WHOI-99-11

Woods Hole Oceanographic Institution

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Navigation for the Derbyshire Phase2 Survey

by

S. Lerner
D. Yoerger
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May 1999

Technical Report

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Approved for Distribution:

Tim Stanton

Timothy K. Stanton, Chair

Department of Applied Ocean Physics and Engineering

1. INTRODUCTION

A subsea forensic survey requires precise positioning of the vessel and vehicles. Precise navigation permits the survey team to control the path of the subsea vehicles in order to execute the survey plan. Additionally, precise navigation allows the survey coverage to be determined and provides the ability to return to specific targets. Precise navigation also allows the assessment team to correlate observations made at different times from different vehicles.

The survey vessel, RV Thomas G. Thompson, was equipped with a p-code Global Positioning System (GPS) receiver. This device permits the vessel position to be determined with a repeatability of about 4 meters (one sigma). This figure was determined from dockside tests. Fixes were provided at one-second intervals.

GPS positioning of the vessel provides two critical capabilities. First, we use GPS to aid in surveying transponders placed on the seafloor. By knowing the vessel position and the acoustic travel-time (therefore range) to the transponder, the transponder position can be determined after guiding the vessel through a sufficient survey pattern. Second, we use GPS as an input to the vessel dynamic positioning system (DP). The dynamic positioning computer controls the vessel position within a few meters of a desired position. Our DP interface allows the navigator to manipulate the desired vessel position interactively, which provides a key capability for precise trackline following and safe navigation of the vehicles near obstacles.

The subsea vehicles were navigated acoustically, as GPS signals do not penetrate seawater. After surveying a network of acoustic transponders, we use acoustic travel times between the vessel, transponders, and vehicles to determine the vessel and vehicle position. For historical reasons, we do not use the GPS vessel position directly in the acoustic navigation solutions. We employed several types of acoustic cycles depending on the vehicle and type of survey.

We employ several different types of coordinates. Ultimately, all our coordinates can be directly converted to latitude and longitude, although lat/lon coordinates are awkward to work with in operational and quantitative mapping contexts. Instead, we work primarily in Universal Transverse Mercator (UTM) coordinates. UTM coordinates provide a standardized set of coordinates that work over wide areas. Under UTM, the surface of the earth is divided in 60 zones. Each zone consists of a slice that incorporates all the area within 3 degrees of longitude on either side of central meridian. For the Derbyshire survey, we were operating in UTM zone 53. As a consequence of the transverse mercator projection, the UTM grid XY coordinate frame is generally rotated slightly from true north/east directions depending on the distance from the central meridian for the current zone.

Internally, our acoustic navigation system works in simple Mercator coordinates using an arbitrary origin. However, these coordinates are of no consequence to the user.

In this report, we summarize the repeatability of our navigation fixes for the Argo vehicle. This repeatability study provides confidence levels for our estimates of photo coverage. To determine repeatability, we selected a number of instances where the vehicle lines crossed. By comparing vehicle offsets from both navigation and imagery, we could estimate the repeatability. We estimate the average navigation error at 3.1 meters, which it well within our expectations of +- 5 meters.

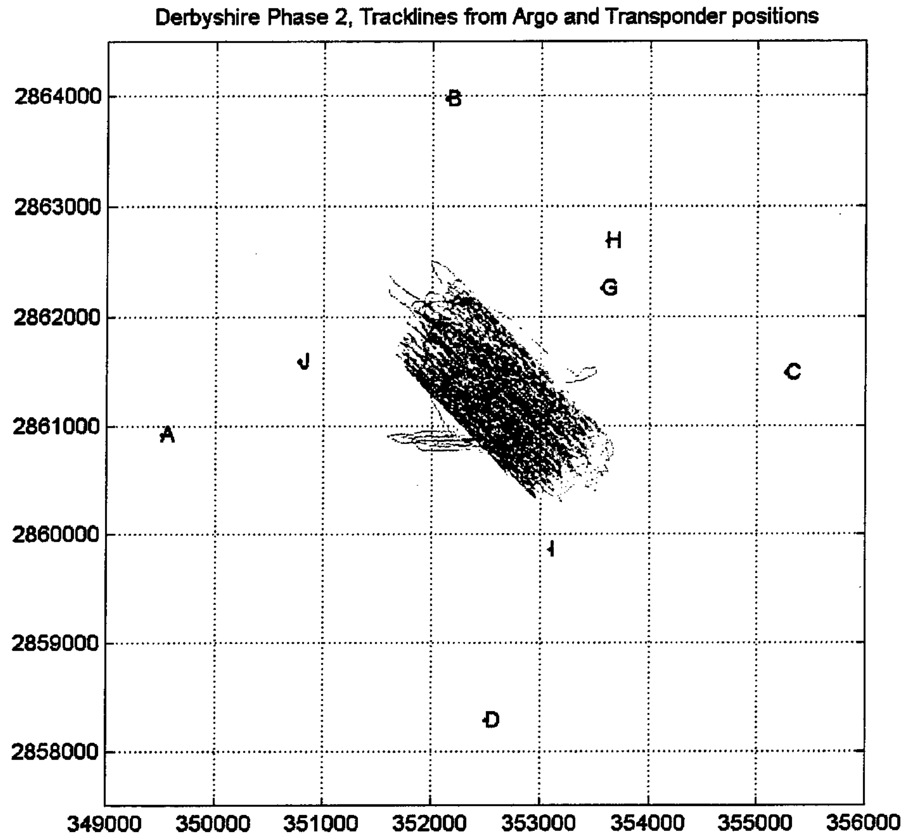


Figure 1: This plot shows the transponder positions and the complete set of Argo tracklines.

2. TRANSPONDER SURVEYS

After each transponder has been placed on the seafloor, its precise position must be determined. Although we record the vessel position when each transponder is launched, they inevitably drift as they descend to the seafloor.

Before any acoustic navigation can be accomplished, we require detailed knowledge of the speed of sound and how it varies as a function of depth. We obtained this information by using an expendable bathythermograph (XBT) to measure the temperature in the first 760 meters, and using historical data to extend the profile all the way to the seafloor.

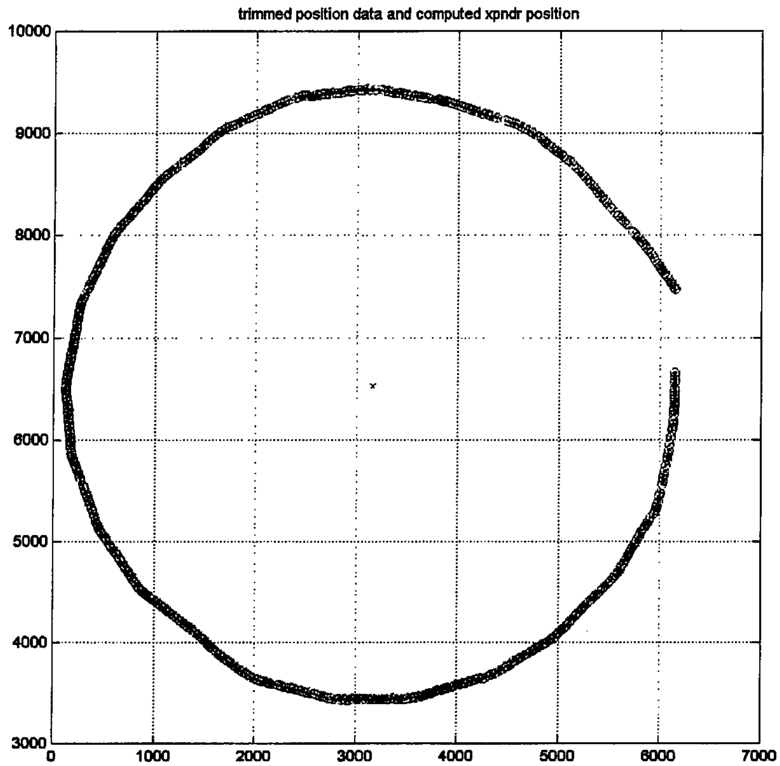
The survey process involves determining the transponder position (in three dimensions). We accomplish this by maneuvering the vessel in a circular pattern around each transponder. The radius of the circle was set to about 70% of the depth of the water. This provides good triangulation geometry without making the survey pattern excessively long.

A minimum of three travel time/vessel GPS fixes are required to fix the transponder position provided they do not lie in along a line. However, we log several hundred points along a circle about the estimated transponder position. This technique allows us to reduce the effect of noise, and more importantly to balance many of the errors. For example, by following a circular survey track we greatly reduce the effect of several error sources on the horizontal position estimate. Errors minimized by a circular track include sound speed errors and the effect of ship movement during an acoustic cycle.

Figure 2 shows a typical survey track. The pattern was driven at a speed of about 4 knots using manual or "hand steering" by the ship's bridge watch (DP is not used for the survey). A circle plotted on the ship's navigational display was provided to help in controlling the vessel. Each survey track required about 2 hours from completion. Results of the completed survey for all transponders are contained in Appendix A.

A survey record consists of the vessel position and the two-way travel time to and from the transponder. Additionally, the vessel heading is recorded, in order to compensate for the horizontal offset between the GPS antenna and the acoustic navigation transducer. No compensation is included for antenna motions induced by vessel pitch and roll. After the survey is completed, the transponder position can be computed by a least-squares solution. The software allows errant travel-times to be removed. A typical survey data set contains about 500 records.

Figure 3 shows the difference between the measured range (from the acoustic travel time) and the estimated range (from the vessel GPS fix and the estimated transponder position). The difference is low (1.4 meters rms) and any systematic errors are on the order of a meter. Figure 4 shows a histogram of the error distribution, which indicates an approximately gaussian error distribution.



*

Figure 2. This plot shows the vessel track during a typical transponder survey. The apriori estimate of the transponder position (based on the launch position) is at the center of the circle. By using a circular survey pattern, we reduce the effect of many errors on the surveyed position.

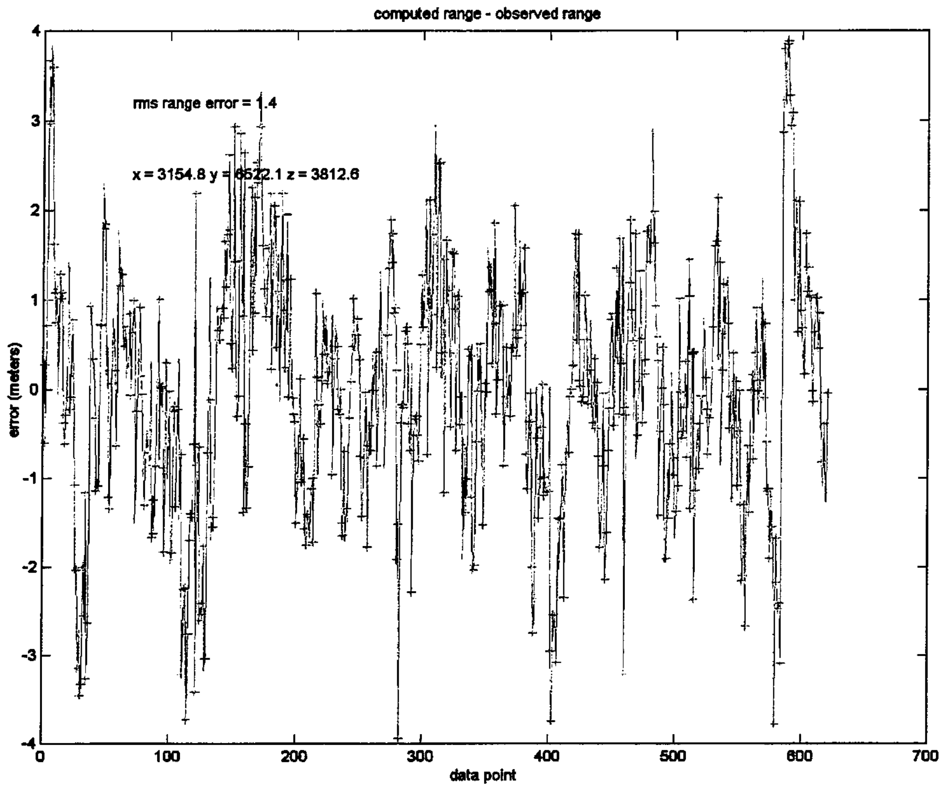


Figure 3. This plot shows the difference between the range computed from the vessel fixes and the surveyed position and the directly measured range.

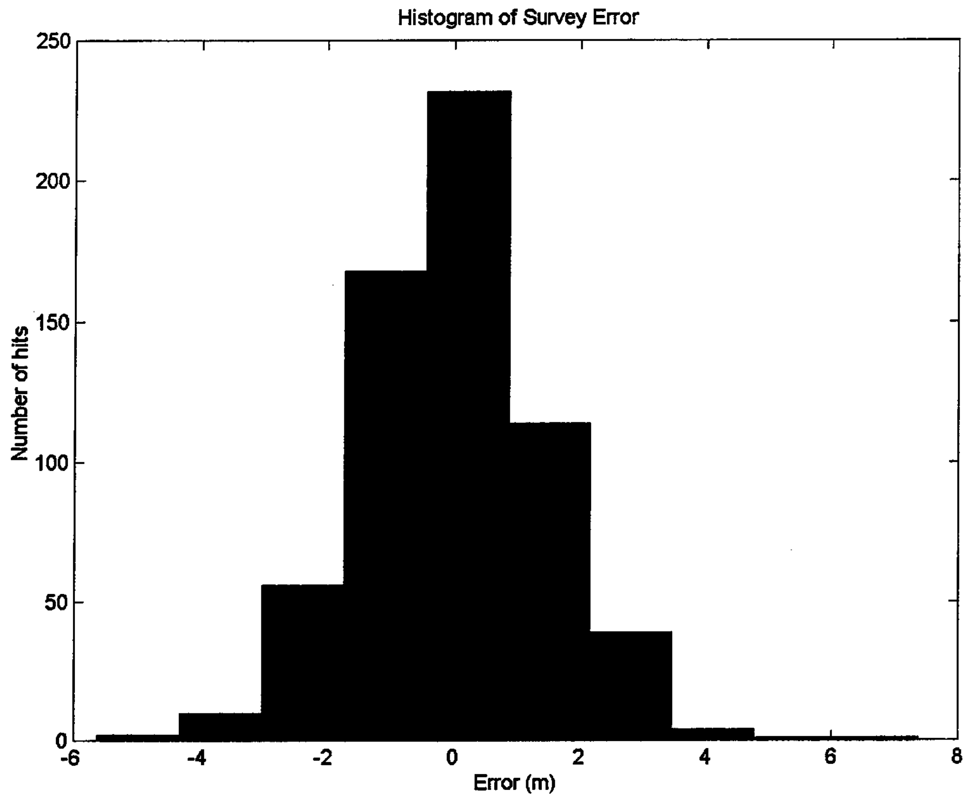


Figure 4. This plot shows the histogram of the range errors. While figure 3 shows some systematic errors, the final error distribution is fairly gaussian.

3. DSL-120 AND ARGO RESULTS

We installed and surveyed six transponders for DSL-120 and Argo navigation (A-E in appendix A). These transponders were set on 50 meter tethers. Due to performance problems related to terrain, transponder C was recovered and reset with a 100 meter tether.

For both DSL-120 side scan sonar and the Argo towsled, we employed "Relay Mode" navigation. In relay mode, an acoustic cycle is executed for the ship, then another acoustic cycle is executed through the relay transponder on the tow wire above the vehicle. The reception of travel times at the vessel from the relay transponder and the transponders permits a 3D navigation solution to be computed. Conceptually, the solution can be compared to a 3 transponder, 3D solution, where the vessel plays the role of one of the transponders. While we usually have more than two transponders in our net (typically we had 5 or 6 during the Derbyshire survey), the navigator selects only two to use at any given time. With the ship effectively acting as a third transponder, we obtain a deterministic, three-dimensional fix with no intrinsic error measure. This cycle is summarized in figure 5.

For the DSL-120, we require excellent navigation for the sonar towfish, however tight trackline following is not necessary because the large swath coverage of the 120 lets us easily prevent any gaps in coverage. However, with Argo, we must navigate the vehicle precisely and maintain tight control of the tracklines in order to produce complete coverage.

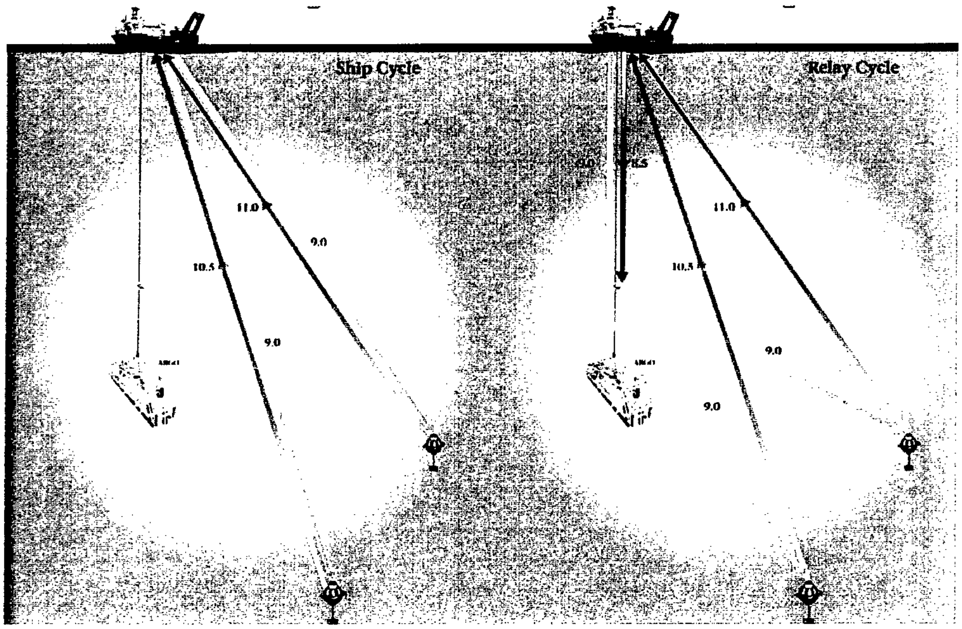


Figure 5: For both Argo and the DSL-120, we employed Relay Mode navigation. To obtain a solution, two cycles are executed. The first cycle determines the travel times between the ship and the transponders, and the second cycle interrogates the transponders through a relay transponder positioned on the tow cable approximately 100 meters above the vehicle.

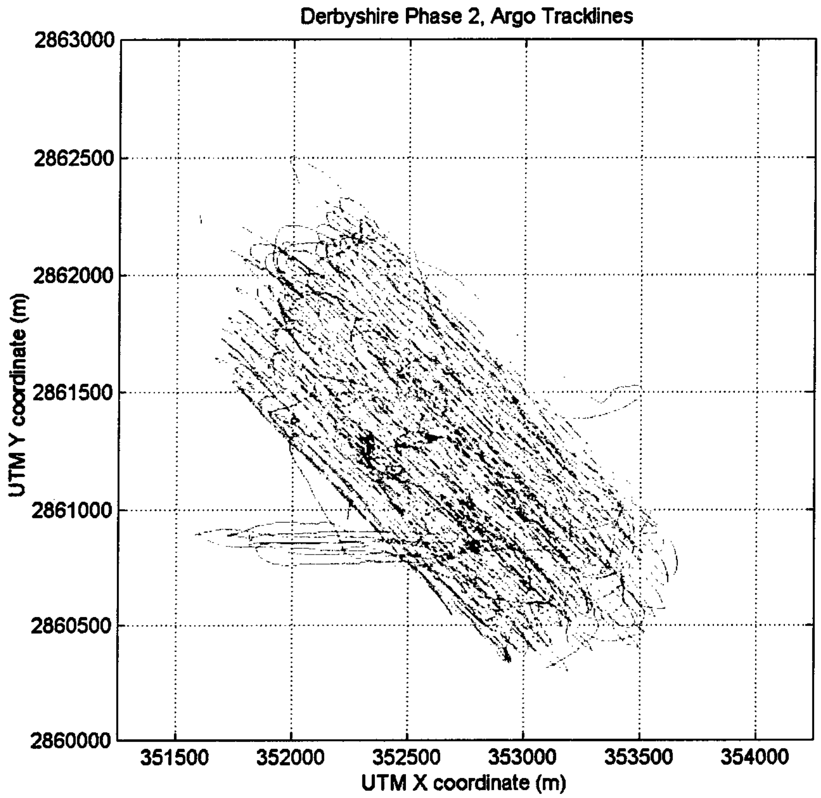


Figure 6: Complete set of Argo tracklines

Our goal was to obtain complete photographic coverage of the entire wreck site. As we control Argo primarily by maneuvering the vessel, this represented a challenge in over 4000 meters of water. In particular, the sluggish response of the vehicle to vessel movements makes the task difficult. Figure 6 shows the complete set of Argo tracklines.

Figure 7 shows the dynamic response of the vehicle to vessel motion along with the response of a simple first-order model. Both vessel and vehicle movements have been transformed into a plane oriented along the nominal trackline direction. While the model is naïve in several ways (it ignores currents, depth changes, hydrodynamic nonlinearities, and out-of-plane motion), it clearly captures much of the relevant dynamics. It performs worst in turns, where the vessel motion is most extreme, velocity changes and out-of-plane motion are the large.

By fitting the model to the vehicle response, we can determine the time constant of the primary vehicle dynamic response to one-dimensional vessel motion. In the model shown in figure 7, the time constant was set to 18 minutes.

From our assumption of a linear first-order dynamic and the time constant, we can also compute the steady-state distance between vessel and vehicle (layback) as a function of vessel speed. A time constant of 18 minutes corresponds to a layback of 1080 meters. We expect that the layback will be dependent on speed in a nonlinear fashion, so these results are most valid around our operating speed during this survey, 0.5 knots = .25 m/second.

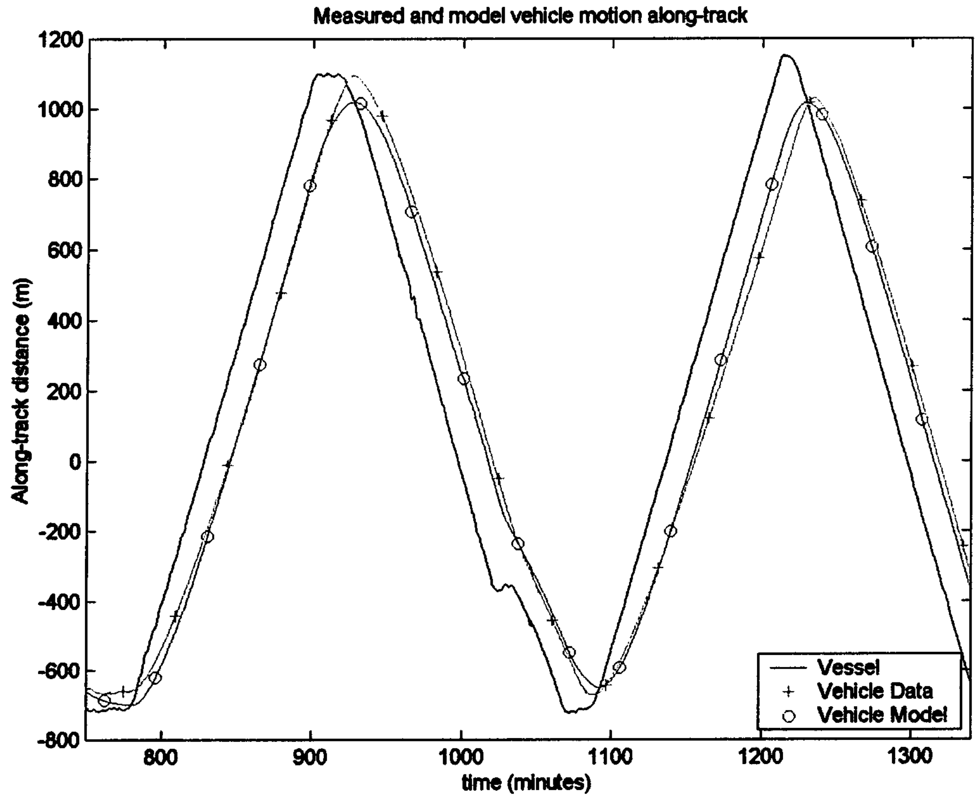


Figure 7 Modelled versus measured vehicle response along track. This plot shows distance traveled by the ship, vehicle, and a model. The model is a simple first-order system with a time constant of 18 minutes.

The navigator performed the job of driving the vehicle along a prescribed trackline. While the bridge watch always retained ultimate control of the vessel, the DP interface in the control van permitted the navigator to command vessel translation interactively. Using his latest estimate of the current across-track offset between vehicle and vessel, the navigator would command a vessel motion that would carry the vehicle down the track. The vehicle motion could be adjusted three ways:

1. The vehicle's thrusters could be used to push the vehicle sideways. While only small corrections could be effected in this manner, thrust provided the fastest response time (time constant of several minutes), but was unsuitable for maintaining a sustained correction.

2. The vehicle's heading could be altered through commands to its autopilot. By increasing the angle of attack, the vehicle body generates a side force through lift. Using heading changes, large corrections in the trackline could be made, but these changes took longer than those obtained by direct thrust (time constant, approximately 5 minutes). A steady offset for a prolonged period could be easily maintained in this way.

3. Finally, the navigator could alter the ship track. This type of correction provided the largest change in the vehicle track, although through the most sluggish mechanism (time constant ~18 minutes as shown

earlier).

Figure 8 shows typical trackline performance. The vessel movements, shown in red, were chosen to induce the vehicle to move along the trackline. Cross-track adjustments were entered at frequent intervals to keep the vehicle on the track. Due to the highly damped and sluggish nature of the vehicle response, these motions had to be exaggerated versions of the desired vehicle motion.

The corners in figure 8 show two different strategies. In the turn at the upper left corner, the navigator drove the vessel continuously. In the turn in the lower right corner, the navigator stopped the ship and commanded a rectangular turn with the vessel. The rectangular turn took more time than the continuous turn, but the vehicle converged on the new trackline sooner with the rectangular turn.

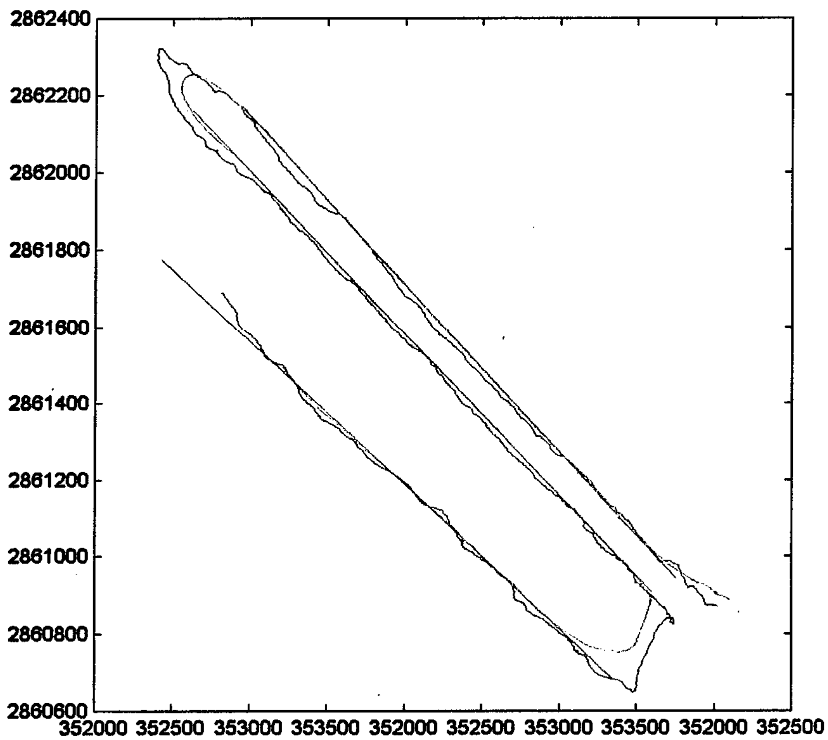


Figure 8: Typical track following performance. The red tracks shows the vessel trajectory, the magenta lines show the desired tracks, and the green trace shows the vehicle track.

Figure 9 shows vehicle off-track error versus time along with the vehicle heading. The errors are quite low, rms = 2.1 meters. Just before 22 hours, the vehicle trackline error starts to grow, and a heading was commanded to change in order to counter the error. This heading change (probably along with side thrust), brought the vehicle back on line.

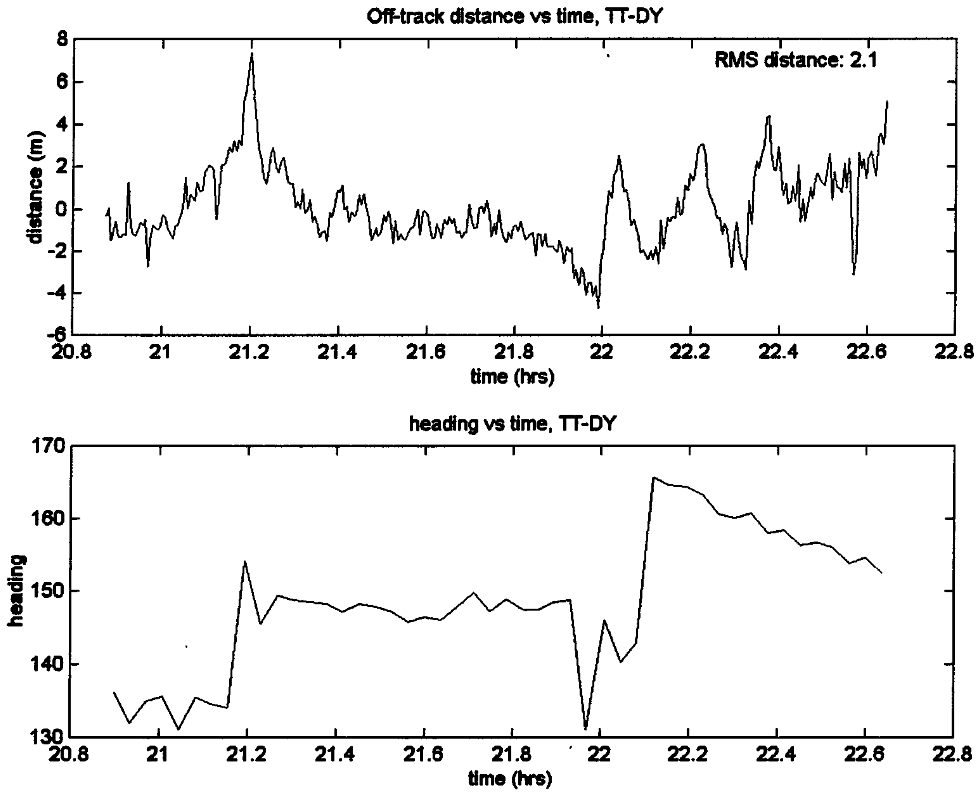


Figure 9. This plot shows trackline error and vehicle heading. As the track error grows just prior to 22 hours, a heading change is applied.

4. JASON NAVIGATION

The requirements for navigation of Jason differed from those of Argo in several respects. Jason navigation had to allow us to revisit locations identified by Argo imagery rather than to obtain complete overlapping coverage. Additionally, since Jason works closer to the seafloor and does not have the option of a relay transponder high on the tow wire, terrain or wreckage can obscure the acoustic paths.

To deal with these constraints, we installed 3 more transponders (H-J in appendix A) on 100 meter tethers. These transponders were located in order to provide good coverage over the major debris regions identified through Argo imagery.

Jason uses a different acoustic cycle than Argo, which allows the position of the ROV and its clump weight (Medea) to be positioned in alternate cycles. Figure 9 shows an ROV navigation cycle. The ship "pings" at 9.0 khz, which excites the transponders. The transponder replies are heard at the ship and the vehicle, which also hears the 9.0 pulse from the ship. This technique allows Jason's position to be determined in 3D in one cycle. Equivalent cycles for Medea were alternated.

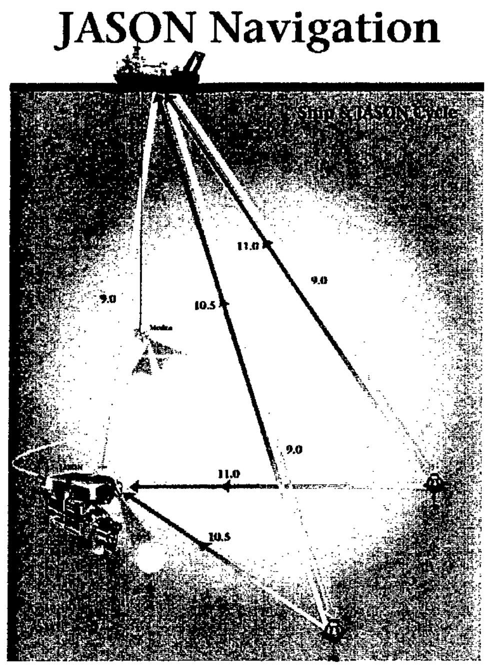


Figure 9. Jason uses a cycle where returns are received at the vehicle and the ship. In each cycle, we obtain a position fix for the vessel and either Jason or Medea.

5. ARGO NAVIGATION REPEATABILITY

In order to judge whether our trackline coverage is as complete as our coverage maps would imply, we studied the accuracy of the Argo navigation. We accomplished this goal by picking points where Argo tracklines crossed, then compared the positional offset determined from the navigation to the offset determined by comparing features in corresponding ESC images.

5.1 ERROR SOURCES

Long baseline acoustic navigation is imperfect for a variety of reasons:

- Our transponder surveys are imperfect, which results in a slightly warped navigation grid. Since we often switch baselines, these switches will result in jumps if the survey is imperfect. We estimate the magnitude of these errors at approximately 2 meters for each transponder.

- The resolution of the acoustic travel time detection is limited by the bandwidth of the acoustic pulses (estimated at +- 1.2 meters based on deepwater trials with fixed elements).

- Tidal currents can deflect the transponders (estimated as +- 1 meter)

- The relay transponder was attached 100 meters above the tow sled, and we anticipate a small offset (+- 1 meter) due to deflection of the cable. Likewise, maneuvering the vehicle with the thrusters could increase this error

As a result of these errors, the navigation would not provide the same positional fix when we returned to an identical position at a later time. Likewise, the apparent position of the vehicle would change when we switch the baseline pair used for navigation. Based on our estimates of these error components, we expect to see errors on the order of +- 5 meters.

5.2 METHODOLOGY

We can exploit the images gathered by Argo to determine navigation error. First, we find a points where two tracklines cross (within a tolerance). Using the DSL Visual program [Lerner et. al], we find the two corresponding images that contain multiple overlapping images. Then, we rotate each image based on the Argo compass reading, then scale from the altitude measurement, and finally translate one of the images to best match a series of tie points on the other image. We obtain an equivalent positional offset purely from the navigation. The navigation error can then be determined as the difference between the offsets determined from the acoustic navigation and the offsets determined from the image tie points.

We analyzed accuracy under two conditions. First, we used 41 intersections between typical tracklines, (which ran from southeast to northwest and vice-versa) and a single east-west tie line. Second, we gathered 18 crossings at random throughout the survey area.

Figure 10 shows the tie line superimposed on the survey tracks. The line cuts across 41 tracklines, and the imagery for most crossings has sufficient features to provide a good match.

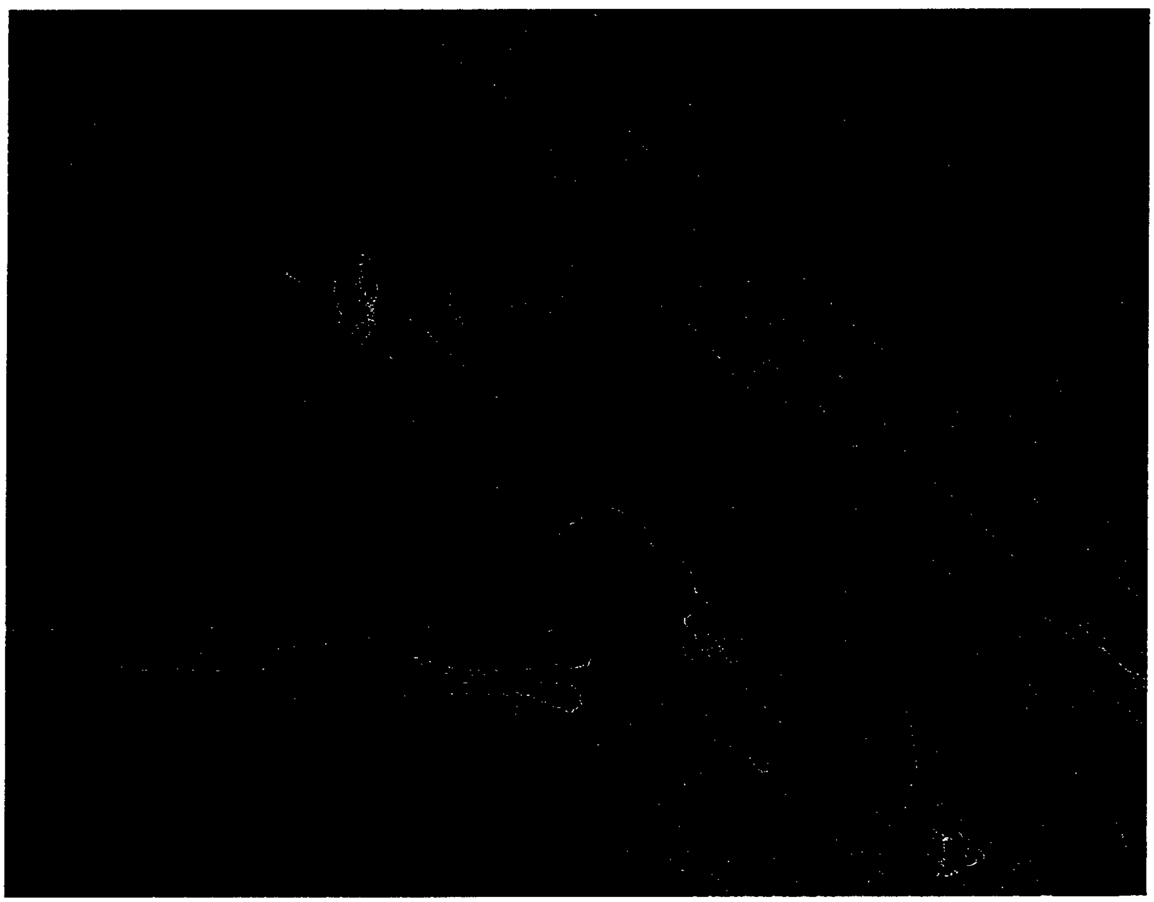


Figure 10. This plot shows the crossing line used to determine navigation repeatability.

A typical image pair is shown in figure 11. These images have both been rotated using the compass so that each image has north approximately pointing up (compass errors can be clearly seen). Features that appeared clearly in both images were chosen manually, then the offsets were computed taking into account the differences in height off bottom (from the altimeter measurement).

Results were obtained for 123 corresponding images/navigation crossings along the tie line. The average error was 3.1 meters. For a more scattered sampling of 18 points over a wider area, the average position error was 1.9 meters. Both these results are well within our expected error magnitude of 5 meters. A collection of representative image pairs are shown in Appendix C.

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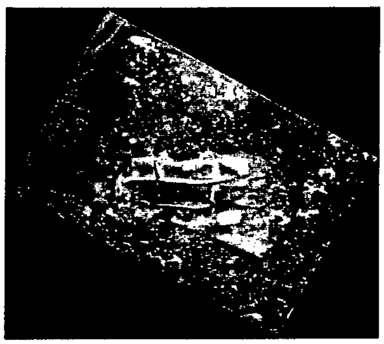

H: 208.7 A: 14.2

tape036/ESC.970325_004138.0106.tif

H: 172.1 A: 14.5

Figure 11: These two images show the same objects in different passes at different headings and altitudes. From tie points manually selected on each image, we can compute the offset between images for comparison to the offset derived from the navigation.

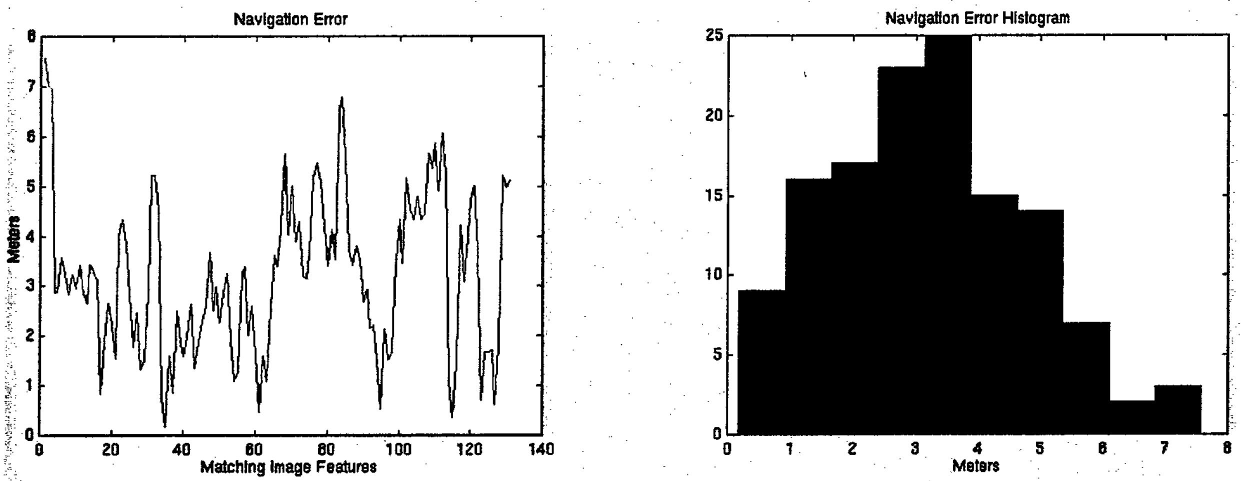

Figure 12. These plots summarize the discrepancies between the navigation and the images for the tie line. The average error is 3.1 meters. A total of 123 image pairs were analyzed.

6. CONCLUSION

This report summarizes the navigation used on the Derbyshire Phase 2 expedition. The schemes used for navigating the tow sleds and ROVs are summarized, as are the survey techniques used to determine the transponder locations. An analysis of the navigation repeatability was undertaken. By registering two images from overlapping areas on different tracklines, we can determine the true position offset between the tow sled. By comparing the position offsets derived from the images to the offsets obtained from the navigation, we can determine the navigation error. The average error for 123 points across a single tie line was 3.1 meters, the average error for a more scattered selection of 18 points was 1.9 meters.

7. APPENDIX A: TRANSPONDER SURVEY INFORMATION

Derbyshire, T.G.Thompson TN-068 Transponder Locations April 1997

UTM ZONE 53

ID	LAT (N)	LON (E)	X	Y	Z	RMS	# PTS	TETHER455		freq	DEPLOYED
A	25 51.53251	133 29.88738	349505.7	2860915.7	3811.8	1.08	572	50M	8.0	11.75	12MARCH
B	25 53.20772	133 31.43631	352127.7	2863979.0	4585.7	.94	531	50M	9.5	11.50	12MARCH
C	25 51.87594	133 33.33230	355266.7	2861485.1	4126.0	1.21	661	50M	8.5	11.25	12MARCH
D	25 50.12524	133 31.69464	352495.3	2858283.6	3814.7	.85	592	50M	7.5	11.00	12MARCH
E	25 50.35818	133 28.97016	347948.6	2858765.4	3416.6	1.60	591	50M	10.5	10.75	12MARCH
F	25 48.78566	133 27.27639	345084.9	2855895.3	3142.4	1.83	418	50M	10.0	10.50	12MARCH
G	25 52.28161	133 32.30105	353552.7	2862253.1	4276.8	.81	684	100M	8.5	11.25	19MARCH
H	25 52.51684	133 32.32947	353605.0	2862686.8	4272.1	.98	602	200M	7.5	11.00	10APRIL
I	25 50.98266	133 32.03608	353083.4	2859860.1	3790.9	.97	601	200M	10.5	10.75	10APRIL
J	25 51.90622	133 30.64569	350780.2	2861591.2	3893.1	.80	653	200M	10.0	10.50	10APRIL

Origin of local grid 25° 48.0′ N 133° 28.0′ E

Transponder tethers are 1/16" galvanized aircraft cable.

Transponder anchors are 100 pounds.

Depth of ship transducer was 5.8M.

Transponder "C" recovered 15 March and redeployed as "G"

8. APPENDIX B: NAVIGATION TIMELINE

Date	Time	Vehicle	
97/03/12	1200	Xpndr	Set and survey xpndrs A-F
97/03/13	1143	DSL-120	Start 120 operations
97/03/15	0500	DSL-120	120 on board
97/03/15	1102	Argo	Argo 12 launch
97/03/19	0748	Argo	Argo recovery
97/03/19	0758	Xpndr	Set and survey xpndr G
97/03/19	1548	Argo	Launch Argo 13
97/03/23	0003	Argo	Recovering, hit a line, electrical problem
97/03/23	0920	Argo	Launch Argo 14
97/03/26	0546	Argo	Argo on deck
97/03/26	1014	Argo	Launch Argo 15
97/03/28	0000	GPS	Pcode GPS lost
97/03/28	0120	Argo	Continue survey by h*and steering
97/03/30	0818	Argo	End Argo 15, on deck, snagged on floating line?
97/03/30	1424	Argo	Launch Argo 16, Pcode GPS still down
97/04/07	0657	Argo	End Argo 16
97/04/07	1130	Argo	Launch Argo 17, Pcode fixed
97/04/08	2122	Argo	End Argo 17
97/04/09	0739	Xpndr	Xpndrs E and F recovered
97/04/09	0305	Argo	Launch Argo 18, cameras looking to the side
97/04/10	0214	Argo	Argo on deck, end of Argo18
97/04/10	0324	Xpndr	Set xpndrs HIJ, survey J and H
97/04/11	0627	Jason	Launch Jason 202
97/04/11	1808	Jason	Recovered Jason after loss of telemetry
97/04/12	2238	Jason	Launch Jason 203
97/04/15	0446	Jason	Jason 203 ended, Jason on deck
97/04/16	0006	Jason	Launch Jason204
97/04/18	0359	Jason	Jason 204, on deck
97/04/18	~0600	Wx	Leave site, bad weather
97/04/23	0830	Wx	Back on site
97/04/23	0900	Jason	Launch, Jason 205
97/04/25	2036	Jason	Jason 205, on deck
97/04/27		Xpndr	Recover xpndrs A, B, G
97/04/27	1055	Jason	Launch Jason 206
97/04/28	0705	Jason	Jason 206, on deck
97/04/28	0925	Xpndr	All xpndrs on board, steaming to Yokohama

APPENDIX C: SAMPLE REPEATABILITY COMPARISONS

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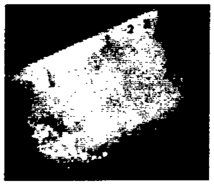

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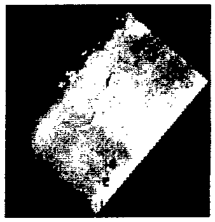
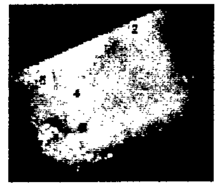


Nav 352943.9610.2861065.302 H 156.1 A 15.31

Nav 352949.7391.2861078.8373 H 313.4 A 11

Point	Wdx	Wdy	Wdxy
1	5.3749	5.3381	7.5753
2	4.1873	5.8814	7.2034
3	3.5515	5.9750	6.9545

tape095/ESC.970408_055625.0185.tif



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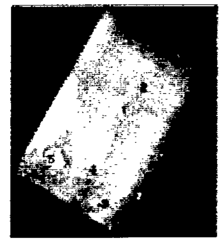
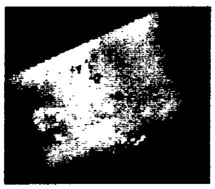


Nav. 352943.9618.2861065.805 H. 156.1 A 15.31

Nav. 352948.3442.2861066.75 H 310.4 A 15.5

Point	Wdx	Wdy	Wdxy
1	2.7950	−0.7423	2.3927
2	2.7380	−0.71276	2.9781
3	3.5608	−0.40315	3.5835
4	3.1678	−0.87263	3.2384
5	2.1786	−0.22517	2.3336

tape095/ESC.970408_055651.0187.tif



tape101/ESC.970331_175513.1315.tif

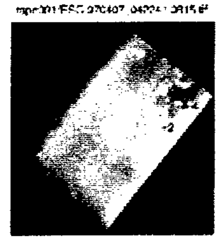
Nav 352941.4292.2861064.3146 H 156.3 A 15

Nav 352942.0559.2861065.2967 H. 315.4 A. 11.2

Point	Wdx	Wdy	Wdxy
1	2.9431	−1.3412	3.2342
2	2.8093	−0.57295	2.8536
3	3.4	0.50035	3.4366

tape095/ESC.970408_055758.0192.tif

tape101/ESC.970407_042241.3815.tif



Nav 352937.8363.2861059.5276 H 200.8 A 15.41

Nav 352935.6240.2861030.3690 H 308.3 A 14.6

Point	Wdx	Wdy	Wdxy
1	−0.48053	−2.827	2.8657
2	−2.5367	−0.61366	2.6685
3	−3.4315	−0.30311	3.4473
4	−3.2798	0.054831	3.28

tape095/ESC.970408_055730.0190.tif

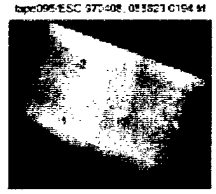
tape055/ESC.970329_221204.0369.tif

Nav 352939.8142.2861062.1816 H. 155 A 14.93

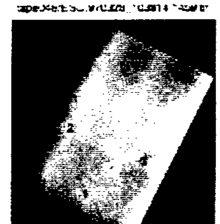
Nav 352939.5566.2861051.3104 H 305.6 A 15.96

Point	Wdx	Wdy	Wdxy
1	3.0777	−0.43960	3.1088
2	0.52542	0.82557	0.61756
3	−1.0866	−1.545	1.89

tape095/ESC.970408_055823.0194.tif



tape[illegible]/ESC.970[illegible]

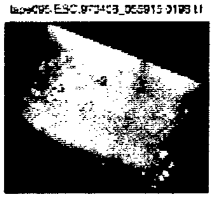


Nav 352934.6537.2861056.7974 H 200.6 A 15.55

Nav 352936.3671.2861055.2029 H 298.4 A 12.8

Point	Wdx	Wdy	Wdxy
1	2.2781	−1.3759	2.6594
2	0.29942	−2.1915	2.2118
3	1.476	−0.44695	1.543

tape095/ESC.970403_055915.0198.tif



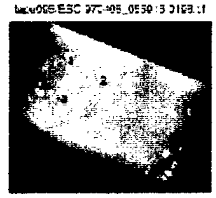
tape[illegible]/ESC.970404_164948.0604.tif

Nav 352931.0631.2861050.2763 H 201.4 A 15.6

Nav 352928.3764.2861048.0395 H 124 A 12.14

Point	Wdx	Wdy	Wdxy
1	−0.30137	−3.9857	3.9966
2	−0.52271	−4.3046	4.0377
3	−0.21355	−2.733	3.8431

tape095/ESC.970408_055913.0193.tif



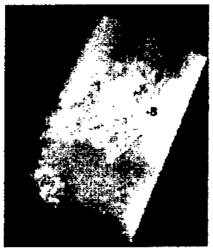
tape030/ESC.970405_194934.0237.tif

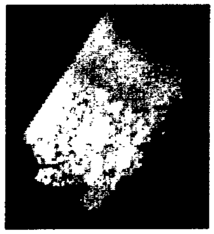
Nav 352931.0691.2861050.2783 H 201.4 A 15.6

Nav. 352923.3367.2861049.3943 H 291.7 A 16.2

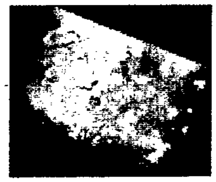
Point	Wdx	Wdy	Wdxy
1	−1.25	−2.5510	2.8411
2	0.13051	−1.7574	1.7685
3	0.53253	−2.4071	2.4654

tape088/ESC 970406_164851 0796 tif





Nav 352928.3756 2861048.0209 H 174 A 12 44

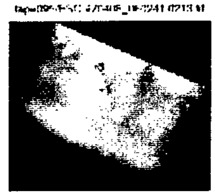


Nav 352921.7167 2861030.2585 H 201 6 A 15 50

Point	Wdx	Wdy	Wdxy
1	2.9731	-4.2938	5.2224
2	2.5730	4.528	5.2084
3	2.2711	-3.9079	4.5190

Nav 352921.7167 2861030.2585 H 201 6 A 15 53

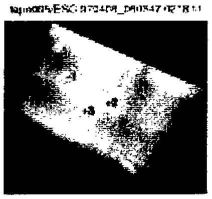
Point	Wdx	Wdy	Wdxy
1	3.79835	-0.1449	0.75243
2	-0.056599	-0.17057	0.17965
3	1.3072	-0.91944	1.5981



Nav 352913.7314 2861027.9217 H 203 7 A 20 5

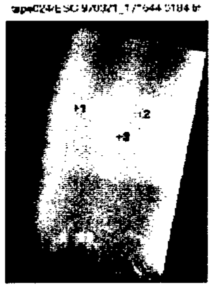
Point	Wdx	Wdy	Wdxy
1	-0.82503	-0.17059	0.84253
2	2.477	0.30329	2.4953
3	-1.5247	-1.0374	1.8442

tape005/ESC 970408_060547 0218 tif



Nav 352908 4354 2861019 8926 H 204 7 A 21 4

tape024/ESC 970321_171544 0184 tif



Nav 352908.2169,2861019.0137 H 280 9 A 17 ?

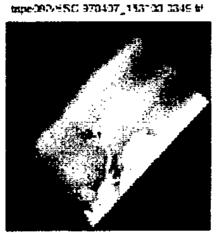
Point	Wdx	Wdy	Wdxy
1	0 83793	-1.042	1 3021
2	1 9906	0.11304	1 9925
3	2.616	-0.17417	2 6218

tape096/ESC 970408 060439 0222 tif

Nav 352904 027 2861014 9439 H 204 9 A 19.36

Nav [illegible] H 183 3 A 18 56

Point	Wdx	Wdy	Wdxy
1	[illegible]	-0 77311	1 3552
2	0 34905	1 8436	1 8770
3	0 22615	2 2665	2 2781

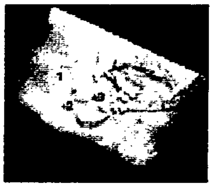


Nav 352900 1328 2861012 3464 H 204 1 A 14 3

Point	Wdx	Wdy	Wdxy
1	3.0655	-2.4342	2.5905
2	2.4173	-2.7745	3.6799
3	0.55677	-2.4436	2.5143

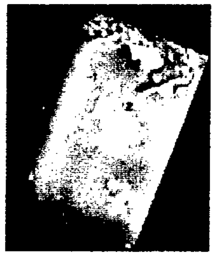
Point	Wdx	Wdy	Wdxy
1	1 8745	2.3151	2 9795
2	0 8675	2.0811	2 2547
3	1.3348	2 5231	2 8755

tape015/ESC 970408_060437 0231 tif



Nav 352891.243.2861301 8729 H 204 4 A 16 2

tape076/ESC 970403 203547 0885 tif



Nav. 352866.3932.2860993 3497 H. 291.3 A. 14.5

Point	Wdx	Wdy	Wdxy
1	-2 5053	-2 364	3.2610
2	[illegible]	[illegible]	[illegible]
3	-0 [illegible]342	-0.75741	1.1139

tape095/ESC 970408_060902 3242 tif

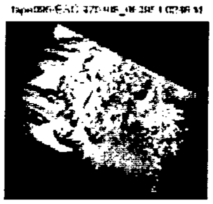
Nav 352875.0338 2860984 0453 H 205 6 A. 15 04

tape347/ESC 970327 220011 3255 tif

Nav 352872 8979,2860987.2328 H. 280 4 15.8

Point	Wdx	Wdy	Wdxy
1	0.41114	1 1624	1 23
2	2.5037	2 7029	3 2697
[illegible]	[illegible]	[illegible]	[illegible]

tape095/ESC 970408_061285 1 0248 tif



Nav 352868 0333.2860973 5869 H 206 3 A 14 6

tape344/ESC 970327 201950 0721 tif

Nav 352866 6383 2860990 3307 H 174 8 A 14 95

Point	Wdx	Wdy	Wdxy
1	-1.8736	0 72355	2.0114
2	-2.6122	0 17212	2 6179
3	-1.0014	0 23468	1 6187

tape095/ESC 970408_061109 0251 tif

Nav 352860 3782.2860989 3437 H 204 6 A 12 9

tape365/ESC 970402_021533 0382 tif

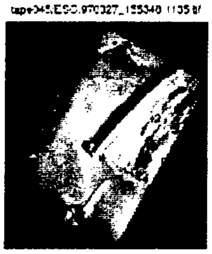
Nav 352850.4290,2860969.1666 H 300.7 A 13 0

Point	Wdx	Wdy	Wdxy
1	0 112	0 4735	0 49827
2	-0 88246	-1 3353	1.6005
3	0 017847	-1 0901	1 0903

tape095/ESC 970408_061109 0251 tif

Nav 352860 3782.2860989 3427 H 204 8 A 12 9

tape345/ESC 970327_155340 1135 tif



Nav. 352859.5335.2860959.5436 H. 298.9 A. 12.9

Point	Wdx	Wdy	Wdxy
1	1 383[illegible]	2.1989	2.5871
2	3 6129	-1 0629	3.6127
3	3 0084	1 5529	3 3847
4	3 6425	1 980	4 1521

tape095/ESC 970408_061109 0251 tif

Nav: 352860.3782.2860989 3437 H. 204.6 A 12 9

tape307/ESC 970317_033002 0378 tif

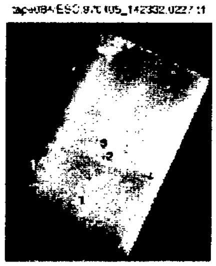
Nav 352852.1757,2860967.4257 H. 141 1 A 14 8

Point	Wdx	Wdy	Wdxy
1	4.6482	-3.2519	5.6728
2	2 9742	-2 72	4 0301
3	3 3036	-3.7173	5.0066
4	2 2695	-3 0725	3 88

tape095/ESC 970408_061215 0254 tif

Nav 352851 7159.2860962 1441 H 236 A 11 3

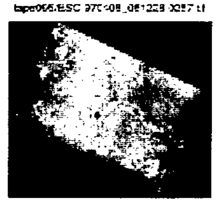
tape084/ESC 970405_142332 0227 tif



Nav 352854 7237 2860560 2318 H 234 8 A 17 14

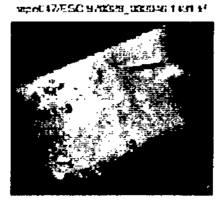
Point	Wdx	Wdy	Wdxy
1	3 0620	-2 9737	4 2917
2	2 0617	-2 4632	3 2127
3	1 6037	2 6822	3 1265
4	3 2625	1 5434	3 6254

tape095/ESC 970408_061229 3257 tif



Nav 352849 0146 2860890 8613 H 205 1 A 14 6

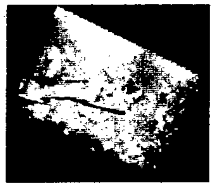
tape347/ESC 970328_033040 1431 tif



Nav 352852 6485 2860958 5774 H 157 5 A 11 7

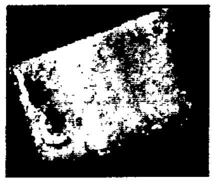
Point	Wdx	Wdy	Wdxy
1	1 274	5 208	5 1748
2	1.5936	-5 208	5 4742
3	3.0739	-1 3609	5 0981
4	1.5430	-3 3815	4 177

tape095/ESC 970409_061307 0263.tif



Nav 352845.735,2860955 496 H. 205 9 A. 14.71

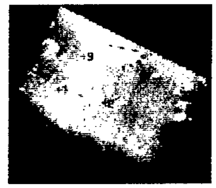
tape022/ESC 970321_150045 3669.tif



Nav 352848 0701 2860953 7095 H 150 4 A 11 75

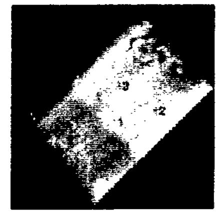
Point	Wdx	Wdy	Wdxy
1	1 6102	2 9102	3 3409
2	1 7152	3 7872	4 1193
3	-1 2934	-0 2828	3 5204

tape095/ESC 970409_061347 0283.tif



Nav 352939.9403,2860950 3459 H: 208 3 A: 12.3

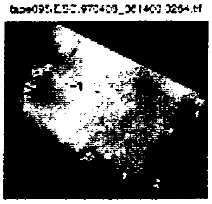
tape205.ESC.970316_192547.1254.tif



Nav 352943 3908 2860948 5324 H 376 A 18.29

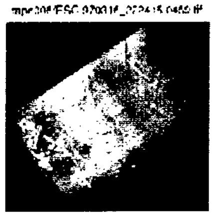
Point	Wdx	Wdy	Wdxy
1	6.1771	-2.2779	3 5827
2	6.644	-1 3201	3 7024
3	5 1964	-1 9522	5 5852

tape095/ESC 970409_061400 3264.tif



Nav 352037.9891 2960948.9671 H 208 4 A 16 37

tape208/ESC 970316_072415 0460.tif



Nav 352837 8730 2860943 2452 H 146.4 A 14 1

Point	Wdx	Wdy	Wdxy
1	1 3633	-3 5913	3 7426
2	1.5648	-2.8757	3.4106
3	2.005	-3.2348	3.8084

tape095/ESC 970409_061439 0267.tif

Nav 352934 2043 2860944 568 H 208 8 A 12 3

tape006/ESC 970316_225812 3883.tif

Nav 352833.5155,2860944 5611 H 307.8 A 13.8

Point	Wdx	Wdy	Wdxy
1	3 2281	-1.4458	3 5363
2	2 3952	-1.2237	2 6897
3	2 3028	-2.1223	2 9086

tape095/ESC 970409_061452 0268.tif

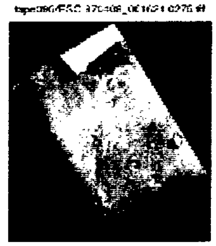
Nav 352831 9758,2860942 5541 H 238 A 13 2

tape033/ESC 970324_130813 0731.tif

Nav 352827 7505 2860941 7517 H 313 1 A 16 04

Point	Wdx	Wdy	Wdxy
1	-0 50067	-2.1082	2.1679
2	0 69173	-2.0905	2 2013
3	-0 51684	-1 4397	1.5297
4	0 33630	-0 4008	0 53753

tape095/ESC 970409_061521 0270.tif



Nav 352816 2639,2860933 3196 H 238 2 A 13 41

tape024/ESC 970321_225409 1705.tif

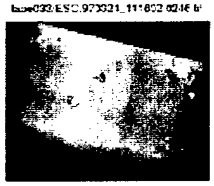
Nav 352817,6924,2860933 5659 H 298.5 A 13 9

Point	Wdx	Wdy	Wdxy
1	-1 578	-1.4375	2 1347
2	1 0063	1 1698	1 5417
3	-0 932	-1 3699	1 6561

tape095/ESC 970409_061611 0274.tif

Nav 352816.4375,2860934.5317 H 236.1 A. 13.2

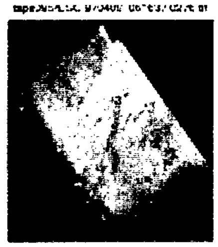
tape032/ESC 970321_111802 0246.tif



Nav 352818 2872 2860934 545 H 196 8 A 15 6

Point	Wdx	Wdy	Wdxy
1	2 5236	2 4304	3.515
2	-4 1494	1 220	4 3208
3	-3 2555	1 058	3 4526

tape095/ESC 970409_061637 0276.tif



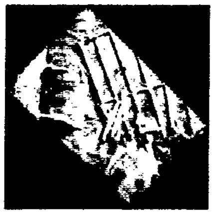
Nav 352814.2823 2860932.7585 H 254 5 A 13

tape035/ESC 970324 191520 3004.tif

Nav 352812 6586,2860935 8636 H 174 6 A 17

Point	Wdx	Wdy	Wdxy
1	-4 9479	1 565	5 1717
2	4 4055	1 1714	4 546
3	-3 6063	2 434	4 3508

tape005/ESC 970408_061730.0283.tif



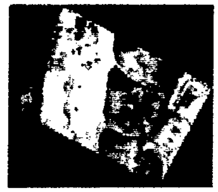
tape032/ESC 970324_211747.0936.tif

Nav 352804.85 14,2880026 201 H 224.4 A 13

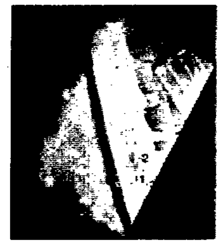
Nav 352808.6705 2880527.1055 H 300.6 A 16.05

Point	Wdx	Wdy	Wdxy
1	4.2091	−2.2801	4.7903
2	3.64	−2.3471	4.3311
3	3.3121	−2.3655	4.4357

tape005/ESC 970408_041900.0282.tif



tape032/ESC 970324_103428.0755.tif

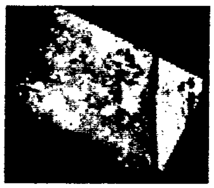


Nav 352802.1765.2880920.5718 H 208.3 A 7.4

Nav 352803.7407 2880032.404 H 207.5 A 14.3

Point	Wdx	Wdy	Wdxy
1	4.1383	−3.9776	5.6713
2	3.8125	−3.7455	5.3655
3	4.4806	−3.7722	5.8571

tape005/ESC 970408_061902.0267.tif



tape004/ESC 970316_100120.3041.tif

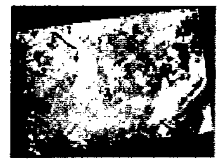
Nav 352796.0167.2880919.1370 H 206.6 A 9.9

Nav 352758.137 2880619.2397 H 303.1 A 14.88

Point	Wdx	Wdy	Wdxy	
1	4.7530	−1.2356	4.9113	
2	6.0726	−0.2833	6.0794	
3	5.2362	−0.42445		5.2533

tape005/ESC 970408_061928.0280.tif

tape002/ESC 970405_090931.1122.tif



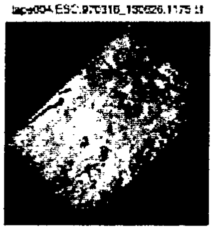
Nav 352793.3706.2880913.1132 H 203.3 A 14

Nav 352795.3074 2880915.0516 H 172.2 A 12.2

Point	Wdx	Wdy	Wdxy	
1	1.0481	−0.2001	1.0671	
2	−0.303537		−0.34313	0.34315
3	−0.2103	−1.4726	1.4857	

tape005/ESC 970408_061928.0280.tif

tape004/ESC 970316_130626.1175.tif



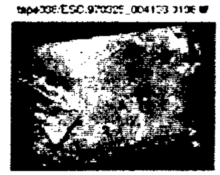
Nav 352793.3705.2880915 1132 H 208.9 A 14

Nav 352754.2212 2880914.5607 H 135.7 A 10.92

Point	Wdx	Wdy	Wdxy
1	2.8882	−3.0553	4.2034
2	1.8404	−2.4573	3.0645
3	2.6172	−2.0947	3.6574

tape005/ESC 970408_063021.0293.tif

tape008/ESC 970325_004133.3106.tif



Nav 352759.0418 2880913.2929 H 208.7 A 14.2

Nav 352755.5657.2880913.5671 H 172.1 A 14.5

Point	Wdx	Wdy	Wdxy	
1	−4.5135	1.3319	4.7261	
2	−4.375	−0.53435		5.0036
3	−3.565	0.8464	3.667	

tape005/ESC 970408_062047.0295.tif

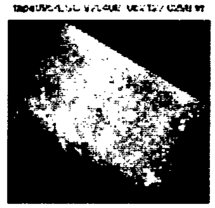
tape032/ESC 970324_085926.1534.tif

Nav 352795.8632.2880907.6237 H 209 A 13.05

Nav 352798.4306.2882917.557 H 173 A 14.83

Point	Wdx	Wdy	Wdxy	
1	0.55477	−0.41425		0.67237
2	1.3849	−1.272	1.6718	
3	−0.43057		−1.6012	1.6717

tape005/ESC 970408_062157.0296.tif



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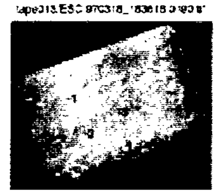
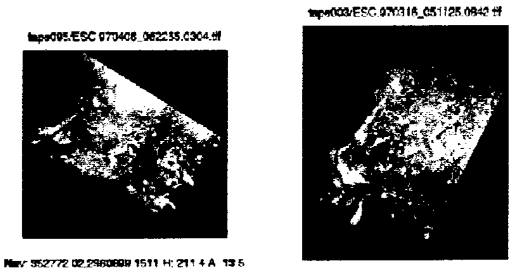


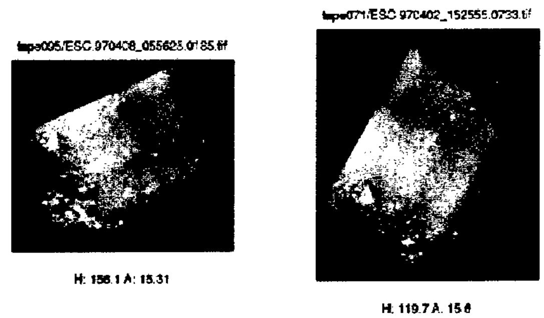
Nav 352782.0817 2880923.5479 H 210.4 A 14.3

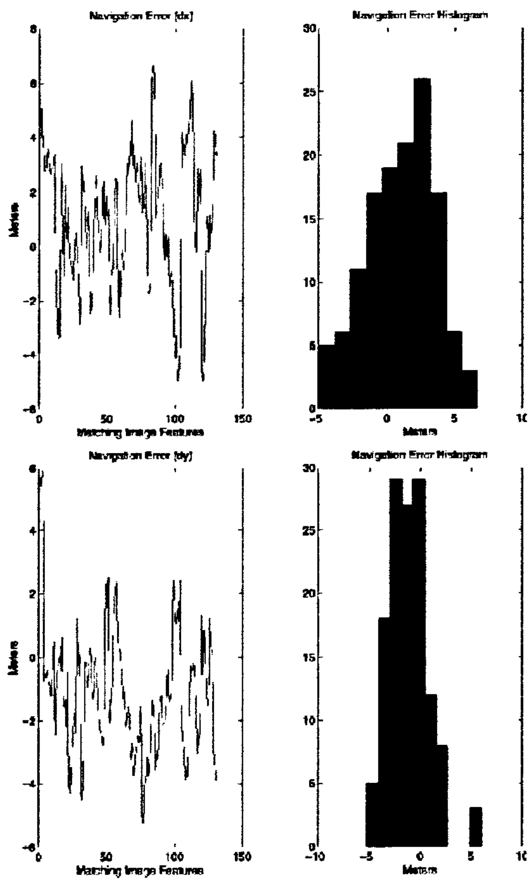
Nav 352782.4133.2880923.8535 H 150.1 A 15.7

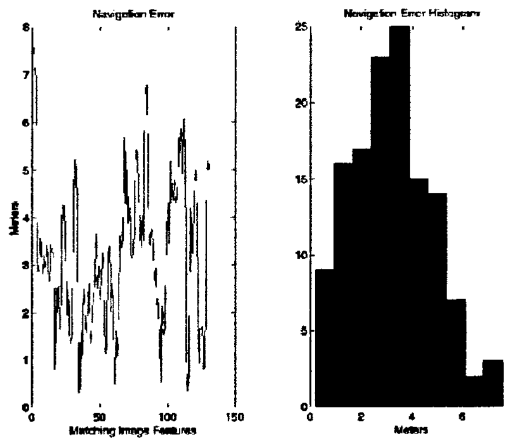
Point	Wdx	Wdy	Wdxy	
1	1.1558	1.2402	1.6953	
2	3.49544	0.58007	3.62625	
3	1.3104	−0.0050577		1.8134



Point	Wdx	Wdy	Wdxy
1	4.2767	−2.9755	5.2105
2	3.5296	−3.4969	4.9636
3	3.3244	−3.901	5.1254







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16. Abstract (Limit: 200 words)

In 1997, the Deep Submergence Operations Group of the Woods Hole Oceanographic Institution conducted an underwater forensic survey of the UK bulk-carrier MV Derbyshire with a suite of underwater vehicles. This report describes the navigation systems and methodologies used to precisely position the vessel and vehicles. Precise navigation permits the survey team to control the path of the subsea vehicle in order to execute the survey plan, provides the ability to return to specific targets, and allows the assessment team to correlate observations made at different times from different vehicles. In this report, we summarize the techniques used to locate Argo as well as the the repeatability of those navigation fixes. To determine repeatability, we selected a number of instances where the vehicle lines crossed. By registering two images from overlapping areas on different tracklines, we can determine the true position offset. By comparing the position offset derived from the images to the offsets obtained from navigation, we can determine the navigation error. The average error for 123 points across a single tie line was 3.1 meters, the average error for a more scattered selection of 18 points was 1.9 meters.

17. Document Analysis a. Descriptors

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Derbyshire

Jason, ARGO, DSL120

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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