PRECISE SINGLE-FREQUENCY PROCESSING USING THE GALILEO E5 ALTBOC SIGNAL FOR PRECISE POSITIONING,IONOSPHERE MONITORING AND LEO ORBIT DETERMINATION

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ABSTRACT:

GNSS has revolutionized many aspects of science such as e.g. deformation monitoring and enabled scientists to realize applications which were unfeasible a few years ago. However in the scientific community the paradigm prevails that accurate results essentially require dual-frequency receivers with a preferred use of carrier phase measurements for precise positioning applications. This way of thinking is primarily motivated by the fact that the (first order) ionospheric delay can be eliminated by use of at least two frequencies, and carrier phase measurements are less affected by multipath effects than range measurements. Therefore, development efforts are emphasized on multi-frequency receivers and positioning techniques. The drawback of the use of multi-frequency GNSS receivers is the expensive cost for their acquisition. The European GNSS Galileo will offer one dedicated signal which is superior to all other signals that are or will be available in space, namely the broadband signal E5. This signal has a bandwidth of more than 90 MHz and will therefore feature a code range noise on centimeter level. Additionally, the impact of multipath effects on this signal is the lowest ever observed compared to the effects on all other available GNSS Signals. Using the full potential of the Galileo E5 broadband signal a precise single frequency positioning should be conceivable. This positioning method uses an additive combination of code range and carrier phase measurements (the code-plus-carrier principle) which allows the complete elimination of the ionospheric (first order) delay. The only complicating feature of this approach is the ambiguity term which is an additional unknown. This will require a longer observation window (at least 20 minutes) in order to allow sufficient convergence of the ambiguity parameters. Since many applications will require a very quick time to first fix (within a few minutes) a rapid convergence algorithm can face this special purpose, which jointly processes range and phase observations using a Kalman filter to predict positions and ionospheric delays. Using the advantages brought by the Galileo E5 broadband signal single-frequency positioning results will reach accuracy in range of sub decimeter to centimeter. This paper focuses on precise positioning and position change detection, which can similarly be employed for precise kinematic orbit determination, too. Moreover, a brief presentation of ionosphere monitoring results is part of this contribution.

1. INTRODUCTION

The purpose of this paper is to assess deeply which performances are achievable by single frequency positioning methods using the full potential of Galileo E5 broadband signal. Two aspects will be emphasized during this assessment process. The first is the ability to provide precise 3D position coordinates and the second one is the ability to detect a position change in a reasonable time window of observation.

In the common sense a precise GNSS application should be linked to a dual or multi-frequency receiver. Such a receiver can estimate the ionospheric group delay and phase advance from the measurements, and essentially eliminate the ionosphere as a source of error [MISRA AND ENGE, 2001]. But the current high cost for the acquisition of a multi-frequency receiver constitutes a huge disadvantage for a wider and mass use of GNSS techniques in many scientific application fields (e.g. the scarce number of IGS stations in Africa).

Many single-frequency approaches have been discussed in the past in order to obtain precise results from a low-cost single-frequency GNSS receiver (HATCH, 1982) or recently [LE and TIBERIUS, 2006]. However the main obstacle to achieve precise single frequency positioning with the currently existing GNSS signals of GPS and GLONASS is the high level of code range noise, which could be up to a few decimeters. In addition the level of multipath effects on these signals is high (SCHÜLER, 2010).

The innovation may come from the European GNSS Galileo, which provides one special broadband signal with bandwidth of 90 MHz. Compared to common signals (e.g. GPS L1) the noise level on the code range measurements (SIMSKY et al., 2008) and the multipath error (SCHÜLER et al., 2010) are reduced by the factor of three and five respectively. This will make it possible to perform code range measurements on centimeter level and will allow a better mitigation of multipath effects [IRSIGLER, 2008]. The drastically increased range precision due to the very low E5 range noise, will allow obtaining more accurate combined code-and-carrier position observables.

Indeed an additive combination of code range and carrier phase measurements (the code-plus-carrier principle) will completely eliminate the ionospheric delay (a major point of uncertainty in precise positioning) due to its dispersive nature (group vs. phase

delay with opposite signs). The new built observation still contain an additional unknown - the ambiguity term – which require a longer observation window in order to allow sufficient convergence of these parameters. The code-plus-carrier principle can be used for data being collected at least for half an hour and longer. For shorter periods of observation a rapid convergence algorithm is foreseen, which uses a filtering technique to jointly process range and phase observations. Tests have been carried out to assess the abilities of the combination of carrier phase and code range measurement of the GPS signals, but due to the high code range noise, the results were not convincing in term of precision (SCHÜLER et al., 2010).
The first part of this paper will explain the algorithms in detail. In the second part using Galileo E5 synthetic data and different predefined test scenarios a statistical analysis will be performed to investigate, whether a single-frequency positioning using Galileo E5 signal is comparable on one hand to the same method using GPS L1 and L5 and on the another hand to multi-frequency carrier phase processing.

2. POSITIONING ALGORITHMS

The approach in this paper is based on Galileo E5 single-frequency precise positioning, because the E5 signal is believed to be accurate enough enabling users to reach accuracy levels that could formerly only be obtained with dual-frequency receivers. This part handles some basic knowledge of the algorithms designed for positioning using the Galileo E5 AltBOC Signal.

2.1 CPC: code-plus-carrier positioning

The classical algorithm for precise positioning over medium to long distances to the nearest reference station is based on the code-plus-carrier principle. Scientific single-frequency receivers provide both range and carrier phase measurements. The following (simplified) observation equations are well-known:

$$\rho = r + \delta I + \delta T + \delta M_{Code} + \varepsilon_{Code} \tag{1}$$

$$\phi = r - \lambda \cdot N - \delta I + \delta T + \delta M_{Phase} + \varepsilon_{Phase} \tag{2}$$

ρ:	code range measurement [m]
ϕ:	carrier phase measurement [m]
r:	geometrical distance [m]
λ:	wavelength of carrier signal [m]
N:	ambiguity term [cycles]
δI:	ionospheric delay [m]
δT:	tropospheric delay [m]
δM:	multipath error [m]
ε:	unmodelled errors [m]

The ionospheric delay influences these two observables basically at the same level of magnitude, but with opposite signs [MISRA and ENGE, 2001]. Thus, the method of code-plus-carrier eliminates the ionospheric propagation delay employing an additive combination of the code range and carrier phase observations. The new derived observation is called the "code-plus-carrier observation" (CPC).

$$\frac{\rho + \phi}{2} = r - \frac{\lambda}{2} \cdot N + \delta T + \delta M_{CPC} + \varepsilon_{CPC} \tag{3}$$

More precisely, the statement above is only true for the 1st order ionospheric effect. According to BASSIRI AND HAJJ [1993], the 1st, 2nd and 3rd order terms of this error on range and carrier phase measurements can be expressed as follows (all other error components are neglected here):

$$\rho = r + \left(\frac{c_1}{f^2} + \frac{c_2}{f^3} + \frac{c_3}{f^4} \right) \tag{4}$$

$$\phi = r - N \cdot \lambda - \left(\frac{c_1}{f^2} + \frac{c_2}{2 \cdot f^3} + \frac{c_3}{3 \cdot f^4} \right), \tag{5}$$

where $c_{1,2,3}$ are factors (c1 is only dependent on the total electron content, TEC). The remaining ionospheric propagation delay on the code-plus-carrier observation will be:

$$\frac{\rho + \phi}{2} = r - \frac{\lambda}{2} \cdot N + \left(\frac{c_2}{4 \cdot f^3} + \frac{c_3}{3 \cdot f^4} \right). \tag{6}$$

Only remainders of the higher-order effects will be present in the observation equation.

In contrast to traditional code range positioning we have to deal in the new built observable with the unknown position and the also unknown ambiguity parameters (as in carrier phase positioning). This will require a longer observation window in order to allow sufficient convergence of the ambiguity parameters.

The approach makes use of double differences in order to get rid of the satellite and receiver clock errors. For this purpose, an access to a global or continental network (e.g. IGS or EUREF) is sufficient as experience taught us that the use of regional networks (shorter baselines) will not further improve positioning accuracy.

Tropospheric delays can still compromise positioning accuracy. For this reason, either external sources providing precise corrections (e.g. numerical weather models) should be available or the injection of additional tropospheric delay parameters into the estimation process is necessary. Multipath errors are site-specific and particularly strong on the code ranges. Here, the use of E5 AltBOC is a key advantage, as this broadband signal shows an ultra-low multipath behavior compared to all other signals [SIMSKY et al., 2008].
The standard deviation of the new "code-plus-carrier observable" (CPC) can be derived as follows:

$$\sigma_{CPC} = \frac{1}{2} \cdot \sqrt{\sigma_\rho^2 + \sigma_\phi^2} \approx \frac{\sigma_\rho}{2} \tag{7}$$

It is approximately half the noise of the range measurements. Correlation between code and phase measurements is omitted in this formula following investigations of BONA [2000].

This method can be employed for data being collected at least for half an hour and longer. Since Galileo E5 ranges are more precise than GPS L1 ranges, so convergence time is considerably faster. Regarding this issue of convergence the methods will be well-suited for monitoring purposes (applications requiring continuously operating equipment), for instance.

2.2 Code-and-carrier (CAC): The rapid convergence algorithm

Many applications require a very quick time to first fix, i.e. the precise position should be delivered within a time of about half a minute to 20 minutes. To achieve maximum flexibility a method of ambiguity resolution has been developed based on a sequential filtering process the so called All-Inclusive Sequential Ambiguity Estimator (ANSA). A Kalman filter estimates the results parameters - i.e. the ambiguities and the (preliminary) rover position – and any other nuisance parameter. Unlike the previous approach (CPC) this algorithm jointly processes range and phase observations and the ambiguities on the original carrier frequencies are immediately determined. The equation depicts the observation vector L:

$$L = \begin{pmatrix} \nabla\Delta PR_{AB}^{ij} \\ \nabla\Delta PR_{AB}^{ik} \\ \vdots \\ \nabla\Delta\varphi_{AB}^{ij} \\ \nabla\Delta\varphi_{AB}^{ik} \\ \vdots \end{pmatrix} \tag{8}$$

L: observation vector

$\nabla\Delta PR_{AB}^{ij}$: pseudorange

$\nabla\Delta\varphi_{AB}^{ij}$: carrier phase

The state vector *X*:

$$X = \begin{pmatrix} (x_A \ y_A \ z_A)^T \\ (\nabla\Delta N_{ABL1}^{ij} \ \nabla\Delta N_{ABL1}^{ik} \cdots)^T \\ ZPD_A \\ (\nabla\Delta ION_{ABE5}^{ij} \ \nabla\Delta ION_{ABE5}^{ik} \cdots)^T \end{pmatrix} \tag{9}$$

X: state vector

consists of:

a. the three components of the Cartesian coordinates of the rover A $(x_A \ y_A \ z_A)$, the coordinates of reference stations B will be held,
b. the original ambiguities for each satellite at the carrier frequency $(\nabla\Delta N_{ABE5}^{ij} \ \Delta N_{ABE5}^{ik} \cdots)$
c. the residual tropospheric propagation delay in zenith direction ZPD_A. It is assumed here that there are no significant azimuthal variations, which is usually justified; through the station-specific modelling the number of parameters can be significantly reduced
d. the residual ionospheric propagation delay, always related to E5, in the direction of the satellite, but double differentiated $\nabla\Delta ION_{ABE5}^{ij}$. Here a satellite-specific modelling is performed, because the ionospheric sub-points in contrast to the troposphere can be up to about 1000 km apart.

The temporal variation of all states is purely modelled, thus the transition matrix for period k is the unit matrix:

$$T_k = E \tag{10}$$

The supposed temporal variability of the parameters is instead reported the filter by an adequate increase in the variance level of the covariance matrix of the predicted states. This task is assumed by the system noise matrix Σ_{SS}, so that the covariance matrix of the predicted state vector Σ_{XX_k} has following form:

$$\Sigma_{XX_k} = T\,\Sigma_{XX_{k-1}}^{*}\,T^T + \Sigma_{SS} = \Sigma_{XX_{k-1}}^{*} + \Sigma_{SS} \tag{11}$$

Σ_{XX}: covariance matrix of the predicted state vector (for the period k)

Σ_{XX}^{*}: updated covariance matrix of the state vector (the epoch k -1)

Σ_{SS}: system noise matrix, here only a diagonal matirx

T: transition matrix

The individual variances of the system noise matrix are defined e.g. for the coordinates by $\sigma_{x,y,z}^2 = q_{x,y,z}^2 \cdot \Delta t$, where $q_{x,y,z}$ is the so-called process noise in a unit of mm/h$^{1/2}$. According to the different groups of parameters we have also to deal with:

- the process noise of the position $q_{x,y,z}$
- the process noise of the ambiguities q_N
- the process noise of the troposphere in zenith direction q_{ZPD} and
- the process noise of the double differentiated Ionosphere in the satellite direction q_{ION}

So you can now react very flexible to different situations by an appropriate choice of process noise coefficient:

a. the rover does not move: $q_{x,y,z}$ is chosen close to zero , i.e. the filter quickly converges or in other words: the variance of the parameter coordinates decreases rapidly with time, as observations are accumulated over time with high weight (fast convergence).
b. the temporal variation of the atmospheric conditions must be estimated accordingly. Thus the troposphere changes in zenith direction over an hour, usually only slightly, here q_{ZPD} is selected with 1cm/h$^{1/2}$. An estimation of the ionosphere variation is a bit difficult, as elevation dependence exists and under adverse conditions greater variations can also occur; thus q_{ION} should be chosen at least as high as q_{ZPD}, in doubt rather something higher.

Besides the aspect of the system noise the initialization of the filter plays an important role. This includes both the state vector X and the associated covariance matrix Σ_{XX}^{*}. The coordinates are initialized from the calculated pseudo-range positions. Approximate ambiguities are derived from the combination of pseudo-ranges and carrier phases. For the ionosphere and the troposphere the residual propagation delays are estimated. For the initialization of the covariance matrix it is true that the standard deviation of the coordinates is approximately known from studies. The standard deviation of the ambiguities may be stated quite high, as with an initialization of e.g. ± 99 cycles after the filter update the filter will quickly converge by the influences of the pseudo-ranges.

3. PERFORMANCES ASSESSMENT OF THE SINGLE-FREQUENCY POSITION APPROACH

The fundamental work here is to show how far Galileo E5 single-frequency positioning is improved compared on one hand to single-frequency positioning using GPS L1 or L5 and on the other hand to traditional dual frequency or in the future multi-frequency carrier phase processing. Moreover an experiment to monitor a rock glacier is performed to show the feasibility of position change detection in a reasonable period of observation by single-frequency positioning using Galileo E5.
For these purposes the first reliable Galileo E5 single-frequency positioning results have been generated using synthetic data, since there were no useable Galileo data (due to satellites deployment delays) to determine a 3D position. The results are analyzed by a set of different statistical methods to find out the achievable accuracies of the single-frequency positioning algorithms. Finally the results are compared with the ones of others GNSS signals and positioning methods.

3.1 Processing Procedures

One current issue is to deal with is the non availability of a sufficient number of Galileo satellites to provide a positioning service. Hence the only way to perform tests at the moment is to generate synthetic data. For the production of synthetic observation data SP3[1] orbital data files are needed. For the derivation of the Galileo satellite coordinates we make use the almanacs data from the Galileo ICD (Interface Control Document), which defines a full walker constellation of 27/3/1 satellites.
Synthetic data were generated for 3 experimental stations (OSLO high latitude; BRUSSEL mid latitude; and OUAGA equator near) for the following epochs:

- GPS-Week 1594, Day 206
- GPS-Week 1612, Day 332
- GPS-Week 1629, Day 086

The positioning results are produced with daily data batches and reduced to 6-hourly and hourly data batches. A further reduction of data batch length was made in order to perform successfully ambiguity resolution.
The processing of the data is carried out by the expert tool of the SX5[2] software application package. The tool is a self-contained GNSS software dedicated particularly to precise static, semi-kinematic and kinematic surveys where high accuracy is to be gained using GNSS carrier phases within relatively short periods. It was extended with respect to efficient single-frequency positioning algorithms and with respect to kinematic orbit determination of LEO satellites in addition to the precise multi-frequency carrier-phase algorithms, which allow having the choice between single-frequency range and phase processing as well as carrier phase only processing.

[1] http://igscb.jpl.nasa.gov/igscb/data/format/sp3_docu.txt
[2] The project "SX5 – Scientific Service Support Based on Galileo E5 Receivers", which receives funding from the European Union within the 7th Framework Programme.

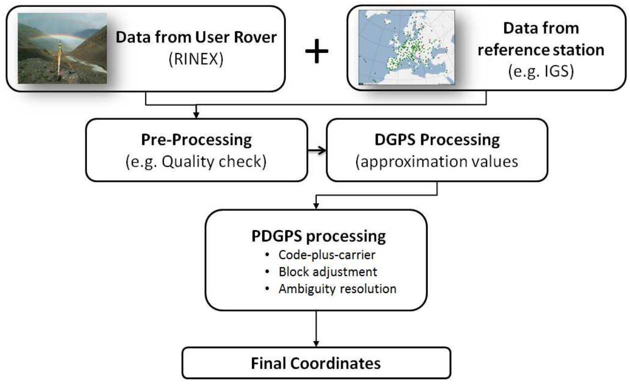

Figure 1: processing steps using the eXpert SGSS tool

The figure above describes a simplified scheme of the processing steps. All precise positioning functions are integrated into this processing engine.
In order to have a sufficient number of precise positioning results, a time series of observation stretching from 1 to 24 hours are processed with sampling interval of 5 s and an elevation mask set at an angle 15° to avoid a big multipath impact on the signals. As a-priori the model TropGrid is used to attenuate the tropospheric effects. The ambiguity terms are solved to their float values, thus this will imply a long convergence time to precise positioning results.

3.2 Positioning results

CPC results for Galileo E5 vs. GPS L1 and L5

A direct comparison of single-frequency positioning using the combination of code-plus-carrier measurements on Galileo E5 and GPS L1, L5 is undertaken in this section. The result generation was exclusively performed with synthetic data and we assumed a full Walker 27/3/1 Galileo constellation, which will be achieved by 2020 according to the current state of development.

Table 1 shows initial results obtained from the single-frequency code-plus-carrier algorithm using a time series analysis stretching from 1 hour to 24 hours.

Time[3] [h]	Horizontal accuracy [m]		Vertical accuracy [m]		3D accuracy [m]	
	GPS L1	Galileo E5	GPS L1	Galileo E5	GPS L1	Galileo E5
1	0.570	0.286	0.780	0.244	0.970	0.370
2	0.346	0.158	0.343	0.121	0.490	0.190
3	0.248	0.075	0.320	0.068	0.400	0.100
4	0.211	0.056	0.295	0.058	0.360	0.080
5	0.175	0.037	0.267	0.051	0.310	0.060
6	0.116	0.026	0.212	0.045	0.240	0.050
12	0.087	0.016	0.0155	0.0032	0.170	0.040
18	0.075	0.013	0.0134	0.0027	0.150	0.030
24	0.064	0.011	0.0121	0.0023	0.130	0.030

Table 1: Comparison of GPS L1 and Galileo E5 positioning accuracies determined with the code-plus-carrier method (synthetic data) for a station in Brussels, Belgium.

[3] Observation time

The Galileo E5 results start with a horizontal accuracy of only around 3 dm. This is 2 times higher for GPS L1. For the vertical component Galileo E5 results are even 3 times better than GPS L1 results. Afterward we see a faster convergence of Galileo E5 results. With a data batch of 6 hours of observation we have already a 3D RMS of 5 cm for E5 compared to 20 cm for GPS L1. Finally with a daily data batch the combination of code-plus-carrier phase measurement using E5 single frequency reaches a 3D RMS of 3 cm whilst GPS L1 only yields 13 cm 3D RMS. Thereby, the great advantage of the Galileo E5 signal can already be seen in the first results of this investigation.
Figure 2 shows a direct comparison of the two time series:

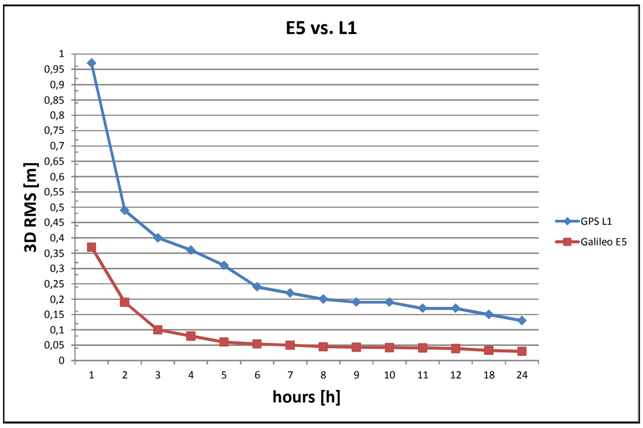

Figure 2: RMS values (3-D) for single frequency results of Galileo E5 and GPS L1

With the modernization of GPS a new civil signal L5 will be broadcasted. L5 is intended to increase precision and robustness of the navigation solution due to mitigation of ionospheric refraction errors and an enhanced signal design with higher signal strength and advanced code structure compared to the existing GPS civil signals [ERKER et al., 2009]. In other hand L5 is improved compared to GPS L1 and has the same center-frequency (1176.45 MHz with a 24 MHz bandwidth) like the sub-carrier E5a of the Galileo broadband Signal E5. Hence, L5 seems to have a similar characteristic like at least one part of the Signal E5.
Table 2 shows the 3D RMS of Galileo E5 and GPS L5 CPC results:

Time [h]	Horizontal accuracy [m]		Vertical accuracy [m]		3D accuracy [m]	
	GPS L5	Galileo E5	GPS L5	Galileo E5	GPS L5	Galileo E5
1	0.309	0.176	0.213	0.100	0.375	0.202
2	0.134	0.089	0.112	0.055	0.174	0.098
3	0.092	0.040	0.101	0.038	0.136	0.055
4	0.069	0.028	0.090	0.033	0.113	0.044
5	0.058	0.028	0.081	0.030	0.99	0.037
6	0.039	0.015	0.069	0.027	0.079	0.031
12	0.025	0.009	0.048	0.018	0.054	0.020
18	0.019	0.007	0.038	0.015	0.042	0.017
24	0.017	0.006	0.035	0.013	0.039	0.014

Table 2: Comparison of GPS L5 and Galileo E5 positioning accuracies determined with the code-plus-carrier method (synthetic data) for a station in Oslo, Norway.

Regarding the table we see an improvement of GPS L5 results compared to the GPS L1 one. This confirms that GPS L5 is more robust than L1 regarding to code noise affection. But comparing the same results to the Galileo E5 results we see that the latter ones are still better. The next plot, which gives also the 3D RMS errors, shows a comparison of the 3 signals:

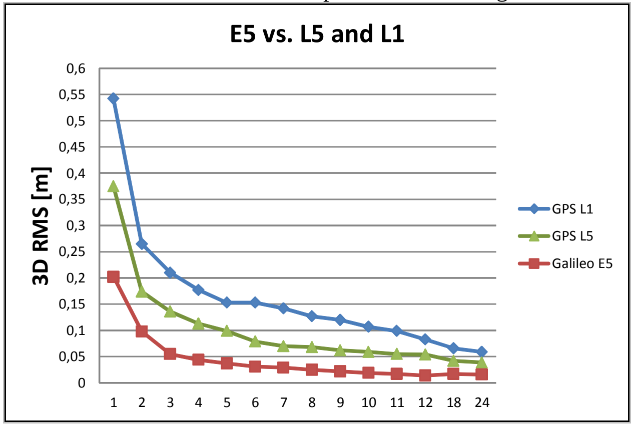

Figure 3: RMS values (3-D) for single frequency results of GPS L1, GPS L5 and Galileo E5

The accomplished tests have allowed us assessing the performances of Galileo E5 CPC and showed a 3D positioning accuracy of 5 cm in critical environments (a station with high multipath influences e.g. BRUSSEL) and 1-2 cm in normal environments for daily data batches. In comparison these results are 3-4 times better than GPS L1 and 2 times better than GPS L5. Regarding the first obtained results it is became clear that the single frequency positioning concept using the potential of Galileo E5 has some innovative aspects and that there is a certain potential to develop. Due to its very low code range noise and the even lower multipath influence on the positioning solution (compared to others GNSS signals like GPS L1 or L5) the Galileo E5 CPC results single frequency are able to fulfill the requirements set for precise positioning.

CPC results for Galileo E5 vs. carrier phase processing

The carrier phase processing is computing the position using measurements of the phase of the received satellite carrier signal relative to the receiver-generated carrier phase at the reception time. Many precise GNSS positioning solutions rely on tracking the carrier phases because of their low measurement noise and low multipath affectation. Due to these facts carrier phase processing accuracy is ranging in mm-level. A user equipped with a multi-frequency GNSS receiver can estimate the ionospheric group delay and phase advance from the measurements, and essentially eliminate the ionosphere as a source of measurement error [MISRA and ENGE, 2001]. Relative ionosphere-free carrier phase positioning, which is based on double differences is the positioning method chosen here in order to get completely rid of the ionospheric error.
Using data batches of 24 hours we have computed carrier phase processing using multi-frequency data of GPS and of Galileo and compared the results with the combination of code-plus-carrier using Galileo E5 signal measurements. The Table 3 shows the errors in the horizontal component of the coordinates, the vertical component and the overall 3D RMS error.

Type of observation	Horizontal accuracy [m]	Vertical accuracy [m]	3D RMS [m]
CPC GALILEO E5	**0.0136**	**0.0180**	**0.0225**

CP IF* combination L1+L2	0.0012	0.0016	0.0020
CP IF combination L1+L5	0.0010	0.0015	0.0018
CP IF combination E1+E5	0.0009	0.0014	0.0017
CP IF combination E5a+E5	0.0009	0.0013	0.0015
CP IF combination L1+L5+E1+E5	0.0006	0.0011	0.0013

Table 3: Resuming 3D RMS values of the carrier phase processing compared to CPC results, CP IF* carrier phase ionosphere-free linear combination

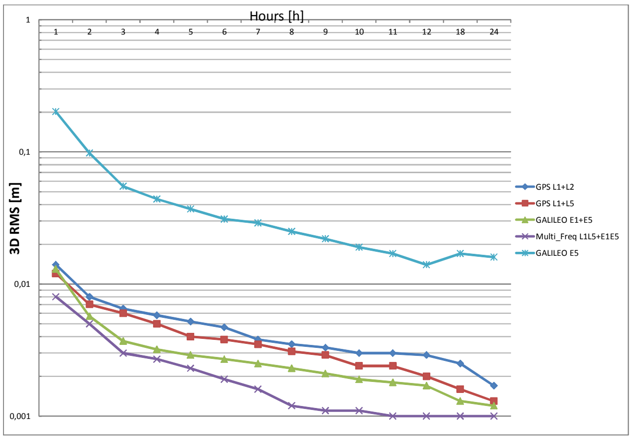

Figure 4: RMS values (3-D) for single frequency results of Galileo E5 compared to carrier phase processing using different signals

Figure 4 shows a plot of the 3D RMS of the single frequency results using Galileo E5 and the results of the carrier combination of different GNSS signals (GPS L1+L2, GPS L1+L5, Galileo E1+E5, multi-frequency GNSS L1L5+E1E5). The graph is logarithmic scaled. Regarding the table and the plot we see that carrier phase processing using multi-frequency measurements has accuracy in mm level. These are 10 times higher than the accuracy that we obtain by a single frequency positioning combining code and carrier phase measurements.
Using carrier multi-frequency processing measurements one can reach results in the range of few millimetres. This is why many precise GNSS applications rely on carrier phase processing. The drawback is the high costs of acquisition of such a receiver. But not every precise positioning application requires mm level of accuracy, therefore the high cost expenditure for a multi-frequency receiver is not justify. Even though Galileo E5 CPC results cannot be compared to multiple frequency results, the accuracy can meet the requirements for lot of precise positioning applications in decimetre and centimetre level. Hence the approach can fill a niche between high precise positioning using carrier phase multi-frequency processing and with conventional single-frequency positioning.

ANSA filtering results: rapid convergence

The rapid convergence algorithm aims to reduce the convergence time of single-frequency positioning using the combination of code-plus-carrier measurements. As already depicted above this algorithm differs from the "traditional" CPC method, because it will jointly process range and phase observations.
In order to test the performances of the algorithm we set an observation network on the site of the University of the Federal armed Forces Munich. The advantage of such a local network is that we can process stations, which will be related over very short baseline to their reference stations. Two stations linked over a short baseline (max. 10 km) have similar atmospheric conditions. Thereby we can eliminate the ionospheric and tropospheric propagation delays by using double differences. Normally the algorithm estimates the ionospheric delay as a function varying in time domain and uses external aiding (e.g. IONEX maps) to obtain a rapid convergence against precise coordinates. Tropospheric delays are also estimated. But in our case none of these methods is needed because of the short baseline.
Using a data batch of 1 hour with a sampling rate of 1sec the solution is computed. The Kalman filter is initialized with appropriated values. The start position is given with a standard deviation of 9m, because short baseline atmospheric delays (ionospheric and tropospheric) are almost non-significant. Nevertheless these values have to be initialized; therefore each of them has a start value of 3mm.
Figure 5 shows the filtered coordinates (X: red, Y: green, Z: blue) and the ambiguity fixed solution (yellow dots). We notice a very fast convergence of the coordinates and that the ambiguities terms can be fixed with a few cycles.

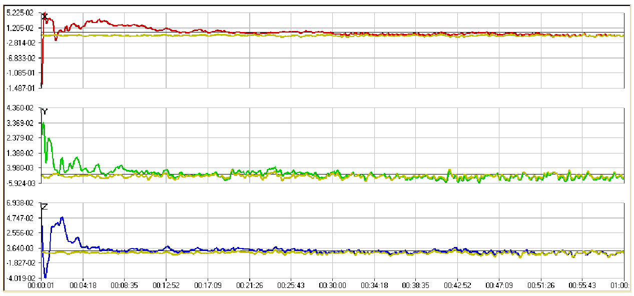

Figure 5: Rapid convergence results: filtered coordinates.

By zooming in the graph we can see that the coordinates converge to a few decimeters within 30 sec and that we can reach centimeter level accuracy within 1min.

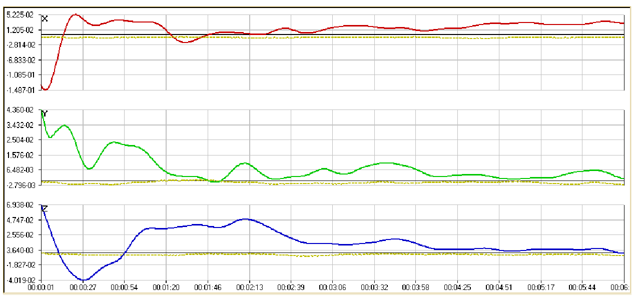

Figure 6: The results of the first 5 minutes of observation

There is a clear advantage to use a filter to get precise coordinates faster. A drawback is that one has to know the exact initialization values before starting the processing, else the filtering will drift in unknown. The method seems to be well suited for short baselines. For long baselines (>10 km) the atmospheric conditions differ and it will be very difficult to estimate the ionospheric and the tropospheric delays, even impossible when the ionosphere is unstable.

4. POSITION CHANGE DETECTION

GNSS is currently used as the main sensor to monitor Earth's surface deformation. The deformations could range from mm-level to m-level over periods of few seconds to several years. The measurements can be performed continuously or repeated after a certain period of time. The main advantage of using GNSS sensors for monitoring activities compared to conventional deformation monitoring sensors is that GNSS requires no line-of-sight between the stations and that the equipment can run without human interaction. In this section we have tried to find out, which performances can be achieved by Galileo E5 single-frequency positioning using the combination of code-plus-carrier measurements.

4.1 Monitoring of a rock glacier using Galileo E5 single-frequency positioning

Rock glaciers are perennially frozen debris masses which creep down mountain slopes. These creep phenomena of mountain permafrost have been studied intensively all over the world in the past few decades [KAUFMANN, 1996]. The experiment carried out here is related to a study of the ETH Zurich on the Dirru rock glacier on the east side of Matertal (Switzerland), where they determined surfaces velocities.
Based on a surface velocities map, we have tried to generate simulated data for the displacement of the Dirru rock glaciers (Switzerland). A virtual network consisting of 5 monitoring stations (DIR1, DIR2, DIR3, DIR4 and DIR5) has been set up. The expected displacements of the stations are ranging between 0.1 m to 1.5 m per year. Based on the station coordinates we have determined the velocities vectors (v_x, v_y and v_z), which have helped to interpolate the expected motion rate of each monitoring station on the glacier. To compute the double differentiated solutions we have chosen the IGS station ZIMM (Zimmerwald) nearby (89 km) as reference, since the reference station should be outside of the movement area. Three measurement campaigns, each lasting one day (GPS weeks 1594, 1603, and 1612) have been carried out in order to detect any displacement of the station.

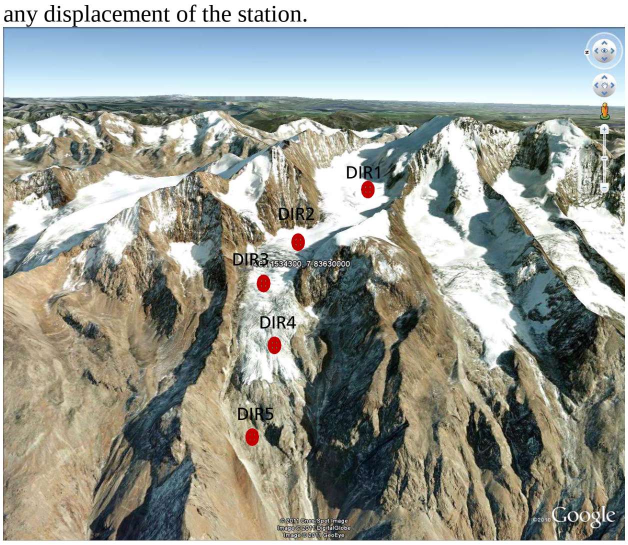

Figure 7: Monitoring network on the Dirru Rock glacier; background map (c) Google and contributors (see caption).

Position change detection means to determine a difference from successive position estimates of a point after elapsing of a certain amount of time. The precision of the successive measured positions is so important that in most of such application carrier phase measurements are used because of their high accuracy (mm-level). The sampling rate of the observed data is important. So for observations carried out at different periods we have to assure the same sampling rate. For the case of Dirru rock glacier we have daily data set with 5sec sampling rate in order to get precise converged data.
The station Dir5 has been chosen to be processed. The expected motion rate for this station is in the range of 70 cm/year. As reference period we set the day of year 206 of the GPS-Week 1594. After 64 days we observed the same station. The data have been computed for GPS L1 and Galileo E5 using the single-frequency CPC principle. The next point scatter plots show the results of the observations with the different systems.

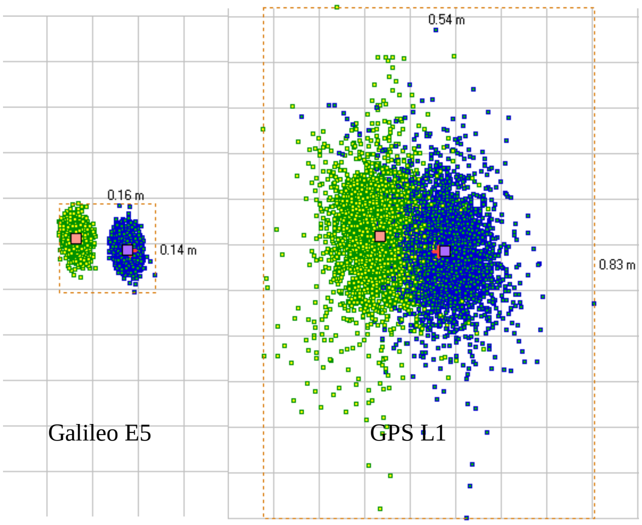

Figure 8: Results of the positions comparison for 2 different periods of observation using single-frequency positioning

The point scatter plots make a clear picture of the detection ability of the 2 sets of data. Due to the high level of noise the GPS L1 measurements cannot identify any change in the coordinates after 64 days. The single shots of the coordinates for the 2 periods are overlapping (blue and green dots). The expected motion rate for 64 days is about 11 cm. If we analyze the 3D RMS for each period we see that GPS L1 measurements have a 3D RMS of around 30cm. This is too bad to allow detecting any change in the position of the station.
For Galileo E5 measurements the situation is completely different. We see a clear difference between the 2 periods of observation, which means that the station has undergone a displacement. The detection rate is still too low due to a 5cm 3D RMS of the Galileo E5 measurements. But the Galileo E5 single-frequency results are accurate enough to detect a position after a short period of time.
After 126 days we performed the same experiment for the same station. The point scatter plots in Figure 9 show the results again.
Due to the long convergence times (20-30min), single-frequency positioning using the CPC principle is well suited for monitoring activities (landslide or glacier monitoring), since changes in such structures can first be detected after a certain period of observation. Using Galileo E5 data we were able to detect deformation of a few centimeters. Single-frequency positioning using Galileo E5 has a certain advantage here compared to carrier-phase processing. Because of the moderate price of a single-frequency system we can use more sensors to determine an exact profile of the deformation.

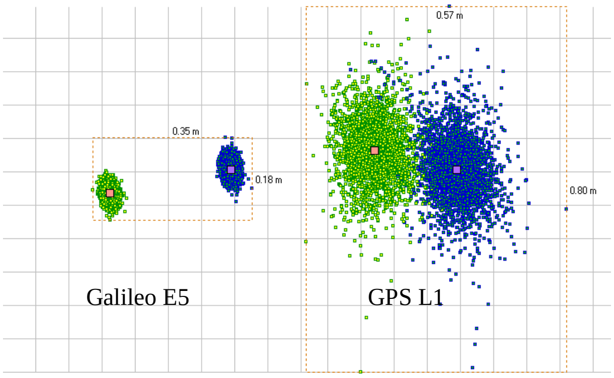

Figure 9: Results of the positions comparison for 2 different periods of observation using single-frequency positioning (after 126 days)

5. IONOSPHERE MONITORING

The code-plus-carrier combination eliminates ionospheric propagation delays. Hence, it can be attractive for single-frequency positioning applications. On the contrary, the code-minus-carrier combination will eliminate all non-dispersive effects (the troposphere) including geometric properties (the position). This combination can be used for monitoring the ionosphere with a single-frequency receiver. Corresponding investigations and developments have been performed within the SX5 project. The main principle of operation is as follows:

1. The code-minus-carrier observables are formed. The corresponding observation equation contains the ionospheric propagation delay and the ambiguity parameters, which need to be resolved in addition to the target parameters. For this reason, cycle slip detection is necessary as one pre-processing step.

2. A single-layer model of the ionosphere is used. Sub-ionospheric points and mapping function values can be computed.

3. Absolute VTEC determination will be possible if a horizontal interpolation function is defined (normally a low-order polynomial), and the zenith ionospheric delay above the antenna site is interpolated from the individual satellite observations. This step is mandatory in order to separate the nuisance parameters (ambiguities) from the target parameters (ionospheric delays).

Several experiments with both real-world GPS data as well as simulated Galileo data were conducted. In particular, 1 Hz data of the available IGS LEO network stations of the year 2003 were analyzed.

The global average RMS (compared to IGS IONEX reference data) for the Vertical Total Electron Content VTEC is 4.2 TECU. The error distribution is - not unexpectedly - a function of latitude with highest RMS to be reached in the region around the geomagnetic equator. For most mid- and high-latitude sites, the RMS obtained is between 1.5 and 2.5 TECU, for equatorial sites it can be 7 TECU and higher.

Regarding the benefits of Galileo E5 ionosphere monitoring, the a standard deviation of unit weight around 0.11 m can be stated compared to 0.38 m for GPS L1 data. This emphasizes the added value of E5 AltBOC processing, although we also have to state that modeling errors can still be significant, especially under disturbed conditions.

6. CONCLUSIONS

This paper has assessed the performances of a single-frequency positioning approach using the Galileo E5 broadband signal. Due to its very low code range noise and the even lower multipath influence on the positioning solution (compared to common signals like GPS L1) the combination of Galileo E5 code-plus-carrier measurements is able to achieve accurate positioning results. The performed tests showed that we can reach 3D accuracy of a few centimeters (1-2cm) with Galileo E5 single frequency positioning. Comparing to the results with GPS L1 or L5 (GPS L1: 20 cm; L5: 1-6cm) we see the potential of the approach. A drawback of the method is the long convergence time (20-30min) to get precise coordinate. Nevertheless a rapid convergence algorithm using a filtering (ANSA) algorithm, which processes time code and carrier measurements at the same to estimate the parameters, has been implemented to deal with this issue. With this algorithm we were able to fix the ambiguities within a few seconds and to determine coordinates on sub-decimeter level. Further tests showed that carrier phase processing is still more accurate (10x order) than the single-frequency approach using Galileo E5, but this kind of processing requires expensive multi-frequency receiver. However not all precise GNSS applications require precision on mm level, therefore the single-frequency positioning approach with Galileo E5 can fill a niche between carrier phase processing (mm level) and usual single frequency positioning (dm level).
Due to the convergence time and the achieved accuracy the approach seems to be suited for monitoring activities, where precise coordinates are needed after a certain period of observation time in order to detect changes. Such a monitoring application has been used for a moving rock glacier scenario comparing the results of single-frequency GPS L1 and Galileo E5 processing. The results show that we were able to detect a change in the coordinates of a monitoring station after a short period of observation time, which was not feasible with GPS L1.
With the start of the first IOV (In-Orbit Validation) satellites we will improve the assessment of the performances of the single-frequency positioning using the full potential of Galileo E5 with real data. Further investigations towards a multi-constellation algorithm, containing the COMPASS B2 AltBOC signal, which is similar to Galileo E5, and optional the GPS L5 signal for better geometry, will be completed to show how far the accuracy increases with more satellites.
Being able to achieve single-frequency positioning with Galileo E5 within centimeter accuracy will be profitable for many GNSS precise applications, which until now make exclusively use of multi-frequency receivers because of the paradigm, that precise positioning can only be achieved by at least 2 frequencies.

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