INERTIAL METROLOGY REPORT

WOODSIDE PLUTO PLATFORM A

OFFSHORE WESTERN AUSTRALIA

Prepared by Joel Gillet
IPOZ Systems LLC
4141 Katy Hockley Rd
Texas, 77493, USA
281-381-3700

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Enquiries: jgillet@ipoz.net

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VOLUME 1

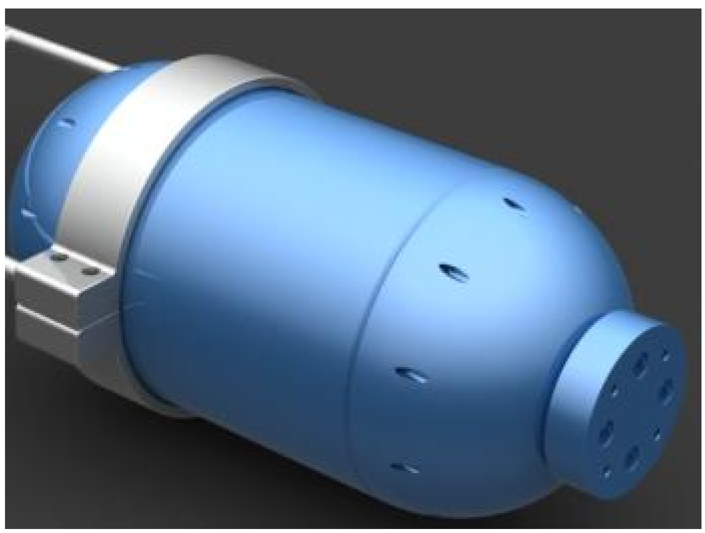
Executive Summary

- Inertial Metrology is a new survey technique for the measurement of distances and orientations underwater, using a single tool in a single ROV dive.

- This type of metrology is done with an Inertial Navigation System (INS), which is a triad of gyroscopes and accelerometers, mounted at 90 degrees of each other (in the 3 axes of space), and controlled by a Kalman Filter based navigation.

- The IPOZ GIPSEA™ metrology tool contains such an INS plus all controlling hardware, power supply with battery, hard drive, and navigation software.

- Pure unaided inertial metrology has been done for the last two years in the US Gulf of Mexico, in West Africa (Congo, Angola) where it has demonstrated productivity, accuracy and simplicity, and now in Western Australia.



- The accuracy of the inertial instrument used in this type of metrology is better than 0.05 degrees in angles (Heading, Pitch and Roll), and is a function of many factors –including length of the survey line- for both distance and depth (X,Y,Z) measurements. At a metrology distance of less than 50m it is better than 50mm horizontally, and about the same in the vertical dimension (depth).

- On January 04 and 05th, 2010 IPOZ Systems LLC of Katy Texas was given an opportunity by Woodside Burrup Pty Ltd of Australia to perform an inertial metrology measurement at the base of the platform Pluto A, in the PLUTO LNG field area in the Indian ocean, North West of Australia (110 miles from the town of Karratha, WA).

- The 2 points to survey were 2 “DOF” type gyro stabbing guides located on the NRV structure and on the flange of a 36” pipe riser on the platform base, at a location marked “EXPORT”.

NRV gyro receptacle

36" pipe riser gyro receptacle

- As will be explained in this document, the distance between the 2 points to measure was at the higher end of metrology distances (135m) previously measured by this type of instrument, so the standard deviation of the distance survey (spread of measures) was expected to be larger than one can expect on a 30m metrology for example. The Angular accuracy is not affected by the distance.

- No depth instrument was used in this survey. The depth accuracy is therefore affected in the same way as the horizontal accuracy: as a function of time of motion, and therefore as a function of the distance between stabbing guides.

- The IPOZ surveyor had no prior knowledge of the actual measurements accomplished with the conventional method of Acoustic LBL, (plus Gyroscope, plus Depth measuring instruments) on this survey. All results were delivered a few hours after the survey was completed. Acoustic results were provided for comparison several weeks later.

- IPOZ having received no prior information on the position or orientation of those 2 receptacle points, used an approximate position given by the ROV display. All coordinates are therefore relative. This doesn't affect the accuracy of the length and orientation results of the metrology.

- As described later in this document the results obtained with the IPOZ method and provided immediately on January 05th, 2010 were:

- Distance (using loop compensation):	135.23m
- Depth Difference (using loop compensation):	-1.25m (NRV is deeper)
- UTM Heading of NRV guide:	252.14 deg
- Pitch of NRV guide:	+1.02 deg
- Roll of NRV guide:	-0.98 deg
- UTM Heading of Flange guide:	357.34 deg
- Pitch of Flange guide:	-0.69 deg
- Roll of Flange guide:	+1.29 deg

In the field report the following information was also given:

- Raw Distance (No loop compensation): 135.08m
- Raw Depth Difference: -0.95m (NRV is deeper)

→ Comparison results from the actual contractual metrology delivered by Neptune Geomatics, and courtesy of Acergy Australia Pty Ltd are for the acoustic line SW5 to SW9 of the acoustic network (Sonardyne Fusion™):

Baseline	Computed from Original Coords	Adjusted	Measured Mean	Measured SD	Difference (Measured Mean - Adjusted)	Mean Scale Factor
SW5<->SW8	135.876 m	135.967 m	[illegible]	0.007 m	-0.024 m	1.0000000
SW5<->SW9	135.077 m	135.207 m	135.230 m	0.006 m	0.023 m	1.0000000
SW6<->SW12	134.266 m	134.602 m	[illegible]	0.003 m	0.150 m	1.0000000

→ The IPOZ inertial result is therefore similar to the acoustic result (to within 0.023m)

Acknowledgements: IPOZ Systems LLC would like to thank all parties involved and working on the vessel Toisa Proteus during this campaign for their constant support and help for all aspects of this demonstration. This includes the FMC workers, for loaning us their office space onboard, the Canyon offshore ROV team for their constant support at all time of day and night, Jeremy Cohen of Acergy and the Woodside representatives Stephen Lumb and David Reeve and in particular Mr Richard Rickett, without whom this demonstration would not have taken place.

1. Introduction

IPOZ Systems LLC is thankful to Woodside Burrup Pty Ltd for the opportunity to demonstrate their GIPSEA™ Inertial Metrology system on the PLUTO LNG field.

After various windows of opportunities appeared and disappeared during the campaign of December 2009, and on the last day before returning to port, on January 4th 2010, one ROV was finally available for the IPOZ demonstration.

Even though the distance between the 2 fixed points to survey was larger (at 135m) than most jumper inertial metrologies done previously, it showcased an opportunity to describe our technology and to study the error model in these circumstances.

Joel Gillet, the IPOZ surveyor for this project has done a certain number of inertial metrologies in the past, including the first. The straight line distance that was surveyed in all these previous cases were between 15m and 35m, and in all cases the length measurement and depth accuracies were better than 0.05m, and angular accuracies were much better than the client specifications (0.30 degrees or 1 degree), more like 0.1 degrees.

Length measurements are influenced by lever arms within the tool which have to be measured carefully, and obviously the drift of the INS during the survey, as well as some random error.

Orientation measurements are influenced by angle biases and offsets of the tool, as well as any misalignment of the stabbing guides and rotation tools when those are used. More error comes from the adapter plates and guides than from the INS. It is therefore important to eliminate hardware misalignment when specifications are 0.1 degrees.

For greater distances than previous metrologies, worse accuracies were expected in distance and depth measurements (but not in angles and attitudes, since these are not influenced by the motion of the tool). It was observed on this project that the standard deviation of the results were actually greater than on shorter surveys, but the averaged (final) result was correct to 2cm or better.

New techniques will be developed to bring down the spread of the measurements (standard deviation) to compensate for the larger distances measured in modern metrologies (these include: stopping on the seabed or on other structures, which was not considered in this project, since no adapter was mounted for it on this ROV).

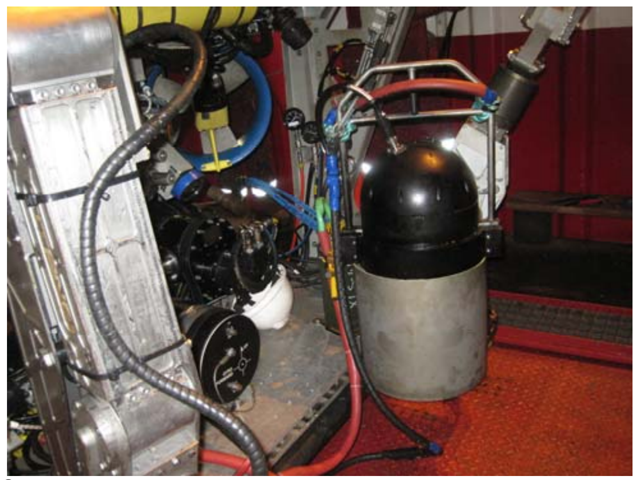
Also it should be mentioned that a reasonable speed of operation helps with the results, and this can depend on the ROV pilot and crew. As seen on this project, some crews take more than twice the time to fly between guides and stab the tool, than other crews.

In future projects, all ROV crews will be trained and well briefed on the procedures to obtain the best results, so that if a change of shift occurs, the new crew is prepared ahead of time. See our suggestions in the conclusion of this report.

Of the 14 loops accomplished in various conditions, only 7 loops were done at sufficient speed and with sufficient loop tie accuracy to be kept for the computations.

Prior to comparison with acoustic reference it was not known with certainty if “loop survey compensations” were the best way to compute the results as on shorter metrology. It is now clear that this is the case. The error model of inertial instruments and its compensation is discussed further in this document.

IPOZ will be able to do metrologies using these inertial tools in one ROV dive of several hours (preferably 3 to 6h minimum depending on distance), and deliver length and depth measurements to 50mm accuracy, and heading, pitch and roll angular measurements to specified accuracy, even when there is no direct “acoustic line of sight” between the 2 extremities of the future jumper (i.e. the 2 FMC receptacles).



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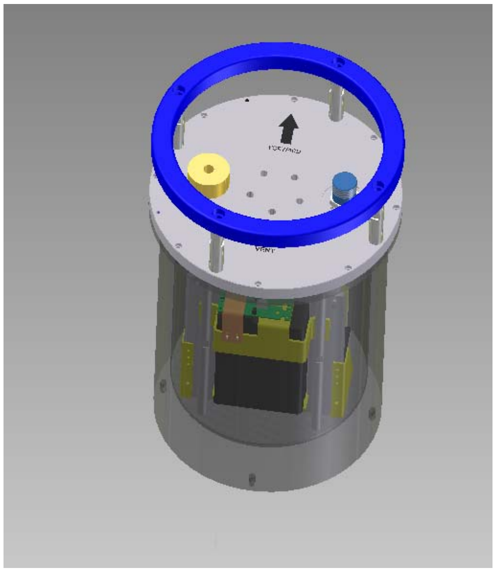
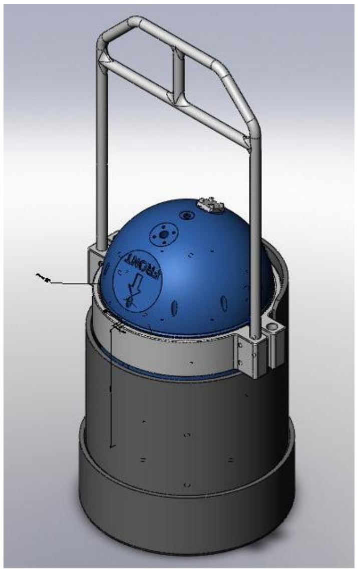
2. Resources

- Personnel. As demonstrated on this project, a single operator with a single tool can do this inertial metrology. Due to variations in the time opportunities to do the survey, it is better to have 2 experienced inertial operators, one of them a supervisor and/or result computer, for shift rotations.

- Hardware. The 1000m rated tool is 42kg in weight. The 3000m is 52 kg. They both consume 1.5 amps at 24v when the battery is fully charged, but closer to 4.5 amps if the battery is discharged. The ROV crew had to create a 4.5 amps connection for the tool since most preset power supplies are for 1.5 amps. This adaptation doesn't take long but needs to be clearly indicated ahead of the dive. Both tools have a hard drive and a 3h battery internally. That battery will be replaced by a 6h battery in a future design. Battery should always be fully charged before diving.



IPOZ 1000m rated tool



IPOZ 3000m rated tool

- Office. The IPOZ surveyor can be setup in the ROV room, when there is enough desk space for him (space for 1 laptop computer), or at the surveyors office location (bridge or other). On this project an FMC container was setup on a deck mezzanine and was kindly made available to IPOZ. The IPOZ surveyor needs at a minimum the normal RS232 connection with his tool (38400 bd), a sound and video connection to the ROV crew (ROV video), and eventually radio comms with main operator and bridge for coordination. When 2 ROVs are working, as was the case on this project, communications with the other ROV crew are also necessary.

- ROV and Vessel time. To perform a contractual metrology, IPOZ will require use of an ROV for several hours as discussed hereunder. As can be seen here, 14 loops were done during this demonstration on January 4th, 2010. In Red appear those that were not accepted. So the metrology could have been finished after 4h of survey (survey starts after a 1h alignment is completed):

LOOP #	LOCAL TIME:	SYSTEM TIME (sec):
1	19:54:33	3507.62
2	20:23:08	5223.00
3	20:43:05	6419.99
4	21:06:28	7823.17
5	21:31:35	8993.15
6	21:53:38	10316.34
7	22:24:57	12194.92
8	22:47:53	13571.10
9	23:04:33	14570.89
10	23:47:25	17143.06
11	0:17:20	18938.04
12	0:40:14	20312.03
13	1:10:20	22118.21
14	2:13:10	25887.97

- Computations were finished 3 hours after the actual survey and this is typical of most inertial surveys. A comprehensive report can be issued upon the surveyor's return to home base.

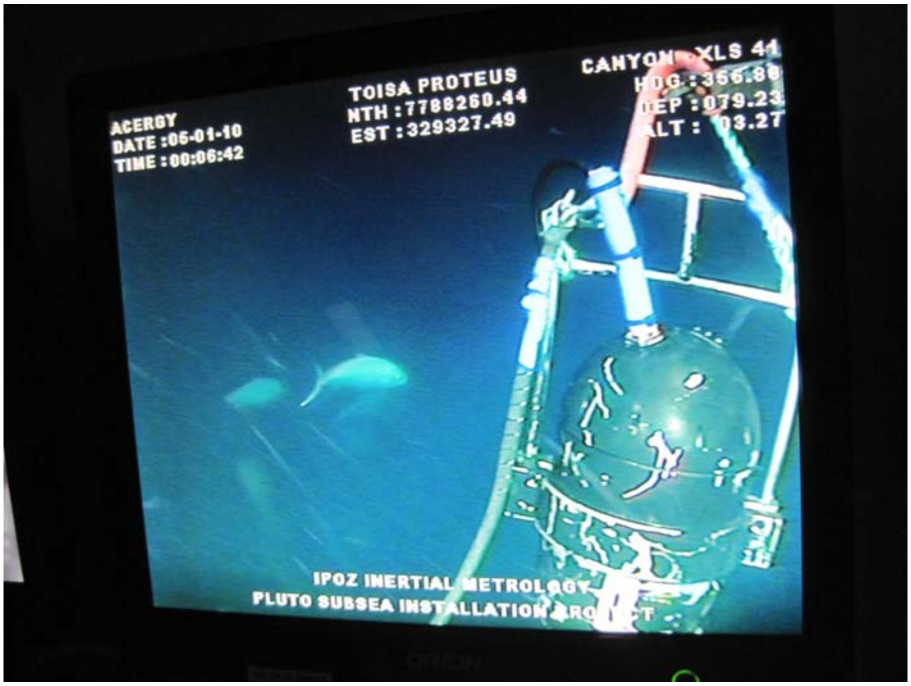
3. Duration discussion.

An IPOZ Inertial Metrology can be done in a few hours.

1h is the minimum required to align the inertial tool at turn on. During alignment the inertial navigation system will automatically sense the earth rotation for North finding, and the gravity vector for axis orientation to the vertical line and horizontal plane. To better stimulate the 3 gyroscopes contained in the INS, several 90 degrees rotations are required. This is done by the ROV 7 functions arm. Most stabbing guides have notches at each 90 degrees quadrant, which allow for those orientations. Angular accuracy of the IPOZ tool after alignment is 0.05 degrees in all directions.

Once aligned, the tool can navigate and do a full loop in a few minutes. Due to the distance involved in this PLUTO Platform A project, a loop was done in 20 minutes on average. The simple flight from one receptacle to the other never took less than 240 seconds non-stop. For more accuracy, it is preferred to stop the INS every 2 minutes or less.

A full stop (or “zero velocity update” known as “zupt”) is handled by the INS navigation firmware to automatically reset most errors (in 3D position and orientation) in the navigation, created by the motion of the unit. To do a zupt an INS must be perfectly still for 10 to 20 seconds.



IPOZ GIPSEA™ tool carried by 7 functions arm of ROV

In future projects, a support should be mounted on the ROV bumper (such as a plate with a stabbing guide, underneath the Inertial tool), to allow complete stops on the seabed. As this ROV was setup, the tool was held by a rope in the 7 functions arm, and would have kept swinging, even if the ROV was stopped on the seabed, preventing zero velocity updates.

Only 7 loops were of sufficient quality to be kept in this survey. So ideally this metrology could have been done in 3 or 4h after alignment.

Mark#4

RAW HDG	HEADING:	ROLL:	PITCH:	Delta East:	Delta North:	Raw Distance :	MAX Time of Flight (s)	TIE:
(raw)	(Corrected)						either way	(m)
132.93	87.93	-1.12	-0.63	-29.16	-132.35	135.52	235	0.28
132.90	87.90	-1.09	-0.65	-29.69	-132.46	135.75	300	0.31
132.86	87.86	-1.05	-0.71	-29.69	-131.31	134.63	300	0.75
132.91	87.91	-1.11	-0.73	-29.54	-131.77	135.04	245	0.32
132.89	87.89	-1.08	-0.74	-29.27	-131.95	135.16	300	0.54
132.89	87.89	-1.09	-0.72	-29.12	-131.77	134.95	240	0.43
132.87	87.87	-1.07	-0.76	-29.69	-131.21	134.53	240	0.89
Avg	87.89	-1.09	-0.71	-29.45	-131.83	135.08		
Stdev	*0.02*	*0.02*	*0.05*	*0.26*	*0.47*	*0.44*		

The other loops took too long between full stops in the receptacles and zero velocity updates to be useful. What happens when a period of 5 or 6 minutes or more goes by without stop or "zupt", is that the error cumulates exponentially, and cannot be compensated properly by the post-processing of the data.

By closing the loop (returning to the start point) the surveyor can see in real-time the quality of the navigation: the difference between the position computed by the INS navigator at the start of the loop and at the end is here called the "tie". This tie should be less than 1m and even preferably around 0.35m or less for maximal accuracy of the survey.

In a field such as the original PLUTO field (at 850m depth), all 10 metrologies could have been done in about 10 to 15h, with results similar to acoustic results (<50mm), since the distances were in the 30 to 40m range.

The IPOZ demonstration was done outside the field at Platform A.

4. Data Results and Discussion

Results. The horizontal distance between the two receptacles surveyed was given shortly after the metrology was completed as 135.230m. Several weeks later, a comparison with the acoustic measurements between these same two points gives an adjusted acoustic measure of 135.207m, and a Mean value of 135.230m.

This shows that the IPOZ results were correct.

These results were computed using a measurement loop compensation spreadsheet. In that spreadsheet the raw measurements are submitted to survey compensations.

The resulting horizontal distance measurement is obtained by using the coordinates provided by the Inertial tool navigation at each point and compensated to eliminate the systematic errors (drift and shift) and computing an “inverse” of those coordinates (Pythagoras).

The coordinates (in GDA94, UTM zone 50S) of the start point (the NRV receptacle) were Read on the ROV video screen:

Easting=	329324.30m
Northing=	7788259.51m
Depth=	-81.00m

These coordinates are approximate and arbitrary, but close enough that they will not affect the distance measurements (a relative measure) or the orientation values.
Every time the tool was placed back on that point, the position was reset to these values. This reset is not always perfect by the time the position is actually recorded, and for that reason the spreadsheet has an “error at start” compensation. That error is subtracted before doing a loop compensation.

Each loop represents the coordinates (Easting, Northing, and Depth) at start (NRV) then at the other point (Flange), and then back at NRV at the end of the loop.

The difference of coordinates between start and end of loop (on the same NRV point) is called the “tie”, or mis-closure. Assuming that the tool will develop a similar error in each direction, the values of the tie are divided by two, before being subtracted to the raw coordinates of the Flange.

It is by “inversing” between the two sets of coordinates of NRV and Flange that was obtained the horizontal distance of 135.230m.

As a commentary, it will be added that even though the variations to average of each loop are not small, the average of them ended up perfectly correct which indicates that these compensations correctly eliminated the systematic errors and left only random errors to be averaged out.

<u>Only in the case of random error is averaging very efficient</u>, and the results proved to be correct to better than 0.023m

The depth difference between the two is showing as 1.246m (NRV is deeper), while the acoustic network depth measurements (Appendix G) show 1.512m a difference of 0.266m.

These depth measurements can be dramatically improved in the future on long baselines done without stops on the seabed by using a depth sensor, which will keep them to within 0.03m.

As for the angle measurements, our heading value for the riser receptacle is within 0.27 degrees of the measurements made by Neptune with Octans gyroscopes (357.340 versus 357.070deg), even though they are showing the flange orientation rather than the receptacle. Several as-built rotations offsets prevented a direct comparison with the NRV receptacle.

The INS used by IPOZ has an angular accuracy of 0.05 degrees or better in all orientations, and that precision (superior to all gyroscopes on the market) can be observed in the standard deviation of these angles from loop to loop.

Conclusion and Discussion

In this demonstration IPOZ Systems LLC showed that their GIPSEA™ inertial metrology tools perform with great accuracy and productivity, and that the computations used to compensate inertial loops correctly eliminate non random errors and provide a correct final result in distance.

To deliver the superior angle results (heading, pitch and roll) that this tool is capable of (at the less than 0.05 degree level), it will always be important to use precise stabbing systems.

In order to minimize the spread of the length and depth results in the future, it is suggested to stop the ROV on the seabed several times during each loop to accomplish full stops or “zero-velocity updates”, in particular if the ROV time of flight between both receptacles is much more than 120 seconds. A depth sensor can easily be added to the tool for better depth measurements.

Communicating with the ROV crews ahead of the metrology, in order to develop the best procedures to minimize time of flight and stabbing efforts will be important to obtain the best results with this tool.

A power supply of 1.5 amp (24v) is sufficient to run the tool when its battery is fully charged before diving, but a source of 4.5 amps is necessary today when the battery needs to be charged. This amount of power should not be required and IPOZ must change the design of its power board to accommodate 1.5 amps maximum draw, since it is the most common source available on most ROV. A 6h battery should be installed in the tool to allow completion of the metrology, even if power fails. Micro interruptions of communications are of no importance for this tool, and no navigation or serial connection problem occurred on this project.

Discussion.

Question: Why didn’t you keep all the surveyed loops?

Answer: When a navigating inertial system spends too much time between stops, the error in navigation becomes exponential, and can’t be eliminated by linear compensation. Because we couldn’t stop between end receptacles on this project, the loops in which the time of flight of the ROV was more than 300s were eliminated. Another good check of validity of a loop is the “tie” or the difference of position given by the navigation at the start of the loop (at the NRV point) and at the end of the loop when the tool is back at the same point (NRV). Whatever difference is observed between these 2 recordings is the final error of the loop (a combination of random and systematic errors). Loops with ties above 1m were eliminated.

Question: How do you eliminate the 2 types of error?

Answer: The systematic error is eliminated by survey compensation. We take the error at the end of a traverse (here the loop), and compensate it all along the survey, following as best as possible the error model. Here the error model is a regular drift that is a function of time between stops and that is assumed to be similar each way, so the final loop error is divided by two.

When the systematic error is correctly removed, only the random error remains. The advantage of this randomization of the error is that it can be nearly eliminated by multiplying the measures and averaging the results. This is why no less than 7 loops results were averaged after compensation.

Question: You assume that the error is equal both ways. Is it not better to compensate as a function of time of flight which can be slightly different between one way and the return?

Answer: This is actually correct. It would be better to compensate strictly in function of the time of flight each way, in particular on such long baselines without stops in between. It implies keeping track of the exact time between stops, which we didn't do on this project. Our current assumption is not too far off the truth though, since our final result is exactly equal to the acoustic result. On request, we can compensate strictly over time in the future.

Question: Your final result is better than 2cm, but the spread of the results is large (30 to 40 cm), what confidence do I have that your assumptions are correct?

Answer: the 3 rules applied here, 1) repeat the measures and eliminate the bad ones first (the outliers that are not done in optimal conditions), 2) eliminate systematic errors according to the best error model and 3) reduce the final random errors by averaging the results, are actual rules of survey that apply to other types of measures, on land and offshore. The fact that the final result is comparable to the value found by the acoustic network using totally different hardware and techniques does confirm it. A lower spread in the result would improve the confidence in the average though, and when possible it would be better to stop the tool at regular intervals on future projects and get all the results to be very similar before averaging.

Question: What is the difference between the raw distance measurements as averaged to 135.080m, and your final "loop compensated" result of 135.230m.

Answer: This raw distance measurement is computed by inversing between the raw coordinates of the NRV point and the Flange point without any compensation. This value would have been a best guess estimate if the error only had a random component to it. There was no certainty at first that the drift could be eliminated out of such long loops, or if it was an important part of the error like it is for shorter metrologies. It is now obvious that an important component of the total error is not random and must be eliminated by survey compensation, before averaging.

Question: Of the 7 loops that you kept, how can we know if one loop computation is not markedly different from the others and therefore influences the final results, in which case you might have found the correct measure by sheer luck?

Answer: One can see the consistency of the assumptions by eliminating one loop at a time out of the whole loop compensation spreadsheet (Appendix F). The loops that were kept are loops 2, 4, 5, 6, 7, 8, 9. If we use all the loops the average is 135.23m. If we delete:

> Loop # 2, the average is 135.19m
> Loop # 4, the average is 135.16m
> Loop # 5, the average is 135.28m
> Loop # 6, the average is 135.25m
> Loop # 7, the average is 135.21m
> Loop # 8, the average is 135.26m
> Loop # 9, the average is 135.29m

Finally, it should be acknowledged that the results obtained with the IPOZ GIPSEA™ tool are not superior to current techniques using acoustic LBL networks for distance measurements, individual gyroscopes for orientation information and depth sensors for vertical measurements.

Acoustic LBL is probably as precise as or better than inertial for distance measurements, and when the network is computed correctly by an experienced and careful surveyor, good QC information can be obtained from the residuals of the least square adjustments.

Gyroscopes available on the market are slightly less accurate in angles than the INS types used by IPOZ, but usually deliver close to 0.1 degree accuracies given enough time to settle. Most of the orientations errors do not come from the sensors but from the adapter plates and stabbing guides they are mounted upon. By design the alignment of these parts is rarely better than 0.1 degrees, and shows slight wobbles, observable when one turns the tool exactly 180 degrees for example.

Depth sensors can show absolute errors that need to be eliminated by water velocity estimation, tide and other computations, but they are extremely accurate in a relative scenario, in particular over short periods of time (10 to 20 minutes for example). Over the short span of a single inertial loop the only remaining relative error of a depth (pressure) sensor would be surface water motions like heave and would be minimal. For that reason mounting a depth sensor on an IPOZ GIPSEA™ tool could improve confidence in the vertical measurements on future projects.

The main differences between inertial and acoustic metrologies are:

1) An inertial system doesn't need direct acoustic “line of sight” to measure between 2 points, and can compute accurate positions within or between structures and at the future jumper locations (receptacle), several meters below the top of the structures,

2) It can operate in any position: it could go to the side, underneath or behind a structure and obtain good positions and orientations in any direction and on the fly.

3) It is not affected by acoustic interferences (drilling operations, pipe vibration, engine noise, products flowing in the pipelines, other acoustic networks in proximity etc…).

4) All measurements can be done by one single tool in one single dive of several hours (3 to 6h), instead of several days necessary for the traditional network acoustic method (which includes: lowering multiple acoustic tripods by crane, placement of tripods in exact location by ROV, lowering tool basket by crane with other beacons, placement of beacons by ROV, supplementary dive for gyroscope survey, other dive for depth measurements, and then the whole recuperation of all hardware etc…).

We believe that IPOZ successfully demonstrated the accuracy and improved productivity for sub-sea metrologies by utilizing our Inertial Metrology tools and our in-house developed procedures. We would welcome your comments and suggestions and trust that IPOZ will be considered for any future Woodside metrology projects.

Joel Gillet
Party Manager
IPOZ Systems LLC