Calibration of a Moving Platform

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ABSTRACT

Most flight calibrations or inspections are completed using relatively well known techniques, with a variety of measurement systems and aircraft platforms. The processes involved are well understood and conform to the requirements or recommendations as detailed in published documents such as ICAO Annex 10 and DOC 8071. Further more, individual regulatory or state documents provide further guidance on how to proceed or which measurements are required for an individual navigational aid.

When a new facility is envisaged or employed on the ground, it is quite possible that new techniques are designed and implemented to assure the safety of the facility. Even in most cases, standard techniques are used based on recognised existing procedures. Where the facility also involves a new environment such as one that includes a truly mobile landing platform, one has to go back to basics to determine an appropriate measurement technique. In addition to carrying out the measurement, new tolerances and acceptance criteria need to be understood and the measurement system tested to ensure that it meets the intended measurement uncertainty.

INTRODUCTION

This paper describes one such project where the requirement was to develop a system that was able to be used on board a Naval Ship in order to assist the calibration and testing of several navigational aids. The platform in question was to be fitted with Radio Direction Finding, TACAN and a type of Precision Approach Radar. A number of technical and operational difficulties were overcome during a 3 year project resulting in the successful inspection of the systems on two different vessels. In addition to the general considerations of the project, this paper also describes the testing and evaluation of the positioning system used to provide a reference against which the navigational facilities were compared.

Due to confidentially issues, the paper concentrates on the system measurement reference system, rather than the detail of performing the TACAN, DF or TACAN Flight Inspections. The presentation accompanying this paper will, however, provide an insight into the operational considerations when performing such inspections.

PROJECT DEFINITION

System Capability

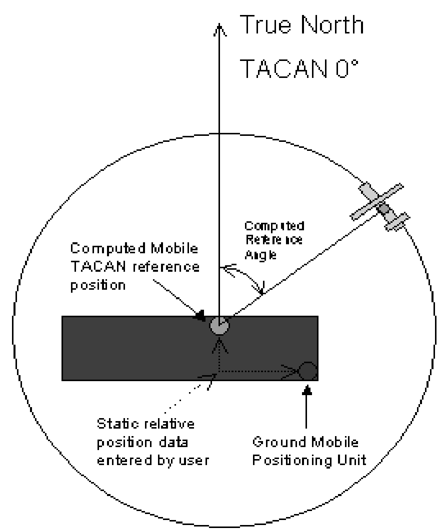

Figure 1: Simple Geometry

In its basic form, the system had to be capable of determining the computed reference angle between true north and the position of the aircraft as per Figure 1. Although this is relatively simple for a fixed land based navigation aid, the position of the vessel was to be constantly changing in any direction. A Ground Reference Positioning Unit was specified that could transmit its position to the aircraft, and with knowledge of the location in relation to the TACAN (or DF), the position of the TACAN (or DF) could be computed in real time.

The same position fixing philosophy was then employed as the basis for a position reference system for Precision Approach Radar calibration. The PAR reference system had the added complication of an Elevation function; therefore a 3D correction system was required. Whilst the 3D function was not an explicit requirement of the Tacan project, the system designers treated the Ground Mobile Positioning Unit (GMPU) as a 2-phase project.

Phase 1: Development of a GMPU capability to allow the FIS system to correctly calculate the aircraft relationship in range, azimuth and height within specified tolerances to a given reference point on the moving platform.

Phase 2: Continued development of the GMPU to allow the FIS system to calculate the aircraft relationship in Elevation to a given reference point, with increased accuracy requirements for both azimuth and height.

Performance Requirements

During **Phase 1** of the project the GMPU and Flight Inspection System (FIS) combined were to be capable of providing the position of the TACAN antenna to an accuracy of:

- 10 Metres in the Horizontal Plane
- 30 Metres in the Vertical Plane

In addition, in shall be possible to calculate the position of the GMPU to an accuracy of:

- 5 Metres in the Horizontal Plane
- 15 Metres in the Vertical Plane

It was not necessary to Roll or Pitch stabilize the position data for Azimuth and Distance reference data at this point in the development.

During **Phase 2** of the project, the additional requirements were to determine:

- An azimuth angle relative to a given reference position to an accuracy of ±0.05° at a range of 0.5 NM (or greater).
- An elevation angle relative to a given reference position to an accuracy of ±0.03° at 0.5 NM (or greater).

These angles had to be Pitch and Roll stabilized, to remove the effect of the ship's movement from the reference position.

SYSTEM SOULTION

Where possible the project required reuse of existing Flight Inspection System (FIS) hardware and software elements to allow easy implementation of the capability within the current FIS and Aircraft fleet. The result was modification and update of software modules within the FIS and use of telemetry inputs that would normally be assigned to ground tracking equipment. In this way, no airborne hardware changes were required. A new ground unit was developed to house the positioning equipment, with data transmission using the same telemetry modules normally used for the standard ground tracking devices.

The GMPU contains dual GPS receivers and an IMU to provide real-time positioning fixing and lever arm correction data to the FIS. Dual GPS are employed to gain heading information, whilst the IMU was used for pitch and roll correction data. The equipment housing was manufactured to withstand some degree of inclement weather and to be mounted such that the system could be left on deck for the period of the trial (up to 2 weeks at a time). As well as transmitting data to the aircraft in real time, the system also records a subset of data that can be used for post analysis.

First, a simple prototype unit was manufactured for Phase 1 to prove the concept and be used for initial work with the TACAN and DF systems, later 2 rugged units were manufactured for the PAR work, which could also be used for TACAN/DF inspections. This dual capability also ensures a measure of system redundancy, as once the ship had sailed, there are no chances to easily make repairs or exchange suspect units.

SYSTEM TESTING

The development of the GMPU and FIS software resulted in four iterations of software used during flight trials and system testing in conjunction with Tacan and PAR flight Inspections. Minor issues were encountered which were easily rectified as per Table 1.

Software Version	Fault reports	Corrective action
Initial issue (A)	1) Elevation Errors (30') 2) Position not always available	1) WGS84 to MSL correction made 2) String handling of the GMPU position improved, also addition of position filter to allow 'coasting mode' to fill in for lost telemetry.
B	Elevation Errors (12')	Sign usage on GMPU position corrected

Software Version	Fault reports	Corrective action
C	Azimuth errors in particular quadrants	FIS software usage of GMPU lever arm data corrected to include E-W as well as N-S vectors.
D	No issues noted	n/a

Table 1: System development issues

Testing of a unit that is always moving proved to be complex, as no additional reference source was readily available to compare results to. Initially this was not thought to cause a problem as GPS was the basis of the absolute accuracy and the constellation is always changing anyway (i.e. no fixed point of reference). The main errors seen were the implementation of the lever arm correction data which was used to determine the TACAN, DF or PAR positions. A simple test was later devised, whereby the GMPU was rotated over a fixed position and the lever arm data set to a large number (200 Metres). The expected output was a near perfect circle and after two slow rotations of the unit whilst an aircraft was returning to base receiving the telemetry data, the result was as per Figure 2.

Two circles were described with a diameter as calculated from the resulting Latitude and Longitude. Minor variations from the expected 400 metres were observed, but considered insignificant given that the rotation of the GMPU over a given spot was, in practice, quite difficult to achieve. A small amount of data drop out was also seen when the aircraft disappeared behind a hanger.

Whilst the system was collecting data for the Azimuth test, the Elevation of the GMPU was also recorded. This allowed an analysis of the height information for the 4700 samples collected (approx 8 minutes of data), summarized in Table 2.

GMPU	Data (metres)
Average Altitude	26.9
Standard Deviation (2σ)	0.53
Max	27.13
Min	26.34

Table 2: Height data during rotation

This showed an improvement to initial trial data that had indicated Static test results giving 7.22 metres maximum altitude change with a Standard deviation (1σ) of 1.62 metres. The increase in accuracy was due to an improved initialization process and compared favorably with the reported standard deviation (1σ) of 0.49 metres later determined for the dynamic runs at sea during 2006. The height accuracy was also tested by placing the unit on a test bed that could be elevated under hydraulic control. This allowed the absolute change to be measured both by tape measure and the GMPU. The results were within 20 cm for any given change over a short period. Longer term height stability was seen to be less accurate and attributed to those introduced by the differential GPS fixing method.

The GMPU, from the static tests at this stage, demonstrated height accuracy (short term) of 0.53 metres (2σ) and an azimuth accuracy of better than 0.37 metres (estimated from absolute error in described circles).

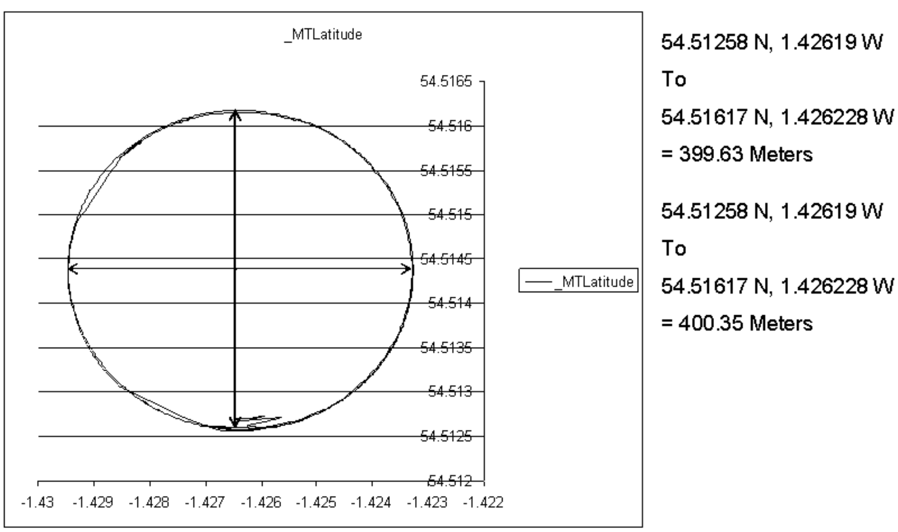

Figure 2: Circle described by rotating GMPU over a fixed position

STATEMENT OF MEASUREMENT UNCERTAINTY

The analysis of the trials and commissioning flights has provided a significant amount of data to determine a measurement uncertainty for the GMPU system. In this case, the system includes the GMPU and its position on the moving platform and the FIS calculations performed using data from that system. Both the GMPU and the Cobham Flight Inspection (CFI) aircraft use a common supplier of differential correction data in real-time. Although both positioning systems vary in their approaches to applying the correction data, as the GMPU and FIS measurement system works in a relative mode, the errors are likely to cancel.

From the data provided by the static and dynamic tests, the assumed accuracy in position data can be assessed from the standard deviations of the results due to the nature of the base positioning system (GPS). Taking the worse case, from Figure 2 and Table 2 the GMPU would contribute 0.53 metres in Elevation and 0.38 metres in Azimuth. The elevation was further validated by the results in Table 6, which shows the variation as being 0.49 m (1σ), including ships movement. Table 6 also shows that during the same period of time the average aircraft EPE was reported to be 3.3 metres.

Using the RSS method for assessing the contribution of each element to the general overall measurement uncertainty provides a figure for Elevation of:

$\sqrt{((\text{GMPU variation } 2\sigma)^2 + (\text{Aircraft EPE})^2) + (\text{Deck Height Error})}$

$$=\sqrt{((0.53)^2 + (3.3)^2 + (0.8)^2)}$$

=3.43 metres (95% uncertainty)

Range (nm)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5
Bin	2	3	4	5	6	7
Error	0.14	0.09	0.06	0.05	0.04	0.03

Table 3: Maximum error contribution- high aircraft EPE

As the acceptance criterion for elevation angles is 0.15° (UK MOD), this would indicate that elevation measurements inside of 3 nm with a high aircraft EPE would be unacceptable. In practice, the aircraft EPE can be maintained below 1.8 given a good GPS constellation (Table 8 data). This results in a typical overall estimated error as shown in Table 4 which on average is $1/5^{th}$ of the nominal tolerance criteria and is therefore considered as acceptable.

Range (nm)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5
Bin	2	3	4	5	6	7
Error	0.09	0.05	0.04	0.03	0.02	0.02

Table 4: Typical measurement error contribution

The aircraft EPE should be evaluated to ensure it is consistent with the measurements being undertaken when using the GMPU system for elevation measurements (i.e. less than 1.8). In addition, the average deck height needs to be taken into account to ensure any variation to the assumed height does not contribute a significant error to the measurement uncertainty calculation.

For GMPU related azimuth data, the alignment of the GMPU heading becomes the critical parameter as other sources of error are much less than 1 metre. Positional errors such as location of the GMPU and facilities under inspection can be reduced to less than 10 cm. The GMPU has demonstrated elevation accuracy to better than 1 metre and as elevation accuracy of GPS systems is generally considered to be worse than azimuth, it is reasonable to assume a similar figure or better for azimuth accuracy. A 0.3° heading error will introduce 4.8 metres of error at 0.5 nm, therefore careful selection and measurement of the alignment reference line should be made to reduce errors to a minimum. It is also, therefore, not possible to quantify *absolute* errors for azimuth alignments until post flight analysis of the heading references is carried out. It is reasonable to assume that given a fixed reference line, *repeatability* of the antenna alignment could be within 1cm over a 10 metre baseline, resulting in a 0.06° *relative* measurement uncertainty between inspections[1].

FLIGHT TRIALS WITH THE GMPU ON A SHP

Assessment of GMPU/FIS height calculations

To determine the repeatability of measurements in flight, the FIS calculated aircraft Z height (ATZ) was compared to the aircraft Radio Altimeter. This was completed for 15 runs to gain a statistical average during the PAR tests on Ship 1. The Radio Altimeter raw data output is non-linear above 480’ and less accurate with height. When below 200’ the aircraft sometimes initiated a climb resulting in an observed lag error which induced a bias to the results, therefore test results were limited to those between 480’ down to 200’.

[1] The errors only affect PAR and not other North aligned facilities such as TACAN or DF.

FIS ATZ minus Rad Alt[2]				Average number of Samples per run
Average difference	St Dev (2σ)	Max diff	Min diff	
7.1	2.0	9.1	5.5	183

Table 5: Summary data (15 runs)

The standard deviation calculated in Table 5 includes aircraft and GMPU induced errors, as well as pitch movements of the vessel under inspection. The results indicate better than expected accuracy of data taking the external influences into account (especially due to ships pitch). The resulting movement of Moving Target altitude will be less than that seen for the GMPU as the GMPU is further away from the ships centre of rotation than the aiming point (see Annex A). The largest source of error is seen as the FIS reported Estimate Position Error EPE which is calculated according to a model and is based on the aircraft position reference GPS/INS/Barometric data at the time. The data indicated that during a run, the height correlation between the radio Altimeter and the FIS calculated Z parameter varied by 2.0 Metres. Whilst not an absolute measure of accuracy against a datum, this provided a figure that was used for the measurement uncertainty of the overall system. The absolute accuracy of the Radio Altimeter was not considered important as the same aircraft was used for the complete set of trials, therefore drops out of the equation.

During the same set of runs, the GMPU altitude was analyzed to determine how much movement could be detected in the moving platform deck height. This parameter was considered important as an initial assumption was made that the deck height would be 14.8 (Ship 2) or 14.6 (Ship 1) for the vessel under inspection.

GMPU Altitude	St Dev (1σ)	Aircraft EPE	Average Number of samples
14.06	0.49	3.31	2070

Table 6: Summary data (20 runs)

The data in Table 6 indicates that the assumed deck height of 14.8 metres was potentially incorrect by 0.8 metres. This is a notable bias figure in the overall measurement analysis as it could introduce a small error in the results, as shown in Table 9.

The effect of any errors is more pronounced as the range decreases, however given that the angle measurement is taken as an average of the data over the completed run, the effect is minimized to an average of 0.01° and therefore could be considered as insignificant. Errors seen at 3NM were also the same outside of this range, therefore later analysis only considered close in ranges.

[2] See Appendix A for ATZ measurement.

Assessment of EPE observed during inspections

As the Aircraft EPE and the assumed deck heights are the two major contributing factors to measurement uncertainty, further analysis of the GMPU and aircraft data showed that the average data for the PAR inspections were as in Table 7.

Dates	Ship	Number of runs	Aircraft EPE		GMPU height	
			Averag e	St Dev (2σ)	Mean	St Dev (2σ)
13/14 Oct 07	1	64	3.7	1.7	13.8	1.044
05/06 Nov 07	2	70	2.1	1.6	14.0	1.036

Table 7: All run data – both ships

During the elevation assessments of Ship 2 and Ship 1, the actual data used for each approach at the time of the inspections was as per Table 8.

The data shows that a correction to the Ship 2 data could be applied to improve the accuracy of the results, allowing for the deck height differences noted. The full contribution of all measurement error sources would provide maximum errors as shown in Table 10 & Table 11.

Ship 2		EPE		GMPU Height		PAR
run	time	average	ST Dev	average	St Dev	Error in result
41	1040	3.8	1.52	13.7	1.42	-0.01
42	1053	3.0	0.16	13.4	1.00	0.01
44	1244	1.4	1.28	11.7	0.98	0.06
45	1253	1.4	0.10	11.9	1.00	0.11
46	1303	1.4	0.10	12.0	1.06	0.07
55	1534	3.0	0.04	14.4	0.94	0.07
	average	2.3	0.53	12.9	1.07	0.05
Ship 1		EPE		GMPU Height		PAR
run	time	average	ST Dev	average	St Dev	Error in result
52	1317	2.1	2.80	14.9	1.42	0.10
53	1326	1.4	0.06	14.9	1.32	0.09
54	1334	1.6	0.86	14.9	1.56	0.09
55	1343	1.4	0.08	14.9	1.42	0.11
56	1352	1.6	0.24	14.7	1.16	0.12
	average	1.6	0.81	14.9	1.38	0.10

Table 8: PAR Elevation error assessments

Range (nm)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0
Bin	2	3	4	5	6	7	8	9	10
Error (deg)	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01

Table 9: Errors introduced via deck height difference (all data analysed)

Range (nm)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	Average degrees
Bin	2	3	4	5	6	7	8	9	10	
Error	0.13	0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.049

Table 10: Ship 2 measurement uncertainty (Elevation Runs)

Range (nm)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	Average degrees
Bin	2	3	4	5	6	7	8	9	10	
Error	0.07	0.05	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.027

Table 11: Ship 1 measurement uncertainty (Elevation Runs)

The data presented showed that the reliability of the elevation angle measurement can be considered to be within 0.05° to a 95% confidence level. This was not quite within the 0.03° target initially envisaged for the elevation measurement uncertainty, but accepted as a realistic figure given the experience gained during the testing program.

GMPU and Ship heading correlation

The azimuth alignment of the GMPU is determined by the setting up of the system dock side to correlate the ships heading with that of the internal IMU. During subsequent ships motion, this alignment is corrected by the secondary GPS system within the GMPU. The alignment of the 2 GPS antennas determines the final alignment of the system. During trials in 2006, QinetiQ were employed by the UK MOD to post analyze the ships and GMPU data. This revealed a difference between the two sets of data as shown in Figure 3.

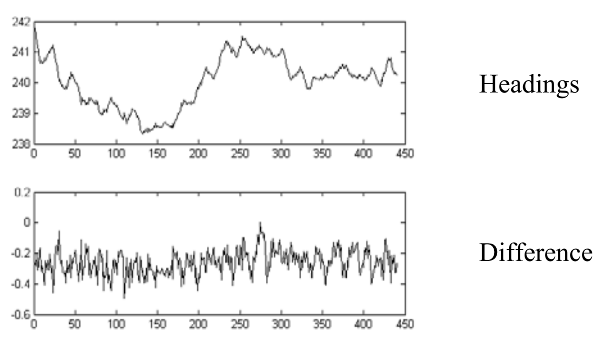

Figure 3: QinetiQ review of heading source data

This source of difference will affect the Azimuth alignment data calculated by the FIS by a similar amount.

It was also noted that the GMPU heading is noisier than the data available from the ships system. The noise appears random in nature and will introduce noise into the calculation of the azimuth reference data. However, the random nature of the noise and the low sample rate used for actual analysis (approx 20 samples per 0.5 NM for PAR Azimuths) should not introduce any further bias errors and therefore was not be considered further.

During the second sets of tests on Ship 2 for the PAR in 2007, a new alignment position of the GPS antennas was used (painted centreline, rather than spurn water rail). To determine alignment errors in flight, a set of correlation fixes were taken as tabulated in Table 12. The results show a 1.56° error in the alignment of the GMPU to the Ships head.

Fix	GMPU	Ship
1	206.40	204.99
2	205.90	204.54
3	206.90	204.80
4	205.80	204.30
5	205.60	204.57
6	205.90	204.54
7	205.89	204.60
8	206.32	204.87
9	206.42	205.00
10	207.78	205.15
average	206.291	204.736
	difference	1.555

Table 12: Ship 2 manual correlation fixes taken in flight

A cross check of the antenna positions determined a 4cm error over a 10 metre base line length, giving rise to -0.29° azimuth error. As this figure is already included within the GMPU figure, the line selected as a reference must be offset from the actual centreline by 1.27°. This was later confirmed during a resurvey of the ship.

A similar check of data during the PAR inspection on Ship 1 determined an alignment difference of 0.07° (Table 13).

Fix	GMPU	Ship
1	5.1	5.2
2	5.6	5.6
3	5.2	5.3
4	4.4	4.5
5	4.6	4.6
6	4.9	4.9
7	4.9	5
8	5.1	5.2
9	5.2	5.3
10	5.2	5.3
average	5.02	5.09
	difference	-0.07

Table 13: Ship 1 manual correlation fixes taken in flight

As it is not possible to realign the GMPU once at sea, therefore any offsets determined must be taken into account in the post analysis phase. The data can only be accurately determined by comparing the recorded ships heading data with the GMPU data whilst at sea. This can be achieved without the use of the FIS system by monitoring the GMPU data on a laptop over a period of time, which provides a larger data set and therefore a greater confidence in the result.

Offsets seen during flight trials may be attributed to factors such as ships hull construction, leeway created by tidal vectors, windage and physical alignment of ships keel with the flight deck runway markings. If it is determined necessary, future GMPU setting procedures or equipment modifications would be embodied to be able to eliminate any heading alignment offsets during flight inspections. This would eliminate the need for post analysis and the risk that large errors do not unduly effect equipment adjustments or result data.

CONCLUSIONS

The GMPU and FIS software have undergone extensive flight-testing and have demonstrated that they are capable of providing a reference system for a moving target platform. The operational version of software (D) demonstrated good performance with repeatable results on 2 platforms with similar results.

Confidence in the PAR system was gained as both Ship 2 and Ship 1 elevation angles as measured were within 0.10°, therefore applying the 0.05° measurement uncertainty in an absolute sense (rather than Root Mean Square) gave reasonable confidence that the actual angles are maintained within 0.15° acceptance criteria for the PAR.

Further accuracy assessments of the entire system will continue as experience is gained using the system, with the declared accuracy of the GMPU Latitude, Longitude and Altitude being:

0.37 m for azimuth related data and;

0.53 m for elevation related data.

Providing an overall (GMPU and FIS) elevation measurement uncertainty of:

Nominally: 1.88 metres (no deck error and 1.8 metres EPE)[3]

Maximum: 3.43 metres (assuming typical deck height error and high EPE)

Currently, azimuth measurement uncertainty for PAR inspections can only be determined after correlation with the ships heading data.

The system has now been used to provide enough confidence in the TACAN, PAR and DF systems to allow Military Aircraft to make approaches to the vessels in poor weather conditions with a Missed Approach Point at 0.5 NM, 200'.

RECOMMENDATIONS

- Assessing new systems of measurement must take into account the measurement uncertainty requirement, with testing to ensure that the theoretical accuracy is matched in practice.
- Measuring systems on a mobile platform introduces more complex error sources, which need to be understood within the measuring system.
- Careful alignment of the measuring devices using multiple GPS's with a short baseline length between antennas is required to improve repeatability of measurements.

[3] This theoretical figure is similar to the measured figure presented and discussed in Table 5 of 2.0 metres.

- No further software changes are proposed for the FIS at this time as the system meets the requirements as originally envisaged. However consideration may be given to adding a smoothing filter to the GMPU heading data to reduce induced noise components.

- Consideration should be given to improving the heading set-up capability, either by adjustment within the GMPU or FIS software's once the ship is underway to reduce alignment errors to a minimum.

FUTURE WORK

The GMPU system has been recently upgraded to provide better position accuracy reporting, however flight trials still have to be performed to assess these improvements.

The FIS software has been upgraded to provide an averaging facility of the GMPU altitude and to improve positing information for the Flight Inspection Pilots.

ACKNOWLEDGMENTS

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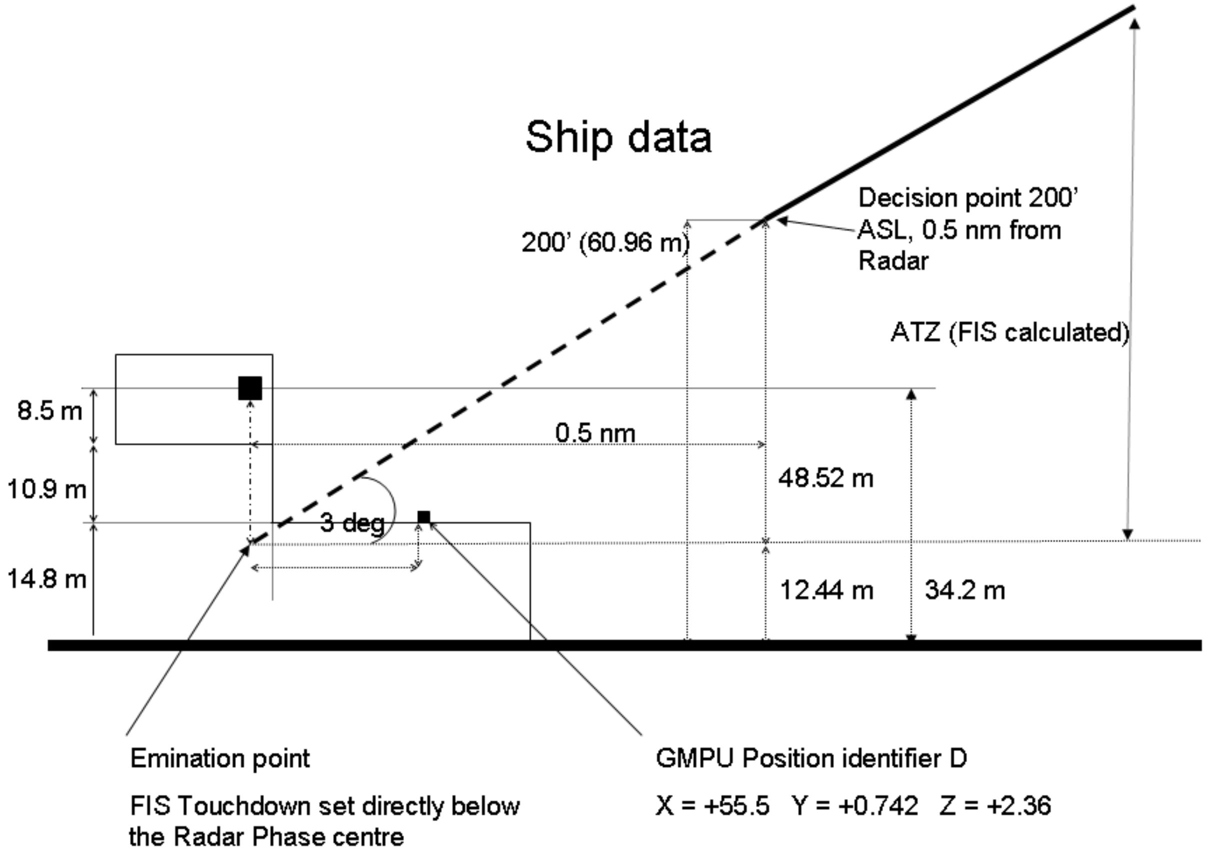
Forsberg Ltd for the development of the GMP units and subsequent system support.

REFERENCES

Various internal CFI papers produced during the specification, development, testing and evaluation of the system capability. M. Spanner 2005 – 2007.

APPENDIX A: REFERENCE CALCULATIONS



The PAR system is designed to bring an aircraft to a point 200' above the sea surface at 0.5NM from the Radar Antenna.

The FIS ATXZ parameter is the height of the aircraft above the Emination Point