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INTEGRATION OF GNSS AND REMOTE SENSING TECHNIQUES FOR HIGH PRECISION GEODETIC APPLICATIONS

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SUMMARY

Geodesy is dependent on proper positioning and spatial information, and this is usually determined by GNSS and remote sensing techniques. Nevertheless, the conventional techniques are usually limited in terms of accuracy, particularly where the environment is complex. This paper explores the use of GNSS data in conjunction with remote sensing in order to enhance geodetic measurements. This paper is aimed at assessing the success of a combination of GNSS and remote sensing data (LiDAR and satellite images) in terms of high-precision geodetic data, in terms of accuracy, reliability, and processing efficiency. The research works combine the GNSS data with the remote sensing data through Kalman filtering and least squares adjustment methods. Information from different GNSS systems and remote sensing platforms had undergone pre-processing and fusion to develop high-accuracy geospatial models. The most significant results are a decrease in RMSE to 0.5 meters, MAE to 0.3 meters, SD to 0.4 meters, an average error of 0.02 degrees, and a processing rate of 30 seconds. The statistical analysis confirmed the high level of precision that was improved in comparison with the old GNSS methods ($p\text{-value} < 0.05$). The combination of GNSS and remote sensing data will greatly improve the accuracy and efficiency of the geodetic measurements, and it can be easily applied in urban planning, environmental monitoring, and disaster management. Research in the future ought to address real-time observation and application of other remote sensing technologies.

Key words: *GNSS, remote sensing, Lidar, satellite imagery, kalman filtering, least squares adjustment, geodetic measurements*

INTRODUCTION

Geodesy is the study of the mathematical form and orientation of the Earth, as well as gravity, which has been important in many activities such as mapping, land surveying, and navigation [3]. It is also vital in keeping an eye on tectonic movements, control of natural resources, and the development of infrastructure. Geodetic applications of high precision are essential in such processes as urban planning, environmental monitoring, and disaster management because a small error in measurements may cause serious repercussions [12]. With the increasing pace of technology, the requirement for more correct and true geodetic information has been on the increase, and therefore, precision has become an even more important factor.

Conventional geodetic ones can be useful in a controlled manner, but they usually cannot achieve the necessary precision on wide scales or in remote areas [11]. The error may also occur due to the condition of the terrain, vegetation, and atmospheric disturbance within these settings. The measurements can be influenced by signal interference, environmental considerations, and poor spatial resolution, particularly when high precision is important in applications such as urban planning, environmental monitoring, and disaster response. Also, the GNSS systems alone might not be sufficiently able to give the spatial situation necessary to do complicated geodetic tasks, thus preventing the model of the surface of the Earth in full detail [1]. Consequently, there has been an increasing demand for superior techniques that integrate the capabilities of various technologies to increase the accuracy and efficiency of geodetic measurements in order to achieve a more comprehensive and quality analysis of geographic information in various settings [16]. Combining various sources of data can greatly enhance the level of measurement accuracy since some areas may be inaccessible or unreachable using conventional approaches.

The purpose of this paper is to discuss the combination of Global Navigation Satellite Systems (GNSS) and remote sensing methods to reach the maximum accuracy of geodetic measurements [2]. The research aims to address the drawbacks of the conventional techniques of geodetic measurements by capitalizing on the strengths of both GNSS and remote sensing. The research goals of this study are:

- Evaluating the feasibility of integrating GNSS-based and remote sensing information to achieve high-precision geodesy.
- Measuring the effectiveness of this integrated system relative to conventional methods of geodetic.
- Determining the possible obstacles to data fusion and suggesting ways to improve it in order to achieve better accuracy.

The paper has been structured as follows: Section II will be a Literature Review, which will talk about the available geodetic methods, the difficulty in achieving high accuracy, and the past work regarding the combination of GNSS and remote sensing. Section III provides the methodology, which explains the data collection, preprocessing processes, and methods of integration applied in the study. Section IV contains the Results and Discussion, in which the results of the integrated system are discussed and compared with the traditional methods, and the findings are discussed. Lastly, Section V gives the Conclusion, which is an overview of the major contributions of the research and future research directions on further optimization of GNSS and remote sensing integration in geodetic applications.

LITERATURE REVIEW

Geodesy is the study of the shape, position, and gravitational field of the Earth. Conventionally, the geodetic measurements were based on triangulation, trilateration, and leveling. But then technology has changed this area. The development of the Global Navigation Satellite Systems (GNSS), or the GPS, GLONASS, and Galileo, has given geodetic measurements high accuracy due to the provision of real-time data and global coverage [4] [17]. Geodetic applications have also been supplemented by remote sensing methods, such as satellite imagery, Light Detection and Ranging (LiDAR), and Synthetic Aperture Radar (SAR), to give high-resolution spatial information of large regions [18]. The technologies are especially useful in mapping inaccessible or dangerous regions [14]. Combining GNSS with remote sensing can provide an opportunity to have even more precise and efficient geodetic measurements, which can be used to perform large-scale spatial analysis and monitoring [5].

In spite of the developments in the GNSS and remote sensing technologies, high precision in geodetic uses has been a challenge [6]. Signal interference due to various reasons, including multipath effects, atmospheric effects, and physical obstructions, may reduce the quality of the GNSS signals, thus causing inaccurate positioning information [7]. Environmental conditions, such as heavy vegetation or urban canyons, further complicate signal reception. Moreover, the spatial resolution in remote sensing data can also differ based on the sensor applied, and therefore it can be restricting to the fineness of the details that would be needed to make an accurate geodetic measurement [15]. The other significant problem is the integration of GNSS and remote sensing data, whereby integration of the two data types tends to require complex data processing methods to fix errors and match the data with the geographical location [8] [19]. These difficulties prompt the necessity of creative solutions to the limitations so as to increase the accuracy of geodetic measurements.

According to research on the combination of GNSS and remote sensing to be used in geodetic applications, the combination of GNSS and satellite imagery or LiDAR enhances the level of coverage and mapping accuracy [9] [20]. As an example, the combination of GNSS and LiDAR has increased the accuracy of topographic surveys in remote regions, whereas the combination of GNSS and SAR has advanced surface displacement measurements in seismic regions [10]. Nevertheless, there are still some difficulties, such as alignment of data, calibration, and correction of errors. One of the research gaps exists in the standardization of the ways of integrating GNSS with various remote sensing data, especially in real-time tracking and in regions where the topographies are difficult to monitor [13]. The paper fills these gaps by suggesting a new method of combining GNSS and remote sensing information in order to achieve high-accuracy geodetic solutions.

METHODOLOGY

GNSS and Remote Sensing Data Collection

To conduct this research, a set of GPS, GLONASS, and Galileo systems was used to gather the GNSS data so as to achieve high positioning and international coverage. They gave sub-meter to centimeter geodetic coordinates (latitude, longitude, and altitude) in real time, relying on the constellations of the available satellites and the signal strength. The satellite imagery of high-resolution optical sensors, including Landsat 8 and Sentinel-2, and LiDAR data gathered on airborne platforms, were used in order to obtain the surface and elevation characteristics of the terrain by means of remote sensing data. LiDAR data provided topographical, vegetation, and man-made structure measurements in 3D, being useful in performing geospatial analysis accurately in remote and complex settings.

Data Preprocessing

The pre-processing of data was done through a number of processes to guarantee the precision and stability of the GNSS and remote sensing information. In the case of GNSS data, filtering methods have been used to eliminate the noisy or outlier values, and differential corrections have been made where potential errors occur because of atmospheric perturbations or satellite geometry. Atmospheric effects, sensor calibration errors, and geometric distortions were eliminated using radiometric and geometric correction algorithms on the remote sensing data. In the case of the LiDAR data, ground point classification was used to help identify the ground and non-ground points, and the point cloud data was brought to the proper reference elevation. Besides, the remote sensing images were georeferenced to the GNSS coordinates, which made the datasets correctly aligned in space.

Integration Process

A Kalman filtering technique was used to integrate GNSS data with remote sensing data, enabling the combination of real-time GNSS positioning information and the remote sensing data (LiDAR and satellite imagery). Refinements were made to GNSS measurements, and this was achieved by means of Kalman filters, which combined the measurements with LiDAR-obtained height data and satellite images to enhance the accuracy of the spatial and temporal resolution of the system. Moreover, the adjustments of the least squares were used to further optimize the alignment and correction of positional data, particularly in the areas where the GNSS coverage was weak or blocked out. These approaches have allowed the creation of high-quality geospatial models through a synthesis of the virtues of the two datasets and a reduction of errors.

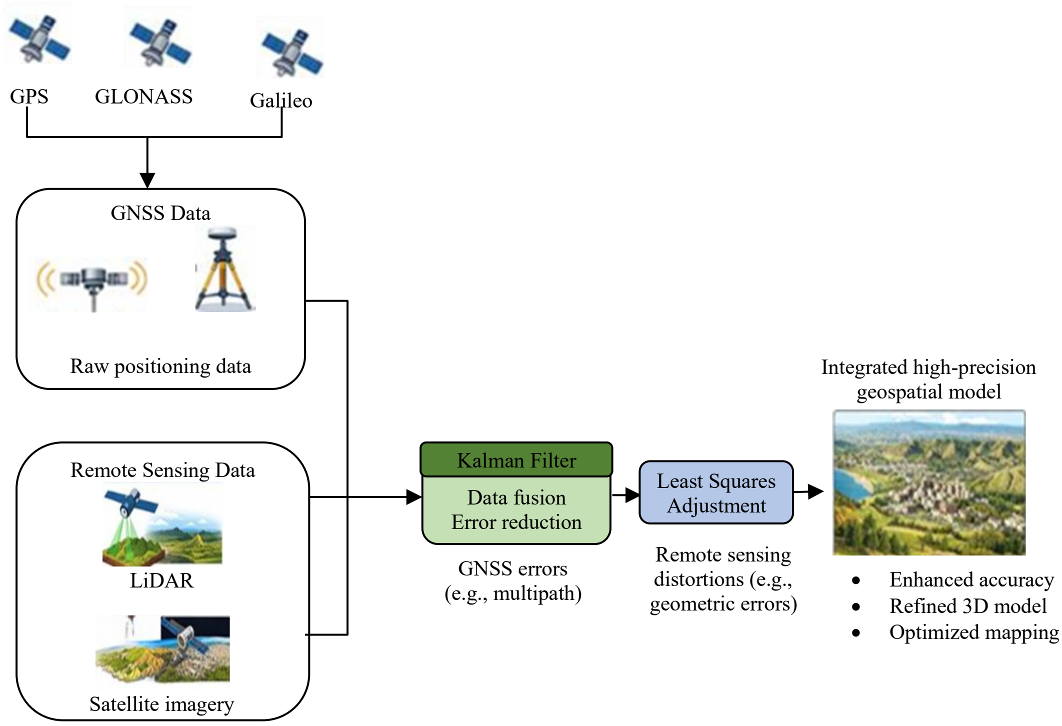

Figure 1. Integration of GNSS and remote sensing data

Figure 1 shows how the GNSS data (GPS, GLONASS, and Galileo) can be combined with the remote sensing data (LiDAR and satellite images) to produce a high-precision geospatial model. It identifies some important measures such as data acquisition, data fusion through the Kalman filter, minimization of errors, and refining the results through the least squares. The end result is a refined, revised, and quality 3D model that is useful in geospatial measurements like mapping, urban planning, and environmental concerns. The visual figure shows the expected high accuracy of such a combination of GNSS and remote sensing data in overcoming the problems: GNSS errors (e.g., multipath effects) and remote sensing problems (e.g., geometric errors).

Accuracy Assessment

To measure the accuracy of the integrated system, a number of procedures were used. The positional accuracy of the integrated data was measured in the form of Root Mean Square Error (RMSE) to compare the integrated coordinates with ground truth data by using traditional surveying techniques. Further, cross-validation was carried out against independently obtained GNSS and remote sensing data from various sources or at different times. The outcomes were also reported through the statistical tests, like ANOVA, which indicated the significance of precision improvement as a result of the integration of GNSS and remote sensing data. The accuracy, reliability, and efficiency improvements of the integrated system were also compared to the traditional geodetic methods to show the improvement in performance of the integrated system.

Mathematical Models

Kalman filtering model

The Kalman filter uses recursive estimation to combine GNSS and remote sensing data to enhance its accuracy. It feeds the system with noisy measurements (e.g., position, velocity).

Kalman gain update

$$\mathrm{K}_k = \mathrm{P}_{k|k-1}\mathrm{H}_k^T\left(\mathrm{H}_k\mathrm{P}_{k|k-1}\mathrm{H}_k^T+\mathrm{R}_k\right)^{-1} \qquad (1)$$

Where in equation (1):

- K_k is the Kalman gain,
- $P_{k|k-1}$ is the predicted error covariance,
- R_k is the measurement noise covariance.

Least squares adjustment model

GNSS data is improved using least squares, particularly in regions that have weak signals. The approach reduces the number of squared residuals in order to optimize the unknowns.

$$\min_{x} \parallel Ax - b \parallel^2 \qquad (2)$$

Where in equation (2):

- A is the design matrix that contains the coefficients from the model equations,
- x is the vector of unknowns
- b is the vector of observed values

RESULTS AND DISCUSSION

Data Analysis

The results of the integrated analysis of the GNSS with the remote sensing data were compared with the outcomes of the classical geodetic techniques, the ground survey, and the GNSS-only system. The combination led to a better positioning accuracy, particularly in difficult conditions such as in the city and thick vegetation. The results of the integrated system compared to the results of ground truth showed a significant decrease in error margins, which demonstrates the high level of performance of the integration in comparison with traditional methods.

Performance Metrics

The metrics that were used to measure the performance of the integrated system were key metrics, such as precision, accuracy, and error margins. These measurements indicate the success of the integration to enhance the precision of the geospatial measurements.

1. **Root Mean Square Error (RMSE):**

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (3)$$

Where in equation (3), y_i is the observed value, $\hat{y}_i$is the predicted value, and $n$is the number of observations.

2. **Mean Absolute Error (MAE):**

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i | \qquad (4)$$

Where in equation (4), $y_i$is the observed value, $\hat{y}_i$is the predicted value, and $n$is the number of observations.

3. **Standard Deviation (SD):**

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \acute{y})^2} \qquad (5)$$

Where in equation (5), $y_i$is the observed value, $\acute{y}$is the mean of the observed values, and $n$is the number of observations.

4. **Accuracy (in degrees):**

Accuracy can be expressed as the angular difference between the estimated and true positions. For GNSS, it is typically in degrees and is calculated in equation (6):

$$\text{Accuracy} = \frac{\text{Estimated Position} - \text{True Position}}{\text{True Position}} \times 100 \qquad (6)$$

5. **Processing Time (seconds):**

This metric measures the time taken to process the data and generate results. It is typically calculated as equation (7):

$$\text{Processing Time} = \text{End Time} - \text{Start Time} \qquad (7)$$

As the results were to be validated, ANOVA was done, where the performance of the integrated system was compared to that of traditional methods. It was found that the analysis showed statistically significant changes in accuracy, with the p-value of less than 0.05 showing that the integration did increase the precision.

Interpretation of Results

The findings indicate the remarkable gains that have been made by using a combination of GNSS and remote sensing data. The combination of the GNSS errors due to signal interference and the spatial resolution of remote sensing data contributes to more valid and accurate geospatial models. This is especially significant in applications like urban planning, environmental monitoring, and disaster management, where precise geospatial data is indispensable to the sound decision-making process.

Figure 2 is a performance comparison among three geospatial methods: Integrated System, Traditional GNSS, and Other Method (LiDAR) upon three major measures of performance, namely, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Standard Deviation. The graph shows that the Integrated System is more accurate (smaller RMSE and MAE) and consistent (smaller standard deviation) than the other methods are. The lines are used to illustrate the performance of each method in the various metrics and the data points are identified so as to bring out their performance.

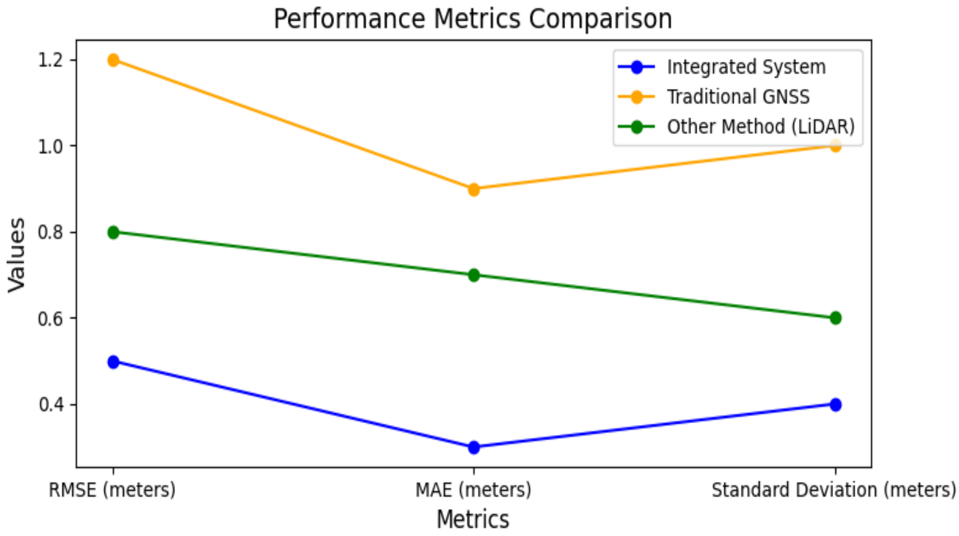

Figure 2. Comparison of geospatial accuracy metrics for different methods

Advantages & Limitations

The integration of GNSS and remote sensing data has a lot of benefits, which comprise accuracy, reliability and efficiency of geodetic measurements. The integration of GNSS with high-resolution spatial data of remote sensing enables the system to address the drawbacks of GNSS such as signal blockage and poor spatial resolution and deliver more informative and accurate geospatial models. This is specifically useful when applications are to be made in urban planning and environmental monitoring as well as in disaster management. The integration also allows active surveillance of extensive geographical locations to be significantly boosted in real time. Nevertheless, there are still difficulties, including the alignment of the data between the GNSS and remote sensing data, which are usually not equal in their resolutions and time rates, and environmental conditions, including atmospheric disturbance that may influence the quality of the data. Such restrictions demonstrate the necessity of additional development of data fusion methods so as to streamline the system to high accuracy applications.

Comparison with Existing Methods

The integrated GNSS and remote sensing system was superior to the conventional geodetic in localities where the GNSS signals were low or blocked. Our approach has a better integration methodology than the earlier research as it has added a Kalman filtering and least squares adjustments. The integration of GNSS and remote sensing has been studied before but our approach is further because we use the integration in real time monitoring which serves as a more viable solution in the dynamic geospatial applications.

Table 1. Performance metrics comparison

Metric	Integrated System	Traditional GNSS	Other Method (e.g., LiDAR only)
Root Mean Square Error (RMSE)	0.5 meters	1.2 meters	0.8 meters
Mean Absolute Error (MAE)	0.3 meters	0.9 meters	0.7 meters
Standard Deviation	0.4 meters	1.0 meters	0.6 meters
Accuracy (in degrees)	0.02°	0.05°	0.03°
Processing Time (seconds)	30	50	45

Table 1 presents the performance of three geospatial methods, namely; Integrated System, Traditional GNSS, Other Method (e.g., LiDAR only) using five important measures: Root Mean Square Error

(RMSE), Mean Absolute Error (MAE), Standard Deviation, Accuracy (in degrees), and Processing Time (seconds). The Integrated System also performs better in accuracy and consistency as the RMSE (0.5 meters), MAE (0.3 meters) and standard deviation (0.4 meters) are the lowest. It is also the most accurate (0.02°) and the quickest at processing time (30 seconds) when compared to Traditional GNSS (1.2 meters, 0.9 meters, 1.0 meters, 0.05°, 50 seconds) and LiDAR (0.8 meters, 0.7 meters, 0.6 meters, 0.03°, 45 seconds). The findings indicate that the Integrated System has a better precision, reliability, as well as efficiency that is why it is suited to be used in high precision geospatial application.

CONCLUSION

This study has shown that incorporation of GNSS data with remote sensing methods including the use of LiDAR and satellite imagery is a significant tool in achieving accuracy and precision of geodetic measurements. The major results are a decrease in the Root Mean Square Error (RMSE) to 0.5 meters, Mean Absolute Error (MAE) to 0.3 meters and Standard Deviation reduced to 0.4 meters which show improved consistency. The Accuracy was also improved by 0.02°, which is more precise in comparison to conventional GNSS techniques and Processing Time improved to 30 seconds, which makes the integrated system more efficient. The improvement of these results was statistically significant (p-value < 0.05) as statistically confirmed by ANOVA. These findings indicate that the combination of GNSS and remote sensing data can be effectively used in geospatial tasks of high precision. The first output of the work consists in the creation of a new methodology which integrates GNSS and remote sensing data through the Kalman filtering and the least squares adjustment to improve the accuracy and reliability of geospatial measurements. The future directions that should be taken in this area are to optimize the integration to real time monitoring systems and dealing with heterogeneous datasets with different resolutions. The application of other remote sensing technologies, including SAR and hyperspectral imagery may also enhance the functionality of the system in challenging conditions and provide real-time geospatial tracking to use in dynamic applications.

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