South Africa

COTO

Committee of Transport Officials

TMH13

AUTOMATED ROAD CONDITION ASSESSMENTS
PART B: POSITIONING

Committee Draft Final
May 2016

Committee of Transport Officials

TECHNICAL METHODS
FOR HIGHWAYS

TMH 13

AUTOMATED ROAD CONDITION ASSESSMENTS
Part B: Positioning

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Compiled under auspices of the:

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Synopsis

TMH13 provides the guidelines and procedures to assist road authorities to plan, execute and control automated road conditions assessments for: roughness, skid resistance, texture, rutting, deflections and distress imaging. Automated measurement concepts as well as background to different devices are provided. TMH 13 is a companion document to TMH 22 on Road Asset Management Systems and as such includes aspects of data capturing, analysis and documentation.

Withdrawal of previous publication:

This publication is new publication.

Technical Methods for Highways:

The Technical Methods for Highways consists of a series of publications in which methods are prescribed for use on various aspects related to highway engineering. The documents are primarily aimed at ensuring the use of uniform methods throughout South Africa, and use thereof is compulsory.

Users of the documents must ensure that the latest editions or versions of the document are used. When a document is referred to in other documents, the reference should be to the latest edition or version of the document.

Any comments on the document will be welcomed and should be forwarded to coto@nra.co.za for consideration in future revisions.

Document Versions

Working Draft (WD). When a COTO subcommittee identifies the need for the revision of existing, or the drafting of new Technical Recommendations for Highways (TRH) or Technical Methods for Highways (TMH) documents, a workgroup of experts is appointed by the COTO subcommittee to develop the document. This document is referred to as a Working Draft (WD). Successive working drafts may be generated, with the last being referred to as Working Draft Final (WDF). Working Drafts (WD) have no legal standing.

Committee Draft (CD). The Working Draft Final (WDF) document is converted to a Committee Draft (CD) and is submitted to the COTO subcommittee for consensus building and comments. Successive committee drafts may be generated during the process. When approved by the subcommittee, the document is submitted to the Roads Coordinating Body (RCB) members for further consensus building and comments. Additional committee drafts may be generated, with the last being referred to as Committee Draft Final (CDF). Committee Drafts (CD) have no legal standing.

Draft Standard (DS). The Committee Draft Final (CDF) document is converted to a Draft Standard (DS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a draft standard. This Draft Standard is implemented in Industry for a period of two (2) years, during which written comments may be submitted to the COTO subcommittee. Draft Standards (DS) have full legal standing.

Final Standard (FS). After the two-year period, comments received are reviewed and where appropriate, incorporated by the COTO subcommittee. The document is converted to a Final Standard (FS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a final standard. This Final Standard is implemented in industry for a period of five (5) years, after which it may again be reviewed. Final Standards (FS) have full legal standing.

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B.1 Introduction

B.1.1 Context and Scope

TMH 13 *Part B* is the second of seven parts on Automated Road Condition Assessments. Part B provides guidance and methodologies on the planning, execution and control of positioning data during automated surveys. This part should be read in conjunction with TMH 13 Part A which includes basic concepts and key definitions of positioning systems. Part A also covers general aspects related to the planning of automated surveys.

TMH 13 Part B is a companion document to Parts C through G which deal with different pavement condition measurements, as well as to TMH 22 on Road Asset Management. Where applicable, reference is made to other documents in the series along with appropriate standards.

Part B focuses primarily on referencing using GPS (Global Positioning System) and peripheral devices used for GPS augmentation, including inertial sensors and distance measuring instruments. As such the positioning technologies included can be used for both spatial and linear referencing. General aspects of location referencing are covered in TMH 22.

The scope of these guidelines are primarily concerned with the needs of roads agencies or managers of road networks. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the needs of the contractor in charge of the actual measurements.

B.1.2 Objectives

The primary objective of these guidelines is to assist road network management personnel to plan, execute and control capturing of positioning data over a road network. Secondary and associated objectives are to provide background, definitions and clarification of key concepts. Content related to the secondary objectives is included in Part A: General.

B.1.3 Layout and Structure of Part B

The document is written in concise format as far as possible to enable network managers to use it firstly as a practical guide, and only secondly as a source of general information on collection of position data.

Concept summaries and checklists are included and clearly highlighted. A comprehensive reference list is provided and related but non-essential aspects are discussed in sidebars. Sidebar boxes are also used to highlight references to other related TMH documents and specifications. The guidelines are structured as follows:

Section B.2 covers the main types of capturing devices and peripheral devices to enhance or supplement positioning data. The main device types covered are GPS receivers, Inertial Measurement Units (IMU), and Distance Measurement Instruments (DMI).

Section B.3 provides guidance and methodologies on the validation and control of GPS, IMU and DMI. The selection of validation sections is discussed, and schemes for device validation and capturing are outlined.

Section B.4 includes operational procedures for positioning systems.

Section 6 and **Section 7** contain References and a Glossary, respectively.

B.2 Positioning Equipment

Data location is a key attribute in any asset management system. Location is the link between different data sets and indispensible in establishing data relationships in modern databases. Whilst linear location referencing has traditionally been the most commonly used reference system, reliance on linear distance measurement and physical reference points or markers can be quite cumbersome. Surface condition, geometric features and operator variability all influences measured distance. GPS coordinates linked directly to the data can assist to minimize these effects. The integration of GPS in all data collection systems is therefore required. To insure accurate and continuous location data, differential corrected GPS (DGPS) in combination with an Inertial Navigation System (INS) is a minimum requirement. Aspects of these equipment and specifications are included in this section. Whilst the section focuses on spatial or point based positioning, equipment requirements to complement linear referencing are also addressed. Because of fast development of these technologies, this section aims at providing network managers with a generic overview of the equipment and current trends.

B.2.1 GPS Receivers

Geo-referencing of road surveillance data rely on the GPS receiver's navigational solution, i.e. Position, Velocity, and Time (PVT). Each satellite transmits modulated or coded signals at two different carrier frequencies in the L-band, denoted L1 and L2 in the GHz range. More frequencies are introduced with the commissioning of additional global satellite constellations (such as GALILEO, GLONASS etc.). Signal modulation is used to enable different satellites to use the same frequencies. This is achieved by assigning a unique code to each satellite, called a pseudo-random noise (or PRN code) to make the signal look like noise. In addition, signals comprise the carrier component which is the radio frequency (RF) sinusoidal signal, and a coded message with satellite information such as almanac and satellite health data. GPS receivers aim at tracking these signals in order to correctly demodulate and extract measurements and calculate the navigational solution.

B.2.1.1 Receiver Components

GPS receivers comprise four generic components, namely the antenna, front end, baseband signal processing, and application processing. Apart from these, other components include the power unit and type of enclosure designed to suit specific target applications (Navipedia, 2011a; GPS World, 2014).

a) Antenna

GPS antennas capture satellite signals, pre-process and feed it to the front end. GPS signal strengths are weak and the antenna usually amplify the signal to drive it through the cable to the receiver.

Antennas are designed to maximise antenna gain (a measure of tracking ability) towards satellites above a given elevation angle. At lower elevation angles, multiple reflections of signals off objects (or multipath signals) cause errors which can be minimized by carefully designed antennas. The phase centre stability (or variation) is another important aspect in high accuracy implementations, such as Real Time Kinematic (RTK) surveys (See section B2.1.2 d). The phase centre of an antenna is essentially the point corresponding to the location fix reported by the receiver. The signal's electrical phase centre moves and differs from the antenna mechanical phase centre as satellites move through the sky.

Figure B.1 Typical Antenna

Antennas must be selected to match the receiver's capabilities and specifications. For example, antennas should be selected to cover signal frequencies transmitted by the satellite constellation(s) and bandwidth supported by the receiver. Many receivers take full advantage of the full signal power transmitted, using wider bandwidths to mitigate position errors caused by multipath and to support RTK applications.

Multiple frequency antennas are required when used with RTK receivers.

Roof mounted antenna types are required for surveillance applications since at least three satellites need to be in view at all times to maintain timing accuracy. Antennas should also be mounted away from reflecting objects to ensure optimum multipath rejection.

b) Front End

The incoming signals captured by the antenna are typically down-converted (high to low frequency), filtered, amplified and digitized (or sampled) by the Front End.

c) Baseband Signal Processing

Baseband processing is performed for each channel. Each channel processes a signal associated with a given satellite, and the information from each channel is integrated to derive the navigational solution. In order to determine which satellites are in view and can be tracked, processing routines generate replica signals based on estimates of the amount of delay (or code delay) and relative motion (or carrier phase) between the transmitted signal and the receiver. When the local signal and replica sufficiently correlate it initializes the tracking process, measures and refines tracking quality through (code and carrier) tracking loops.

d) Application Processing

After correctly tracking the signals, the receiver uses the information from the tracking loops and performs different tasks to provide meaningful results to the user.

B.2.1.2 Receiver Characteristics and Types

GPS receivers are designed to accommodate various application constraints; to mitigate different environmental constraints, and with processing capabilities which differ in terms of receiver performance, cost, power consumption, expandability, and autonomy (Navipedia, 2011b and 2011c).

As opposed to commercial portable navigation devices commonly used in vehicles and phones, professional-grade receivers (sub-meter accuracy) are required for road surveillance applications. To achieve the desired accuracy, receivers have to compensate for environmental influences. Reflections on surrounding surfaces that distort the received signal, or multipath, can be accommodated by multipath mitigation techniques implemented in receivers. Atmospheric delays caused by the ionosphere and troposphere affect the signal during its propagation. The solution accuracy of receivers is therefore directly linked to its ability to correct for these delays. The type of platform and casing selected, for example, are influenced by factors such as temperature, humidity, moisture resistance, shock and vibration ranges.

Receiver performance is a trade-off between solution availability, solution continuity, data integrity, and accuracy. Receiver types differ in terms of the characteristics outlined above and in approaches to solution computations. Typical differentiating receiver applications and implementations are presented below (Navipedia, 2011b).

a) Multi-constellation

Utilisation of multiple satellite navigation systems is a cost-effective alternative to increase solution availability. Accordingly multi-constellation receivers are becoming more widely available, allowing interoperability and compatibility among satellite constellations forming part of the Global Navigation Satellite System (GNSS).

As an example, the NavCom's SF-3050 receiver provides 66-channel tracking, including multi-constellation support for GPS, GLONASS and Galileo. It also provides patented interference rejection and anti-jamming capabilities.

Figure B.2 NavCom SF-3050 Receiver

b) Multi-frequency

Receiver accuracy is improved by multi-frequency signal processing for removal of frequency-dependent errors on signals. For example, the correction of ionospheric delays, which represent the main contributor to overall measurement error. Typically, however, receiver components are centred on one of the desired frequencies and the same amount of radio frequency (RF) hardware is replicated to process every added frequency. Multi-frequency therefore implies trade-off between cost, size, power consumption, performance etc.

As an example, the Starfire (commercial SBAS global service provider – see Part A) user equipment is dual frequency (L1 and L2 bands). Some receivers are upgradeable allowing users to upgrade from a single frequency receiver to multi-frequency receiver facilitated through a software bundle upload, without the need to purchase a new receiver.

c) Augmentation

GPS accuracy is limited by how well the various error sources are known at the user location. In Part A, augmentation systems were introduced as systems providing permanent infrastructure to determine and model GPS errors and to transmit this information to users. Sarfire and Omnistar are examples of commercial augmentation service providers. To utilise such a service, a compatible receiver is required and a service fee is normally charged. These receivers are similar to other receivers but include special software (included in the application processing component) that allows the receiver to lock onto the code used by the satellites and to compute the corrections to the GPS signals.

Service providers offer different levels of service associated with the use of different technologies and therefore positioning accuracies. Conventional differential GPS (DGPS) typically use *single frequency* code differences (or pseudo range differences) between the user and reference station. The accuracy of single base DGPS solutions, decrease as the distance from the reference station increases. The use of multiple reference stations improves the accuracy of DGPS over the single baseline approach. Virtual base or reference station (VBS or VRS) solutions are based on this principle. The Standard Omnistar VBS service and associated receivers is an example of the implementation of this solution. The OmniSTAR 8315 receiver shown in Figure B.3 is used in such applications. Sub-meter accuracies can be achieved using this type of augmentation and receiver.

Commercial operators also provide premium services which allow the use of *dual frequency receivers* employing both code and carrier phases for improved positioning accuracies. Omistar's Extra Performance (XP) and High Performance (HP) services provide accuracies of 10 and 15 cm, respectively.

Whilst these systems improve accuracy significantly it should be noted that the receiver design is still indispensible in delivering sub-meter accuracies, including aspects such as low noise radio frequency (RF) electronics, antenna design, multipath rejection, and error source mitigation capabilities including differential correction algorithms.

Figure B.3 OmniSTAR 8315 receiver

d) Differential

Differential correction was introduced in Part A. External information, such as measurements from other receivers in the vicinity, is used by the user receiver in a differential way to improve the solution accuracy. The most widely used differential techniques include:

- DGPS: Differential GPS, and
- RTK: Real-Time Kinematics

RTK receiver application software includes carrier-phase algorithms which monitor the actual signal wave itself. These are the algorithms used in real-time kinematic positioning (RTK) solutions - differential systems in which the user (or rover) station requires base-station observation data in real-time. Kinematic GPS using carrier-phase observations is usually applied in surveillance measurements where the relation between physical elements and data collected in a moving vehicle is needed.

Accuracies of 1 to 2 cm (RMS) can be achieved. However, accuracies are still dependent on the receiver type, e.g. single versus dual frequency receivers (Novatel, 2013).

e) Assistance

With Assisted-GPS (or A-GPS) information is accessed by the receiver usually through wireless communication. Information may include almanac and/or ephemeris (positional) data used to improve acquisition speed, i.e. the initial search for satellites can be performed faster. The information received can also be used to improve other performance aspects such as solution availability, continuity, and accuracy.

f) Software Receivers

A significant portion of the receiver comprises processing components, including algorithmic and signal processing tasks. For this reason software receivers over more traditional hardware platforms have gain much attention due to additional flexibility, reconfiguration capabilities, upgradability, and expandability. One disadvantage, however, is its efficiency concerning processing load (or CPU usage) especially in mobile platforms (Navipedia, 2011b).

B.2.2 Inertial Navigation System

Part A highlighted that whilst differential correction technology enhances existing GPS data, it cannot create GPS data. In the context of Part B, Inertial navigation systems are primarily used to extrapolate the positioning solution through the use of external/ inertial sensors when GPS signals are unavailable. These systems therefore enhance the performance of GPS receivers in terms of solution continuity.

In addition, inertial sensors are used to complement other measurements, such as height sensors used for roughness and rutting measurements (See Parts C and D, respectively). An inertial reference is required through measurement of vertical movement and orientation of the surveillance vehicle (measurement base) at all times. Outputs from inertial sensors with post-processing software can also produce road geometric parameters, including cross-fall, vertical grade and horizontal curvature. These parameters are used in road safety assessments, together with skid resistance measurements (See Part E). Typical inertial sensor outputs, namely: heading, roll and pitch are also important for correcting camera and laser measurements used in road surveillance applications.

Figure B.4 shows the components of a typical Inertial Navigation System (INS), namely a GPS receiver, Linear Distance Measurement Instrument (LDMI) and Inertial Measurement Unit (IMU) with processor, internal GPS receiver etc. The figure also shows typical environments where GPS signal loss may occur, including tunnels, cities, tree canopies, and topographical obstructions.

Figure B.4 Components of an Inertial Navigation System (INS)

a) GPS Receivers

GPS receivers were described in the previous section. External GPS receiver output is fed to the rest of the system to be analysed and combined with inertial data. Inclusion of an assisted-GPS internal receiver gives the system access to raw GPS satellite data providing accurate time alignment data to integrate all the data sources.

Because the inertial system calculates current position by using a previously determined position (known as dead reckoning) they are subject to cumulative errors or accuracy drift over time. GPS complement inertial sensors in estimating and correcting the errors in the inertial navigation solution.

In some systems, two external GPS receivers (and antennas) are used. Heading and pitch can be determined accurately by measuring the 3D off-set between two or more GPS antennas fixed to the vehicle.

b) Inertial Measurement Unit (IMU)

The IMU is the main component of an inertial navigation system and contains three accelerometers and three gyroscopes that measure vehicle acceleration and orientation. These measurements are used to calculate vehicle body movement, speed and attitude. Attitude solutions typically consist of heading (yaw or azimuth), roll and pitch as defined in Figure B.5.

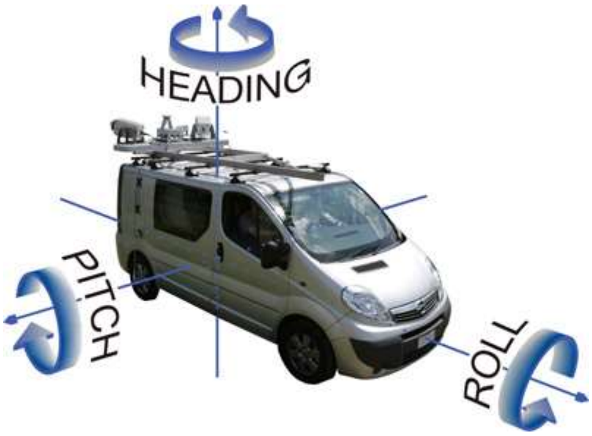

Figure B.5 Heading, Roll, and Pitch (Teccon, 2014)

Normally, an IMU with navigation processor and support electronics is called an Inertial Navigation System (INS) (Mandapat, 2001). Figure B.6 shows IMU from Applanix.

As indicated above, the process of dead reckoning is used to calculate position which is subject to accuracy drift over time. The latter is due to inherent sensor error characteristics which accumulate over time. Therefore, position data from these systems must be corrected periodically (using GPS) and are used only as a short-term supplement during GPS outage.

Figure B.6 Inertial Measurement Unit (Applanix, 2010)

c) Distance Measuring Instrument (DMI)

The DMI is usually a wheel-mounted rotary shaft encoder that measures linear distance travelled. Typically, the DMI is a high precision distance encoder (>1800 pulses per wheel revolution) connected to the rear wheel of the measuring vehicle. Each slight turn of the wheel generates an electrical pulse that relates to the short distance travelled. These pulses can come from a wheel-mounted encoder or from the vehicle's internal electronic. The distance pulses are fed into the rest of the system and serve as a distance and speed reference.

The DMI helps constrain GPS-outage drift. It also serves as a speed sensor used to constrain potential velocity errors in the IMU during GPS outages or to detect that the vehicle is at rest, thereby allowing it to perform self-calibrations. Without this measure, changing accelerometer biases cause exponential position error growth. In addition, the more accurate the heading determination at the start of an outage, the longer a system can stay on target.

Figure B.7 Wheel-mounted DMI (IMS, 2014)

d) Navigation Processor

The processor includes the interfacing hardware-and-software, setup-and-operation software. As an example, Figure B.8 shows the Applanix (POS LV model) central processing computer that houses the internal GPS receivers, mass storage system, data processing, and power distribution units for all system components.

This system is used to precisely time-tag external sensor data and run real-time and post-processing integrated navigation software. The software performs the integration of the inertial data from IMU with data from the GPS receiver. Data from the IMU is passed on to the navigation processor, which calculates a dead reckoning navigation solution with the use of navigation equations typically run through a Kalman filter.

This mathematical filter is used to estimate the slowly growing position errors in the IMU. The navigation processor then outputs the position and orientation of the IMU, typically in local vehicle coordinates (latitude, longitude, altitude, heading, roll and pitch) (Mandapat, 2001; Mostafa et al, 2001).

Figure B.8 Typical central processing computer (Applanix, 2010)

B.2.3 Equipment Specifications

Specifying positioning equipment and therefore accuracy can have a significant impact on system cost and performance. For all surveillance measurements, positioning systems equipped with differentially corrected GPS (DGPS) with inertial sensors/ inertial measurement unit (IMU) and distance measuring instrument (DMI) are required as a minimum to ensure accurate and continuous positioning data. In addition, such a system provides positioning data to accommodate both linear and spatial referencing demands.

Whilst the same positioning systems can be used in most pavement surveillance surveys, detailed consideration should be given to 3D mapping applications where scanning lasers are used (See Part G). More specific requirements related to measurement of features such as road geometry (see Part E) are included in the relevant parts of THM 13.

Table B.1 summarises the specifications for GPS equipment. Table B.2 includes generic specifications for inertial sensors. The distance measuring instrument (DMI) should have an accuracy of 0.2 per cent and a resolution of at least 1800 pulses per wheel revolution.

Table B.1 Equipment Specification for GPS

Parameter	Minimum GPS Requirements for Pavement Surveillance Applications
Receiver Type/ Tracking	12 Channel L1/ C/A
Augmentation	DGPS
Accuracy	98% of readings < 1 m
Sampling Interval	10 Hz
Initialization Time	< 20 sec
System Output	NMEA-0183 or equivalent
Operating Temperature Range	0℃ – 50℃

Table B.2 Equipment Specification for Inertial Sensors

Parameter	Minimum Requirements for Inertial Sensors used in Pavement Surveillance Applications
Sensor Range	± 2G
Resolution	10 μG
Bandwidth	DC to 300 Hz
Roll and Pitch	0.03º
Heading	0.2º
Sample Interval	1 – 200 Hz
System Output	NMEA-0183 or equivalent
Operating Temperature Range	0°C – 50°C

B.3 Validation and Control Testing

A validation program should be conducted prior to acceptance of the equipment and/or before data collection starts. Part A on Planning a Survey, introduced aspects of calibration, validation, and measurement control that require consideration during the survey planning process.

It should be understood that calibration of the equipment only confirms that a measurable or specified tolerance can be achieved for individual system components. Calibration does not confirm the appropriateness of the parameter measured from a moving vehicle on the network under consideration. Moreover, the objective of equipment validation is not to adjust the system outputs to match a predetermined benchmark.

Equipment is either accurate and calibrated (i.e. the equipment is "valid") or it is not. If it is not, the equipment should be fixed by the manufacturer. The validation process encompasses equipment calibration (of system components), including the effects of operational variables. Validation therefore confirms that the equipment, operator, and adopted measurement protocol, working together as a system, can provide meaningful data of sufficient accuracy while operating under normal surveying conditions.

Important!

Calibration of the equipment only confirms that a measurable or specified tolerance can be achieved for individual system components. Calibration does not confirm the appropriateness of the parameter measured from a moving vehicle on the network under consideration.

Validation confirms that the equipment, operator, and adopted measurement protocol can provide meaningful data of sufficient accuracy while operating under normal surveying conditions.

In the following subsections, guidelines are provided for the validation and control testing of positioning equipment. Since positioning forms an integral part of any of the network level surveillance measurement types, this section should be read in conjunction with other relevant parts of TMH 13.

B.3.1 General Approach

General aspects of calibration, validation and control testing were highlighted in Part A. An introduction to the selection of reference sections and devices, and reference surveys were also presented in Part A. Guidelines on selection of validation sections and reference devices are provided in Section B.3.2. The two primary aspects validated are the accuracy (or bias, i.e. the error between validated and reference measurements) and repeatability (i.e. the variations between repeated measurements) of the parameters under consideration. More detailed guidelines on validation of positioning equipment are provided in Section B.3.4.

B.3.2 Validation Section Requirements

At least 10 reference points should be selected and the road centreline coordinates established by a registered surveyor. These locations may also coincide with datum locations and should preferably be located in a loop section. Table B.8 provides requirements for the selection of validation sites.

B.3.3 Validation Process

B.3.3.1 GPS Validation

GPS data should be validated by comparing co-ordinates at several benchmark locations, set out and maintained by a registered surveyor or surveying authority. It is recommended that this check be carried out at five to ten benchmark locations.

GPS benchmark locations should be roughly one km apart, and the dynamic accuracy of the GPS data system should be checked by completing several survey loops through the benchmark locations. These checks should preferably also be performed over more than one day, and at different times of the day.

The benchmark locations should include locations where normal GPS reception would be difficult i.e. tall trees or buildings next to the road. These locations would validate the ability of the Inertial Navigation System to compensate for a loss in the GPS signal.

The GPS should be within 5 m of the vertical and horizontal benchmark values, and for repeat dynamic measurements. This accuracy should be achievable 90 per cent of the time.

Table B.3 Considerations for Selection of Validation Sites

Example Parameter	Minimum number of Sections/Sites	Minimum section length	Parameter Ranges
GPS data	10	N/A	N/A
DMI	1	1 km	N/A
Grade and Cross-fall	10	N/A	Vertical Grade: -10 to +10%
			Cross-fall: -3 to +10%

B.3.3.2 Inertial System Validation

The validation of dynamic measuring equipment should include checks for vertical grade, horizontal curvature and cross-fall.

Once the performance of the Inertial sensor(s) used for gradient and cross-fall is accepted based on valid calibration certificates, it must be demonstrated that the zero condition is correctly defined and that there is no bias in the recorded measurements.

Data from a minimum of five runs at each of three speeds should be collected at a minimum of 10 validation sites (Table B.3) and the average grade and cross-fall for each of the sites should be reported. It is recommended that the data be reduced to 30 m moving average values. The measured gradient and cross-fall for the average of five runs at each site should be within 5 per cent of the reference grade and cross-fall. Repeatability of the measurements can be accepted if the coefficient of variation of the five repeat runs at each site is less than 5 per cent.

B.3.3.3 DMI Validation

Validation of the distance measuring system should be checked on calibration sections that are located on a tangent section of the road and that are at least 1 km long. The length of the section should be measured beforehand using a high precision instrument.

The validation consists of driving the vehicle over the section at a specific speed. At the start of the section the distance measurement device is initiated and at the end of the section it is stopped again. The measured distance is then checked against the benchmark values. A run-in distance of at least 150 m should be used to bring the vehicle up to speed before the start of the section.

The distance validation should be performed at different speeds. It is recommended that at least three different speeds be used, which should include the specified surveying speed.

For each measurement speed, three runs should be made. The reading of the distance measurement device should be recorded at each run. The output at each run should be roughly within 1 per cent of the benchmark value.

B.3.4 Control Testing

Control testing should be performed from time to time during the survey to ensure that the equipment output is still valid and that the accuracy and precision of the device is still within specification.

Control testing should be performed on validation sections and the same criteria as used for validation apply. However, control testing need not be performed on all validation sections, and normally control testing on two or three sites would suffice.

Control testing should be performed on a regular basis as part of the survey process. If control testing shows that the measured values are no longer within the specified limits, then any data collected since the last successful control test should be discarded and re-measured. *Under no circumstances should control test data be used to adjust or calibrate the equipment outputs.*

Control testing should be carried out as frequently as possible within the constraints of the network and survey budget to prevent unnecessary time and cost of re-measure.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of re-measuring all data collected since the last control test.

As a rough guideline, control testing can be requested on a monthly basis or at five stages (equally spaced in terms of length surveyed) during the survey process.

B.4 Operational and Quality Control Procedures

This section of the guidelines deals with the daily checks and procedures that need to be carried out during the course of surveillance surveys that positioning equipment, namely GPS, inertial sensors and DMI. It should be noted that, while the guidelines cover the basic operational aspects and their influence on measurement, the guidelines are intended mainly for network managers, and not for contractors.

The network manager is not responsible for performing daily checks or following of proper operational procedures. However, a proper understanding of the elements that influence measurement and of the procedures that a contractor should perform each day, will allow the network manager to exercise better control over the measurement process. The guidelines in this section thus focus on how operational procedures can be controlled.

The operators of measurement devices should – in addition to the elements covered in this section – have an in-depth understanding of the influence of all operational elements on the measurement process. Relevant standards and operational manuals should be consulted for detailed operational procedures.

As noted before, measurement and capturing of positioning are usually integrated sub-systems of other systems used in surveillance surveys. As such, this section should be read in conjunction with Parts B through G.

B.4.1 Planning and Operational Processes

Before survey procedures can start each day, specific system checks should be performed in an official and orderly way at the hand of an official "Check List". The operator will sign the Check List at the end of the procedure and thereby generate a traceable quality assurance record as part of the Quality Control Plan (See Part A).

The contractor's check list will depend on the system type and the recommendations from the manufacturer. However, as a minimum the following daily checks should be performed:

- Satellite Availability: Most vendors provide software for checking availability. The satellite almanac should be checked for good geometry along the project road. If the route is long and substantial time will elapse during the survey, multiple sites should be checked.
- Obstructions: Check that all equipment especially antennas are mounted securely and clear from any obvious obstructions that can cause multipath effects.
- Batteries/ Power Supply/ Cabling: Where applicable, ensure that batteries are fully charged for both computers and the measuring device. Check that power supplies and all cabling are on board and that all connections are good.
- Warm-up Time: The measuring and data acquisition systems should be subjected to sufficient warm-up time according to the manufacturer's recommendations.
- Check all components: The antennas, connecting cables, GPS external receiver, IMU/ INS and DMI should be checked to ensure cleanliness and correct configuration.
- Output and Data Collection: Check that the system is in good working order.
- Atmospheric activity: Check as part of pre-planning and daily planning. Report adverse conditions since it may impact on system accuracy.

The network manager cannot ensure that all the checks are rigorously performed each day. However, as a minimum form of control over operating procedures, spot checks should be performed from time to time. These checks should be performed randomly on a weekly or two-weekly basis. During each check, the operator should be asked to stop the vehicle and a control check should be performed by the network manager. Table B.4 provides guidelines for items to monitor during random control checks. The procedure should be documented and should form part of the Quality Control Plan.

Table B.4 Checklist for Operation Control Checks on Positioning Systems

Control or Decision Aspect
1. Confirm geometry and availability of satellites.
2. Request and inspect the daily checklist. Ensure it meets the Quality Control Plan format.
3. Inspect the vehicle and ensure that all components are mounted securely, check for cleanliness, and that no obvious obstructions are present in the vicinity of the antennas.
4. Confirm that the GPS receiver is functioning and that the DGPS signal is received

B.4.2 Data Capture and Documentation

The contract specifications should provide details on the format required for the captured data. In general reference should be made to TMH 20 for requirements on formats and data types. As a minimum, the specifications should state the format of the required files (e.g. Comma Delimited ASCII file, Spreadsheet format) and the required columns. For positioning data, the required columns would typically include at least the following:

- Operator name;
- System ID;
- Date and Time;
- Section details (separate columns for Section name, lane, direction, region, etc.);
- Measurement speed
- GPS data:
  - latitude, longitude and height;
  - Number of satellites, PDOP, DGPS
- Grade, curvature and cross-fall

The contractor should also provide a definition sheet to define any codes or abbreviations used in the file and column naming. Details of the format in which the output will be provided should ideally be submitted with the contractor's quality control plan.

The specifications (see Part A) should stipulate the deadline for delivery of data files on completion of the survey. It is important to minimize delays between the time of survey and data analysis, in order for errors to be identified as soon as possible. Ideally, some data files should be given to the network manager while the survey is in progress, so that the data can be checked and any inconsistencies identified at an early stage.

The contractor should flag any data files or parts thereof for which measurements are regarded as unusual or in which excessive variations may occur because of environmental effects. Operators should therefore be trained not only in the vehicle operation aspects, but also in the interpretation of data. Also, operators should be aware of the impact of certain pavement and environmental parameters on the precision of measurement, so that files recorded under non-optimal conditions can be clearly flagged for detailed analysis.

B.4.3 Data Checking and Troubleshooting

When the data has been received, the network manager should perform some control checks on a few data files. The objective of these checks should be to ensure the measurements correspond with basic engineering judgement, and that the data are consistent with that of earlier surveys.

A typical control check may include importing the GPS data from a few files in GIS for verification with previous GPS data or the GIS network definition. The following should be verified:

- The DGPS parameter in the data files should be set to ensure that DGPS was used.
- Starts and Ends of the section must correspond to previous data or the Road Definition (See Figure B.9).

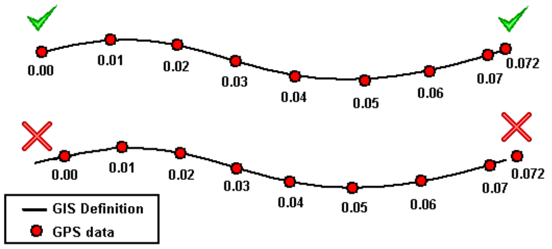

Figure B.9 Survey Start and End not correct

- Completeness. There must be no "gaps" in the GPS data stream (See Figure B.10).

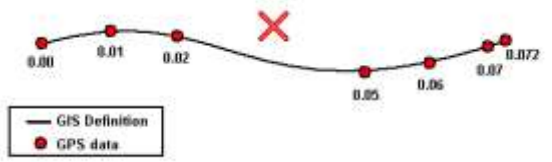

Figure B.10 GPS Data missing

- Linear distance. Reference points must have the same linear distance than previous data or the Road Definition (See Figure B.11).

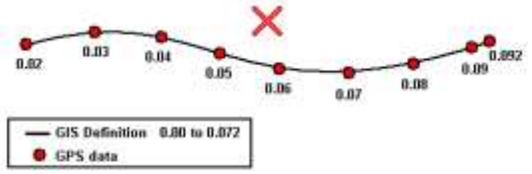

Figure B.11 Linear distance reference not correct

- "Jumps" or "Spikes" in the GPS data. The GPS data must follow a "smooth line" with no sudden "jumps" or "spikes" (See Figure B.12 and Figure B.13).

Figure B.12 "Jump" in GPS data

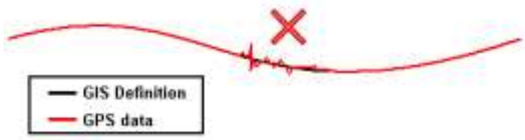

Figure B.13 "Spikes" in GPS data

- The filling of data by the Inertial system must be seamless and not noticeable (See Figure B.14).

Figure B.14 Inertial System not functioning

- The survey direction must correspond to the Road Definition (See Figure B.15).

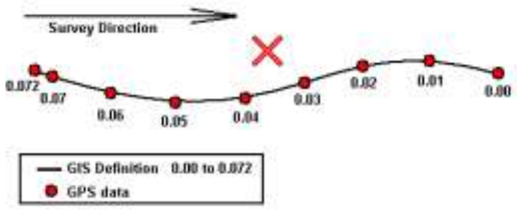

Figure B.15 Survey direction not correct

- GPS data points should be equally spaced at the desired reporting interval (i.e. 10 metres) (See Figure B.16).

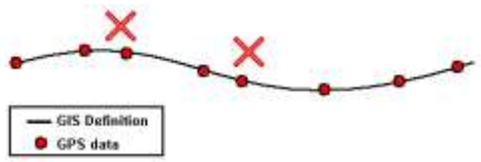

Figure B. 16 GPS data not equally spaced

B.5 References

Appanix, 2010. **Land Brochure**. <http://www.applanix.com/products/land.html>

GPS World. 2014. **GPS World 2014 Receiver Survey**. <www.gpsworld.com>

IMS. 2014. **IMS Online/ Distance Measuring**. <http://www.ims-rst.com/data-collection.shtml>

Mandapat, R.E. 2001. **Development and Evaluation of Positioning Systems for Autonomous Vehicle Navigation**. Master's Thesis. University of Florida, USA.

Mostafa, M., Hutton, J., Reid, B., and Hill, R. 2001. **GPS/IMU Products - The Applanix Approach**. Photgrammetric Week 01, D. Fritsch & R. Spiller (Eds). Wichmann Verlag, Heidelberg.

Navipedia. 2011a. **Receiver Types**. <http://www.navipedia.net/index.php/Receiver_Types>

Navipedia. 2011b. **Receiver Characteristics**. <http://www.navipedia.net/index.php/Receiver_Characteristics>

Novatel. 2013. **Positioning Modes of Operation**. NovAtel Application Note APN-051. <www.novatel.com/support/search/items/Application%20Note>

Novacom. 2010. **Receivers**. <http://www.navcomtech.com/navcom_en_US/products/equipment/receivers/receivers.page?>

Omnistar. 2010. **OmniStar VBS**. <http://www.omnistar.com/SubscriptionServices/OmniSTARVBS.aspx>

Teccon. 2014. **Teccon Mobile Mapping/ Technologie**. <www.mobile-mapping.be>

B.6 Glossary

Antenna Phase Centre (APC): The point in an antenna where the GPS signal from the satellites is received. The height above ground of the APC must be measured accurately to ensure accurate GPS readings. The APC height can be calculated by adding the height to an easily measured point, such as the base of the antenna mount, to the known distance between this point and the APC.

Autonomous positioning: (GPS/GLONASS/Galileo) a mode of operation in which a GNSS receiver computes position fixes in real time from satellite data alone, without reference to data supplied by a reference station or orbital clock corrections. Autonomous positioning is typically the least precise positioning procedure a GNSS receiver can perform.

Base station: See reference station.

Channel: a channel of a GPS receiver consists of the circuitry necessary to receive the signal for a single GPS satellite.

Data files: Files that contain Proprietary, GPS, NMEA, RTCM, or any type of data logged from a GPS receiver.

DGPS: see Differential GPS.

Differential GPS (DGPS): A positioning procedure that uses two receivers, a rover at an unknown location and a reference station at a known, fixed location. The reference station computes corrections based on the actual and observed ranges to the satellites being tracked. The coordinates of the unknown location can be computed with sub-meter level precision by applying these corrections to the satellite data received by the rover.

Dilution of Precision (DOP): A class of measures of the magnitude of error in GPS position fixes due to the orientation of the GPS satellites with respect to the GPS receiver. There are several DOPs to measure different components of the error. Note: this is a unitless value (see also PDOP).

Distance Measuring Instrument (DMI): A wheel-mounted rotary shaft encoder that measures linear distance travelled.

DMI: See Distance Measuring Instrument

DOP: See Dilution of Precision.

Dual-frequency: A type of GPS receiver that uses both L1 and L2 signals from GPS satellites. A dual-frequency receiver can compute more precise position fixes over longer distances and under more adverse conditions because it compensates for ionospheric delays. The SF-3050 is a multi-frequency GNSS receiver.

Dynamic mode: When a GPS receiver operates in dynamic mode, it assumes that it is in motion and certain algorithms for GPS position fixing are enabled in order to calculate a tighter position fix.

EGNOS (European Geostationary Navigation Overlay Service): A European satellite system used to augment the two military satellite navigation systems now operating, the US GPS and Russian GLONASS systems.

Ellipsoid: A mathematical figure approximating the earth's surface, generated by rotating an ellipse on its minor axis. GPS positions are computed relative to the WGS-84 ellipsoid. An ellipsoid has a smooth surface, which does not match the earth's geoidal surface closely, so GPS altitude measurements can contain a large vertical error component. Conventionally surveyed positions usually reference a geoid, which has an undulating surface and approximates the earth's surface more closely to minimize altitude errors.

GAGAN (GPS Aided Geo Augmented Navigation): An Indian satellite system that provides a set of corrections for the GPS satellites, which are valid for the Indian region. They incorporate satellite orbit and clock corrections.

Galileo – a GNSS system currently being built by the European Union (EU) and the European Space Agency (ESA). Galileo uses the same concepts for positioning as GPS.

GIS (Geographical Information Systems): A computer system capable of assembling, storing, manipulating, updating, analyzing and displaying geographically referenced information, i.e. data identified according to their locations. GIS technology can be used for scientific investigations, resource management, and development planning. GIS software is used to display, edit, query and analyze all the graphical objects and their associated information.

Global Positioning System (GPS): Geometrically, there can only be one point in space, which is the correct distance from each of four known points. GPS measures the distance from a point to at least four satellites from a constellation of 24 NAVSTAR satellites orbiting the earth at a very high altitude. These distances are used to calculate the point's position.

GLONASS (Global Orbiting Navigation Satellite System): The Russian Federation's GNSS system, managed by the Russian Space Forces (Russian: VKS). GLONASS uses the same concepts for positioning as GPS.

GNSS: Global Navigation Satellite System.

GPS: See Global Positioning System.

GPS time: A measure of time. GPS time is based on UTC, but does not add periodic 'leap seconds' to correct for changes in the earth's period of rotation. As of September 2002 GPS time is 13 seconds ahead of UTC.

IMU: See Inertial Measurement Unit

Inertial Measurement Unit (IMU): A device which utilises a combination of gyroscopes and accelerometers to provide velocity and orientation information.

L-Band: The group of radio frequencies extending from approximately 400MHz to approximately 1600MHz. The GPS carrier frequencies L1 (1575.4MHz) and L2 (1227.6 MHz) are in the L-Band range.

L1 carrier frequency: The primary L-Band carrier used by GPS satellites to transmit satellite data. The frequency is 1575.42MHz. It is modulated by C/A code, P-code, or Y-code, and a 50 bit/second navigation message. The bandwidth of this signal is 1.023MHz.

L2 carrier frequency: The secondary L-Band carrier used by GPS satellites to transmit satellite data. The frequency is 1227.6MHz. It is modulated by P-code, or Y-code, and a 50 bit/second navigation message. The bandwidth of this signal is 10.23MHz.

Multi-Frequency-GNSS Receiver: A type of receiver that is capable of using multiple signals, for example, GPS (L1, L2, L2C, L5), GLONASS (G1, G2), Galileo (E1, E5a), StarFire L-band, SBAS (WAAS, EGNOS, MSAS, GAGAN), and QZSS signals. The use of multiple signals provides compensation for ionospheric effects. In addition, reception of multiple signals provides redundancy that results in a more stable navigation solution during adverse conditions.

Multipath error: A positioning error resulting from interference between radio waves that has travelled between the transmitter and the receiver by two paths of different electrical lengths.

PDOP: See Position Dilution of Precision.

Phase centre: The point in an antenna where the GPS signal from the satellites is received. The height above ground of the phase centre must be measured accurately to ensure accurate GPS readings. The phase centre height can be calculated by adding the height to an easily measured point, such as the base of the antenna mount, to the known distance between this point and the phase centre.

Position: The latitude, longitude, and altitude of a point. An estimate of error is often associated with a position.

Position Dilution of Precision (PDOP): Measure of the magnitude of Dilution of Position (DOP) errors in the x, y, and z coordinates.

Post-processing: A method of differential data correction, which compares data logged from a known reference point to data logged by a roving receiver over the same period of time. Variations in the position reported by the reference station can be used to correct the positions logged by the roving receiver. Post-processing is performed after you have collected the data and returned to the office, rather than in real time as you log the data, so it can use complex, calculations to achieve greater accuracy.

PRN (Uppercase): Typically indicates a GPS satellite number sequence from 1 – 32.

prn (Lower Case): See Pseudorandom Noise.

Pseudo-random noise (prn): A sequence of data that appears to be randomly distributed but can be exactly reproduced. Each GPS satellite transmits a unique PRN in its signals. GPS receivers use PRNs to identify and lock onto satellites and to compute their pseudo-ranges.

Pseudo-range: The apparent distance from the reference station's antenna to a satellite, calculated by multiplying the time the signal takes to reach the antenna by the speed of light (radio waves travel at the speed of light). The actual distance, or range, is not exactly the same because various factors cause errors in the measurement.

PVT: GNSS information depicting Position, Velocity, Time in the NCT proprietary message format.

Radio Technical Commission for Maritime Services: See RTCM.

Range: The distance between a satellite and a GPS receiver's antenna. The range is approximately equal to the pseudo-range. However, errors can be introduced by atmospheric conditions which slow down the radio waves, clock errors, irregularities in the satellite's orbit, and other factors. A GPS receiver's location can be determined if you know the ranges from the receiver to at least four GPS satellites. Geometrically, there can only be one point in space, which is the correct distance from each of four known points.

Real-Time Kinematic (RTK): A GNSS system that yields very accurate 3D position fixes immediately in real-time. The base station transmits its GNSS position to roving receivers as the receiver generates them, and the roving receivers use the base station readings to differentially correct their own positions. Accuracies of a few centimetres in all three dimensions are possible. RTK requires multi-frequency GNSS receivers and high speed radio modems.

Reference station: A reference station collects GNSS data for a fixed, known location. Some of the errors in the GNSS positions for this location can be applied to positions recorded at the same time by roving receivers which are relatively close to the reference station. A reference station is used to improve the quality and accuracy of GNSS data collected by roving receivers.

Repeatability: The expected standard deviation of measures obtained in repeated tests, when using the same instrument and measurement team on a single, randomly selected test section.

Reproducibility: A measure of the ability to reproduce a measured result by another measurement device or measurement team working independently (definition after Wikipedia, 2007).

Resolution: The resolution of a device specifies the smallest measurement increment that the device is capable of.

Rover: Any mobile GNSS receiver and field computer collecting data in the field. A roving receiver's position can be differentially corrected relative to a stationary reference GNSS receiver or by using GNSS orbit and clock corrections from a SBAS such as StarFire.

RTCM (Radio Technical Commission for Maritime Services): A standard format for Differential GNSS corrections used to transmit corrections from a base station to rovers. RTCM allows both real-time kinematic (RTK) data collection and post-processed differential data collection. RTCM SC-104 (RTCM Special Committee 104) is the most commonly used version of RTCM message.

RTK: See Real-time kinematic.

SBAS (Satellite Based Augmentation System): This is a more general term, which encompasses WAAS, StarFire and EGNOS type corrections.

Signal-to-Noise Ratio (SNR): A measure of a satellite's signal strength.

Single-frequency: A type of receiver that only uses the L1 GPS signal. There is no compensation for ionospheric effects.

Validation: The process of determining if a measurement device, when operated according to a established procedure and within established operating ranges, can operate effectively and reproducibly (definition after Wikipedia, 2007).

Verification: The process of proving or disproving the correctness of a system or measurement device with respect to a certain formal specification.

WAAS (Wide Area Augmentation System): A US satellite system that provides a set of corrections for the GPS satellites, which are valid for the North American region. They incorporate satellite orbit and clock corrections.

WADGPS (Wide Area Differential GPS): A set of corrections for the GPS satellites, which are valid for a wide geographic area.

WGS-84 (World Geodetic System 1984): The current standard datum for global positioning and surveying. The WGS-84 is based on the GRS-80 ellipsoid.