CAMP LLC

Vehicle to Infrastructure (V2I) Consortium

Vehicle-to-Infrastructure Safety Applications Project

Task 15 Interim Report SPaT Challenge Intersection Verification

Submitted to the United States Department of Transportation Federal Highway Administration (FHWA)

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Acknowledgement and Disclaimer

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Executive Summary

This report describes the work completed during Task 15 of the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project. Task 15, titled “Signal Phase and Timing (SPaT) Challenge Intersection Verification,” was conducted from May through December 2017.

The goals of Task 15 were to:

- Validate the process outlined in the SPaT Challenge Verification Document [1] to verify that intersection Roadside Units (RSUs) transmitting Signal Phase and Timing (SPaT) and intersection map messages can support the Red Light Violation Warning (RLVW) Application developed earlier in the V2I-SA Project
- Provide deployment guidance via the SPaT Challenge Verification Document to infrastructure owners and operators (IOOs) participating in the American Association of State Highway and Transportation Officials (AASHTO) SPaT Challenge [2] regarding:
    - Which equipped intersections could benefit from providing positioning corrections to support the RLVW application
    - What methods could be used to provide positioning correction information to equipped vehicles when positioning corrections are needed at an intersection

The V2I-SA Project is being conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The participating companies in the V2I Consortium are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Nissan, Subaru, Volvo Technology of America, and VW/Audi. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H00002, Work Order 0003.

<u>Validation of Verification Process</u>

The validation work followed the verification process outlined in the SPaT Challenge Verification Document, which was developed earlier in the V2I-SA Project and was provided to the Infrastructure Owners and Operators / Original Equipment Manufacturers (IOO/OEM) Forum in March 2017. Two medium-level-complexity intersections in Southeast Michigan were used for the validation work. The roadway operator and their RSU contractor conducted the system-level verification in the verification process. The V2I-SA Technical Team conducted the message-level and application-level verifications using a test vehicle and the RLVW Application developed earlier in the project. All four approaches to each intersection were driven with the test vehicle and messages received by the vehicle were recorded for analysis.

The verification process assumes that the geographic map of the intersection ingress lanes, location of the stop bar, and egress lanes are within the required level of accuracy and are encoded in the MAP message as per the SAE J2735 Standard.

No anomalies were found in the verification process during the work in Task 15. However, SPaT message issues related to transmission of the Time to Next Phase and an incorrect

flashing red phase status were identified and referred to the RSU vendor for resolution. These discoveries underscored that step 5 in the verification process must be executed carefully to ensure that the SPaT data transmitted by the RSU is verified against the actual raw data from the signal controller and that the RSU has interpreted the information from the controller correctly.

Literature Review of Satellite-based Positioning Error and Correction Techniques

To understand the various sources of errors in satellite-based positioning systems and the effectiveness of correction techniques for different intersection configurations, a literature review was conducted and discussions were held with leading providers of Global Navigation Satellite Systems (GNSS) receivers. From the material obtained during these activities, a summary of GNSS error sources, a discussion of the Radio Technical Commission for Maritime Services (RTCM) message standard, and approaches for positioning corrections for different intersection configurations was prepared.

The key outcome of this study is to categorize the location of intersections by type of satellite visibility such as open sky / clear visibility versus partial or obstructed visibility (e.g., urban canyons) and the level of complexity of SPaT and MAP combinations (e.g., multiple lanes and multiple signal phases) where lane-level positioning is required. The intersections with high satellite visibility under open sky location with complex SPaT and MAP combinations that require lane-level positioning would benefit the most from positioning correction information.

The information developed during Task 15 was incorporated into the updated SPaT Challenge Verification Document provided to the IOO/OEM Forum on November 11, 2017 [3]. It should be noted that the sources of corrections are not discussed in the updated document. It is expected that other IOO/OEM Forum members who are researching this topic would provide their findings for incorporation into a future edition of the SPaT Challenge Verification Document.

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ARP	Antenna Reference Point
ASN.1	Abstract Syntax Notation One
BeiDou	A Chinese Satellite Navigation System
CAMP	Crash Avoidance Metrics Partners LLC
CSW	Curve Speed Warning
CV	Connected Vehicle
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
DOTs	Departments of Transportation
DSRC	Dedicated Short-Range Communications
EE	End-Entity (Device)
eGUI	Engineering Graphical User Interface
FHWA	Federal Highway Administration
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russian)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
I2V	Infrastructure-to-Vehicle
ID	Identification Number
IOO	Infrastructure Owners and Operators
LOS	Line-of-Sight
MAP	SAE J2735 Map Message
MDOT	Michigan Department of Transportation
MEO	Medium Earth Orbit
MHz	Megahertz or One Million Cycles Per Second
MIB	Management Information Base
NAVSTAR	Navigation Satellite Timing and Ranging (a Network of Global Positioning System Satellites)
NLOS	Non-Line-of-Sight
NTCIP	National Transportation Communications for ITS Protocol
OBU	Onboard Unit

OEM	Original Equipment Manufacturer
PCAP	Packet Capture (DSRC Packet Capture)
PPP	Precise Point Positioning
PRN	Pseudorandom Noise
PSID	Provider Service Identifier
RF	Radio Frequency
RLVW	Red Light Violation Warning
RSU	Roadside Unit
RSZW/LC	Reduced Speed Zone Warning / Lane Closure
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
SAE	SAE International
SBAS	Satellite-based Augmentation System
SC-104	Special Committee 104
SCMS	Security Credential Management System
SPaT	Signal Phase and Timing
TMT	Technical Management Team
UDP	User Datagram Protocol
UERE	User Equivalent Range Error
V2I	Vehicle-to-Infrastructure
V2I-SA	Vehicle-to-Infrastructure Safety Applications (Project)
WAAS	Wide Area Augmentation System

1 Introduction

This report presents the work conducted during Task 15 of the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project. Task 15, titled "Signal Phase and Timing (SPaT) Challenge Intersection Verification," was conducted from May through December 2017. The goals of this task were to:

- Validate the process outlined in the SPaT Challenge Verification Document [1] to verify that intersection Roadside Units (RSUs) transmitting Signal Phase and Timing (SPaT) and intersection map messages can support the Red Light Violation Warning (RLVW) Application developed earlier in the V2I-SA Project
- Enhance the SPaT Challenge Verification Document by providing RLVW deployment guidance to the infrastructure owners and operators (IOOs) participating in the American Association of State Highway and Transportation Officials (AASHTO) SPaT Challenge [2] regarding:
    - Which equipped intersections could benefit from providing positioning corrections to support the RLVW Application
    - What methods could be used to provide positioning correction information to equipped vehicles when positioning corrections are needed at an intersection

The primary outputs of Task 15 were a revised SPaT Challenge Verification Document [3], which incorporated information obtained during the execution of Task 15, and this report.

The V2I-SA Project is being conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. The companies participating in the V2I Consortium are Ford, General Motors, Hyundai-Kia, Honda, Mazda, Nissan, Subaru, Volvo Technology of America, and VW/Audi. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H00002, Work Order 0003.

As part of the work previously completed in the V2I-SA Project, a RLVW Application, a Curve Speed Warning (CSW) Application, and a Reduced Speed Zone Warning with Lane Closure (RSZW/LC) Application were designed, developed, tested under controlled conditions with professional drivers and refined to improve performance. In addition, demonstrations of the applications were conducted for selected stakeholders and industry representatives to foster information exchanges between the project and organizations that could potentially deploy the technology in the future. Other outreach efforts included engagement with the Infrastructure Owners and Operators / Original Equipment Manufacturers (IOO/OEM) Forum regarding the developed applications. These efforts are described in a previously submitted comprehensive report covering Tasks 1-12 of the V2I-SA Project [4]. Tasks 13 and 14 are currently ongoing in the V2I-SA Project.

2 Background on SPaT Challenge Verification Document

The SPaT Challenge Verification Document [1] was prepared by the V2I-SA Project Technical Management Team (TMT) and was initially provided to the IOO/OEM Forum in March 2017. The purpose of the document is to:

- Provide a high-level overview of the architecture used in the RLVW Application developed by the V2I Consortium
- Discuss requirements for the over-the-air messages used by the RLVW Application to obtain:
  - Signal Phase and Timing (SPaT) information
  - Map of an equipped intersection
  - Global Positioning System (GPS) corrections
- Present a framework for verifying the performance of an equipped intersection to support the RLVW Application

The information presented in the SPaT Challenge Verification Document is derived from the work conducted by the V2I-SA Project in developing and testing the RLVW Application. The document is intended to aid state and local departments of transportation (DOTs) in verifying Infrastructure-to-Vehicle (I2V) system deployments made as part of the AASHTO SPaT Challenge. It is anticipated that the SPaT Challenge Verification Document will remain a "work in progress" for the immediate future. It is further anticipated that information obtained by the IOOs in deploying infrastructure during the SPaT Challenge will be incorporated into the document as "lessons learned" documented for the benefit of others also tasked with systems deployments.

The verifications needed to confirm the performance of an equipped intersection are twofold:

1. Confirmation that the intersection is broadcasting a properly formatted message, as described in the latest version of the SAE J2735 standard[1]
2. Confirmation that the data contained in the broadcast messages are accurate

The RLVW Application warns the driver of an equipped vehicle approaching an equipped signalized intersection when there is a potential of running the red light. The warning is based on information received from infrastructure- and vehicle-based sensors. The application combines the SPaT and intersection map information from a Roadside Unit (RSU) with the vehicle kinematic data for determining if a warning should be issued. The

[1] At time of preparation of this document: "Dedicated Short Range Communications (DSRC) Message Set Dictionary." SAE J2735_201603, 30-Mar- 2016.

RLVW Application concept and information flow from the infrastructure are depicted in Figure 1.

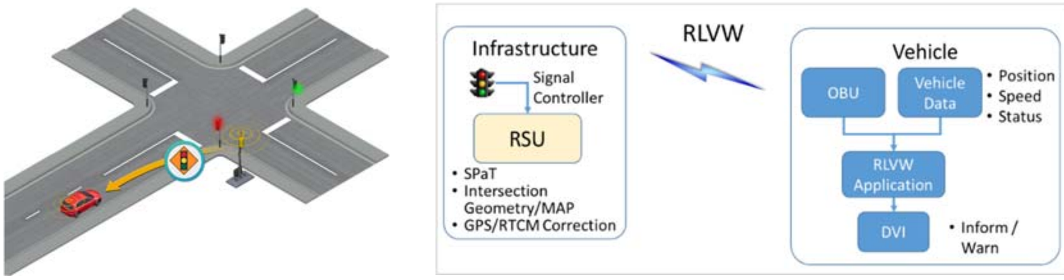


Figure 1: Illustration of RLVW Application Concept and Information Flow for RLVW Safety Application

The next section of the report presents a detailed description of the process used to verify the performance of an intersection equipped with an RSU transmitting SPaT and map messages in SAE MAP messages format.

3 SPaT and MAP Verification of an Installation

For a SPaT and MAP installation at an intersection, correct transmission of the DSRC messages needs to be verified prior to bringing the intersection online for use with the RLVW Application. The steps for verifying the installation are outlined in the SPaT Challenge Verification Document[1]. In general, intersection verification should be performed as follows:

1. **System-Level Verification (required)** ensures that the system is built according to the required architecture and that it correctly implements support protocols. The requirements for this verification are generally covered by documents such as the draft RSU Specifications (available from FHWA) and, optionally, the SCMS EE Requirements[5]. The system-level verification is NOT included as part of this document and it fully relies upon referenced documents.
2. **Message-Level Verification and Validation (required)** is the next step of the verification process during which the messages generated by the RSU are received and verification of the encoding format and information completeness is performed. The data content is then validated for correctness of the information. This verification shall be performed using equipment and personnel from a source other than from the vendor that manufactured or installed the RSU equipment. This ensures proper encoding and decoding of the messages transmitted and received by devices made by different vendors, as per the standard.
3. **Application-Level Verification (optional)** is the additional step recommended to ensure correct operation of the completed installation functionality at the application level using a vehicle. This would require a reference vehicle equipped with the RLVW Application. Different test scenarios can be executed using the reference vehicle to validate proper reception of SPaT and lane-level map from the RSU. It would be beneficial for the local agency responsible for verifying the intersection installation to have an equipped vehicle with the application along with data collection system.

The following subsections provide additional guidance to the message- and application-level verifications.

3.1 Message-level Verification and Validation

Verification and validation of Messages is described in the following subsections.

3.1.1 Message-level Verification

The Message-level Verification is intended to verify the transmitted message content. As previously mentioned, it is desired to have objective verification equipment (e.g., a laptop with a DSRC radio) that can receive and decode messages, perform validation tests and display additional information for visual verification.

In general, the Message-level Verification shall address all of the Minimum Performance Requirements that were previously outlined in the SPaT Challenge Verification Document. In addition, the following steps can provide structure to conduct verifications:

MAP message

- Verify Provider Service Identifier (PSID) and msgid are valid
- Verify lane ID is correctly specified
- Verification of node points
  - Maximum distance between the node points meets the requirements
  - Verify positional accuracy requirements for the node points
- Verify stop bar location for all the lanes and approaches
- Verify MAP attributes
  - Maneuver (ingress, egress)
  - Direction (e.g., through movement, left turn, right turn)
  - Association with the correct signal group
- Verify that the reference point is correctly specified (e.g., mid-point of intersection)
- Verify the lane geometry
  - All straight-through lanes are correctly specified
  - All turn pockets are correctly specified
  - Lane width is accurately measured and specified
  - All node points are at the center of the lane and are within the permitted error threshold (0.5 m)
- Verify the node points for ingress lanes extend to the minimum length as specified in Section 3.2.4.1 of the SPaT Challenge Verification Document [1]
- Verify PSID and msgid are valid
- Verify that signal phase lane ID mapping is correctly specified
- Verify that the signal phase timing is correct

3.1.2 Message-level Validation

This process validates the correctness of the data incorporated in the MAP and SPaT messages by comparing it to the raw intersection map data points and SPaT information from the signal controller. Steps for validating the contents of transmitted SPaT and MAP messages are depicted in Figure 2.

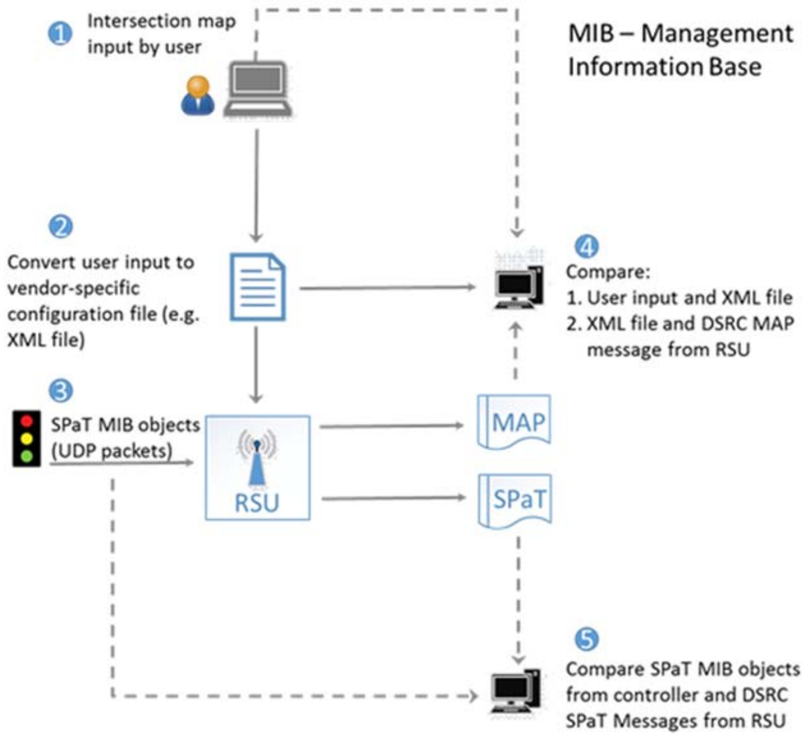


Figure 2: Steps for Conducting SPaT and MAP Message Validation

1. User inputs all the information required to describe an intersection as defined in the SAE J2735 standard (e.g., reference point, lanes, node points)

2. Convert the user-provided map input to vendor-specific configuration file, consisting of required data elements and input to the RSU

   a. In the case of an RSU from Savari, the vendor-specific configuration file is in a vendor-defined xml format

   b. The RSU converts and encodes the vendor-specific configuration file to ASN.1 along with required security and data encryption for broadcasting the MAP message

3. Interface the RSU with the signal controller to acquire SPaT Management Information Base (MIB) objects (i.e., User Datagram Protocol, UDP, packets) for encoding and broadcasting SPaT message

   a. Broadcast encoded MAP message

   b. Broadcast encoded SPaT message

For SPaT and map data verification, it is required to capture DSRC packets (i.e., Packet Capture or PCAP) and decode them to verify data in the transmitted message.

4. Map data verification

    a. Capture DSRC MAP message (RSU vendors have tools to capture wireless packets)

    b. Compare and verify the user input data with the data in the converted vendor-specific configuration file (e.g., xml file)

    c. Compare and verify the MAP message data received from the RSU with the user input data

5. SPaT verification

    a. Capture DSRC SPaT message

    b. Compare and verify the SPaT MIB from the signal controller with the received DSRC SPaT message from the RSU

3.2 Application-level Verification

Application-level verification can be conducted by driving a test vehicle and visually verifying parameters shown by the application engineering Graphical User Interface (eGUI). In addition, the OBU vendor may provide data-logging and analysis tools to log and visualize data for verification. An example of geometry of an intersection for application verification is shown in Figure 3. The following elements should be verified at the application level to ensure proper interpretation of the received message:

- Verify identification of an approaching intersection
- Verify performance of map matching in a given lane by driving:
    - At the center of the lane
    - Hugging the left side of the lane
    - Hugging the right side of the lane
- Verify distance to the stop bar
- Verify map attributes
    - Verify allowed maneuvers (through, left, right, through and right) for each lane
    - Lane id
    - Approach (ingress, egress)
- Perform visual inspection to verify the signal phase for the associated lane
    - Lane and signal group matching

    - Signal phase identification
- Perform visual inspection to validate the signal phase time for the associated lane
    - Signal duration identification – Visual inspection
    - Signal time delay – Visual inspection

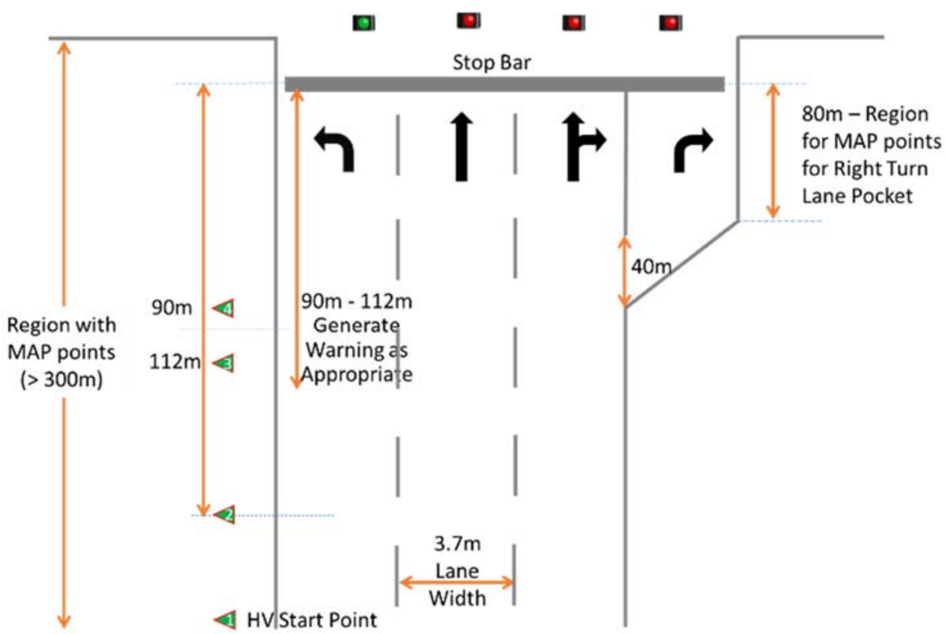


Figure 3: Example of an Intersection Geometry for Application Verification

4 Validation of Verification Steps

To validate the steps described in Section 3 for verification of the SPaT and MAP messages, verification processes were conducted at two signalized intersections in Southeast Michigan. The intersections are in Warren, Michigan on Mound Road at 12 Mile Road and at 13 Mile Road as shown in Source: Imagery ©2019 Google, Imagery ©2019 Maxar Technologies, U.S. Geological Survey Map Data © 2019 United States

Figure 4. Mound Road runs north-south and has four lanes in each direction separated by a median. 12 Mile and 13 Mile Roads run east-west and have two lanes for through movements and one or two lanes for right turn movements. Both intersections have near and far signal lights and associated controllers.

A prototype test vehicle, developed earlier in the V2I-SA Project, was used for the verification testing. This vehicle was equipped with the RLVW Application that included software installations to conduct message- and application-level verifications for both the 2015 and 2016 versions of SPaT/MAP. The RLVW Application in the test vehicle also had an eGUI to visualize data in real-time and data logging capability. Tests and observations conducted during the validation of the verification steps are described in the following sections.

Source: Imagery ©2019 Google, Imagery ©2019 Maxar Technologies, U.S. Geological Survey Map Data © 2019 United States

Figure 4: Test Intersections Used for Verification

4.1 System-level Verification

This verification was conducted by the local authorities at the city, county and state level by the City of Warren, Macomb County and the Michigan Department of Transportation (MDOT) contractors responsible for equipping the intersections with the RSU, interfacing with the signal controller, developing an intersection map and transmitting SPaT and MAP messages as prescribed in the SAE J2735 standard. Both intersections were initially programmed to transmit the 2015 version of the standard and were later updated to transmit the 2016 version.

4.2 Message-level Verification

For this verification, the test vehicle was driven along the north and south directions on Mound Road at 12 Mile and 13 Mile Road intersections and in the east-west directions on 12 Mile and 13 Mile Road intersections. In total, eight runs were made to cover all four directions at the two intersections. The received SPaT and MAP messages were logged and the data elements in the messages were verified on the application eGUI.

4.3 Application-level Verification

Application-level verification can be conducted by driving a test vehicle and visually verifying parameters shown by the application eGUI. In addition, the OBU vendor may provide data-logging and analysis tools to log and visualize data for verification. An example of geometry of an intersection for application verification is shown in Figure 5.

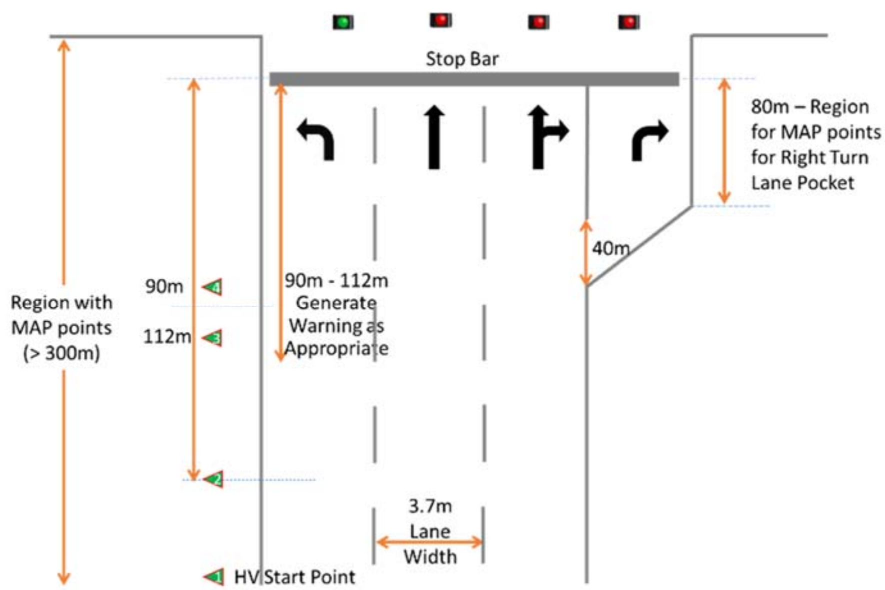


Figure 5: Example of an Intersection Geometry for Application Verification

The following elements should be verified at the application level to ensure proper interpretation of the received message:

- Verify identification of an approaching intersection
- Verify performance of map matching in a given lane by driving:
  - At the center of the lane
  - Hugging the left side of the lane
  - Hugging the right side of the lane

- Verify distance to the stop bar
- Verify map attributes
  - Verify allowed maneuvers (through, left, right, through and right) for each lane
  - Lane id
  - Approach (ingress, egress)
- Perform visual inspection to verify the signal phase for the associated lane
  - Lane and signal group matching
  - Signal phase identification
- Perform visual inspection to validate the signal phase time for the associated lane
  - Signal duration identification – visual inspection
  - Signal time delay – visual inspection

4.4 Outcome of Verification and Observations

When the intersections transmitted 2015 and 2016 versions of the SPaT/MAP messages, the following were observed:

Time to Next Phase: It was observed during the application–level verification that "time to next phase" during the green phase would initially show 65535s. Further investigation revealed that the RSU was receiving the correct values for time remaining in the current signal phase (green, yellow and red) for vehicle, pedestrian crossing and overlap from the signal controller. However, it was reporting the time remaining for the pedestrian movement phase as the time remaining in the current signal phase for vehicle. The RSU supplier identified the issue in their software and made the correction.

Verification step 5 highlights checking and verifying the raw SPaT data from the signal controller against the SPaT data converted by the RSU for broadcasting the SPaT message. This step is represented by the boxes in blue shown in Figure 6.

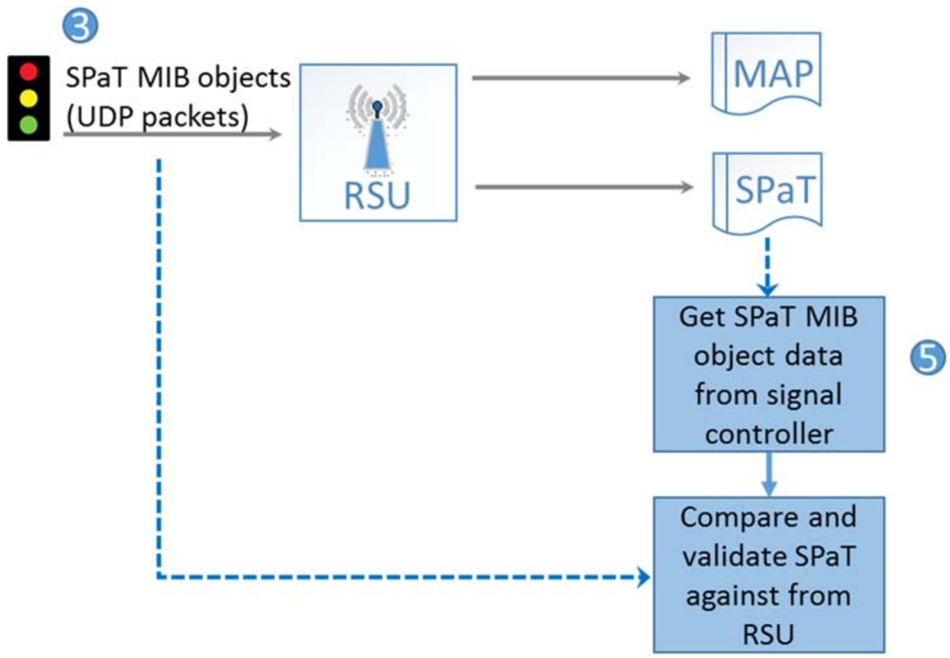


Figure 6: Highlighted Step for SPaT Message Validation

Flashing Red: On decoding the SPaT message in the application, it was observed that although the signal phase was red, the SPaT message indicted a flashing red phase. The root cause of the problem is unclear. As work in this task concluded, MDOT and the RSU supplier were examining the National Transportation Communications for ITS Protocol (NTCIP) “message” and translation from NTCIP message to SPaT message.

Based on the validation work conducted in this task, no revisions to the intersection verification process were identified.

5 Satellite-based Positioning System Error and Correction Techniques

The material presented in this section addresses two questions raised during discussions with the IOOs:

- Do all intersections equipped to send SPaT and MAP messages also need to send GPS positioning correction messages?
- When positioning corrections are needed at an intersection, what methods can be used to provide positioning correction information to equipped vehicles?

For the RLVW Application to perform as intended, a vehicle needs to accurately identify the approach lane and associate it with a signal phase using the MAP/SPaT message received from the RSU for the intersection. It is critical that the location of the vehicle (determined by the on-board GPS) is within a required degree of accuracy. Satellites broadcast their signals in space with a certain accuracy, but what is received depends on additional factors. Accuracy improvement can be accomplished by a broadcast of position correction information. In the subsection below, errors associated with a satellite-based positioning system and various techniques used for correction, message standard and data formats used for transmitting corrections, and assessment of position correction for different intersection configurations are described.

A satellite-based positioning system provides autonomous geo-spatial positioning. It allows receivers to determine their location (longitude, latitude, and altitude/elevation) to a precision within a few meters using time signals transmitted along a line of sight by radio from satellites. The system can be used to provide position, navigation or for tracking.

A satellite navigation system with global coverage is termed as global navigation satellite system (GNSS). As of December 2016, the United States' network of GPS satellites (NAVSTAR), the Russian Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and the European Union's Galileo are global operational GNSSs. China is in the process of expanding its regional BeiDou Navigation Satellite System into a GNSS. Additionally, France, Japan and India are in the process of developing regional navigation and augmentation systems as well.

Global coverage for each system is generally achieved by a constellation of 18–30 medium Earth orbit (MEO) satellites. The actual systems vary, but use orbital inclinations of greater than 50 degrees and orbital periods of roughly twelve hours at an altitude of about 20,000 kilometers.

As shown in Figure 7, GNSSs consist of three major components or "segments:"

1. Space Segment: The space segment is defined by the number of satellites in the constellation. The main functions are to transmit radio-navigation signals, and to store and retransmit the navigation message sent by the Control Segment. These transmissions are controlled by highly stable atomic clocks on board the satellites.

2. Ground Segment: Also referred to as Control Segment or Operational Control System is responsible for the proper operation of the system that monitors the status of satellites, determines the ephemerides and satellite clock offsets
3. User Segment: This segment consists of L-band radio receiver/processors and antennas which receive the signals, determine pseudo ranges (and other observables), and determine position coordinates

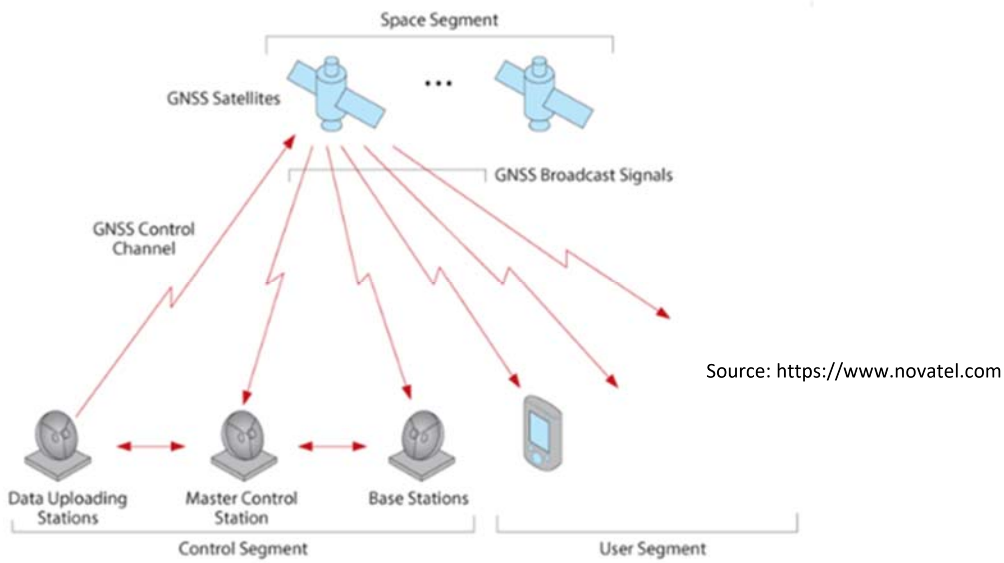


Figure 7: GNSS Satellite System

The following subsection focuses on receiver positioning errors and various techniques employed for position corrections.

5.1 GNSS Error Sources

The analysis of errors computed using the GNSS is important for understanding how it works and what magnitude of errors should be expected. User Equivalent Range Error (UERE) refers to the error of a component in the distance from the receiver to the satellite. These errors are given as ± errors, implying that they are unbiased or zero mean errors and are used in computing standard deviations. Table 1 shows contributing error source and error range.

Table 1: Contributing Source and Error Range

Contributing Source	Error Range
Satellite Clocks	~ ± 2 m
Orbit Errors	~ ± 2.5 m
Ionospheric Delays	~ ± 5 m
Tropospheric Delays	~ ± 0.5 m
Receiver Noise	~ ± 0.3 m

Multipath	~ ± 1 m

Ephemeris and Clock Errors: While the ephemeris data is transmitted every 30 seconds, the information itself may be up to two hours old. Variability in solar radiation pressure has an indirect effect on accuracy due to its effect on ephemeris errors. The satellites' atomic clocks experience noise and clock drift errors.

Signal Arrival Time Measurement: The position calculated by a receiver requires the current time, the position of the satellite and the measured delay of the received signal. The position accuracy is primarily dependent on the satellite position and signal delay.

Atmospheric Effects: Inconsistencies of atmospheric conditions affect the speed of the satellite signals as they pass through the Earth's atmosphere.

- Ionosphere: Effects are smaller when the satellite is directly overhead and greater for satellites near the horizon
- Troposphere: Affects signal reception delay. The effects are localized and change quickly with atmospheric pressure and humidity

Receiver Noise: This error affects the measurements.

Multipath Effects: Multipath is caused when the radio signals reflect off surrounding terrain (e.g., buildings, canyon walls, hard ground). These delayed signals cause measurement errors that are different due to dependency on the wavelength of the radio signals.

Geometric Dilution of Precision: Describes error caused by the relative position of the GPS satellites. Basically, the more signals a GPS receiver can "see" (spread apart versus close together), the more precise positioning solution it can provide. From the observer's point of view, when visible satellites have narrow angular separation (close together) in the sky, the Dilution of Precision (DOP) value is high but when satellites have wider angular separation, the DOP is low, providing better positional accuracy.

5.1.1 Resolving Position Errors at the Receiver

Many techniques are used to resolve errors that could improve the position accuracy of a receiver from a few meters to a few centimeters depending on the data collection technique and the data receiver used. Differential correction is a data collection technique that removes errors in GNSS data created by selective availability and other factors.

All current GNSS satellites transmit radio frequency (RF) signals in the L-band (L1 at 1575.42 MHz and L2 at 1227.60 MHz). Coarse Acquisition (C/A) code is broadcast on this frequency. These signals consist of, at the very least, an RF carrier modulated by a pseudorandom noise (PRN) code. Each satellite has a unique pseudo-random code. Physically it is a complex digital sequence of "on" and "off" pulses. The signal almost looks like random electrical noise and hence the name "Pseudo-Random Noise." GNSS measurement employs the following two methods:

1. Code-Phased Measurement: This method compares the pseudo random code with an identical code in the received signal from the satellite. The wide pseudo random codes used are so wide that they are not perfectly synced with the received signal.

As a result, code measurements are precise to the meter level, resulting in positioning accuracies of a few meters. The measurement after applying the differential correction technique results in an accuracy of 1-5 meters. It can be further improved by averaging more than 180 records. A commonly used code-phased differential GNSS technique is depicted in Figure 8.

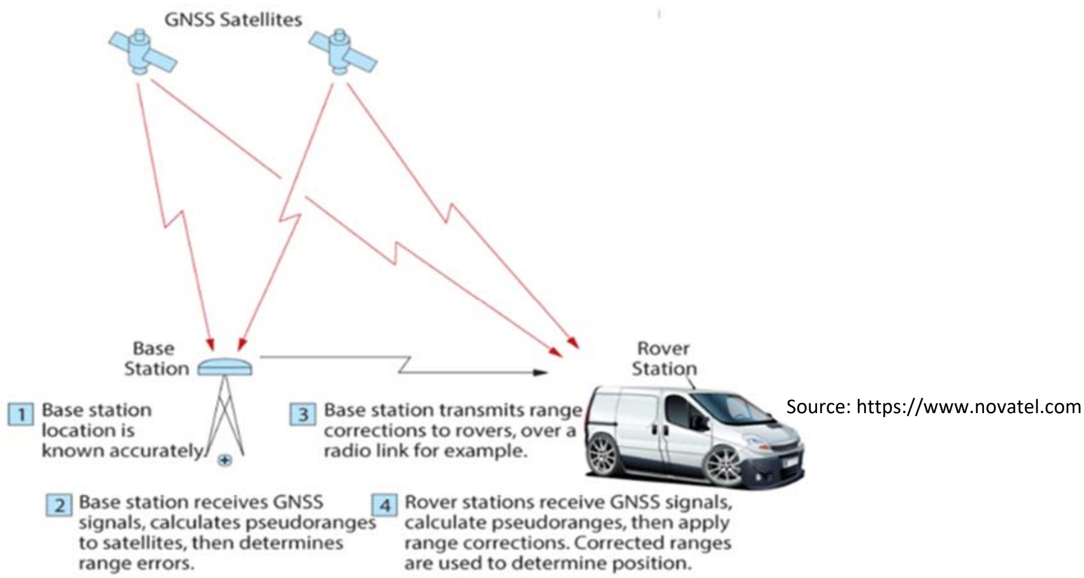


Figure 8: Code-phased Differential GNSS Method

2. Carrier-phased measurement – This method measures the range between a satellite and receiver in units of cycles of the carrier frequency. This measurement can be made with very high precision (of the order of millimeters). Real-Time Kinematic (RTK) uses this method and provides ranges that are orders of magnitude more precise than those available through code-based positioning. The RTK method is shown in Figure 9.

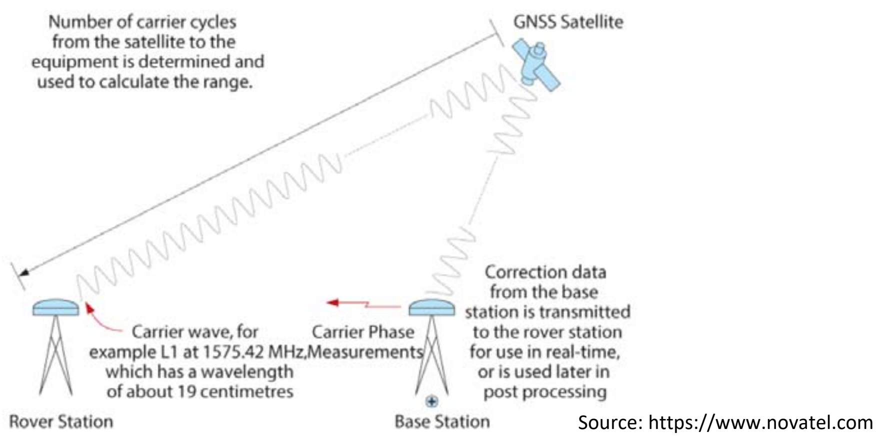


Figure 9: Carrier-phased RTK Correction System

For applications where the rover stations are spread over a large distance between the rover and the base station (10 mm degradation with every kilometer away from base station), a Satellite-Based Augmentation System (SBAS) or a Wide Area Augmentation System (WAAS) is a system that supports wide-area or regional augmentation through additional satellite-broadcast messages. Such systems are commonly composed of a network of multiple ground stations located at accurately-surveyed points. Corrections are uplinked to the satellite and then broadcast to GNSS/GPS receivers as shown in Figure 10.

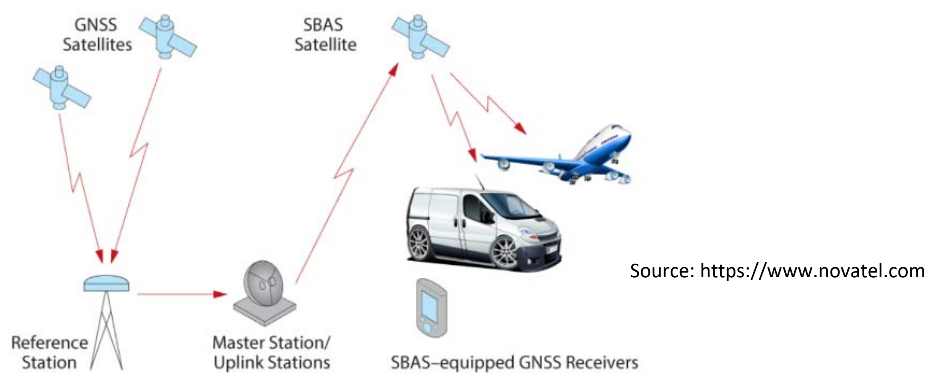


Figure 10: Wide Area Augmentation System

Additionally, Precise Point Positioning (PPP) systems are deployed commercially by private service providers. This method provides very precise positions up to few-centimeter level using a single (GNSS) receiver. PPP approach combines precise clocks and orbits calculated from a global network to calculate a precise position with a single receiver, which can be double- or single-frequency, and corrections are delivered via satellite or over the Internet. A typical PPP solution requires time to converge to high accuracy in order to resolve any local biases. Such systems are fee-based services from the providers. A PPP system is shown in Figure 11.

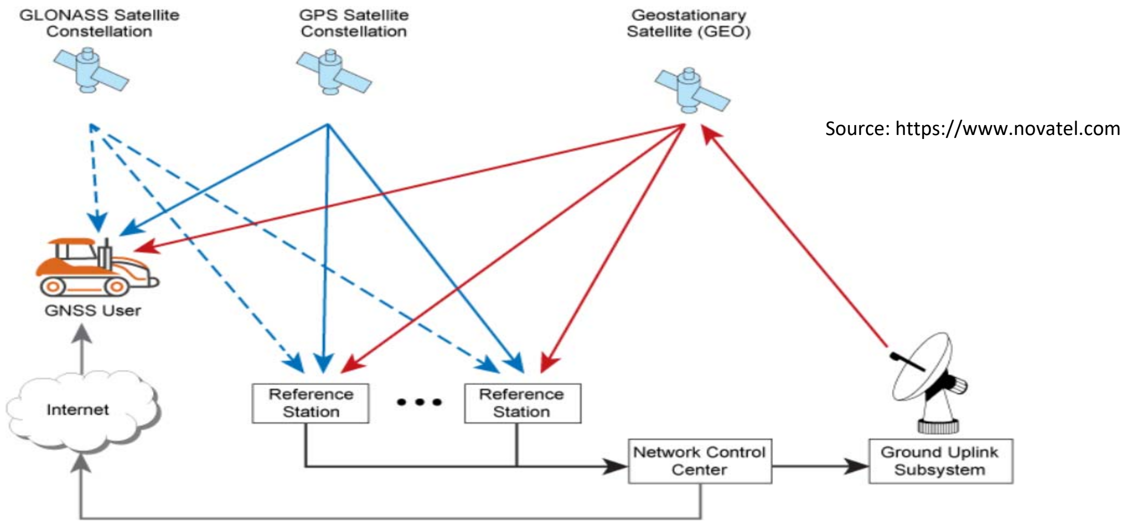
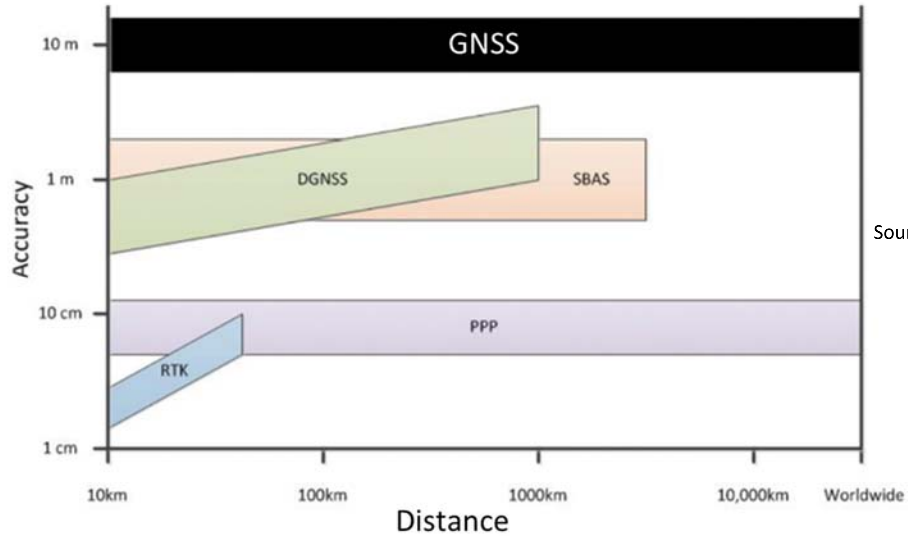


Figure 11: Carrier-phased PPP Correction System

As described, different correction methods improve position accuracy from a few meters to a few centimeters. Which correction method is appropriate depends on the application and the capability of the receiver, in addition to fee-based vs. free services. Figure 12 shows accuracy and practical range for each method.

The GNSS provides a global positioning solution within meter-level accuracy. Other methods that provide centimeter-level accuracy, such as PPP and RTK, are available. These two methods provide significantly better accuracies compared to Differential GNSS (DGNSS) or single-point positioning when employing corrections provided by GNSS augmentation systems such as SBAS as shown in Figure 12. Figure 12 also shows the different limitations in baseline (distance between base station and rover receivers) for each correction method, which constrain their use to within a certain range from base receivers or reference networks. While the DGNSS is useful over a longer baseline, SBAS covers a wide range of area. RTK is limited to a few kilometers in that as the distance increases, the accuracy and availability of a solution decreases. PPP on other hand is not affected by baseline length and can provide full accuracy anywhere globally. As discussed earlier, there is no one GNSS correction method that best suits the intended application/situation.



Source: https://www.novatel.com

Figure 12: Accuracy and Range of Correction Methods

Table 2, compiled from information from various sources, provides a detailed comparison of the different position correction methods discussed.

Table 2: Comparison of Various Position Correction Techniques

	Base Station	Rover Station	Positioning Technique	Cost	Correction Source	Coverage	Accuracy
DGNSS	Receiver at known location	Requires one or more constellations	Code-phase	Less expensive than RTK $	Receive corrections from base station	~ Tens of kilometers	± 1 m
SBAS	Reference station and Master station	User: SBAS-capable receiver and a GNSS antenna	Code-phase	Free	Receive corrections from satellites	Wide area or regional augmentatio n	± 2 m
PPP	Network of global reference stations	User: PPP-compatible receiver Antenna capable of receiving GNSS and L-Band frequencies	Carrier-phase	Subscription based $$	Receive corrections from satellites	Worldwide	± 3 cm Long convergenc e time, ~ 20–30 min
RTK	Receiver at known location	Requires two or more constellations	Carrier-phase	Subscription based $$	Receive corrections from base station	~ 50 Km	± 2 cm or so Available immediately

5.2 RTCM Message Standard

One method to implement RTK-based correction is the use of RTCM messages. The internationally accepted data transmission standards for DGNSS are defined by RTCM, particularly by its Special Committee SC-104. RTCM SC-104 is a standard that defines the data structure for differential correction information for a variety of differential correction applications. It was developed by the Radio Technical Commission for Maritime Services (RTCM) and has become an industry standard for communication of correction information. It is a binary data protocol. Table 3 provides different versions of the standard that constitutes correction message.

Table 3: Different RTCM Versions

RTCM - 2.0 (Code correction → DGPS)
RTCM - 2.1 (Code + Phase correction → RTK)
RTCM - 2.2 (…+ GLONASS)
RTCM - 2.3 (….+ GPS Antenna Definition)
RTCM - 3.0 (….+ Network RTK & GNSS) • Message type 1001 – GPS L1 observations at 5 Hz • Message type 1005 – Antenna Reference Point (ARP) coordinates at 2 Hz

RTK using RTCM 3.x version is more efficient than the RTCM 2.3 and is the preferred method. SAE J2735 message - MSG_RTCMcorrections is used by an RSU to encapsulate RTCM differential corrections. These messages are "encapsulated" for transport on the DSRC channel and then can be re-constructed into the final expected formats defined by the RTCM standard for use directly by various positioning systems to increase the absolute and relative accuracy estimates.

5.3 Position Correction for Different Intersection Configurations

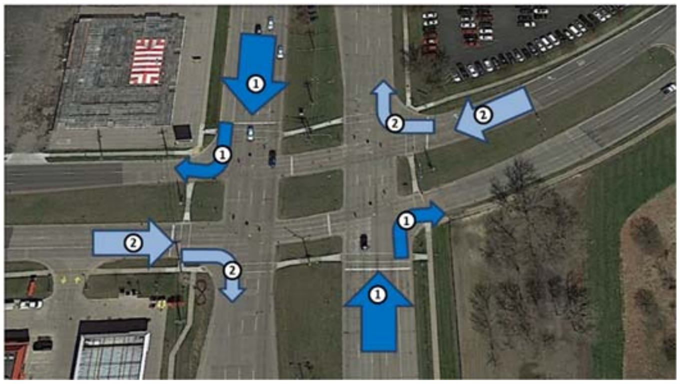
In the following subsections, three scenarios relevant to different intersection configurations and effectiveness of position corrections for the RLVW Application are described. A combination of different intersection configurations, consisting of simple to complex SPaT and lane associations under open sky clear satellite visibility and under low or poor satellite visibility conditions (e.g., urban canyon or obstructed satellite view) are described.

5.3.1 Open Sky Clear Visibility Satellite Intersections

In the first scenario shown below in Source on this page: Map data ©2019 Google Imagery ©2019, DigtalGlobe U.S. Geological Survey. Used with permission. Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 13, the vehicle is operating under open sky, with clear visibility of satellites. The intersection has multiple lanes in all directions and has near-far traffic lights in all directions. The intersection permits two types of movements: straight through and right turn. However, the signal phases for the intersection can be grouped into a few signal groups. For example, the intersection below is managed by using two signal groups: Group

1 for all the north-south lanes (straight-through and right turn), and Group 2 for all east-west lanes. The positioning challenge at such intersections is low due to open sky. In addition, although a vehicle could be mapped to a wrong lane when positioning accuracy degrades, the RLVW Application would not be affected as all the lanes in a given direction are governed by the same signal group. Hence, it can be said that providing position correction at such location may not add significant benefit.



Intersection Configuration:
- Multiple lanes in each direction
- Near-far traffic lights in all directions

Complexity - Low:
- Simple – Straight-through and right turn
- Maximum 2 signal phase associations – Straight and right turn movements
- Positioning challenge - Low

Position Correction May Not Add Significant Benefit:
- Limited lane-level map matching is required

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Figure 13: Scenario #1 - Open Sky Clear Visibility Satellite Intersection

5.3.2 Low/Poor Satellite Visibility Intersections

In the second scenario, considered below, the vehicle is in an urban canyon setting, with obstructed sky/satellite visibility. The intersection itself is an average intersection with no near-far traffic lights. However, it has multiple lanes in all directions as well as signal phases in all the directions. The positioning challenge is high at such intersections, but due to obstructed satellite visibility, providing corrections would not offer required benefits.

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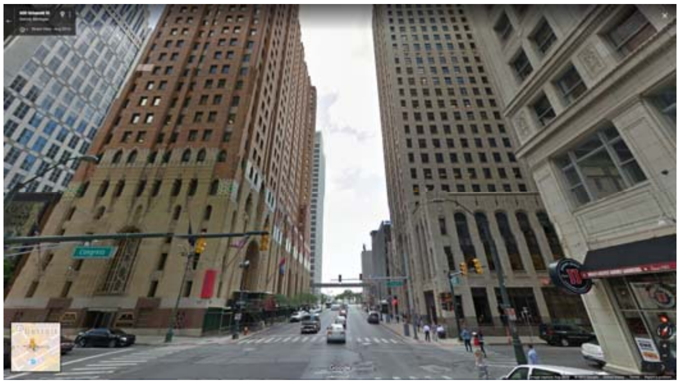
Figure 14 further explains the positioning challenge faced in urban canyons. The buildings along the road block the view of the GNSS receiver/antenna, and reduce the number of satellites in direct line of sight (LOS). As a result, the GNSS receivers are forced to use signals that have multipath which introduce high positioning error.



Intersection Configuration:
- Typical no near-far traffic lights

Complexity - High:
- Multiple lanes in each direction
- Multiple signal phases in each direction
- Urban canyon, obstructed satellite visibility, makes it difficult to use correction
- Positioning challenge - High

Position Correction Would Not Provide Required Benefits

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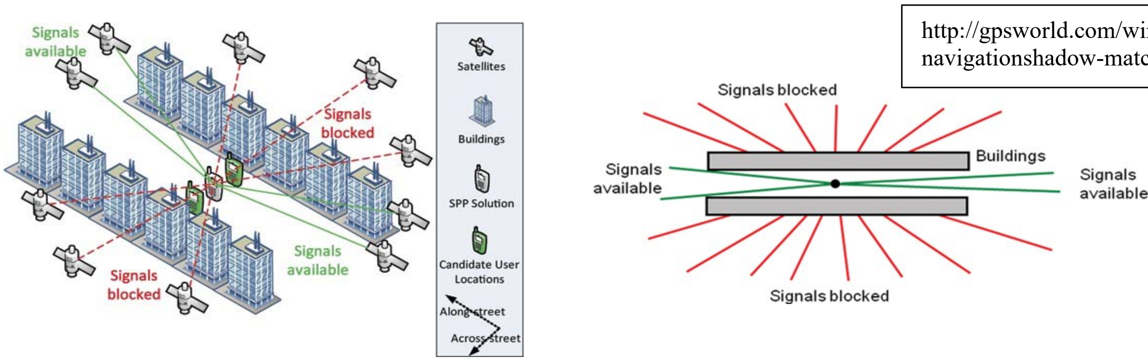
Figure 14: Scenario #2 - Low/Poor Satellite Visibility Intersection

5.3.2.1 Positioning Challenge in Urban Canyon

Poor GNSS positioning accuracy is common in urban canyons where tall buildings block the direct LOS signals from many, sometimes most, of the satellites, effectively casting GNSS shadows over the adjacent terrain. Without direct signals from four or more satellites, an accurate position solution cannot be determined. Sometimes, a degraded position solution can be obtained by using signals that can only be received by reflection off a building, known as non-line-of-sight (NLOS) signals.

Signals with lines of sight going across the street are much more likely to be blocked by buildings than signals with lines of sight going along the street as depicted in Figure 15. As a result, the signal geometry, and hence the positioning accuracy, will be much better along the direction of the street than across the street. For example, for a building-height-to-street-width ratio of three and direct signals from constellations of four satellites, the cross-street position uncertainty can exceed 20 meters, while the along-street uncertainty is within 5 meters. Lane-level positioning is important for advanced intelligent transportation systems that can direct individual vehicles to maximize traffic flow and prioritize emergency vehicles.



http://gpsworld.com/wirelesspersonal-navigationshadow-matching-12550/

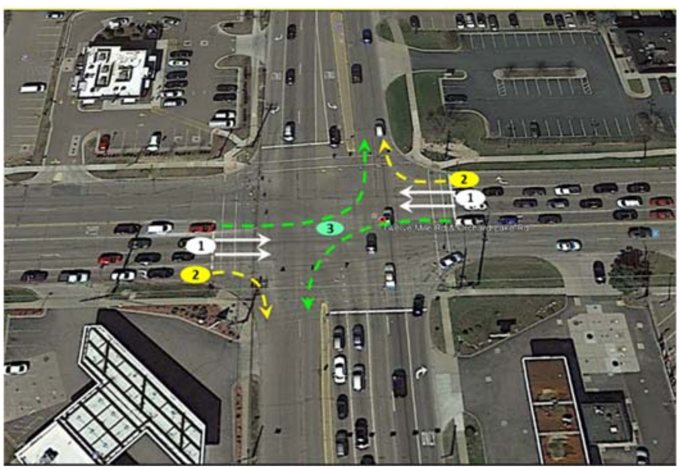
Figure 15: Signal Geometry of GNSS Satellites in an Urban Canyon (Aerial Perspective)

If it is not possible to calculate a sufficiently accurate position solution using the visible satellites, shadow matching techniques use the nonvisible satellites as well. This technique, described in a *GPS World* article titled "Shadow Matching: Improved GNSS Accuracy in Urban Canyons" [6], requires a 3D model of a city's buildings. By knowing where the buildings are and how big they are, the technique deduces positional information from the knowledge that certain signals are blocked. These are becoming more accurate and widely available and have already been used to predict GNSS signal availability and multipath interference.

5.3.3 Open Sky Clear Visibility Satellite Intersections Complex SPaT/MAP

In the third scenario shown below in Source on this page: Map data ©2019 Google Imagery ©2019, DigtalGlobe U.S. Geological Survey. Used with permission. Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 16, the vehicle is operating under open sky, with clear visibility of satellites. The intersection has multiple lanes in all directions and does not have near-far traffic lights. The intersection has multiple signal phases in each direction. This means the vehicle needs to know exactly its lane to associate with the correct signal phase. As a result, at such intersections, the positioning accuracy requirement is very high. Hence, it can be said that providing position correction at such locations would certainly improve positioning accuracy.



Intersection Configuration:
- Typical, no near-far traffic lights

Complexity - High:
- Multiple lanes and multiple signal phases in each direction
- Lane-level positioning is required

Position Correction Would Certainly Provide Required Benefits

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Figure 16: Scenario #3 - Open Sky Clear Visibility Satellite Intersection Complex SPaT/MAP

As summarized in Table 4, the greatest benefit from position corrections could be derived for a signalized intersection under open sky with clear visibility, where the lane geometry to approach the intersection is complex and has multiple signal phases in each direction. A vehicle approaching such an intersection needs to know its lane position exactly in order to associate with the correct signal phase. As a result, the positional accuracy requirement is high and providing position correction at such locations would certainly improve positioning accuracy.

Table 4: Summary of Benefit from Position Correction

		Satellite Visibility	
		Open Sky / High Satellite Visibility	Obstructed Satellite Visibility
Intersection Configuration	Combination of Less Complex SPaT / MAP Configuration	Some benefit can be achieved	May not achieve desired benefit
	Combination of Highly Complex SPaT / MAP Configuration	**Most benefit can be achieved**	Cannot achieve desired benefit

6 Summary

Task 15 of the V2I-SA Project involved two primary efforts. The first was the validation of the process outlined in the SPaT Challenge Verification Document to verify that intersection RSUs transmitting SPaT and intersection map messages can support the Red RLVW Application developed during the V2I-SA Project. The second effort involved enhancing the SPaT Challenge Verification Document to provide RLVW deployment guidance to the IOOs participating in the AASHTO SPaT Challenge regarding where and how GPS positioning correction information could be provided.

Validation of the Verification Process

The purpose of conducting the validation of the verification process was to step through the defined process and refine, if necessary, to ensure that no key steps were missed or misaligned. The validation exercise followed the verification process outlined in Section 3 of this report which was taken from the SPaT Challenge Verification Document. Two medium-level-complexity intersections in Southeast Michigan were used for the validation work. The verification process assumes that the geographic map of the intersection ingress lanes, location of the stop bar, and egress lanes are within the required level of accuracy and are encoded in the MAP message as per the SAE J2735 Standard.

The roadway operator and their RSU contractor conducted the system-level verification in the verification process. The V2I-SA TMT conducted the message-level and application-level verifications using a test vehicle and the RLVW Application developed earlier in the project. No anomalies were found in the verification process. However, SPaT message issues related to transmission of the Time to Next Phase and an incorrect flashing red phase status were identified and referred to the RSU vendor for resolution. These discoveries underscored that step 5 highlighted in the verification process diagram (see Section 4.4, Figure 6) must be validated carefully to ensure that the SPaT data transmitted by the RSU is verified against the actual raw data from the signal controller and that the RSU has interpreted the information from the controller correctly.

The verification of correctly mapped ingress lanes associated with SPaT was done through the application-level verification. The application level-verification, though optional in the SPaT/MAP verification process, provided valuable insight about the SPaT issues identified during validation testing.

Literature Review of Satellite-Based Positioning Error and Correction Techniques

To understand various sources of errors in satellite-based positioning systems and effectiveness of corrections techniques for different intersection configurations, a literature review was conducted and discussions were held with leading providers of GNSS receivers. From the material obtained during these activities, a summary of GNSS error sources, a discussion of the RTCM message standard, and approaches for positioning corrections for different intersection configurations was prepared. Section 5 of the report details this information.

The key outcome of this study is to categorize the location of intersections by type of satellite visibility such as open sky / clear visibility versus partial or obstructed visibility (e.g., urban canyons) and the level of complexity of SPaT and MAP combination (e.g., multiple lanes and multiple signal phases) where lane-level positioning is required. The intersections with high satellite visibility under open sky location with complex SPaT and MAP combinations that require lane-level positioning would benefit the most from positioning correction information.

It should be noted that the sources of corrections are not discussed in the report. It is expected that other IOO/OEM Forum members who are researching this topic would provide their findings for incorporation into a future edition of the SPaT Challenge Verification Document.

7 References

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