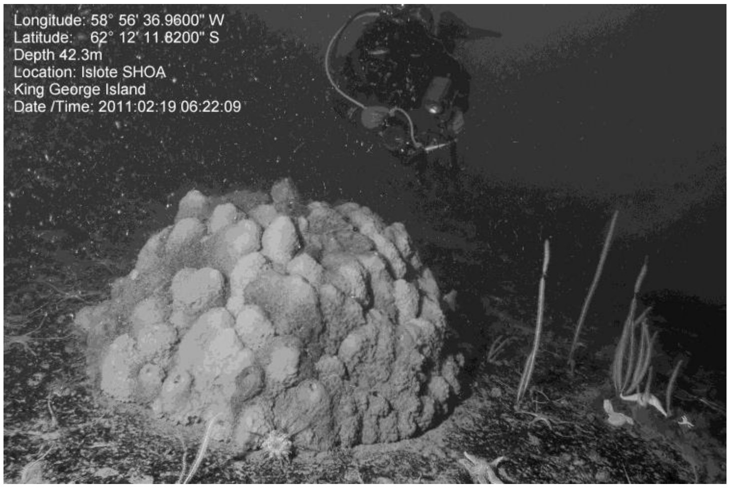


Figure 10.19. Huge sponges like Mycale tylotornota, Koltun 1964, occupying only a small area, were detected by scuba divers in a depth of 42m and marked with the GPS.

10.5.3. Underwater Monitoring in Shallow Water Applying a Scooter

The task to be fulfilled by divers in scientific underwater monitoring is often to swim along predefined courses and to document the ground with animals and plants of any form. Depending on the task and on the size of objects under investigation the speed of motion is more or less fast. While planning the operation, the required speed of the scuba diver is usually overestimated. Steps of too long distances are then expected. One facility is offered now-an underwater scooter. The Rostock research divers completed some dives with scooters and gained valuable experience:

- Scooter and underwater GPS complement one another excellently (similar to a car and the road navigation system).
- Planned courses (routes) can easily be followed without going up to change the course (hazardous “Yo-Yo” dives are avoided).
- The camera diver should ideally be towed by the scooter. This requires a towing rope of about 3 m (depending on the visibility under water) to be attached to the pull ring of the camera diver’s crotch belt. Thus, both hands remain free for camera handling. In the interest of high-quality underwater shots, the camera diver’s attention should not be drawn off by navigation or driving tasks.
- A powerful scooter must be used, which is capable of moving both the scooter driver and the camera diver through the water. The scooter power should cover a minimum running time of 1 hour at a speed of 0.2...0.5m/s.
- The underwater GPS attached to the scooter should have a sufficiently long antenna cable (S≈WDmax+5m). Lower angles of attack of cable create a lower hydrodynamic resistance while diving. In order to correct the geo-position due to the long antenna cable, now the offset Cx must be reduced by the length of the towing rope.

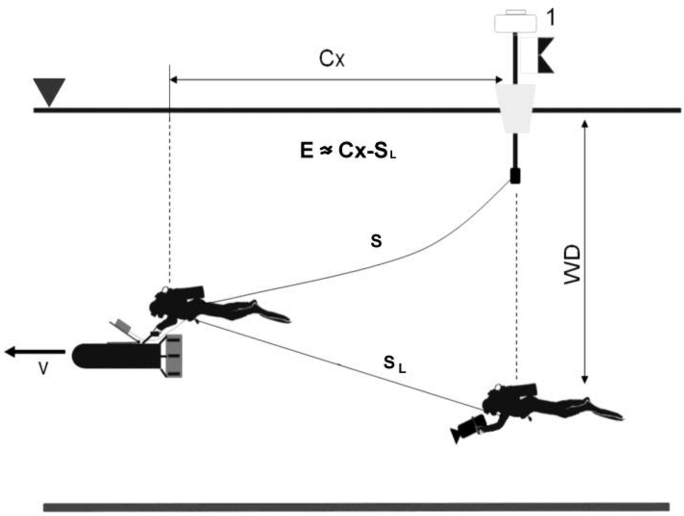


Figure 10.20. Sketch of the dive applying Scooter, underwater GPS and video camera (Including CTD probe).

Thus arises the device configuration of devices (Figure 10.20). The scooter application helped to at least double the distance covered by the divers, because the air consumption was greatly reduced. The video images are of much better quality than those which are produced during the fin swimming (less camera shakes). Accidental discoveries during a Scooter dive applying underwater video and GPS can be found again easily. In Figure 10.21, an old anchor is seen, which possibly is of archaeological interest and which had been discovered during a scooter dive with biological objectives (A video example can be seen at http://www.fotau.uni-rostock.de/berichte/monitoring-vor-nienhagen/). There is another valuable option in the evaluation of results: The geo-positions appearing in the video image allow the drawing of conclusions about the size of covered or populated areas. The formulas (5) can also be used for this.

Figure 10.21. Video freeze of a Scooter dive (including underwater GPS).

10.6. DISCUSSION

During the last 12 years, several researchers have used divers or equipment towed by boat which has recorded GPS positions at certain intervals [29, 30], but did not mention if and how the distance between boat and camera were corrected. Kenyon et al. [31] described a method in which divers were equipped with digital video cameras and other instruments and towed behind a small boat. They recorded the tow path by a GPS receiver onboard and applied a layback model for mapping the videos more accurately. However, no details about the layback model or its accuracy are given by the authors.

We used an underwater scooter in some of our experiments to increase monitoring range underwater, especially when we worked at a constant depth. A scooter is not recommended for less experienced divers because buoyancy control is more difficult and the risk of barotraumas and decompression sickness increases. Using a diver-towed GPS system together with a scooter always requires a layback model to correct the deviation between the diver and the GPS antenna.

We can summarize that diver-towed GPS systems or combinations of permanent recordings from boat and dragged camera systems are widely used, but it is still an exception that probable error terms are mentioned by the monitoring teams [15]. The best signal quality will be achieved when the GPS system remains on the water surface, because the performance of a GPS receiver can be significantly degraded by using long antenna cables (> 5m). Calculation based using 35dB GPS antenna (Receiver Minimum Input Level = 20dB) showed that LMR/CNT 195and RG59 cable types will completely loose the signal when longer than 21m whereas a LMR/CNT600 cable might transmit data over a distance of 91m [32]. However, our own praxis experiments demonstrated that signal performance is strongly reduced when using any kind of long cable decreasing the accuracy of the GPS position. The usage of small inline amplifiers may reduce this problem.

The decision to use a GPS device below water for navigation or to use a towed GPS at the surface depends on the monitoring design proposed by the survey group. The advantage of taking the GPS below water is the repeatability of transects without any additional markers and the possibility to mark points of interest directly below water. Kuch et al. [33] worked in the same way as we did and developed a GPS diving computer for underwater tracking and mapping. The main difference between the development of Kuch et al. and our GPS unit is the integration of the GPS information in the diving computer and the usage of a serial port for communication between the computer and the GPS transmitter, a Telit GM862-GPS module, which was fixed at the buoy system.

Working with a towed underwater GPS requires a profound knowledge of the different error resources; the signal degradation along the cable as mentioned before, the accuracy of the GPS locations measured by the GPS and the control of the vertical position of the surface buoy above the diver. Signal degradation by long cables can be reduced by amplifiers and better accuracy of GPS locations can be obtained in different ways and is discussed in detail elsewhere [34]. Enhancing the accuracy of the position of the surface buoy up to sub-meter exactness is primarily a question of the investment made. From a practical point of view it must be questioned if a GPS with sub-meter accuracy makes sense when the GPS is diver-towed, because the correction of the deviation of the buoy in relation to the diver is much more difficult to handle. A layback model as presented by us can correct this error very precisely, but only if all parameters are known and there is no unsteady current sideways or if a uniform current through the water column exists.

A towed GPS may not be the only possibility to track a route below water, so there are other techniques to transmit a signal below water. These techniques are not only developed for diving purposes but also for tracking marine organisms. Acoustic transmitters have been implanted in marine fish or attached externally. These transmitters emit a pulse of sound called a ping, decoded by acoustic receivers. To measure the distance to a diver or a marine organism, the time from transmission of a ping to its reception is measured. If the speed of sound is known, the information can be converted into a range. Movement patterns of individuals can be tagged with passive acoustic receivers, actively or with high resolution passive acoustic monitoring systems [35].

The ability to detect the emitted signal varies with the environmental conditions, such as surface conditions, physical disturbances and underwater substrates and vegetation [36]. Another tag developed for marking marine mammals in a different way. The tag consists of, among other things, a depth, speed, three axes of magnetic field, three axes of acceleration and a GPS. The GPS works only when the tagged individual is at the surface, however the combination of sensors allows the reconstruction of the full underwater trajectory [37]. Nevertheless several error corrections can be done to improve the accuracy [38].

Recently, Shb Instruments Inc. announced the Navimate™ that should provide divers with GPS navigation and positioning while underwater. The GPS signal is transmitted via a floating radio antenna using acoustic signals. Unfortunately, positioning errors, accuracy of transmitted signals and other problems related to acoustic signal transmission are often not reported, although field studies demonstrate that they are common [36, 39]. The accuracy and precision for tracking diving operations can be improved using long baseline (LBL) or GPS intelligent buoys, but these systems are expensive and often time-consuming. Nevertheless, a lot of research and development remains to be done for yielding a good performance in the presence of multi-path effects and acoustic outliers [40, 41].

A final comment should be made in relation to the usage of Google Earth maps for choosing sampling sites or mapping [12]. Google Earth hosts cost-free high-resolution images, which represents a unique resource for scientific research. Nevertheless the applicability of these maps for navigation is limited when exact positioning is needed [42, 43]. Ground-truthing should be done in any case.

CONCLUSION

For research diver, the high precision of the geo-position of underwater navigation system is very important. This chapter showed a basic method for how to determine the distance between the GPS antenna and the position of the diver applying a tethered underwater GPS. In certain cases of application it was possible to correct the error by calculation. The necessary algorithms are provided as well. Thus all parameters and procedures required for the simplest determination of positions under water by means of GPS should be known, in order to perform a scientific underwater monitoring with sufficient precision.

Also changes of the hardware of devices can already be foreseen. The GARMIN GPS 76(csx) used previously, is no longer being produced. But, the Garmin GPS 78 does not fit into the existing underwater housing. This new GPS handheld is slightly smaller than its preceding models. Here we have the same situation as encountered for underwater photography and underwater videography-when a new camera does not match an old underwater housing. This means, new underwater housings must be built that fit exactly to the GPS handheld applied. The same applies if soon the Galileo GPS will be used. The future use of an antenna amplifier will help to keep the loss of GPS signal strength small even with long cables.

From the point of view the aim of no use of an antenna cable should be to completely in the future. The data transmission should be done wirelessly in hydro-acoustic form. Appropriate technical solutions exist already today, but the wireless transmission of the GPS signals through water alone is not sufficient. There will be some development efforts required to integrate distance and direction measurements into the navigation system. It is the only way to determine the spatial distance between the GPS antenna and the diver, in other words, the components of the distance vector must be sufficiently precise as well.

APPENDIX 10.1. SYMBOLS UND ABBREVIATIONS

A -	Starting position point = position of the GPS-buoy	[φ1, λ1]
B -	target position point = position of the video camera	[φ2, λ2]
$\vec{C}$ -	difference between GPS-buoy position and diver as vector with the components (Cx, Cy, Cz=WD)	[m]
Cx_m-	average value of the Cx with WD=const. and v=0,1 … 1,0m/s calculated by KABKUR	[m]
Cx_th-	theoretical value of Cx, calculated with a simple formula	[m]
d -	diameter of antenna cable	[m]
E -	distance	[m]
EXIF-	exchangeable image file format	
$\vec{F}_0$ -	initial force at lower cable end	[N]
$\vec{F}_g$ -	total external force at upper cable end	[N]
GPS-	Global Positioning System	
i -	name of an element (index)	[-]
IPTC-	International Press Telecommunications Council	
K -	empirical factor	[-]
n -	amount of cable elements	[-]
nm -	nautical mile = 1.851m	
Q -	weight of a cable element in the water	[N]
q -	weight of 1m antenna cable in the water	[N/m]
RE -	Radius of the earth at aquator	[m]
R_{GPS}-	error range of the GPS-handheld	[m]
RP -	Radius of the earth over the latitude φ	[m]

S -	length of the antenna cable	[m]
SL -	length of the towing rope	[m]
T -	Time	[hh:mm:ss]
dT -	Time difference	[sec]
UW-	GPS- Underwater-Global Positioning System	[-]
v-	current, speed, velocity, inflow	[m/s]
WAAS-	wide area augmentation system	[-]
WD-	depth of diver	[m]
XMP-	Extensible Metadata Platform	
x,y,z-	Cartesian coordinates	[m]
Δ…-	difference of …	
φ -	Latitude	[°]
λ -	Longitude	[°]
ω -	angle of course / bearing	[°]

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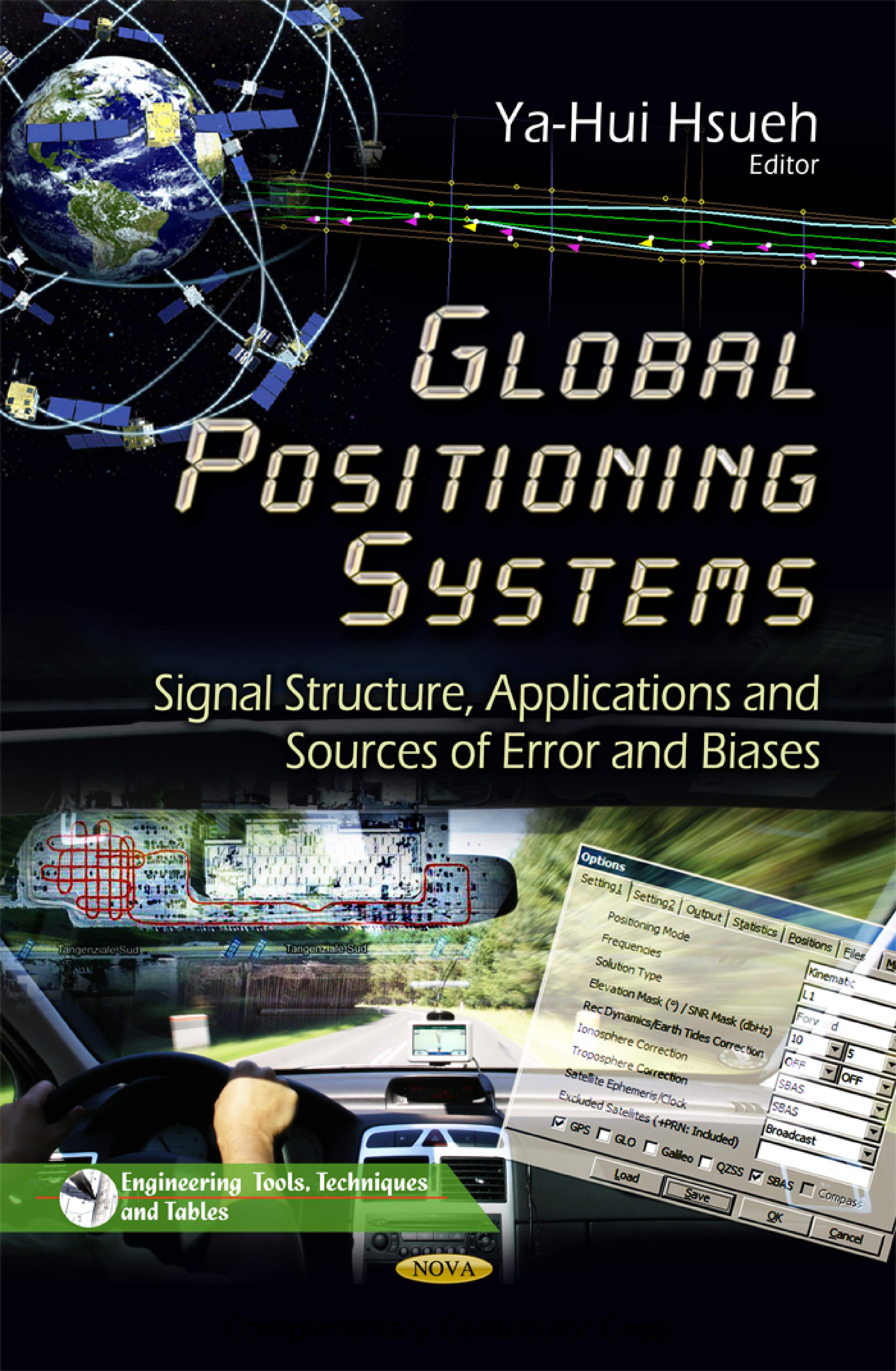

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