H24VLP Location Technology

Project 2 – Integration of GNSS and INS

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History of changes at `https://github.com/DfAC/TeachingSlides/`.

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1. Introduction

Welcome to the second project of H24VLP Location Technology Practical[1]. We will focus on navigation applications of the Inertial Navigation Systems (INS)[2], in our case consisting of integrated GNSS and inertial measurement unit (IMU) deployed on a moving platform (NGI Van). This practical learning outcomes are:

- Practical understanding of the IMU;
- Practical understanding of the INS;
- Ability to process and analyse the INS dataset;
- Understand the advantages and limitations of integrated GNSS and IMU system.

We will use an existing dataset, with the route combining three different environments:

- semi-urban;
- rural;
- dense urban (down town).

The goal of this practical is to understand the advantages and limitations of integrated GNSS and IMU systems. You will gain it by assessing the performance of three types of IMU sensor:

- navigation grade POSRS unit with Digital Laser gyros;
- tactical grade SPAN LCI with fiber optic gyros;
- low cost Microstrain 3DM-GX4-25 with MEMS sensor.

[1] History of changes at `https://github.com/DfAC/TeachingSlides/`.
[2] For more informations check lectures or `https://en.wikipedia.org/wiki/Inertial_navigation_system`

1.1 Practical Layout

This practical will consist of two supervised lab classes, with aim to provide you with tools and knowledge to complete the task. Apart from that, you are expected to work in your own time, and to facilitate this, each group will be provided with two IE dongles for the duration of thee weeks.

Week 1 Introduction to the practical. By the end of this practical you should have processed all GNSS data and get ready to process IMU data.
Week 2 INS processing. By the end you should have processed all INS data and start introducing data gaps.
Week 3 Group presentation.

1.2 Dataset description

Approximately 90 minutes trajectory have been collected using NGI van, demonstrated to you earlier. Trial was run in around Nottingham (see figure 1.2) starting and ending with a static period[3]. NGB2 was used as a reference station for the duration of the trials. Figure 1.1 and table 1.1 demonstrate experimental setup used.

All collected data has been converted to *Inertial Explorer* native format. Those files are:

NGB2.* NGB2 reference station;
POSRS.* IMU and GNSS data for POSRS (navigation grade);
SPAN_54.* IMU and GNSS data for SPAN (tactical grade);
microstrain.imr IMU data for low cost Microstrain IMU;

1.3 Supporting Document on Moodle

Following document are also provided for your reference:

POSRS.pdf Document outlining POSRS characteristics;
SPAN.pdf Document outlining SPAN characteristics;
Microstrain.pdf Document outlining Microstrain characteristics;
InertialExplorer850_Manual.pdf Full manual for IE 8.50;
H24VLP_P2_IMU.pdf This document[4].

1.4 Handling of data

You are being provided with all relevant data from onset of your project. I suggest:

- Keep all your data in a single project folder structure which you can backup on your own computer before leaving the Photogrammetry Lab;
- Place all given data file in the same
  RAW subfolder
- Create the separate project file for each IMU and put them in the project folder (main folder of the
  RAW subfolder);
- Please name each project accordingly (GNSS, SPAN, POSRS, MicroStrain ect);
- IE is producing a large number of files - the critical ones are **.cfg*, all other ones can be restored from RAW data.

[3] You will explore both GNSS and IMU data to identify those periods properly.
[4] History of changes at `https://github.com/DfAC/TeachingSlides/`.

1.5 Workflow

In order to process and understand the data, you will have to:

1. Process SPAN vs NGB2 data, as explained in section 2.. The aim of this step is to:
   (a) Identify static periods for IMU processing;
   (b) Create an ideal GNSS trajectory, that will be used in next steps.
2. Process Loosely Coupled (LC) IMU and GNSS data. You will:
   (a) Process POSRS, using GNSS.cmb [5], as explained in section 3.1.;
   (b) Process SPAN, using GNSS.cmb and by transferring alignment from POSRS, as explained in section 3.2.;
   (c) Process Microstrain, using GNSS.cmb and transferring alignment from POSRS, as explained in section 3.3.).
3. Process only IMU data (without GPS data) for each sensor, as explained in section 4.. You will use this to estimate the required GNSS gaps for each IMU system. Use this step to better understand limitations of each sensor.
4. You will introduce artificial GNSS denied environment, by introducing gaps (outages) in the GNSS data set for each sensor, as explained in section 5. The aim is to:
   (a) Verify your understanding of last step;
   (b) Demonstrate the performance of each integrated GNSS and INS system for navigation, by highlighting differences between systems.
   (c) Duration of GNSS gaps, combined with exploratory analysis of all results should allow you to **Characterise the performance of each integrated GNSS and INS system for navigation and tracking applications**.
5. Draw conclusions and prepare presentation by visualising and summarising your work. While a brief description of outputs provided by IE can be found in section 6, you are expected to show your own judgement and expertise in selecting output supporting your narrative. It is likely that IE output will be sufficient for that, but you are welcome to summarise some of the results in the tables or plot additional graphs using comparing exported coordinates.

Following sections will explain the basics of using IE, which should be sufficient to carry out the required task. If you need more information check the **Inertial Explorer Manual** provided.

[5] This is trajectory created in the previous step.

II Processing Data

2. Processing GNSS data

To compare performance of IMU component, we will use the same GNSS data set for each project - SPAN GNSS data, collected at 1Hz observation rate.

2.1 Creating a new project

- Open *Inertial Explorer* and go to ***File->New Project->Project Wizard***;
- Navigate to project folder and create a new project - GNSS;
- We will use SPAN GNSS data as a rover;

  1. Select required GNSS & IMU files (SPAN_54.*);
  2. antenna height 0m, Measured to APR, use antenna profile as per figure 1.1;
  3. Next;

- We will use NGB2 as reference station;

  1. Select *I would like add Base Station Data*;
  2. Select *Add Station From File* and select NGB2.* files;
  3. antenna height 0.502m, profile *LEIAR25.R4*;
  4. position 52°57’06.95636"N 1°11’02.39879"W 91.2006m;
  5. Measured to APR;
  6. NEXT, NEXT, Finish, Finish.

2.2 Processing GNSS data

To process data select ***Process->Process GNSS*** or press ***F5***

- Processing Method: *Differential GNSS;*
- Processing Direction: *Both*;
- Profile GNSS: *Ground Vehicle*, don’t change any *Advanced..* options;

- Make sure th add description/User name - we can recover previous settings so description is very important.

2.2.1 Understand the data

With complex dataset it is important to fully understand the dataset. First check overview summary using ***View->Processing summary***. To visualise data go to ***Output->Plot Results*** **or press F7**.

- Lets start with looking at data overlap by selecting *File Data Coverage* plot.
- Check plot settings.
- To check quality of the position use the following plots:
  - Combined Separation
  - Combined Separation(Fix)
  - Estimated Position Accuracy
  - Quality factor
  - Float/Fixed Ambiguity Status
- To obtian more information about our baseline use the following plots:
  - Local Level Vector - don't neglect height component
  - Distance Separation
  - RMS - Carrier Phase

NOTES

Every plot have menu accessible by right clicking on it. Selecting *Properties* allows to modify plot display. Plot range can be modified from same menu using *X-Axis* and *Y-Axis*. *Apply to All* subcommand match all open plots to the current one. *Compute statistics for..* provide quantification of plot data. Use ***Ctr+C*** to copy window content. If you ever close background map, use ***Output->Show Map window*** .

2.3 Improving GNSS data

This section discuss how we can improve quality of the data.

2.3.1 Using Precise Orbits

The precise orbits latency is 12-18 days, with the rapid product available for GPS rapid within the day[1]. This is useful for baselines exceeding 15km or if you suspect problems with broadcast ephemerides. It will automatically download precise orbits and clock files[2] relevant to the current project. To do so

- Select ***File->Add precise Files***;
- Check if time and date is correct, tick GLONASS and press Download for combined GPS and GLONASS data (some files might be overwritten)[3];
- Press OK to exit window;
- In ***View->Project Overview*** you should be able to see all the files you added;

[1] For more details check `http://bit.ly/IGS_products`.

[2] For double differencing you only need precise orbits. Note, that you also need to have broadcast orbits and you should have data 2h before and after the period of interest for best accuracy.

[3] GPS only data provide higher resolution clocks, which might be useful for PPP.

- Re-process GPS data,as explained in section 2.2..

2.3.2 Introducing static data in GNSS processing

For the successful initialisation of IMUs we need to identify the static periods at the beginning and the end of dataset. We can do using GNSS data only, improving its accuracy in the process - IE is using extended kalman filter (EKF)[4] for calculations and will use different settings based on the rover static or kinematic status.

Looking for static periods

- use *Acceleration Profile* or *Velocity Profile* plots to identify static periods.
- create new file Static.txt with each row identifying static period as NAME START_TIME END_TIME NOTE as follows[5]:

```
NGI_Start 201200.0 203505.0 Intial_Period_NGB_Yard
NGI_End 221200.0 223505.0 End_Period_NGB_Yard
```

- use **View->GNSS Observations->Remote->Insert Static/Kinematic Markers** and select *Use user generated file to define static periods* to import static data;
- plot *File data coverage* to check if data is properly changed;
- process GNSS data again;
- Assess quality each static period using *Static Session Convergence* plots.

Once you happy with identified static periods (they should be between 5-10 min long) compare results using any other plots that we discussed. You can also use your experience from the first project to fine tune processing parameters such as: excluding poor satellites or change cut off angles[6]. Once you happy with results save and exit the project. As an extra precaution you might consider making a copy of *GNSS.cmb* and re-naming it, for example as *GoodData.cmb*.

[4] For more details check `http://bit.ly/KalmanPics`.
[5] More information at page 32 of IE manual.
[6] Be careful with changes here, especially when changing KF or Ambiguity Resolution (AR) related parameters. Make sure you identify those changes properly in processing history.

3. Processing LC GNSS and IMU

To compare performance of IMU component, we will use the same GNSS data set for each project - created in last section. You should not need to re-process GNSS - should you do so you will have to re-process all LC project as well.

Following subsection will explain detailed settings and workflow for each sensor. The general workflow is the same:

- To create a new project
  1. Navigate to project folded and name project (POSRS, SPAN, Microstrain);
  2. Select required GNSS & IMU files (for ex POSRS.*);
  3. antenna height 0m, Measured to APR, use antenna profile as for SPAN as this is GNSS rover data you are using;
  4. There is not need to add base station data;
  5. Finish.
- To process Loosely Coupled GNSS/IMU solution go to ***Process->Process LC***
  1. Select required IMU files only (*.imr);
  2. Check orientation of axis and level arms (those are values AFTER the rotation) following table 1.1;
  3. in **Advanced...**:
     - select proper time period for the dataset from first static period to end of last static period identified in section 2.3.2.
     - select proper method for forward and backward initial alignment
     - press OK.
  4. Change description and user;
  5. Click process.

3.1 Processing POSRS

In ***Process->Process LC*** choose:

update data *External Trajectory;* Use *Browser External* to select *.cmb file.
POSRS Profile *SPAN Airborne (uIRS)*
Lever Arm Offset use POSRS lever arms from table 1.1 and select ***Z to ARP***
Body to IMU Rotation: *180,0,90*

3.1.1 POSRS Workflow

1. Run all automatic. There should be small separation between pitch and roll (70 arc-sec), aligned with large jumps in heading at the beginning and the end (up to 700 arc-sec). This tend to indicate weak starting (and finishing) angle estimate. Everything else should be smooth (within 70 arc-sec).
2. Plot *Acceleration Profile* and *Velocity Profile* to check if static periods are matching ones from GNSS only processing. Make sure that dataset start and finish on static period changing *IMU Time Range* in ***Advanced...*** if necessary.
3. Knowing static periods go to ***Advanced...***and in ***Method for Initial Alignment*** select *Static Coarse+Fine align* for both reverse and forward. Use Coarse: 60-100s, Fine 100-200s. If you have longer static dataset extend fine alignment period. Results should be within 10 arc-sec and there should be no separation between pitch and roll. There will be large jumps in heading at the beginning and end (up to 100 arc-sec)
4. Transfer alignment that is use reverse value for forward solution and vice versa.

    - In ***Advanced...*** for the ***Method for Initial Alignment*** select *Transfer Alignment (enter known attitude)* and press *Enter Attitude* button. You will do the same for forward and reverse solution.
    - Click *Get From Trajectory* and select *reverse* POSRS data (*.rim) for forward and *forward* POSRS data (*.fim) for reverse. Estimated StdDev for both should be similar. Increase it tenfold (x10) to loosen EKF.
    - Click OK
    - Click *Enter Position and Velocity*, click *Get from Trajectory* and select the same files (they should be already selected). Click *Extract*.
    - I suggest increase estimated StdDev tenfold (x10) to loosen EKF.
    - Click OK three times to get back to *Process Loosely Coupled* screen.
    - Process data

5. Results should be within 10 arc-sec for heading and 2 arc-sec for rest. There should be no separation between pitch and roll. Heading separation should be largest in the middle and no jumps at the beginning/end.

3.1.2 Checking results

To check quality of solution:

- To check lever arm in ***Process->Process LC*** go to ***Advanced...->States*** and check *Solve for lever arms.* After reprocessing the data plot *IMU/IMU-GPS Level Arm* and compare results with values given. Make sure to reprocess data without *Solve for lever arms* for final results and remaining plots.
- Plot *Attitude Separation* to check IMU initialisation.
- Heading (orientation of axis) can be checked by *IMU Heading COG difference* and *Attitude(Azimuth/Heading)* plots.

- To check final position, and quality of LC results plot *Combined Separation, Combined Separation (fix)* and *IMU/GPS position misclosure*.

3.2 Processing SPAN

In ***Process->Process LC*** select:

update data: *External Trajectory* (select same *.cmb file as for POSRS processing)
SPAN Profile: *SPAN Ground (LCI)*
Lever Arm Offset use SPAN lever arms from table 1.1
Body2IMU Rotation: *0,0,90*

3.2.1 SPAN Workflow

1. Run all automatic. This is purely to check if data is ok.
2. After checking for static data run *Static Coarse+Fine align*.
   - Recommended settings Coarse: 120s, Fine 480s.
   - If you have longer static dataset extend fine alignment period.
   - This should be big improvement over automatic ones, roughly 3-4x more than POSRS - otherwise check your static periods.
3. If all is correct transfer alignment from POSRS as described in section 3.1. Your final accuracy will be lower than POSRS one.

3.2.2 Checking results

Same as for POSRS.

3.3 Processing Microstrain

In ***Process->Process LC*** select:

update data External Trajectory; Use Browser External to select *.cmb file.
Profile: *SPAN Ground (ADIS16488)*

- go to ***Advanced...->States***
- Under *Error Model* un-check *Lock Selection* and select ***Automotive (Low Precision)*** error model

Lever Arm Offset use POSRS lever arms from table 1.1
Body2IMU Rotation: *180,0,90*

Follow section 3.2.1 to obtain all results. Bear in mind that this sensor is of much lower accuracy the other ones and it might be more logical to focus on the smaller subset of the data.


4. Processing IMU on its own

To assess the duration of the gaps (outages) in the GNSS data you will first assess the quality of IMU by processing it on its own. Results will show you system fee-wheeling performance. I advice to copy and rename project control file for each IMU. To run each IMU you need to define starting and ending orientation and position for IMU - this is what you did already in previous section using *Transfer Alignment*. With those setting in place you can process IMU only data.

1. In **Process->Process LC** check **Process IMU Data only** box;
2. Depending on desired outcome select Both in **Processing Direction**;
3. Provide proper description;
4. Click **Process**.

Process high end IMUs using three **Processing Directions**: Both, Forward and Reverse. Analyse data using plots from last section. Once you have the understanding of sensors accuracy and of duration of GNSS outages you want to introduce head to next section.

5. Artificial GNSS outage

To create an artificial GNSS outage you will remove epochs from GNSS generated trajectory - GNSS.cmb file, as explained in section 2.2.. In *.cmb file each epoch is represented as:

```
Out {Tim: 121252.00 121252.000000 1777                    %HHMMSS.SSS GPS Week
Geo: 52 57 07.03189 -1 11 00.40441 80.5757 0.061         %vehicle location
Loc: 37.235 2.335 -10.564 0.054 -0.028 -0.002
Sta: 2 0.025500 1.31 1.420 0.960 1.040
Rms: 0.0282 2.180 0.000 0.023 0.0406 7.880 1.126
Var: 3.85994e-003 6.52259e-004 ...
Ecf: -7.457 37.397 -7.025
Acc: -0.010 0.013 0.025
Flg: K L 7 6
Sep: 0.136 -0.211 0.151 0.069 0.108 0.077
Wgt: 2 2 39 61
Cov: -4.00800e-004 7.41043e-005 ...
}
```

Delete *Out{...}* to remove whole epoch. Make sure you don't remove static data used by IMU to initialise. Start with small data gaps and slowly increase their duration. Make sure you work on copy of the GNSS.cmb.
Once file has been produced reprocess relevant IMU project using altered GNSS trajectory file. I also suggest experimenting with different settings of **Processing Direction** in **Process->Process LC** to fully understand system accuracy.

6. Visualising and exporting results

Previous sections should provide you with enough technical knowledge to successfully process the data and understand the performance of three integrated INS systems. A critical part of your assessment is to draw the conclusions and prepare visualisations and summary of data supporting your findings. It is likely that IE output, discussed below, will be sufficient for that, but you are welcome to summarise some of the results in the tables or plot additional graphs using exported coordinates/data. You are expected to show your own judgement and expertise in selecting output supporting your narrative.

6.1 Graphical results

- To save all active plots use ***Output->Build HTML Report***
  - Data will be saved in **Html** folder;
  - Save at least two set of plots (testing and final) for each sensor. This is for your reference - you don't need to present them all.
- To output trajectory to Google Earth use ***Output->Export to Google Earth...***. In case of multiple exports it recommended to change the output parameters using ***Export*** tab:

  Optimize output for trajectory comparison in GE creates new colour for the each export[1]. For each run a new folder is created.

  Use concise epoch description for lower memory usage shortens output information allowing for quick display in Google Earth.

  Hold epochs and events to ground is mutually exclusive with **Output MSL height for better compatibility with GE elevation data**. Those settings should be used respectively for terrestrial and aviation data only.

[1] On this occasion colours won't follow Quality Numbers from table 1.2.

6.2 Coordinates

NOTES

To use ***Export Wizard*** combined solution (*.cmb) must exist. It is generated after each LC/TC processing run. It can be also be created using ***Process->Combine Solution***. Use extreme caution if using this option.

To output post-processed coordinates as ASCII

- Select ***Output->Export Wizard***
- Select output profile.
  - Create your own profile using Modify or New buttons.
  - I suggest output either in local grid (East, North, Ellipsoidal Heigh) or Absolute ECEF-XYZ.
  - Once happy click OK and Next

NOTES

IE does not produce correct OSGB coordinates. For this experiment you can use any grid coordinates, as long as yu are consistent and describe it properly. If you need OSGB coordinates, export data as ECEF XYZ and convert it to OSGB using Grid InQuest[a] or Ordnance Survey online tool[b].

[a] `http://www.ordnancesurvey.co.uk/docs/gps/grid-inquest-executable.zip`
[b] `https://www.ordnancesurvey.co.uk/gps/transformation`

- Select ***Use processing datum*** and click Next
- Define your output parameters
  - Define time interval for output (you can interpolate up to 200Hz with POSRS/SPAN. I recommend 0.5-5 Hz to keep file sizes reasonable.)
  - Define lever arm using table 1.1 .

NOTES

If you followed instruction correctly, your GNSS and IMU level arm are calculated to **antenna ARP** but output lever arm will be estimated to **antenna phase centre**. This means that for EXPORT ONLY your level arm has to be calculated using equation $Arm^Z_{exprt} = Arm^Z - AntProfile^Z_{L1} - AntHeight$.
Relevant Arm values can be read from table 1.1. Antenna profile can be checked using (**View->Project Overview**).

- Uncheck *View ASCII* and click *Finish*.

6.3 Checking results

Check IMU solution against GNSS one. Export values at ARP (**SUBTRACT antenna L1 height offsets**). It should agree to few mm in clean environment. Check between different IMU solutions. SPAN/POSRS should agree on mm to cm level.

Appendixes

A	Lever Arms
B	Quality Indicators
C	Test route

A Lever Arms

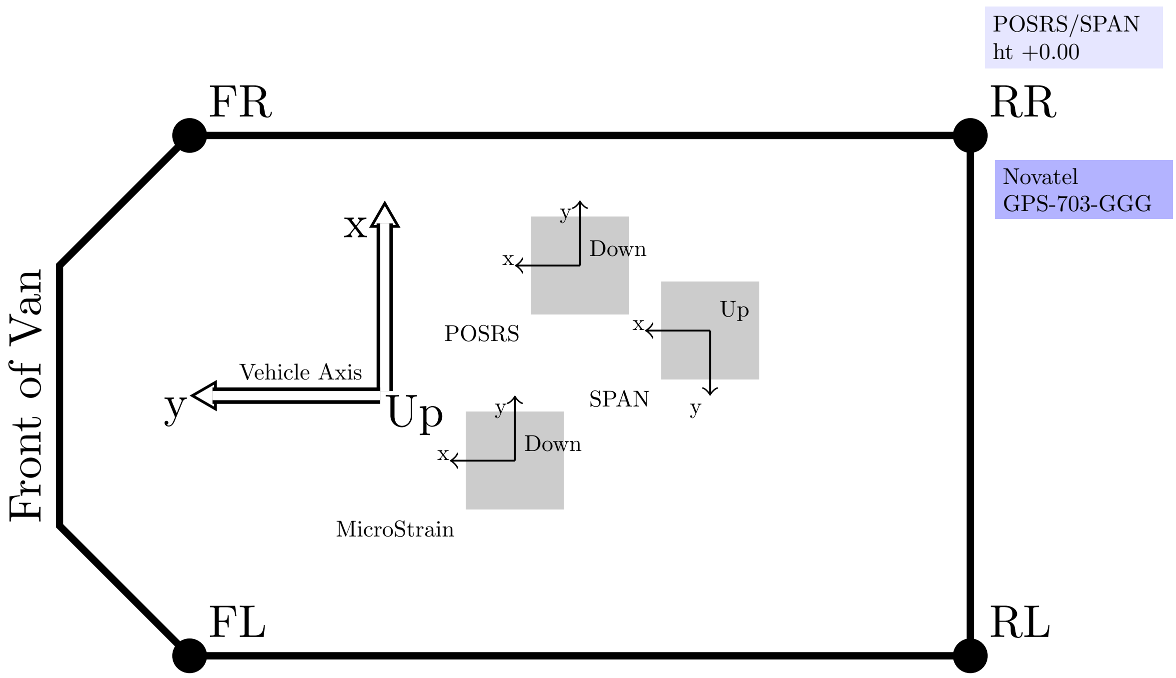

Figure 1.1: Van experiment layout

IMU Sensor	Antenna Mount	Lever Arm[a] X	Y	Z
POSRS	RR[b]	0.198	-0.830	0.552
	FL	-1.134	2.338	0.557
SPAN	RR[b]	0.307	-0.626	0.543
	FL	-1.025	2.542	0.583

Table 1.1: Lever Arms for POSRS and SPAN

[a]Lever arm is estimated to the ARP. Direction IMU to antenna.
[b]Mount used in the trials.

B Quality Indicators

Inertial Explorer use colour coded Quality Indicators (IQ) to indicate quality of any positioning solution. Use it to assess the accuracy of your solution.

QN	Color	Description	3D Accuracy (m)
1	Green[a]	Fixed integer	0.00 – 0.15
2	Cyan [a]	Converged float or noisy fixed integer	0.05 – 0.40
3	Blue	Converging float	0.20 – 1.00
4	Purple	Converging float	0.50 – 2.00
5	Magenta[b]	DGPS	1.00 – 5.00
6	Red[b]	DGPS	2.00 – 10.00
	Grey	Data haven't been processed	

Table 1.2: IE Quality Number description

[a] **Recommended for LC integration**.
[b] Do not use for LC integration.

C Test route

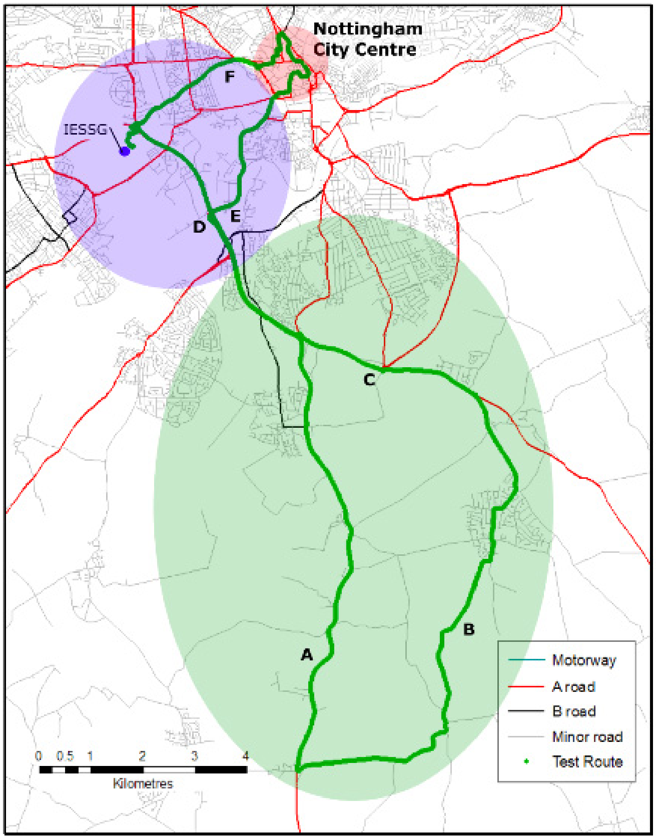

Figure 1.2: Test route