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AN INITIAL ANALYSIS OF THE SOLAR STORMING EFFECTS ON THE DETERMINATION OF COORDINATES USING GNSS

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Abstract. The present work aims to investigate Solar Storming effects on the determination of geodetic coordinates. Preliminary results of an analysis of satellite and ground – based measurements during extremely strong geomagnetic storm on 11th September 2005 are presented. A similar situation was also observed on 30th October 2003 and 8th November 2004. The disturbance of the Sun, solar wind, and magnetosphere during these periods was weaker than during the similar period in 2003 with respect to a number of parameters. Nevertheless, the presented data indicate that the declining phase of solar cycle 23 is one of the most active intervals over the entire period of comprehensive studies of the solar–terrestrial coupling precisely because of the events that occurred in the autumn of 2003 and 2004. Satellite orbit errors and their consequences on the accuracy of ground positioning will also be investigated. It is expected that the results of this research will provide useful conclusions, which will be helpful for a wide range of applications that use Global Navigation Satellite Systems (GNSS) for high accuracy real time measurements. At the same time, this research is expected to be of practical interest for space weather applications as well as for all applications that rely on good real time knowledge of satellite positions.

Keywords: solar storming effects, geodetic coordinates, ground positioning, global navigation satellite systems.

1. Introduction

Since the beginning of global satellite positioning, the challenge has been 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, such as ionospheric errors, are still being examined and modeled (Kappenman 1990; Leick 2004; Zelenyi 2004):

– When a ground receiver determines its position, there are many possible sources of error or uncertainty (Leick 2004);
– Ionospheric and tropospheric delays – signal delays due to the signal passing through the atmosphere;
– Orbital errors (ephemeris errors) – errors caused due to satellites transmitting inaccurate orbit parameters;
– Signal multipath – this error can arise when signals are reflected off objects (buildings, hills, etc.), before reaching receivers;
– Receiver clock errors – the receiver clock is not as accurate as the atomic clocks on the satellites, which can lead to timing errors;
– Number of satellites visible – 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.

Some of the methods used to find out ways to eliminate these errors are:

– Differencing;
– Using more signal frequencies;
– Modeling ionospheric errors.

Ionosphere and troposphere delays and orbit errors are affected by the level of solar storm activity. It is generally assumed that satellite orbit errors are eliminated by differencing (in other words by using two or more receivers simultaneously) and by using more signal frequencies (Kappenman 1990).

The objective of these experimental investigations is to examine the effects of satellite orbit errors on the accuracy of ground positions determined by different measuring techniques (code, phase, single point, differential, post-processed and real-time).

2. Solar Observations

The intensity of solar storm activity varies according to a well established 11–12 year cycle (El-Alaoui 2006; Fuller-Rowell 1997; Gonzalez 1994). Records of activity which are visible as sunspots have been kept for several hundred years (Fig. 1).

The solar cycle is just embarking on the upward leg of its cycle, and the next solar cycle high is confidently predicted in 2011–12 (Yermolaev 2004; Odenwald 2008; Panasyuk 2003). Further, there have been widespread and respectable reports that this coming cycle is expected to be about 50% more intensive than the previous cycle. Extensive details on the science of solar activity as well as current intensity levels are obtainable at (http://www.swpc.noaa.gov). These details have become available as a result of enormous investment in the launching of specialized solar observation space missions, clearly justified by society‘s increasing dependence on space-based communications technologies. As explained at (http://www.swpc.noaa.gov) and repeated below, solar storming levels have now been categorized as far as they can affect human society, and the categories can be seen in detail at (http://www.swpc.noaa.gov/NOAAscales).

The fact that the above mentioned solar storming phenomena can affect satellite navigation leads clearly and obviously to the consequence that these effects can also disturb attempts by surveyors to determine positions with high (centimetric) precision (Radzeviciute 2006). Meanwhile, it was recently announced that the next cycle, known as Solar Cycle 24, has now started (http://spaceflightnow.com/news/n0704/29solarcycle).

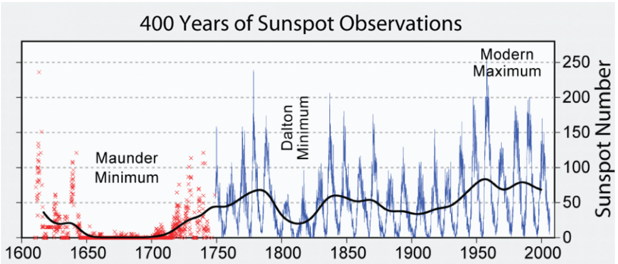

Fig. 1. Sunspot observations

Solar Storming Effects on the Determination of Geodetic Coordinates.

The solar events that can affect satellite ephemerides and thus ground positions are primarily geomagnetic and solar radiation storms. Such events are categorized on a severity scale from 1 to 5 and are reported regularly in weekly summaries by the NOAA Space Weather Prediction Center (SWPC) (http://www.swpc.noaa.gov/NOAAscales).

Geomagnetic storms of categories G2-G5 and solar radiation storms of categories S2-S5 can, according to (http://www.swpc.noaa.gov/NOAAscales). affect satellite navigation and alter satellites orbits.

Days with solar activity and days without solar activity are analyzed to be able to compare predicted and precise ephemeris based receiver positions.

The actual storms have been extracted from the NOAA archive and are registered from 2002 and up to date (Table 1).

Table 1. Overview Geomagnetic and Solar Radiation Storm levels per year

Year	Geomagnetic Storm			Solar Radiation Storm		
	G3	G4	G5	S3	S4	S5
2002		x	x	x	x	x
2003						x
2004			x	x	x	x
2005					x	x
2006		x	x		x	x
2007						
2008						

Year 2002 – there are storms of level G3 but none of level G4 or G5. No Solar Radiation storms were registered.

Year 2003 – there are events of Geomagnetic storms and solar Radiation storms as well. Events of Geomagnetics Storms have occurred starting from the end of May until the second part of November (20.11.2003). Geomagnetic Storms were of different scales from G3 to G5 but mostly were G3. On 29.10.2003 there were both Geomagnetic and Solar Radiation Storms. On this date three levels of Geomagnetic storm G3, G4 and G5 were reached with around one hour difference. There was also an overlap between Geomagnetic Storms and Solar Radiation Storms.

Year 2004 – there are Geomagnetic Storms of G3 and G4 but no Solar Radiation Storms.

Year 2005 – there are Geomagnetic Storms of G3, G4 and G5. There are of Solar Radiation Storms of level S3.

Year 2006 – there are Geomagnetic Storms and Solar Radiations Storms of level G3 and S3. March of 2006 was the start of the Solar Minimum. Even though the rest of the year was expected to be quiet with no solar storms, occasional G3 – Geomagnetic Storms and S3 – Solar Radiations Storms occured in December 2006.

Year 2007 – there are no storms registered. This year is also Solar Minimum with very low activity.

Year 2008 – a reversed polarity sunspot appeared on 04.01.2008 and based on the characteristics of this sunspot, this marks the start of the cycle 24.

Storms that we registered from the NOAA archive occurred during the 23th solar cycle. This cycle started in 1996, reached its peak in 2000–2002 and from the end of year 2006 until January 2008 was at minimum. The Solar minimum of cycle 23 was predicted to be finished by the middle of 2007 slthough, in the end, it lasted until 04.01.2008. If we compare the predictions for cycle 23 from year 2003 to 2006 with the actual activity for cycle 23 (with the storms extracted from SWPC archive) we can see that the prediction was quite reliable, although in year 2003 the activity is higher and it gradually goes down on the following years and goes lower toward 2006 while approaching solar minimum.

As we are in the beginning of a new solar cycle we may be lucky to have some new storms to experiment with during our project. While waiting, however, we work with the storms that are registered so far. The Solar Maximum for cycle 24 is expected in 2011 or 2012.

Selected storms are presented on Table 2. These storm dates will be used to experiment with the data received at Gjøvik University College‘s reference station (GJOV).

Table 2. Priority list of solar storms to be used on research experiments

Year	Geomagnetic Storm level	START		END		THRESHOLD REACHED	
		Date	Time	Date	Time	Date	Time
2003	G4	29.05.2003	18:00:00	29.05.2003	21:00:00	29.05.2003	20:13:00
	G5	29.10.2003	06:00:00	29.10.2003	09:00:00	29.10.2003	08:39:00
	G5	29.10.2003	18:00:00	29.10.2003	21:00:00	29.10.2003	20:56:00
	G4	29.10.2003	06:00:00	29.10.2003	09:00:00	29.10.2003	07:44:00
	G4	29.10.2003	18:00:00	29.10.2003	21:00:00	29.10.2003	19:22:00
	G4	29.10.2003	21:00:00	29.10.2003	00:00:00	29.10.2003	22:39:00
	G5	30.10.2003	21:00:00	30.10.2003	00:00:00	30.10.2003	22:30:00
	G4	30.10.2003	18:00:00	30.10.2003	21:00:00	30.10.2003	19:59:00
	G4	30.10.2003	21:00:00	30.10.2003	00:00:00	30.10.2003	21:31:00
	G4	20.11.2003	15:00:00	20.11.2003	18:00:00	20.11.2003	16:50:00
	G4	20.11.2003	18:00:00	20.11.2003	21:00:00	20.11.2003	20:16:00
	S4	29.10.2003	00:30:00	29.10.2003	10:50:00	29.10.2003	06:15:00
2004	G4	27.07.2004	09:00:00	27.07.2004	12:00:00	27.07.2004	11:08:00
	G4	27.07.2004	12:00:00	27.07.2004	15:00:00	27.07.2004	14:57:00
	G4	28.11.2004	00:00:00	08.11.2004	03:00:00	08.11.2004	01:10:00
	G4	28.11.2004	03:00:00	08.11.2004	06:00:00	08.11.2004	05:22:00
	G4	28.11.2004	06:00:00	08.11.2004	09:00:00	08.11.2004	07:45:00
	G4	10.11.2004	06:00:00	10.11.2004	09:00:00	10.11.2004	08:10:00
	G4	10.11.2004	09:00:00	10.11.2004	12:00:00	10.11.2004	11:10:00
2005	G5	15.05.2005	06:00:00	15.05.2005	09:00:00	15.05.2005	08:49:00
	G4	15.05.2005	06:00:00	15.05.2005	09:00:00	15.05.2005	07:36:00
	G5	11.09.2005	06:00:00	11.09.2005	09:00:00	11.09.2005	06:45:00
	G4	11.09.2005	06:00:00	11.09.2005	09:00:00	11.09.2005	06:37:00

Year 2004 has storms of level G4 while Years 2003 and 2005 have others categories of storms as well. With reference to the solar events we consider year:

– 2003 as "complicated";
– 2004 as "simple";
– 2005 as "moderate".

3. Data Analysis

Having selected the storm periods to be studied, it was decided to also select periods where there was no notified activity in ordeer to establish a „benchmark" of stormless activity against which stormy activity could be compared. Then it was necessary to select the actual storm time periods for further study.

Comparison days with solar activity and days without solar activity are analyzed to compare predicted and precise ephemeris based satellite positions. The difference is analyzed:

– During the storm;
– 24 hours after the storm;
– 5-10 hours before the storm;
– Clear days with no storm activity.

The following table gives a list of the days analyzed (Table 3).

Table 3. Analyzed days

Day	Day Status
26.10.2003	Clear day
29.10.2003	Storm day
30.10.2003	Storm day
31.10.2003	Day after the storm
08.11.2004	Storm day
09.11.2004	Day after the storm
11.09.2005	Storm day
12.09.2005	Day after the storm
29.09.2005	Clear day

Comparison of Differences between Predicted and Precise Satellite Orbits. Day 26.12.2003. This day has been selected for analysis because there was no sun activity at all and we want to compare the difference on satellite positions when no sun activity is reported. Even though there was no storm on this specific day and no storms on the days before we still get very high differences on satellite position for GPS satellite PRN25 on 1 minute interval analysis.

Day 30.10.2003. On this day the Sun was active from:

– 18:00 until 21:00 (Solar storm level G4);

– 21:00 until 00:00 (Solar storm level G5).

The extracted data from the GJOV – archive is analyzed using fiveminute, one-minute and one-second interval. A day before (29.10.2003) there was report of solar radiation storm of level S4 in addition to geomagnetic storm of level G4 and G5. Solar radiation storm was reported from 00:30 to 10:50 AM and it reached the threshold on 06:15AM on the same day 29.10.2003.

Data for the same period of time on 30.10.2003 has also been analyzed on 1 minute interval time. We found differences on satellite positions for some satellites which didn't show up on 5 minutes interval analysis.

Comparision of Differences between Predicted and Precise Receiver Positions. For ground positions, the following days are analyzed (Table 4).

Table 4. Analyzed days

Day	Day Status
30.10.2003	Storm day
08.11.2004	Day after the storm
26.12.2003	Clear day

The differences between broadcast and precise ephemeris ground positions on in geocentric coordinates (x, y and z) is analyzed for these time periods:

– 01:00AM – 02:00AM;

– 05:00PM – 06:00PM.

We chose these periods because we had found big differences in satellite positions during these time periods. The highest ground difference on this day goes up to 29.2 m in the z direction.

From 01:00:00 AM until 01:00:50 the average of ground differences is around 1.7m. At 01:00:51 the difference goes up to 26.62 meters, changing the ground difference between broadcast and precise ephemeris to 28.64 m in just one second. While analyzing satellite orbits for the same period of time when this change happened on the ground position, we found out that GPS satellite PRN23 disappeared from view at the very same second when the difference on ground position increases by 28.6 m. So with one less visible we observed much lower accuracy.

Day 09.11.2004. On this day there are sudden changes on ground positions. A difference of up to 40 m is also a result of few visible satellites and the difference of greater than – 80 m is a result of high differences between broadcast and precise ephemeris for satellite position for satellite PRN04 when it first becomes visible.

Day 26.12.2003. The following day is clear with no storms on the previous day and no storms on this particular day. During this period of the day, especially when the difference increases dramatically, the number of available satellites is only three. Three satellites are not enough to calculate x, y, z position.

Because of the large amount of data for the analyzed days, we have made a short overview with minimum, maximum and mean values for comparison between broadcast and precise ephemeris, for each specific day (Tables 5–7).

Table 5. Overview of days analyzed at 5 minutes interval

Analysis – 5 Minutes Interval		Δx			Δy			Δz		
Day	Strom Level	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
29.10.2003	G5	−5.3706	6.5733	−0.6396	−4.1779	7.0551	0.2243	−9.7924	11.2402	−0.3947
30.10.2003	G4, G5	−9.9977	8.3805	−0.9577	−9.9977	8.3805	−0.9577	−9.9977	8.3805	−0.9577
31.10.2003	Day after the Strom	−5.7421	8.4147	−0.8587	−5.7421	8.4147	−0.8587	−5.7421	8.4147	−0.8587
08.11.2004	G4	−3.4103	1.7173	−0.4882	−3.4103	3.0036	−0.0174	−4.3374	3.8217	−0.4079
09.11.2004	Day after the Strom	−2.6519	3.1324	−0.5975	−2.1292	2.3976	−0.2665	−2.9867	1.4841	−0.2793
11.09.2005	G4, G5	–	3.2520	−0.3994	−5.9688	3.5444	0.0476	−4.0433	2.5186	−0.7556
12.09.2005	Day after the Strom	−7.3588	3.2533	−0.3979	−8.8592	6.4266	0.0873	−6.5421	3.2932	−0.7852
29.09.2005	Clear day	−3.2291	2.4443	−0.3543	−5.8685	4.1772	−0.4769	−4.0414	6.5892	−0.4591

Table 6. Overview of days analyzed at 1 minute interval

Analysis – 1 Minute Interval		Δx			Δy			Δz		
Day	Strom Level	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
26.12.2003	Clear day	−54.6135	6.3250	−0.5470	−42.9916	5.6864	−0.2010	−3.6451	62.9963	−0.3391
30.10.2003	G4, G5	−19.2898	34.1338	−0.9620	−31.6132	8.3939	0.4611	−20.5342	49.5373	−0.0701
31.10.2003	Day after the Strom	−10.8997	28.4481	−0.8503	−15.1390	7.4969	0.4158	−7.2638	39.1018	−0.2282
09.11.2004	Day after the Storm	−52.8790	0.0994	−1.2195	−1.0174	21.5461	0.3246	−1.8289	32.6866	−0.3697

Table 7. Overview of days analyzed at 1 second interval

Analysis – 1 Second Interval		Δ*x*			Δ*y*			Δ*z*		
Day	Strom Level	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
26.12.2003	Clear day	−54.6135	1.9009	−0.0360	−42.9916	1.2251	−0.7555	−1.9667	62.9963	−0.7155
30.10.2003	G4, G5	−19.2898	34.1338	−1.1870	−31.6132	4.2955	−0.4194	−10.4873	49.5373	−0.5945
09.11.2004	Day after the Storm	−2.3042	0.8867	−1.0873	−3.5349	1.1972	−0.4753	−1.8894	25.9063	0.0554

4. Discussion and Conclusions

This project concentrates on solar disturbance of GPS satellite orbits. The idea was to include GLONASS in the study as well, but due to different ephemeris parameters, coordinate and time systems between GPS and GLONASS, we decided not to pursue GLONASS further at this time in this study.

The study periods were selected by examining solar storm archives maintained by Space Weather Prediction Center (SWPC), formerly known as Space Environment Center (SEC). Days with Category G4 and G5 Geomagnetic and S4 and S5 Solar Radiation storms including a 24 hour period after the storm, were investigated in more detail. Broadcast and IGS precise orbits and ground positions were calculated for these periods and the differences between broadcast and precise positions were calculated and analyzed. Broadcast orbits were calculated from broadcast ephemeris data using code pseudo-ranges measured on the L1 frequency. An automated data processing procedure is implemented by using programs which are developed during this project.

The results show that:

– GPS satellite orbits, during the selected study periods, do not tend to be disturbed by geomagnetic or solar radiation storms. Broadcast orbits contain occasional extreme errors, which we think result from receiver's anomalous interpretation of the broadcast signal. These errors show up only for a few epochs, when a satellite first becomes visible.

– Broadcast positional errors during periods with solar activity are of similar size as errors during periods with no solar activity.

– A ground receiver's position can be affected by orbital errors. This inaccuracy increases when combined with weak satellite geometry and/or low number of visible satellites.

The original questions that stimulated this project were as follows:

– Can high levels of solar storming affect the satellite's orbital locations?

– What effect can orbital disturbance have on the accuracy of a ground receiver's positions?

– Can orbital errors be eliminated by using differential observing techniques?

– What practical steps can and/or should surveyors take to manage these errors?

Since we did not find any indication that the satellite orbits are seriously affected by sun activity, other questions are obviously dependent on this conclusion. The last questions can probably only be answered by simulation, which could not be fulfilled because of limited time.

The main focus on this project, meanwhile, was to find out if solar activity affects the GPS satellite orbits. Based on the selected study periods we have not seen any indication of the solar activity on the GPS satellite orbits. However this conclusion is reliable only as far as the periods selected for this study are concerned.

5. Recommendations

Considering the fact that the positions of satellites in orbit are affected by many parameters, we have to note that our research is done by considering only solar activity. Other parameters that can affect satellite orbits are not taken into consideration. Since this project is a Master Project and it had a limited time frame (only four months), it explains exclusion of other parameters which we think are absolutely important and should be studied parallel with solar storms.

Solar activity is a large subject in itself. To understand how it affects satellite orbits, it is necessarily to study in detail its nature, its dynamics and how it reaches the earth. This is a subject which definitely needs a long term study.

Longer study periods after reported storm should be considered.

Position determinations throughout this study were based on single frequency code pseudo- range measurements. Eventual future research should consider using phase measurements, which provide higher accuracy measurements.

The research should also be expanded to include other GNSS.

More sophisticated analysis tools and more powerful computers should be used, especially with short (one second).sampling intervals.

More advanced programming knowledge may be appropriate if further research is undertaken.

Finally, this paper presents a glimpse of a first set of experiments which were necessarily constrained by limitations well outside the authors' control. It is clear that the conclusions require additional confirmation by means of testing other storm periods and for different intervals and lengths of time.

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