Active GNSS Networks and the Benefits of Combined GPS+Galileo Positioning

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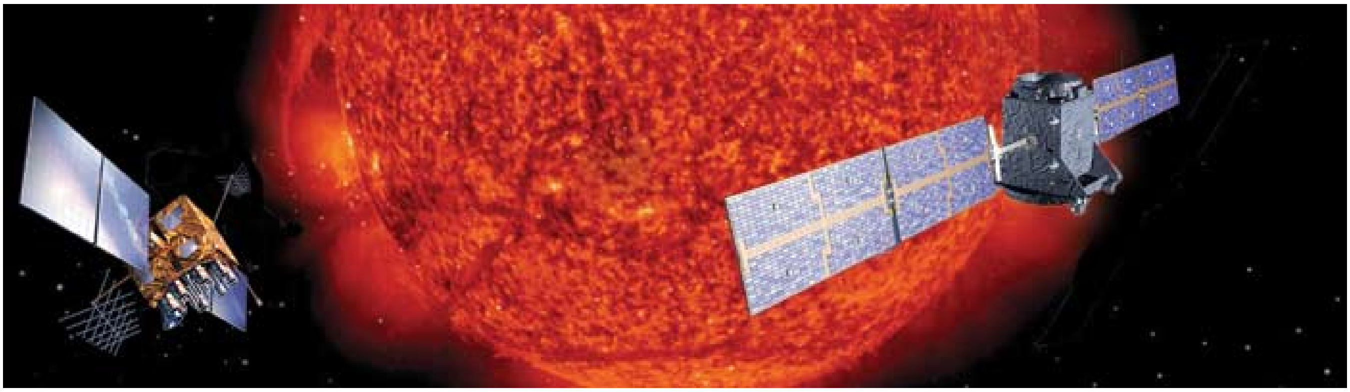

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Over the past 10 years, GNSS reference networks have simplified and extended the range of high-precision positioning over longer distances with the aid of differential corrections, including those provided by so-called "virtual" stations. However, a number of operational and environmental factors — including accurate and timely characterization of local ionospheric and tropospheric conditions — continue to limit the full realization of these techniques' potential. Access to and use of additional satellite signals from multiple GNSS systems could help address these limitations. Among the candidate combinations are the use of signals from the U.S. Global Positioning System and the European Galileo system now under development. With the aid of simulations of a dense German reference network currently in operation, this column examines the potential benefit of GPS + Galileo positioning under a variety of ionospheric conditions.

Without question GPS has revolutionized precise positioning since its advent about 20 years ago. Real-time methods to quickly fix carrier phase integer ambiguities — the key to precision — have been developed and are often referred to as RTK ("real-time kinematic") techniques.

RTK is an advanced manifestation of the principle of *differential positioning*, a method that requires at least one reference station with known coordinates to simultaneously track GNSS satellite signals. Carrier phase measurements are used in addition to pseudoranges due to their superior accuracy.

Nevertheless, ambiguity resolution is only possible as long as the user (the "roving receiver") is located in the vicinity of this reference station — let us say, within a radius of approximately 10 kilometers. Within this short range the benefits of the often-employed "double differences" technique can be effectively exploited: Differences of observations between a primary and a secondary satellite are formed on both the rover and the reference site and these two quantities are then subtracted, yielding a derived measurement between both sites that is free of satellite and receiver clock offsets or errors.

Fortunately, the atmospheric errors are spatially correlated and can be reduced in the double difference measurements to a reasonable extent. Thus, it is relatively easy to fix ambiguities of short baselines, whereas it becomes increasingly difficult to do so over longer baselines due to decorrelation of the atmospheric delays.

As a result of this decorrelation, the service area of conventional RTK systems allowing for quick ambiguity fixing covers about 300 square kilometers. To provide service in an area the size of the contiguous United States (9,800,000 square kilometers) would require more than 30,000 reference stations. Even for a country as small as Germany (357,000 square kilometers) more than 1,100 reference sites would still be needed to provide complete coverage — an enormous challenge in terms of infrastructure installation, operations, and maintenance costs.

The solution for this problem: Use multiple reference stations to derive atmospheric corrections. Because the coordinates of these fixed stations can be determined precisely — or can be treated as tight constraints — the atmospheric (ionospheric and tropospheric) effects on GNSS signal propagation can be derived from the correlated data.

These station-, baseline-, or satellite-specific corrections can be interpolated at the rover site. Hence, atmospheric errors can be significantly reduced and GNSS reference networks can substantially increase the distance between stations while still providing the accuracy level on conventional RTK systems.

The reference networks that provide such correction data are often called "active GNSS networks," referring to their continuous operation. Most of them offer both real-time and post-processing services.

By adding to the number of satellite signals available to these networks, users on the road/in the field can improve their performance by allowing optimization of satellite geometry (the selection of a subset of available signals that reduces the dilution of precision (DOP) factor), use of multiple frequencies for carrier phase integer ambiguity resolution, and for achieving so-called "overdetermined solutions." With multiple GNSS systems under development in addition to GPS that are increasingly compatible or even interoperable, this prospective approach is becoming ever more attractive.

This article outlines the added value from combined GPS+Galileo data processing — rather than GPS-only data processing — in the framework of active GNSS network positioning. In particular, we will look at how such an approach can improve performance in the presence of traveling ionospheric disturbances that produce marked increases or decreases of signal propagation delays.

Methodology

The simplified observation equations for pseudo-ranges and carrier phases are

$$\nabla\Delta PR_{AB}^{ij} = \left(PR_B^j - PR_A^j\right) - \left(PR_B^i - PR_A^i\right) = \nabla\Delta\rho_{AB}^{ij} + \nabla\Delta ION_{AB}^{ij} + \nabla\Delta\, Trop_{AB}^{ij}$$

$$\nabla\Delta\varphi_{AB}^{ij} = \left(\varphi_B^j - \varphi_A^j\right) - \left(\varphi_B^i - \varphi_A^i\right) = \frac{\nabla\Delta\rho_{AB}^{ij}}{\lambda} - \frac{\nabla\Delta ION_{AB}^{ij}}{\lambda} + \frac{\nabla\Delta\, Trop_{AB}^{ij}}{\lambda} - \nabla\Delta N_{AB}^{ij}$$

where PR_A^i denotes a pseudorange measurement at station A to satellite i; φ a carrier phase measurement; ρ, the geometric range; ION, the ionospheric propagation delay of the particular carrier frequency, and Trop, the tropospheric propagation delay. The wavelength is given by λ, and N is the ambiguity term. ∇ denotes a satellite-to-satellite difference, and Δ is the station-to-station difference.

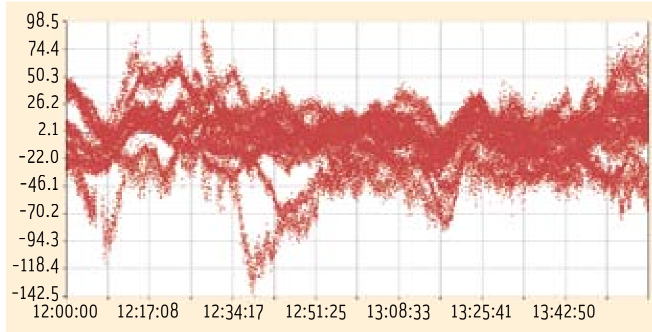


FIGURE 1 Double difference ionospheric delays derived from dual frequency GPS data during typical (i.e. relatively calm) ionospheric conditions as currently observed in mid-latitudes; baselines: 56-78 km. (x-axis: GPS time hh:mm:ss; y-axis: ∇ΔION in millimeters).

Using at least dual-frequency GNSS receivers, it is possible to figure out the double-difference ionospheric and tropospheric delay terms. The geometric distance can be treated as a known value at first instance, although the reference network will also be monitored with respect to the coordinate components from time to time (if not continuously). **Figure 1** portrays a typical time series (two hours of data, unsmoothed) of double-difference ionospheric delays over baseline lengths of 56-78 kilometers. The magnitude of the delays is clearly significant for precise positioning.

The remaining task is to provide interpolated corrections to the user. A variety of methods exist, an overview and investigation of which are discussed in the papers by L. Dai et alia and G. Fotopoulos et alia cited in the Additional Resources section at the end of this column. A commonly employed approach makes use of surface interpolation functions of the following kind:

$$\nabla\Delta D = a_{\varphi\varphi}\cdot\Delta\varphi + a_{\lambda\lambda}\cdot\Delta\lambda + a_{\varphi\lambda}\cdot\Delta\varphi\cdot\Delta\lambda + a_{hh}\cdot\Delta h$$

where ∇ΔD is the double-difference delay (either ionospheric or tropospheric delay); $a_{\varphi\varphi}$, $a_{\lambda\lambda}$ and a_{hh} are the northward, eastward, and radial gradients determined with help of the reference network delays; Δφ, Δλ, and Δh are the difference in latitude, longitude, and height between the current user position and the master reference station.

Note that we do not normally need to model a height gradient a_{hh} for the ionospheric delay as the height-dependency of this error is not that large in comparison to the tropospheric propagation delay. Even for troposphere, the determination of height gradients is only recommended if the reference network in use features expressed height variations that allow for accurate determination of this component. In the simplest case, only the northward and eastward gradients are provided to the user. This essentially requires nothing more than a triangle of network stations surrounding the user receiver, (see **Figure 2**).

Please note that orbit errors are sometimes determined in addition to ionospheric (dispersive) and tropospheric (non-dispersive) propagation delays. This type of correction data is not considered here because orbit errors are no longer considered to be a problem taking into consideration the improvements of the GPS ground segment (more precise orbits) and the availability of precise IGS ultra-rapid orbits in real-time. Moreover, the Galileo orbits are supposed to be relatively accurate (well below the meter level) due to the increased service model that is to be considered.

Data Dissemination

Three major concepts for broadcasting the GNSS correction information to the user have been developed in the past. The classical concept is called FKP,

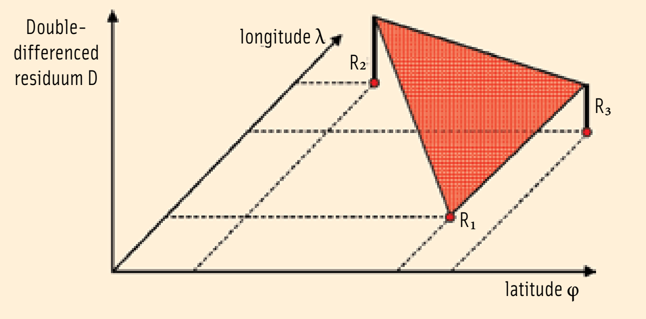


FIGURE 2 Illustration of the standard plane modeling method using northward and eastward gradients and three reference stations R1,2,3.

which is an abbreviation of the German term "Flächenkorrekturparameter" (area correction parameters).

As a matter of fact, the FKP concept was developed in particular for German active networks and is still the default dissemination model in that country. In the FKP approach, measurement data of the nearest reference station plus the coefficients ($a_{\varphi\varphi}$, …) of the error interpolation functions are broadcast to the user.

Another popular approach is found in the so-called "virtual" reference or base station concept. This technique does not require the dissemination of correction coefficients. Instead, simulated (virtual) GPS data are generated at a location in the vicinity of the rover itself.

The interpolated atmospheric corrections derived from the GNSS network are used to represent these synthetic data as if "real" observation were observed at this site. In virtual reference mode the corrections are applied in the network server whereas in other modes the corrections are applied in the field.

The advantage of the virtual approach — at least from a historical perspective — derives from the fact that the processing scenario is now artificially reduced to a short-baseline analysis. Thus, users can continue to employ their "old" positioning software, which might not be able to handle area correction parameters.

The second advantage is related to the data volume to be transferred as it is no longer necessary to broadcast the correction data — they are already incorporated into the measurement data transmitted from the network. Furthermore, the correction interpolation algorithm can be freely selected by the service provider and is not constrained by any given algorithm and format specification.

The major drawback in virtual techniques, however, lies in the fact that this dissemination method is not very well suited for kinematic applications that require the rover to move over large distances with respect to the initial position of the virtual reference station. In that case, the rover-reference baseline will increase and the atmospheric artifacts will become a problem again.

Means to overcome this shortcoming include providing the virtual data on a complete grid or intermittently moving the locus of the virtual station so as to remain virtually close to the user. All these creative, but potentially cumbersome work-arounds are not necessary in case of the FKP procedure.

Finally, a new method called MAC (Master Auxiliary Concept) is currently being implemented as an extension of the FKP concept. In MAC, the complete set of raw data of one reference station (the master station) is transmitted as well as all corrections of all other stations (auxiliary stations). This increases the flexibility in applications because the user can decide how to work with these correction data, that is, how to interpolate them.

Unfortunately, this approach increases the data volume to be transmitted in comparison to the FKP approach. That factor might not be a problem in regions in which GPRS and UMTS broadband communication is available, but it can cause communication problems in areas with GSM only which is normally limited to just 9600 bauds.

Goals of the Future

Europe is developing its own GNSS, Galileo, that will add an additional global constellation to the existing GPS, which itself is currently undergoing modernization as well. Undoubtedly, a number of benefits will arise from using multiple GNSS systems, including, in addition to Galileo, Russia's GLONASS and China's Compass. (See, for example, the article "GPS + GLONASS for Precision," in the July/August 2007 issue of *Inside GNSS*, which describes a dual-system virtual reference network in South Carolina, USA.)

More specifically, the questions to be answered within the scope of active GNSS network positioning are: Can network inter-station distances be increased without losing any significant service performance? A sparser network density would allow saving infrastructure costs. Can ambiguity resolution be performed more quickly than nowadays employing such combined methods? Can we increase the reliability of ambiguity fixing?

Synthetic GNSS Data

For combined GPS/Galileo applications, these questions can currently only be answered with the help of simulated data. We used in-house software to generate "synthetic data," including pseudoranges and carrier phase measurements for the following GNSS and the following carriers: GPS, L1, L2, and L5; Galileo: E1 (same center frequency as GPS L1), E6, E5a (same center frequency as GPS L5), E5b and E5ab, see Table 1 for all center frequencies.

Apart from standard features such as receiver noise simulation, we exercised care to model *multipath effects* based on a Fourier analysis/synthesis using templates from real GPS data collected

Signal		Center frequency
GPS	L1	1575.42 MHz
	L2	1227.6 MHz
	L5	1176.45 MHz
Galileo	E1	1575.42 MHz
	E5a	1176.45 MHz
	E5b	1207.14 MHz
	E5ab	1191.795 MHz
	E6	1278.75 MHz

TABLE 1. Center frequencies of GPS and Galileo

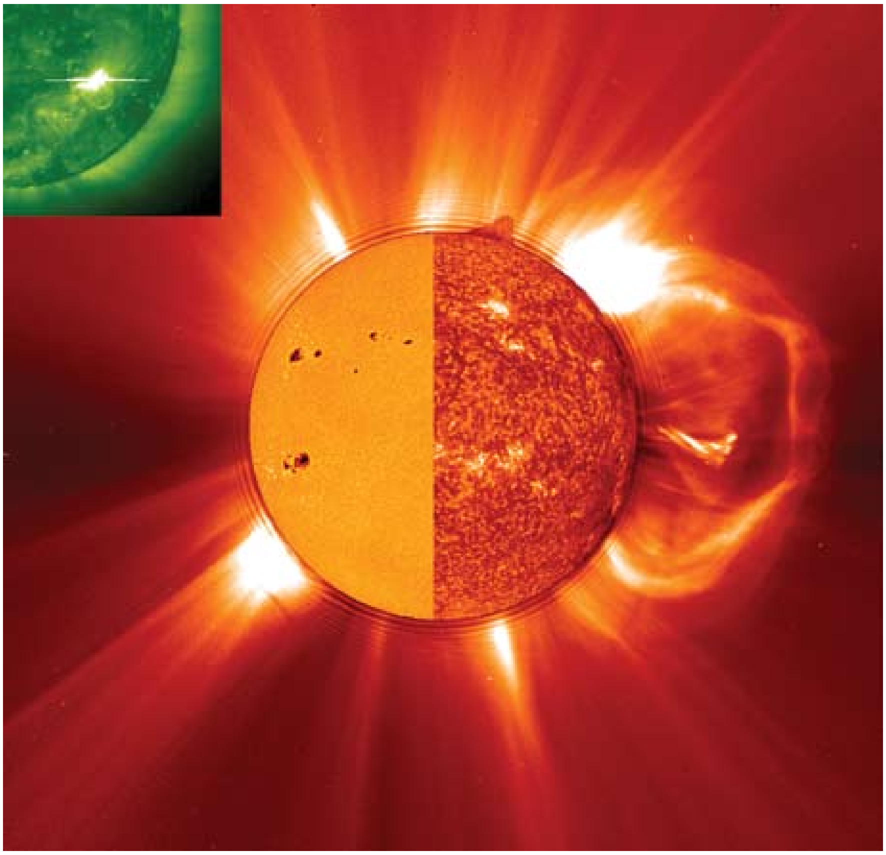
“Medium scale” Amplitude [TEC] / Duration [min] / Velocity [km/h] + Amplitude [m] / Duration [min]	
M I	0.1 / 45 /130
M II	1.0 / 45 / 180
	+ 0.6 / 25
M III	1.5 / 45 / 180
	+ 0.8 / 25
M IV	2.3 / 45 / 180
	+ 1.2 / 25
M V	3.0 / 45 / 180
	+ 1.7 / 25
M VI	3.7 / 45 / 180
	+ 2.0 / 25
M VII	4.5 / 45 / 180
	+ 2.2 / 25

TABLE 2. Simulation settings for the ionosphere for several different scenarios MI - M VII: combined modeling of medium-scale travelling ionsopheric disturbances (MSTIDs) and extreme increase/decrease of ionospheric delay (e.g., during an ionospheric storm)

under typical conditions. The 80 most dominant waves — those frequencies/amplitudes that differed significantly from noise, i.e., that are believed to be caused by multipath — are identified and scaled according to the multipath envelopes of the new signals, taking into consideration the benefits from using typical signal processing methods to mitigate this effect. The simulations assumed noise levels for each frequency and multipath conditions as are typically seen in suburban areas.

Regarding *tropospheric effects*, the simulation can incorporate actual GNSS signal path delays recorded at numerous weather fields and/or weather fronts with individual motion parameters can be simulated, allowing the modeling of both normal conditions and extreme events. In this study, we assume that the total tropospheric delay in zenith direction varies by four centimeters within a period of 50 minutes. This is a rather strong event for mid-latitude regions, but we chose it intentionally in order to test the ability of the sequential filter to soak up such effects.

For this study, to address *ionospheric effects*, we modeled diurnal and long-term trends using ionosphere maps (for



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example, from the International GNSS Service). We also simulated medium-scale ionospheric traveling disturbances (MSTIDs), which are considered to be of high importance for RTK applications because these disturbances can quickly degrade the ability to successfully fix ambiguities.

Such a combined modeling of MSTIDs plus extreme increase/decrease of ionospheric delay (e.g., to simulate conditions during an ionospheric storm) was applied with specific scenarios in mind. **Table 2** shows the seven different scenarios, representing low (M I) and very high (M VII) ionospheric activity.

The values in the first line of each row in Table 2 characterize the *traveling disturbance*, which can be thought of as a kind of sine wave with certain amplitude, frequency (duration), and velocity. (These values are considered to be representative according to the results outlined in the paper by M. Hernández-Pajares et alia cited in the Additional Resources section.)

The second line of each row gives the parameters of a flank of a time series typical of an ionospheric storm — if simulated.

Several dual-, triple- and multiple-carrier frequency combinations were taken into consideration during the simulation runs. Further details of the simulation tests can be found in the paper by T. Schüler et alia [2007] listed in Additional Resources.

User Positioning

More than three signals are planned to be available for Galileo users, but not all will be freely available. For example, E6 belongs to a proposed Commercial Service that is currently not well-defined due to the failure to set up a Galileo concessionaire.

Furthermore, it is doubtful whether users of the existing commercial networks including the German system discussed in this column would be willing to pay an additional fee for usage of an E6 signal. However, the broadband signal E5ab — a real innovation for precise positioning due its small multipath errors on code ranges that are beneficial for quick ambiguity resolution — offers

FIGURE 3 Stations of the German active reference station network (Each red dot indicates a reference station)

FIGURE 4 Type "Small": a typical AdV network triangle with a baseline length of 19 kilometers between rover and nearest reference station

subcarrier tracking. So, in total, Galileo signals on E1, E5a, and E5b (and even E5ab) will be available for positioning (basically free of any additional costs for the user).

A number of rover positioning and ambiguity resolution strategies have been implemented within the scope of this work. The best performing approach of those methods tested is a flexible Kalman filter approach called "ANSA" ("All Inclusive Sequential Ambiguity Filter"). This approach takes into consideration the fact that residual atmospheric errors will always be present after interpolation of GNSS network corrections and, consequently, it tries to estimate these errors as additional parameters.

Thus, the complete parameter set of estimated errors become:

- user receiver coordinates
- satellite-specific double difference residual ionospheric delays
- station-specific (at user position) residual tropospheric delay in zenith direction
- float ambiguity parameters on the original carrier frequencies (no linear combination)

where the ambiguities are of major concern during this first processing step. Efforts are undertaken to fix these ambiguities to their integer values as soon as possible using a search method in the observation space.

This approach is essentially what is called "geometry-dependent" ambiguity resolution in the literature. It should be distinguished from "geometry-free" ambiguity resolution in which a direct combination of code ranges and carrier phase measurements is employed to resolve the ambiguities without any knowledge of the antenna position.

In our case, both observation types are, of course, processed in the sequential filter, too. Moreover, à priori atmospheric delays can be injected as "pseudo-observations" in order to prevent the filter from a possible divergence, which may occur during periods of weak geometry (basically in the GPS-only scenario). (If tropospheric and/or ionospheric delay parameters are included in the filter, the time series of these estimates can show a divergence from the true value rather than a convergence. Typical reasons are a poor geometry and/or too few observations, i.e., situations that do not allow for estimation of so many parameters. This problem will be of minor concerns when combining multiple GNSS data.)

The variance or standard deviation assigned to the delays, both for initialization and for continuous injection of the pseudo-observables, associated with these pseudo-observations is situation-dependent. The value will be small, that is, more "accurate," either when we are confident that the external correction data are precise or if we fear that a

FIGURE 5 Type "Thinned Out": A slightly sparser network triangle with a baseline length of 55 kilometers to the nearest reference site.

FIGURE 6 Type "Challenging": Network triangle configuration with a baseline length of 95 kilometers to the nearest reference station.

divergence of the additional parameters might occur.

We assign a large value — that is, we treat the delays as "inaccurate" — when we believe that the Kalman filter has the strength to derive accurate additional parameters "by itself," i.e., from the data available. Normally a compromise between extreme values is exercised.

All results presented in this column were obtained under a strict time constraint: Ambiguity fixing had to be accomplished no later than 40 seconds after initialization. We added this "game-over criterion" based on the current performance of the performance in the German active reference network described in the next section, where more than 60 percent of the Bavarian users are actually able to obtain a first fixed position after that very interval. An improved positioning service should, of course, allow for at least a similar (but hopefully larger) percentage of users being able to obtain a fix within that time period.

Network Selection

Germany operates a relatively dense GPS active reference station network established as a joint project of the Working Committee of the Surveying Authorities of the 16 states of the Federal Republic of Germany (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland or AdV). The network consists of more than 250 stations with station-to-station distances between 30 and 50 kilometers, see Figure 3.

Area correction parameters allow the modeling of dispersive (i.e., ionospheric) and non-dispersive (i.e. tropospheric and orbit) errors that can be broadcast to the user or, alternatively, virtual reference station data can be generated and transmitted to the roving receiver.

The AdV network provides mainly three different types of differential correction services: one based on pseudorange measurements (including carrier-phase smoothing) that provides an accuracy level of 0.5-3 meter; a real-time service producing positioning accuracies of 1-2 centimeters (horizontal) and 2-6 centimeters (vertical), respectively; and a one-centimeter to millimeter-level service that uses "near-online" data or in the postprocessing mode employing the original reference station data in the standard RINEX format (1 Hz data).

The AdV reference stations stipulate the nationwide official spatial reference system. Therefore, the main user groups are the state survey agencies, real estate cadastre authorities, and other institutions conducting official surveying tasks. However, the AdV network also supports applications in maritime shipping, hydrography, engineering surveying, and so on.

For the purposes of our research described in this column, we selected the region of the federal state of Thuringia, that is a subset of the AdV network. The Thuringian component of the network is particularly useful for such investigations as it features a high density of stations.

Ionospheric and tropospheric corrections are generated using the method of area correction parameters, a standard approach employed in the AdV system. We should mention that results using the area correction parameters are — in this study — effectively equivalent to those from virtual reference data due to the fact that the same correction methods would be applied to the virtual data by our in-house software. Thus, no distinction between these two "different" approaches is made here.

Different network setups are considered with smaller (about 30 kilometers) and larger (up to about 300 kilometers) inter-station distances. Triangle network elements with different baseline lengths were used for this purpose (see Figures 4 through 7). The blue stations represent reference sites spanning a triangle from which the area correction parameters are derived. The red station is the rover station connected to the nearest reference station.

Software

The generation of synthetic GNSS data, active network corrections, and the

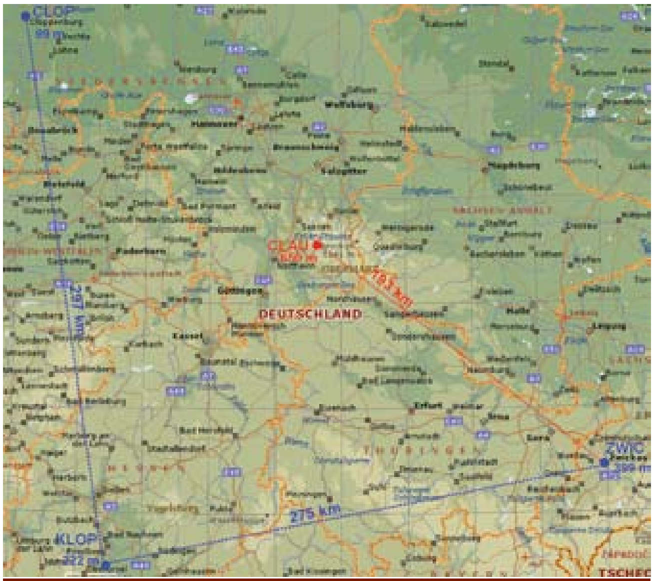

FIGURE 7 Type "Extreme": Network triangle configuration with a baseline length of 193 kilometers to the nearest reference station.

user positioning were carried out with the University FAF Munich in-house software package "PrePos GNSS Suite" — modules NEREUS and Semika. (See http://www.unibw.de/ifen/software/prepos for further information.)

We should stress that all results presented hereafter characterize the positioning performance and ambiguity resolution capabilities of this software and its underlying algorithms. No conclusions are made about the performance of network and/or positioning software of any receiver manufacturer or any third party software supplier as the algorithms used in those packages are essentially unknown to the authors.

Results

Let us first have a look at results obtained via the shortest possible baseline to the nearest reference station (network type "small"). This baseline is as short as approximately 20 kilometers. The distribution of the 3D coordinate errors (differences to the nominal coordinates) is shown in **Figure 8** (GPS only) and **Figure 9** (GPS+Galileo). Refer to **Table 2** for a description of the MSTID parameters reflected in the legends for Figures 8 through 15.

We can see an improved positioning performance in the case of combined GPS+Galileo positioning: the number of differences smaller than one centimeter is about 10 percent larger. Furthermore, no coordinate errors larger than 10 centimeters occur. In the case of GPS-only positioning, these differences are related to positioning runs where the ambiguities could not be fixed, which results in a decreased positioning accuracy.

The ambiguity success rates over the short baseline displayed in **Figures 10** and **11** are similar, but a clear decrease can be observed in case of GPS-only processing during strong ionospheric activity (MSTID scenarios VI and VII). In contrast only a very marginal decrease occurs in the case of GPS+Galileo positioning. (As a matter of fact, it is almost impossible to see any variation in the diagram, but the numerical results show a slight decrease).

When using the "Thinned Out" network (**Figures 12** and **13**), the ambiguity statistics in case of GPS+Galileo are still very satisfactory whilst the GPS-only results clearly begin to deteriorate: Ambiguity fixing was not possible in about 10 percent of the 40-second data batches for strong ionospheric behavior and a small percentage of incorrect fixes must be reported.

Network type "Challenging" features inter-station distances of 160 to 174 kilometers (between reference stations) and a shortest baseline to the rover of nearly 100 kilometers. **Figures 14** and **15** portray the ambiguity-resolution success rates. Regarding GPS-only, a number of users will become rather dissatisfied with the positioning service at these distances (at least if the ionosphere is not behaving in a very calm manner). The percentage of successful and correct ambiguity fixes drops down to less than 50 percent under the strongest conditions simulated in these scenarios, whereas a combined GPS+Galileo solution is still relatively stable at a level of clearly more than 95 percent.

So far, only dual frequency analysis results have been shown. **Figure 16** presents some results obtained with dual- and triple-frequency data for the same network triangle. In order to avoid any visual overload, only the results for the

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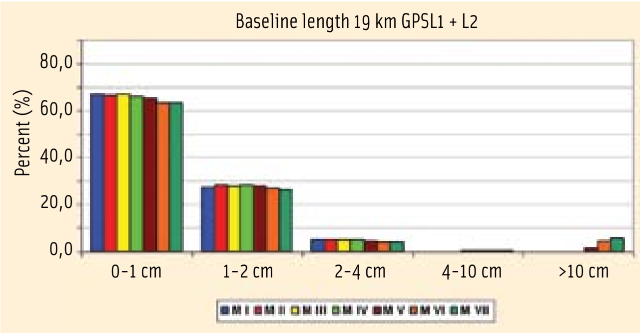

FIGURE 8 Network type "small"; current GPS-only configuration (L1 and L2); 3D position difference to nominal coordinates. See Table 2 for a description of the ionospheric parameters reflected in the legend.

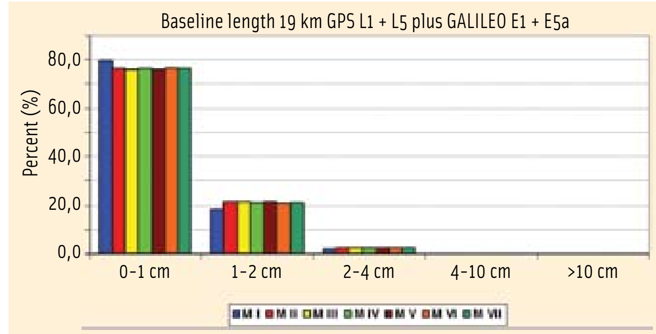

FIGURE 9 Network type "small"; dual frequency GPS and Galileo configuration; 3D position difference from nominal coordinates

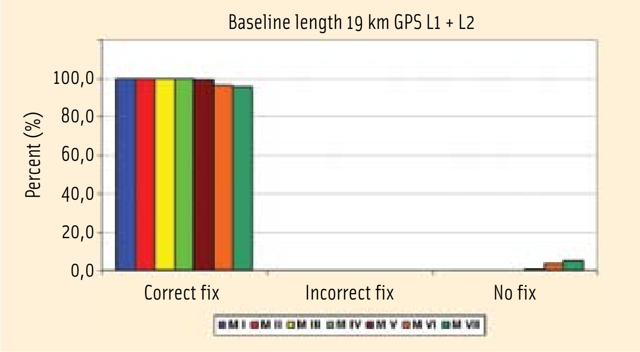

FIGURE 10 Network type "small"; current GPS only configuration (L1 and L2); statistics of correct ambiguity fixing

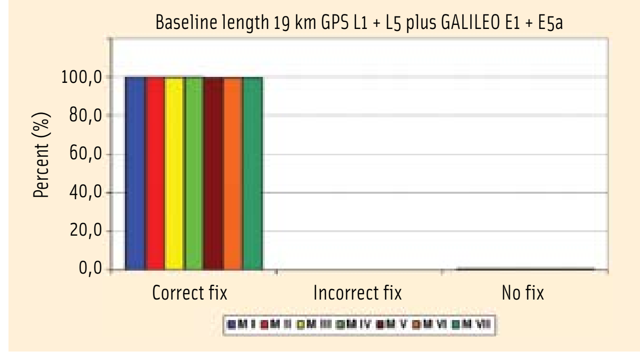

FIGURE 11 Network type "small"; dual frequency GPS and Galileo configuration; statistics of correct ambiguity fixing

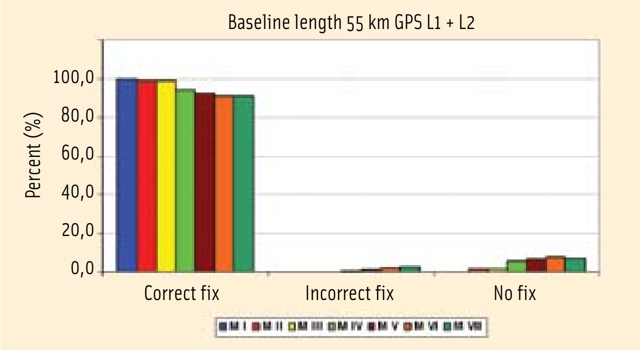

FIGURE 12 Network type "Thinned Out"; current GPS only configuration (L1 and L2); statistics of correct ambiguity fixing

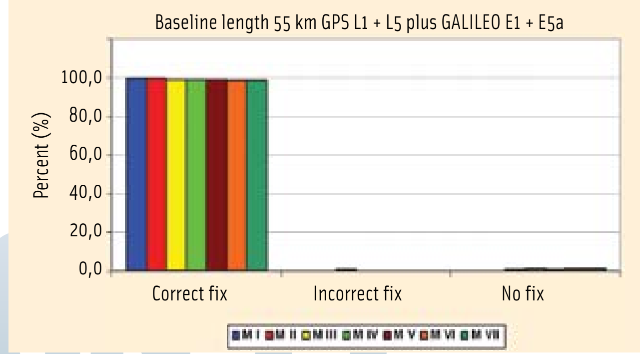

FIGURE 13 Network type "Thinned Out"; dual frequency GPS and Galileo configuration; statistics of correct ambiguity fixing.

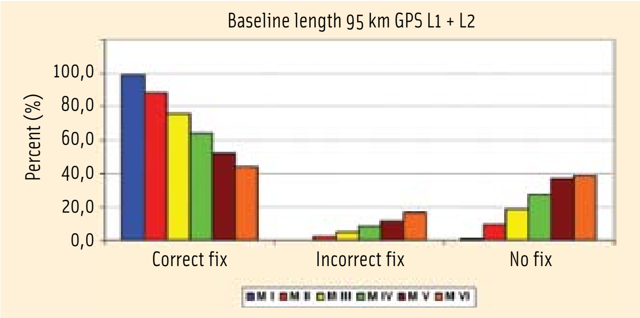

FIGURE 14 Network type "Challenging"; current GPS only configuration (L1 and L2); statistics of correct ambiguity fixing

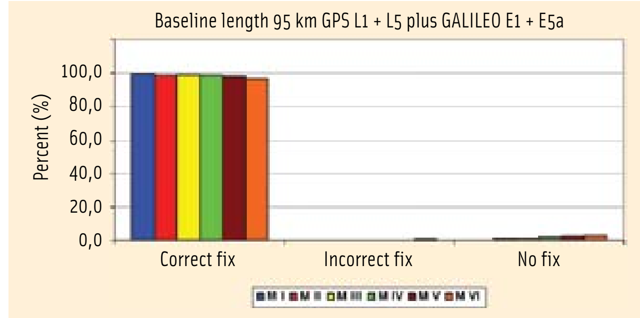

FIGURE 15 Network type "Challenging"; dual frequency GPS and Galileo configuration; statistics of correct ambiguity fixing

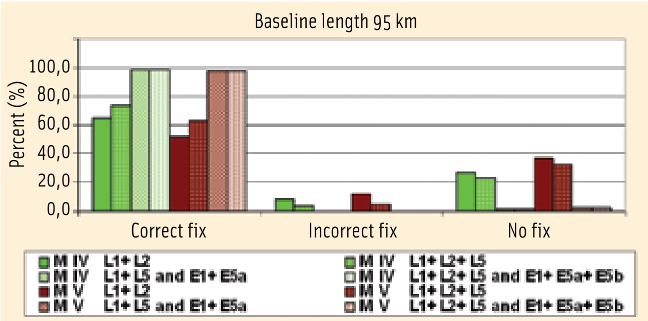

FIGURE 16 Network type "Challenging"; dual/triple frequency GPS and Galileo configurations; statistics of correct ambiguity fixing; only scenarios M IV and M V (strong ionospheric behavior)

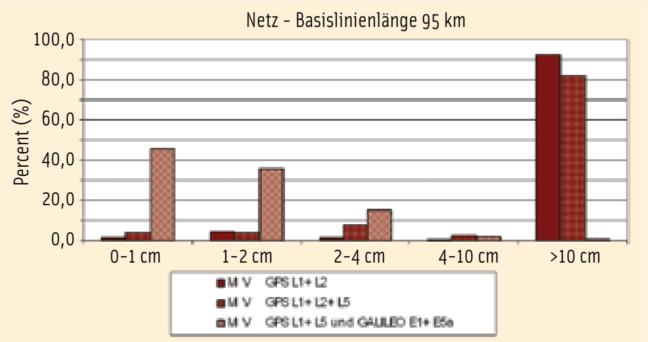

FIGURE 17 Network type "Challenging"; dual/triple frequency GPS and Galileo configuration; only scenario M V; 3D position difference to nominal coordinates

more challenging atmospheric conditions were selected.

We can conclude from this figure that a gain occurs in ambiguity-resolution success rates from triple- versus dual-frequency data, but it is far from that benefit derived from using a dual-GNSS constellation rather than the GPS-only one. This indicates that a large part of the benefits arises from the improved satellite geometry. This fact is also clearly reflected in the distribution of the coordinate errors as depicted in Figure 17.

Finally, let us have a look at the "Extreme" network type with a distance of almost 200 kilometers to the nearest reference station. The ambiguity results portrayed in Figure 18 for ionospheric activity scenario VI (strong) once again make clear that a quantum step in ambiguity resolution is achieved by adding the second GNSS. However, triple-frequency GPS+Galileo still adds an extra 10 percent to the success rate, and use of all theoretically available Galileo carriers gives an additional increase of a few percent.

A GPS+Galileo dual-frequency receiver would clearly be more beneficial for the user than a GPS-only, triple-frequency system.

Conclusions and Further Work

The results presented here illustrate the added value of combined GPS+Galileo positioning making use of active GNSS networks. The following points should be mentioned:

Reference networks as dense as the German AdV net can be significantly thinned out without any loss of service performance compared to the current state. The situation appears to be generally unproblematic as long as inter-station distances of approximately 100 kilometers (between the reference stations) are used. On the contrary: We can expect that a combination of GPS+Galileo will — despite of a sparser network — show a higher ambiguity resolution success rate when compared to denser GPS-only networks.

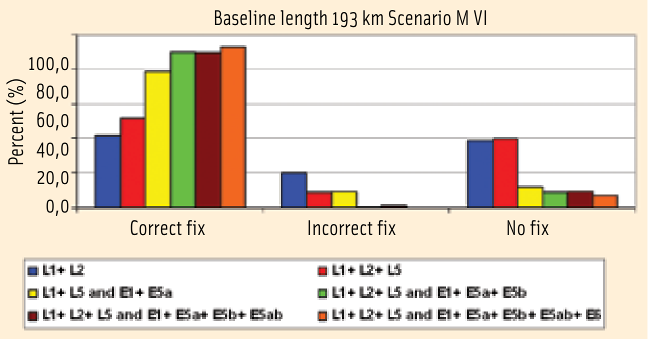

FIGURE 18 Network type "Extreme"; use of two/three/four/five frequencies GPS and GALILEO configuration; statistics of correct ambiguity fixing; only scenarios M VI (strong ionospheric behavior)

But even inter-station distances of up to 200 kilometers show an ambiguity-resolution success rate of 97 percent for a ionospheric activity such as scenario M VI, although this success rate is slightly higher (99 percent) in the 100-kilometer network. However, in networks with inter-station distances of 300 kilometers, the success rate drops to 78 percent. So, 200 kilometers might therefore be seen as a threshold if the current service performance is not to suffer significantly in the future.

We would also like to stress that the use of dual-frequency dual-GNSS receivers showed very good results in these simulations for the geometry-dependent ambiguity-resolution strategy employed. However, adding a third frequency (or even more signals) only exhibits a slight improvement in the success rates, though this improvement is still significant, especially for the longest baselines considered here. Nevertheless, a GPS+Galileo dual-frequency receiver would clearly be more beneficial for the user than a GPS-only triple-frequency system, provided that receiver prices do not show drastic differences.

Finally, we must anticipate larger residual errors of the interpolation atmospheric corrections when using a sparser GNSS network. However, improved algorithms such as those employed in the approach followed for this study are able to deal with this problem by estimating the residual errors — provided that a fortunate geometry is present (i.e., sufficient number of satellites and good geometrical distribution of the satellites.) The chances for this are higher when using both GPS and Galileo.

Nevertheless, our own experiences indicate that active network corrections are still beneficial even when a sparser network is used because the accuracy of these corrections is still superior to other correction approaches normally available. At least this is true for the ionospheric propagation delays. One might argue whether it could be possible to replace the tropospheric correction by those obtained from numerical weather models as outlined in the paper by T. Schüler et alia [2000] cited in Additional Resources.

Although these results are rather promising for the future, there are several aspects of improvements for the future. The correction methods could be improved, for instance. A tomographic model of the ionosphere, for example, could help to better model this type of delay.

Moreover, only GPS and Galileo have been taken into consideration in this study. As mentioned earlier, GLONASS might become worth to being incorporated in this scheme in the future, but this is still unclear (only 9 active satellites were seen during the work carried out for this study). Furthermore, China plans to establish another GNSS, the Compass system. Consequently, at least three GNSSes could be available for the user in the future.

Acknowledgments

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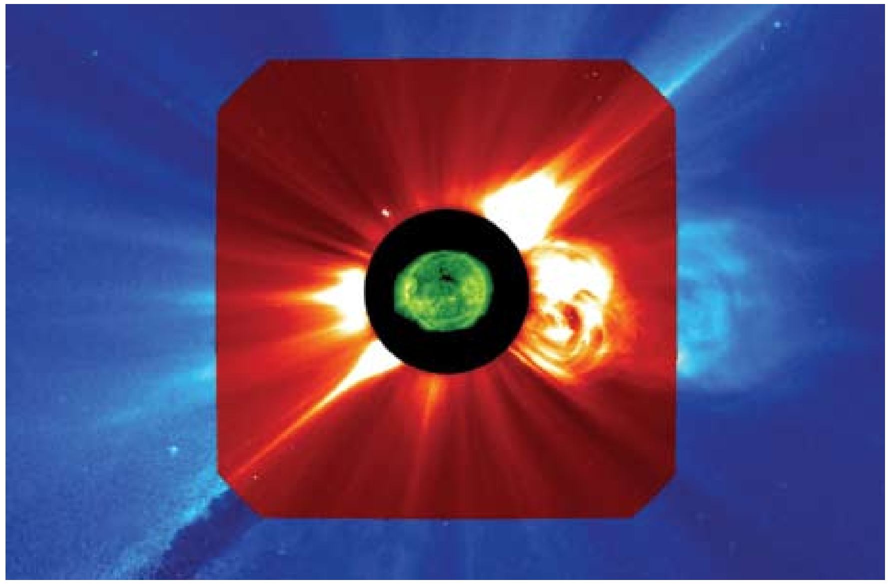
Manufacturers

The German active GNSS network described in this column is **SA*POS*,** the Satellite Positioning Service of the German National Survey, Hannover, Germany. Background maps from the Encarta World Atlas, **Microsoft Corporation,** Redmond, Washington, USA.



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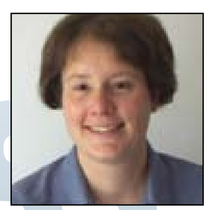

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