

Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping

1

Series Editor

Dr. Nikolas Xiros
School of Naval Architecture and Marine Engineering
University of New Orleans
2000 Lakeshore Dr. Ste 914
New Orleans, LA 70124
USA
E-mail: nxiros@uno.edu

For further volumes:
<http://www.springer.com/series/10523>

Chrystel Gelin

A High-Rate
Virtual Instrument
of Marine Vehicle
Motions for Underwater
Navigation and Ocean
Remote Sensing



Springer

Author
Chrystel Gelin
San Diego, CA
USA

ISSN 2194-8445
ISBN 978-3-642-32014-9
DOI 10.1007/978-3-642-32015-6
Springer Heidelberg New York Dordrecht London

e-ISSN 2194-8453
e-ISBN 978-3-642-32015-6

Library of Congress Control Number: 2012943050

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Dedication

This work was conducted on the basis of the author's thesis within Florida Atlantic University's Ocean Engineering Graduate Program requirements with the advice of Dr. N. Xiros and advisory committee members Drs. M. Dhanak, F. Driscoll, P. Beaujean and J. VanZwieten.

This book is dedicated to my family, friends and colleagues who have supported me through the years and kept on believing in the work I did and its happy ending.

I'm dedicating it particularly to my dear husband, Gregory, who has put up with these many years of me working long hours, my teeth grinding preventing him from sleeping and the overall stress on our household during that journey.

I also dedicate this work to my tiger team, my grandmother, Lea, my mother, Chantal, my father, Jacques, my little brother, Cyril and my best friend Anne. Finally I look forward for my son, James, to be of age to share that work and experience with him and why not inspire a scientific path...

Thank you. Stubbornness does pay sometimes ...

Contents

List of Figures	XI
List of Tables	XVII
1 Introduction	1
1.1 Autonomous Surface Vessels for Hydrographic Data Acquisition	1
1.2 Gateway USVs	2
1.3 Proposed System	4
1.4 Problem Statement	4
1.5 Contributions.....	5
1.5.1 Book Outline	6
2 Instrumentation and Data Acquisition System	7
2.1 The Sensors	7
2.1.1 Acoustic Doppler Current Profiler (ADCP)	7
2.1.2 Inertial Measurement Unit IMU	10
2.1.3 Compass TCM2.....	11
2.1.4 Tilt Sensor	12
2.1.5 Global Positioning System GPS	13
2.2 Data Acquisition System	13
2.2.1 Host Computer	14
2.2.2 Target Computer	14
2.2.3 USV Hardware Layout	15
2.2.4 Computer Networking	16
2.2.5 Software Overview	17
3 Data Processing	19
3.1 Reference Frames	19
3.1.1 Earth-Centered Reference Frames	20
3.1.2 North East Down Reference Frame	21
3.1.3 Body Fixed Reference Frame	21
3.1.4 Vessel States	22
3.2 Coordinate Transformation	23
3.2.1 Transformation from Geodetic to ECEF and from ECEF to NED	23

3.2.2	Transformations from Component Reference Systems to Body Fixed Reference System	24
3.2.3	Transformations from Body Fixed Frame to NED	25
3.3	Data Fusion	25
3.3.1	Data Fusion Overview	26
3.3.2	Estimation of the Euler Angles	27
3.3.2.1	Estimation of the Ship's Velocity and Position	33
3.4	ADCP Processing	34
4	Motion Observation and Experimental Results	37
4.1	Vertical Motion	37
4.1.1	Study of the Acceleration	37
4.1.2	Velocity Calculations	42
4.1.2.1	Vertical Velocity Resulting from Integrating Acceleration and Removing the Induced Trend	42
4.1.2.2	Vertical Velocity Resulting from High-Pass Filtering the Integrated Acceleration	43
4.1.2.3	Vertical Velocity Using the Data Fusion Technique	44
4.1.3	Vertical Position Calculations	45
4.1.3.1	Vertical Position Calculated Using the High Pass Filtered Integrated Velocity	46
4.1.3.2	Vertical Position Calculated Using the Data Fusion Technique	46
4.2	Data Acquisition System Lab Testing	47
4.2.1	Step 1: Processing of Individual Measurements	49
4.2.2	Step 2: Validate the Choice for the Data Fusion Frequency	56
4.2.3	Step 3: Low-Pass Filtering of the Merged and DGPS Data at the Data Fusion Frequency and Conclusion on Their Agreement Using the Crosscorrelation Method	59
4.2.4	Step 4: High-Pass Filtering of the Merged Signals to Conclude on the Signals Standard Deviation	60
5	At-Sea Experiment of Data Acquisition System	61
5.1	Motion Data Acquisition Measurements and Navigational Data Fusion Results	62
5.2	ADCP Unreferenced and Corrected Measurements	64
5.2.1	Correction of the ADCP Data in the Beam Coordinate Frame	65
5.2.1.1	Water Current Measured for the First Maneuver, L-Shape Track Heading South Then East	65
5.2.1.2	Water Current Measured for the Second Maneuver, Linear Track Heading South Then North	73
5.2.2	Correction of the ADCP Data in the North-East-Up Frame, the ADCP's Earth Reference Frame	77
5.2.2.1	Water Current Measured, at the First Bin, in the NEU Frame for the L-Shape Track and the Linear Track	78

5.2.2.2 Water Current Measured Observing the ADCP
Velocity Profiles in the NEU Frame for the L-Shape
Track and the Linear Track.....79

5.3 Conclusion on the At-Sea Mission.....84

6 Conclusion85

References93

Appendix A – Native Output of the Instruments95

Appendix B – Setup and Acquisition of the ADCP.....97

List of Figures

Fig. 1 Autonomous Surface Craft ACES.....	2
Fig. 2 Autonomous Surface Craft DELFIM, part of the ASIMOV project, designed, and built by the Institute for System and Robotics, beginning in 1998.....	3
Fig. 3 Diagrammatic representation of the FAU Autonomous Surface Vessel.....	4
Fig. 4 Picture of an RDI Acoustic Doppler Current Profiler.....	8
Fig. 5 Diagram of transmission principle of an Acoustic Doppler Current Profiler, mounted onboard a ship, showing the 4 directions of the 4 beams.....	8
Fig. 6 ADCP Beam orientation with beam 3 at 45 degrees with respect to the heading, looking from underneath the boat.....	9
Fig. 7 ADCP velocity standard deviation in function of the size of the bins and number of pings per ensemble chosen on the mission command set....	10
Fig. 8 BEI Inertial Measurement Unit Motion Pack II.....	11
Fig. 9 TCM2-20 biaxial inclinometer and a triaxial magnetometer compass module.....	11
Fig. 10 Fredericks Company ± 60 degree Angle Range tilt sensor.....	12
Fig. 11 Diagrammatic representation of the 24 satellites of the Global Positioning System.....	13
Fig. 12 Picture of the GARMIN Global Positioning System 76 receiver.....	13
Fig. 13 Overview of the data acquisition system, including the sensors, computers and links.....	14
Fig. 14 Picture of the acquisition setup.....	15
Fig. 15 Block diagram of the acquisition hardware, including the sensors, computers and links.....	16
Fig. 16 Belkin 802.11g Wireless Cable/DSL Gateway Router and the 802.11g Wireless Notebook Network Card.....	16
Fig. 17 Block diagram of the links between the host PC, the target PC104 stack, the sensors, and Operating Systems of the entities.....	17
Fig. 18 Representation of the axis of the Earth Centered Earth Fixed and Earth Centered Inertial Frames.....	20
Fig. 19 Schematic representation of the North East Down reference frame.....	21
Fig. 20 Ship-fixed coordinate reference frame (red) and 6 degrees of Freedom motion variables for a marine vessel (sway, surge, heave, pitch, roll and yaw) (Fossen 1994).....	22

Fig. 21 Diagram of the sensors output variables and the coordinate transformations23

Fig. 22 Representation of the Ellipsoid parameters24

Fig. 23 Acceleration measurements in function of the rotation angles.....28

Fig. 24 Comparison between the low frequency estimates of Euler angle $\phi L(a)$ ($\theta L(b)$) obtained from the IMU (blue) and from the Tilt sensor (red).....29

Fig. 25 Diagram of the data fusion IMU / TCM2/ Tilt sensor to obtain Euler angles, β30

Fig. 26 Comparison between the Euler angles ϕL (a), θL (b) from accelerometers, blue and ϕ (a), θ (b) from data fusion, red and between the compass heading, blue and Euler angle ψ from data fusion in red (c). The black is the difference of blue and red signals31

Fig. 27 During the third part of the test, high frequency set of motion, comparison between the high frequency component of the integral of Euler rate $\dot{\phi}$ (a), $\dot{\theta}$ (b), $\dot{\psi}$ (c) in blue, and the high frequency component of the merged Euler angle ϕ (a), θ (b) and ψ (c) in red. The black is the difference of the two signals in each plot.....32

Fig. 28 In red, PSD of Merged Euler angle ϕ (a), θ (b) and ψ (c); in blue, PSD of Euler angle from tilt sensor ϕL (a), θL (b), and $\psi L(c)$; in black, PSD of integrated Euler rate $\dot{\phi}$ (a), $\dot{\theta}$ (b), and $\dot{\psi}$ (c).....33

Fig. 29 Diagrammatic representation of the data fusion of the IMU data and the GPS data used to obtain the ships velocity V33

Fig. 30 ADCP beam and reference frame.....35

Fig. 31 Vertical motion experiment setup.37

Fig. 32 Vertical motion experiment: raw vertical acceleration A_z38

Fig. 33 A_z spectrum from top to bottom for the set 1 (a), 3 (c) and 5 (e) of periods about 5, 15 and 25 s (left side) and filtering effect on the signal (right side) for the set 1 (b), 3 (d) and 5 (f)39

Fig. 34 Measured and filtered acceleration for periods about 5 (a), 15 (b) and 25s (c). Acceleration measurements are in black while filtered accelerations are in red.40

Fig. 35 A_z PSD for the set 1, 2 and 3 (b) of periods about 5, 10 and 15 s, and for the set 4, 5 and 6 (a) of periods about 20, 25, and 35 s.40

Fig. 36 Close up of the acceleration for the set 1 (a), 3 (b) and 5 (c) of periods about 5, 15 and 25s with the expected motion in red, the system acceleration in blue and the difference between the signals in black.41

Fig. 37 Difference, in black, between the expected velocity V_z , red, and the obtained velocity using the *detrend* function on the integrated acceleration in blue for the set 1 (a), 3 (b) and 5 (c).....43

Fig. 38 For the sets 1 (a), 3 (b) and 5 (c), velocity obtained using a high-pass filter on the integrated acceleration, in blue, plotted against the expected velocity V_z , in red. The difference between the two signals is in black.....44

Fig. 39 For the sets 1 (a), 3 (b) and 5 (c), velocity obtained by data fusion, in blue, plotted against the expected velocity V_z , in red. The difference between the two signals is in black.45

Fig. 40 For the sets 1 (a), 3 (b) and 5 (c), position obtained using a high pass filter on the integrated velocity, in blue, plotted against the expected position Z, in red. The difference between the two signals is in black.46

Fig. 41 For the sets 1 (a), 3 (b) and 5 (c), position obtained by data fusion, in blue, plotted against the expected position Z, in red. The difference between the two signals is in black.47

Fig. 42 IMU, tilt sensor, and TCM2 compass attached to a rigid plate attached to the cart.47

Fig. 43 Methodology used to find the data fusion frequency between IMU and GPS measurement to recover full frequency estimate of the system’s position and velocity.49

Fig. 44 Square path, as perceived by the DGPS.49

Fig. 45 Square path proceeding in a zigzag pattern between corners, as perceived by the DGPS.50

Fig. 46 Circle path as perceived by the DGPS.51

Fig. 47 Roll and Pitch of the cart measured by the tilt sensor during the first trajectory ((a) and (b)), the second trajectory ((c) and (d)) and the third trajectory ((e) and (f)).52

Fig. 48 PSD of the north component, in blue, and the east component, in red, of the IMU acceleration during square trajectory (a), square path by processing in zigzag course (b) and the circle trajectory (c).53

Fig. 49 Influence of frequencies above 2Hz on the IMU acceleration measurements for the three trajectories of the on shore test of the data acquisition system.54

Fig. 50 PSD of the DGPS position (a), DGPS velocity (b) and IMU acceleration (c) for the first trajectory of the on shore test, following a square path. The blue signal corresponds to the north component of the measurement and the red signal to the east component.55

Fig. 51 Data fusion diagram between the IMU acceleration data and the DGPS velocity measurements in order to obtain the enhanced velocity estimate.56

Fig. 52 PSD at particular steps of the data fusion process between the DGPS north component velocity and the IMU north component acceleration.57

Fig. 53 Comparison in the time domain between the merged velocity (red) and the velocity obtained by direct integration of the raw IMU acceleration signal (black). The blue signal is the DGPS velocity measurement. The upper panel shows the north component of the signal (a) and the lower, the east component (b)58

Fig. 54 Data fusion diagram between the DGPS position measurement and the merged velocity estimate obtained by fusing the IMU acceleration data and the DGPS velocity.59

Fig. 55 Crosscorrelation (a) (respectively (b)) between the north, (respectively east) component of the DGPS velocity and the north (respectively east) component of the merged velocity estimates. Similarly, (c) (respectively (d)) corresponds to the crosscorrelation between the north (respectively east) component of the DGPS position and the north (respectively east) component of the merged position estimates.....60

Fig. 56 The Florida Current.....61

Fig. 57 Trajectory perceived by the DGPS during the first (a) and second (b) maneuver at sea.62

Fig. 58 Close ups around the data fusion frequency, 0.05Hz, of the PSD of the velocity measurement from the DGPS (blue), the acceleration estimate from the IMU (black) and the enhanced estimate of the velocity obtained by data fusion (red).....63

Fig. 59 Time series of the vessel’s enhance velocity measurement obtained by data fusion with its north (east, down) component in blue (red, black) for the first maneuver (a, b, c) and second maneuver (d, e, f)63

Fig. 60 Diagram of the necessary reference frame transformations to transform the vessel’s enhanced velocity measured by the data acquisition system into the ADCP Beam coordinate frame.65

Fig. 61 Ship velocity, in blue, along beam 2 (a), and 3 (d) compare to the contaminated measurement of the water current, in black, along beam 2 (b) and 3 (e), and to the true water current, in red, along beam 2 (c) and 3 (f) during the first maneuver while the beams 2 and 3 are looking forward.66

Fig. 62 Ship velocity, in blue, along beam 1 (a), and 4 (d) compare to the contaminated measure of the water current, in black, along beam 1 (b) and 4 (e), and to the true water current, in red, along beam 1 (c) and 4 (f) during the first maneuver while the beams 1 and 4 are looking aft.67

Fig. 63 Uncorrected ADCP velocity profile along beam 2, looking forward, during the first maneuver going south then east.....68

Fig. 64 Corrected ADCP velocity profile along beam 2, looking forward, during the first maneuver going south then east.69

Fig. 65 Uncorrected ADCP velocity profile along beam 3, looking forward, during the first maneuver going south then east.....69

Fig. 66 Corrected ADCP velocity profile along beam 3, looking forward, during the first maneuver going south then east.70

Fig. 67 Uncorrected ADCP velocity profile along beam 1, looking aft, during the first maneuver going south then east.....70

Fig. 68 Corrected ADCP velocity profile along beam 1, looking aft, during the first maneuver going south then east.71

Fig. 69 Uncorrected ADCP velocity profile along beam 4, looking aft, during the first maneuver going south then east.....71

Fig. 70 Corrected ADCP velocity profile along beam 4, looking aft, during the first maneuver going south then east.....72

Fig. 71 Ship velocity, in blue, along beam 2 (a), and 3 (d) compare to the contaminated measure of the water current, in black, along beam 2 (b) and 3 (e), and to the true water current, in red, along beam 2 (c) and 34 (f) during the second maneuver while the beams 2 and 3 are looking forward.74

Fig. 72 Ship velocity, in blue, along beam 1 (a), and 4 (d) compare to the contaminated measure of the water current, in black, along beam 1 (b) and 4 (e), and to the true water current, in red, along beam 1 (c) and 4 (f) during the second maneuver while the beams 1 and 4 are looking aft.75

Fig. 73 Diagram of the necessary reference frame transformations to transform the ADCP data into the North-East-Up coordinate frame where the enhanced velocity measurement of the vessel is available.77

Fig. 74 Time series of the north component of the ship (blue), of the contaminated water current measured by the ADCP in the middle of the first bin (black) and of the water current resulting from its correction (red) in the NEU during the first (a, b an c) and the second maneuver (d, e, and f).....78

Fig. 75 Time series of the east component of the ship (blue), of the contaminated water current measured by the ADCP in the middle of the first bin (black) and of the water current resulting from its correction (red) during the first (a, b an c) and the second maneuver (d, e, and f).78

Fig. 76 Uncorrected north component of the ADCP velocity profile during the first maneuver of the mission at sea, creating an L-shape track going south then east.80

Fig. 77 Corrected north component of the ADCP velocity profile during the first maneuver of the mission at sea, creating an L-shape track going south then east.80

Fig. 78 Uncorrected east component of the ADCP velocity profile during the first maneuver of the mission at sea, creating an L-shape track going south then east.81

Fig. 79 Corrected east component of the ADCP velocity profile during the first maneuver of the mission at sea, creating an L-shape track going south then east.....81

Fig. 80 Uncorrected north component of the ADCP velocity profile during the second maneuver of the mission at sea, following a straight line track going south then north.82

Fig. 81 Corrected north component of the ADCP velocity profile during the second maneuver of the mission at sea, following a straight line track going south then north.82

Fig. 82 Uncorrected east component of the ADCP velocity profile during the second maneuver of the mission at sea, following a straight line track going south then north. 83

Fig. 83 Corrected east component of the ADCP velocity profile during the second maneuver of the mission at sea, following a straight line track going south then north. 83

Fig. 84 Diagram of the data fusion IMU / TCM2/ Tilt sensor to obtain Euler angles, β 86

Fig. 85 Diagram of the data fusion between the IMU acceleration data and the DGPS velocity measurements in order to obtain the enhanced velocity estimate..... 88

Fig. 86 Diagram of the data fusion process between the DGPS position measurement and the merged velocity estimate obtained by fusing the IMU acceleration data and the DGPS velocity. 88

Fig. 87 Google Earth visualization of the mission at sea with the two maneuvers, first goes south-east then south-north..... 91

List of Tables

Table 1	Specifications of the 300 KHz ADCP RDI Workhorse Sentinel	9
Table 2	Specifications of the BEI Inertial Measurement Unit MotionPakII	11
Table 3	Specifications of the TCM2 biaxial inclinometer and a triaxial magnetometer compass module	12
Table 4	Specifications of the Fredericks Company ± 60 Degree Angle Range tilt sensor	12
Table 5	Specifications of the GARMIN Global Positioning System 76 receiver	13
Table 6	Mean and standard deviation of the tilt sensors' roll and pitch as well as the influence it could have on the IMU acceleration if not considered for the three trajectories of the on shore test of the data acquisition system.	52
Table 7	Results from the peaks of frequency detection corresponding to the cart's motion for the three trajectories.....	56
Table 8	Estimates of the standard deviation of the merged velocity signal for the three trajectories of the on shore data acquisition test.	60
Table 9	Ship's enhanced velocity measurement, uncorrected and corrected ADCP water current measurement in beam coordinates, at the first bin, during the first maneuver	67
Table 10	Estimates of uncorrected and corrected ADCP water current measurement looking at the velocity profiles in beam coordinates during the first maneuver.	73
Table 11	Ship's velocity, uncorrected and corrected ADCP water current measurement in beam coordinates, for the first bin, during the second maneuver	75
Table 12	Estimation of uncorrected and corrected ADCP water current measurement looking at the velocity profiles in beam coordinates during the second maneuver.....	76
Table 13	Ship's velocity, uncorrected and corrected ADCP water current measurement in North-East-Up coordinates, for the first bin, during the first and second maneuver.....	79
Table 14	Estimation of uncorrected and corrected ADCP water current measurement looking at the velocity profiles in NEU coordinates during the first and second maneuver.....	84
Table 15	Estimates of the standard deviation of the merged velocity signal for the three trajectories of the on shore data acquisition test.	89

Table 16 Summary of water current estimates obtain by correcting the ADCP data during the two maneuvers at sea.90

Table 17 Estimated standard deviation of the ADCP velocity during the first and second maneuver at sea in correlation to the bin size, using the standard deviation of the error velocity.....91

Table 18 RS232 Registers.....97

Table 19 PD0 standard output data buffer format.....98