Good Practice for deployment and use of iGPS/iSPACE NIMTech deliverable 3.1(2)

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1   INTRODUCTION

The iGPS/iSPACE system is a flexible, scalable, large volume coordinate measurement system that comprises a number of active transmitters and one or more intelligent receiver(s) along with sophisticated software (iSPACE). The coordinates of each receiver are determined in terms of the azimuth and elevation angles between each of the transmitters to the receiver. Each transmitter rotates and sweeps two fan-shaped laser beams throughout the working volume at approximately 40 rpm. The centre of the two fan-shaped beams are separated by 90° around the rotation axis and the beams are inclined by 30° either side of the vertical. An infrared strobe pulse is emitted at the start of every second rotation. Signal processing electronics associated with the receivers detect the strobe pulse and the passage of the two rotating beams. The azimuth and elevation angles between each transmitter and each receiver are determined by the relative timings of these light beam signals. Figure 1 shows an iGPS transmitter and a schematic representation of the rotating fan beams and the timing of the fan beam signals, t_1 and t_2, at the receiver relative to the strobe pulse. The horizontal and vertical angles between a transmitter and receiver pair are derived from the average of t_1 and t_2, and the difference between t_1 and t_2, respectively.
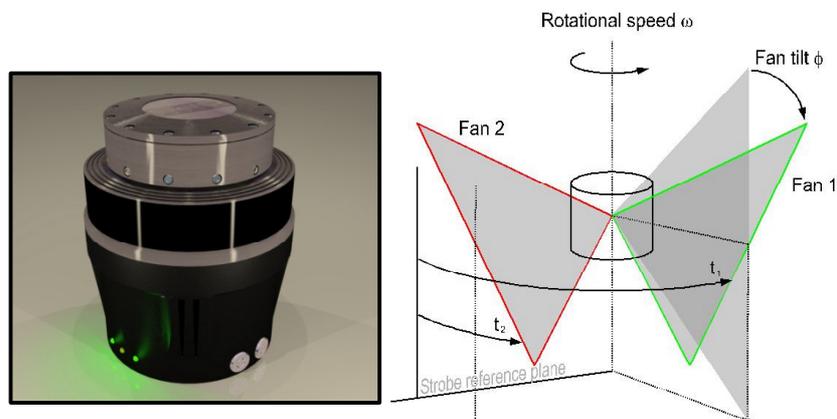

Figure 1 An iGPS transmitter (left) and a schematic representation of the rotating fan beams and their relative timing to the strobe (right).

The receiver is a cylindrical photo detector coupled to signal processing electronics.

Figure 2 Shows a Vector Bar – a combination of two receivers mounted in-line with a probing sphere – that can be used as a hand-held probe.
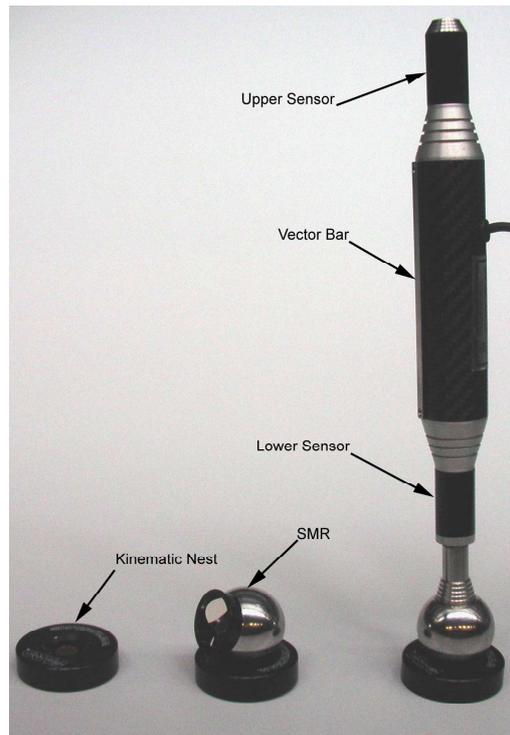
Figure 2 iGPS Vector Bar comprising two receivers in-line with a probe ball.

The position (location and orientation) of each transmitter must be determined prior to use. This can be achieved by triangulation in a similar way to the bundle adjustment procedures familiar in photogrammetry.

The iGPS/iSPACE product is sold in several standard configurations ranging from a four-transmitter, single vector bar system to an eight-transmitter system with reference receiver monuments plus multiple measurement receivers. The most basic four-transmitter system uses the known distance between the two receivers on the vector bar to introduce a length scale into the system, whereas the monument based setup use the calibrated coordinates of the monuments to provide scale and a self-monitoring ability. The flexibility of the system means that any of the standard configurations can be extended by adding more transmitters and/or receivers as necessary to improve accuracy, volume, or coverage.

In this document, we describe aspects of good practice associated with deployment and use of iGPS. The accompanying software can be used to simulate an iGPS setup for any configuration of transmitters, receivers and calibration method.

In the next section, we describe some of the main error sources specific to iGPS. Section 3 describes the different methods available for calibration. Section 4 gives instructions on how to use the simulation software that accompanies this document to investigate the likely performance of different setups and configurations of iGPS systems.

2   ERROR SOURCES

The potential error sources associated with any metrology system can be broadly split into the following categories [1]:

- The user
- The instrumentation
- The workpiece
- The environment

These topics have been covered in a generic sense in [1], which should be read in conjunction with this document, so here we will concentrate on instrument errors specific to iGPS.

2.1 IGPS INSTRUMENT ERRORS

The main sources of uncertainty associated with the iGPS system have been described by [2], they are :

- System calibration
- Multipath
- Noise floor
- Sensor orientation
- Kinematic effects

System calibration is discussed in section 3 below, the other sources of error are described briefly below.

The iGPS system effectively derives its data from the relative timing of optical pulses detected at the receiver. Anything that affects the shape or timing of these pulses will degrade the measurement.

2.1.1   Multipath

A multipath error occurs when a pulse is detected at the receiver due to a reflected beam. The iGPS signal processing software is able to detect and filter reflected pulses so some extent. However, elimination of obvious sources of reflection is considered good practice. For example, when operating a receiver near floor level, or near some other reflective surface, non-reflective matting should be applied to the reflective surface to prevent reflections. Cardboard or carpet tiles are both work well.

Multipath errors are more prevalent for systems deployed with fewer transmitters. Extra transmitters offer better multipath error rejection.

2.1.2   Noise floor

There is a trade-off between the noise floor setting and the operating range that can be covered. A low noise threshold will lead to smaller signals being detected and therefore increase range, but at the expense of the increased likelihood of multipath or false detection errors.

The noise floor setting should be set carefully for the application. System calibration parameters will be different for different noise floor settings, so once the system is calibrated the noise floor settings should not be changed. Conversely, if the application or configuration changed, the noise floor should be carefully adjusted.

2.1.3   Sensor orientation

Each receiver is a cylindrical photo detector. The effective position of the detector therefore depends on its relative orientation to the transmitter, so the orientation of the receiver leads to a systematic error.

The system is able to compensate for this provided some information is available to allow orientation of the receiver to be determined. For example, the two receivers on the vector bar are rigidly coupled together allowing their orientation with respect to the transmitters to be determined.

The accuracy of the correction will be better for smaller corrections, so it is advantageous to maintain a constant vertical orientation of the receivers if possible.

2.1.4 Kinematic effects

There is necessarily no synchronisation between the transmitters, so strobe and fan-beam pulses from the transmitters arrive at the detectors at slightly different times. If the receiver has moved during this time, an error will be introduced.

2.1.5 Lines of sight

The number of transmitters visible by a receiver also influences the accuracy of locating that receiver. The minimum number of transmitters visible to a receiver is two. However, the greater the number of transmitters and the larger their angular spread, the better. For higher accuracy applications a minimum of four and preferably eight transmitters should be considered.

3   SYSTEM CALIBRATION METHODS

The iGPS/iSPACE system is flexible and configurable. There are endless possible configurations and means of calibration. There are three standard setups are offered by the manufacturers, with four, six or eight transmitters (know as 4-series, 6-series and 8-series).

Each set-up can be configured in up to three different ways, the x-series, the s-series and the i-series. The different configurations refer to the method employed to calibrate the setup.

3.1 X-SERIES

The x-series is the simplest configuration. Calibration is achieved using a scale bar that is moved to different positions within the measurement volume. This is the lowest accuracy configuration. It has no health monitoring capability and is therefore applicable to short-term applications (in other words it requires more frequent calibration). Any drift in transmitter position due to, for example, environmental changes will not be compensated, so frequent calibration may be necessary.
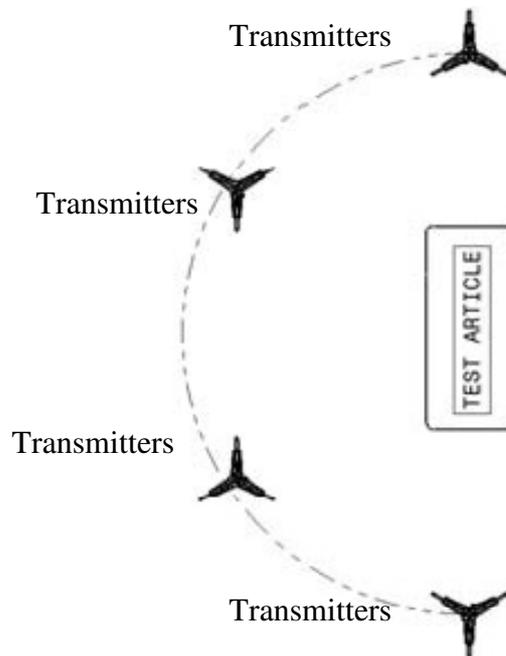

Figure 3 An example of an x-series configuration.

The accuracy of the calibration will depend on the accuracy of the scale bar calibration, the length of the scale bar (the longer the better), the number of scale bar measurements made and the distribution of scale bar measurements within the volume. As a guide, the scale bar should be at least one third the length of the longest dimension being measured.

3.2 S-SERIES

The s-series configuration builds on the x-series by the addition of a number of fixed base stations. The base stations are fixed receivers positioned strategically within the volume. They are used by iSPACE to track drift in the system. This health monitoring capability makes the s-series configuration more suitable for longer-term applications (less frequent re-calibration).
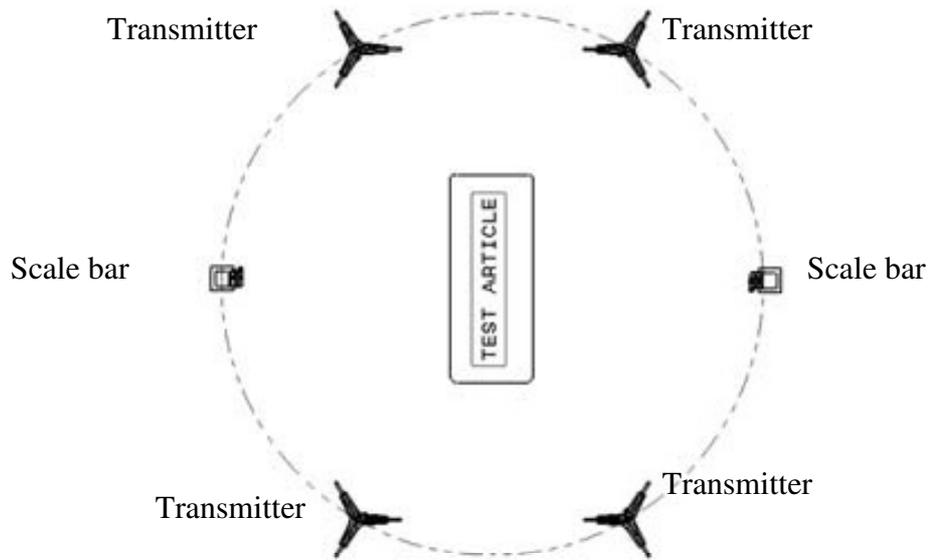
Figure 4 An example of an s-series configuration with two scale bars.

3.3 I-SERIES

The i-series configuration is the most accurate configuration. It uses a network of fixed reference monuments to provide scale and system calibration. The position of each monument must be determined during setup using, for example, a laser tracker survey.

Figure 5 An example of an i-series configuration with four transmitters and four monuments.

Once calibrated, the reference monuments provide a network of reference points against which the system can monitor drift, and establish scale.

This configuration is therefore the most robust and accurate.

As an example, tests performed by NPL and the University of Bath [3] indicate that a setup with eight transmitters and a network of twelve receiver monuments calibrated using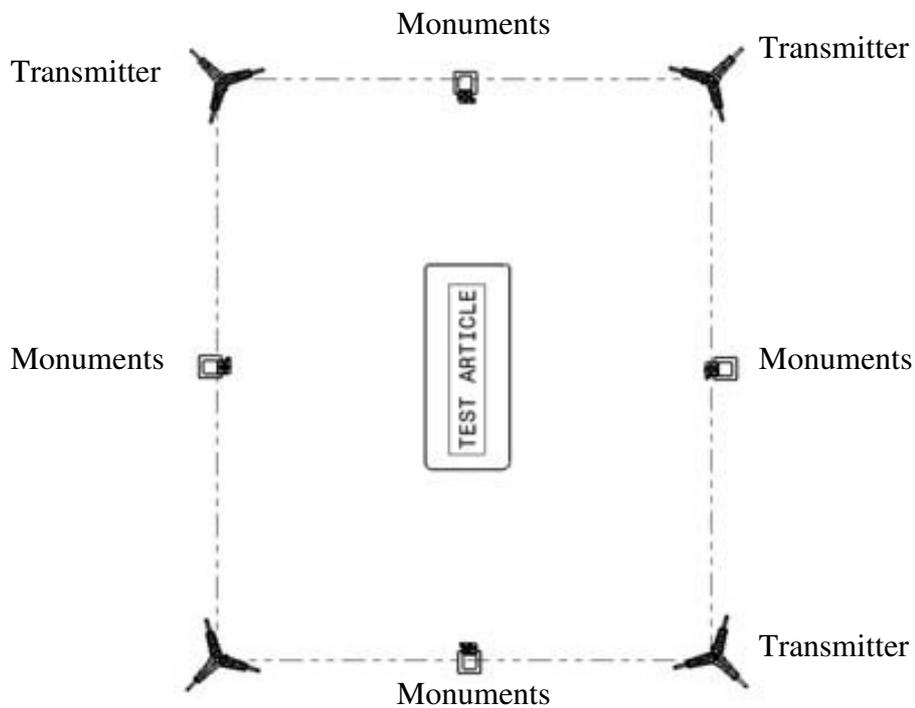 a laser radar was able to achieve a length measurement uncertainty of 170 µm (*k=2*) for lengths up to 12 m in a volume of 10 m x 10 m x 2 m.

3.4 OTHER CONFIGURATIONS
Other setups, not limited four, six or eight transmitters are, of course, possible. For example, more transmitters could be deployed to improve line-of-sight issues or to extend the measurement volume. The same methods of calibrating the setup, as described above, will apply.

The simulation software that accompanies this document can be used to simulate the relative performance of different setups and configurations. Operation of the software is described in the next section.

4   SIMULATION SOFTWARE

4.1 INTRODUCTION
The iGPS simulation software was developed to allow the user to simulate different setups of an iGPS system using any combination of transmitters and receivers and to gain an understanding of the likely system performance. The current version allows users to load, view, analyse and save data acquired by iGPS systems.

4.2 USING THE SOFTWARE
There are three main sections in the current software. They are: "Load Data", "View" and "Data Analysis". Users should follow the order of the section when using the software. Users should be able to find detailed information about the software in the section "Help".

Figure 6 Main menu of the software.

Users are required to input the information regarding the experimental setup and to load necessary data prior to performing the analysis. This can be done by load necessary data in "Load Data" section.
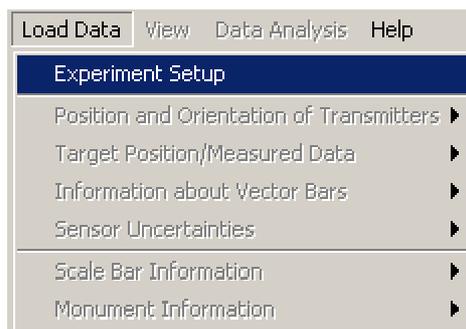
Figure 7 User interface of "Load Data" section.

In the "Experiment Setup" panel, users are required to input the number of transmitters, number of targets and number of vector bars. These settings are important particular if users opt to input data manually in the following section. Users also have to choose the way they would like to run the simulation. There are two approaches: "Measurement using scale bar" or "Measurement using monument". Both the scale bar and the monument are rigid bodies. The difference between them is that the scale bar has two targets fixed on two ends and the monument can have three or more targets. Besides, we assume users use vector bars to collect data from the scale bar targets, but use fixed receivers to collect data from the monument targets.

Figure 8 Experiment setup panel.

The structures of the two procedures "Measurements using Scale Bar" and "Measurements using Monument" are similar. An example of measurement using a scale bar is given in the following section.

4.2.1 Data Loading

Click the button "Confirm experiment setup"; the software then asks the user to load or input data, as shown in Figure 9. The user can either chooses to load data prepared in an Excel file or to input manually into the software. It is recommended to prepare the data in Excel so that they can be retraced in the future. If users select to load from Excel file, the size of the data is determined by the data loaded from Excel. However, if users choose manual input, the data size is determined by the information provided in the "Experiment Setup" section. Users can always change the "Experiment Setup" when need.

Figure 9 Load Data section. Left-scale bar approach. Right – monument approach.

4.2.2   Data Preparation

In order to run the software it is important to prepare the following data beforehand. The list of data files required is given in Table 1. These data have to be prepared and stored using Excel with file extension .xls. All location information and scale information are prepared in millimetre units.

Table 1 List of data files required.

Scale Bar Approach	Monument Approach
Transmitter.xls	Transmitter.xls
VectorBar.xls	VectorBar.xls
Targets.xls	Targets.xls
Sigma.xls	Sigma.xls
ScaleBar.xls	*Monuments.xls*
ID.xls	ID.xls
IA.xls	IA.xls

Note: the names are not compulsory.

How to prepare the data file "Transmitters":
  ➢ Create an Excel file. ('Transmitters.xls' is suggested name.)
  ➢ Create a new worksheet with name **tau**.
  ➢ The data must be an $nS \times 6$ matrix (nS is the number of transmitters). The first three columns are location of transmitters in Cartesian coordinates and the second three columns are orientation of those transmitters. The units are mm and degree respectively.
  ➢ Do not add column name or row name in the file.

	A	B	C	D	E	F
1	-3000	0	500	0	0	0
2	3000	0	500	0	0	0
3	0	-3000	-500	0	0	0
4	0	3000	-500	0	0	0

tau

Figure 10 An example of the data file "Transmitter".

How to prepare the data file for "Information of VectorBar":
  ➢ Create an Excel file. ('VectorBar.xls' is suggested name.)
  ➢ Create two worksheets, one with name **cc0** and the other with name **sigC**.
  ➢ **cc0** is the distance from the top sensor and the bottom sensor of the vector bar to vector bar probe centre. The unit of **cc0** is mm. Therefore, one vector bar requires a pair of parameters. Assuming there are nV numbers of vector bars, there will be $2nV$ of parameters required. In Figure 11, there are two vector bars, both the same, overall 40 mm length, with sensors 20 mm apart.
  ➢ **sigC** is the standard deviation associated with the **cc0** parameters of the vector bar geometry.
  ➢ Do not add column name or row name in the file.

	A	B	C
1	40		
2	20		
3	40		
4	20		
5			
6			
7			

cc0 / sigC

	A	B	C
1	0.005		
2	0.005		
3	0.005		
4	0.005		
5			
6			
7			

cc0 \ sigC

Figure 11 An example of the data file "VectorBar". Left – parameter "cc0". Right – parameter "sigC".

How to prepare the data file for "Target Positions/Measured Data":
- ➢ Create an Excel file. ('Target.xls' is suggested name.)
- ➢ Create three new worksheets, with name **X**, **IU** and **sigC**, where the targets location, the measurement strategy and the standard deviation of the target measurements can be stored respectively.
- ➢ The target location is an $nX \times 3$ matrix, where nX is the number of targets. The location is represented by (x, y, z) in Cartesian coordinates. The unit is mm.
- ➢ The worksheet **IU** stores the measurement strategy. Assume each transmitter can see each target; the size of the data will then be an $(nS * nX) \times 3$ matrix. The columns are target index (j), station index (k) and vector bar index (h). For example, the index of target 6 measured by station 1 using vector bar 2, will be [6 1 2]. See highlighted area in Figure 12.
- ➢ The worksheet **sigV** stores the parameter that controls the size of the random perturbations of the two angles specifying the orientation of the vector bars.

	A	B	C	D
1	-2000	-2000	-1000	
2	-2000	-2000	0	
3	-2000	-2000	1000	
4	-2000	-1000	-1000	
5	-2000	-1000	0	
6	-2000	-1000	1000	
7	-2000	0	-1000	
8	-2000	0	0	
9	-2000	0	1000	
10	-2000	1000	-1000	
11	-2000	1000	0	
12	-2000	1000	1000	
13	-2000	2000	-1000	
14	-2000	2000	0	
15	-2000	2000	1000	
16	-1000	-2000	-1000	
17	-1000	-2000	0	
18	-1000	-2000	1000	
19	-1000	-1000	-1000	
20	-1000	-1000	0	
21	-1000	-1000	1000	
22	-1000	0	-1000	
23	-1000	0	0	
24	-1000	0	1000	
25	-1000	1000	-1000	
26	-1000	1000	0	
27	-1000	1000	1000	
28	-1000	2000	-1000	
29	-1000	2000	0	

X / IU / sigV

	A	B	C	D
1	1	1	2	
2	2	1	1	
3	3	1	1	
4	4	1	1	
5	5	1	1	
6	6	1	2	
7	7	1	1	
8	8	1	2	
9	9	1	1	
10	10	1	2	
11	11	1	1	
12	12	1	1	
13	13	1	1	
14	14	1	2	
15	15	1	2	
16	16	1	1	
17	17	1	2	
18	18	1	1	
19	19	1	2	
20	20	1	2	
21	21	1	2	
22	22	1	1	
23	23	1	1	
24	24	1	1	
25	25	1	1	
26	26	1	1	
27	27	1	2	
28	28	1	2	
29	29	1	1	

X \ IU / sigV

	A	B	C
1	0.05		
2			
3			

X / IU \ sigV

Figure 12 An example of the data file "Targets". Top left – parameter "X". Top right – parameter "IU". Bottom – parameter "sigV".

How to prepare the data file "Sigma":
- ➢ Create an Excel file. ('Sigma.xls' is suggested name.)
- ➢ Set a worksheet with name "**sig**".
- ➢ There are four parameters required: sig_{AA}, sig_{AR}, sig_{EA} and sig_{ER}. They are, respectively, the uncertainty of absolute value of azimuth angles, uncertainty of relative value of azimuth angles, uncertainty of absolute value of elevation angles and uncertainty of relative value of azimuth angles.

	A	B
1	0.05	
2	0.000005	
3	0.05	
4	0.000005	
5		

Figure 13 An example of the data file "Sigma".

How to prepare the data file "ScaleBar":
- ➢ Create an Excel file. ('ScaleBar.xls' is suggested name.)
- ➢ Set three worksheets with name "**XD**", "**IUD**" and "**sigD**" respectively. "**XD**" stores the position of the scale bar target, where in this example, a 2 m scale bar is used. "**IUD**" stores the measurement strategy of the scale bar. Assume each transmitter can see each scale bar position; the size of the data will then be a $2nS \times 3$ matrix. The columns are scale bar target index (j), station index (k) and vector bar index (h). For example, the index of scale bar target 2 measured by station 3 using vector bar 1, will be [2 3 1]. See highlighted area in Figure 14. "**sigD**" is the standard deviation associated with the scale bar target distance measurements.

	A	B	C	D
1	0	0	1000	
2	0	0	-1000	
3				

	A	B	C	D
1	0.002			
2				
3				

	A	B	C
1	1	1	1
2	2	1	1
3	1	2	1
4	2	2	1
5	1	3	1
6	2	3	1
7	1	4	1
8	2	4	1
9	1	1	2
10	2	1	2
11	1	2	2
12	2	2	2
13	1	3	2
14	2	3	2
15	1	4	2
16	2	4	2

Figure 14 An example of the data file "ScaleBar". Top left – parameter "XD". Top right – parameter "sigD". Bottom – parameter "IUD".

How to prepare data file "Monuments":
  ➢ Create an Excel file. ('Monuments.xls' is suggested name.)
  ➢ Set three worksheets with name "**XM**", "**IUM**" and "**sigM**" respectively. "**XM**" stores the position of the monument targets, where in this example, a square frame is used. "**IUM**" stores the measurement strategy of the monument. Assume each transmitter can see each point on the monument; the size of the data will then be a $2nS \times 3$ matrix. The columns are monument target index (j), station index (k). For example, the index of monument target 2 measured by station 3, will be [2 3]. See highlighted area in Figure 15. "**sigM**" is the standard deviation associated with the monument target distance measurements.
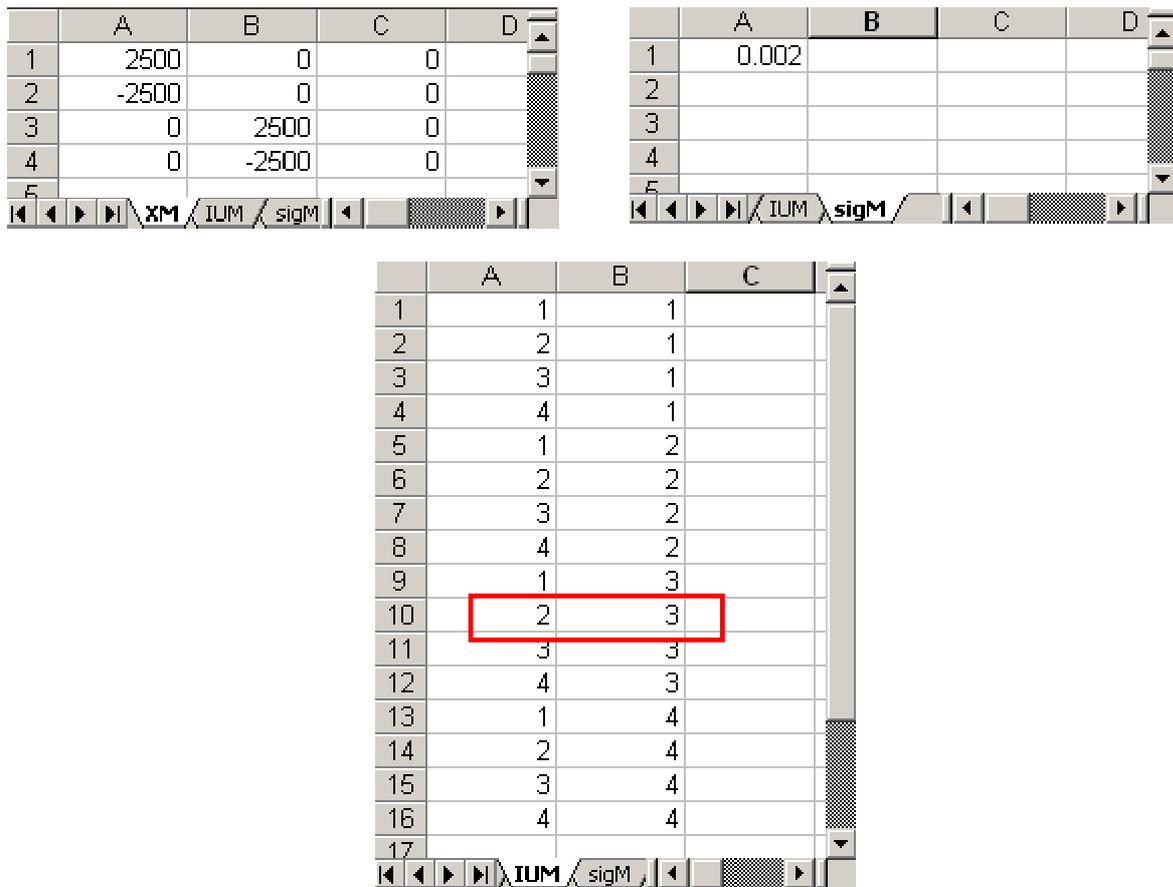

Figure 15 An example of the data file "Monuments". Top left – parameter "XM". Top right – parameter "sigM". Bottom – parameter "IUM".

The last two Excel files **ID** and **IA** are required for data analyses.

How to prepare data file "**ID**":
  ➢ Create an Excel file. ('ID.xls' is suggested name.)
  ➢ Set the worksheet with name "**ID**". **ID** is the index of targets for the inter-target distance calculation. It is an $m \times 2$ matrix, where m is the number of inter-garget distances. The software will calculate the inter-target distance between the target $X_{ID(1)}$ and the target $X_{ID(2)}$. For example, users have to input [3 2 1] in the file if the distance between target 32 and target 1 is required, see highlighted area in Figure 16.

Figure 16 An example of data file "ID".

How to prepare data file "**IA**":

➢ Create an Excel file. ('IA.xls' is suggested name.)
➢ Set the worksheet with name "**IA**". **IA** is the index of targets for the inter-target angle calculation. It is an $n \times 3$ matrix, n is the number of inter-target angles. The software will calculate the inter-target angle between the side $X_{IA(1)}$ -$X_{IA(2)}$ and the side $X_{IA(2)}$ -$X_{IA(3)}$. For example, users have to input [1 14 7] in the file if the angle between side X_1 -X_{14} and side X_{14} -X_7 is required, see highlighted area in Figure 17.

Figure 17 An example of data file "IA".

4.2.3   Access data from user interface.

The software allow user to edit data directly. Simply go to the corresponding section and make changes, see Figure 18 and Figure 19.
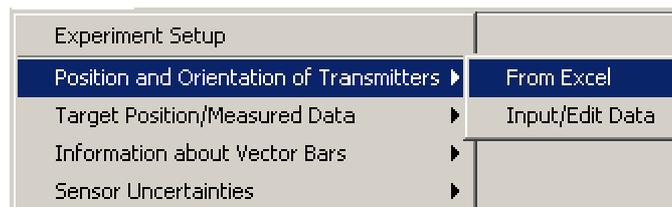

Figure 18 Data input options.

Figure 19 An example of editing data in the software

After the data has been loaded, go to "View" from the top menu bar, and click "View Experiment Setup", the experiment setup can be viewed. An example is shown in Figure 20. The software also provides the ability for the user to rotate or save the image by applying the corresponding command from the top menu bar.
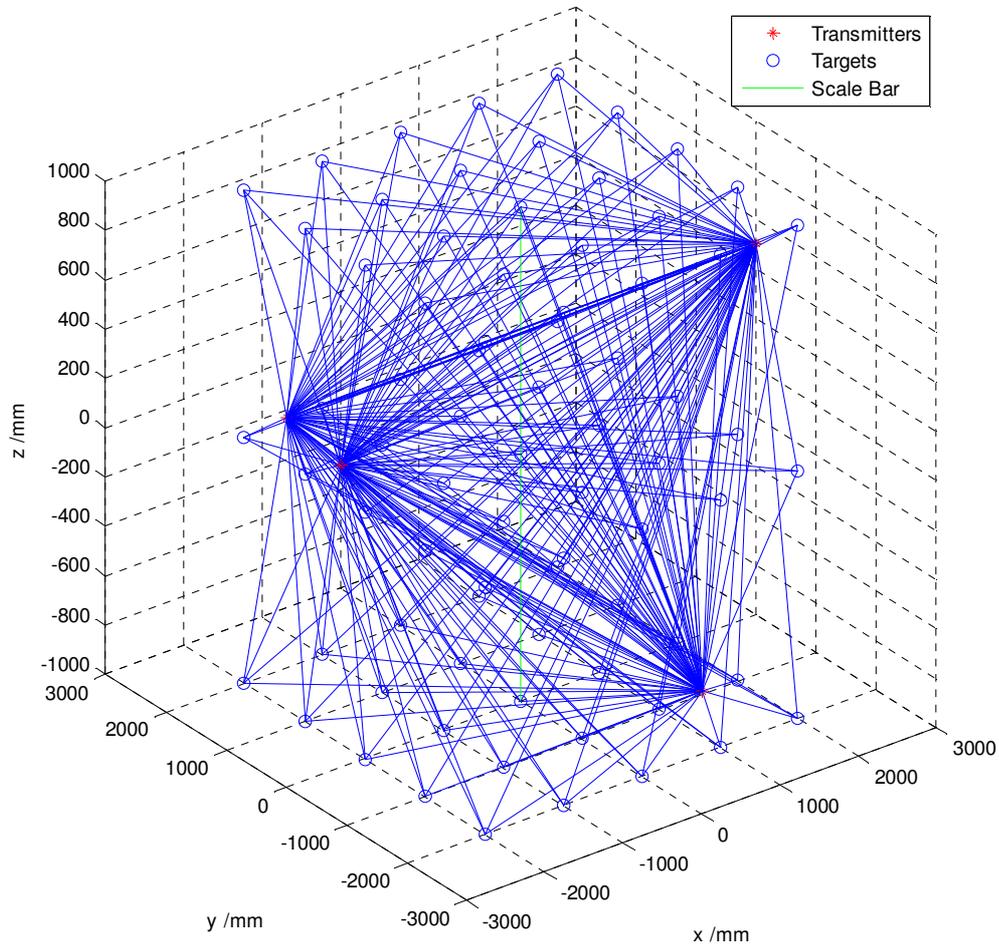

Figure 20 An example of iGPS experiment setup

4.2.4   Data analysis

Clicking "Data Analysis" from the top menu bar, the software then guides user to setup parameters for analysis. Two parameters are required. One is the inter-target distance index *ID*, the other is the inter-target angle index *IA*. The preparation of those indices has been introduced in section 4.2.2.
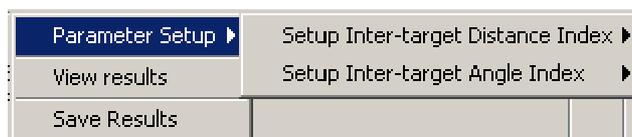

Figure 21 Parameter Setup menu.

Click "View Results" from the top menu bar, a list of parameters will then be shown on the "Data Analyses" panel. There are five parameters provided in the current version of software, as shown in Figure 22. The explanation of these parameters is given in Table 2.
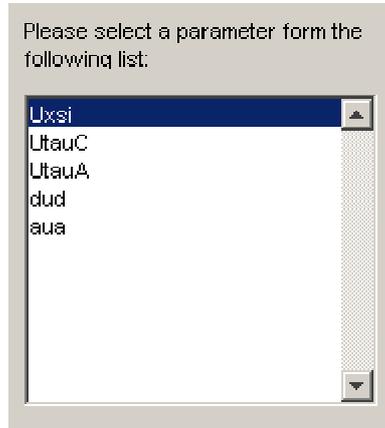

Figure 22 The list of parameters.

Table 2 Explanation of parameters.

Uxsi	Uncertainties in target (receiver) locations in Cartesian coordinates / μm.
UtauC	Uncertainties in transmitter locations in Cartesian coordinates / μm.
UtauA	Uncertainties in transmitter orientation in angles / arcsecond.
dud	Inter-target distances and uncertainties of distances between the targets *ID(1)* and *ID(2)* / mm.
aua	Inter-target angles and uncertainties of angles. The indices were specified as in IA / arcsecond.

The user can select the parameters from the list on the panel to view. For example, when the user clicks parameter "*Uxsi*", the software will display the value of this parameter and also plot the parameter on the right hand side of the panel. Examples of parameters Uxsi, UtauC and UtauA are given in Figure 23, Figure 24 and Figure 25 correspondingly.

Figure 26 shows the results of the parameter *dud*. *dud* is a $(nX\text{-}1) \times 2$ matrix that includes *d* (inter-target distances) and *ud* (uncertainties of inter-target distances). The right hand side of the panel is the plot of *ud* against *d*.

Figure 27 shows the results of the parameter *aua*. Parameter *aua* is a 2×2 matrix. It includes parameters *a* (inter-target angles) and *ua* (uncertainties of the inter-target angles). The right hand side of the panel is the three-dimensional plot of all targets. The angles investigated are highlighted in the figure on the right hand side of the panel. The numbers shown are the index of the targets. Users can rotation the image for best visualisation.

All uncertainty calculation is based on $k = 1$.

Uncertainties in target locations in Cartesian coordinates

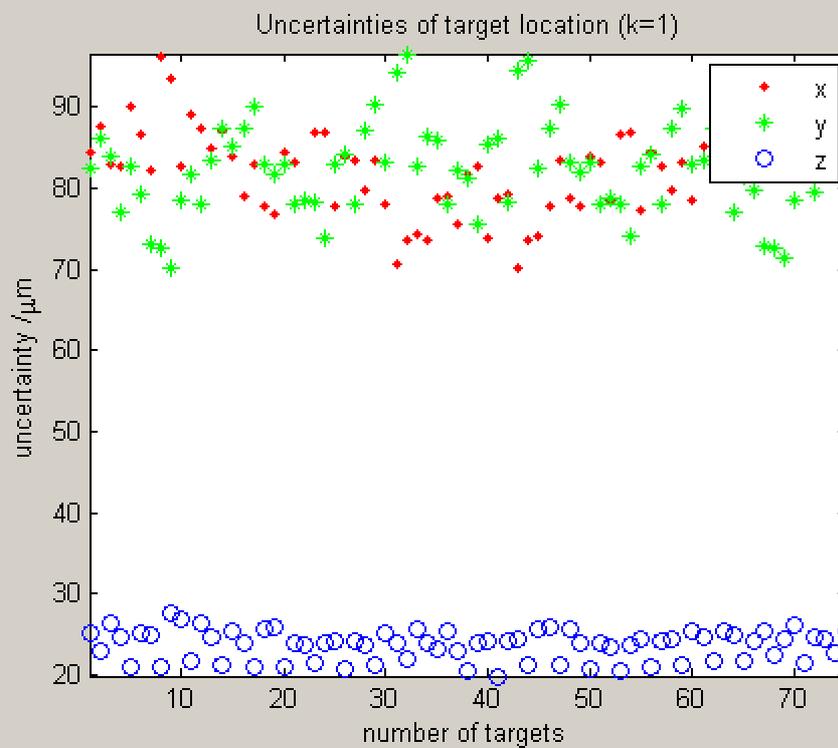|	x /μm	y /μm	z /μm
1	84.3285	82.4441	25.0972
2	87.5036	85.9876	22.8391
3	82.8376	83.9898	26.3895
4	82.7027	77.1258	24.7611
5	90.1490	82.7510	20.9292
6	86.7120	79.2878	25.0711
7	82.2355	73.0424	24.9114
8	96.1070	72.5793	21.1165
9	93.5792	70.2142	27.7036

Figure 23 Investigation of parameter *Uxsi*.

Uncertainties in transmitter locations in Cartesian coordinates.

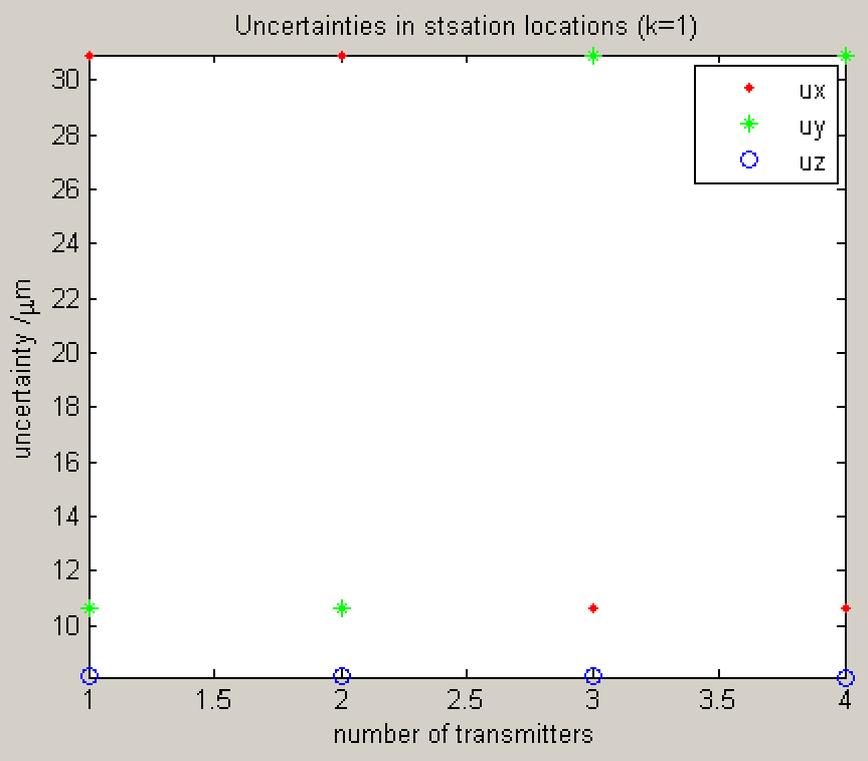|	x /µm	y /µm	z /µm
1	30.9330	10.6326	8.1018
2	30.9314	10.6288	8.0982
3	10.6526	30.9437	8.0974
4	10.6528	30.9437	8.0962

Uncertainties in stsation locations (k=1)

Figure 24 Investigation of parameter *UtauC*.

Uncertainties in transmitter orientation in angles.

	θ /arcsecond	φ /arcsecond	ψ /arcsecond
1	0.8086	0.5566	0.7314
2	0.8081	0.5572	0.7313
3	0.5577	0.8078	0.7304
4	0.5577	0.8070	0.7305

Figure 25 Investigation of parameter *UtauA*.

Inter-target distances and uncertainties of distances.

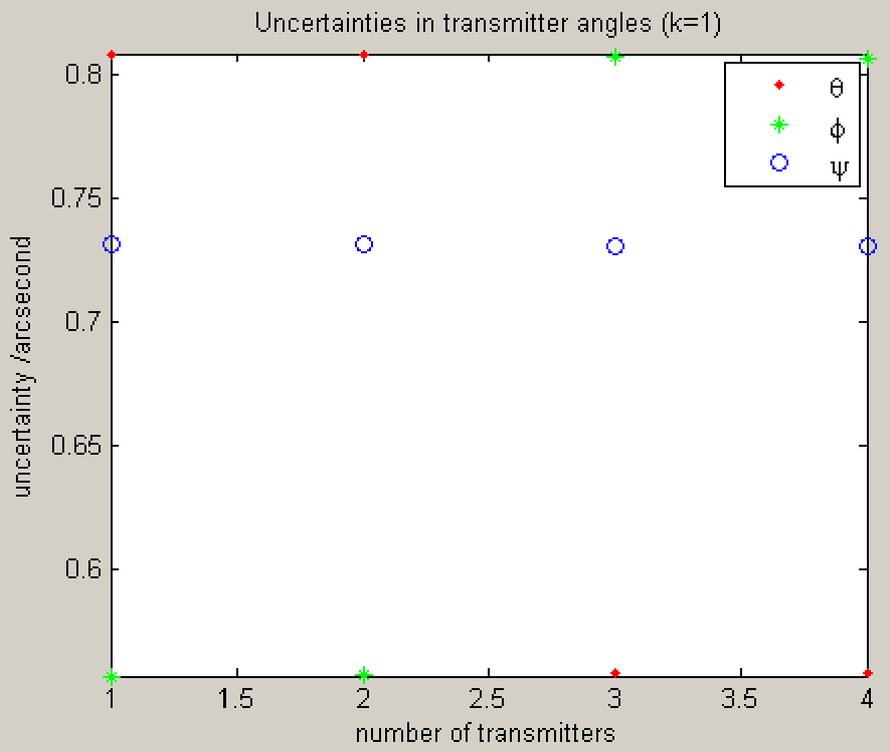|	d /mm	ud /mm
1	2.2361e+03	0.1006
2	2000	0.1140
3	2.2361e+03	0.1002
4	2.4495e+03	0.1068
5	2.2361e+03	0.1239
6	2.4495e+03	0.1110
7	3000	0.1108
8	2.8284e+03	0.1221
9	3000	0.1126

Uncertainties of inter-target distance (k=1)

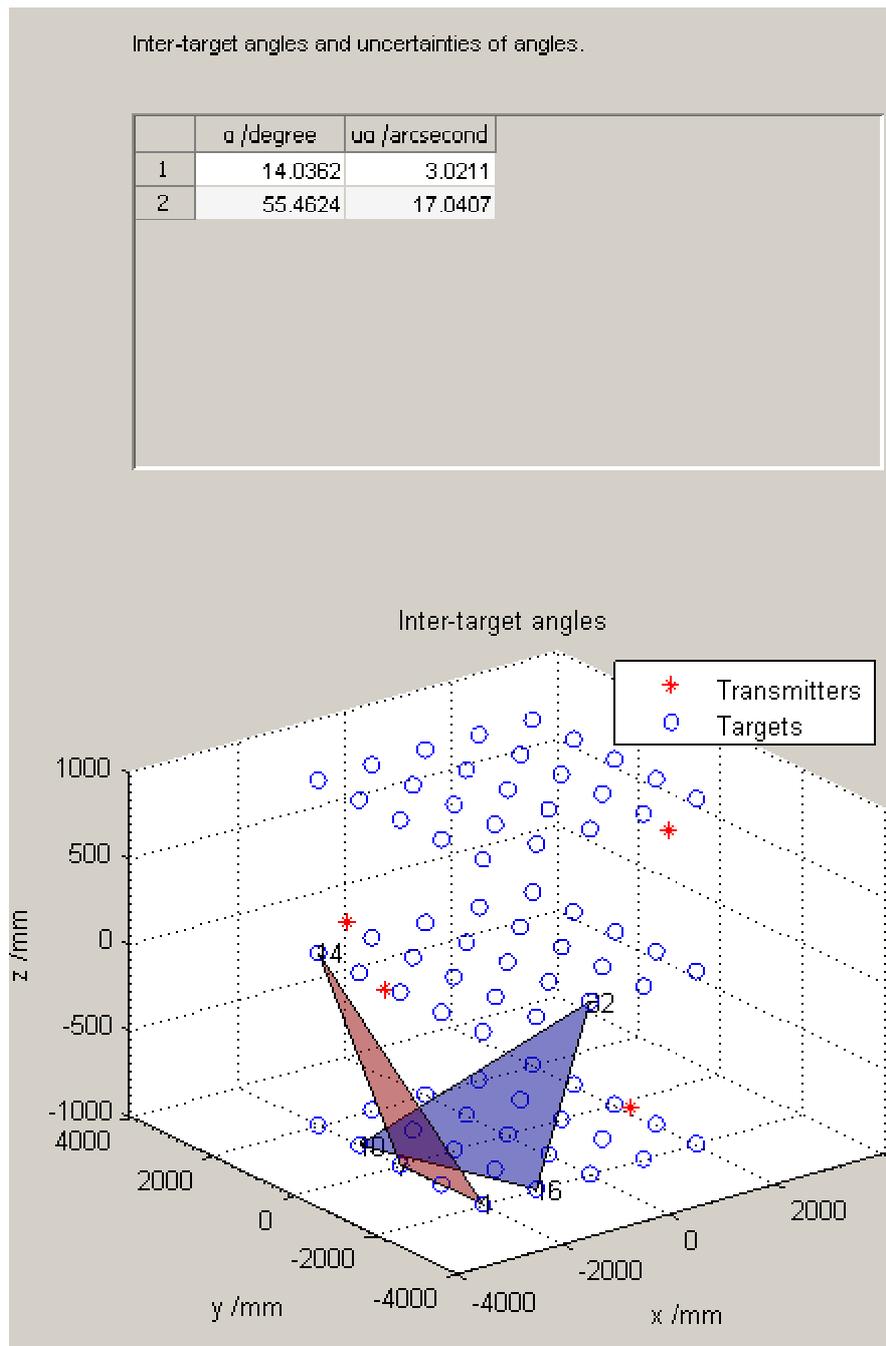**Figure 26 Investigation of parameter *dud*.**

Figure 27 Investigation of parameter *aua*.

4.2.5   Save final results

Click the "Save Data" on the "Data Analysis" window. The software will then save all listed parameters in a user defined .xls file.

5   REFERENCES

[1] Best Practice for non-contacting CMMs. Project 2.3.1/2/3 – Large Scale Metrology, UCL, NPL, Leica. MPU 8/61.1 – 09 12 1999.

[2] Grün, A. and Kahmen, H. (eds.), Optical 3-D Measurement Techniques IX, Vol. I, Vienna / Austria, Jul. 1-3, 2009, pp. 131-140, 2009.

[3] NPL REPORT ENG 23, iGPS Capability Study, Ben Hughes, Alistair Forbes, Wenjuan Sun, P Maropoulos, J Muelaner, J Jamshidi, Z Wang February 2010.