System for Performance Monitoring with Respect to Ionospheric Activity at High Latitudes

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BIOGRAPHIES

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Rune I. Hanssen is Technical Director at the Geodetic Institute of the Norwegian Mapping Authority. He holds a M.Sc. in cybernetics from the University in Oslo, and has worked with GNSS engineering and management for more than 20 years, in particular with the SATREF™ network and EGNOS.

ABSTRACT

The ionospheric activity varies geographically with an increased activity level around the Equator and at high latitudes in the arctic and polar regions. At high latitudes the general ionospheric activity is further affected by auroral activity causing increased disturbances and scintillation effects which are difficult to handle in ionosphere modeling. The ionospheric influence on the performance of the GNSS systems in general and EGNOS and GALILEO in particular is of great concern for Norway, which is located at high latitudes, extending from about 60° to 80° north.

The Norwegian Mapping Authority has therefore developed a regional ionosphere model for Norway, the SATREF™ Ionosphere Model, which is currently running in post mission. The model is based on data from a number of GNSS stations placed in the area of interest. The model outputs L1 ionospheric delay and the model can be configured to output delays for a given location or for a predefined grid with grid nodes located within the model coverage area around Norway. With the SATREF™ Ionosphere Model it is possible to follow the development at high latitudes as the ionospheric activity increases during the coming six years.

The SATREF™ Ionosphere Model is based on the SATREF™ network of permanent GNSS stations and the corresponding infrastructure. The network forms the basis for the development of a monitoring system for investigating and monitoring the performance of EGNOS at high latitudes. Monitoring of the performance as a function of ionospheric activity is highly relevant, and is one of the main requirements to the system. Other requirements are for instance performance monitoring with respect to UDRE and the GPS satellite geometry.

With this paper the background for the monitoring system is described, as well as the implemented procedures. Also, results and conclusions of the initial investigations of performance as a function of ionospheric activity are presented and discussed.

An initial verification of the SATREF™ ionosphere model by comparing the model with the IGS Global Ionosphere Model show compliance within approximately 20 cm. A comparison between the SATREFTM ionosphere model and the EGNOS ionosphere model show compliances at the level of about 30 cm. Further results of the paper are analyses of the performance of the EGNOS ionosphere model in several grid points that show a significant bias for some grid points located in the area of the Norwegian Sea.

The monitoring system provides an independent evaluation of the performance valid for the high latitude region covered by the SATREF™ network. The procedures used for monitoring can, however, be mapped and used at lower latitudes for similar work, and the paper is therefore highly relevant also for developers, system providers and users working at mid and low latitudes.

INTRODUCTION

Generally, during design and development of the Global Navigation Satellite Systems that are available today, the main focus in terms of the performance has been on the mid and low latitudes, where the majority of the population is located, and where the need for reliable navigation is highest. However, the human activities at high latitudes have increased significantly the last years and the need for reliable navigation is consistently
increasing, both for safety of life and environment issues. This is one of the drivers for the Norwegian Mapping Authority in developing a monitoring system for the investigation and monitoring of the performance of GNSS at high latitudes.

Monitoring of the performance as a function of ionospheric activity is highly relevant because of the high ionospheric variability in the arctic area, and this is one of the main requirements to the system.

This paper describes the monitoring system as well as the initial results. The following sections first provide a description of the background and motivation for the system. The main parts of the system are the SATREF™ network and SATREF™ Ionosphere Model both of which are then introduced. This is followed by a description of the test data used and the verification of the SATREF™ Ionosphere Model, before it is being used for evaluation of the EGNOS ionosphere model.

All positions given in the paper are geographic latitude and longitude.

BACKGROUND AND MOTIVATION

Norway is located at high latitudes, extending from about 60° to 80° north. The Northern most land area is the Svalbard group of islands, Figure 1.

Figure 1. Map of Norway and surrounding countries. From www.geopolar.no.

In addition to the land masses Norway also covers a large ocean area, the Norwegian Sea, which is located between the mainland of Norway and the islands of Jan Mayen and Svalbard. The Norwegian Sea is a major area of interest for oil and gas exploration and exploitation, and there is a considerable need for a reliable navigation system both on the surface of the sea and for operations in the air.

The Norwegian Mapping Authority runs the SATREF™ network of GNSS stations, which is described in the following section. Data from the stations is used for providing various real time services, and when running the high level real time kinematic positioning service called CPOS, estimates of the ionospheric variability are produced and displayed in the control centre. Several years of experiences have shown that often very large differences occur between the ionospheric variability in the Northern and Southern part of Norway. The two plots in Figure 2 illustrate this. Both plots are from February 28, 2008 and show the level of ionospheric variability given by the I95 index.

Figure 2. I95 ionosphere index for February 28, 2008. North (top) and South (bottom) of Norway. Plots generated with the Trimble GPSNet software.

The I95 ionospheric index is introduced by Wanninger (1999). The index describes the ionospheric variability for a number of GNSS reference stations for a time interval. I95 thus indicates that 95% of the ionospheric gradients (the level of variability), estimated for the given stations within the time interval, are less than the index-value. In this case the upper plot shows the results based on a network of GNSS reference stations located between latitude 68.5° N and 70° N, and the bottom plot shows the results from a network located between latitude 58° N and 63° N both in mainland Norway.

The two plots illustrate the major difference in ionospheric conditions which can often be seen between the northern and southern part of Norway.

This has lead to decisions on first developing an ionosphere model for Norway, and then, as a next step, analysing the performance of EGNOS as a function of ionospheric activity given by the SATREF™ Ionosphere Model.
SATREF™ NETWORK OF GNSS STATIONS

The SATREF™ GNSS network has from its start in 1989 been operated by the Geodetic Institute of the Norwegian Mapping Authority (NMA).

The SATREF™ GNSS network consists of a number of permanent geodetic GNSS stations located at the Norwegian mainland and Svalbard. There is also one station at Jan Mayen and one in Iceland. Totally there are over 80 permanent GNSS stations, and the number is continuously increasing as new stations are established every year. The permanent GNSS stations have traditionally been equipped with GPS only receivers. To modernize the stations all receivers are now exchanged with combined GPS/GLONASS receivers.

The GNSS network is used for determination and maintenance of the geodetic reference frame, one of the main responsibilities of the Norwegian Mapping Authority. Since 1999, the network has also been used for various GNSS real time services, improving the users’ position accuracies down to the centimetre level. To ensure reliable data and stable services, quality control and monitoring are important functions for the network.

The most advanced permanent geodetic stations are founded on bedrock and equipped with computer for storage and extra power backup, in addition to GNSS dual frequency receiver and communication equipment. These stations are established with the aim of supervising the reference frame. The more standard permanent GNSS stations are most often located on concrete buildings and contain GNSS receivers and communication equipment. These stations are established with the aim of improving the real time services, but are also contributing to the determination of the reference frame. All stations are connected in a communication network, and the GNSS raw data is transmitted in real time to the control centre located at the premises of NMA in Hønefoss, Norway. Here, the data is checked, processed for providing real-time services, and stored in archives for post-processing purposes.

Selected stations of the SATREF™ GNSS network also form the basis for a routine monitoring of the EGNOS performance. The selected permanent GNSS stations are equipped with receivers for EGNOS tracking. The data from these receivers is analysed on a daily basis, and used for weekly reports on the EGNOS performance in Norway.

SATREF™ IONOSPHERE MODEL

For positioning and navigation several approaches for correcting the ionospheric effect exists, such as the use conventional ionosphere models, the use of ionosphere free linear combinations of observations from different frequencies etc. Common for these approaches are, however, that they all leave some amount of residual effects in the positioning and navigation solutions. See for instance Misra and Enge (2006) for a description of various differential positioning and processing algorithms, or Ovstedal (2002) for a description and discussion on ionosphere models for point positioning.

Residual ionospheric effects do affect the GNSS users, especially at high latitudes. The NMA therefore initiated development of a regional ionosphere model based on the SATREF® network of permanent GNSS stations in 2007.

The SATREF™ Ionosphere Model is based on estimation of the ionospheric delays from dual frequency GPS observations, using the geometry free linear combination of observations from the L1 and L2 frequencies. Also, the receiver differential code biases are estimated in a pre-processing step. Satellite differential code biases are extracted from the IGS Global Ionosphere Models.

The estimated vertical ionospheric delays at the ionosphere pierce points are then used as the basis for a spatial ionosphere model. The spatial model is grid based, and interpolation of the vertical delay values from the ionosphere pierce points to the grid points is based on an interpolation scheme combining ordinary kriging and inverse distance dependent weighting.

The algorithms and considerations behind the development of the SATREF™ Ionosphere Model as well as the initial validation of the model are described in more detail by Jensen et al. (2007).

TEST DATA

For the tests described in the following, four recent days of data were selected. When selecting test days the latest upgrade of the EGNOS software to version 2.0.4 was considered. This upgrade was carried out on November 19th 2007, and since no data may be older than this date, no days with very high ionosphere activity are included in the test set. A previous test with the SATREF™ Ionosphere Model and high ionospheric activity data from 2003 is described by Jensen et al. (2007).

The test days were selected so there is one day with low ionospheric activity, to be used as reference, and three days with medium ionospheric activity. Characteristics of the test days are provided in Table 1.

The K index values are based on observations from the magnetometer run by the University of Tromsø, and installed in Tromsø which is located at approximately 70°N in Norway (see Figure 3). For a description of the K-index see for instance Jensen (2002).

<table>
<thead>
<tr>
<th>Data set</th>
<th>Date</th>
<th>K index</th>
<th>Ionosphere activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY 015</td>
<td>Jan. 15, 2008</td>
<td>2 – 4</td>
<td>Low</td>
</tr>
<tr>
<td>DOY 033</td>
<td>Feb. 02, 2008</td>
<td>2 – 6</td>
<td>Medium</td>
</tr>
<tr>
<td>DOY 059</td>
<td>Feb. 28, 2008</td>
<td>2 – 6</td>
<td>Medium</td>
</tr>
<tr>
<td>DOY 324</td>
<td>Nov. 20, 2007</td>
<td>1 – 5</td>
<td>Medium</td>
</tr>
</tbody>
</table>
The SATEF™ Ionosphere Model was run based on GPS data collected in 13 GNSS stations. The locations of the 11 stations in mainland Norway are shown in Figure 3. The Southern most station, Kristiansand, is at 58° N and the most Northern station, Vardo, is located at 70° N. Furthermore, data from one station in Höfn on Iceland, and one station at the island of Jan Mayen located North of Iceland (see Figure 1) was included.

Figure 3. Location of used GNSS stations in Norway.

SATEF™ IONOSPHERE MODEL VS. GIM

For verification purposes a comparison between the SATEF™ Ionosphere Model and the Global Ionosphere Model (GIM) of the International GNSS Service (IGS) was carried out. See Dow et al. (2005) for a general description of the IGS.

The GIM models are grid based, and made available in post mission from the IGS web site (http://igscb.jpl.nasa.gov/). The performance of the IGS GIM is on the web site indicated to be 2 – 8 total electron content units (TECU), corresponding to a signal delay of about 0.3 to 1.3 meter on the GPS L1 frequency.

The GIM files are made available in the IONEX-format which is described by Schaefer et al. (1998). To access GIM files in the IONEX-format software, developed by Ola Ovstedal of the Norwegian University of Life Sciences, was used. The software is based on subroutines from the Astronomical Institute, University of Berne (http://www.aiub-download.unibe.ch/ionex/).

The verification of the SATEF™ Ionosphere Model was carried out using 20 of the GIM grid points located around Norway. The mean and standard deviation of the differences of the L1 ionospheric delay as estimated with the two models is shown in Table 2. The test is based on samples every 30 seconds throughout the 24 hours of a day, i.e. 2880 epochs for each of the 20 grid points totalling 57580 differences behind each of the values in Table 2.

No filtering or outlier detection has been applied to the differences - the results in Table 2 are based on all available ionospheric delays.

Table 2. Statistics of differences SATEF™ Ionosphere Model minus IGS GIM.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Mean [meter]</th>
<th>Std.dev. [meter]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY 015</td>
<td>-0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>DOY 033</td>
<td>-0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>DOY 059</td>
<td>-0.04</td>
<td>0.18</td>
</tr>
<tr>
<td>DOY 324</td>
<td>-0.05</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The compliance between the SATEF™ model and the GIM is generally better than 20 cm. The offset between the two models, given by the mean of the differences, is between 2 and 5 cm, basically negligible. But it is noteworthy that the bias is consistently negative indicating that the SATEF™ ionospheric delays are estimated to slightly lower values than the GIM ionospheric delays. The standard deviation of the differences varies with the level of ionospheric activity. With the higher activity level on DOY 059 and DOY 324 the standard deviation is close to 20 cm, where it is only 12 cm on the calm day DOY 015.

The size of the standard deviation is mainly driven by the smooth output of the GIM versus the unfiltered output of the SATEF™ Ionosphere Model. The ionospheric delays of the GIM are estimated based on a global network of GNSS stations, and the global nature of the model implies filtering of all local or small scale regional effects. See for instance Figure 6 which shows a typical plot of the SATEF™ Ionosphere Model (red) and GIM (green) as functions of time. With the SATEF™ model no smoothing or filtering is applied, so the model is much more sensitive to local high frequency ionospheric variations. This is indicated with the plot in Figure 6 where the red curve is noisier. Therefore, a certain standard deviation in the differences between the two models must be expected.

The compliance between the two models is slightly better here than with the comparisons shown by Jensen et al. (2007). This is because the model now includes correction of the time offset between the C/A code and the P code on the L1 frequency, the so-called C1-P1 bias. The bias is described and discussed in more detail by Jim Ray et al. in an IGS mail which is available at: https://goby.nrl.navy.mil/IGStime/mail/24Jun99.1

As described above, the results of the verification of the SATEF™ Ionosphere Model towards the IGS GIM are acceptable. The next step is now to use the SATEF™
ionosphere model for evaluating the performance of the
EGNOS ionosphere model.

**SATREFTM IONO. MODEL VS. EGNOS MODEL**

The EGNOS ionosphere model is based on GPS data collected in the Ranging and Integrity Monitoring Stations (RIMS). The EGNOS ionosphere model is produced as a grid based model, where the grid nodes, the vertical ionospheric delay, and the estimated accuracy is transmitted with the RTCA messages to the users. The location of the current EGNOS ionosphere grid points (IGP) are shown in Figure 4 as red circles. The area used for the tests in this paper is marked with a black square.

![Figure 4. Current EGNOS ionosphere grid points (red circles) and test area (black square). Plot generated using the EUROCONTROL Pegasus software.](image)

Performance of the EGNOS ionosphere model varies with the data availability, and an estimate of the accuracy is transmitted along with the correction given by the grid ionosphere vertical error (GIVE). During normal operation, a delay modeling accuracy of 55 cm is common for Southern Norway. When the ionospheric delay is estimated by EGNOS to be poor, the delay for the given grid point is marked as “not monitored”. In these cases no ionospheric delay for the given grid point is available for the user, and since the EGNOS user needs ionospheric delays from at least three grid points to compute a valid ionospheric delay, situations occur where no ionospheric delay can be computed by the user. This often happens in the North, where the distances between the RIMS stations are relatively large and the ionospheric variability is relatively high.

A comparison between the SATREFTM and the EGNOS ionosphere models is carried out based on extraction of ionospheric delays and GIVES for EGNOS grid points using the Pegasus software. The 16 grid points located at latitudes 60°, 65°, 70°, and 75° N and longitudes 0°, 10°, 20°, and 30° E were used for the following test.

The mean and standard deviation of the differences of the L1 ionospheric delay as estimated with the SATREFTM Iosphere Model and the EGNOS ionosphere model are shown in Table 3. The test is based on all samples available during the 24 hours, and the total number of samples is shown in the last column of Table 3. Missing samples occur when EGNOS grid points are marked “not monitored”. The largest number of samples is available on the day with low ionospheric activity, DOY 015.

**Table 3. Statistics of differences SATREFTM Iosphere Model minus EGNOS ionosphere model.**

<table>
<thead>
<tr>
<th>Data set</th>
<th>Mean [ meter ]</th>
<th>Std. dev. [ meter ]</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY 015</td>
<td>-0.12</td>
<td>0.15</td>
<td>6868</td>
</tr>
<tr>
<td>DOY 033</td>
<td>-0.10</td>
<td>0.20</td>
<td>6230</td>
</tr>
<tr>
<td>DOY 059</td>
<td>-0.15</td>
<td>0.20</td>
<td>6435</td>
</tr>
<tr>
<td>DOY 324</td>
<td>-0.12</td>
<td>0.23</td>
<td>6189</td>
</tr>
</tbody>
</table>

The compliance between the SATREFTM model and the EGNOS model is slightly worse than the compliance between the SATREFTM model and the GIM. The offset between the two models, given by the mean of the differences, is here between 10 and 15 cm, with no significant difference between the four days. Again we see consistently negative offsets indicating that the SATREFTM ionospheric delays are estimated to slightly lower values than the EGNOS ionospheric delays. The standard deviation varies with the level of ionospheric activity just as with the GIM, and the lowest standard deviation is present on DOY 015, where the ionospheric activity is low.

Considering the number of samples for each day, given in the last column of Table 3, it is interesting to see the difference in the number of samples per grid point, and to investigate whether there is a correlation between the number of samples and the mean and standard deviation of the differences for the points. This is illustrated in Figure 5 for the 16 grid points on DOY 033.

![Figure 5. Mean of differences, SATREFT minus EGNOS model, in meter (left) and number of samples (right). Data from February 2, 2008. Black starts indicate location of GNSS stations used.](image)
Referring to the left plot in Figure 5, the mean is significantly larger for the grid points located to the West, where the dots are dark blue, and the bias is about 40 cm in three of the points. All four grid points located at 75° N are also affected by a bias larger than the mean. The best compliance is shown with the orange and red dots to the East where the bias is about ±5 cm.

Looking at the number of samples, the plot on the right in Figure 5, there seems to be a correlation between a large number of samples and a low bias for all the grid points to the East. For the four grid points located at 75° N there is a lower number of samples, which indicates a larger number of ionospheric delays marked as “not monitored”. The lack of ionospheric information in the northern grid points is a behaviour commonly known in the Arctic. It is expected to be caused by the large distances between the RIMS stations to the North, and thereby also a reduced amount of data available for estimation of the EGNOS ionospheric delays.

The very low number of only 100 samples for the grid point at 75° N, 0° E is, however, worse than expected, but on this day it might be caused by the fact that the RIMS station on Svalbard was in failure mode. This grid point, however, has the lowest number of samples on all the test days, also on DOY 059 with only about 200 samples, even though all RIMS stations seem to have been operational on this day.

Looking at the mean values on the left plot in Figure 5 again, we will now focus on the grid points located to the West, where we see a large bias between the two models, even though the number of samples is reasonable. To investigate this further, the output of all three ionosphere models is plotted as a function of time for all grid points. In Figure 6 the plots for two of the grid points are shown from DOY 033 (the same data as Figure 5). The time given is GPS-time, which is one hour after local time.

The plots in Figure 6 illustrate the smooth behaviour of the IGS GIM with the soft green line. The red line is the SATREFTM model, and since no filter is applied to the SATREFTM model the line is more irregular. This makes the model more sensitive to local small scale variations and since one of the purposes with the model is to identify the local behaviour of the ionosphere it is deliberate that no filter has been added. The resolution of the EGNOS model is limited by the transmission requirements, so the delays are given at 0.125 meter intervals. Also the delays are transmitted with a temporal resolution of about 3-4 minutes and these two factors together explain the discrete nature of the blue EGNOS line in Figure 6.

Figure 6 shows that the EGNOS model for the grid point at 65° N, 0° E is biased considerably with respect to the SATREFTM model and the GIM. There is also a bias for the grid point on 65° N, 10° E but it is much smaller.

This behaviour is also found for the grid point at 70° N, 0° E with the same magnitude, and it is visible, but smaller, for the grid points at 75° N, 0° E and 60° N, 0° E as well. The offset of the EGNOS ionosphere model is thus present for all grid points located at the zero-meridian on these four test days, but it is not significant for any other of the grid point tested.

Based on our data and analyses we are not able to explain the reason to this behaviour. The grid points with the bias are all located between Norway and Iceland in the Norwegian Sea, and the distances to the nearest RIMS stations on Iceland and in Trondheim are relatively long, about 800 km. But it would have been expected that the grid points were marked as “not monitored” if problems had occurred during the data processing. Therefore, the conclusion here is that the bias is present, but no explanation has so far been found.

The bottom plot in Figure 7, show a situation where both the SATREFTM and the EGNOS ionosphere models show a signature of higher ionospheric variability between 2 and 4 hours in the morning. The signature can also be identified in Figure 2, which is based on data from the same day. But the signature is not found with the IGS GIM (green line in Figure 7), and this is thus a nice illustration of the global smoothing effect of the GIM.

Figure 6. February 2, 2008. Ionospheric delay of EGNOS model (blue), SATREFTM Ionosphere Model (red), and IGS GIM (green). Top plot is grid point 65° N, 0° E. Bottom plot is grid point 65° N, 10° E.

Figure 7 shows the same grid points as Figure 6 but for another day, February 28, 2008. The image is the same with a bias for the grid point at 65° N, 0° E. The bias is found for all the four test days, and the size of the bias is on average about 40 cm on all four days – also for the calm day (DOY 015).

Based on our data and analyses we are not able to explain the reason to this behaviour. The grid points with the bias are all located between Norway and Iceland in the Norwegian Sea, and the distances to the nearest RIMS stations on Iceland and in Trondheim are relatively long, about 800 km. But it would have been expected that the grid points were marked as “not monitored” if problems had occurred during the data processing. Therefore, the conclusion here is that the bias is present, but no explanation has so far been found.
FUTURE WORK

The analyses described in this paper show that the estimates of the ionospheric delay estimated with the SATREF™ Ionosphere Model generally take on slightly lower values than the estimates produced by the IGS GIM. The difference is generally only a few cm, and has therefore been ignored for this work, but the fact that it is present does indicate that it might be beneficial with a minor tuning of the SATREF™ model.

A test run with the EUROCONTROL Pegasus software will be carried out, where the program is configured to read the SATREF™ Ionosphere Model instead of the EGNOS ionosphere model. An analysis of the EGNOS performance with respect to accuracy, integrity, and availability in mainland Norway will then be carried out to investigate whether the performance parameters are affected by the use of another ionosphere model.

As the work on the development of the SATREF™ monitoring system progresses, the system can be used for further investigations on the EGNOS performance at high latitudes, not only related to the ionosphere. This could be investigations on the EGNOS performance with respect to UDRE and GPS satellite geometry.

As part of the project, the SATREF™ Ionosphere Model will be modified to be able to run in near real time.

CONCLUSION

With this paper the background for, and the elements of, the SATREF™ system for GNSS performance monitoring has been described. Development of the system is argued with the large difference in ionospheric activity between North and South in Norway. The SATREF™ GNSS network, and the SATREF™ Ionosphere Model have been introduced, and a verification of the SATREF™ Ionosphere Model with the IGS GIM has been described in detail. The verification shows differences between ionospheric delays estimated with the two models in 20 grid points for four days. The mean of the difference is only a couple of cm and the standard deviation is between 12 and 19 cm, which are acceptable.

The SATREF™ Ionosphere Model has then been used for an evaluation of the EGNOS ionosphere model using the same four days of data and 16 grid points. This evaluation shows a mean of the differences between the two models at 12 to 15 cm and standard deviations of 15 to 23 cm for the four days. With the evaluation it is also noted that the number of available delays from the EGNOS model is significantly reduced for grid points located at high latitudes, in this case at 75° N.

A further analysis of the mean of the differences between the SATREF™ and the EGNOS ionosphere models shows large offsets between the models for grid points located in the Western part of the test area. All the grid points with large offsets are located along the zero meridian. The offset has been detected, but no explanation for the offset has so far been found.

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REFERENCES


