# DESIGN OF MULTI-CONSTELLATION GNSS DEFORMATION MONITORING NETWORK BY PARTICLE SWARM OPTIMIZATION METHOD

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**ABSTRACT:** Global Navigation Satellite System (GNSS) has become the main technique for ground deformation monitoring. In order to meet predefined quality criteria, optimized design of GNSS network is an essential part of such monitoring tasks. Classically, the trial and error method is used in optimization of GNSS network. Recently, intelligent techniques which can be applied in optimization problems, such as the Particle Swarm Optimization (PSO) algorithm, can also be used for the design of a network. Additionally, with the rapid advances in GNSS, the benefits of integrated multi-constellation GNSS should be brought to the deformation analysis through an appropriate network design procedure. In this study, the multi-constellation GNSS were applied and terrestrial obstruction effects were considered to evaluate the quality of a network positioning result. Then, the minimum detectable principal strain index was introduced as the optimal design criteria. Finally, the PSO method was adopted for an automatic design of deformation monitoring network. The results revealed significant improvement in the accuracy of deformation analysis when multi-constellation GNSS systems were applied. Moreover, an automated optimization method of the multi-constellation GNSS monitoring network configuration was achieved by PSO method. Through the optimization of the monitoring network, the minimum detectable principal strain index was massively improved. Consequently, the profit of introducing the multi-constellation GNSS techniques in the ground deformation monitoring tasks can be maximized with the proposed automatic network design approach.

## 1. INTRODUCTION

For the ground deformation monitoring tasks, a high-accurate positioning technique such as Global Navigation Satellite System (GNSS) is typically required to capture sophisticated deformation signals. GNSS provides 24-h continuous and high-precision positioning in all-weather condition and at most locations. Nowadays, GNSS has been extensively used worldwide for monitoring crustal motions, landslides etc. (Hollenstein et al., 2008; Malet et al., 2013). In order to precisely measure ground deformation and meet predefined quality criteria, optimized design of GNSS network is an essential part of such monitoring tasks. Classically, the trial and error method has been used to solve the geodetic network design problem. Recently, some intelligent techniques have been started to be applied in optimization problems such as the Particle Swarm Optimization (PSO). PSO proposed by Eberhart and Kennedy (1995) is a search heuristic method, which imitates the social behavior of flying birds flock, has been found to be robust and fast in solving nonlinear and multi-object problems (Shi and Eberhart, 1998). The algorithm has also been used to design of a GNSS network (Yetkin et al., 2011; Dwivedi and Dikshit, 2013; Doma and Sedeek, 2014).

With the advances of satellite techniques, different nations/institutions have developed their own satellite system, including the U.S.A Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the European Galileo and the Chinese BeiDou Navigation Satellite System (BDS) (Hegarty and Chatre, 2008). The increasing number of GNSS satellite improves accuracy and availability of GNSS (Ji et al., 2010; Alkan et al., 2015). The benefits of integrated multi-constellation GNSS should be brought to the deformation analysis. Therefore, the main objective of this study was to apply multi-constellation GNSS in deformation monitoring task and optimize the network through an appropriate design procedure. For the purpose, terrestrial obstruction effects were considered to evaluate the quality of a network positioning result more accurately. The strain sensitivity index - minimum detectable principal strain index (Han et al., 2011) was used as the optimal design criteria to reflect the capability of a network in monitoring potential strain. Moreover, PSO algorithm was applied in the GNSS network optimization problem to reach predefined accuracy criteria. The paper ends with a conclusion and possible directions for future research.

## 2. METHOD

Methods in this study included four major parts: satellite orbit calculation, terrestrial obstruction effects analysis, strain analysis and PSO algorithm. They will be introduced separately in the following sections.

### 2.1 Satellite Orbit Calculation

GNSS positioning is based on the trilateration concept, thus the quality of positioning highly relies on the geometry formed by the satellites visible to a specific ground location. In order to conduct a satellite visibility analysis, estimation of satellite orbits becomes the first step in such an analysis. Satellite position in space can be calculated by using six Keplerian orbital elements (Figure 1), which is based on the normal orbital theory (Leick, 2004).

1. a: semi-major axis of satellite orbit
2. e: eccentricity of satellite orbit
3. Ω: right ascension of the ascending node
4. I: orbital inclination
5. ω: argument of perigee
6. ν: true anomaly

The position of satellites was computed with a, e and ν elements in the orbital frame first. Further, the parameters of Ω, I and ω were used as rotation angle to obtain the satellite coordinates in the inertial coordinate system. Then, the result was converted into the Earth-Centered-Earth-Fixed (ECEF) coordinates with the rotation of Greenwich Sidereal Time (GST). Generally, Kepler elements can be obtained from broadcast ephemeris and almanac file. In fact, the time system and orbital parameters provided in ephemerides and almanac files are different according to each GNSS system. For example, the GLONASS almanac contains a set of modified Keplerian orbital parameters such as correction to the mean value of orbital inclination and period. Moreover, GLONASS time system is adjusted for leap seconds while GPS and BDS system are not. Hence, time and parameter conversions between multi-GNSS systems are required before orbital theory applied for the calculation of satellite orbits.

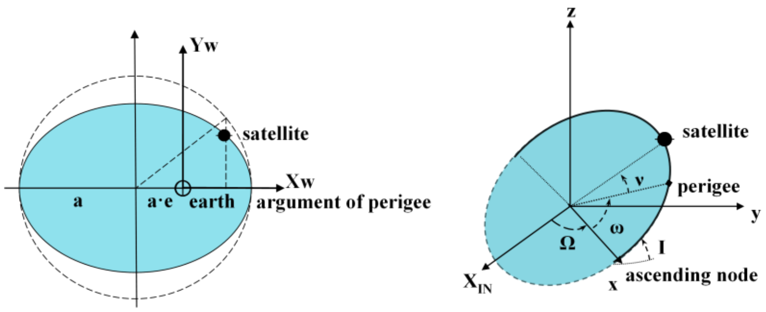



Figure 1. Satellite's Orbit and Keplerian orbital elements.

### 2.2 Terrestrial Obstruction Effects Analysis

Once the position of a satellite has obtained, the important part of the quality evaluation of positioning – satellite visibility analysis could be determined. Normally, a mask angle was used as a simulation of obstructed environment around the receiver. The satellite was identified as visible to the receiver only if the elevation angles of satellites were higher than the mask angle. In this regard, current satellite visibility analysis programs assumed receivers located at an open area and the environmental obstructions around receivers were treated as the same by using a single mask angle. This assumption may be suitable for an open and simple positioning environment. However, it may result in overestimation of the quality of satellite positioning, especially in the environment with complicated surface variations (e.g., a mountain or urban area).

To improve prediction of satellites visibility, Light of Sight analysis between receiver and satellite applied with terrestrial topographical information. Firstly, the elevation angles (*El*) of all obstructions around receiver were computed (Figure 2). Then, the obstruction angle was determined by maximum elevation angle ($El_{max}$) in each direction of the receiver (Han and Li, 2010; Han et al., 2015). The satellites which had a larger elevation angle than $E_{lmax}$ would be identified as visible to the receiver. After the visible satellites with respect to the receiver are conducted, they were used to form observation equations by relative positioning model to compute the quality of positioning.

With the terrestrial obstruction effects analysis, the quality of positioning could be evaluated more realistically.

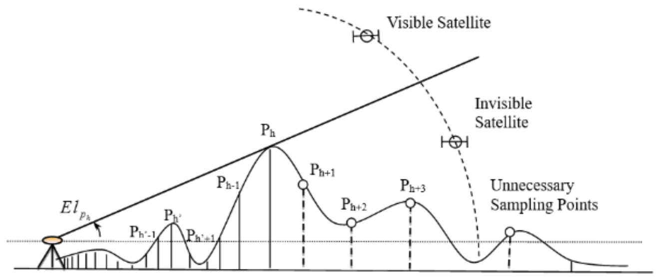



Figure 2. Sampling points of obstructions and the maximum of elevation angle (Han et al., 2015)

### 2.3 Strain Analysis

Strain analysis is widely used in the investigation of earth's surface deformation because it provides a numerical measurement of the relative deformation behavior of a target area. In order to quantify the capability of GNSS network in detecting deformations, the principal strain parameters were computed by the positional observations of the deforming network between two epochs. Han et al. (2011) proposed the strain sensitivity index - the minimum detectable principal strain parameter ($\Delta_{max}$) of the network, which was based on sensitivity analysis techniques, could estimate the critical lower-bound of the deformation signals under a given network configuration. Moreover, properties of matrix and eigen-theory were also applied to eliminate the perturbation from reference frame variation, then a direct estimation of principal strain parameters was obtained. As the $\Delta_{max}$ gets larger, the capability of the network to detect strain will be worse. Therefore, the minimum detectable principal strain parameter can indicate the sensitivity of monitoring network and be used as an evaluation index of how well a network can detect deformations.

### 2.4 Particle Swarm Optimization

PSO used a number of particles to represent a bird flock. Each particle was considered as a potential solution, it flies around in the search space and looks for the best solution. In the process of optimization, the particle kept storing the coordinates of its local best solution ($\mathbf{X}_{\mathbf{Pbest}}$) and global best solution ($\mathbf{X}_{\mathbf{Gbest}}$), which the particle has got so far. If the $\mathbf{X}_{\mathbf{Pbest}}$ had a better performance than the current $\mathbf{X}_{\mathbf{Gbest}}$, then the $\mathbf{X}_{\mathbf{Gbest}}$ would be replaced by the local best solution $\mathbf{X}_{\mathbf{Pbest}}$. Subsequently, the moving direction and velocity of the particle were adjusted according to the track of its own flying experience as well as the flying experience of its companions (equation 1). Once the velocity of each particle has computed, each particle flew towards a new position (equation 2) and the new fitness value was calculated. In an iterative process, the updates of velocity and position of particles were repeated until the predefined criteria was met (Shi and Eberhart, 1998).

$$\mathbf{v}_i(\mathrm{t}+1) = w \cdot \mathbf{v}_i(\mathrm{t}) + C_1 \cdot r_1 \cdot [\mathbf{x}_{\mathbf{Pbest}} - \mathbf{x}_i] + C_2 \cdot r_2 \cdot [\mathbf{x}_{\mathbf{Gbest}} - \mathbf{x}_i] \quad (1)$$

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{v}_i(\mathrm{t}+1) \quad (2)$$

where, $i$ is the index of particles. $C_1$ and $C_2$ are two positive constants, which represent the individual learning and social learning ability of particles, respectively. $r_1$ and $r_2$ are uniformly distributed random numbers in the range [0, 1], which can provide the diversity of the swarm. $w$ is an inertia weight term of a time function.

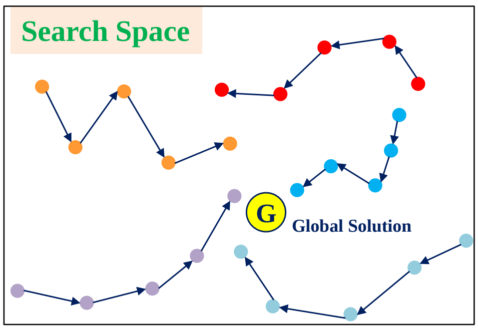



Figure 3. The searching process of PSO

## 3. SIMULATION RESULTS AND DISCUSSION

In this study, Taitung County in Taiwan was selected as the study area to establish a GNSS deformation monitoring network consisted five monitoring stations (Figure 4). The preliminary design of GNSS network is shown in Figure 5. In the calculation of satellite position, the actual almanacs from the information-analytical center official website were used to determine GPS and GLONASS satellite orbits. The coordinates of BDS satellites were computed by broadcast ephemeris. The temporal resolution of satellites position was selected as five minutes. Moreover, 30m digital elevation model (DEM) was applied to estimate the obstruction line. In the following sections, the performance of positioning and strain analysis between GPS-only and multiple GNSS system (GPS + GLONASS +BDS) have been compared first. Horizontal dilution of precision (HDOP) and a number of visible satellites were used to assess the quality of positional estimations. Strain sensitivity index was calculated to evaluate the performance of strain analysis. In order to meet the quality criteria, PSO method was adopted for an automatic design of GNSS deformation monitoring network. A new optimized monitoring station was searched by PSO method and added to the current network. In the optimization process, the terrestrial obstruction effects analysis and strain analysis were conducted again to get the new fitness value of the network until the required quality was met.

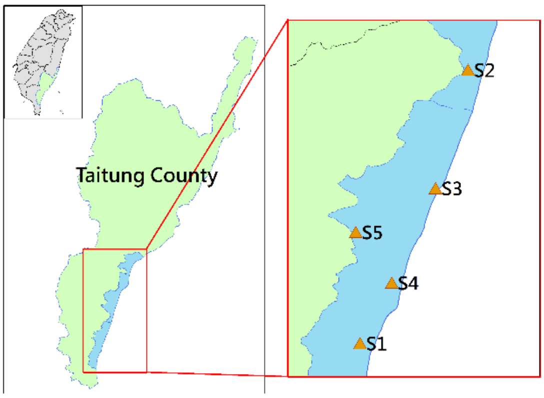



Figure 4. Geographic locations of monitoring stations

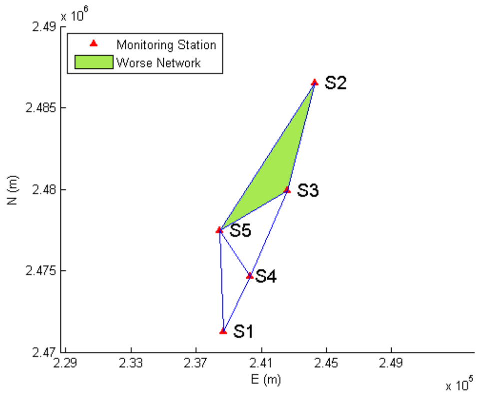



Figure 5. GNSS deformation monitoring network

### 3.1 The Performance of Positioning and Strain Analysis

Through the terrestrial obstruction effects analysis, the west side obstruction could be observed in stations S3, S4 and S5 from sky plots in Figure 6. The maximum obstruction angle of S3 was even closed to 30 degrees.

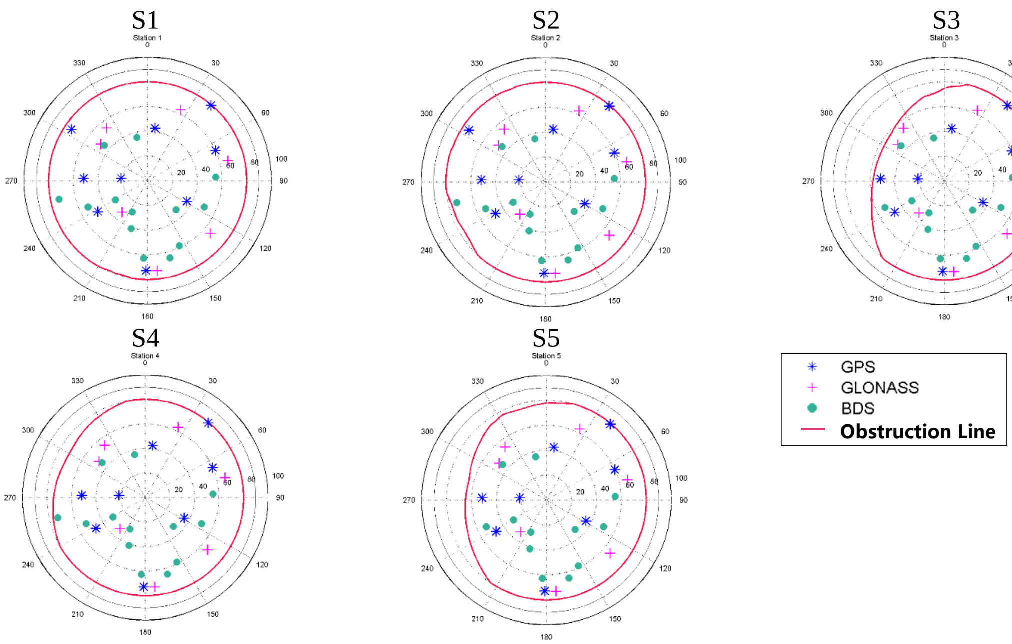



Figure 6. The predicted sky plots with obstruction lines

Compared to the stations in an open area such as S1 and S2, the stations in a highly obstructed environment, such as S3 and S5, obviously had fewer visible satellites and poor HDOP values (Figure 7). It shows that the quality of satellite positioning cannot be guaranteed in a tough monitoring environment. In the GPS-only used situation, the average amount of visible satellites was under 10 and the average HDOP value was over 2. As GPS, GLONASS and BDS systems were combined, there were more than 20 satellites could be observed in each station and the HDOP value was reduced to under 1.5. It means the multiple GNSS technique improves not only the number of visible satellites but also the quality of positioning. Especially, the benefit of applying multiple GNSS in the critical environment is extremely significant.

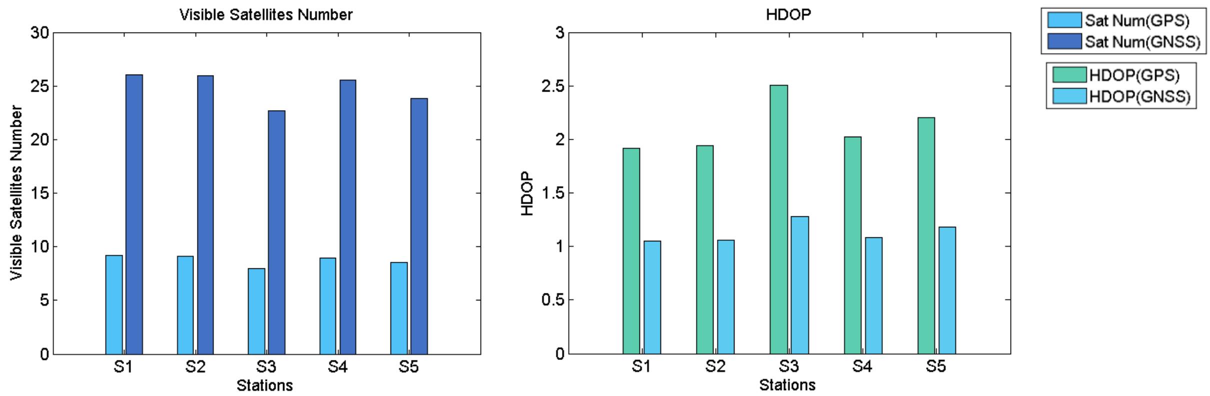



Figure 7. In GPS-only and multiple GNSS system applied situation, the visible Satellites number and HDOP performance of each station

After the evaluation quality of satellite positioning, the triangulation networks for strain analysis were constructed by the monitoring stations, as shown in Figure 5. Then, the minimum detectable principal strain parameter ($\Delta_{max}$) of each network was computed. In the strain analysis, the strain detecting capability of a network is highly dependent on the accuracy of positional measurement and its network configuration. The network (S2, S3 and S5), which was shown in Figure 5 with green area, had a lower sensitivity of strain detecting both in GPS-only and multiple GNSS applied case due to its narrow shape of the network. In GPS-only case, its minimum detectable principal strain of triangulation networks was 16.627 ppm. In multiple GNSS case, its sensitivity of strain detecting of networks was improved to 9.097 ppm, which was elevated up to 45.3%. With the multiple GNSS systems applied, the twice of capability in detecting strains was obtained when compared to the GPS-only case. It means the smaller signals of deformation can be detected with using multiple GNSS.

Table 1. The strain sensitivity index of deformation monitoring network

| Network | | | Minimum Detectable Principal Strain ($\Delta_{max}$) | | Improvement of $\Delta_{max}$ |
|---|---|---|---|---|---|
| Composed Stations | | | GPS | GNSS | |
| S1 | S4 | S5 | 13.564 ppm | 7.671 ppm | 43.4% |
| S3 | S4 | S5 | 5.692 ppm | 3.146 ppm | 44.7% |
| S2 | S3 | S5 | 16.627 ppm | 9.097 ppm | 45.3% |

* Improvement of $\Delta_{max}$ = $\Delta_{max(GPS)} - \Delta_{max(GNSS)} / \Delta_{max(GPS)}$

### 3.2 Optimization of Network by PSO

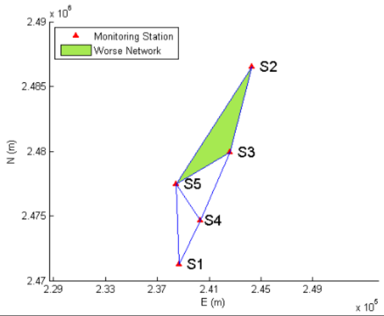
In this deformation monitoring case, the network was required to be able to detect at least 4 ppm strains. However, the minimum strain detecting capability of preliminary multiple GNSS applied network was 9.097 ppm. The network should be optimized to reach the required 4 ppm criteria. Therefore, the aim was to determine the optimized position of a new monitoring station based on PSO algorithm. The summary of all parameters used in the algorithms is presented in Table 2. The result of optimization network was shown in Table 3. As the first new station (A1) was added to the network, its minimum strain detecting capability was improved to 4.401 ppm, which was close to the above set design criteria. Based on the 1st optimization network, the second new station (A2) was added. The minimum detectable principal strain parameter was 3.389 ppm, which have reached even performed better than the required quality criteria. The sensitivity of the network strain detecting was elevated about 62.7% (from 9.097 ppm to 3.389 ppm). Additionally, the shape of the narrow triangulation network (S2, S3 and S5) mentioned above was improved at the same time.

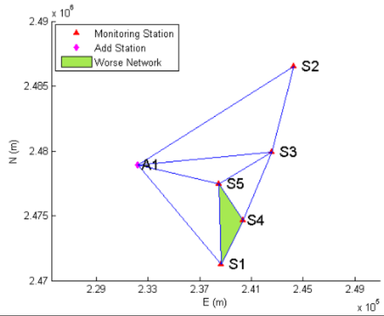
Table 2. PSO parameters

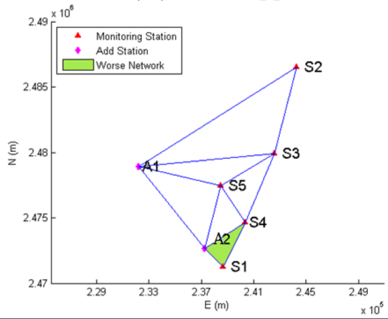
| Parameter | Value |
|---|---|
| Particles Swarm Size | 10 |
| Max. Iteration | 80 |
| $C_1$&$C_2$ | 1.1,1.75 |

Table 3. Optimization Network

| Preliminary Network | 1st Optimization Network (A1 added) | 2nd Optimization Network (A2 Added) |
|---|---|---|
| $\Delta_{max(wn)}$ = 9.097 ppm | $\Delta_{max(wn)}$ = 4.401 ppm | $\Delta_{max(wn)}$ = 3.389 ppm |




*$\Delta_{max(wn)}$ is the minimum detectable principal strain parameter of the worse network

## 4. CONCLUSION

The design of the network is an essential prior work on ground deformation monitoring tasks. Additionally, the accuracy and availability improvement of multiple GNSS is found in other research. Therefore, the major motivation of this study is to bring the benefit of multiple GNSS into ground deformation monitoring analysis through an appropriate optimization network design procedure and technique. Through the numerical analyses, a comparison of positioning and strain analysis of GPS-only and multiple GNSS has shown a reliable deformation analysis could still be guaranteed even in a GNSS-hostile area when the multi-constellation GNSS systems are implemented. Moreover, this study has presented results of a multiple GNSS monitoring network design problem using global optimization techniques – Particle Swarm Optimization algorithm. The capability of strain detecting of the GNSS network was significantly improved. It means PSO have successfully and efficiently solved the GNSS network optimization problems. In addition, the benefit of multiple GNSS was brought into deformation monitoring tasks with the optimization procedure. The present investigation can be extended further with multi-objective network optimization problems as a potential research topic to construct a high accuracy and reliability ground deformation monitoring network.

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