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Finland's EGNOS Monitoring and Performance Evaluation (FEGNOS)

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Abstract:
This document is the final report for the FEGNOS project. It describes the work performed within the scope of this project. It also lists some of the planned continuing activities and future publication plan.

Disclaimer:

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Project Executive Summary

The European Geostationary Navigation Overlay Service (EGNOS) is the first European operated satellite navigation system and is a precursor to Galileo, the full Global Navigation Satellite System (GNSS) under development by Europe. At present, EGNOS augments the US GPS satellite navigation system and makes it suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels. EGNOS can also support new applications in many different sectors such as agriculture (for high-precision spraying of fertilizers), transport (enabling automatic road-tolling or pay-per-use insurance schemes) [1] or even precise personal navigation services for general and specific usage. Finland being a high latitude (>60^0 N) country, the availability of EGNOS GEO satellites are always very challenging due to their very low elevation angles. Finnish Geospatial Research Institute (FGI) at National Land Survey of Finland (NLS) has been maintaining 20 permanent GNSS reference network stations all over Finland. The objective of this project is to monitor and analyze the performance of EGNOS in all those reference stations 24/7 in order to clarify that the EGNOS system performance reaches its target, also in Finland. FGI is the only public entity in Finland that has both the necessary infrastructure and knowledge for monitoring EGNOS performance. This undergoing experience and knowledge would give the opportunities to identify weaknesses in EGNOS system performance, especially at high northern latitudes. The outcome of this project will eventually be contributed to the future improvements of EGNOS, especially if we think of the expected performance and the promise of EGNOS in the north arctic area.

Project Duration

01.10.2015 –30.06.2016

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Table of Contents

List of Acronyms and Abbreviations

Term	Description
DGNSS	Differential Global Navigation Satellite System
EGNOS	European Geostationary Navigation Overlay Service
ESSP	European Satellite Services Provider
ETRF	EGNOS Terrestrial Reference Frame
FGI	Finnish Geospatial Research Institute
FinnRef	The Finnish Permanent GNSS network
FEGNOS	Finland's EGNOS Monitoring and Performance Evaluation
FEGCoT	FEGNOS Data Collection Tool
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HNSE	Horizontal Navigation Solution Error
HPE	Horizontal Position Error
ITRF	International Terrestrial Reference Frame
NLS	National Land Survey of Finland
NMEA	National Marine Electronics Association
OS	Open Service
PVT	Positioning, Navigation and Timing
PM	Project Manager
RIMS	Ranging and Integrity Monitoring Station
SBAS	Satellite-Based Augmentation System
SDCM	System for Differential Corrections and Monitoring
SoL	Safety of Life service
SPS	Standard Positioning Services
T0	Start date of the project = 01.10.2015
VPE	Vertical Position Error
VNSE	Vertical Navigation Solution Error
WP	Work Package

1. Introduction

Standard Positioning Services (SPS) of GNSS (receiver in stand-alone mode) can be augmented with code-based Differential GNSS (DGNSS) or with Satellite-Based Augmentation System (SBAS). In general, augmentation system offers higher positioning accuracy than positioning made in stand-alone mode. In addition, SBAS offers information on availability and integrity of corrections and SPS ensuring positioning in safety critical applications.

In this project, we investigate the achievable real-time accuracy in different user scenarios with the state-of-the-art geodetic GNSS receiver in Finland with corrections from Finnish National Land Survey's (NLS) Differential GNSS (DGNSS) Service, from European EGNOS (European Geostationary Overlay Service) [1], [2] service and from Russian SDCM (System for Differential Corrections and Monitoring) service [3], [4]. Accuracies are determined based on the data obtained from a series of test measurements. Tests are performed in both static and dynamic modes.

EGNOS performance is monitored at RIMS (Ranging and Integrity Monitoring Stations) stations and results are also publicly visible at European Satellite Services Provider's (ESSP's) web pages [2]. The EGNOS performance analysis at RIMS stations is very optimistic, mainly for two reasons: i) these stations' GNSS pseudorange data are utilized to compute the corrections, and ii) the stations are stationary and located usually outdoor with very good sky visibility. Therefore, the EGNOS accuracy reported in ESSP may not always reflect the real picture of the expected accuracy within its area of coverage. In recent years, researchers in Norway have been monitoring EGNOS performance [5], [6] with the PEGASUS software [7]. It was shown in [5] that the EGNOS performance can be degraded adversely by ionospheric disturbances at high latitudes. In addition, the geometry of GPS satellites can sometimes be poor at northern latitudes, contributing to degraded positioning performance. Recently, Finland has also undertaken a similar project entitled 'Finland's EGNOS Monitoring and Performance Evaluation (FEGNOS)' in order to monitor the performance of EGNOS in Finland [8].

2. Augmentation Services

2.1 NLS's DGNSS Service

In the beginning of 2014, FGI opened a positioning service based on the Differential GNSS (DGNSS) corrections for GPS and GLONASS [9]. The positioning service is based on real time data streams from permanent GNSS stations covering the whole Finland, called the FinnRef [10], [11]. FinnRef network has 20 permanent GNSS reference station as shown in Fig. 1. The positioning software utilized in the service is called GNSMART and was developed by the company named GEO++ GmbH [12]. The primary function of FinnRef is to offer geodetic-grade GPS/GNSS measurements used for forming and maintaining the national coordinate system (EUREF-FIN). In addition, the FinnRef network is used for many GNSS-related research activities. For example, it is now possible to analyze the positioning performance of different augmentation services via FinnRef network. FinnRef network has been established in mid 1990's and it has recently been upgraded during 2012-14.

The user of the open positioning service can either choose to use correction from a single station (nearest or any selected) or correction interpolated from multiple station data to certain spot nearby the user (rover). Corrections enhance the L1 code-based positioning solution and they include differential pseudorange corrections both for GPS and GLONASS satellites seen by the reference station(s). The DGNSS service sends this information in an RTCM 2 message, specifically types 1, 3 and 31. Corrections are provided to users via internet using the NTRIP-protocol [13].

The GNSMART software is also capable of providing different types of RTK corrections. These corrections are, at the moment, generated only for research purposes and are not provided in the public positioning service. In this project, we used Network RTK (GPS+GLONASS) corrections to get accurate reference solutions (fixed only used) for comparison of DGNSS, EGNOS and SDCM accuracies.

2.2 European Geostationary Overlay Service (EGNOS)

EGNOS is an augmentation system providing correction data and integrity information for improving GPS (GPS L1 Coarse/Acquisition civilian signal) Positioning, Navigation and Timing (PVT) over Europe. Main services of EGNOS are Open Service (OS) [1] and Safety of Life service (SoL) [14]. The SoL service has strict minimum performance parameters especially designed to meet the requirements of civil aviation. SoL service has been operational since 2011. EGNOS corrections refer to EGNOS Terrestrial Reference Frame (ETRF), which is closely aligned to the International Terrestrial Reference Frame (ITRF) and to WGS84 coordinate system used by GPS. EGNOS comprises of two main segments in space and ground. RIMS stations all over the service area collect raw GPS data measurements on which corrections and integrity data formation in the processing centers are based on. The corrections and integrity information are sent to users via geostationary satellites, namely PRN 120 and PRN 136, as of February 2016 [2]. Elevations of these satellites are relatively low in Finland as compared to most other European countries.

2.3 System for Differential Corrections and Monitoring (SDCM)

System for Differential Corrections and Monitoring, abbreviated SDCM (СДКМ, Российская система дифференциальной коррекции и мониторинга) is Russian operated SBAS system [15]. SDCM has a similar working principle like other existing SBAS systems. Monitoring stations are mostly located in the territory of the Russian federation. The nearest ones to Finland are in Saint Petersburg, Svetloe observatory and Lovozero in North. SDCM data is transmitted to user via three geostationary satellites with PRN numbers 125, 140 and 141. SDCM provides services for both GPS and GLONASS. GPS and GLONASS use different coordinate systems WGS84 and PZ-90.02, respectively. SDCM generates corrections in WGS-84 by matrix transformation of GLONASS data from PZ-90.02. In SBAS messages, SDCM data for GLONASS and GPS are presented in single time scale, i.e., GPS time scale [15].

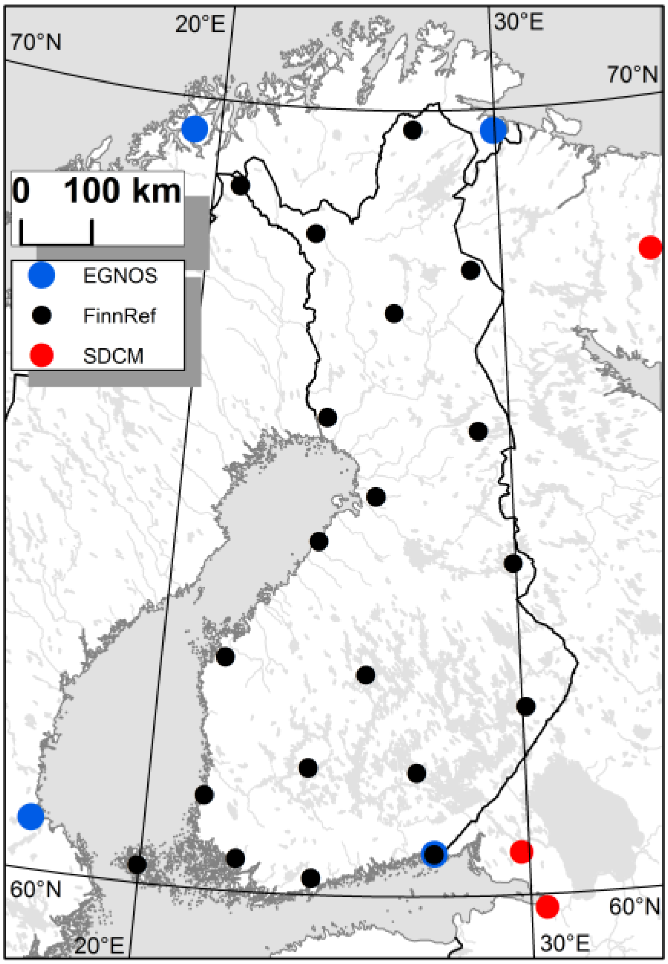


Fig. 1. Permanent GNSS-stations (FinnRef), EGNOS RIMS stations and SDCM reference stations around Finland.

3. Work Package Status

3.1 WP1000 – Literature review and EGNOS system study

Several publications and standards have been studied so far as listed in references [1]-[16]. This work package lasted for the entire 10 month duration of the project. The objective of this work package was to enrich the knowledge on EGNOS by reading relevant research papers, technical documents and instruction manuals of different analysis tools like EGNOS ICD, PEGASUS, RTKlib, RTCA/DO-229, etc.

3.2 WP2000 – EGNOS signal monitoring in all FinnRef stations

EGNOS signal monitoring in all FinnRef stations has been carried out for one year time frame during Nov'2015 – Oct'2016. In order to monitor the EGNOS data, there is a necessity to collect data from all FinnRef stations. Data was collected from all 20 FinnRef stations. Each FinnRef station is equipped with a dual-frequency geodetic grade receiver, i.e., Javad Delta-G3T receiver. Each receiver generates 1-hour binary Javad-proprietary 'JPS' data at 1 Hz rate. Data is pushed and saved to the network sever after every 1 hour. This means that there are in total 24 data sets for each single day for one single station. All the stations binary JPS data are then organized under one directory, which is named after the Day Of Year (DOY) for that particular year. The FEGNOS data collection and analysis flow chart is shown in Fig. 2. The flow chart describes how data was collected from all FinnRef stations, and then pre-processed to be utilized by the EGNOS analyzing tool called 'PEGASUS' from Euro Control [7].

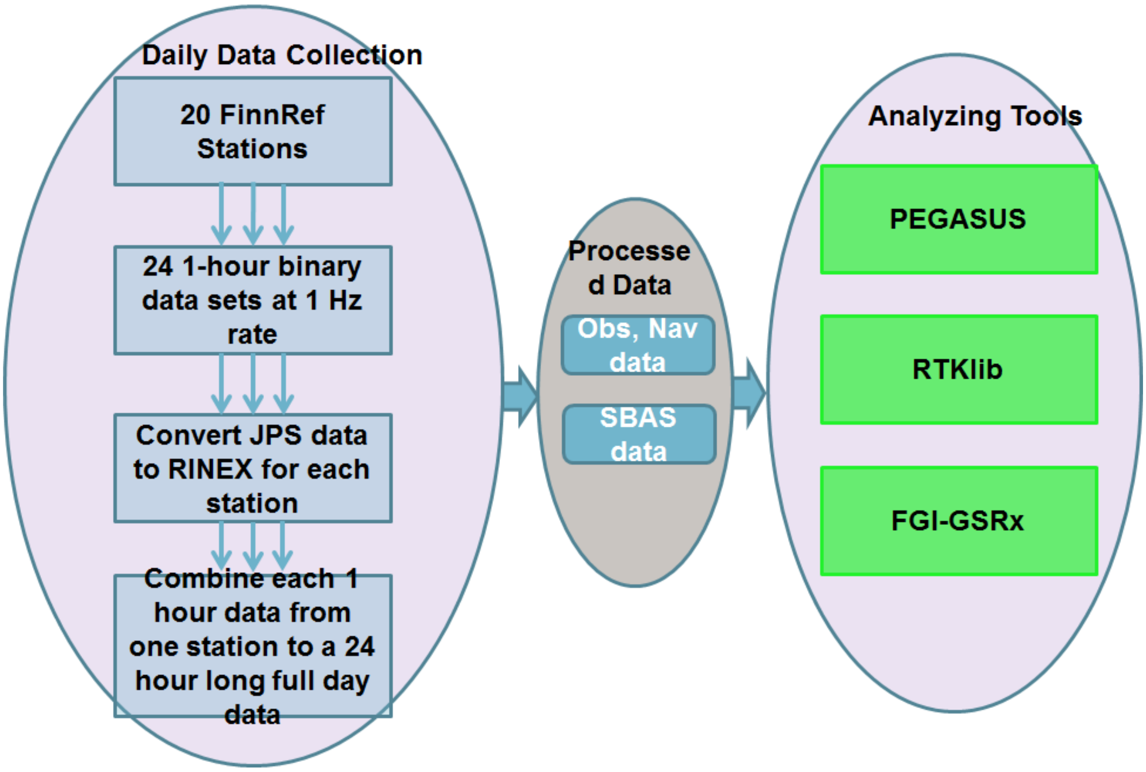


Fig. 2. FEGNOS data collection and analysis flow chart

FEGNOS data collection tool (FEGCoT) was developed in Matlab in order to collect everyday data automatically from all 20 FinnRef stations. The main working principal of FEGCoT is shown in Fig. 3. The main working principle for FEGCoT is based on the following three steps:

I. Collect: It collects 1-Hz hourly data from the FinnRef server and then saves those data to the local hard disk for further processing.

II. Convert: The raw binary 'JPS' format hourly data were converted to RINEX Observation, Navigation and SBAS data files.

III. Combine: It combines 24 1-hour data sets from each station to 1 single 24-hour data for every RINEX file type (i.e., observation, navigation and SBAS).

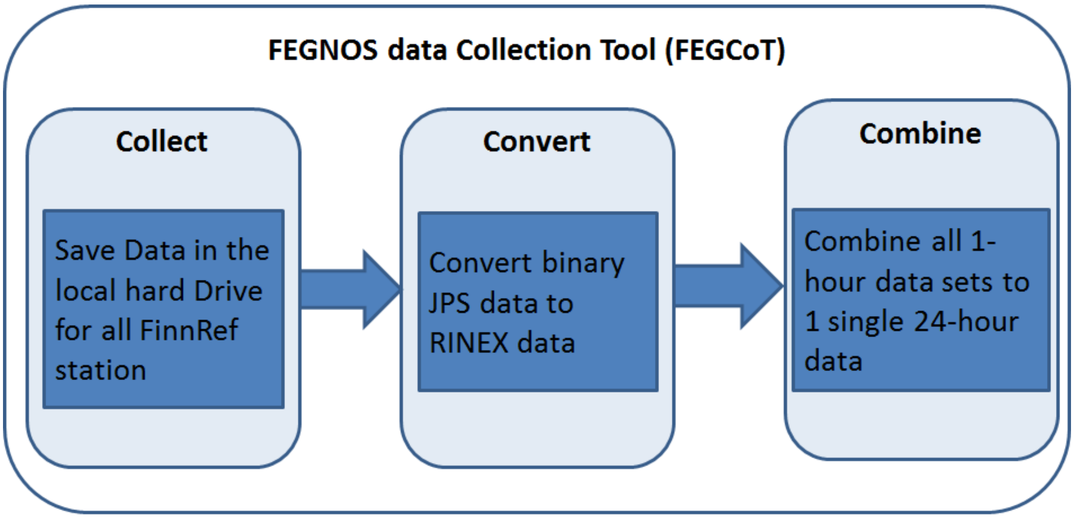


Fig. 3. FEGNOS data Collection Tool (FEGCoT)

3.2.1 Experiments with real time data analysis

Experiments were performed with Javad Delta receivers (Delta-G3T), which were connected via signal splitters to one single antenna. The antennas used in the tests were NovAtel GPS-702-GG and Javad JPL designed choke ring antenna with 'Dorne Margolin' elements. During the static tests, the NovAtel antenna was mounted on a tripod, and on a specific metal plate in Masala rooftop at the FG I premises. At all FinnRef stations, Javad JPL antennas are mounted on top of three meter steel masts. During all kinematic tests, NovAtel antenna was mounted on the roof-rack of a passenger car. High quality coaxial antenna cables were used to connect the antenna with the receiver. Furthermore, we also needed a computer with internet connection to feed DGNSS and Network RTK corrections in real-time. We used GNSSSurfer (V1.08) to send corrections to the receiver. Corrected coordinates and other information were written to a file in Javad's proprietary text message format. 10° satellite cut-off angle was used in all the tests. Dynamic positioning mode was configured in the receiver while doing kinematic tests and static mode was configured for static measurements. Positioning interval was set to 1 second. Maximum allowed correction age (DGNSS, EGNOS and SDCM) was set to 30 seconds for all the tests.

3.2.1.1 Static test scenarios

The main idea behind the static experiments was to find out with relatively long time series what kind of accuracy can be reached in good and challenging positioning environments and also how location of the rover station with respect to the reference stations affects the offered solution (distance to the reference station(s)) in case of DGNSS. Three full days of data were collected at each test session. In addition to DGNSS, EGNOS and SDCM stand-alone tests were performed in order to understand the offered positioning accuracy of the receiver without applying any correction. For static tests, reference coordinates were measured with long PRS (Pseudo Reference Station) measurements and for Masala metal plate point, we had earlier measured the true coordinates with static relative GPS. Reference point in thick forest was ensured with tachometer.

In DGNSS tests, both nearest station and network-based approach were tested. Static DGNSS tests were done at three locations as shown in Fig. 4. Three test locations are in: i) Lahti in the middle of four FinnRef stations (nearest 101 km), ii) in Masala (nearest 10 km), and iii) in Metsähovi just beside the station. In Masala, tests were done in two reference points, at good visibility condition at the rooftop of FGI main building and just behind it in the thick forest. In both Lahti and Metsähovi, visibility was good. Photos from the test sites are shown in Fig. 5.

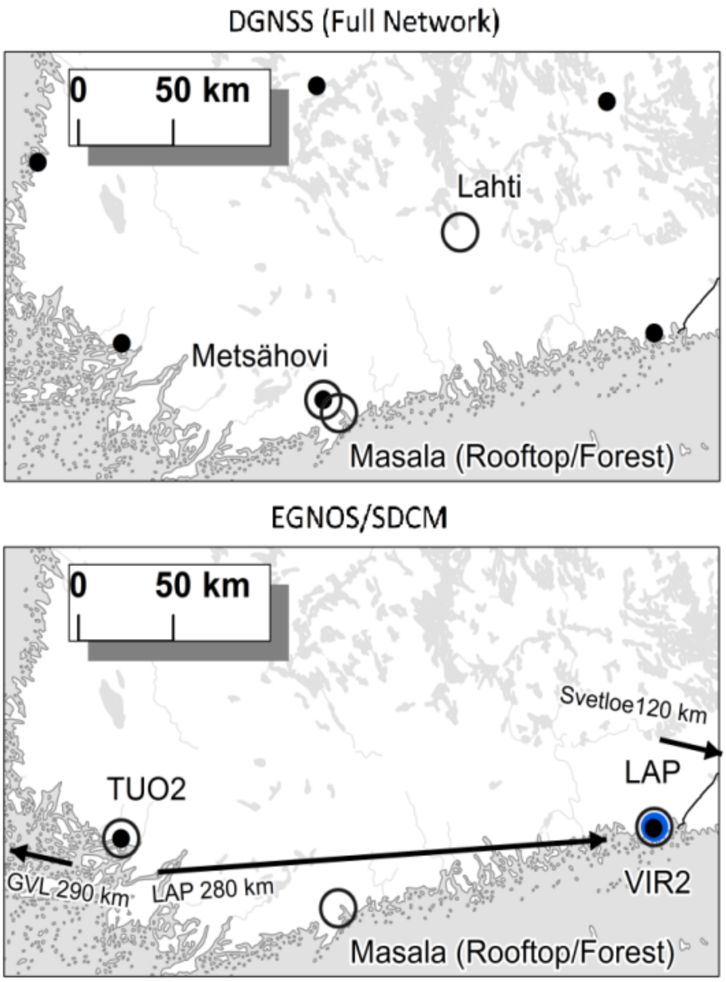


Fig. 4. Static test points.

Static accuracy of EGNOS and SDCM were tested in Masala rooftop and in forest conditions. In addition, simultaneous tests at two permanent FinnRef stations were conducted. In these tests, two receivers were left in station TUO2 (at Tuorla) and other two in VIR2 (at Virolahti). The idea behind this was to find out if there was any reference station distance dependency in EGNOS or SDCM. TUO2 lies in the middle of LAP and GVL RIMS stations (280 and 290 km) and VIR2 just beside the LAP RIMS station at Virolahti. For SDCM, test sites were located respectively about 400 kms and 120 kms outside from the nearest monitoring station (Svetloe). Receivers were connected via splitters to antennas of permanent FinnRef stations.

Fig. 5. Pictures from test sites in Masala (Forest), in Lahti and in FinnRef station VIR2.

3.2.1.2 Kinematic

During the kinematic tests, three receivers were simultaneously used. One receiver was used for collecting reference coordinates (via Network RTK). Other two receivers were used to collect positioning solutions with corrections from either Network DGNSS and EGNOS or EGNOS and SDCM respectively. Only those time epochs with fixed PRS solutions were used as reference. Due to this, at challenging GNSS condition, we had time-to-time measurement gaps in the reference position solution. Kinematic tests were conducted with a passenger car in three different scenarios: i) at open area in Siuntio, Finland (TD 1), ii) at Helsinki city center, Finland (TD 2), and iii) at typical Finnish road environment (TD 3). In all the above cases, positioning solutions were achieved with Network DGNSS and EGNOS. Comparison of EGNOS and SDCM was performed in a separate car drive test in eastern Finland (TD 4) at condition typical for Finnish road environment. Static data when the car was stopped was not used in the accuracy calculation. The test drive locations are shown in Fig. 6.

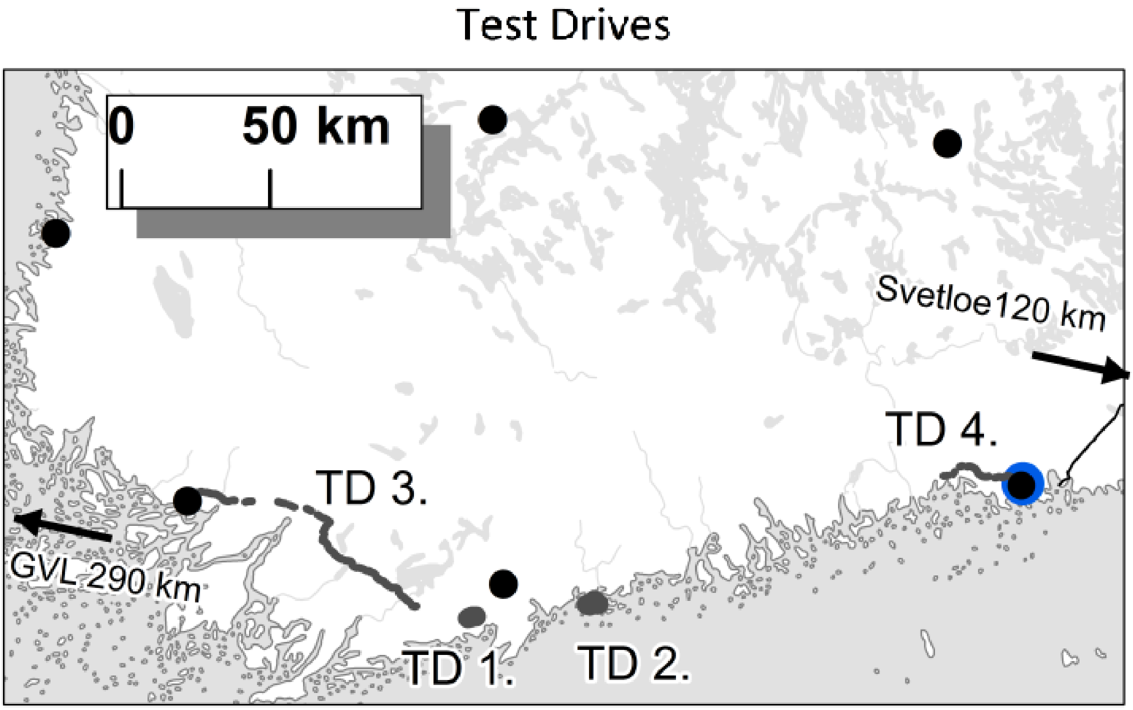


Fig. 6. Locations of kinematic tests.

Open area tests were conducted in a 3-km long road. The road was in the middle of fields (as shown in Fig. 7). Mean elevation of obstacles was estimated to be under 10° from the horizon but still there were a few places with much higher elevations for obstacles, for example, due to power transmission-lines and trees. The route was driven back and forth for five times at a speed of 48 km/h with a total driving time of 39 minutes.

City center test was conducted in the capital of Finland, Helsinki. A 50-minute driving test was carried out in more or less narrow streets. The average driving speed without considering any stops was 32 km/h.

During the two tests in typical Finnish road environments, the car was driven in a two-lane highway and in a motorway from Raasepori to Turku and from Virolahti towards the west of Finland. Surroundings en route varied much from open field spots to motorway tunnels and bridges. Most of the time, trees and small hills were blocking lower elevation satellites. In TD 3, the driving time was about 1 hour and 23 minutes at an average speed of 75 km/h and in TD4, the driving time was about 30 minutes at an average speed of 65 km/h.

Fig. 7. Antenna on roofrack in Siuntio (TD 1).

3.2.1.3 EGNOS tests in Air

Flight experiments were conducted along with NLS aerial and laser scanning flights during May 4 –May 9, 2016. The airplane used for this work was two-engine turboprop Rockwell 690A Turbo Commander Cessna plane, as shown in Fig. 8. Total number of flights in test was 9 and the total flight time was about 26 hours (i.e., 94350 epochs). Epoch interval was set to 1 second. Receiver was turned on at ground before and after flights. A geodetic grade Javad Delta 3GT receiver was used in the flight tests. The GNSS antenna named Antcom G5ANT_42AT1 was permanently mounted on the top side of the plane. Receiver was configured to save raw GNSS data and real-time EGNOS corrected positioning solutions. Only GEO PRN120 was set for tracking and obtaining the EGNOS corrections. The maximum age of EGNOS correction messages was set to 360 seconds; i.e. in case of unavailability of EGNOS correction messages, the receiver was allowed to use corrections which are not older than 360 seconds.

Fig. 8. Cessna plane to perform aerial photography and laser scanning during summer

The raw data was post-processed with Inertial Explorer software to get accurate reference coordinates in order to find out the accuracy of EGNOS corrected solutions. Post-processed solutions were phase-based relative solutions. Static GNSS reference raw data was obtained from 2-4 nearest FinnRef stations [9].

GNSS signal reception environment for aviation can generally be considered good due to the nice satellite visibility. But during maneuvering of the plane, visibility of satellites in certain directions can be blocked due to rolling and pitching of the plane. The Aircraft speed in our flight tests varied between 0-490 km/h (mean speed of different flights varied between 270 km/h to 390 km/h) and the maximum altitude from the ground level was about 5300 meters. Most of time the Aircraft was flying at certain altitudes: 5000 m, 3000 m or 1200 m. Routes for the test flights in Southern Finland and the location of the RIMS station in South-Eastern Finland is shown in Fig. 9.

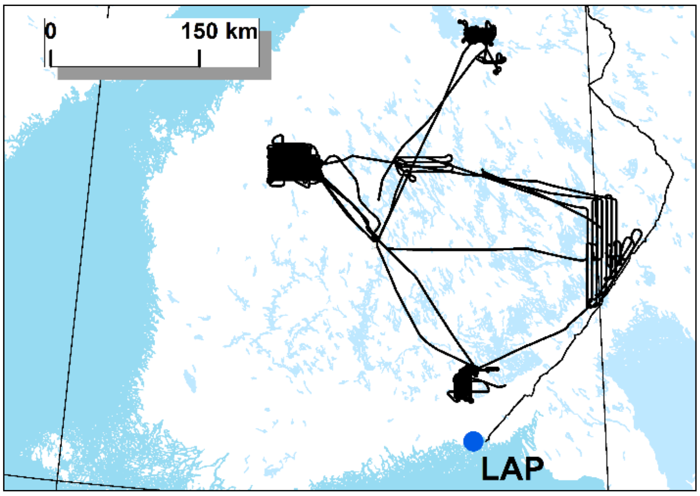


Fig. 9. Routes of test flights in Southern Finland and RIMS station in South-Eastern Finland.

3.3 WP3000 – Performance evaluation of EGNOS in all FinnRef station via PEGASUS tool

3.3.1 Data Collection

EGNOS signal monitoring in all FinnRef stations has been carried out for a one year time frame during 04 November, 2015 till 31 October, 2016. There are in total about 360 days of data from the 20 FinnRef stations out of 366 days of a year (2016 is a leap year). DOY allocation for the collected year-long data set is elaborated in Table I. No data was available during DOY 233 and 234 of 2016 due to some technical fault in the FinnRef stations. There are 57 days of data from year 2015, and 303 days of data from the year 2016.

PEGASUS software was utilized to process the collected raw data from the Javad receivers in all those stations. The GPS vs. GPS+EGNOS performance were analyzed in all those stations. The analysis was carried out in three different cases:

a. Applying EGNOS corrections from EDAS server,
b. Applying EGNOS corrections from Rx-decoded EGNOS messages, and
c. GPS-only solution without any EGNOS correction.

Table I. DOY allocation for the year-long data set

DOY	Duration	Year	Number of Days
309 – 365	04 November – 31 December	2015	57
001 – 232	01 January – 19 August	2016	232
235 – 305	22 August – 31 October	2016	71
			360

The combined 24-hour RINEX data for each particular station are processed via 'PEGASUS' software. The key configuration parameters used in the data analysis are listed in Table II. Two 'PEGASUS' modules are used for data analysis:

I. **'Convertor' module**: The 'Convertor' module translates the RINEX observation, navigation and SBAS data into a generic format which will then be utilized by the 'GNSS_Solution' module for detail analysis. 'Convertor' can also use input from different GNSS/SBAS receivers and then transform the recorded binary data into readable ASCII data.

II. '**GNSS_Solution**' **module** [7]. The 'GNSS_Solution' module is used to compute a position solution in conformance with the MOPS (Minimum Operational Performance Standards) standards for GNSS receivers used in avionics (GPS, SBAS or GBAS) [15]. In other word, 'GNSS_Solution' module can be considered as a post-processing MOPS-compliant GNSS receiver. It interfaces with other PEGASUS component, notably the 'Convertor' module.

The elevation cut-off angle and the minimum accepted SNR are kept low in order to have more satellites to be considered for user position computation. The detailed elaboration of the configuration parameters can be found in [7]. It is good to note here that the range measurements from EGNOS satellites are advised not to be used for position computation [1].

Table II. Configuration parameters for 'PEGASUS'

PEGASUS Version No.	4.8.4
Elevation cut-off angle	5º
Filter smoothing constant	100 seconds
Maximum data gap	10 seconds
Maximum divergence repetition	3 seconds
Minimum accepted Signal-to-Noise Ratio (SNR)	20 dB
Range measurements from GEOs for position computation	Not considered
Airborne Accuracy Designator (AAD)	Class A
Ignore almanac	Yes

A Matlab-script was written in order to download EDAS provided daily SBAS messages automatically from the EDAS server. All the PEGASUS-related processing was also executed from a Matlab-based script.

3.3.2 Result Analysis

The EGNOS/GPS performance was analyzed for the above-mentioned cases with the collected year-long data set from 20 FinnRef stations. There were in total 360 days of measurements from 20 different stations. The operational time or up-time of each FinnRef station was monitored throughout the FinnRef network nodes on daily basis. The average up-time of each station for the one year data set is shown in Fig. 10. As seen in Fig. 10, most of the stations were up for more than 98%, while only few have up-time close to 95%.

According to EGNOS Open Service (OS) horizontal and vertical accuracy requirements, the 95% Horizontal Navigation System Error (HNSE (95%)) should be less than 3 meters, and the 95%Vertical Navigation System Error (VNSE (95%)) should be less than 4 meters in EGNOS service provision area [1]. The horizontal and vertical position errors at a defined time epoch are computed as the difference between the estimated navigation position and the actual position in horizontal and vertical planes, respectively. The HNSE (95%) and VNSE (95%) are computed for all FinnRef stations with the year-long data set.

The yearly EGNOS performance in terms of HNSE (95%) and VNSE (95%) are shown in Figs. 11 and 12, respectively. It can be observed that the GPS+EGNOS offers significant accuracy improvement as compared to GPS-only solution in all the stations. Vertical accuracy improvement for EGNOS is greater than the horizontal improvement, mostly due to the better mitigation of ionospheric error as compared to the GPS. It is also observed that the Rx-Decoded EGNOS performance is not as good as the performance when corrections are obtained from the EDAS server. This might be due to the poor visibility of EGNOS satellites in north-eastern latitudes, which resulted in data aging or partial data loss of EGNOS messages.

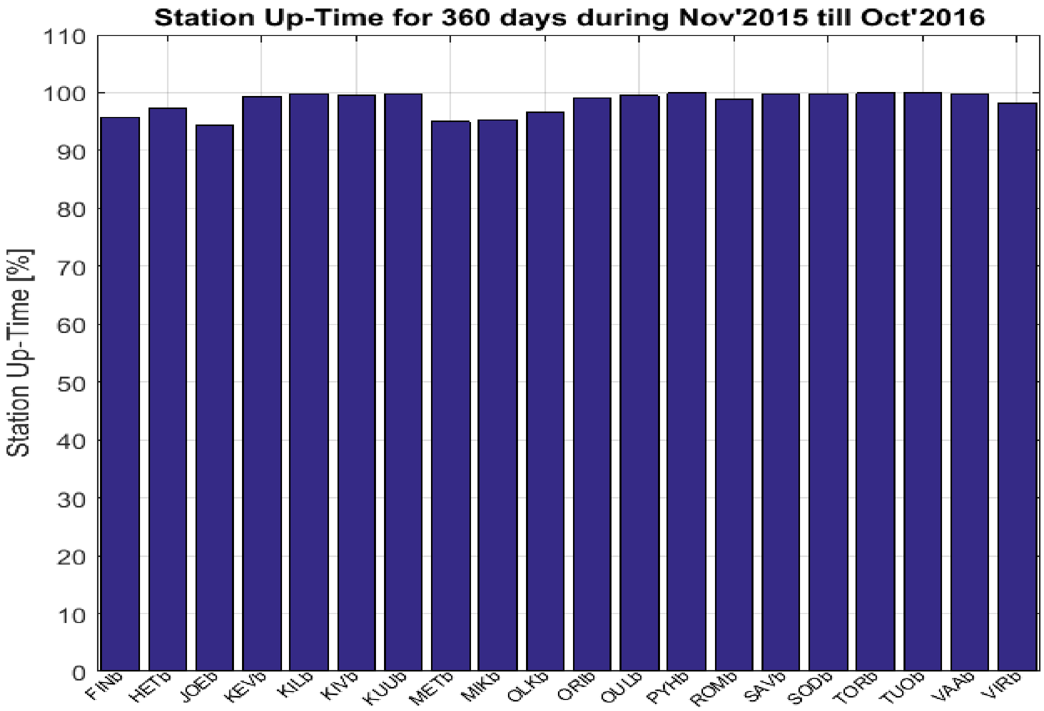


Fig. 10. Station up-time for all FinnRef stations for the year-long data set

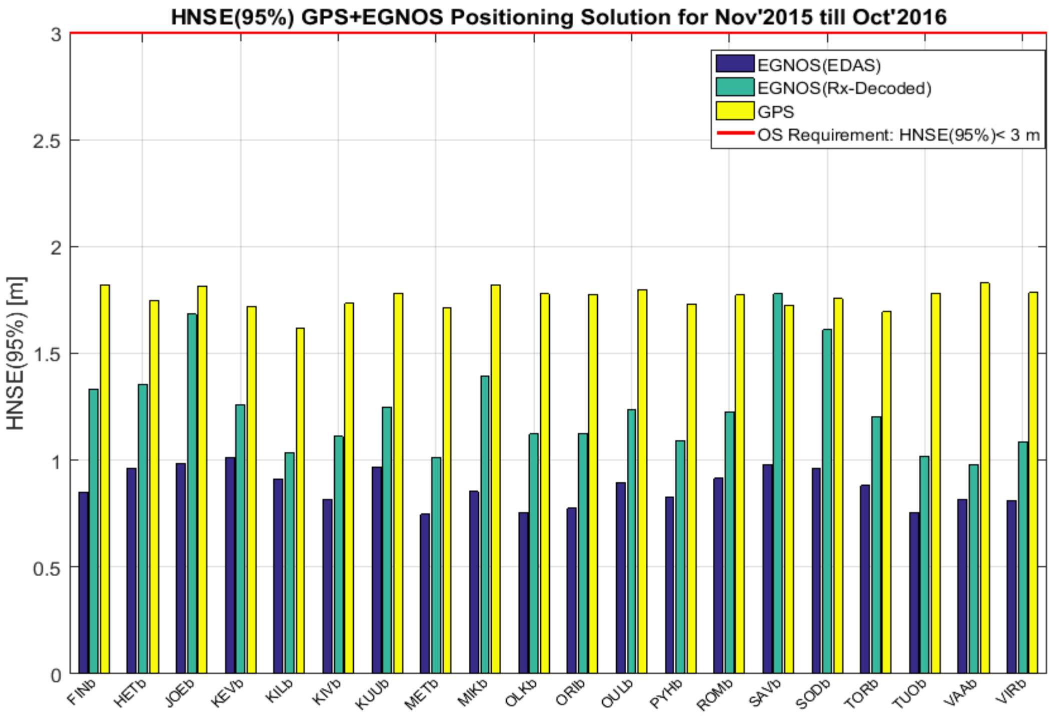


Fig. 11. HNSE (95%) in all FinnRef stations

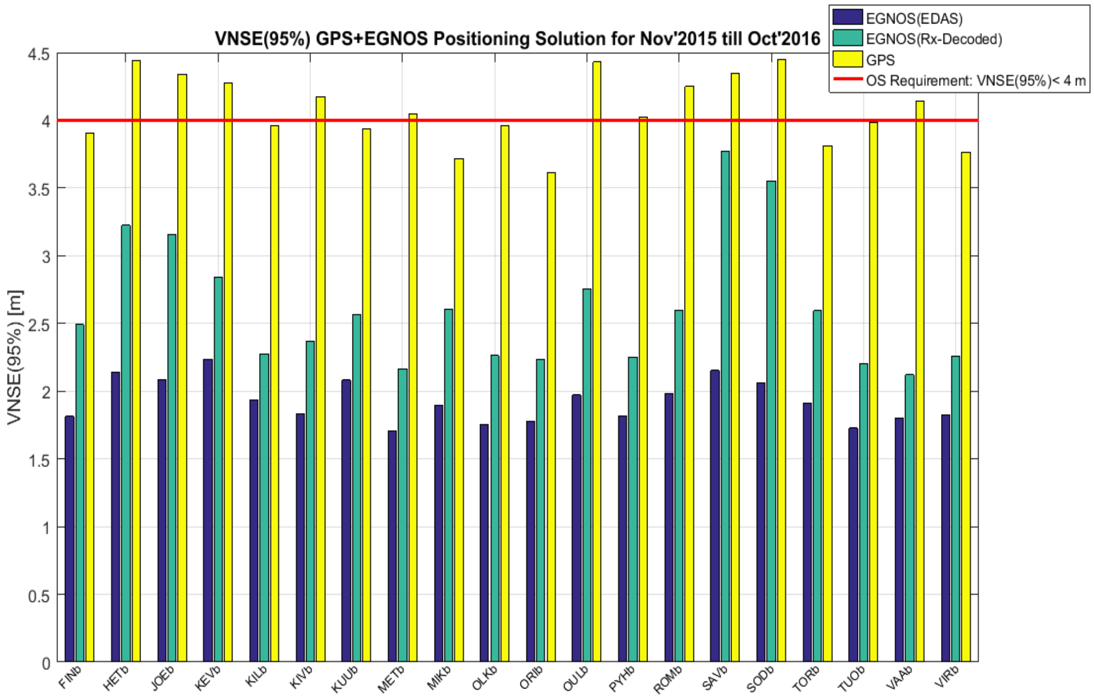


Fig. 12. VNSE (95%) in all FinnRef stations

The daily EGNOS performance in terms of VNSE(95%) are shown for the two cases: i. applying EGNOS corrections from EDAS server provided EGNOS messages, and ii. applying EGNOS corrections from Receiver-Decoded (Rx-Decoded) EGNOS messages, in Figs. 13 and 14, respectively. For a better understanding, the percentage of EGNOS OS requirement failure when analyzed at a daily basis with EDAS offered corrections is presented in Fig. 15. The percentage of EGNOS OS requirement failure was computed from the number of days where the HNSE(95%)>=3 meters in case of horizontal navigation solution error and VNSE(95%)>=4 meters in case of vertical navigation solution error. As observed from Figs. 13 and 15, the EDAS offered EGNOS corrections fail to meet the OS requirement only in a few instances. Similarly, the percentage of EGNOS OS requirement failure when analyzed at a daily basis with Rx-Decoded corrections is presented in Fig. 16. It can be well-noticed from Figs. 14 and 16 that the Rx-Decoded EGNOS performance fails to meet the OS requirement on many instances. However, the daily fluctuations are averaged out as the year-long data is taken into account, providing satisfactory performance on the whole.

The yearly EGNOS performance in terms of VNSE (99%) is shown in Fig. 17 along with the location of FinnRef stations in a map of Finland. The stations highlighted in red are the worst three stations in terms of accuracy. These stations are located in the north-eastern border of the EGNOS coverage area. Relatively lower availability of GPS satellites coupled with the lower number of RIMS stations at north-eastern latitudes contributed to the poorer than expected positioning performance in the north-eastern coverage area of EGNOS.

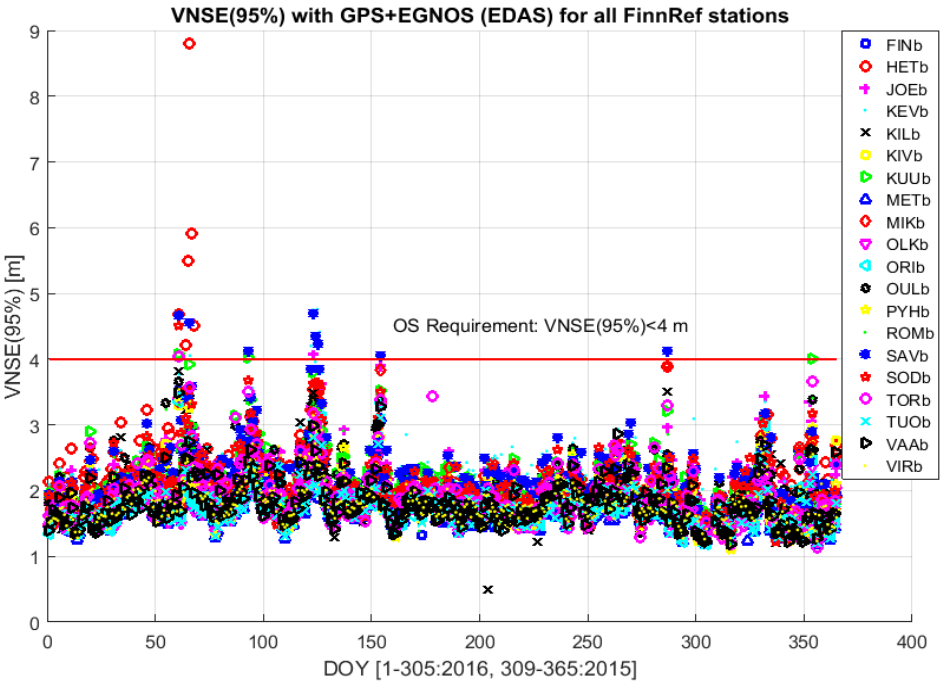


Fig. 13. DOY vs. VNSE (95%) performance with GPS+EGNOS (EDAS) corrections

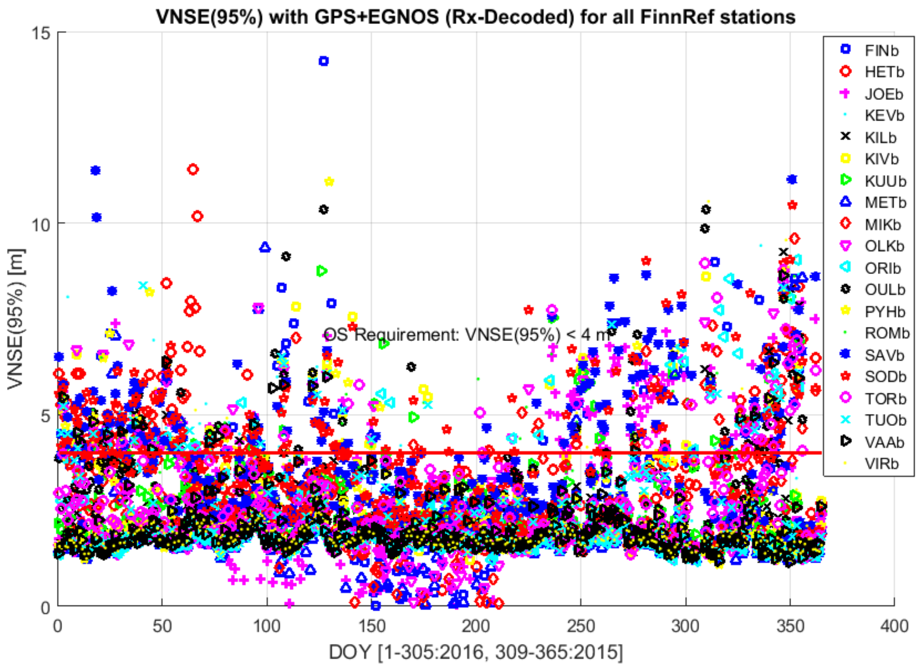


Fig. 14. DOY vs. VNSE (95%) performance with GPS+EGNOS (Rx-Decoded) corrections

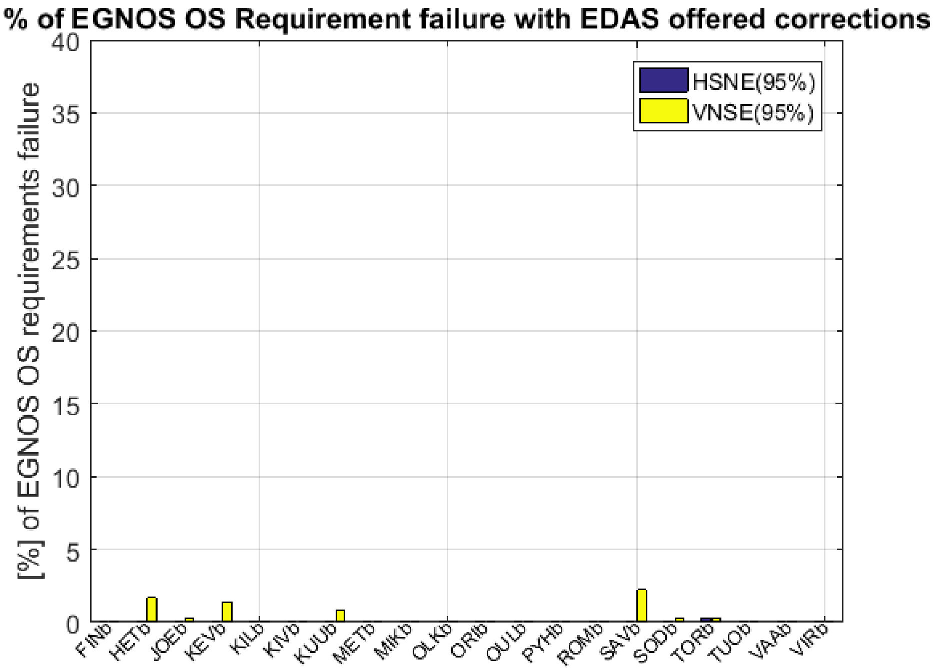


Fig. 15. Percentage of EGNOS OS requirement failure with EDAS offered EGNOS correction messages

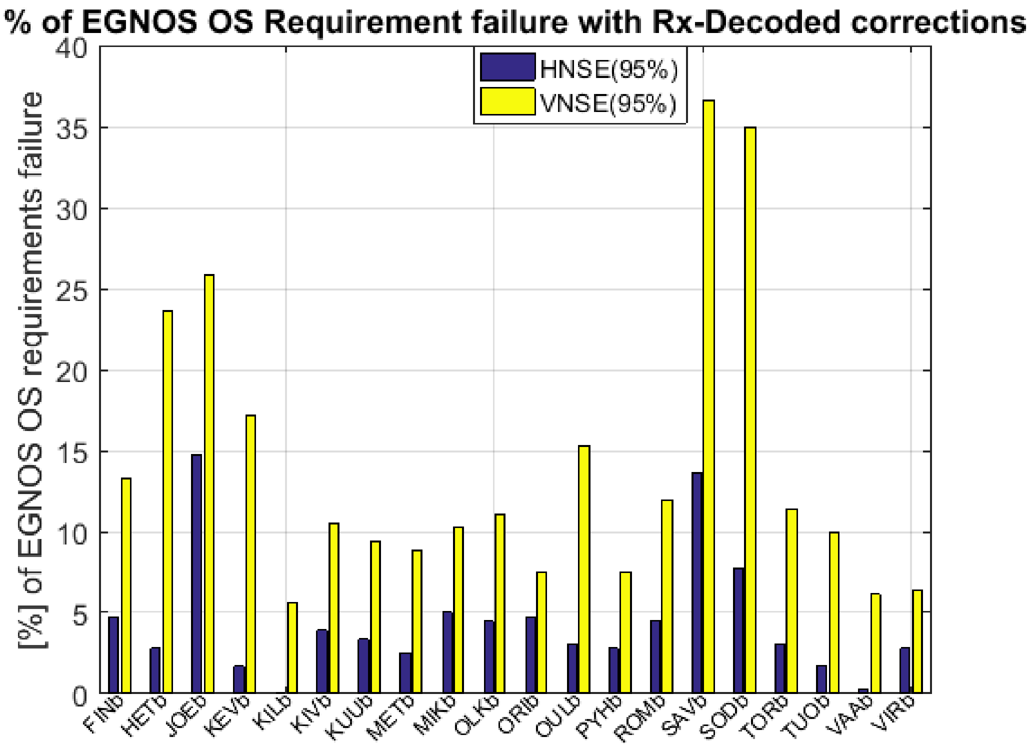


Fig. 16. Percentage of EGNOS OS requirement failure with Rx-Decoded EGNOS correction messages

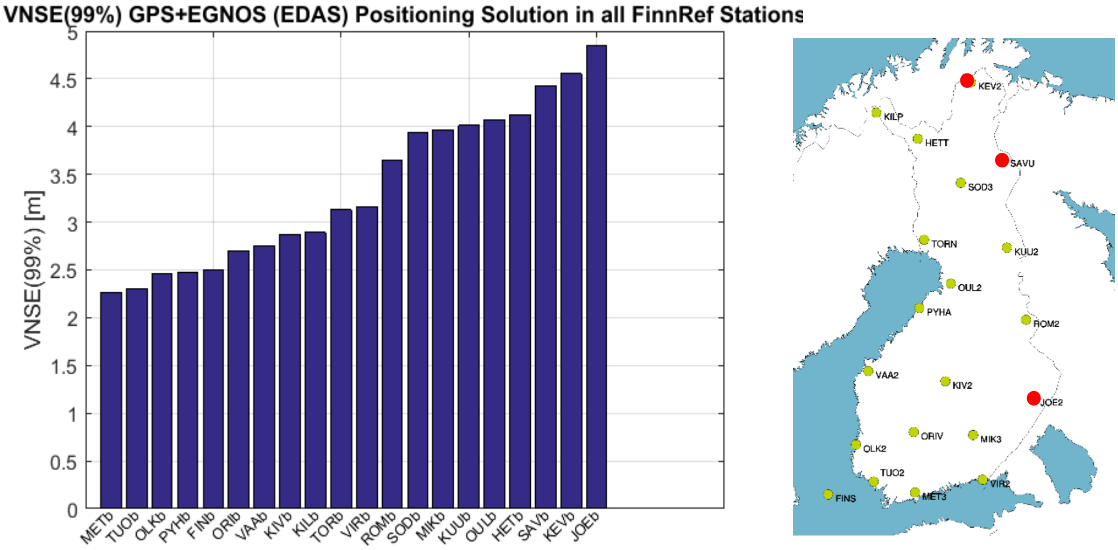


Fig. 17. Sorted VNSE (99%) performance with GPS+EGNOS (EDAS) corrections for all FinnRef stations (left); location of FinnRef stations in map: stations marked with red are the worst three stations in terms of performance

3.3.1 Performance Analysis of EGNOS, SDCM and Differential GNSS

The results are presented in this section for the test environments described in the previous section. The initial accuracy of the receivers used was evaluated first without applying any corrections. The stand-alone accuracy statistics are presented in Table III.

Table III. Stand-Alone GPS Accuracy in Static Condition

	Horizontal/Vertical Error [m]	
Site	***95 %***	***Max***
Rooftop (Good Condition)	2.90/5.48	4.78/9.42
Forest (Challenging Condition)	3.85/6.71	21.53/45.20

3.3.1.1 Static, Good Condition

Sub-meter accuracies (95% percentile) for both horizontal and vertical coordinates were reached only with DGNSS. EGNOS reached this level in horizontal coordinates but vertical accuracy was slightly poorer, but still meets the Open Service (OS) requirement (<4 m). The interesting observation with SDCM is that it offers comparable performance to EGNOS, even outside its coverage area. The horizontal and vertical accuracies are slightly worse than those of EGNOS. DGNSS accuracy decreases only a little when distance between reference station and rover grows. Therefore a homogenous accuracy can be reached all over Finland. No significant difference exists between the solutions offered by the nearest station and the network-based DGNSS correction approaches in this test environment. The accuracy statistics for DGNSS and SBAS systems are shown in Table IV and V, respectively.

Table IV. DGNSS Accuracy in Static, Good Condition

	Nearest St.		***Network***	
	Horizontal/Vertical Error [m]			
Site	***95 %***	***Max***	***95 %***	***Max***
Metsähovi	0.35/0.65	1.25/2.41	0.34/0.61	1.36/2.48
Masala	0.36/0.62	1.87/4.02	0.35/0.54	1.29/3.88
Lahti	0.50/0.75	1.34/4.84	0.40/0.68	1.64/4.86

Table V. SBAS Accuracy in Static, Good Condition

	EGNOS		***SDCM***	
	Horizontal/Vertical Error [m]			
Site	***95 %***	***Max***	***95 %***	***Max***
Masala	0.81/1.47	2.65/4.62	1.01/1.65	4.80/9.64
TUO2	0.93/1.65	2.81/4.71	1.05/1.59	2.96/4.13
VIR2	0.97/1.72	2.43/9.66	1.31/2.01	3.35/5.24

3.3.1.2 Static, Challenging Condition

Positioning accuracy in challenging environment decreases with all the tested augmentation services. But DGNSS loses relatively the most of its accuracy, about four to six times, while EGNOS and SDCM only about two times. One single major deflection was in vertical accuracies where SDCM reached clearly the best value. Occurrences of larger errors became more common in challenging condition. Maximum error values of DGNSS stayed the smallest. Accuracy statistics are shown in Table VI.

Table VI. DGNSS and SBAS Accuracy in Static, Challenging Condition

	Nearest St.		***Network***	
	Horizontal/Vertical Error [m]			
Site	***95 %***	***Max***	***95 %***	***Max***
Masala (Forest)	1.47/3.30	9.11/9.32	1.47/3.21	5.28/10.54
	EGNOS		***SDCM***	
Masala (Forest)	1.66/3.46	15.91/67.82	1.52/2.58	22.51/24.72

3.3.1.3 Kinematic, Good Condition

Like the previous test cases, here also Network DGNSS offered better accuracy than EGNOS. During the test there was a drop in number of satellites which may have at least partly affected the EGNOS vertical accuracy. With network DGNSS, the number of satellites also dropped, but due to support of multi-GNSS (GPS+GLONASS), there were still enough satellites visible than in the GPS-only case. The accuracy statistics for this test case are shown in Table VII.

Table VII. Network DGNSS and SBAS Accuracy in Kinematic, Good and Challenging Conditions

	Horizontal/Vertical Error [m]			
Site	***95 %***	***Max***	***95 %***	***Max***
	Network DGNSS		***EGNOS***	
Field Road (TD 1)	0.54/0.43	0.62/0.88	2.03/4.79	2.13/6.14
High-/Motorway (TD 3)	2.91/3.61	6.18/8.99	5.90/9.42	12.48/53.03
	EGNOS		***SDCM***	
High-/Motorway (TD 4)	7.43/4.24	7.93/4.87	4.64/5.13	18.07/23.51

3.3.1.4 Kinematic, Challenging Condition

All the tested augmentation services lose their accuracy the most in challenging kinematic condition and the offered accuracy from each system varies a lot during every drive. The best accuracy was obtained with Network DGNSS. EGNOS and SDCM performance was fairly similar. The results were analyzed only from drives at main roads. For the city center condition, we did not really get enough RTK-GNSS fixed solutions for reference. Thus, accuracy was not possible to be measured reliably with this test configuration. The accuracy statistics are shown in Table VII.

3.3.1.5 Flight Tests

The performance of EGNOS decreases in the flight tests as compared to performance in static test cases. But, anyway the offered EGNOS accuracy met the Open Service performance requirements (horizontal < 3 m and < 4 m 95 % of time). Accuracy values were calculated for those epochs when reliable reference coordinates were available. The horizontal ground plot is shown in Fig. 16. The position error fits into Gaussian distribution quite nicely, as can be seen from Fig. 17. Table VIII shows the accuracy of EGNOS corrected navigation solutions for all the flight tests.

Table VIII. Accuracy

Site	*95 %*	*Max*
Vertical	2.47 m	5.69 m
Horizontal	3.55 m	3.39 m

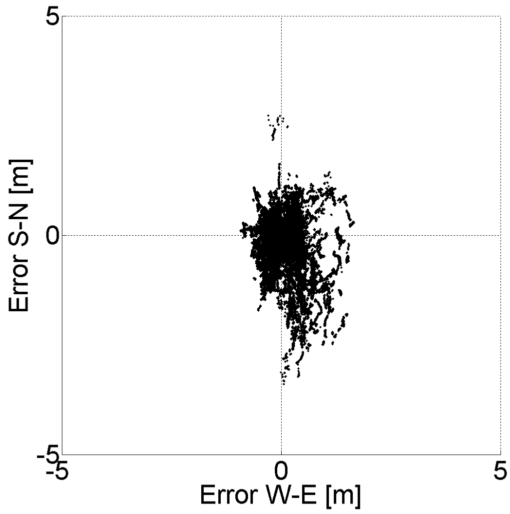
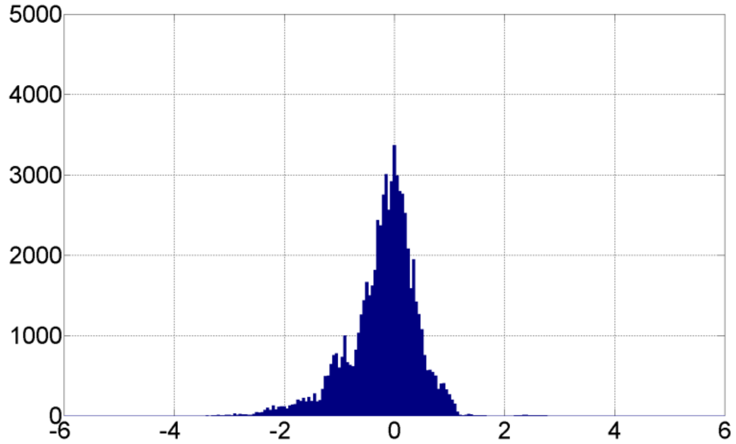
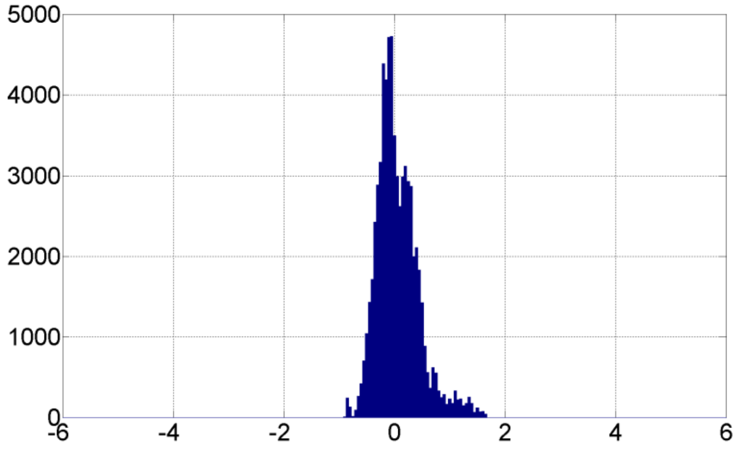


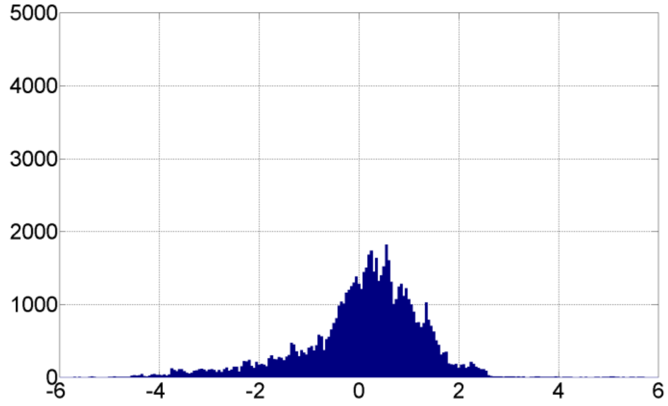
Fig. 16. Scatter of all EGNOS positionings during all flights.



North



East



Height

Fig. 17. Histograms of all EGNOS positionings during all flights divided into north, east and height component

3.3.1.6 Availability of EGNOS in Road Tests

In challenging environments, the availability of augmented solutions was low due to the poor visibility of the SBAS satellites. The poorest performance was obtained in city center condition. In this condition, SBAS performs poorly due to lack of corrections coming from one or two satellites. DGNSS solutions were then more often available as the receiver received corrections via the internet connection. The availability statistics are shown in Table VIII. In Masala (rooftop), full availability was not achieved with DGNSS most probably due to a gap in the internet connection.

Table VIII. Network DGNSS and SBAS Availability

		Availability [%]		
		Network DGNSS	***EGNOS***	***SDCM***
Static	Masala (Rooftop)	98.08	99.99	99.54
	Masala (Forest)	100.00	95.40	77.11
Dynamic	Open Field Road (TD 1)	99.38	99.96	-
	City Center (TD 2)	89.13	34.07	-
	High-/Motorway (TD 3)	97.29	82.93	-

	Availability [%]			
		Network DGNSS	*EGNOS*	*SDCM*
	High-/Motorway (TD 4)	-	91.41	86.09

3.3.1.7 Availability of EGNOS in Air space in Finland

Out of the total 26 flight hours, 6.4% of the time GEO PRN 120 was not tracked. The total number of breaks was about 190. The shortest breaks were only 1 second long (i.e., one missed epoch) and the longest one 179 seconds. The EGNOS data breaks occurred mostly when the plane was gaining or losing altitude (also in take-offs and approaches) and while turning to another direction. Breaks in GEO tracking occurred because the body of the plane came in between line of sight from antenna to satellite. Pitching angle of plane (e.g. plane's nose up and antenna behind body under it) during take-offs/climb or descends at certain directions may cause loss of signal from low elevating GEOs, as can be seen from Fig. 18. Two examples of EGNOS data gaps are also shown in Fig 19.

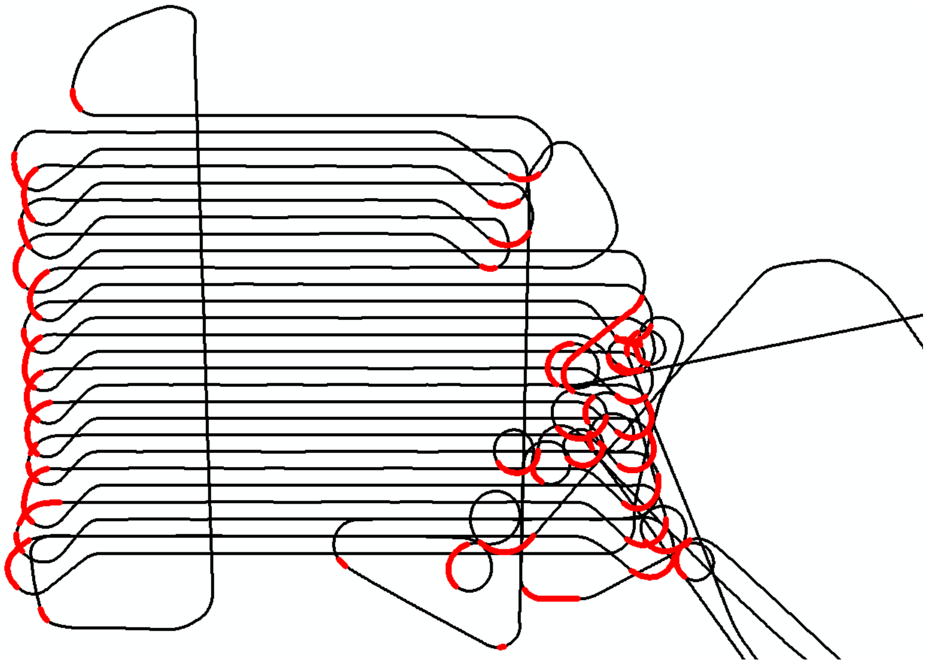


Fig. 18. Flying lines and breaks (red markings) in tracking GEO PRN120

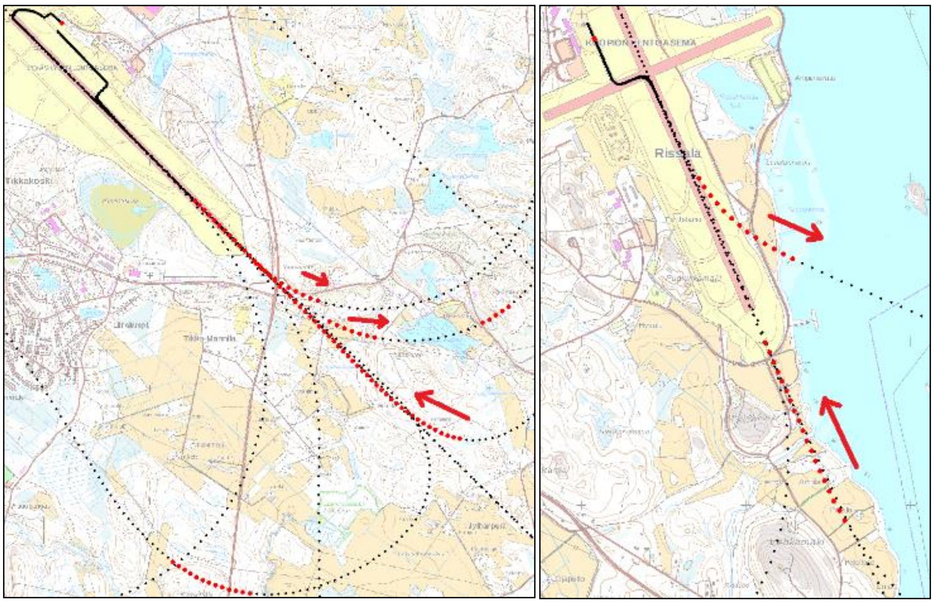


Fig. 19. Approaches and take-offs with breaks (red dot) in tracking GEO PRN120 at Jyväskylä airport (left) and in Kuopio

3.4 WP4000 – EGNOS-capable software-defined GNSS receiver analysis

The FGI-GSRx software receiver can now connect to SISNet server and can download the EGNOS messages from the server for the requested time frame. At the moment, ionospheric delay corrections are applied. Implementation of other correction parameters is ongoing. Some initial results were obtained with two old short data sets as presented in Table IX. Further analysis is required with large data sets in order to compare the performance of GPS and GPS+EGNOS with the FGI-GSRx software receiver. EGNOS satellite acquisition and tracking will be done in future. In addition to downloading the EGNOS correction data from EDAS server, the FGI-GSRx is now capable of acquiring and tracking the EGNOS satellites. The SBAS satellite tracking results are shown in Fig. 20. The data decoding part is ongoing at the time of writing this report.

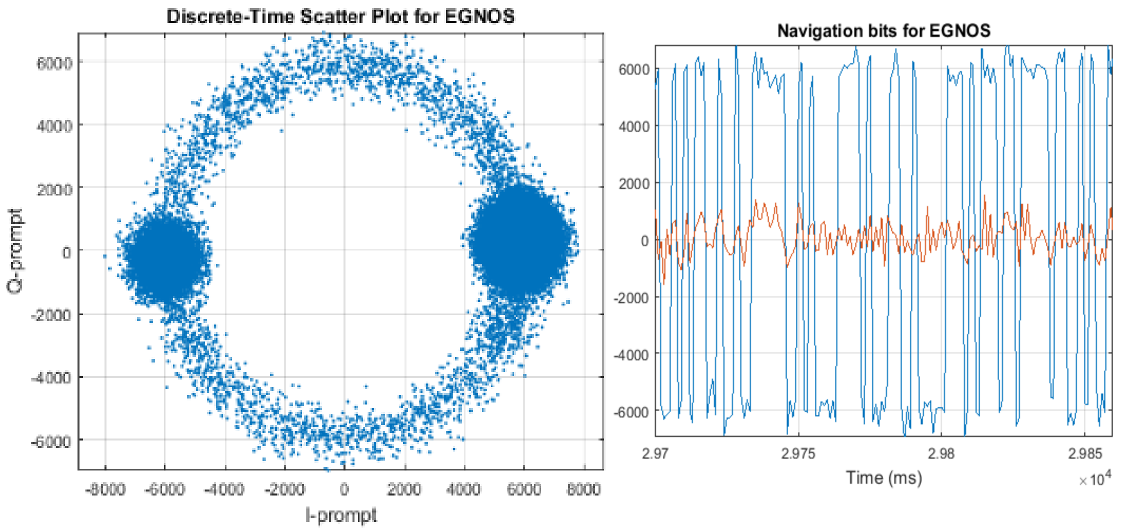


Fig. 20. SBAS satellite tracking status: (left) clear separation of navigation bits; (right) in-phase and quad-phase amplitudes over time

Table IX: Performance comparison of GPS and GPS+EGNOS with FGI-GSRx

Data set	System	HNSE (95%)	VNSE (95%)	HRMS	VRMS
06 March, 2015	GPS	3.17	3.23	2.12	6.82
	GPS+EGNOS	2.17	5.20	2.17	2.92
23 February, 2015	GPS	2.90	3.90	1.86	2.04
	GPS+EGNOS	3.41	3.92	1.69	1.81

3.5 WP5000 – Monthly EGNOS reporting

The final report will present one year long overview of the performance of EGNOS in Finland as experienced by the FinnRef GNSS reference stations. The result part of the report may contain information on the following topics:

I. Availability and continuity of EGNOS-based APV-1 service for civil aviation.

II. Comparison of Positioning accuracy of EGNOS vs GPS without EGNOS, where in both the cases the same processing strategy was used to process the raw data. The EUROCONTROL provided PEGASUS software will be used to process the raw GNSS data [4].

At the time of the final report writing, we have collected data during Nov'2015 till Jul'2016 for 9 months. The remaining months, i.e., August, September and October'2016 data collection and analysis process will be completed by November'2016. Therefore, the yearlong performance analysis of EGNOS in Finland during Nov'2015 till Oct'2016 will be provided in November'2016.

3.6 WP6000 – Dissemination Activities

The Project Manager (PM) of the project visited Norwegian Mapping Authority (NMA), Honefoss, Norway during 26-27 August for a training on PEGASUS. In addition, PM also attended the EGNOS Service Provision Workshop 2015 in Copenhagen, Denmark during Sep 29-30, 2015. There will be two presentations in upcoming ENC'2016 conference in Helsinki, where the results and outcomes of FEGNOS will be presented. In addition, Zahidul Bhuiyan delivered a lecture on differential corrections and different augmentation systems in a training school on 'Fundamentals of GNSS for ITS applications' organized by European COST Action: TU1302 Satellite Positioning Performance Assessment for Road Transport (SaPPART) in Aveiro, Portugal. The PM of the project will also be attending the EGNOS Service Provision Workshop 2016 in Warsaw, Poland during Sep 27-28, 2016.

3.6.1 Accepted publication

The accepted publications during the next few months, based on the work carried out within the scope of the FEGNOS project.

1. Marila, S., Bhuiyan, M. Z. H., Kuokkanen, J., Koivula, H., and Kuusniemi, H. (2016) "Performance Comparison of Differential GNSS, EGNOS and SDCM in Different User Scenarios in Finland," European Navigation Conference, Helsinki, Finland.
2. Bhuiyan, M. Z. H., Marila, S., Koivula, H., Kuusniemi, H. and Söderholm, S. (2016) "Finland's EGNOS Monitoring and Performance Evaluation," European Navigation Conference, Helsinki, Finland.
3. M. Z. H. Bhuiyan, S. Marila, S. Honkala, A. Soderini, S. Söderholm, S. Thombre,J. Kuokkanen, H. Koivula and H. Kuusniemi (2016) "Performances of EGNOS and Two Other GNSS

Augmentations in Finland –FEGNOS Project Results," Nordic Geodetic Commission's (NKG) Summer School, Båstad, Sweden.
4. Bhuiyan, M. Z. H., Kuusniemi, H., Soderini, A., Honkala, S., Marila, S. (2017) "Performance of EGNOS in North-East European Latitudes," abstract accepted in ION-ITM'2017, California, USA.

3.6.2 Planned publication

Here we list some of the planned publications during the next few months, based on the work carried out within the scope of the FEGNOS project.

5. Marila Simo et al. (2016) "Performance analysis of National Differential GNSS, EGNOS and SDCM in Finland," to be written.

3.6.3 Web-site Inauguration

A project web-site was inaugurated in the steering group meeting for the dissemination purpose. The web address is: www.fegnos.net. Anyone who has some interest on EGNOS performance in Finland can go to the web site and find information about the ongoing FEGNOS project.

3.6.4 Project Reports

The following project reports were submitted to the funding authority.

1. Initial Project Report, delivered on 23 December, 2016
2. Mid Term Project Report, delivered on 20 April, 2016
3. Interim Final Project Report, delivered on 09 September, 2016

The following project report will be submitted by December'2016:

4. Final Project Report, to be delivered on 16 December, 2016

Apart from the above project reports, the following monthly reports were delivered to the funding authority:

5. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for November 2015**, delivered on 09 September, 2016
6. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for December 2015**, delivered on 09 September, 2016
7. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for January 2016**, delivered on 09 September, 2016
8. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for February 2016**, delivered on 09 September, 2016
9. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for March 2016**, delivered on 09 September, 2016
10. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for April 2016**, delivered on 09 September, 2016
11. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for May 2016**, delivered on 09 September, 2016
12. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for June 2016**, delivered on 09 September, 2016
13. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for July 2016**, delivered on 09 September, 2016

The remaining 3 months (August, September, and October of the year 2016) will be delivered along with the final report by 16 December, 2016.

14. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for August 2016**, to be delivered on 16 December, 2016

15. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for September 2016**, to be delivered on 16 December, 2016
16. Finland's EGNOS Monitoring and Performance Evaluation: **Monthly Report for October 2016**, to be delivered on 16 December, 2016

4. The Way Forward

The continuation of the FEGNOS is planned, and therefore, a proposal was submitted to European Space Agency to secure funding for the continuation. The continuation project named as FEGNOS-2 would provide EGNOS performance monitoring service in real-time in all FinnRef stations. The performance monitoring service would provide an opportunity to identify weaknesses in EGNOS system performance, especially at high northern latitudes. The outcome of this project would contribute to the future improvements of EGNOS, especially if we think of the expected performance and planned upgrades to EGNOS in the North and North-East European area, including the EGNOS RIMS to Kuusamo, Finland. The FEGNOS2 project would include setting up a continuous EGNOS performance analysis service on the 20 permanent GNSS stations of the FinnRef network by assessing and analyzing the availability and the accuracy of the signal providing information in the form of "EGNOS traffic lights" in real-time. This kind of a tool could also be used outside the FinnRef stations as a more general assessment means with any set of data. FEGNOS2 would also include dynamic test campaigns at land, air and sea, including an Arctic maritime test campaign onboard an icebreaker by Arctia Ltd. to assess the performance of EGNOS and Galileo in high latitudes.

5. Conclusions

According to the results presented in Section 3.3.1, NLS's DGNSS solutions offer better accuracy and availability in almost all the test environments as compared to SBAS. In kinematic mode in good environments, the DGNSS accuracy was almost as good as in static tests. The SBAS accuracies in kinematic mode were not as good as compared to the results obtained in the static mode. The flight tests data showed that the performance of EGNOS meets the OS requirements.
Availability of SBAS is limited in challenging condition like in typical road environments or in urban/sub-urban streets. SBAS corrections come usually only from the one or two geostationary satellites which can easily be blocked by obstacles. The availability of SBAS solutions can be improved further in such condition by allowing receiver to use aging correction after SBAS signal is lost. The same notion also holds for DGNSS in case of an internet connection failure. In case of the flight tests, EGNOS data breaks occurred mostly when the plane was gaining or losing altitude (also in take-offs and approaches) and while turning to another direction. It is important to note here that the availability of EGNOS PRN 136 is much better than EGNOS PRN 120 in Finnish territory. This observation is also verified by the reception of EGNOS correction messages in all 20 FinnRef stations, where the rate of successful reception of EGNOS messages is much better for PRN 136 than that of PRN 120. It was also shown in the analysis that the Russian SBAS system SDCM works reasonably well also in Finland outside its main coverage area.

The advantage of utilizing multiple GNSS systems is evident, especially when there are not enough satellites with one single system. It is quite interesting to notice the fact that SDCM works reasonably well in Finland outside its main coverage area, though more tests are required to understand what level of accuracy we can expect from SDCM in different parts of Finland. The same goes also for EGNOS.

EGNOS performance analysis for a year-long timeframe was presented in the context of Finland. The following key observations can be made based on the results analysis of the year-long data set:
- The use of EGNOS significantly improves the positioning performance as compared to GPS stand-alone.
- The vertical accuracy improvement for EGNOS is higher than the horizontal improvement as compared to the GPS-only performance.
- The performance of EGNOS with receivers' own decoded message corrections is not as good as the performance obtained through EDAS provided EGNOS corrections.

- The percentage of EGNOS OS requirement failure when analyzed at a daily basis with Rx-Decoded corrections is significant. This is mostly due to the poor visibility of GEO satellites at north-eastern latitudes.

This finding emphasizes the fact that there is a greater need in the north-eastern latitudes for an alternative solution to the GEO satellites broadcasting EGNOS corrections. The existing alternative solution is to download the corrections from internet through EDAS at the cost of an additional communication link for the internet. The other possible alternative could be broadcasting corrections via IGSO satellites, or by any other means.

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