Enhancing Lidar-GPS Fusion for Localization: Integrating Ionospheric Modeling with NeQuick G and V2V Implementation

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Abstract

Lidar (Light Detection and Ranging) provides high-resolution mapping and odometry for localization but faces limitations when used alone. Conversely, GPS positioning is impaired by ionospheric irregularities—such as Total Electron Content (TEC) variations, scintillation, and gravity waves—which distort satellite signals and reduce accuracy. This work explores a multi-modal fusion approach that integrates Lidar and GPS to optimize localization by compensating for ionospheric-induced errors. In the first phase, we focus on enhancing the GPS component of the Lidar-GPS fusion using the Galileo-based NeQuick G model, a mathematical framework for simulating ionospheric variations. Utilizing NASA's Archive of Space Geodesy Data, we analyze the spatio-temporal distribution of Vertical TEC (VTEC). By applying Particle Swarm Optimization (PSO), we identify global VTEC maxima at different altitudes, shedding light on worst-case ionospheric disturbances. For example, our analysis predicts that on January 1, 2027, at 12:00 AM UTC, the highest VTEC values occur at coordinates (-9.8, -88) near Peru, a critical region where GPS accuracy may degrade. This phase aids in forecasting GPS performance fluctuations in high-disturbance zones and informs the optimization of Lidar-GPS fusion for precision applications, including autonomous vehicles and V2V communication. The second phase is an aspirational extension aimed at implementing a Vehicle-to-Vehicle (V2V) communication model using Lidar sensors. This planned work will address challenges such as third-vehicle occlusion and background visible light noise. By integrating Lidar landmark matching, SLAM, and 3D point cloud processing, we intend to enhance localization reliability in dynamic multi-vehicle environments. Ultimately, this study bridges atmospheric science and vehicular localization, demonstrating the synergy between Lidar-based SLAM, ionospheric modeling, and the potential for robust Lidar-driven V2V networking to improve autonomous navigation and road safety.

Introduction

Accurate localization is crucial for applications such as autonomous vehicles, UAV navigation, and geospatial mapping. While LiDAR (Light Detection and Ranging) provides high-resolution spatial data, it lacks absolute positioning. On the other hand, GNSS (Global Navigation Satellite System), including GPS and Galileo, offers absolute positioning but suffers from ionospheric errors, which distort signals due to Total Electron Content (TEC) variations, scintillation, and gravity waves [12].

To improve localization accuracy, we explore LiDAR-GPS fusion, incorporating ionospheric modeling through the Galileo-based NeQuick G model [13]. This model estimates electron density distributions, enabling real-time ionospheric delay corrections for GNSS. Our approach integrates NASA's Archive of Space Geodesy Data to analyze TEC variations and applies Particle Swarm Optimization (PSO) to identify high-TEC regions where GNSS errors peak.

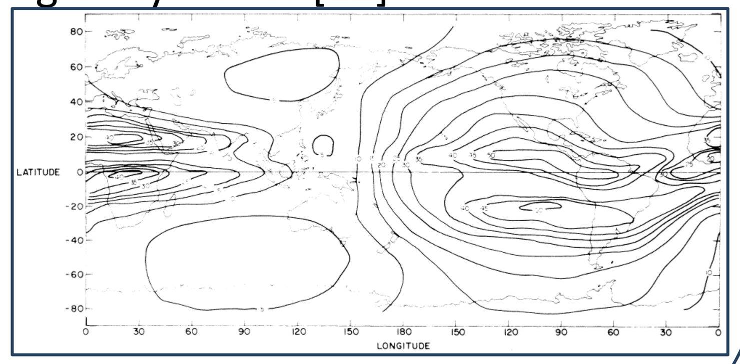


Fig.1: Contours of inonthly average ionospheric time delay, units of nanoseconds at 1.6 GHz.

By mitigating ionospheric disturbances in LiDAR-GPS fusion, we enhance positioning reliability for high-precision applications. Future extensions of this work include Vehicle-to-Vehicle (V2V) LiDAR networking, addressing challenges such as third-vehicle occlusion and background light interference.

GNSS Receiver, [2]

Method/Experiment

- We worked on two phases. First to predict the worst-case scenario for the signal delay as a function of ionospheric refraction. Then we explore the V2V available IEEE standards in a way to achieve reliable conncection and hence better localization.
- We used the NASA Geodecy archive data to input the three Galileo coefficients (a0, a1, a2); NeQuickG model to calculate the Az based on the location and a's Electron density is then calculated, then integrated to get the Slant Total Electron Content (STEC) yielding the calculation of the Ionospheric delays.

Data and Analysis

This section covers the two phases for GPS-LiDAR fusion: enhancing the GPS component, then aspiring to build a prototype for the V2V communications kit.

Phase-1: Enhancing the GPS component of LiDAR-GPS fusion

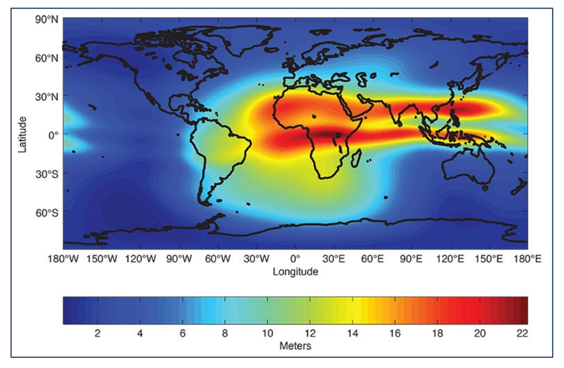
- Galileo-based NeQuick G model

GNSS positioning accuracy is affected by ionospheric irregularities, which introduce signal delays and distortions. To mitigate these errors, we utilize the NeQuick G model, a three-dimensional ionospheric electron density model developed for Galileo GNSS corrections. By integrating NeQuick G, we enhance GPS precision in our Lidar-GPS fusion framework, improving localization in ionosphere-affected environments, [1].
GNSS receivers detect, decode, and process signals from the GNSS satellites (e.g., GPS, GLONASS, Galileo, BeiDou, and others), [2]. The satellites transmit the ranging codes on two radio-frequency carriers, allowing the locations of GNSS receivers, shown in Fig. 2, to be determined with varying degrees of accuracy, depending on the receiver and post-processing of the data.

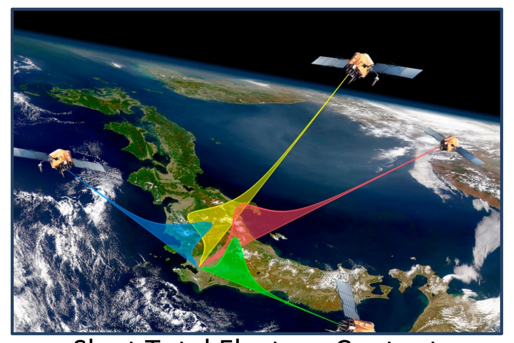
$$Az = a_0+a_1\mu+a_2\mu^2$$

Where a's are the ionospheric coefficients broadcasted in the navigation message by the Galileo satellite coefficients (found in NASA's Geodecy Archive); μ is the modified dip latitude, or MODIP, calculated as:
$\mu = I/\sqrt{\cos(\Phi)}$

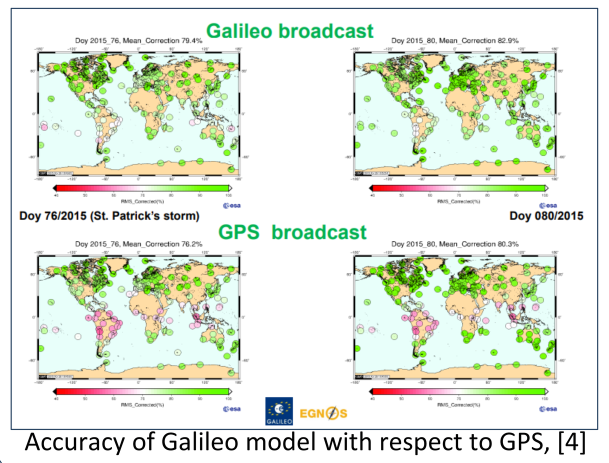
I is the true magnetic inclination, or dip in the ionosphere (usually at 300 km), and Φ the geographic latitude of the receiver.



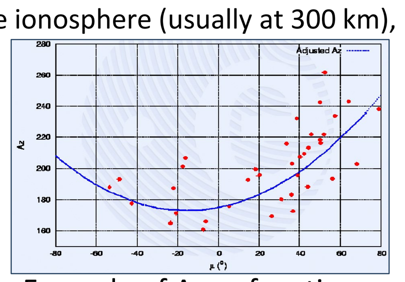
Global vertical Total Electron Content map generated with NeQuick G model at 13h UT for a day in April and Az=193, [1].



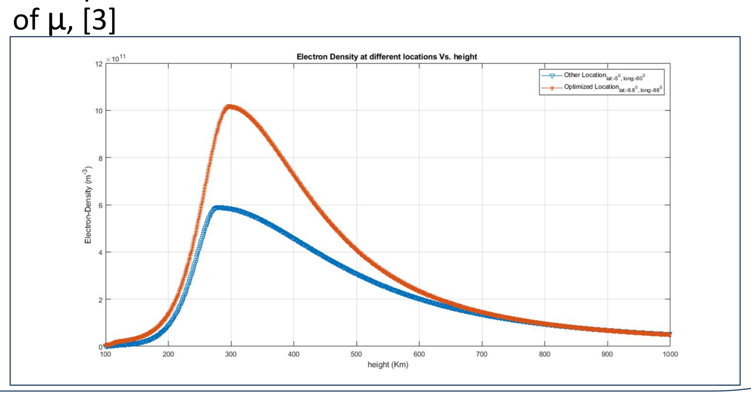
Slant Total Electron Content Applications in GNSS by NeQuicK G Model, [4]



Accuracy of Galileo model with respect to GPS, [4]



Example of Az as function of μ, [3]



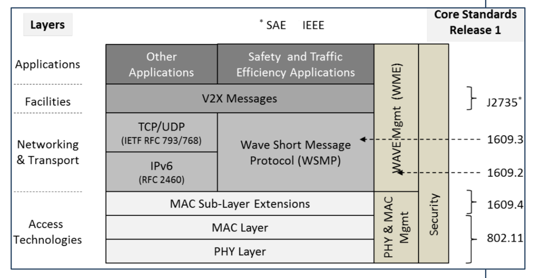
Phase-2: Aspired Integrations

Lidar-based localization relies on landmark matching, where detected features (e.g., buildings, road signs) are compared to a known map to refine positioning. Simultaneous Localization and Mapping (SLAM) enables real-time mapping and self-localization in dynamic environments by fusing Lidar and sensor data. 3D point cloud processing reconstructs spatial structures, enhancing object recognition and navigation precision. These techniques form the foundation for robust autonomous localization, which we extend to Vehicle-to-Vehicle (V2V) communication while addressing IEEE P1920.2 physical layer standards for inter-vehicle Lidar networking.

A team of student researchers at RIT has developed a secure vehicle-to-vehicle (V2V) communications testbed using USRP-based software-defined radios and IEEE 1609.2 cryptographic authentication, [6, 7]. Their system ensures message integrity and legitimacy, addressing critical security challenges that have hindered large-scale V2V deployment. Featuring a real-time visual interface, their work provides a foundation for future research, aiming to enhance road safety, enable autonomous vehicle coordination, and improve traffic efficiency while mitigating cyber threats

USRP-based test bed under IEEE 1609.2 standard, [6]

Focusing on the Physical Layer to implement a prototype for the Dedicated Short-Range Communications (DSRC), we are putting out efforts to invest in both IEEE 802.11 and P1920.2 standards as shown in Fig.



Protocol stack and related core standards for DSRC in the U.S., [8]

Conclusion

Our work targets the enhancement of GPS-LiDAR fusion through two phases: Enhancing the GNSS performance through predicting the worst case scenario as function of VTEC using Particle Swarm Optimization. The second phase, aspiring integrations, covered some IEEE Standards protocols as P1920.2 and IEEE 802.11 that support the V2V physical layer. Future work involves prototyping the reached standards on microcontroller kits.

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