GNSS Localization Techniques and Improvement Methods

1. Review of GNSS Localization Techniques

(a) Differential GPS

Differential GPS (DGPS) enhances the accuracy of standard GPS by using a network of fixed ground-based reference stations to correct the signals received from GPS satellites. Here's how it works:

1. **GPS Basics**: Standard GPS determines a receiver's location by calculating the time it takes for signals from multiple satellites to reach the receiver. However, these signals can be affected by various sources of error, such as atmospheric conditions, satellite clock errors, and signal reflection, leading to inaccuracies in the calculated position, often ranging from 5 to 15 meters.
2. **Reference Stations**: DGPS introduces fixed ground-based reference stations at known locations. These stations also receive GPS signals from the satellites. Since the exact position of the reference stations is already known, any difference between the calculated position (based on the GPS signals) and the known position indicates the errors affecting the GPS signal.
3. **Error Calculation**: The reference station calculates the difference (or "correction") between the known position and the position indicated by the GPS signals. These corrections account for errors like atmospheric delay or satellite clock discrepancies.
4. **Broadcasting Corrections**: The calculated corrections are then transmitted to DGPS-enabled GPS receivers via radio signals. These receivers use the correction data to adjust their own calculations, effectively cancelling out much of the error in the GPS signal.
5. **Enhanced Accuracy**: By applying the corrections, DGPS can significantly improve the accuracy of GPS, often reducing positional errors to within 1 to 3 meters, making it particularly useful for applications requiring high precision, such as surveying, navigation, and certain types of autonomous systems.

Advantages of DGPS

1. **Enhanced Accuracy**:
   - DGPS improves positional accuracy to within 1 to 3 meters, compared to the 5 to 15 meters typical of standard GPS. This precision is critical in applications where small positional errors could lead to significant issues.
2. **Reliability**:
   - By correcting for errors such as satellite clock discrepancies and atmospheric conditions, DGPS provides more reliable and consistent positioning data. This reliability is particularly important in safety-critical applications.
3. **Wide Area Coverage**:
   - With networks of reference stations, DGPS can provide enhanced accuracy over large areas. Regional and national DGPS networks can cover vast geographical areas, benefiting a wide range of users.
4. **Real-Time Corrections**:

- DGPS provides real-time corrections, which is crucial for dynamic applications like navigation and tracking. Users receive immediate updates, ensuring their positional data is current and accurate.

Applications of DGPS

1. **Maritime Navigation**:
    - DGPS is extensively used in maritime navigation to ensure the safe passage of vessels through narrow channels, ports, and harbors. The enhanced accuracy helps prevent grounding and collisions, especially in poor visibility conditions.
2. **Aviation**:
    - In aviation, DGPS supports precision approaches and landings, especially in areas without Instrument Landing Systems (ILS). It enhances the safety and efficiency of aircraft operations, particularly at smaller or remote airports.
3. **Surveying and Mapping**:
    - Surveyors use DGPS to achieve the high levels of accuracy required for creating maps, establishing property boundaries, and other geospatial tasks. DGPS reduces the need for post-processing of GPS data, making the process faster and more efficient.
4. **Agriculture (Precision Farming)**:
    - DGPS is a key technology in precision agriculture, enabling farmers to optimize field operations such as planting, fertilizing, and harvesting. The accuracy allows for precise application of inputs, reducing waste and increasing crop yields.
5. **Geophysical Research**:
    - Scientists use DGPS for monitoring tectonic plate movements, volcanic activity, and other geophysical phenomena. The high precision of DGPS allows for the detection of minute changes in the Earth's surface, contributing to better understanding and prediction of natural events.
6. **Construction and Engineering**:
    - DGPS is used in construction and civil engineering for tasks like site surveys, machine control, and alignment of structures. The accuracy provided by DGPS ensures that projects are built according to precise specifications, reducing errors and rework.
7. **Autonomous Vehicles**:
    - DGPS is critical for the operation of autonomous vehicles, including drones, driverless cars, and robotic systems. The high positional accuracy ensures safe and efficient navigation, particularly in complex environments.
8. **Emergency and Rescue Operations**:
    - In search and rescue missions, DGPS aids responders by providing accurate location data, which is essential for quickly locating individuals or objects in distress, especially in challenging terrains or adverse weather conditions.

(b) Real-Time Kinematic (RTK)

Real-Time Kinematic (RTK) is a GPS-based positioning technique that provides highly accurate, centimeter-level precision in real-time. RTK achieves this by using carrier-based ranging, which involves measuring the phase of the GPS signal's carrier wave rather than just the signal's timing code.

- B**asic GPS Positioning**:

  - Standard GPS works by measuring the time it takes for signals to travel from satellites to a receiver, using the timing code (pseudo-range) to determine distance. While effective, this method typically results in position accuracy within a few meters due to various errors.

- **Carrier-Based Ranging**:

  - RTK enhances accuracy by using the phase of the carrier wave of the GPS signal. The carrier wave has a much shorter wavelength (about 19 cm for GPS L1), allowing for more precise distance measurements compared to the pseudo-range based on the code signal, which has a longer wavelength (about 300 meters).

Real-Time Processing:

- The rover uses the corrections from the base station to adjust its calculations of the GPS signal's phase, thereby achieving high-precision positioning in real-time. The process is continuous, ensuring that the rover's position remains accurate as it moves.

1. Accuracy

- **RTK**:
  - **Accuracy Level**: RTK provides centimeter-level accuracy, typically within 1 to 2 centimeters horizontally and 2 to 4 centimeters vertically.
  - **Precision**: The use of carrier-phase measurements allows RTK to achieve extremely high precision, making it suitable for applications where very small positional errors are critical.
- **DGPS**:
  - **Accuracy Level**: DGPS improves GPS accuracy to within 1 to 3 meters.
  - **Precision**: While DGPS significantly enhances the accuracy compared to standard GPS, it does not achieve the same level of precision as RTK. DGPS is more focused on correcting timing errors rather than resolving phase ambiguities.

2. Complexity

- **RTK**:
  - **System Complexity**: RTK systems are more complex due to the need for real-time phase ambiguity resolution, carrier-phase measurements, and a continuous communication link between the base station and rover.
  - **Equipment**: RTK requires a base station and a rover, both of which must have sophisticated receivers capable of processing carrier-phase data. The setup and maintenance of these systems are more demanding.

    - **Data Processing**: RTK involves real-time data processing with advanced algorithms to resolve phase ambiguities, making it computationally more intensive.
- **DGPS**:
    - **System Complexity**: DGPS is less complex compared to RTK. It primarily involves calculating and broadcasting corrections based on timing errors in the GPS signals.
    - **Equipment**: DGPS requires a reference station and a DGPS-capable receiver, which are less complex and generally less expensive than RTK systems.
    - **Data Processing**: DGPS uses simpler algorithms to apply corrections to the GPS signals, focusing on improving positional accuracy by compensating for known sources of error.

3. Typical Use Cases

- **RTK**:
    - **Surveying and Mapping**: RTK is commonly used in land surveying and geospatial mapping where centimeter-level accuracy is required.
    - **Construction and Engineering**: RTK is used for tasks like machine control, grading, and alignment, where high precision is essential.
    - **Autonomous Vehicles**: RTK supports the navigation of autonomous vehicles, including drones and self-driving cars, where accuracy is critical for safety and efficiency.
- **DGPS**:
    - **Maritime Navigation**: DGPS is widely used for safe navigation in maritime environments, helping vessels avoid obstacles and navigate through narrow channels.
    - **Aviation**: DGPS supports aircraft navigation, particularly for non-precision approaches where meter-level accuracy is sufficient.

(c) ASSISTED GPS (A-GPS)

Assisted GPS (A-GPS) enhances GPS performance by utilizing network assistance from cell towers or the internet to speed up the initial positioning process. When a device with A-GPS is turned on, it quickly obtains approximate location data, satellite orbital information (ephemeris), and precise time from the network. This helps the GPS receiver identify which satellites to connect with, significantly reducing the "Time to First Fix" (TTFF). A-GPS is especially beneficial in environments where satellite signals are weak or obstructed, such as urban canyons or indoors, ensuring faster and more reliable positioning.

A-GPS offers faster initial positioning and improved performance in challenging environments (e.g., urban areas) by using network assistance, making it ideal for mobile devices and general navigation. However, its accuracy (5-10 meters) is lower compared to DGPS and RTK. DGPS enhances accuracy to 1-3 meters using ground-based reference stations, suitable for applications like maritime navigation. RTK delivers centimeter-level precision through real-time carrier-phase corrections, ideal for surveying and autonomous vehicles. While A-GPS excels in speed and ease of use, DGPS and RTK are superior for high-precision applications.

(d) Precise Point Positioning (PPP)

Precise Point Positioning (PPP) is a GNSS-based technique that achieves high-precision positioning using a single receiver, without the need for a nearby reference station. PPP combines satellite clock and orbit corrections, ionospheric and tropospheric delay models, and advanced error mitigation techniques to deliver accuracy within a few centimeters to decimeters.

The receiver processes the raw GNSS data, including the carrier-phase measurements, and applies corrections derived from global reference networks, such as the International GNSS Service (IGS). Unlike RTK, which requires real-time corrections from a local base station, PPP relies on precise correction data typically transmitted via the internet or satellite.

PPP is ideal for applications requiring high accuracy in remote or globally distributed locations, such as scientific research, geodetic measurements, and surveying in areas where establishing local reference stations is impractical. However, PPP usually requires longer convergence times compared to RTK.

Comparison of PPP and RTK:

1. Accuracy:

- **RTK:** Provides centimeter-level accuracy (1-2 cm), making it ideal for applications requiring extreme precision, such as land surveying, construction, and autonomous vehicle navigation.
- **PPP:** Delivers decimeter to centimeter-level accuracy (typically within a few centimeters), sufficient for scientific research, geodetic measurements, and other high-precision tasks, but slightly less precise than RTK.

2. Cost:

- **RTK:** Generally more expensive due to the need for additional equipment like base stations and real-time communication links (radio, cellular, or internet). Ongoing maintenance and infrastructure costs can also be significant.
- **PPP:** Typically less costly, as it requires only a single high-quality GNSS receiver. There are no base station or communication link costs, making it more economical for global or remote operations.

3. Requirements:

- **RTK:** Requires a base station (or access to a network of base stations) and a rover receiver. It also needs a reliable, real-time communication link between the base and rover to transmit corrections.
- **PPP:** Requires only a single GNSS receiver and access to precise satellite orbit and clock corrections, usually obtained via satellite or internet. No need for a nearby base station or real-time communication with a reference station.

2. Methods to Improve GNSS Localization

(a) . Kalman Filter and EKFs

A Kalman Filter is a mathematical algorithm used to estimate the state of a system (like position, velocity) by combining noisy measurements over time, providing a more accurate and smoothed representation of the data, particularly useful in GNSS localization where raw GPS readings can be affected by noise and sudden fluctuations; it achieves this by continuously predicting the next state based on a dynamic model and then updating that prediction with new measurements, effectively filtering out noise and providing a more reliable position estimate.

1. Modeling the System

The Kalman Filter operates on the principle of combining predictions with measurements to estimate the true state of a system. For GNSS, the system state might include position, velocity, and possibly other parameters like clock bias.

Prediction Step:

- **System Model**: Defines how the state evolves over time. For GNSS, this could involve kinematic equations that describe the movement of the receiver.
- **Prediction**: The Kalman Filter uses this model to predict the next state based on the current state estimate and control inputs.

2. Handling Noise

GNSS measurements are subject to various types of noise, such as:

- **Measurement Noise**: Random errors in the GNSS signals due to atmospheric conditions, satellite clock errors, etc.
- **Process Noise**: Errors in the system model that can arise from simplifications or unforeseen factors.

- **Measurement Model**: Relates the predicted state to the observed measurements.
- **Correction**: The Kalman Filter updates the state estimate by weighing the difference between the actual measurements and the predictions. This correction helps reduce the impact of measurement noise.

(b) Particle Filters

The Particle Filter, also known as Sequential Monte Carlo (SMC) methods, is a sophisticated technique for state estimation in systems with non-linear and non-Gaussian characteristics. Here's a detailed overview and explanation of its suitability for GNSS applications:

Overview of the Particle Filter

1. **State Representation**:
    - The Particle Filter uses a set of particles to represent the state of the system. Each particle is a possible state and collectively, the particles approximate the probability distribution of the system's state.
2. **Initialization**:
    - At the start, particles are generated based on an initial distribution. This can be uniform or based on prior knowledge or estimates.
3. **Prediction Step**:
    - Each particle is updated according to a system model that describes how the state evolves over time. This involves applying the system dynamics to each particle to predict its next state.

Suitability for Non-Linear and Non-Gaussian Systems

1. **Handling Non-Linearity**:
    - Particle Filters are well-suited for non-linear systems because they do not require the linearity assumption. They can directly model complex, non-linear dynamics by propagating particles according to the system's true non-linear model.
2. **Addressing Non-Gaussianity**:
    - Unlike methods that assume Gaussian distributions, Particle Filters can handle non-Gaussian noise and distributions. The use of particles allows the filter to approximate a wide range of probability distributions, including those that are highly skewed or multimodal.

1. Computational Complexity

- **Kalman Filter**:
    - **Computational Complexity**: The Kalman Filter is computationally efficient with a complexity of O(n2) for each time step, where n is the number of state variables. This is because it involves matrix operations like inversion and multiplication.
    - **Scalability**: Suitable for systems with moderate state dimensions. As the state dimension increases, the computational cost grows quadratically, which can become a limitation for very large systems.
- **Particle Filter**:
    - **Computational Complexity**: The computational complexity of the Particle Filter is $O(M \cdot n)$, where M is the number of particles and n is the number of state variables. Each particle requires computation for both prediction and update steps.
    - **Scalability**: The number of particles, M, needs to be large enough to represent the state distribution accurately. As M increases, computational cost grows linearly with M, which can be substantial for high-dimensional state spaces or if the particles are computationally expensive to propagate.

2. Accuracy

- **Kalman Filter**:
    - **Accuracy**: The Kalman Filter provides optimal estimates under the assumption of linearity and Gaussian noise. It minimizes the mean squared error of the estimates if these assumptions hold true. In cases of non-linearity or non-Gaussian noise, the Kalman Filter can produce suboptimal estimates.
    - **Extensions**: Variants like the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) address non-linearity but can still struggle with highly non-Gaussian distributions.
- **Particle Filter**:
    - **Accuracy**: Particle Filters are more flexible in handling non-linear and non-Gaussian systems. They approximate the true state distribution with particles, which allows them to model complex distributions more accurately. The accuracy depends on the number of particles and how well they represent the state space.
    - **Particle Number**: To achieve high accuracy, a large number of particles may be required. This can make the filter more accurate but at the cost of increased computational demands.

3. Robustness

- **Kalman Filter**:
    - **Robustness**: The Kalman Filter is robust to moderate deviations from linearity and Gaussian assumptions. However, it can become unstable if the assumptions are significantly violated or if there are large model mismatches. Its performance can degrade in the presence of strong non-linearity or non-Gaussian noise.
- **Particle Filter**:
    - **Robustness**: Particle Filters are robust to non-linearities and non-Gaussian noise because they do not rely on linear or Gaussian assumptions. They can handle a wide range of error characteristics and complex system dynamics. However, they can be less stable if the particle distribution is not well-managed, leading to issues like particle degeneracy (where a few particles dominate the estimation).

(c) Sensor Fusion

Sensor fusion is the process of combining data from multiple sensors to produce more accurate, reliable, and comprehensive information than could be obtained from any single sensor alone. In the context of GNSS (Global Navigation Satellite System) localization, sensor fusion enhances the accuracy and robustness of positioning by integrating data from various sensors such as IMUs (Inertial Measurement Units), LiDAR (Light Detection and Ranging), and others.

Urban Canyons

Urban canyons are areas with tall buildings that can obstruct GNSS signals or cause multipath effects (where signals bounce off buildings and create false position readings). Sensor fusion can mitigate these issues in several ways:

1. **IMU Integration**: IMUs measure acceleration and angular velocity, providing high-frequency data on movement and orientation. When GNSS signals are blocked or unreliable, the IMU can estimate the vehicle's or user's movement based on inertial data. Sensor fusion combines IMU data with GNSS measurements to provide continuous and accurate positioning, even when GNSS signals are intermittently lost.
2. **Map Matching**: With the help of LiDAR or other mapping sensors, sensor fusion can match GNSS positions to detailed maps of the urban environment. This helps correct GNSS errors by using known features of the environment to infer the true position. For example, if a vehicle is detected to be in a location where it can't be due to building layouts, the system can adjust the position estimate accordingly.
3. **Multipath Mitigation**: By combining GNSS data with other sensor inputs, sensor fusion can reduce the impact of multipath effects. For instance, if LiDAR provides distance measurements that contradict the GNSS position due to multipath, the system can adjust the GNSS data to account for these discrepancies.

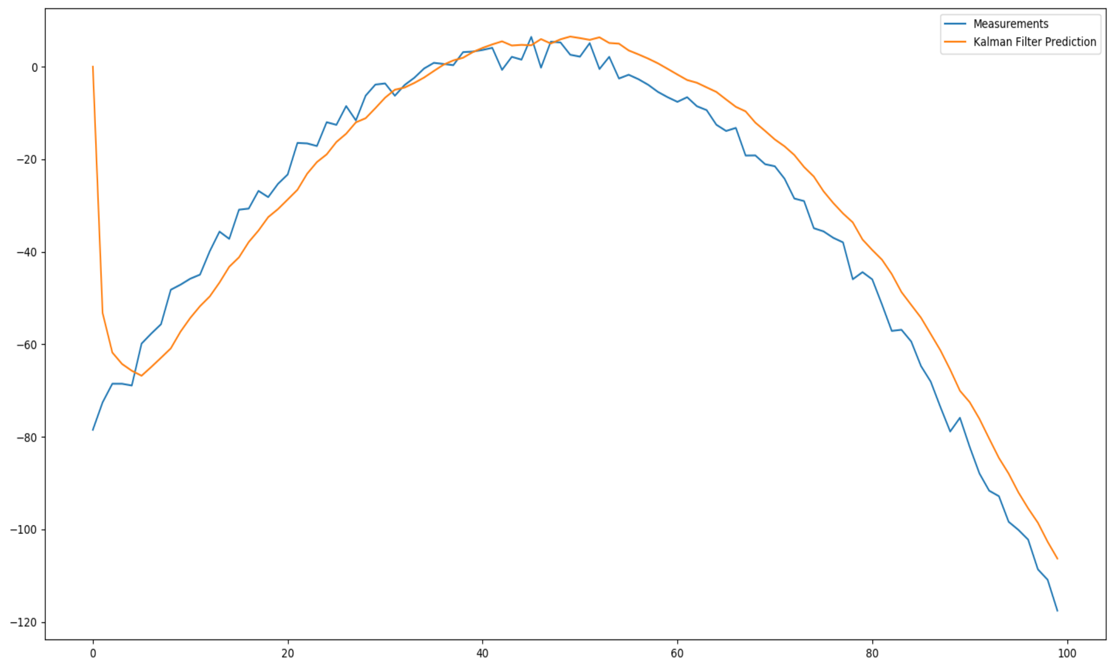
Indoor Environments

Indoors, GNSS signals are often weak or non-existent, making it challenging to obtain accurate positioning. Sensor fusion can address these challenges in the following ways:

1. **Indoor Mapping and SLAM**: LiDAR, visual sensors (like cameras), and other sensors can be used for simultaneous localization and mapping (SLAM). SLAM creates detailed maps of indoor environments and estimates the position within these maps. Sensor fusion integrates these maps with any available GNSS data (if the environment allows for occasional GNSS fixes) to enhance indoor positioning accuracy.
2. **Wi-Fi and Bluetooth Beacons**: In indoor environments, sensor fusion can incorporate data from Wi-Fi or Bluetooth beacons to provide additional localization information. These signals can be used to estimate position based on known beacon locations and signal strength.
3. **IMU for Continuous Tracking**: IMUs can provide continuous tracking of movement even when GNSS signals are not available. By fusing IMU data with other indoor positioning systems (like Wi-Fi or LiDAR), the system can maintain accurate location estimates despite the lack of GNSS.
4. **Environmental Context**: In complex indoor environments, other sensors like cameras can be used for visual recognition and feature extraction. Combining these sensors with GNSS (if it occasionally works) helps to refine and correct the position estimates.

   Simulation with Numpy environment

   # Output


Measurements
Kalman Filter Prediction
0
−20
−40
−60
−80
−100
−120
0
20
40
60
80
100