Federated Filter Approach for GNSS Network Processing

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Abstract

A large number of service providers in countries all over the world have established GNSS reference station networks in the last years and are using network software today to provide a correction stream to the user as a routine service. In current GNSS network processing, all the geometric related information such as ionospheric free carrier phase ambiguities from all stations and satellites, tropospheric effects, orbit errors, receiver and satellite clock errors are estimated in one centralized Kalman filter. Although this approach provides an optimal solution to the estimation problem, however, the processing time increases cubically with the number of reference stations in the network. Until now one single Personal Computer with Pentium 3.06 GHz CPU can only process data from a network consisting of no more than 50 stations in real time. In order to process data for larger networks in real time and to lower the computational load, a federated filter approach can be considered. The main benefit of this approach is that each local filter runs with reduced number of states and the computation time for the whole system increases only linearly with the number of local sensors, thus significantly reduces the computational load compared to the centralized filter approach.

This paper presents the technical aspect and performance analysis of the federated filter approach. Test results show that for a network of 100 reference stations, with the centralized approach, the network processing including ionospheric modeling and network ambiguity fixing needs approximately 60 hours to process 24 hours network data in a 3.06 GHz computer, which means it is impossible to run this network in real time. With the federated filter approach, only less than 1 hour is needed, 66 times faster than the centralized filter approach. The availability and reliability of network processing remain at the same high level.

Keywords: GNSS, Network RTK, Federated Filter

1. Introduction

The network RTK technology was one of the most interesting research topics in high precision GPS real time positioning in the last few years (Chen et al, 2003, 2004, 2005; Kolb et al, 2005, Landau et al, 2002; Vollath et al, 2000, 2001). Comparing with traditional single base RTK technology, network RTK removes a significant amount of spatially correlated errors due to the troposphere, ionosphere and satellite orbit errors, and thus allows performing RTK positioning in reference station networks with distances of 40 km or more from the next reference station while providing the performance of short baseline positioning.

Trimble provides the Network RTK software solution GPSNet™ since 1999 (Vollath et al, 2000). Currently more than 2000 reference stations are operating in networks in more than 30 countries using the Trimble GPSNet solution. Data processing in GPSNet utilizes the mathematically optimal Kalman filter technique to process data from all network reference stations. This comprehends modelling all relevant error sources, including satellite orbit and clock errors, reference station receiver clock errors, multipath and particularly ionospheric and tropospheric effects.

To optimize real-time computational performance, the Trimble patented FAMCAR (Factorized Multi-Carrier Ambiguity Resolution) methodology has been used to factorize uncorrelated error components into a bank of smaller filters, i.e. Geometry filter and Geometry-free filters and code-carrier filters (Vollath et al, 2004, Kolb et al, 2005). This approach results in significantly higher computational efficiency. However, due to the fact that the geometry filter still contains a large number of states (several hundreds to thousand states depending on the number of stations in the network), GPSNet until now was able to process 50 reference stations on a single PC server only, larger networks are divided into sub-networks and operated by multi-server solutions.

In recent years, more and more service providers have setup reference networks to provide nation-wide or region-wide RTK services. Many of them contain more than 50 reference stations, i.e. JENOBA, Japan (338 stations), ASCOS, Germany (136 stations); Ordnance Survey, United Kingdom (86 stations), and many existing network operators intend to extend their network to serve larger areas. In order to allow the processing of larger networks on one single PC, an efficient approach – Federated Geometry Filter – has been developed and implemented in Trimble's latest infrastructure software (GPSNet version 2.5).

2. Centralized Geometry Filter

The geometry filter plays an important role in the GNSS network data processing. It provides not only the float estimation of ionospheric-free ambiguities for later network ambiguity fixing, but also provides ZTD (troposphere zenith total delay) for numerical weather prediction (Vollath et al, 2003). This filter is usually running with a centralized Kalman filter. A typical setup of the state vector in the filter is:

- Tropospheric zenith total delay (ZTD) per station
- Receiver clock error per station
- Satellite clock error per satellite
- Ionosphere-free ambiguity per station per satellite
- Orbit errors

Table. 1 gives number of states in the filter with given number of stations and number of satellites observed at each station. For a 20 station network and 12 satellites observed in each station, the filter has 328 states; for a 120 station network and 18 satellites observed in each station, the filter has 2472 states. With the increase in the number of stations in the network and number of satellites observed on each station, the number of states thus processing time will increase dramatically.

Table 1. Number of states in the centralized geometry filter

Stations	Satellites	States
20	12	328
	15	400
	18	472
40	12	608
	15	740
	18	872
80	12	1168
	15	1420
	18	1672
120	12	1728
	15	2100
	18	2472

Fig. 1 shows the number of multiplications required for one filter step (one epoch of data sent through the filter) for a given number of stations with the assumption that 12 satellites are observed on each station. As the most expensive operation in the filter is the multiplication, this figure can be approximately interpreted as the relationship between number of stations and computational load of the filter. In Fig. 1, the blue bars give the number of multiplications in billions for number of station from 10 up to 120. The pink line in the figure represents the function $(36X)^3$, which fits perfectly to the required multiplications. So, it is clear that the computational time increases cubically with number of stations in the network.

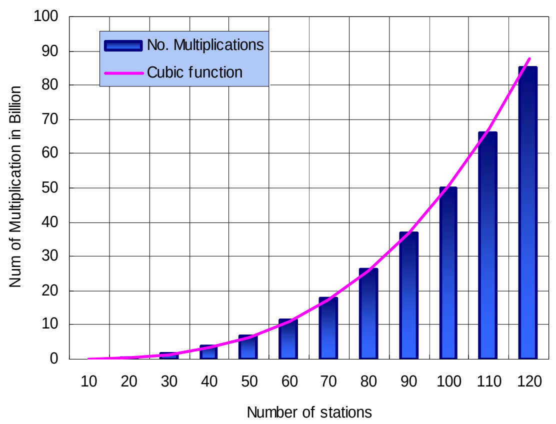

Fig. 1 Relation between number of reference stations and required multiplication of one filter step

3. Federated Geometry Filter

The Federated Kalman filter was introduced by N. A. Carson (1990). The basic idea of federated filter is that:

1. A bank of local Kalman filters runs in parallel. Each filter operates on measurements from one local sensor only. Each filter contains unique states for one local sensor and common system states for all the local sensors.
2. A central fusion processor computes an optimally weighted least-square estimate of the common system states and their covariance.
3. Then the result of the central fusion processor is fed back to each local filter to compute better estimates for the local unique states.

So, the main benefit of this approach is that each local filter runs with reduced number of states and the computation time for the whole system increases only linearly with the increase of the number of local sensors. This significantly reduces the computational load compared to the centralized filter approach.

For GNSS network processing, each reference station can be treated as a local sensor with unique states like ZTD, receiver clock error and ionosphere-free ambiguities (2+n, where n is number of satellites in the system), and common states like satellite clock errors and orbit errors (n+m*n, where n is number of satellites in the system and m is number of orbit error parameter per satellite). Therefore the federated filter approach can be applied. As there are still too many common states, a further step can be taken to further reduce the computational load. The satellite orbit error states are estimated with a frame filter. This frame filter uses only a subset of the reference stations in the network to estimate the orbit error parameters. Then the estimated orbit errors are applied directly to observation processed in the local filters.

Fig.2 illustrates the block diagram of a Federated Geometry Filter for GNSS network processing. This approach contains one frame filter, a bank of single station geometry filters (one per reference station) and one central fusion master filter.

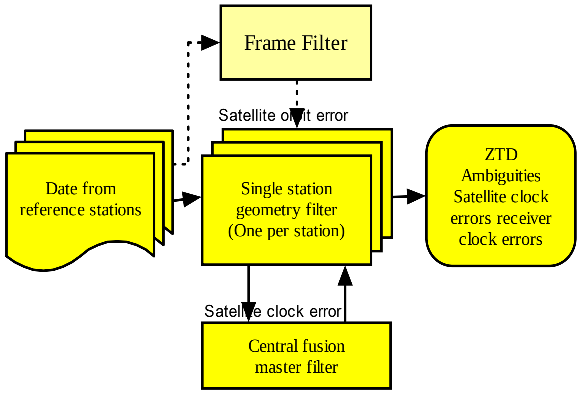

Fig. 2 Block diagram of a Federated Geometry Filter

4. Performance Analysis

The performance analysis includes two parts. One is the post-processing performance comparison between the centralized geometry filter approach and federated geometry filter approach. It is focusing on the server performance – availability, reliability of the network processing and processing time. The other part is the real-time performance analysis focusing on the RTK rover positioning and fixing performance in the network.

4.1 Post-processing Performance

The post-processing performance study uses a post-processing version of GPSNet. The first test performed is to check the availability (percentage of fixed ambiguities) and reliability (percentage of correctly fixed ambiguities) with both the centralized geometry filter approach and the federated geometry filter approach. Four days of data (days 289, 290, 291 and 322 of the year 2003) from the Bavarian Land Survey Department BLVG network (45 GPS stations, Germany) and three days of data (days 113, 114 and 115 of the year 2003) from the German ASCOS sub-network (28 GPS/GLONASS stations) were used in the test. Table 2 summarizes the test results. For the GPS only network (BLVG), both approaches give similar results in terms of availability and reliability. For the GPS/GLONASS network, the federated filter approach gives a slightly lower availability which is contributed from the GLONASS satellites.

Table 2. Post-processing performance test (availability and reliability)

Network	Centralized Approach		Federated Approach	
	availability	reliability	availability	reliability
BLVG289	98.86	100	99.05	100
BLVG290	99.05	100	99.06	100
BLVG291	98.99	100	98.98	100
BLVG322	97.79	100	97.40	100
ASCOS113	92.98	100	92.48	100
ASCOS114	96.26	99.85	94.75	99.87
ASCOS115	92.48	99.93	90.85	99.95

The second analysis is to check the processing time needed by the centralized and federated geometry filter approaches. In this test, one day data of 123 reference stations from five German states [Bayern, Nordrhein-Westfalen, Hessen, Thüringen and Niedersachsen] was used as shown in Fig. 3.

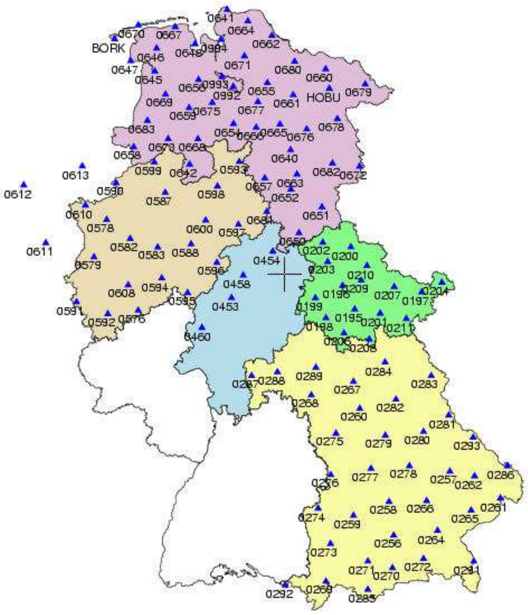

Fig. 3 Test Network

From these 123 stations, we selected 50, 60, 70 up to 100 stations to run network processing with both approaches. The total processing time (including data preparation, ionosphere modeling and network ambiguity fixing) of each process for one day of data is summarized in Table 3. For a 50 station network, the federated filter approach uses 20 minutes to process the data, while the centralized filter uses 173 minutes. For a 100 station network, the federated filter approach uses 38 minutes, while the centralized filter approach used 358 minutes (nearly 2.5 days) to process one day of data, which means it is impossible to process data in real-time. Table 3 also gives the ratio of processing time between centralized filter and federated filter approach. For a 50 station network, the federated filter approach is 8 times faster and for a 100 station network, the federated filter approach is 66 times faster than the centralized filter approach. This test proves that the federated filter approach is highly computationally efficient for large networks (Table 3).

Table 3 Processing time comparison

Number of Stations	Centralized [Minute]	Federated. [Minute]	Ratio
50	173.35	20.57	8.42
60	280.83	25.56	10.98
70	455.03	31.28	14.55
80	697.83	38.23	18.25
90	1152.47	53.15	20.52
100	3581.46	56.85	66.50

4.2 Real Time Performance

For the real time test, two GPSNet systems were set up in parallel. One was running with the centralized filter approach. Real time data streams of 45 stations from the BLVG network were used in this configuration. Another system was running with the federated filter approach. Real-time data streams of more than 100 stations from the German SAPOS network were used in this configuration. Two Trimble 5700 rovers located in Trimble Terrasat office were used to verify the rover positioning and fixing performance. The VRS data streams generated from these two systems were streamed to both rovers respectively. The nearest reference station was 16 km away in both cases.

Fig. 4a – 4c show the north, east and height rover position errors in meters. The figures show that the rover positioning performances from these two systems are very similar. Typically the difference is within 1 mm. Table 4 summarizes the statistics of position errors over one day, which indicate that the positioning performances from both systems are the same from a statistical point of view.

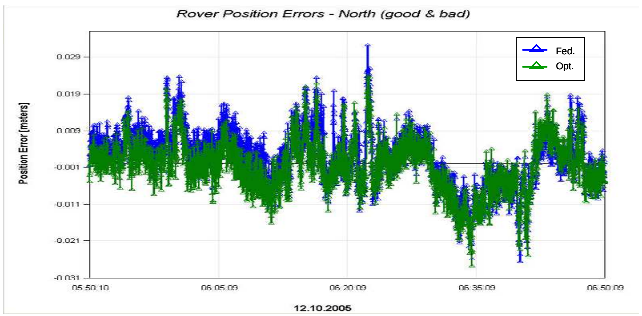

Fig. 4a Rover position error – North [m]

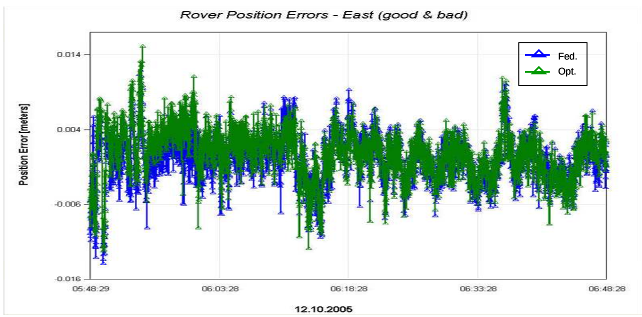

Fig. 4b Rover position error – East [m]

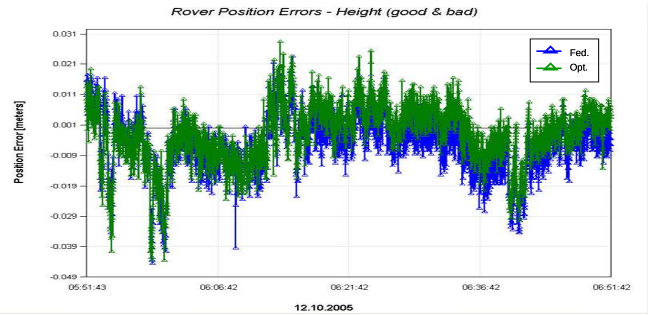

Fig. 4c Rover position error – Height [m]

Table 4 Position error statistics

		Centralized [m]	Federated [m]
Mean	North	0.001	0.002
	East	-0.006	-0.006
	Height	0.001	0.005
1-Sigma	North	0.008	0.007
	East	0.005	0.005
	Height	0.013	0.013
RMS	North	0.007	0.007
	East	0.008	0.008
	Height	0.013	0.013

Another test conducted in real time is to check the RTK fixing performance. The test setup is the same as the positioning performance test. Table 5 summarizes the RTK fixing performance during one day in terms of mean fixing time, 68%, 90%, 95% quantiles and minimum, maximum fixing time. Though the minimum and maximum fixing times for the rover in the system running the federated filter approach are longer than the centralized filter approach, other statistics are very much the same.

Table 5 RTK fixing performance

	Mean [s]	68% [s]	90% [s]	95% [s]	Min [s]	Max [s]
Centralized	24.8	27	30	34	13	508
Federated	24.7	27	29	35	16	561

5. Summary

In summary, the federated geometry filter approach is significantly faster than the centralized geometry filter approach in case of large networks. Performance analyses show that availability and reliability of network processing are comparable and the rover performance stays the same compared to the centralized filter approach.

Acknowledgement

We thank the Land Survey departments of Bavaria, Hessen, Nordrhein-Westfalen, Niedersachsen, Baden-Württernberg, Thüringen and E.on Ruhrgas GmbH for providing us data and real-time data streams from their networks during the test and allowing us to use the data in this research.

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