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VERIFICATION OF THE INDOOR GPS SYSTEM BY COMPARISON WITH POINTS CALIBRATED USING A NETWORK OF LASER TRACKER MEASUREMENTS

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ABSTRACT

This paper details a method of determining the uncertainty of dimensional measurement for a three dimensional coordinate measurement machine. An experimental procedure was developed to compare three dimensional coordinate measurements with calibrated reference points. The reference standard used to calibrate these reference points was a fringe counting interferometer with the multilateration technique employed to establish three dimensional coordinates. This is an extension of the established technique of comparing measured lengths with calibrated lengths. Specifically a distributed coordinate measurement device was tested which consisted of a network of Rotary-Laser Automatic Theodolites (R-LATs), this system is known commercially as indoor GPS (iGPS). The method was found to be practical and able to establish that the expanded uncertainty of the basic iGPS system was approximately 1 mm at a 95% confidence level.

KEYWORDS

Coordinate Uncertainty, CMM, iGPS, Indoor GPS, Spatial Analyzer, USMN

1. INTRODUCTION

Accurate measurement is of central importance to producing high quality products. In traditional manufacturing the master part definition existed as a physical reference model. A rational system of jigs, fixtures and gauges therefore embodied a direct system of traceability back to this master part. In modern engineering the master part is represented digitally as a mathematically precise 3D geometric model. The scale of the model is defined according to internationally agreed length standards based on the wavelength of light, with traceability back to time standards. In order to ensure part conformance, measurements should be taken using instruments which have been calibrated so as to ensure traceability back to these length standards as maintained by national standards bodies such as the National Physical Laboratory.

Modern dimensional measurement systems do not simply measure lengths as is the case with traditional instruments such as micrometers and height gauges. Current industrial systems typically measure the three dimensional position of points on objects and therefore verification by the measurement of lengths cannot ensure the traceability of all coordinate measurements made by the instrument (Flack 2001).

The system verified in this work is a large volume frameless and distributed coordinate measurement machine that is made up of a network of Rotary-Laser Automatic Theodolites (R-LATs), this system is known commercially as indoor GPS (iGPS). Each R-LAT consists of a transmitter and a sensor. The transmitter utilizes a rotating head to sweep two fanned lasers through the measurement volume; the transmitter also houses a strobe which fires a timing signal covering 360 degrees of azimuth, as shown in Figure 1. The sensor is able to detect the incidence of these lasers and deduce the azimuth and elevation angle from the transmitter to the sensor from the time differences between the strobe and the two lasers reaching the sensor (Hedges, Takagi et al. 2003 ; Muelaner, Wang et al. 2008).

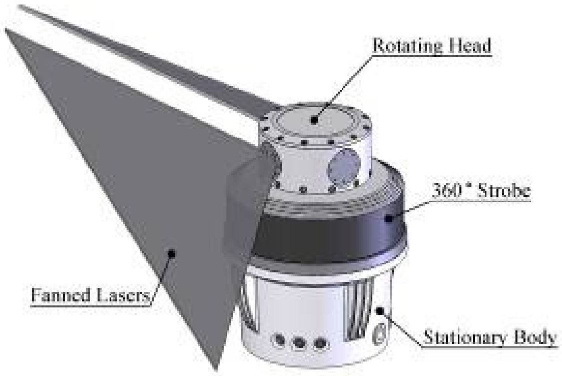

Figure 1: Main Components of R-LAT Transmitter

In order to detect the three dimensional coordinates of the sensor it must receive optical signals from at least two transmitters. It is then possible to use triangulation to fix the position of the sensor assuming that the transmitter positions are known. Normally, a bundle adjustment (Triggs, Mclauchlan et al. 1999) would be carried out as part of the setup procedure for the network. The bundle adjustment is used to establish the relative positions of the transmitters. If more than two transmitters are visible then some form of least squares fitting can be employed to reduce the uncertainty of the position.

Once the transmitter positions have been determined, the network of R-LATs then constitutes a large volume frameless coordinate measurement machine. This type of measurement network has advantages such as the ability of the one way communication, from the transmitter network to the sensors, to support a virtually unlimited number of sensors. Additionally, a sensor is able to move behind obstructions to the line of sight loosing and regaining connection to various transmitters without loosing connection to the network as a whole and not requiring any re-aiming of transmitters.

Typically, measurements are taken using a 'vector bar' shown in Figure 2. This is a calibrated device housing two sensors and with a 1.5" diameter precision sphere mounted at one end. The sensors and the sphere are mounted on a common axis. Since the position of the sensors can be calculated the position of the vector bar is also known and the rotation can also be calculated in two axes. The position of the sphere is therefore known enabling it to be used as a measurement probe.

2. VERIFICATION STRATEGY

The body of literature concerning the verification of coordinate measurements is primarily concerned with comparison with calibrated lengths. The ISO 10360 standard for coordinate measuring machines (BSI 2002) is a well established work applicable to conventional gantry based coordinate measurement machines (CMMs) using contact probing and operating in the discrete-point probing mode. The ASME standard for evaluating 'Laser-Based Spherical Coordinate Measurement Systems' (ASME 2006) is the only current standard dealing with large volume frameless metrology instruments. It is applicable to Laser Trackers (Lau, Hocken et al. 1985) and Laser Radars (RICHARD and KENDALL 2006).

Both of the above standards are based on a methodology of measuring calibrated lengths at various orientations in order to test the isolated and combined accuracy of the instruments' sub-systems. Such sub-systems are the probing error and x, y, z encoders on a CMM, while on a laser tracker they are the two angle encoders, the interferometer and the probing error of the retro-reflector.

Applying the principle of isolating sub-systems previous work has been carried out to characterize the performance of an individual R-LAT (Muelaner, Wang et al. 2008). The work reported here is concerned with the coordinate measurement performance of the complete iGPS system. This could be carried out using the established method of measuring calibrated lengths, however, since this would not ensure traceability of coordinate measurements made by the system it was decided to develop a method based on three dimensional coordinates.

The direct comparison of coordinates is not new, such an approach has, for example, been carried out to compare points measured on a surface with a laser scanner to points measured on the same surface with a conventional gantry type CMM (Anchini, Di Leo et al. 2007). However, such an approach does not give traceability since the coordinate measurements made by the CMM do not have direct tractability to a length standard.

A tracking interferometer has been used to measure the distance to a CMM head from multiple positions. These distances were then used to calculate coordinates using multilateration. Multilateration is a technique of combining multiple one-dimensional measurements to give three-dimensional measurements. It is therefore similar to the more widely known technique of triangulation but while triangulation combines multiple angular measurements multilateration combines multiple length measurements. The difference between the nominal and the measured coordinates was then used to create an error map (Schwenke, Franke et al. 2005). The work described here follows essentially the same method with a few notable exceptions; standard industrial instruments are used such as a laser tracker and the measurements are used for verification by an assessment of measurement uncertainty (BSI 1995) rather than for error mapping.

The approach employed in this work involves the use of kinematic nests, shown in Figure 2, to allow the repeatable positioning of both the reference measurement system and the system undergoing verification. These nests are commonly used to position the spherically mounted retro-reflectors (SMRs) used by Laser Trackers. Although the use of such nests will introduce additional uncertainty, this can be shown to be relatively small and quantifiable through repeated measurement with the reference system.

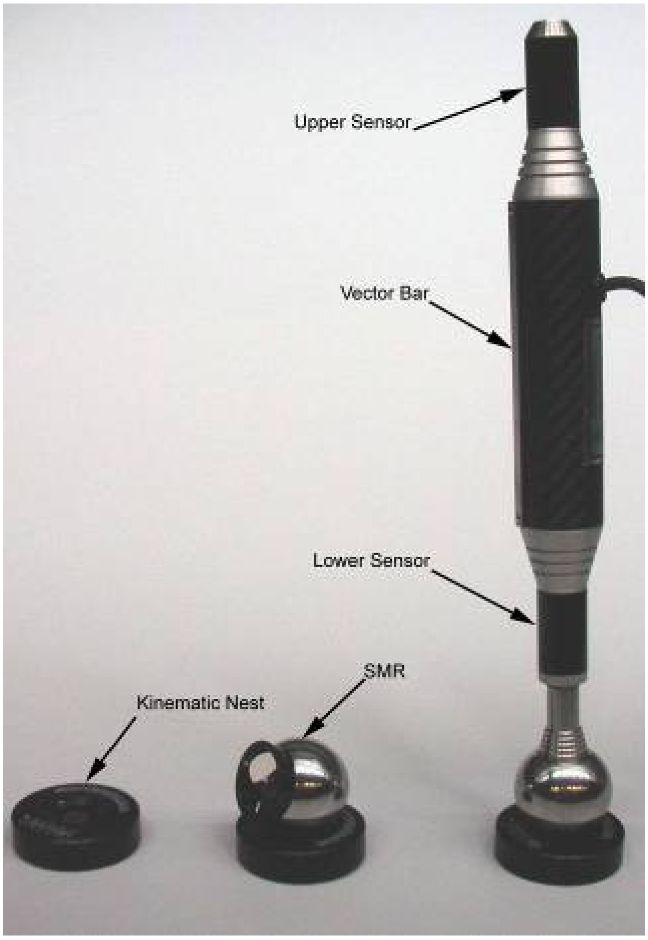

Figure 2 : Kinematic Nests with SMR and Vector Bar

3. EXPERIMENTAL PROCEDURE

Two tests were carried out at different locations both of which represented typical production environments. Although there were some differences between the tests the basic procedure was the same. The actual setup used for the tests carried out at the Bath LIMA is shown in Figure 3.

3.1. R-LAT NETWORK SETUP

The R-LAT network was setup using the supplied interface software (Metris 2007) according to the user manual (Metris 2007). This involved positioning and starting the transmitters, setting various parameters and then connecting a vector bar to the network. The network consisted of 4 transmitters.

A bundle adjustment was carried out as specified in the user manual (Metris 2007). This involved taking measurements using the vector bar at 8 observation points within the working volume. The bundle was initially calculated using the known distance between the sensors on the vector bar to apply scale. Accurate lengths between two kinematic nests were then calibrated using an interferometer and the scale was reapplied by taking measurements of these nests with the vector bar.

3.2. COORDINATE NETWORK CALIBRATION

The reference coordinates were created using kinematic nests designed to accept a 1.5” steel ball. A number of nests were glued to the concrete slab forming the floor of the test venue while others were mounted on either a granite table or theodolite stands.

Following the initial layout the coordinates of each kinematic nest were measured using a Laser Tracker. Measurements were taken from a number of positions allowing the results to be combined to improve accuracy using a technique similar to multilateration which is explained in section 0. The number of positions differed between the tests.

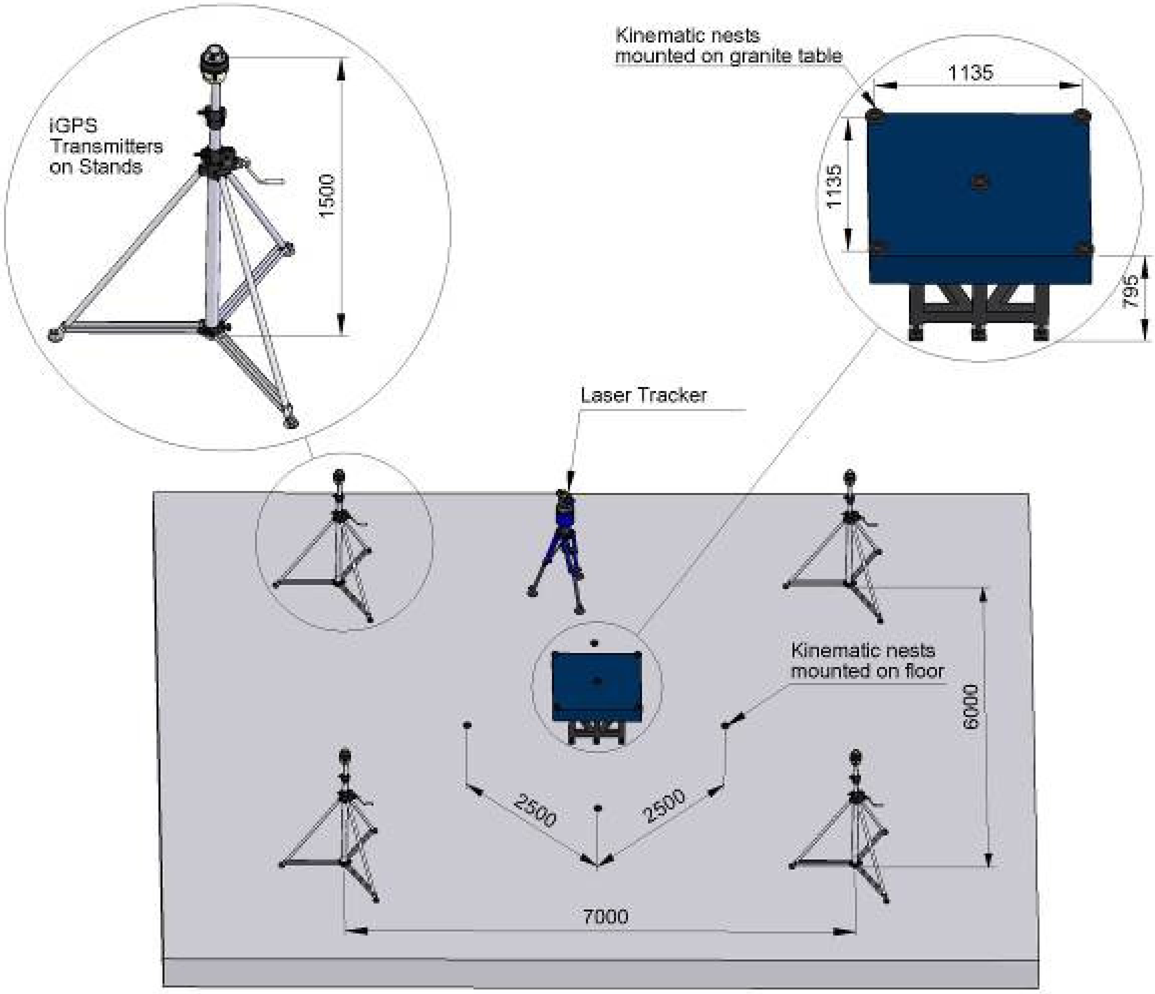

Figure 3: Test Setup for Tests at the Bath LIMA

3.3. REPLICATED MEASUREMENTS

Following the coordinate network calibration the iGPS Vector Bar was used to make repeated measurements of the position of each kinematic nest. A 1.5” probe tip was used which was the same size as the SMR used for the Laser Tracker calibration. The points measured by the two methods are therefore equivalent. Each point was measured in turn using the Vector Bar and the measurements were then repeated a number of times measuring all the points in a circuit. The number of measurements of each point differed between the tests.

The system has a sampling frequency of approximately 40 Hz resulting from the rotational velocity of the transmitter heads. Due to the substantial effects of environmental disturbances such as turbulence on optical measurements (Estler, Edmundson et al. 2002) more accurate measurements can be made by averaging over a period of time. A single measurement of a coordinate position was therefore considered to be an average of 80 instantaneous measurements, this was regarded as giving a good compromise between accuracy and operation time (Muelaner, Wang et al. 2008).

An interface program was created to automate the measurement process and export of text files for further analysis. This interface software used rotation data from the Vector Bar to ensure that the Vector Bar was orientated vertically to within ±2 Degrees. The graphical user interface is shown in Figure 4.

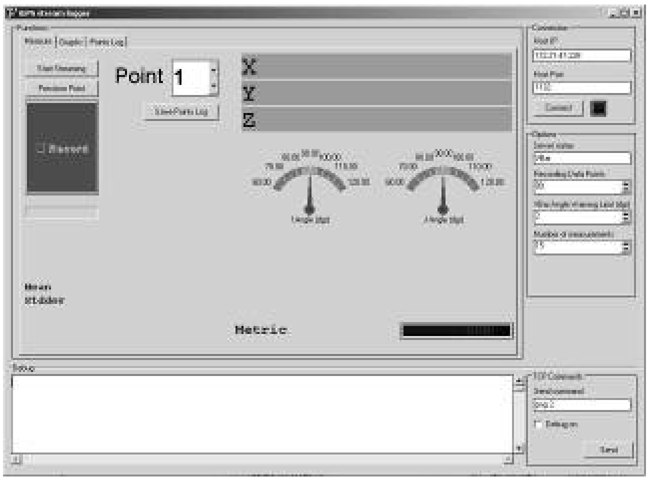

Figure 4 : Interface Software used to Collect Measurement Data

3.4. INDIVIDUAL EXPERIMENTS

Although both tests used the experimental procedure detailed above there were some differences in the details of the setup and calibration. These differences are detailed in Table 1. The SMR nests for tests carried out at Bath's Laboratory for Integrated Metrology and Assembly (LIMA) were located on the floor and a granite table. For the tests carried out at a large aircraft assembly area at Airbus Broughton, the nests were located on the floor and on theodolite stands.

Table 1 : Details of Individual Experiments

Location	Bath LIMA	Airbus Broughton
Date	27/2/08	4/3/08
Laser Tracker Positions	2	5
No. of Points	9	15
Measurements per Point	25	6
Transmitter Layout	9 m x 7 m rectangle	12 m x 12 m square
Scale Lengths Used to Bundle	5.6 m	8.3 m, 8.9 m 9.4 m, 11.2 m

4. ANALYSIS OF RESULTS

The analysis of results consisted of two stages. Firstly the calibration measurements of the coordinate network from multiple Laser Tracker positions were combined to obtain a reduced uncertainty for the point positions. The actual iGPS measurements were then analysed to calculate the uncertainty of the system.

4.1. COORDINATE NETWORK CALIBRATION

The measurements from multiple Laser Tracker positions were combined into a single survey of the coordinate network using a technique which produces results similar to multilateration, reducing the coordinate uncertainty. This was achieved using a commercial code, Unified Spatial Metrology Network (USMN) which runs in the Spatial Analyzer (SA) software produced by New River Kinematics (NRK). This combines Monte Carlo analysis with best fitting of point clouds (Calkins 2002 ; New River Kinematics 2007).

The fundamentals of this technique are that the uncertainty of a particular measurement is simulated using knowledge of the position of the measurement instrument and the non-isotropic uncertainty of the instrument. The simulation is of the Monte Carlo type with repeated simulated measurements made, each consisting of the nominal measurement value with random noise added to it. In this way a point cloud or 'uncertainty field' of simulated measurements is created around each nominal measurement point. This uncertainty field can then be used to calculate the standard deviation of the coordinate measurement in each axis.

Each series of measurements of all the points from a single measurement station represents one point group. All of the point groups can then be best fitted to each other using a least squares minimization algorithm. The best fitting is weighted according to the uncertainty of each measurement. In this way points with, for example, a large standard deviation in the z-direction are allowed to deviate more in the z-direction from fitting to the corresponding points. The point groups are best fit to one another for each measurement in the uncertainty field in turn creating a new composite uncertainty field of the weighted best fits.

The repeated best fitting to generate a composite uncertainty field represents a second level of Monte Carlo simulation which is used to find the combined uncertainty for the coordinate measurements from multiple stations. Since the uncertainty of measurements taken using a Laser Tracker is known to be considerably better in range than in angle (Faro 2007) the distance measurements will be given greater weight than the angle derived measurements. The end result of this approach is therefore similar to multilateration. It is not however pure multilateration since the angle derived measurements are still used to some extent.

4.2. ANALYSIS OF IGPS MEASUREMENTS

The mean of the replicated measurements of each point was calculated and these averaged measurements were best fitted to the calibrated positions using a least squares minimization algorithm. The distance between the mean position as measured using the iGPS network and the calibrated point position after best fitting all the points was then calculated, this deviation will be referred to here as 'Mean Error'.

The standard deviation of each coordinate for each replicated measurement was calculated and the magnitude of the standard deviations was also found. The expanded uncertainty at a 95% confidence level was estimated by adding two standard deviations (2 Sigma) to the Mean Error.

The uncertainty in the calibration of the coordinate network was found to be less than 10% of the uncertainty calculated for the iGPS measurement. The calibration uncertainty was therefore regarded as having a negligible effect on the iGPS uncertainty.

The length between each point position was also calculated and a comparison made in this way between the Laser Tracker Calibration and the iGPS measurements. The Mean Error, standard deviation and expanded uncertainty were calculated for the length based measurements in the same way as for the coordinate measurements.

5. RESULTS

The results presented here illustrate a direct comparison of coordinate measurements (Figure 5 & Figure 6) with a length based verification strategy (Figure 7 & Figure 8).

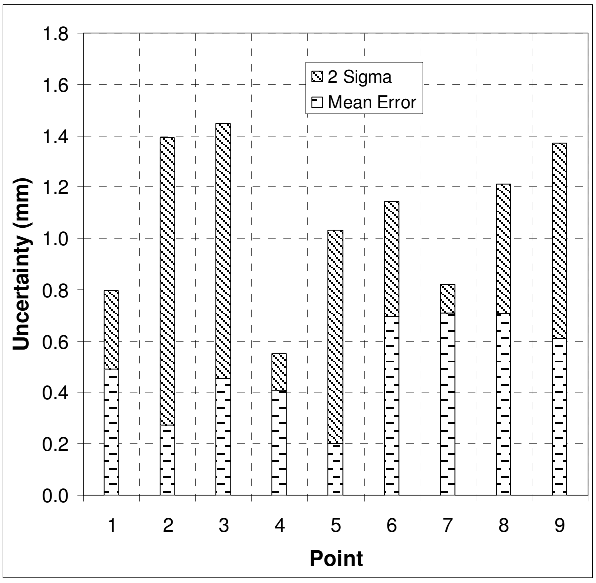

Figure 5: Magnitude of Coordinate Uncertainty for Tests Carried Out at Bath LIMA

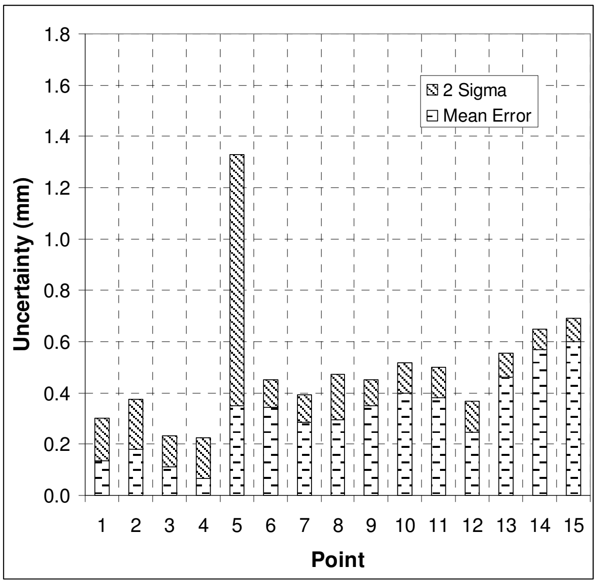

Figure 6: Magnitude of Coordinate Uncertainty for Tests Carried Out at Airbus Broughton

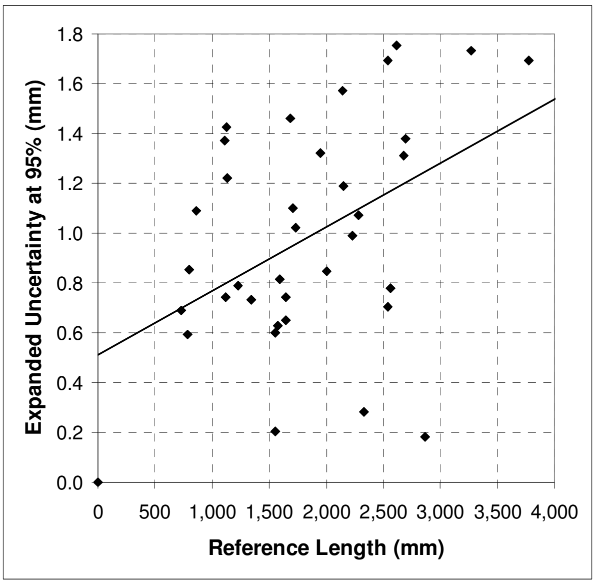

Figure 7 : Comparison of Lengths for Tests Carried Out at Bath LIMA

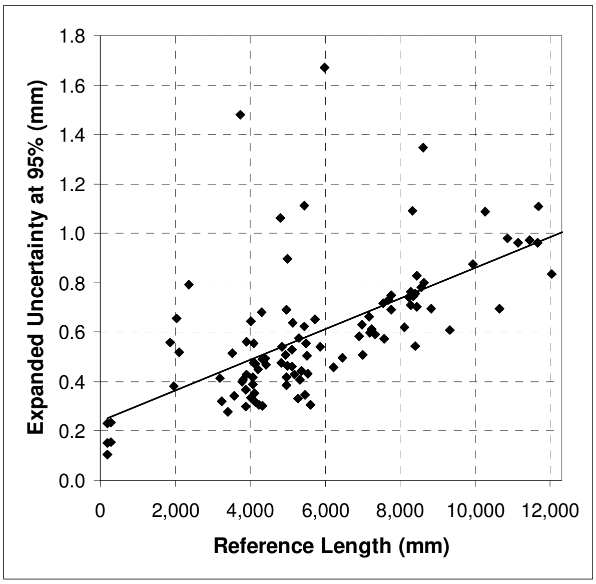

Figure 8: Comparison of Lengths for Tests Carried Out at Airbus Broughton

The performance of the system was somewhat different on the two tests. The tests carried out at the Bath LIMA show the expanded uncertainty made up approximately equally of the Mean Error and the variability as illustrated in Figure 5. These tests also showed very little evidence for the uncertainty being dependent on the reference length as can be seen in Figure 6. The tests carried out at Airbus Broughton showed the system to have a generally lower expanded uncertainty and in particular considerably less variability, which can be clearly seen in Figure 7. Point 5 however showed a considerably higher variability. There was also somewhat more evidence of a length dependence as shown in Figure 8.

The difference in performance between tests may be partially explained by differences in the setup procedure. The setup of the iGPS system at Airbus Broughton involved a larger number of lengths to scale the bundle adjustment. However, this would be expected to effect the system bias (Mean Error) rather than the variability. It is also possible that the small number of replicates (just six per point) gave a standard deviation that was not representative of the true variability of the system; this would also explain the very high standard deviation seen on point five. If the standard deviation is calculated based on all of the points together then the results become more consistent, both across the points and with the results of the tests conducted in the Bath LIMA.

Table 2 summarizes the results of the tests. The updated uncertainties were used for the Airbus Broughton results with the standard deviations calculated based on all the points.

Table 2 : Coordinate Uncertainty for Tests Carried Out

Location	Bath LIMA	Airbus Broughton
Date	27/2/08	4/3/08
Max Standard Deviation (mm)	0.560	N/A
Average Standard Deviation (mm)	0.289	0.377
Max Mean Error (mm)	0.711	0.600
Average Mean Error (mm)	0.505	0.318
Max Uncertainty at 95%	1.445	1.224
Average Uncertainty at 95%	1.084	0.806

The expanded uncertainties calculated using length based verification were similar to the coordinate results discussed above. The length based results showed a considerably wider range of results as shown in Figure 7 and Figure 8.

6. CONCLUSIONS

The test results indicate an expanded coordinate uncertainty magnitude at a 95% confidence level of between +/- 0.8 mm and +/- 1.1 mm. It should be noted that these tests were carried out using a basic version of the iGPS interface software which is not the state of the art interface.

Previous work to verify the performance of an R-LAT showed that the angular uncertainty of an individual transmitter receiver pair was approximately 0.5 arc seconds at a 95% confidence level (Muelaner, Wang et al. 2008). From basic trigonometry this is equivalent to 0.012 to 0.048 mm within the 5-20m range. This is considerably less than the total uncertainty of the network acting as a coordinate measuring machine is shown be this work. These results indicate that there are additional sources of uncertainty inherent in the combined system. This shows the importance of combined system tests in addition to isolated tests of sub-systems.

The technique demonstrated here is appropriate for the verification of all types of coordinate measurement instrument. The calibration of points for these tests was carried out using a Laser Tracker. If pure multilateration was applied so that only the interferometric measurements were used in the calibration of the reference points then traceability would be improved. Future work will develop a more rigorous mathematical approach in order to ensure traceability of the point calibration.

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