

INVESTIGATION OF THE EFFECTS OF SPECIFIC SOLAR STORMING EVENTS ON GNSS NAVIGATION SYSTEMS

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Abstract. Global positioning system (GPS) satellites operate at 1.2 and 1.5 GHz. The GPS signals travel through the atmosphere and are affected by space weather in the same way as other technological systems in space and on the ground. Space weather has been defined as the condition where the sun influences solar wind, the magnetosphere, and the ionosphere and thus can upset the performance and reliability of space borne and ground based technological systems. Adverse conditions in the space environment can cause disruption of satellite operations, communications, and navigation. Solar storms can add small delays to the GPS satellite signals and therefore impact accuracy. The purpose of this article is to investigate and to determine the effects of specific solar events on GNSS navigation systems. In parts of the Nordic countries, GPS is available with a precision of 1 centimetre through an auxiliary system of permanent tracking stations called position accuracy on the centimetre level (CPOS). This paper discusses the possible effects of space weather activity and uses these tracked data to investigate the effect of specific solar storms on single point positioning. Comparisons are made between the effects in northern and southern Norway.

Keywords: GNSS, space weather, single point, precise point positioning, CPOS.

1. Introduction

GNSS is a satellite system that is used to identify the geographic location of a user's receiver anywhere in the world. Positioning with GNSS is based on computing the user position from satellite position and user range measurements that are biased and contain random errors.

Inside the global positioning system are many different technologies that all combine and work together to find position on land, at sea, and in the air. The global positioning system depends on a number of GPS satellites orbiting the earth. GPS satellites transmit a unique

navigational signal centred on two L-band frequencies of the electromagnetic spectrum: L1 at 1575.42 MHz and L2 1227.60 MHz. Each of the satellites continuously transmits on both frequencies the following information: exact orbit information, rough orbits of all other GPS satellites, and general system health. The radio signals travel a long distance before they reach the GPS device. During this stage, it passes through vacuum (in space) and the different layers of the earth's atmosphere.

Since the beginning of global satellite positioning, it has been a challenge to eliminate and correct the error sources that affect positioning accuracy. Scientists have found mathematical solutions to reduce these errors as much as possible. Some of the errors can be totally eliminated, while others can be corrected to a certain degree. Some of the errors, like ionospheric errors, are still being examined and modelled.

The goal of this paper is to examine whether the errors in a satellite's orbital location, due to high solar activity, can affect the accuracy of ground receivers and, if so, how these errors can be controlled.

When a ground receiver determines its position, there are many possible sources of errors:

- Ionospheric and tropospheric delays – signal delays due to the signal passing through various layers of the atmosphere;
- Orbital errors (ephemeris errors) – errors caused due to satellites transmitting inaccurate orbit parameters;
- Signal multipath – these errors can occur when the signal is reflected off objects before reaching the receiver;
- Receiver clock errors – the receiver clock is not as accurate as the atomic clocks on the satellites, which can lead to timing errors;
- The number of visible satellite – accuracy is better if the receiver observes more satellites;
- Geometry of the satellites – relative position of the satellites in the sky affects the accuracy, best if the satellites are spread widely.

Researchers have been trying to find out ways to eliminate these errors. Some of the methods used are:

- Differencing;
- Using more signal frequencies;
- Modelling ionospheric errors.

The first sources of errors, ionospheric and tropospheric delays and orbit errors, are affected by levels of solar radiation activity. It is generally assumed that satellites' orbit errors are eliminated by differencing, in other words by using two or more receivers simultaneously (Büga 1999).

2. Description of research data

The sun goes through an 11-year cycle from stormy to quiet and back again. Solar maximum appears when

sunspots are most numerous and solar minimum occurs when the number of sunspots is lowest. Even though sunspots are darker and therefore cooler areas on the sun, the sun is generally hotter during solar maximum than at solar minimum. Regarding solar cycles, there are 250 years of observations of which only the last 150 years are considered truly reliable.

Sunspots are dark areas on the surface of the sun. They appear dark because their temperature is lower compared to the overall surface temperature of the sun. Sunspots are magnetic regions on the sun that are thousands of times stronger than the earth's magnetic field. They typically last for several days, but large sunspots can remain for several weeks. The magnetic field is stronger on the darker area of the sunspot (umbra) and is weaker on the lighter area of the sunspots (penumbra). Sunspots are active areas that are strong emitters of ultraviolet light and X-rays. Sunspots are often sites for the emission of solar flares.

Predicting the activity level of a solar cycle is very important. An active sun can cause geomagnetic storms which may disrupt communications and power systems on earth. Additionally, mission planning for space requires prediction of the sun's activity years in advance. Nowadays there is a prediction panel for solar cycle. This panel includes members of NOAA, NASA, ISES and other US national representatives together with some representatives from European countries. The objective of this panel is to forecast how an upcoming solar cycle will develop, based on the records from previous observations and cycles (Kunches 2007).

There are different techniques used for predicting the amplitude of a solar cycle. Prediction of the maximum is more reliable 2 to 3 years after the solar minimum. Predictions of maximum before that time are not so reliable.

Although the onset and the peak of the cycle can be predicted to the nearest year or two, the occurrence of sunspots and especially solar flares cannot be reliably predicted because the number of these events is not constant from cycle to cycle. The current cycle is on Cycle 24, which began in January 2008 and at the time of writing has not yet reached its peak. The generally reported opinion in scientific circles is that this will be a medium high cycle, the same as or somewhat higher than Cycle 23 (Kunches 2007; Jakowski *et al.* 2002).

The largest cycle in the history of storm records is Cycle 19, which began in April 1954 and ended in October 1964. This cycle peaked in 1957 with a yearly sunspot number of 190, just at the time that the first space physics satellites were being launched (Odenwald *et al.* 2008).

Solar flares are violet explosions in the sun's atmosphere with energy equivalent to tens of millions of hydrogen bombs. They can last from minutes to a couple

Table 1. The coordinates of the chosen CPOS station

Station	Municipality	Description	Latitude	Longitude	X, metres	Y, metres	Z, metres
Kristiansand	Søgne	KRSS	58 04 57.69192	07 54 26.69267	3348108.747	465030.109	5390612.707
Ny Ålesund	Svalbard	NYA1	78 55 46.38780	11 51 55.09294	1202418.320	252628.900	6237689.865

of hours and they cause solar storms, which are categorised as:

- geomagnetic storms,
- solar radiation storms,
- radio blackouts.

Geomagnetic storms are a disturbance in the earth's geomagnetic field caused by solar wind pressure that usually reaches earth's magnetic field 24 to 34 hours after the event.

The solar wind energizes electrons and ions in the magnetosphere and they enter the earth's upper atmosphere near the polar regions. By interacting with the molecules and atoms of the upper atmosphere, the electrons and ions start to glow in different colours known as auroras. Geomagnetic storms can also have a significant impact on GNSS satellite systems by pushing the satellites away from their predicted orbits and in this way affect the ground positioning accuracy (Baker 2005).

Solar radiation storms are caused by elevated levels of solar radiation that occur when the number of energetic particles (protons) increases. These storms have a negative impact on the flight industry and also space

flights. Radiation exposure of astronauts and also of passengers flying on polar routes is extremely high.

Radio blackouts are a disturbance of the ionosphere caused by X-ray emissions from the sun. Radio blackouts can influence communications by degrading communications facilities for hours or even days.

The Space Environment Centre in Boulder, Colorado, USA, grades solar storms from minor to extreme.

With the use of data obtained from the Space Environment Centre and the NOAA archive, a priority list of major solar storms was extracted. From these lists, a major event in October 2003 was selected for study compared with an apparently completely storm-free period in October 2010. On 2003.10.30 there were geomagnetic storms of level G1 to G5, and a solar radiation storm S3. On 2010.10.30 there was no solar activity.

In parts of the Nordic countries – Norway, Denmark, Finland and Sweden – GPS is available with a precision of one centimetre through an auxiliary system called position accuracy on the centimetre level (CPOS). This is a Norwegian service for both GPS and GLONASS users who need to determine position to the centimetre level without a base station of their own. To support this service, a number of permanent tracking stations have been established. Two of these stations were chosen for this research. The CPOS station called NYA1 is located in Svalbard (Spitzbergen) north of northern Norway and the second station, KRSS, is located in southern Norway (Fig. 1). The coordinates of these stations are computed in two independent ways:

- Precise point positioning (solution in ITRF2005, transformed to EUREF89);
- GNSS baselines from the four closest EUREF89 benchmarks.

3. Observations

The experimental work in this paper is based on the theoretical methods of satellite orbit and ground receiver position determinations. The investigation procedure is made up of a sequence of several steps:

- Compute the broadcast satellite orbit positions;
- Compute precise satellite orbit positions;
- Compute ground position at KRSS and NYA1 using both the precise and broadcast satellite positions;
- Compare broadcast and precise receiver positions.



Fig. 1. CPOS station located in Norway. Station NYA1 is located in northern Norway and station KRSS is in southern Norway

Determination of the start and end time for selected days of high solar activity was chosen from 22.30 on the day when the solar burst started, and up to 23.30. An interval of 5 minutes was discussed.

Broadcast ephemerides were obtained from the KRSS and NYA1 CPOS stations. Precise orbits, with a 15-minute sample interval were obtained from the IGS website managed by the Jet Propulsion Laboratory of the California Institute of Technology. The IGS website provides GNSS data and products to the scientific community. The IGS website maintains precise orbit records from 1992 which are stored in the SP3 format. The accuracy of precise final orbit data is generally less than 0.05 meters.

Days with solar activity and days without solar activity are analysed to be able to compare the differences between the coordinates based on broadcast ephemerides and the known high precision coordinates of the CPOS stations. The differences are presented in Tables 2 and 3.

The results show that the differences are significant. In general, the differences at KRSS and NYA1 show extreme position error values, especially in the vertical dimension (Figs 2 and 3).

The graphs for storm-free 2010 (Figs 4 and 5) and table 3, however, generally show that the differences for positions are quite small. On the other hand, there is a sudden increase in the height difference between 23.05 and 23.10 at NYA1.

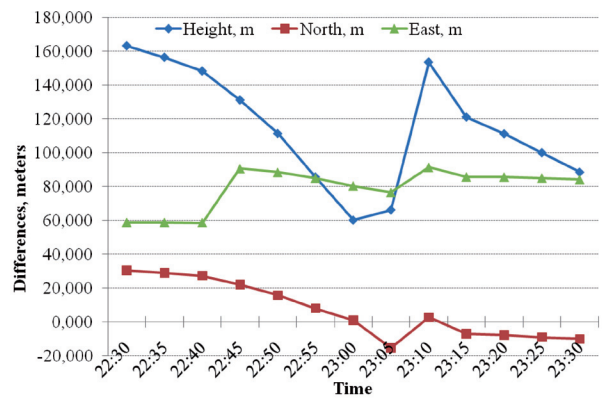


Fig. 2. Values of CPOS station called KRSS in 2003

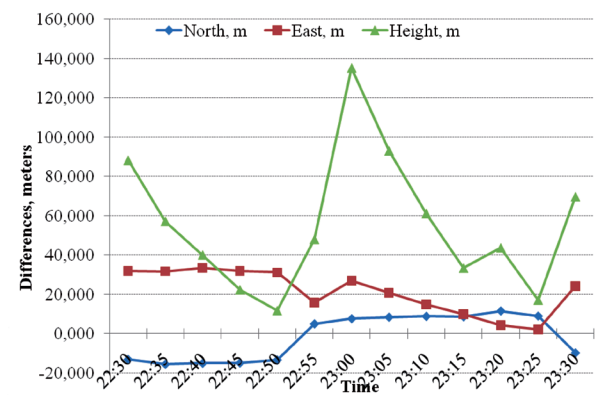


Fig. 3. Values of CPOS station called NYA1 in 2003

Table 2. The differences of CPOS stations in 2003

Epoch hh:mm:ss	North, metres	East, metres	Height, metres
KRSS			
22:30:00	30.374	58.600	163.227
22:35:00	28.841	58.598	156.437
22:40:00	27.194	58.540	148.291
22:45:00	21.969	90.618	131.170
22:50:00	15.685	88.471	111.348
22:55:00	7.955	85.017	85.683
23:00:00	0.870	80.362	60.132
23:05:00	-15.492	76.427	66.181
23:10:00	2.516	91.359	153.523
23:15:00	-7.049	85.713	121.108
23:20:00	-7.905	85.577	111.156
23:25:00	-9.130	85.046	99.985
23:30:00	-10.217	84.174	88.490
NYA1			
22:30:00	-13.124	31.871	88.182
22:35:00	-15.570	31.727	57.164
22:40:00	-15.052	33.491	40.072
22:45:00	-14.895	31.940	22.343
22:50:00	-13.367	31.147	11.770
22:55:00	5.006	15.809	47.986
23:00:00	7.635	26.873	135.165
23:05:00	8.431	20.698	92.970
23:10:00	8.830	14.888	61.141
23:15:00	8.628	9.913	33.418
23:20:00	11.558	4.291	43.695
23:25:00	9.020	2.161	17.158
23:30:00	-9.763	24.177	69.721

Table 3. The differences of CPOS stations in 2010

Epoch hh:mm:ss	North, metres	East, metres	Height, metres
KRSS			
22:30:00	17.928	67.370	159.903
22:35:00	17.788	67.966	153.962
22:40:00	16.431	68.426	145.635
22:45:00	14.475	68.738	134.912
22:50:00	13.061	70.266	122.160
22:55:00	10.737	71.263	106.646
23:00:00	7.456	72.004	87.850
23:05:00	3.863	73.218	69.445
23:10:00	0.283	73.615	50.607
23:15:00	-3.074	74.437	35.185
23:20:00	-6.062	74.697	21.327
23:25:00	-8.315	74.330	12.369
23:30:00	-10.401	73.721	6.046
NYA1			
22:30:00	14.934	15.440	83.918
22:35:00	10.821	15.429	69.536
22:40:00	4.616	10.564	73.390
22:45:00	3.096	12.726	57.690
22:50:00	-7.848	13.230	74.585
22:55:00	-5.449	15.992	52.119
23:00:00	-2.883	17.853	33.002
23:05:00	-0.277	18.975	22.354
23:10:00	21.160	19.341	147.817
23:15:00	23.349	20.386	124.002
23:20:00	16.169	20.388	122.369
23:25:00	10.972	4.915	145.568
23:30:00	8.918	4.114	126.583

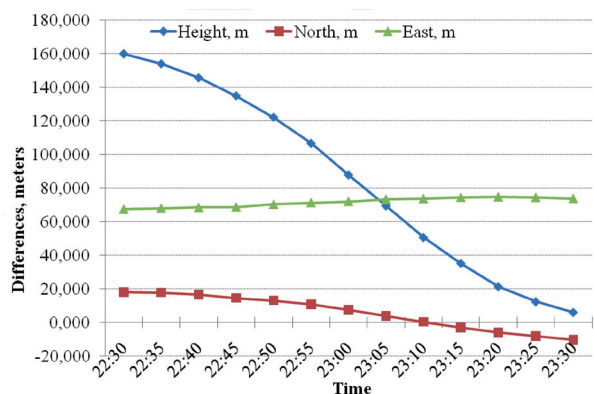


Fig. 4. Values of CPOS station called KRSS in 2010

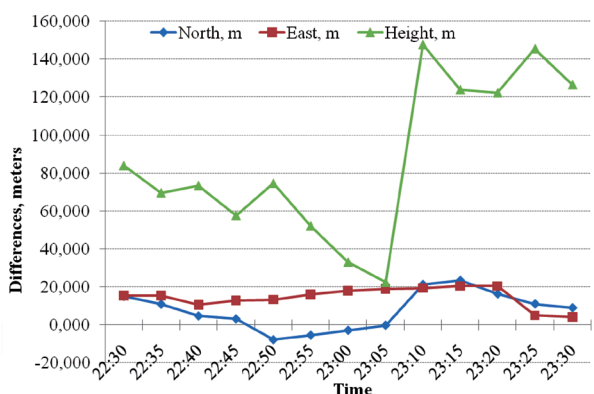


Fig. 5. Values of CPOS station called NYA1 in 2010

4. Conclusions

1. This paper concentrates on solar disturbance on GPS satellite orbits. The idea was to investigate differences between broadcast ephemerides compared with two chosen CPOS stations.
2. In general, looking at north and east positioning of 2003 and 2010, it is noticeable that these differences are mostly within 100-metre vector distance of the true position. This is within GNSS navigation accuracy specifications.
3. Nevertheless, the north and east curves for the storms of 2003 are noticeably further apart and less smooth. This indicates disturbed system stability under storm conditions.
4. For 2010 the height vector of KRSS is smoothly changing. At NYA1 the same height vector appears unstable, particularly with a change of some 100 metres over 5 minutes. This can be explained by the fact that NYA1 is so far north that it detects satellites over the pole that are invisible from KRSS.
5. Further, the satellites over the pole will inevitably be low and therefore particularly vulnerable to atmospheric effects.
6. The same can be seen under stormy conditions, but much emphasised.
7. Meanwhile, both KRSS and NYA1 during 2003 exhibit a significant discontinuity around 2300. The discontinuity is visible in all three axes but most significant in height. This is unsurprising because information

taken from the Space Weather Center indicated that this was a time of the most severe storm activity.

8. In other words, solar storm activity clearly affects the stability of GNSS positioning, with particularly emphasis on Polar latitudes.
9. Therefore, it is argue that, where positioning stability is important (especially in height), it is most relevant to maintain a high awareness of the levels of solar activity. This can be done by closely monitoring how position coordinates change over time. The rule seems to be that unstable coordinates indicate the possibility of solar activity disturbance.

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CHARAKTERINGŲ SAULĖS AUDRŲ POVEIKIO GLOBALINEI NAVIGACINEI PALYDOVINEI SISTEMAI TYRIMAS

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Santrauka. Pasaulinės padėties nustatymo sistemos palydovų signalai transliuojami 1,2 ir 1,5 GHz dažniu. Juos veikia kosmoso oras, kartu daroma įtaka ir kitai techninei sistemai tiek erdvėje, tiek ant žemės paviršiaus. Kosminis oras apibrėžiamas kaip būsena. Jo sąlygos daugiausia priklauso nuo tokių Saulės reiškinių, kaip Saulės vėjas ir Saulės vainiko masės čiurkšlės. Dėl šių priežasčių gali būti sutrikdytas antžeminių technologijų sistemų našumas ir patikimumas. Neigiamos sąlygos kosminėje erdvėje gali sukelti palydovų darbo, ryšių ir navigacijos sutrikimų. Šio straipsnio tikslas – ištirti ir nustatyti charakteringų Saulės audrų poveikį globalinei navigacinei palydovinei sistemai. Kai kuriose Skandinavijos šalyse (Norvegijoje, Danijoje, Suomijoje, Švedijoje) globalinės navigacinės palydovinės sistemos paslaugos suteikia galimybių nustatyti padėtis vieno centimetro tikslumu, taikant pagalbinių nuolatinių stebėjimo stočių tinklus. Šiame straipsnyje aptariama galima kosminio oro sąlygų įtaka antžeminio taško padėties nustatymo tikslumui. Pateikiami tyrimo rezultatai ir lyginimai analizuojant Šiaurės Norvegijos ir Pietų Norvegijos nuolatinių stebėjimo stočių matavimų rezultatus.

Reikšminiai žodžiai: GNSS, kosminis oras, taškas, padėties nustatymo tikslumas, CPOS.