Manoeuvring Trials Using the *MUN Explorer* AUV:

An Overview of the Vehicle's Response during Sea Trials

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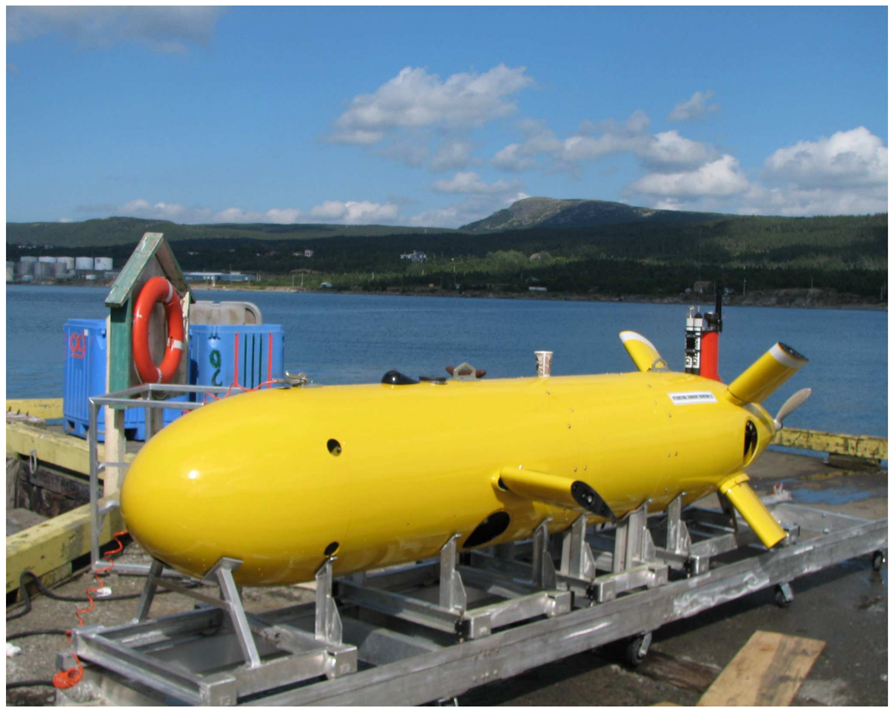
Introduction – **The *MUN Explorer* AUV**

The *MUN Explorer* AUV is a multi-user vehicle primarily for research purpose in Newfoundland and other parts of Canada.



Designed and built by the International Submarine Engineering Ltd (ISE), in Vancouver, BC, Canada

Objectives

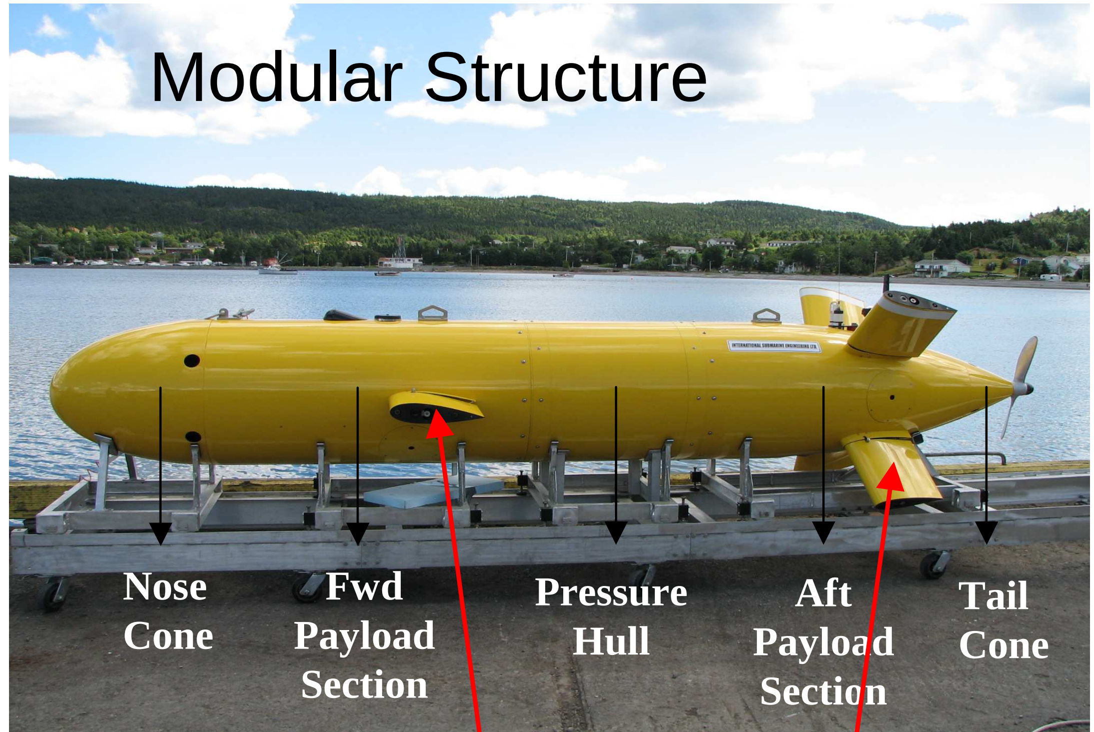
Perform various sea trials using the *MUN Explorer* AUV in order to:

- use the experimentally-obtained manoeuvring data to validate a hydrodynamic simulation model based on "component build-up method".
- study the performance of the vehicle in different operational scenarios

  - path keeping ability, path changing ability
- study the efficiency of the vehicle as a sensor platform to perform environmental monitoring as well as to collect useful information (data).
- assess the quality of data acquired and identify the limitations, if any

The *MUN Explorer* AUV - **Features**

- Length – 4.5 m
- Diameter – 69 cm
- Mass – 630 kg
- Displacement – 636 kg



4 aft X-planes

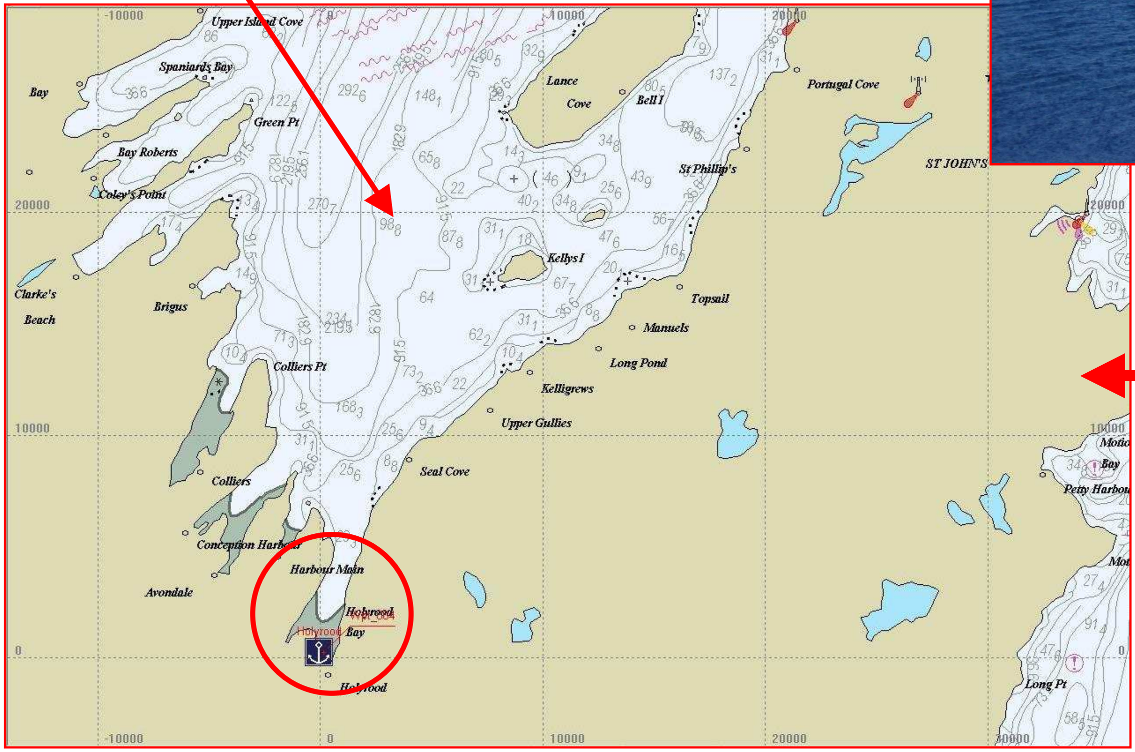
2 forward dive planes

Propulsion – twin-bladed propeller
Manoeuvring – six control planes
Energy – Lithium ion batteries
Retractable communications mast
Maximum speed - 2.5 m/s
Maximum depth - 3000 m
Maximum payload – 150 kg

Experimental Setup – **Location**

Holyrood, Newfoundland

Conception Bay



Topographical map in electronic chart - “FleetManager”

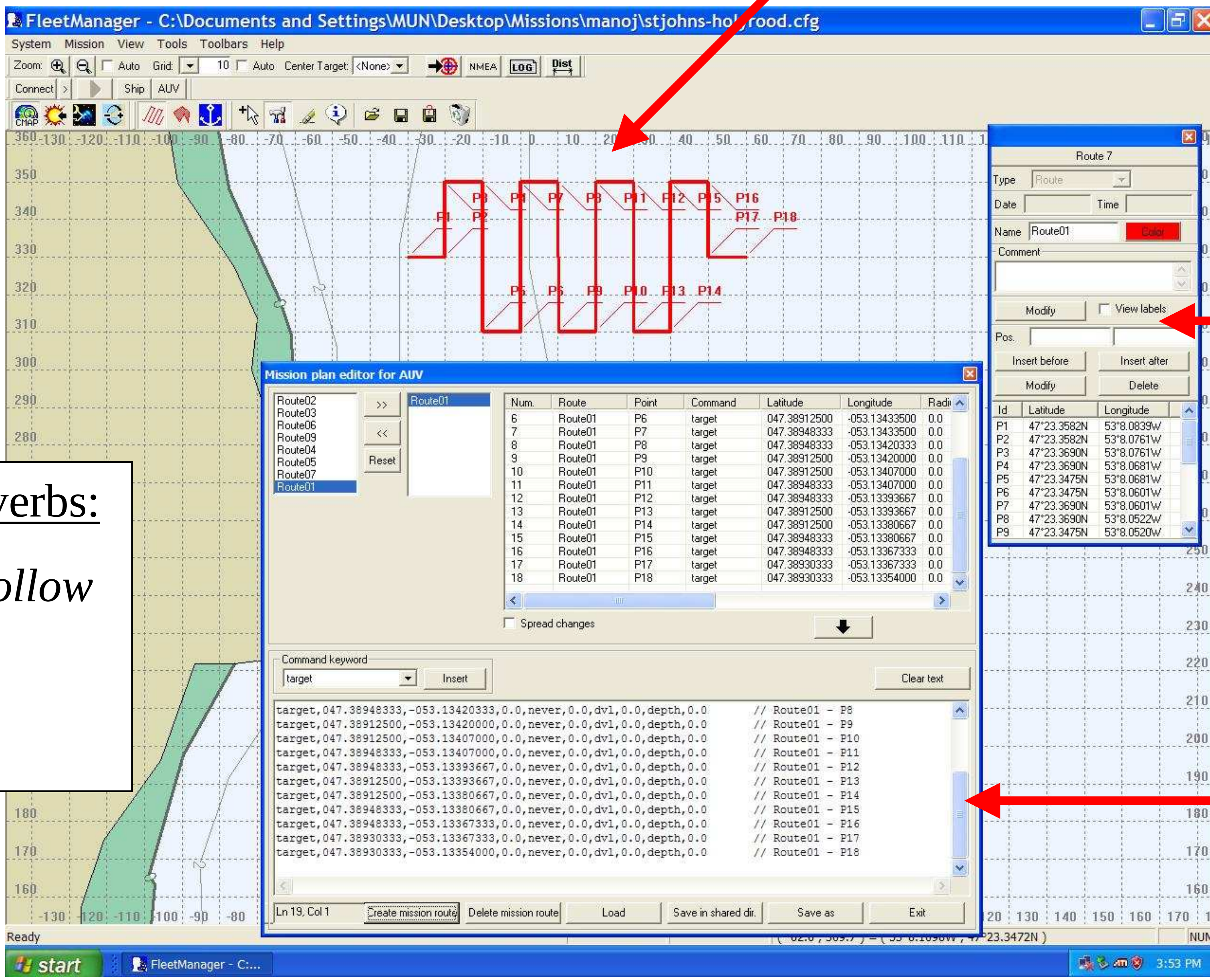
Experimental Setup – **Launch & Recovery**

Deployment of the AUV

Recovery of the AUV

Experimental Setup – **Planning with "FleetManager"**

Route defined as a series of waypoints



Route properties dialog box

Mission plan editor

Task verbs:

line_follow

target

circle

Manoeuvring tests

The following manoeuvres were performed with the AUV in Holyrood, Newfoundland:

1. Straight-line Tests (acceleration/deceleration)
2. Turning circles
3. Horizontal zigzags
4. Vertical zigzags
5. Helix

Straight-line (1) and horizontal plane manoeuvres (2 & 3) were performed at a depth of 3 m

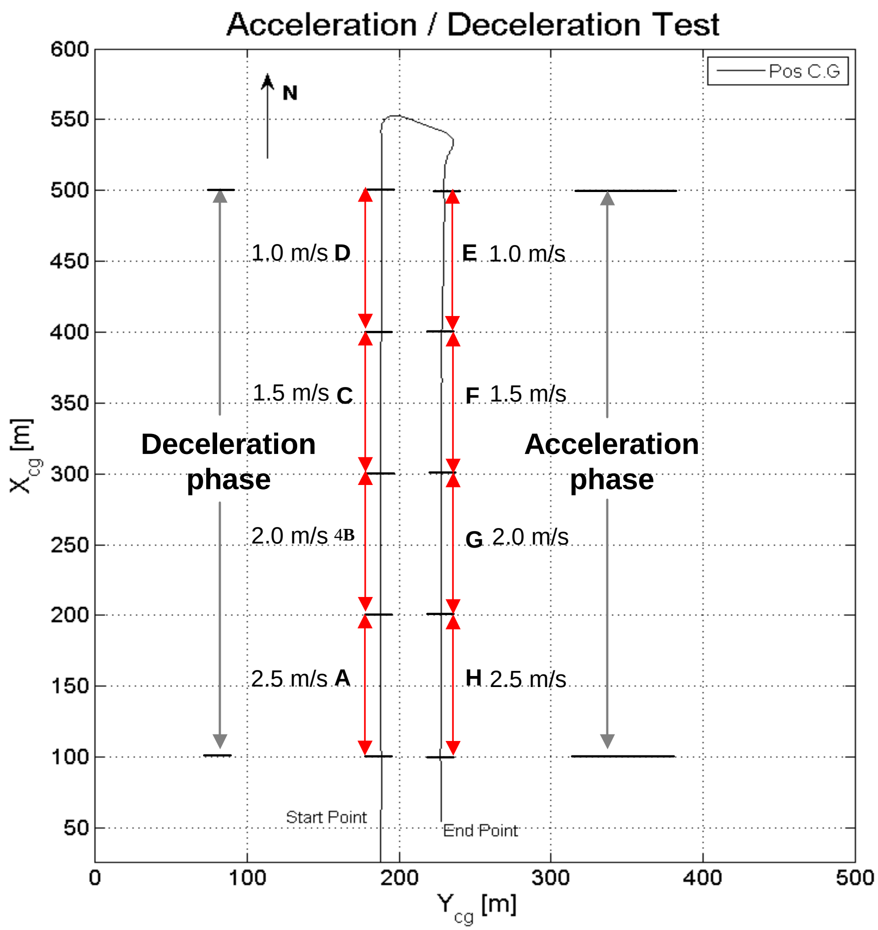
The vertical plane manoeuvres (4 & 5) were performed between depths of 3 to 10 m

All data were collected at a sampling frequency of 10 Hz

Manoeuvring Tests – Straight-line Test

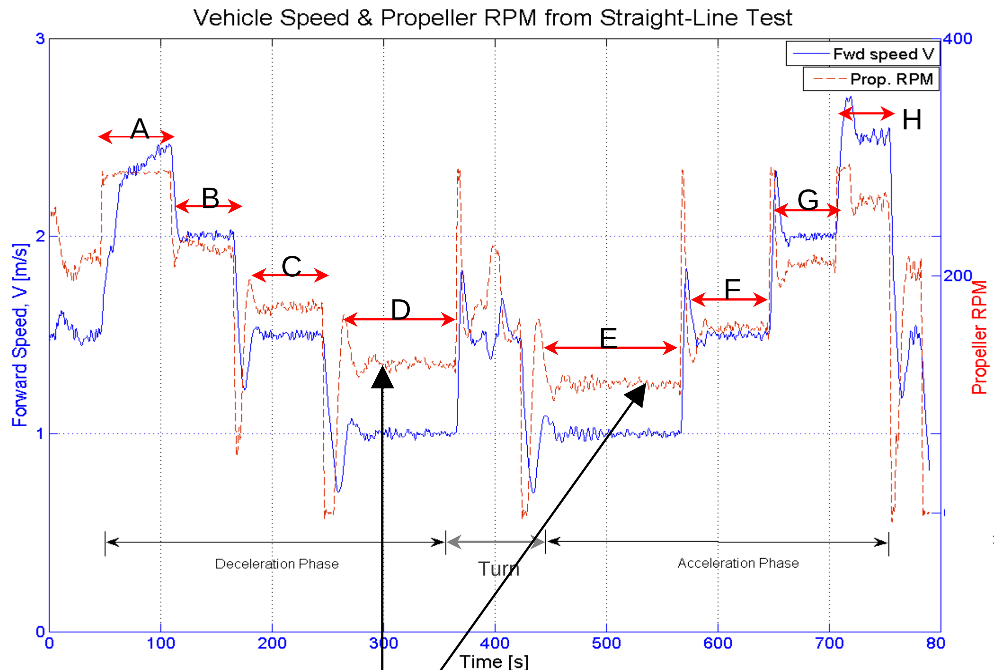
Steps

- AUV dives to a depth of 3m
- Starts the *deceleration* phase from the South end at a speed of 2.5 m/s
- Starts the *acceleration* phase from the North end at a speed of 1.0 m/s



Offset from the course ~ 0.2% to 0.3% of the dist. traveled

Manoeuvring Tests – Straight-line Test

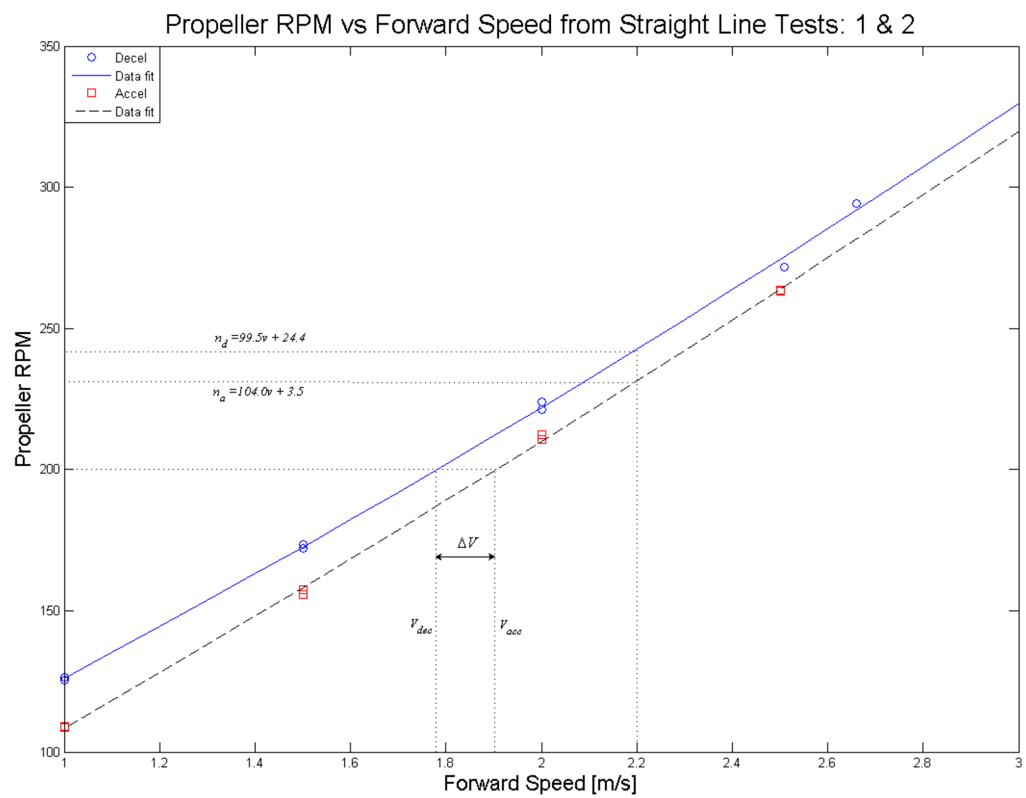


In-line current velocity estimated to ~ 0.20 m/s

rpm vs. speed data was used to develop a simple propulsion module for simulation model

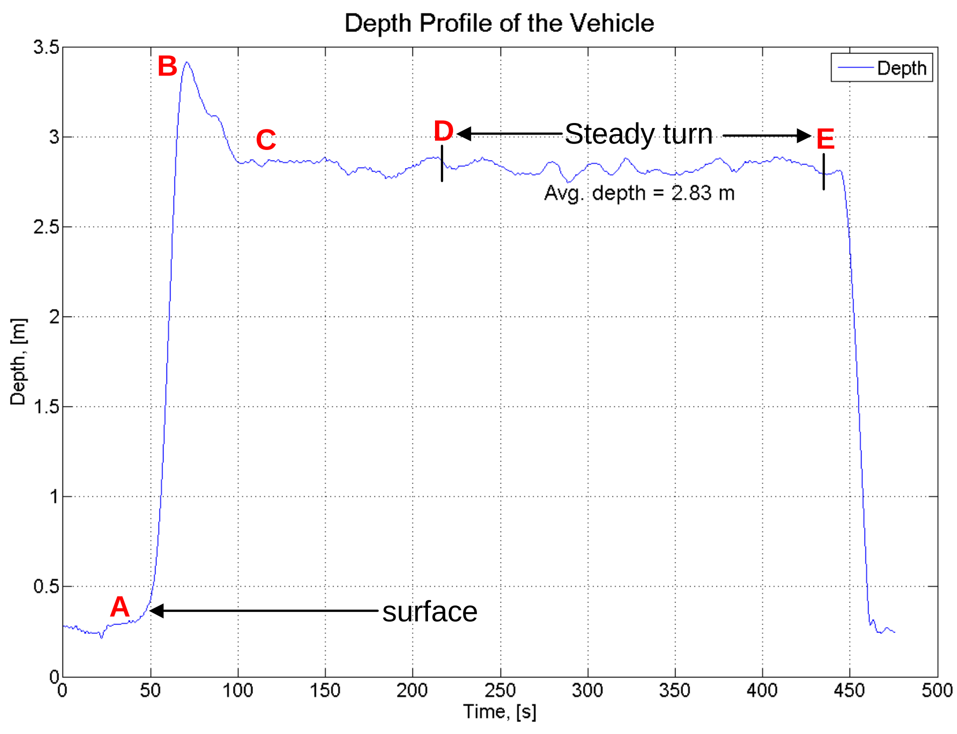
Different rpm for same speed

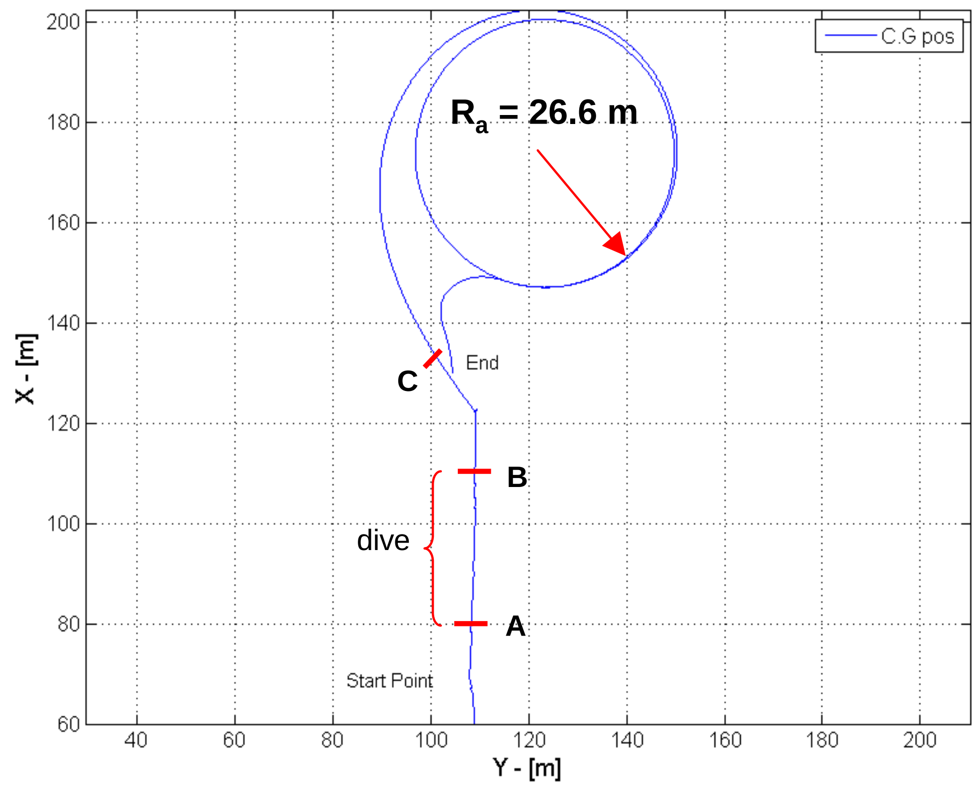
Presence of in-line north-to-south current



Manoeuvring Tests – Turning Circles

- All circles were performed at a depth of approx. 3 m
- Circles were performed at speeds of 1, 1.5 and 2 m/s
- Forward speed and radius of turn were the command inputs



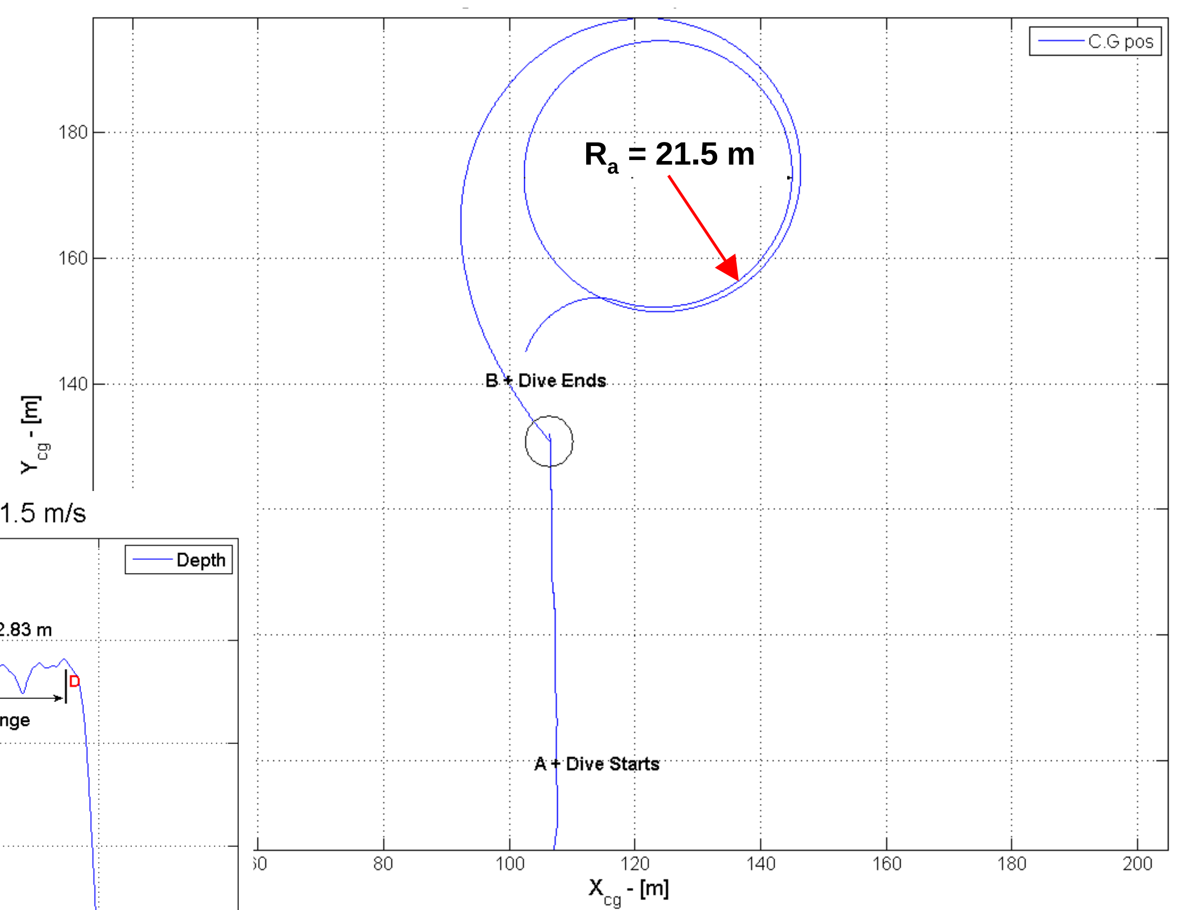


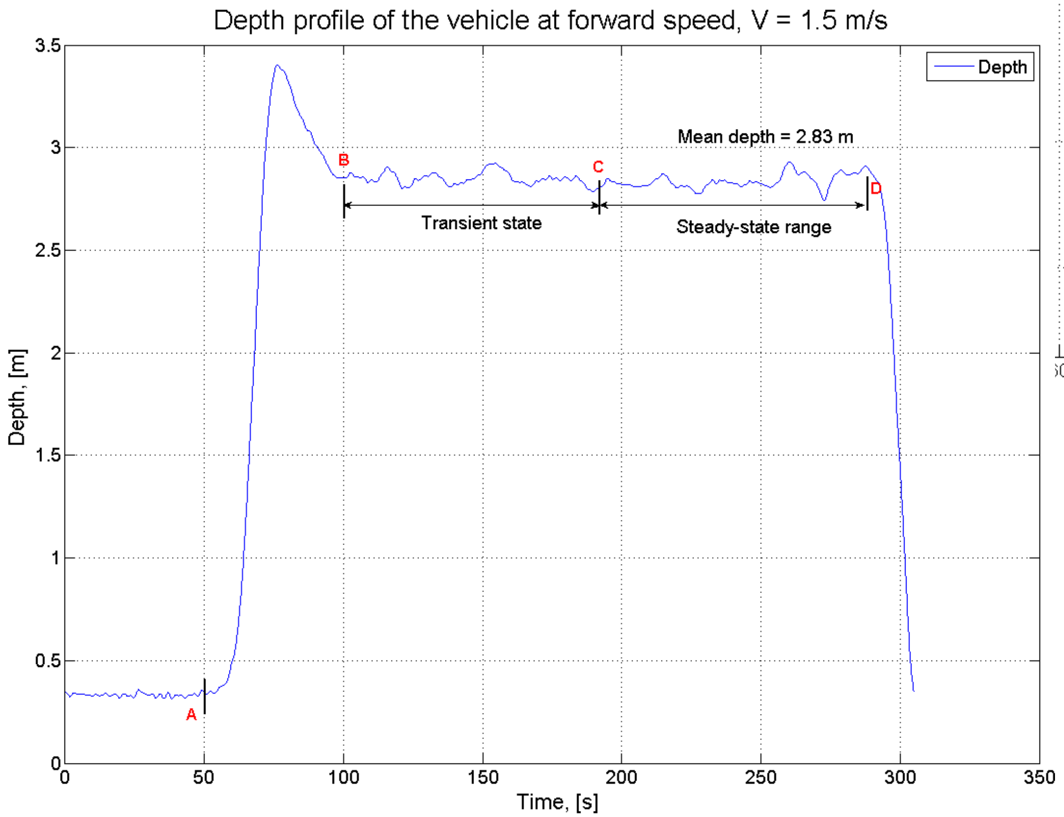
Response of the vehicle to a command radius, $\mathbf{R_c}$ **= 16 m** at speed of **1 m/s**

$$R_a > R_c$$

Manoeuvring Tests – Turning Circles

Response of the vehicle to a command radius, **R_c= 16 m** at speed of **1.5 m/s**

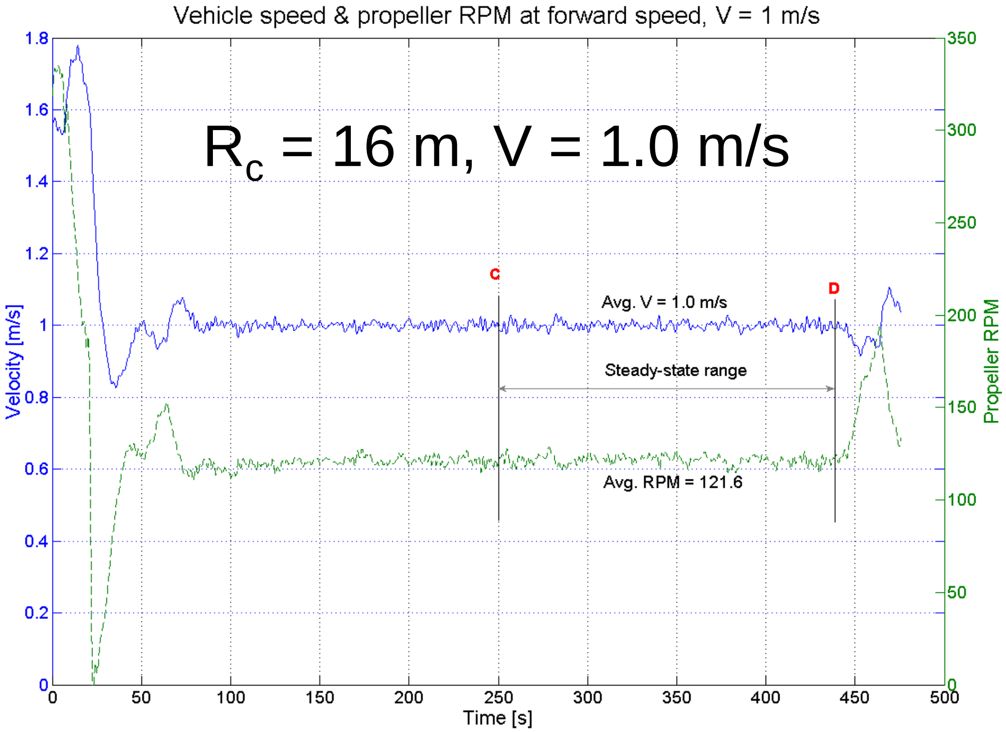


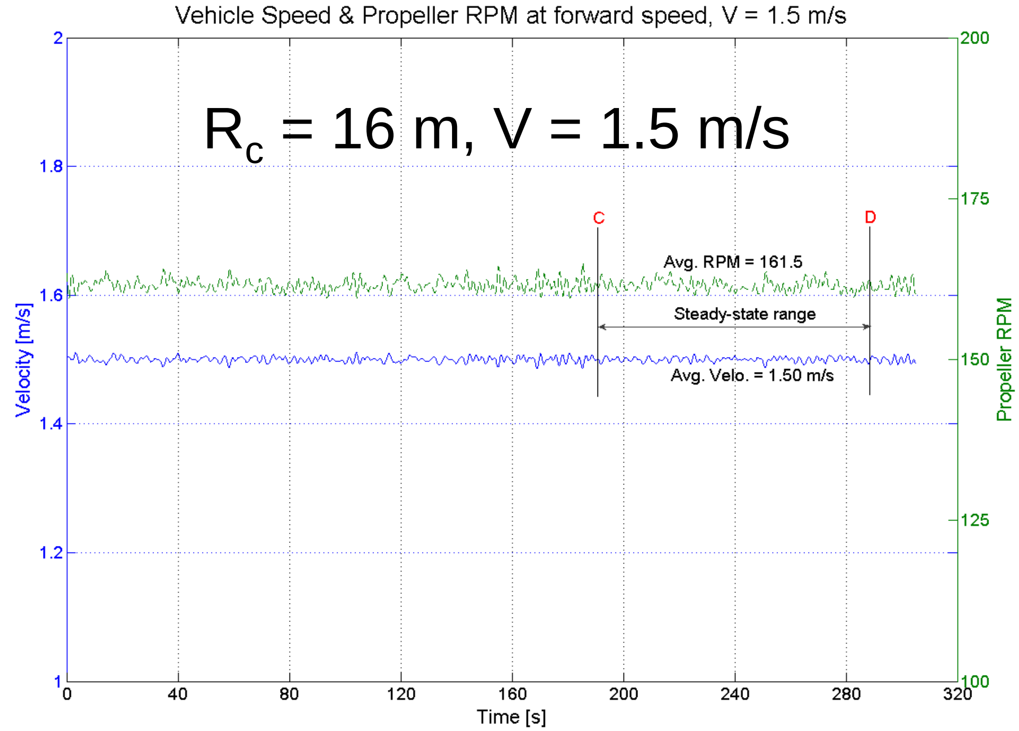


$R_a > R_c$

Manoeuvring Tests – Turning Circles

Vehicle speed and propeller rpm





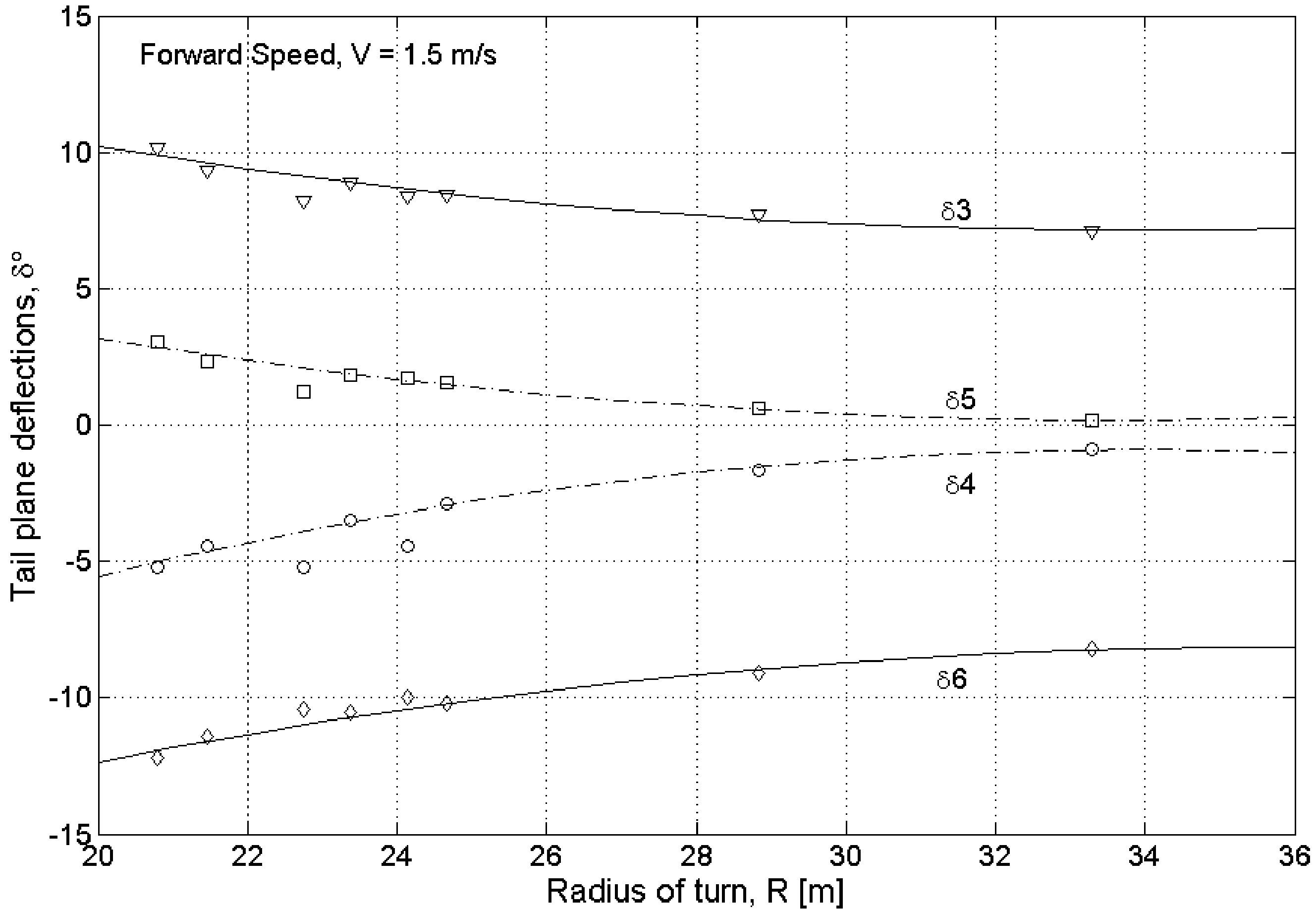
- Vehicle speed during steady turn portion was the same as the command speed – No speed loss
- No noticeable increase in prop. rpm to maintain command speed during steady turn

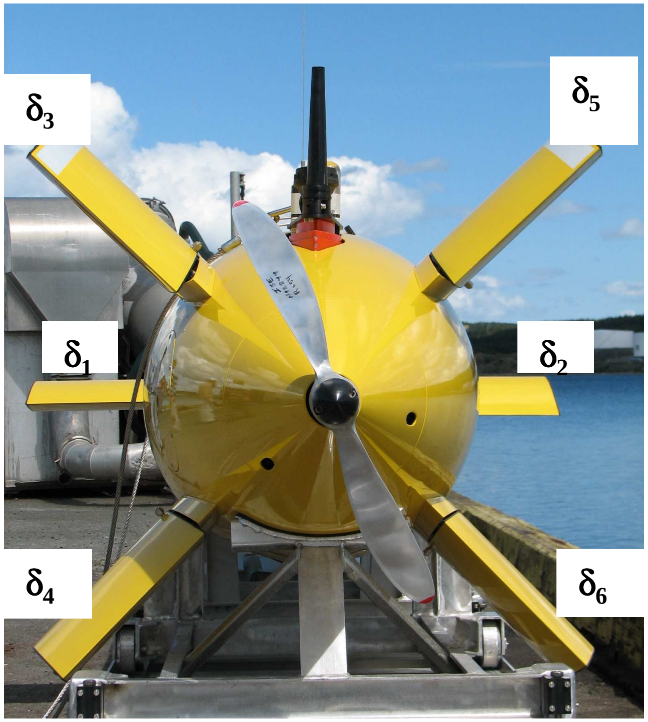
Manoeuvring Tests – Turning Circles

STEADY-STATE PARAMETERS FROM THE ANALYSIS OF TURNING CIRCLES																							
Sl.	Depth	Speed	Control Plane Angles						Radius			AoA	Drift	Angular disp		Ang. Rates			Lin. Vel. Comp			Turn	Day
No.	d	Va	Dive Planes		Tail Planes				Rc	Ra	RPM	(α)	(β)	Roll	Pitch	p	q	r	u	v	w	rate, r'	
	[m]	[m/s]	δ1	δ2	δ3	δ4	δ5	δ6	[m]	[m]		[deg]	[deg]	[deg]	[deg]	[deg/s]			[m/s]				
V_c = 1 m/s																							
1	2.81	1.0	-4.2	4.2	10.3	0.1	-1.8	-12.5	**10**	22.5	121.4	-4.8	6.5	0.00	-4.81	0.21	0.00	2.56	0.997	-0.114	-0.084	0.200	1
2	2.81	1.0	-4.8	4.8	10.6	0.0	-1.8	-12.6	**12**	23.8	122.9	-4.9	5.8	-0.01	-4.96	0.21	0.00	2.41	0.997	-0.101	-0.086	0.189	2
3	2.84	1.0	-5.2	5.3	10.2	0.3	-2.4	-12.2	**14**	25.0	122.4	-5.0	5.2	0.00	-5.06	0.20	0.00	2.30	0.997	-0.092	-0.088	0.180	2
4	2.37	1.0	-5.0	5.1	10.3	0.4	-2.1	-12.3	**14**	25.1	121.9	-5.0	5.3	0.00	-4.98	0.20	0.01	2.30	0.997	-0.093	-0.087	0.179	2
5	2.82	1.0	-5.1	5.1	10.2	0.9	-2.4	-11.8	**16**	26.6	121.6	-5.1	5.2	0.00	-5.08	0.19	0.00	2.18	0.997	-0.091	-0.089	0.169	2
6	2.84	1.0	-5.4	5.4	10.1	1.0	-2.7	-11.5	**18**	28.0	121.6	-5.2	4.9	0.00	-5.13	0.18	0.00	2.05	0.997	-0.085	-0.090	0.161	2
7	2.84	1.0	-5.3	5.3	9.9	1.2	-2.8	-11.6	**18**	28.1	122.6	-5.1	5.1	0.00	-5.10	0.18	0.00	2.07	0.997	-0.090	-0.089	0.160	2
8	2.83	1.0	-4.9	5.0	9.8	1.6	-2.8	-11.3	**20**	29.7	118.6	-5.1	5.2	0.00	-5.22	0.17	0.00	1.95	0.996	-0.091	-0.089	0.152	1
9	2.85	1.0	-5.4	5.5	9.7	2.8	-3.5	-10.5	**25**	33.4	122.2	-5.4	4.0	0.00	-5.40	0.16	0.00	1.70	0.996	-0.069	-0.094	0.135	2
10	2.86	1.0	-5.8	5.8	9.4	2.8	-3.7	-10.3	**30**	37.5	121.8	-5.3	3.8	0.00	-5.36	0.14	0.01	1.53	0.996	-0.066	-0.093	0.120	2
V_c = 1.5 m/s																							
1	2.84	1.5	-0.4	0.5	8.2	-3.5	1.2	-10.4	**10**	22.8	172.6	-1.8	6.4	0.00	-1.79	0.12	0.00	3.73	1.500	-0.164	-0.046	0.198	2
2	2.84	1.5	0.6	-0.5	8.4	-3.4	1.7	-10.0	**12**	24.2	171.9	-1.6	5.6	0.00	-1.57	0.09	0.00	3.49	1.500	-0.148	-0.041	0.186	2
3	2.83	1.5	-1.3	1.3	10.2	-5.2	3.1	-12.2	**14**	20.8	161.7	-1.8	2.4	0.00	-1.83	0.14	0.01	4.21	1.500	0.063	-0.048	0.216	3
4	2.83	1.5	-1.6	1.6	9.3	-4.5	2.3	-11.4	**16**	21.5	161.5	-1.9	2.3	0.00	-1.88	0.13	-0.01	3.91	1.500	0.060	-0.048	0.210	3
5	2.84	1.5	-1.8	1.8	8.9	-3.4	1.8	-10.5	**18**	23.0	161.6	-1.9	2.2	0.01	-1.91	0.12	0.00	3.66	1.500	0.057	-0.049	0.195	3
6	2.84	1.5	-1.9	1.9	8.9	-3.6	1.9	-10.6	**18**	23.7	161.4	-1.9	2.1	0.00	-1.85	0.12	0.00	3.65	1.500	0.056	-0.049	0.190	3
7	2.83	1.5	-1.7	1.7	8.4	-2.9	1.5	-10.2	**20**	24.7	161.6	-1.8	2.0	0.00	-1.91	0.10	-0.01	3.45	1.500	0.052	-0.047	0.183	3
8	2.84	1.5	-1.7	1.6	7.7	-1.7	0.6	-9.1	**25**	28.8	161.5	-1.9	1.7	0.00	-1.88	0.10	0.01	2.99	1.500	0.044	-0.050	0.156	3
9	2.83	1.5	-1.5	1.4	7.1	-0.9	0.2	-8.2	**30**	33.3	161.5	-1.8	1.5	0.00	-1.81	0.08	0.00	2.59	1.500	0.038	-0.047	0.135	3
V_c = 2 m/s																							
1	2.86	2.0	2.3	-2.6	10.9	-9.3	6.7	-12.1	**10**	17.6	212.5	0.0	2.7	0.00	-0.03	-0.01	0.02	6.46	2.001	0.094	-0.001	0.255	3
2	2.86	2.0	2.3	-2.6	7.2	-4.7	3.2	-8.4	**12**	24.2	225.3	0.0	5.5	0.01	-0.01	-0.02	-0.01	4.51	2.000	-0.183	0.000	0.186	4
3	2.88	2.0	2.1	-2.2	6.6	-5.2	3.1	-7.4	**14**	25.3	230.7	0.0	5.3	-0.01	-0.03	0.04	0.00	4.43	2.005	-0.181	-0.001	0.178	4

- In all tests $R_a > R_c$ – the exact reason for this discrepancy is unknown
- Negligible roll motion even during a turn

Manoeuvring Tests – Turning Circles





- ➢Fwd speed & control plane deflections will be used as control inputs to the simulation

Manoeuvring Tests – Horizontal Zigzags

Test runs on the surface before the actual runs at 3 m depth

Options available:

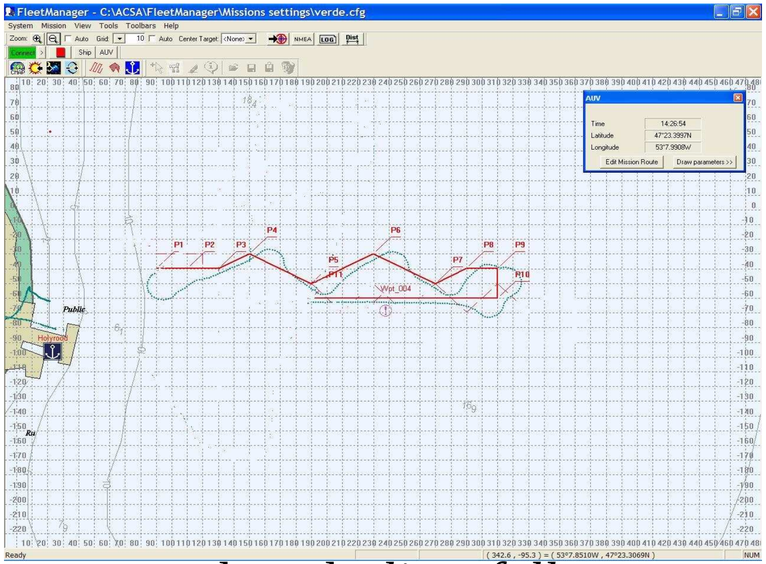
The vehicle can execute the mission using any of the two possible commands:

1. *line_follow*

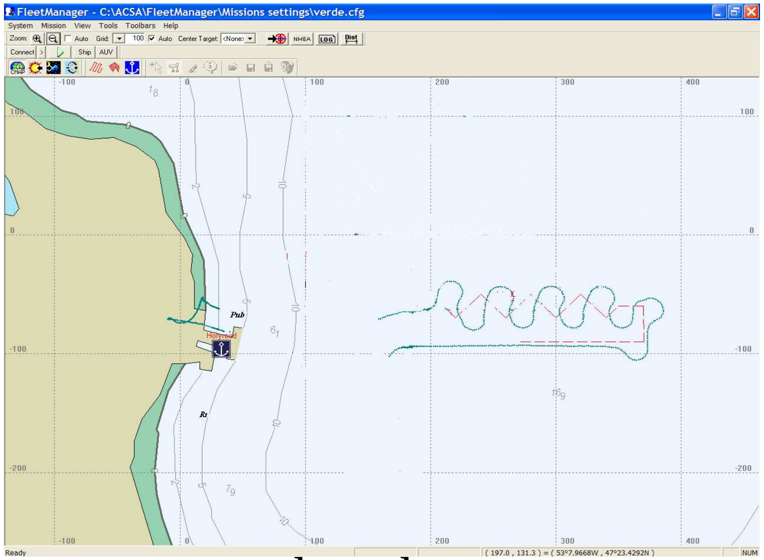
   Vehicle follows a straight line path defined by series of waypoints

2. *target*

   Vehicle targets the waypoint without necessarily following a straight line.



task verb: *line_follow*

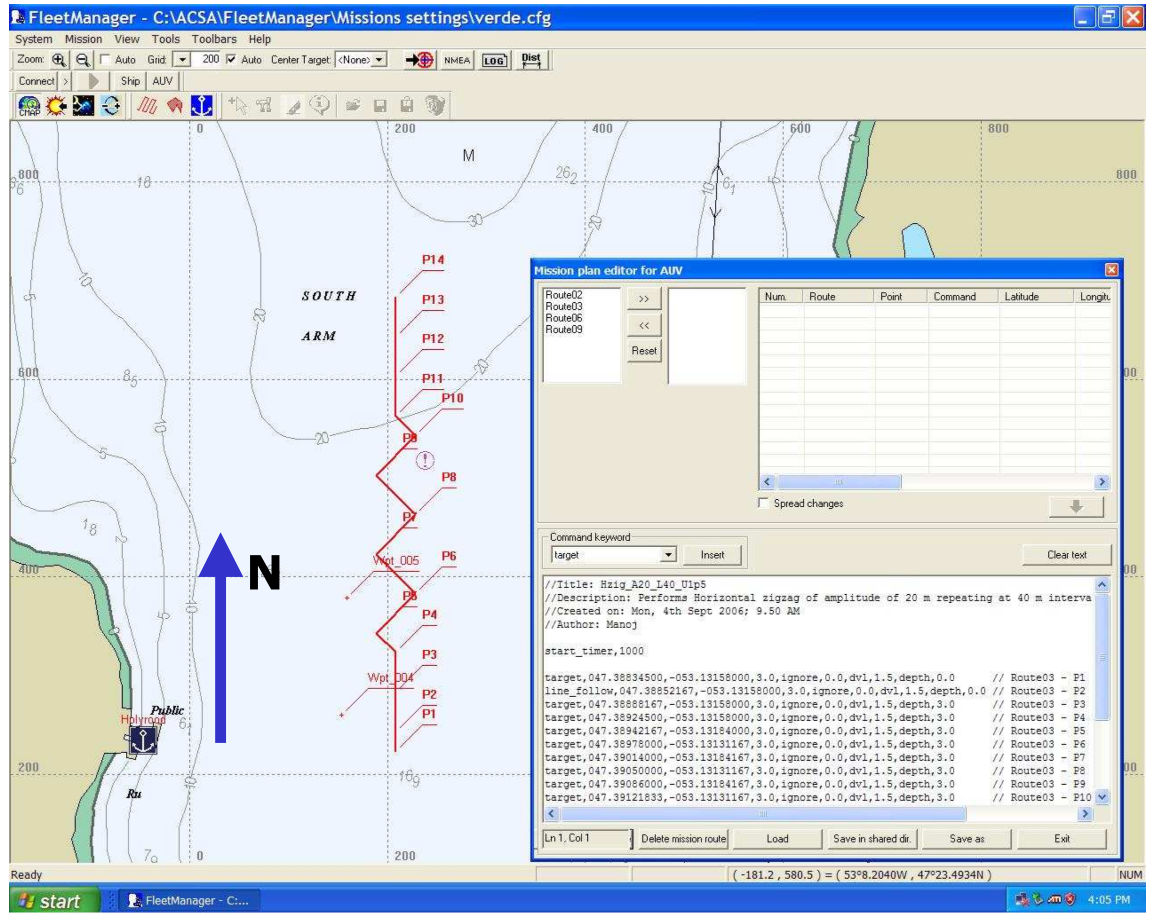


task verb: *target*

Manoeuvring Tests – Horizontal Zigzags

Steps

- AUV dives to a depth of 3m
- Follow the grid points selected on the graphical chart
- AUV surfaces at the end of the mission
- Radio connection established and vehicle can be piloted

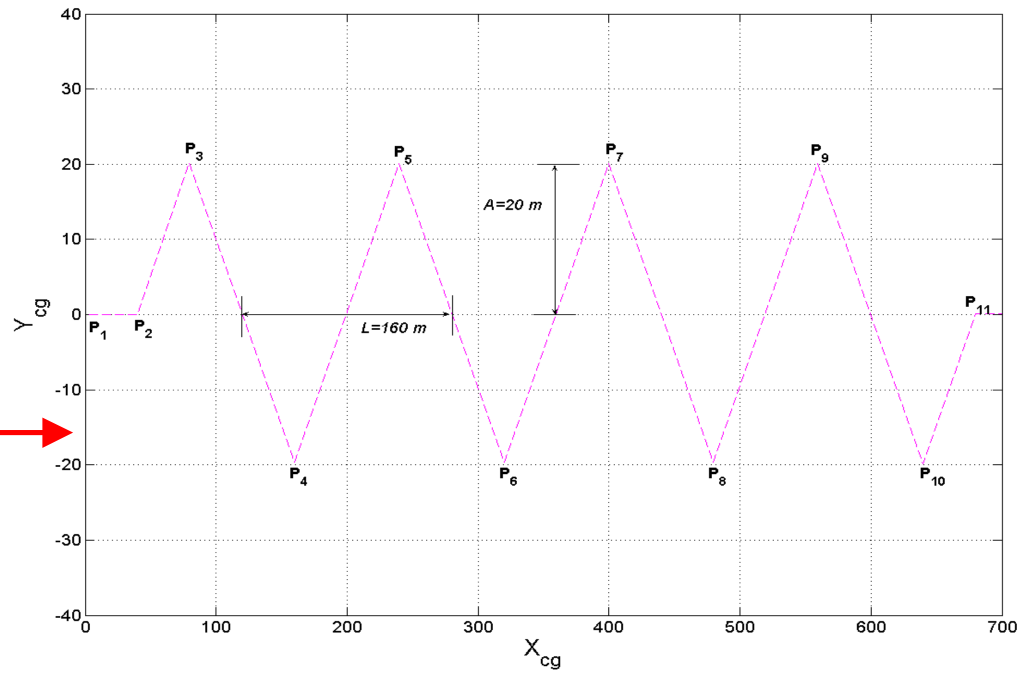


Manoeuvring Tests – Horizontal Zigzags

Horizontal Z-Test Plan

Test No.	Fwd Speed, V [m/s]	Width of path (A) [m]	Cycle length (L) [m]
1	1.5	10	160
2	2.0	10	160
3	1.5	20	160
4	2.0	20	160

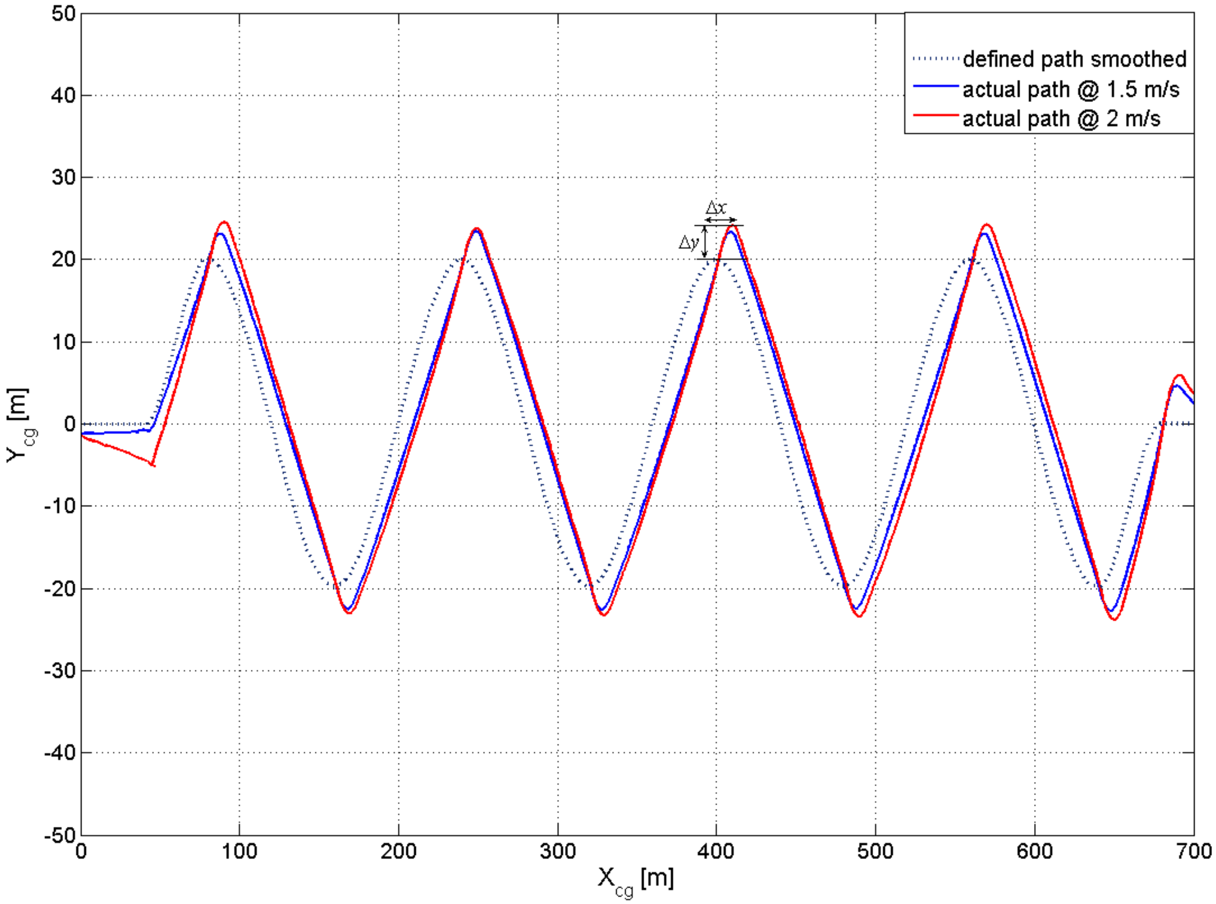
Defined path for A20, L160



Manoeuvring Tests – Horizontal Zigzags

Trajectory of the vehicle

HZ-Tests 3 & 4: A20, L160



Overshoot:

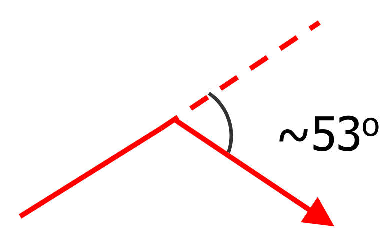
U = 1.5 m/s

Δy = 3.0 m (0.7 LOA)
Δx = 8.6 m (1.9 LOA)

U = 2.0 m/s

Δy = 3.9 m (0.9 LOA)
Δx = 10.1 m (2.3 LOA)

Vehicle passes exactly through the waypoints



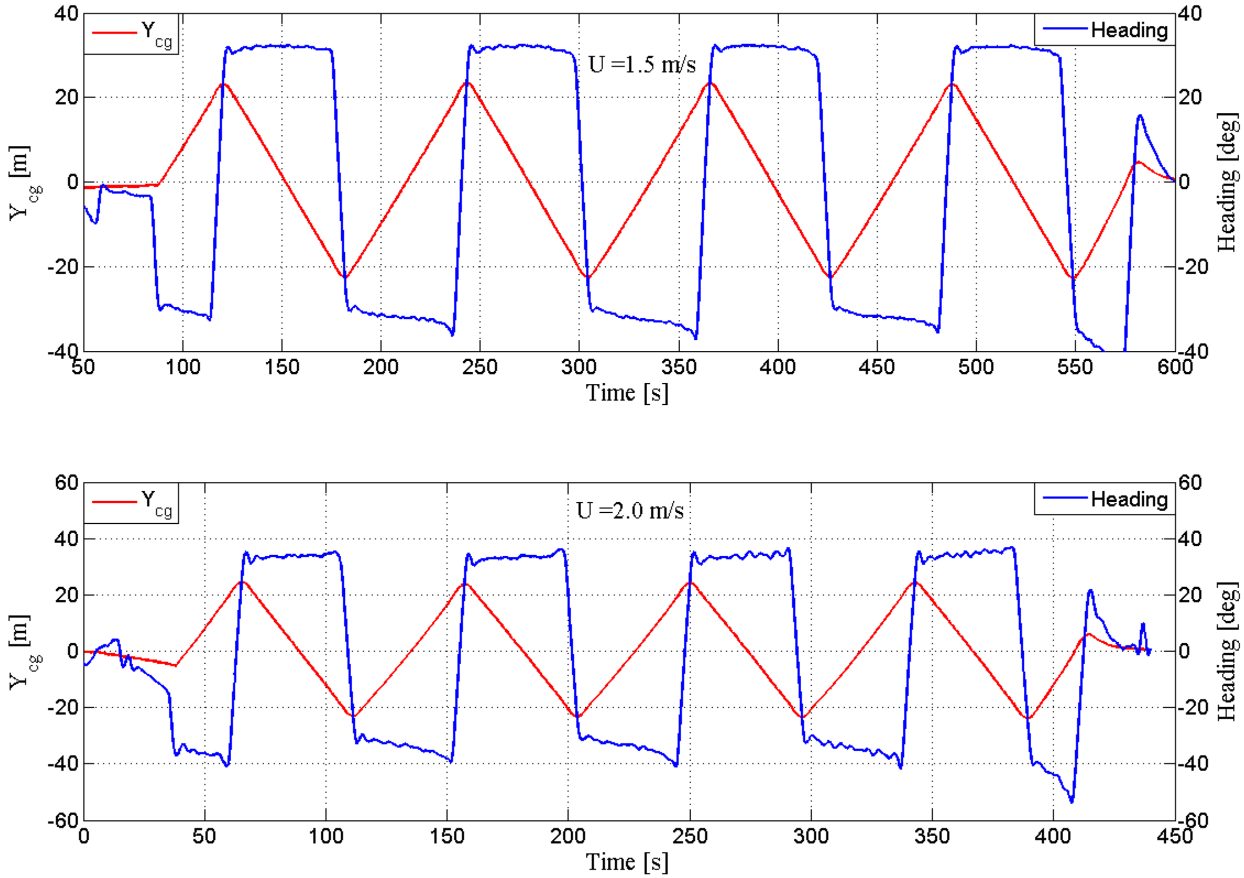
Change in heading

Manoeuvring Tests – Horizontal Zigzags

Vehicle trajectory & heading

HZ-Tests 3 &4 :

A20, L160



@ U = 1.5 m/s

@ U = 2.0 m/s

Periods of constant heading – 14 to 16 LOA

Cycle length too large

Manoeuvring Tests – **Horizontal Zigzags**

Horizontal Z-Test Plan

Test No.	Fwd Speed, V [m/s]	Width of path (A) [m]	Cycle length (L) [m]
1	1.5	10	160
2	2.0	10	160
3	1.5	20	160
4	2.0	20	160
5	**1.5**	**10**	**80**
6	**1.5**	**20**	**80**

Observations:

- Periods of constant heading ranging from 14 to 16 LOA

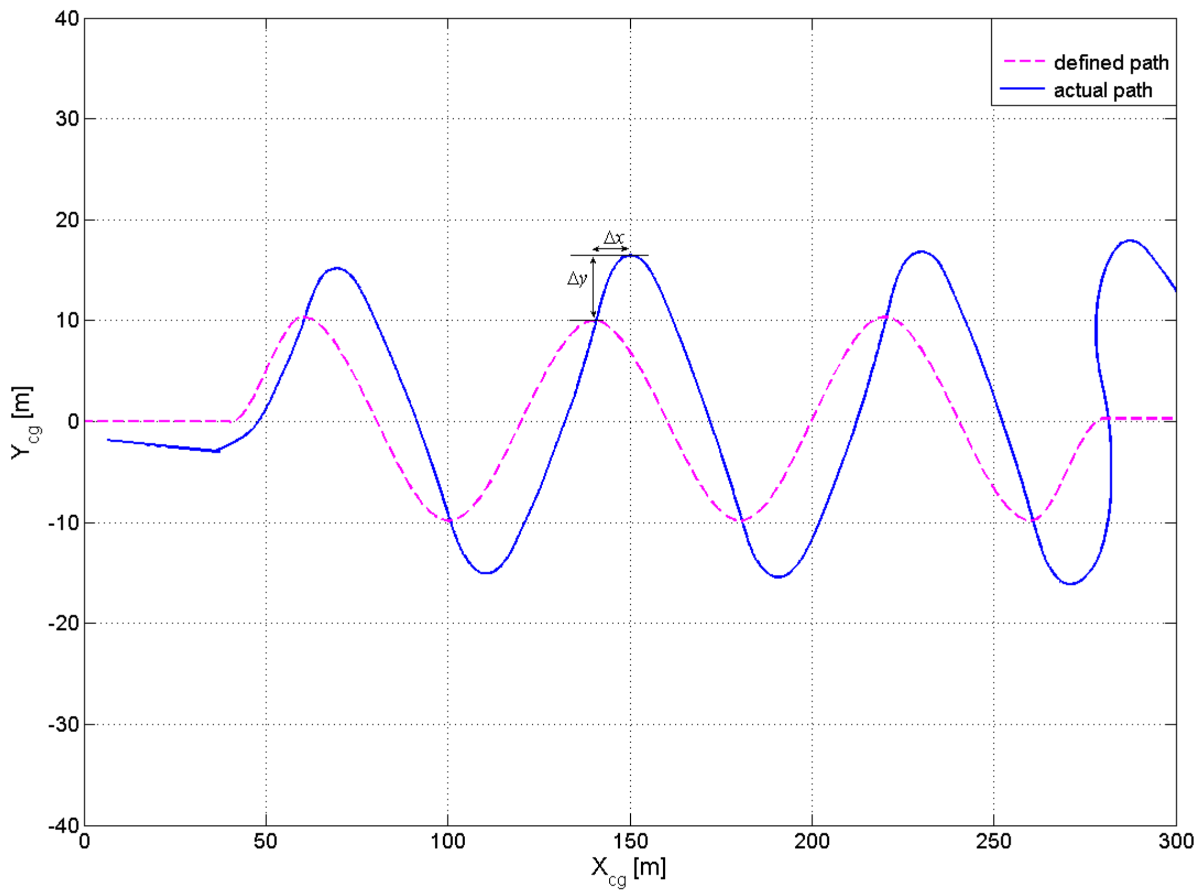
Modification:

- Modify the tests by changing the cycle length (L).

Manoeuvring Tests – Horizontal Zigzags

Trajectory of the vehicle

Z-Test 5: A10, L80



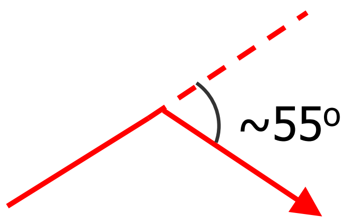
- trajectories much closer to a conventional zigzag
- increase in overshoot noticed

Overshoot:

U = 1.5 m/s

Δy = 5.8 m (1.3 LOA)

Δx = 10.5 m (2.3 LOA)



Change in heading

Manoeuvring Tests – Horizontal Zigzags

Summary

Overshoot width of path, turning time and heading change

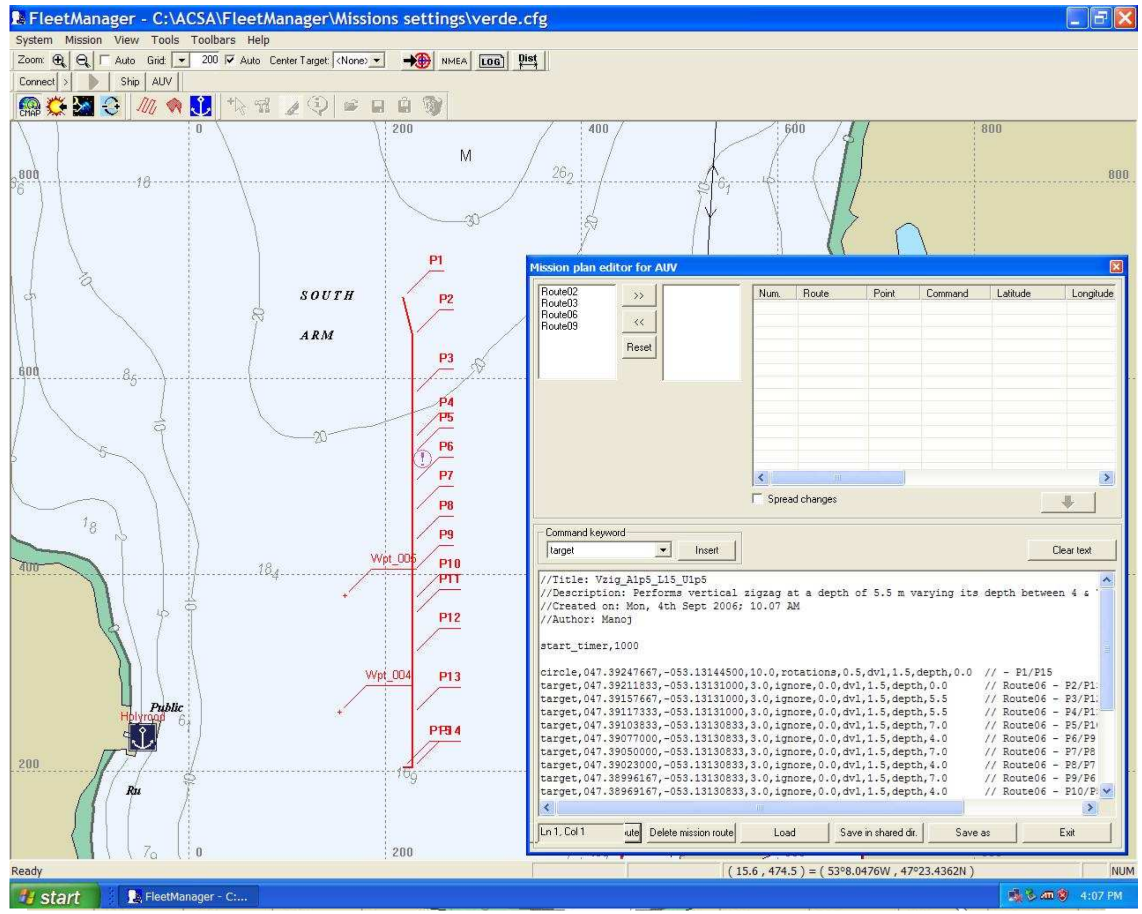
Test No.	V [m]	A [m]	L [m]	Overhoot width Δx [m]	Δy [m]	Turn time [s]	Dist. in LOA	Heading change
1	1.5	10	160	5.5	1.2	8.5	15.3	28^o
2	2.0	10	160	6.3	1.5	9.7	14.1	28^o
3	1.5	20	160	8.6	3.0	11.8	16.4	53^o
4	2.0	20	160	10.1	3.9	11.1	16.1	53^o
5	1.5	10	80	10.2	5.8	19.2	5.8	53^o
6	1.5	20	80	11.1	8.9	21.2	8.3	90^o

- Constant heading portion considerably reduced by reducing the cycle length
- Change in heading: same for tests 3 & 5 but overshoot observed for test 5 > tests 3; consequently the turning time
- The initial four tests happened to be less successful than the latter two tests in producing a desired horizontal zigzag result. However, the lessons learned are valuable in designing future experiments of similar nature.
- From initial tests, the AUV seems to change course by ~28º in approx. 8 - 10 sec and ~53º in approx. 11 sec. The quickness at turns would be a desirable feature in obstacle avoidance.

Manoeuvring Tests – Vertical Zigzags

Steps

- ➢ AUV dives to a depth mid-way between the maximum and minimum depths defined
- ➢ The AUV attempts to reach the prescribed waypoints at different levels in the same vertical plane
- ➢ AUV gets back to the mean depth after the mission and from there to the surface

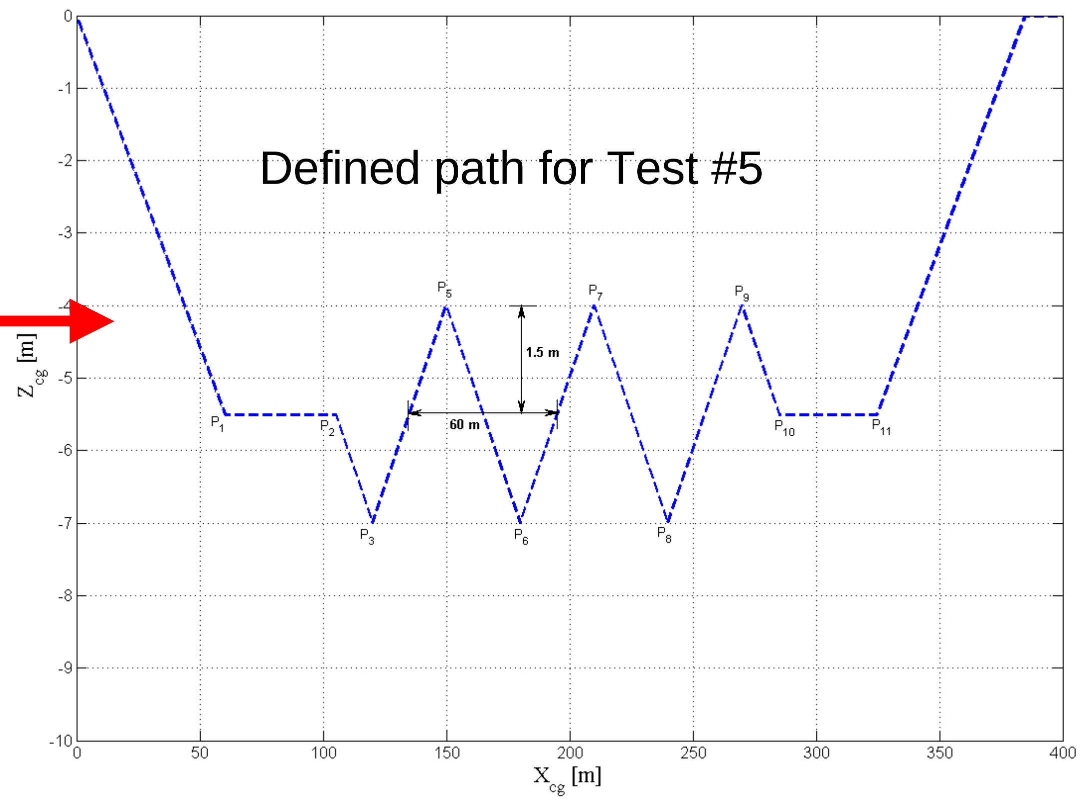


Manoeuvring Tests – Vertical Zigzags

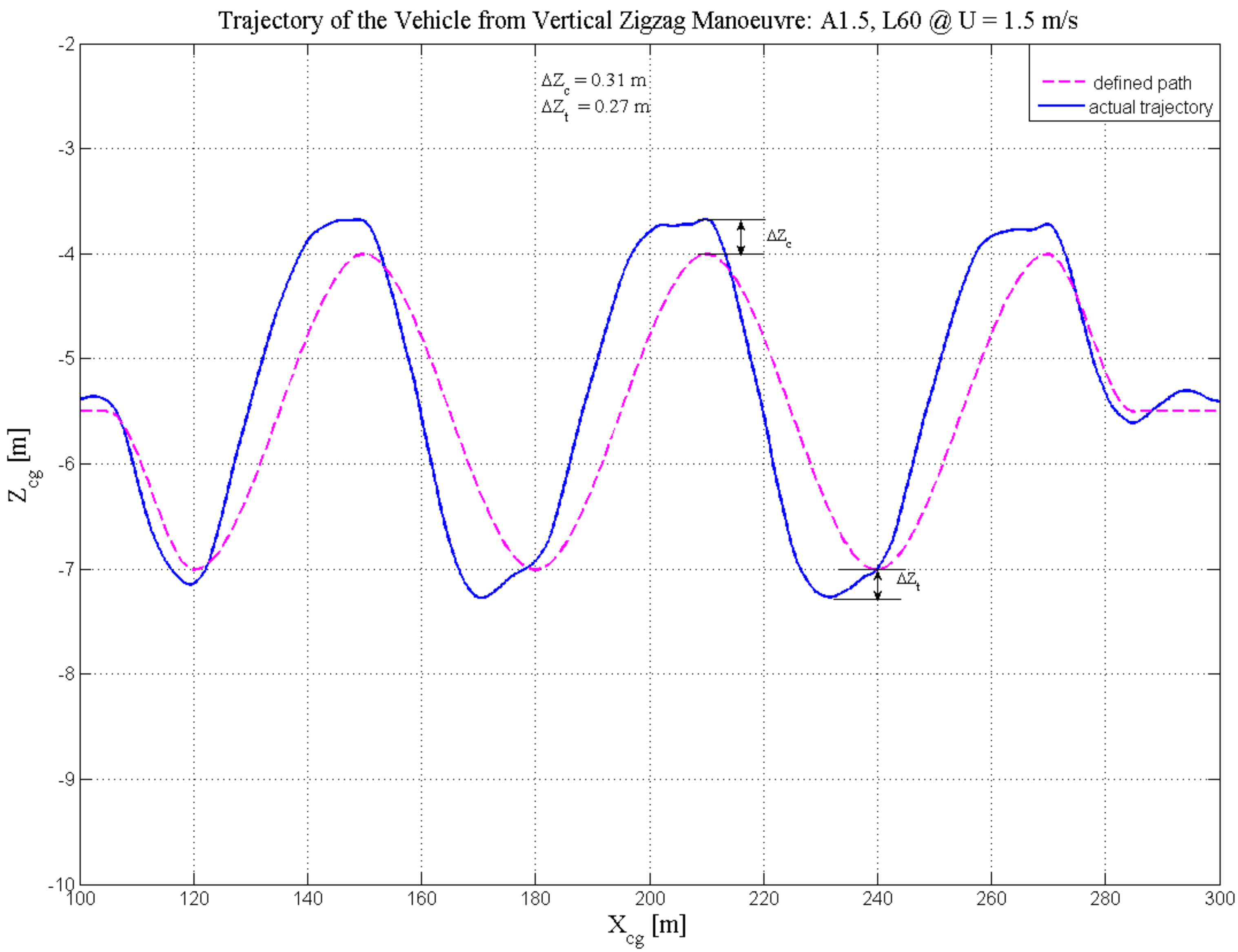
Vertical Z-Test Plan

Test No.	Fwd Speed, V [m/s]	Depth of path (A) [m]	Cycle length (L) [m]
1	1.5	1.5	140
2	2.0	1.5	140
3	1.5	3.0	140
4	2.0	3.0	140
5	**1.5**	**1.5**	**60**
6	**1.5**	**3.0**	**60**

Results from initial tests proved that the cycle length provided was large

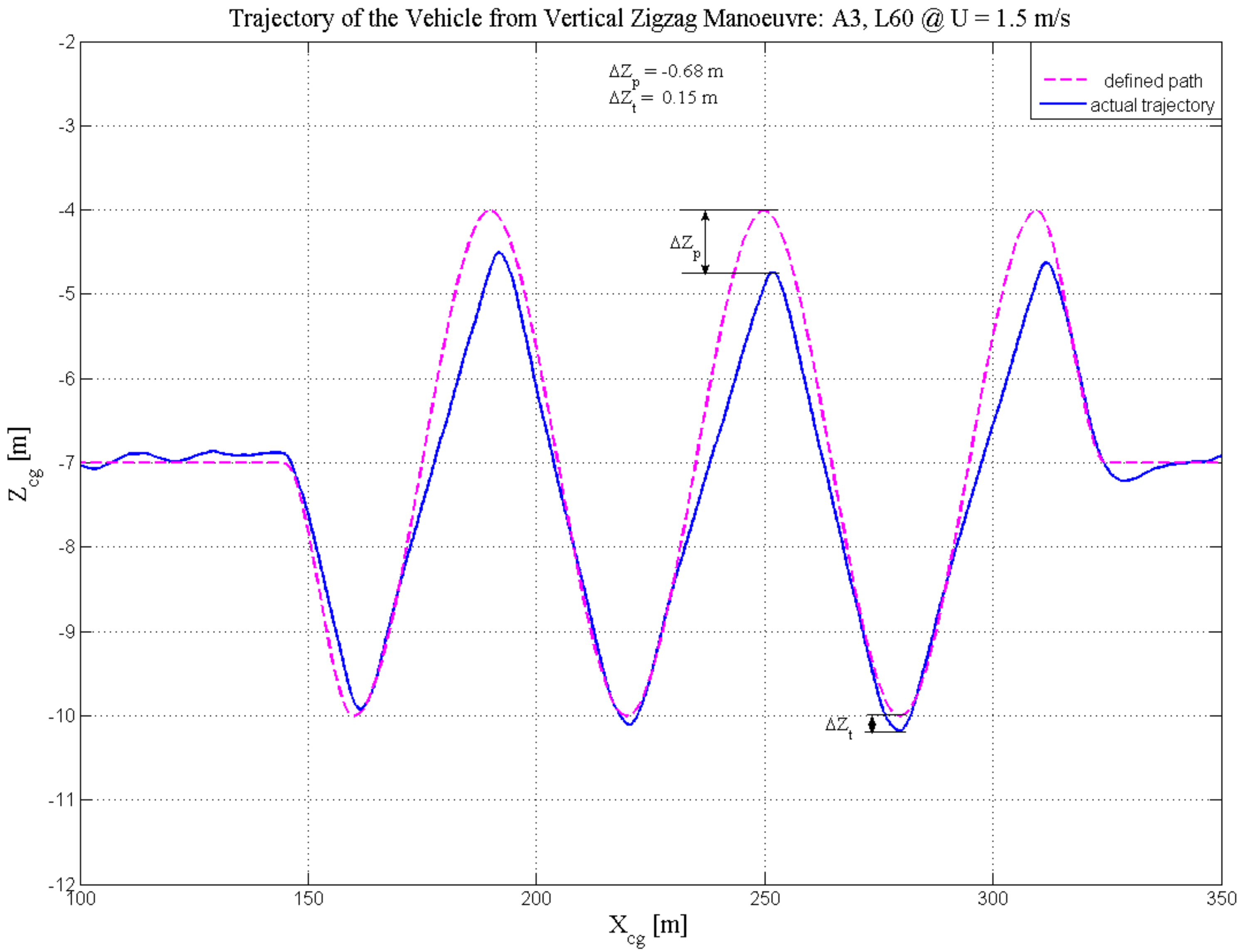


Manoeuvring Tests – Vertical Zigzags



Vehicle operated in *depth-by-heave* mode

Manoeuvring Tests – Vertical Zigzags



Vehicle operated in *depth-by-heave* mode

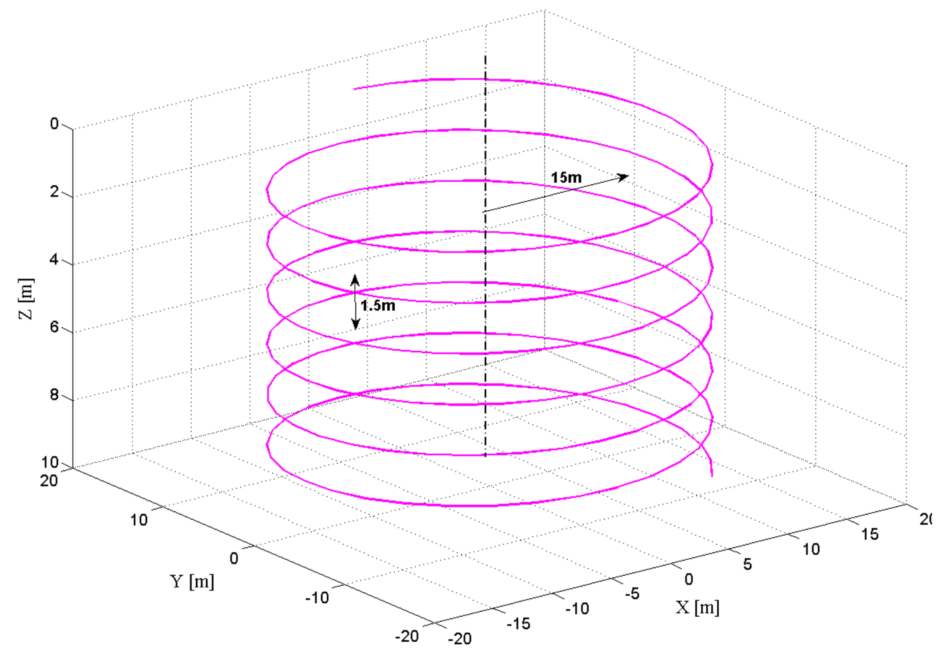
Manoeuvring Tests – **Vertical Zigzags**

- Vehicle used *depth-by-heave* mode rather than *depth-by-pitch* mode for all depth changing manoeuvres
- The overshoots from defined path/waypoints were found to be insignificant
- Established rough ascent/descent slopes that would produce a trajectory closer to conventional depth-changing manoeuvres

Manoeuvring Tests – Helical manoeuvre

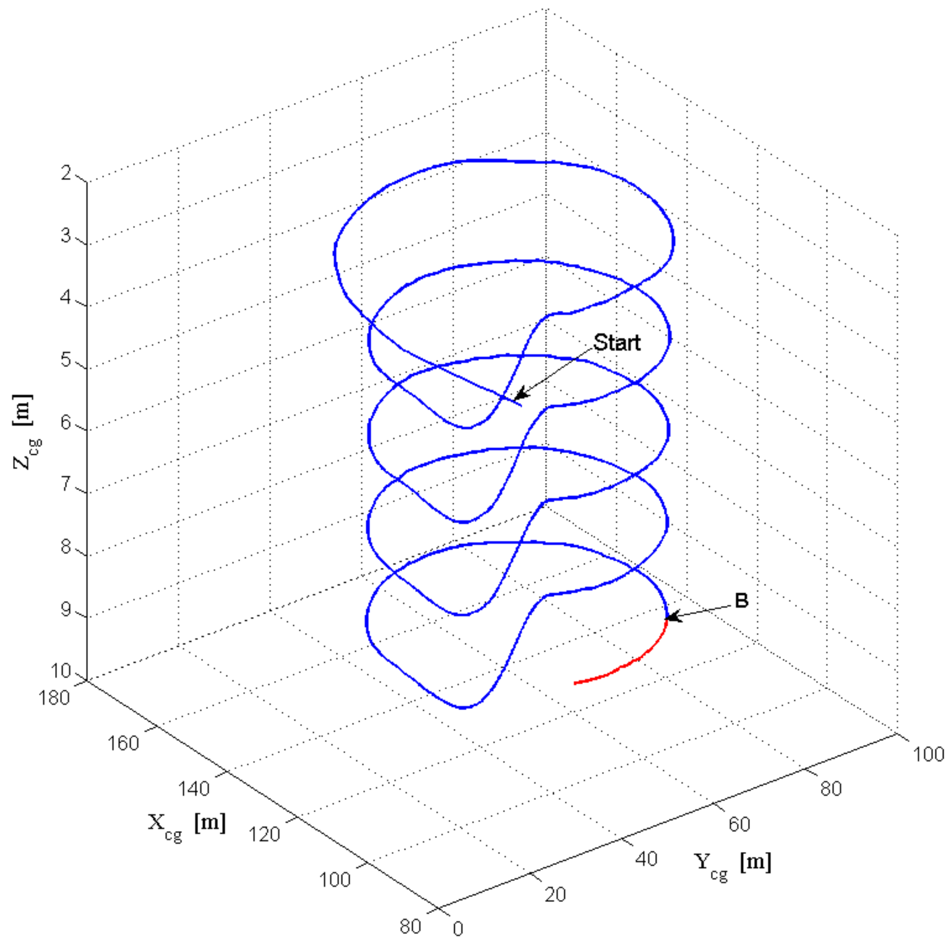
- attempt to exercise all six DOF
- dive while turning, expect roll motion
- “task verb" used: *circle* (centre, radius, speed, depth)
- commanded *circle* (centre, 15 m, 1.5 m/s, [3, 4.5, 6, 7.5, 9 m])
- not all results were as expected

Planned clockwise descent of 9 m



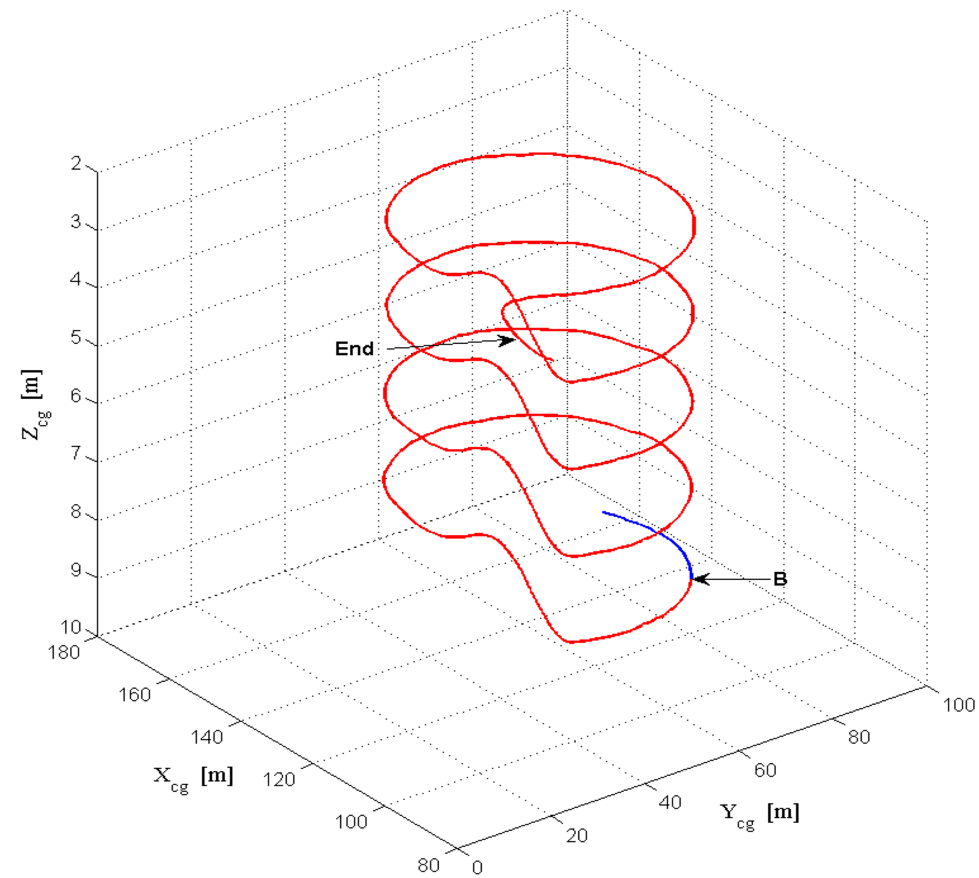
Manoeuvring Tests – Helical manoeuvre

Helix Manoeuvre: Downward spiral from 3 m to 9 m depth

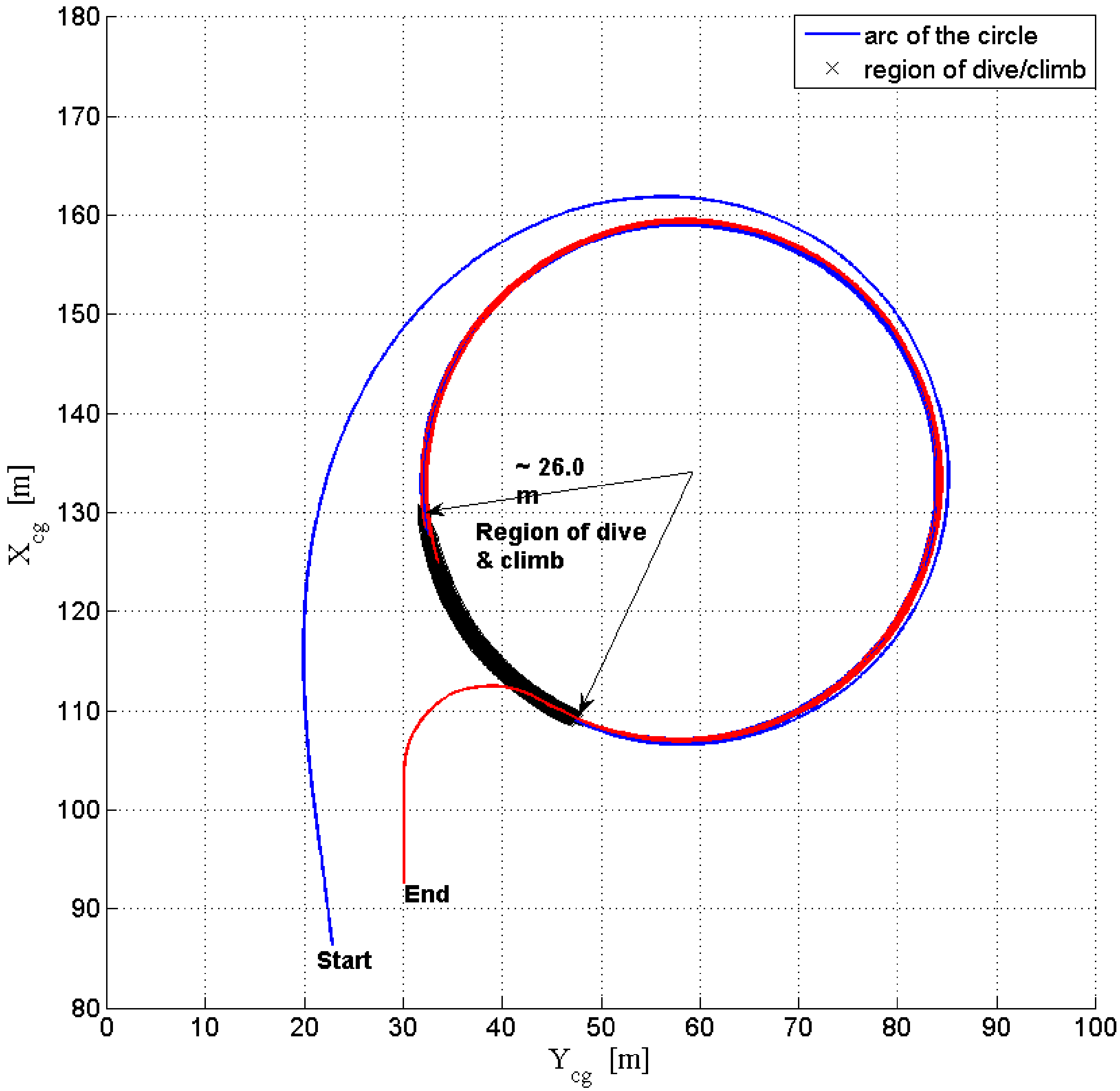


Measured results

Helix Manoeuvre: Upward spiral from 9 m to 3 m depth



Manoeuvring Tests – Helical manoeuvre



Plan view of measured helical manoeuvre

- one complete circle takes approx 108 sec
- descent or ascent phase takes approx 15 sec
- actual radius 26 m
- achieved common centre for all circles during helix

General Conclusions

- The vehicle is capable of maintaining the command speed even during a turn.
- Recommend using constant prop. rpm rather than constant velocity for *vehicle dynamics* testing.
- Negligible roll motions noticed during turns
- The AUV is very efficient in following a path defined by series of waypoints; a quality essential for a sensor platform (Straight-line tests & HZ-Tests)

- we're obtaining high-quality data

- we're learning how the controllers actually work and how the vehicle responds to various “task verbs”.

- we're extracting useful information for validation of the simulation code

AUV Team (2006)– Memorial University of Newfoundland

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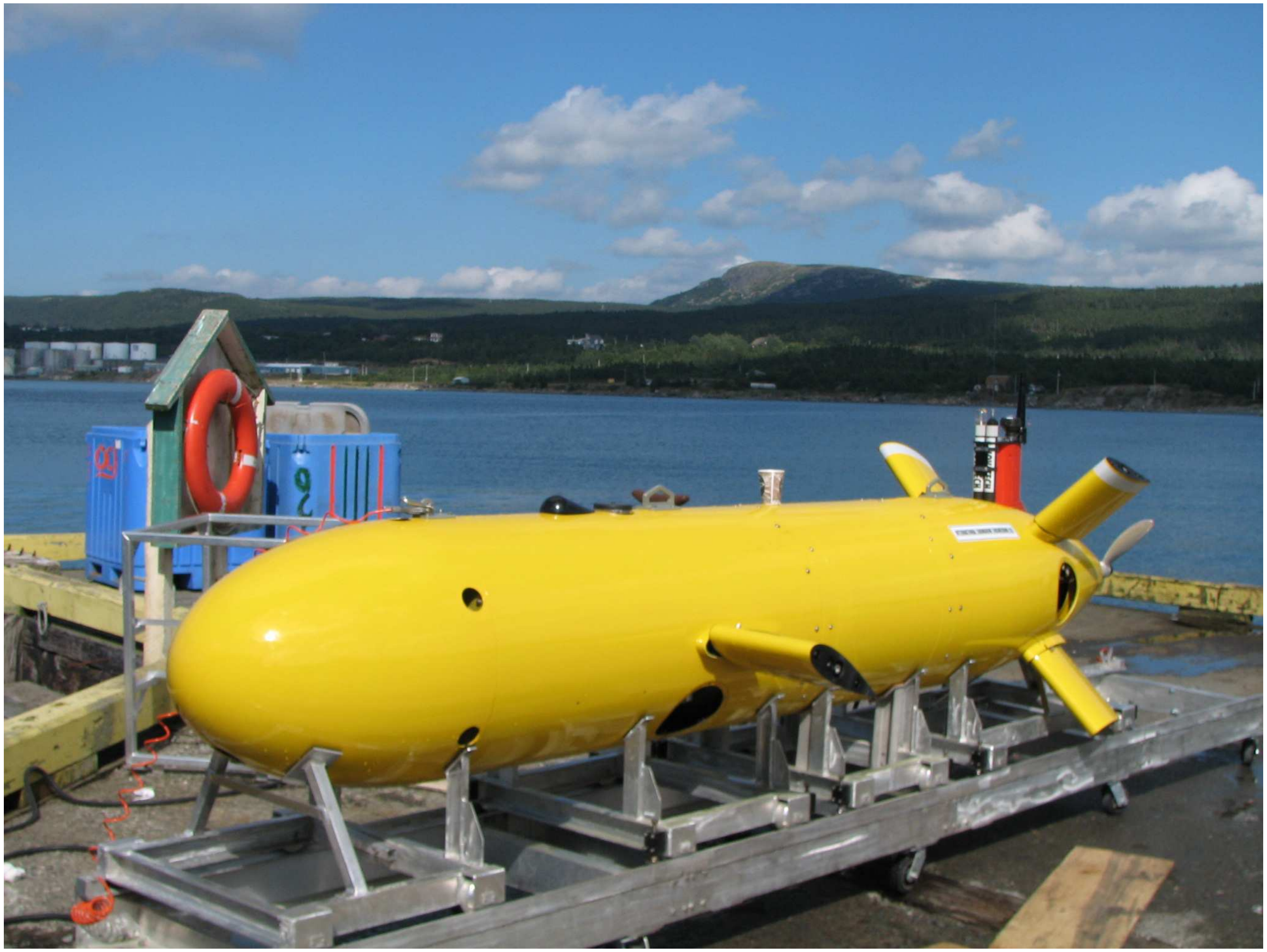
Questions?



MUN *Explorer* AUV

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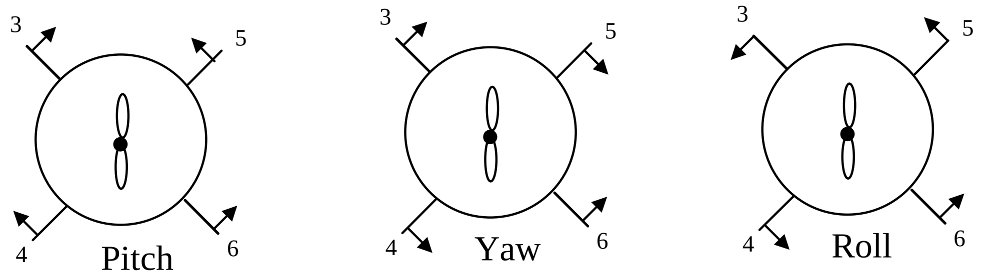
Horizontal Zigzag – Control deflections

Control plane configurations and sign conventions for ‘X’ tail configuration

The effective tail plane deflections (configuration) for a positive Pitch, Yaw and Roll control

Tail Planes



$$\delta P = (\delta_3 + \delta_4 - \delta_5 - \delta_6)/4$$

$$\delta Y = (\delta_3 - \delta_4 + \delta_5 - \delta_6)/4$$

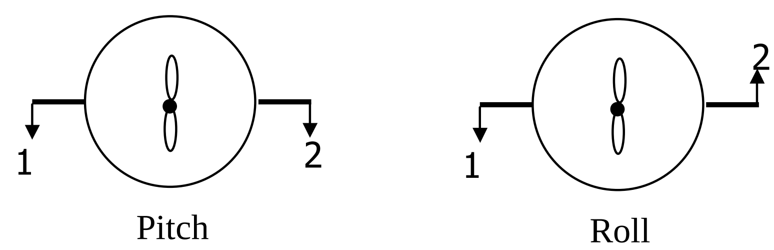
$$\delta R = (-\delta_3 - \delta_4 - \delta_5 - \delta_6)/4$$

Bow Planes

The effective bow plane deflections for a positive Pitch and Roll control

$$\delta P_D = (-\delta_1 + \delta_2)/2$$

$$\delta R_D = (-\delta_1 - \delta_2)/2$$



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