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INVESTIGATION INTO THE RATE OF CHANGES IN KEPLERIAN ORBITAL ELEMENTS FOR GPS SATELLITES UNDER SOLAR STORMING

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Abstract. Positioning using a satellite requires defining the instantaneous positions of navigation satellites. The established positions are predicted and transmitted to the users applying satellites, and, however become degraded with accuracy in cases solar events divert the satellites from their path. Meanwhile, getting satellite coordinates with reference to the made predictions involves computing effort. The question addressed in this paper is whether orbit disturbances can be detected by examining these predictions so that computing coordinates are avoided.

The paper argues that detection is possible but requires further experiments on confirmation due to the fact there have been relatively few solar storms in recent years while collecting data on satellite tracking. Also, the paper also suggests that detection by examining orbital parameters is of a limited practical value when compared with the ease of interpreting satellite coordinates measured in meters.

Keywords: GPS satellite, Keplerian orbit, navigation message, solar activity, solar storm, space weather.

1. Introduction

The environment in space has significant effects on GPS satellites. Currently, there are 27 active GPS satellites flying in orbit around the Earth. These satellites transmit their predicted position (the broadcast ephemeris) to the users, which is known as a “navigation message”. Position predictions are developed by the system control segment based on tracking observations (Kaplan, Hegarty 2006; Leick 1995).

The satellites move predictably according to the laws of physics and do not escape the Earth’s gravity that, in fact, holds them in orbit. The location of GPS satellites is given in the navigation message in the form of Keplerian elements.

The Keplerian model presents the satellites orbiting in an ellipse of a constant shape and orientation. Actually, to define a position of a satellite, a minimum set of six time-tagged numbers called satellite orbital elements or Keplerian elements is required. These numbers define an ellipse, orient it about the Earth and place the satellite on the ellipse at a particular time. Six orbital elements used to completely describe the motion of a satellite within orbit are summarized below:

a – semi-major axis;
e – eccentricity;
Ω – right ascension of the ascending node;
ω – argument of perigee;
i – inclination;
v – true/mean anomaly.

Keplerian elements provide a mathematical description of satellite orbit. Satellite tracking software reads Keplerian elements. Reality is more complex and the model used includes small corrections called perturbations that are extra parameters (OL 1989; Stewart, Tsakiri 1998).

As already noted, the broadcast ephemeris is obtained from a GPS receiver. Meanwhile, precise ephemerides based on tracking can be obtained from an archive on the World Wide Web (IGS).

2. Description and Assumptions of the Issue

The presented investigation is motivated by solar activity and its effects on GNSS systems. More specifically, the conducted investigation compares solar stormy and stormless days and shows how these events can be seen in the satellite’s orbital motion. Logically, orbital motion implies knowledge of a position in orbit. However, significant computations are necessary to take a position in orbit considering Keplerian elements. The question is whether these storm events can be seen directly in variations in Keplerian elements, therefore avoiding extra computations.

Solar storms consist of three major components: solar flares, solar proton events (SPEs) and coronal mass ejection (CMEs). CMEs can interact with the Earth's magnetic field to produce geomagnetic storms. Though not all solar storms produce all three elements, the largest parts of those tend to (Program 2011; Baker 2005).

Solar storms vary in size and impact on GNSS and Earth. The National Oceanographic and Atmospheric Administration (NOAA) delivers space weather impacts on satellite navigation, called NOAA Space Weather Scales. Three categories of descriptive scales of space weather are given:

- geomagnetic storms – disturbances to the geomagnetic field caused by gusts in the solar wind that blows the Earth;
- solar radiation storms – elevated levels of radiation that occur when the number of energetic particles increases;
- radio blackouts – disturbances to the ionosphere caused by X-ray emissions from the Sun (Crosby 2008; Marusek 2007; Koskinen *et al.* 2001).

Each scale provides the lists of possible effects seen in each category of activity. Five levels of severity from 1 to 5 (from minor to extreme) of space weather are defined and regularly reported in weekly summaries distributed by the Space Environment Centre (SEC). Essentially, geomagnetic storm categories from G2 to G5 and solar radiation storm categories from S2 to S5 can affect satellite navigation and specifically have an effect on altering satellite orbits. The days with particularly significant solar activity were selected as the object for experimentation (Table 1). When using data obtained from SEC and NOAA archives, a priority list of the major solar storms was extracted. The main major event from the list made in October 2003 was chosen for the study and compared with an apparently completely storm free period in October 2010. On 30 October 2003, geomagnetic storms of categories G1 and G5 and a solar radiation storm of category S3 were recorded. Data was collected one day before and one day after the storms. Meanwhile, for comparison purposes, a similar storm free period at was chosen the end of October 2010 (Zubinaite, Preiss 2010).

Table 1. Selected solar activity events as an object for experimentation

Date	Space weather Scale									
	G1	G2	G3	G4	G5	S1	S2	S3	S4	S5
29.10.2003		▨	▨	▨	▨			▨	▨	
30.10.2003	▨	▨	▨	▨	▨			▨		
31.10.2003		▨	▨					▨		
29.10.2010										
30.10.2010										
31.10.2010										

In some parts of the Nordic countries, including Norway, Denmark, Finland and Sweden, GPS is available with a precision of one centimetre using an auxiliary system *Position Accuracy on the Centimetre Level* (CPOS). This is Norwegian service for both GPS and GLONASS users who need to determine a position without their own base station. To support this service, a number of permanent tracking stations have been established. Two of those were chosen to carry out this experiment. CPOS station *NYA1* is located in Svalbarg (Spitzbergen), the north of Norway, and the second station *KRSS* is located in the south of Norway. The coordinates of the stations are computed in two independent ways:

Precise point positioning (solution to ITRF2005 transformed to EUREF89).

GNSS baselines from four closest EUREF89 benchmarks. GPS navigation message files of these tracking stations were obtained taking into account two time periods with the help of Norwegian Mapping Authority. At the early stage, six Keplerian elements are clearly required to describe an instantaneous position of the satellite in its orbit. The sixth element, in fact, describes an angular distance of the satellite around its orbit from the perigee of orbit. The previous five Keplerian parameters are necessary to describe the orbit itself. Therefore, five elements for each different time of ephemeris – t_{oe} were extracted from the selected CPOS stations.

Then, the average of all values for each satellite are taken and then subtracted from individual values to get residuals.

3. Data Analysis

The results of the performed investigation are presented in the following graphs (Figs. 1–20), i.e. variations in the Keplerian parameters of GPS satellite orbits regarding solar activity and non-solar activity days.

Figures (1–10) show variations in five parameters during three stormy days in 2003. For comparison purposes, Figures (11–20) indicate variations in stormless days in 2010.

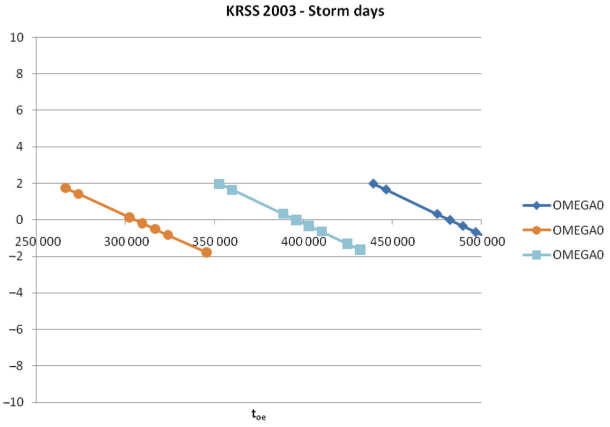

Fig. 1. Right ascension of the ascending node during three stormy days in 2003 using CPOS stations (KRSS)

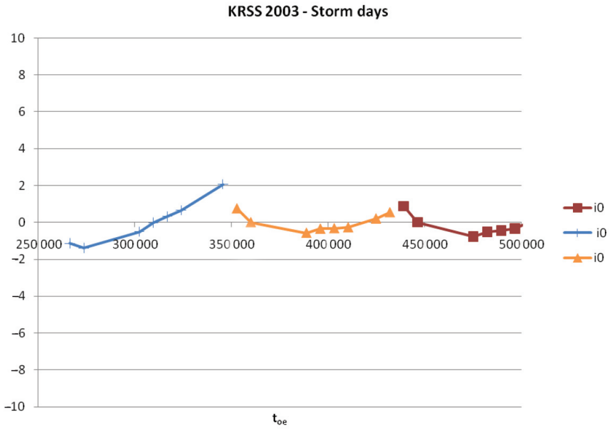

Fig. 2. Inclination for three stormy days in 2003 using CPOS stations (KRSS)

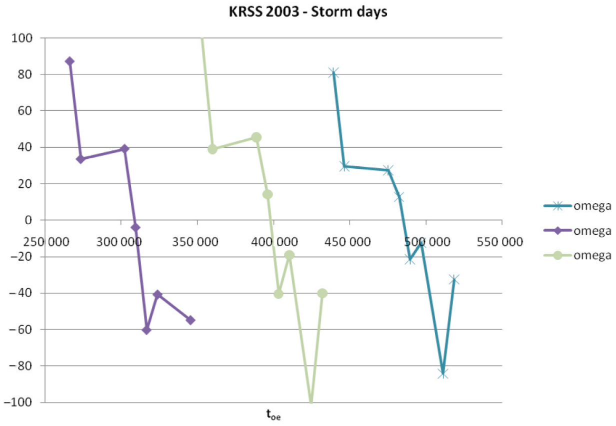

Fig. 5. Argument of perigee of three stormy days in 2003 using CPOS stations (KRSS)

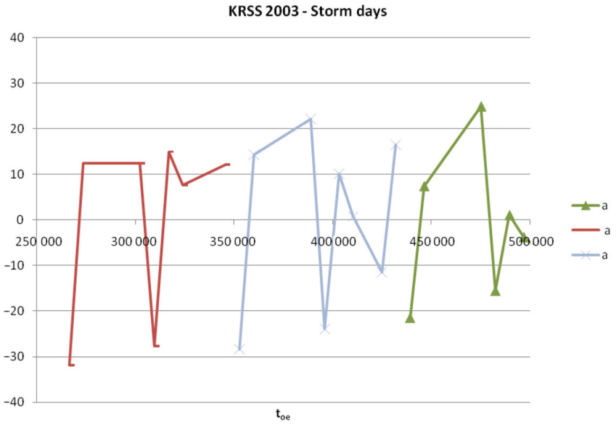

Fig. 3. A semi-major axis of three stormy days in 2003 using CPOS stations (KRSS)

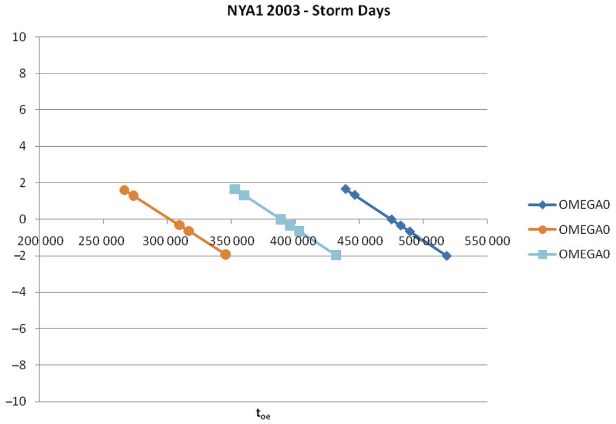

Fig. 6. Right ascension of the ascending node during three stormy days in 2003 using CPOS stations (NYA1)

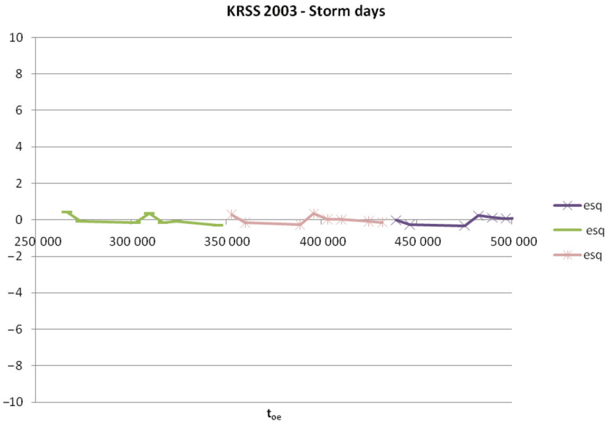

Fig. 4. The eccentricity of three stormy days in 2003 using CPOS stations (KRSS)

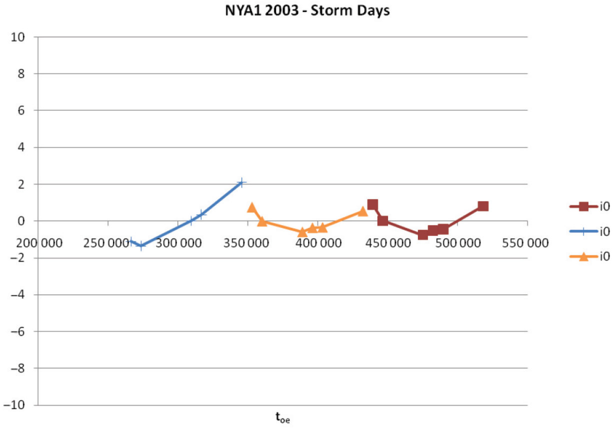

Fig. 7. Inclination for three stormy days in 2003 using CPOS stations (NYA1)

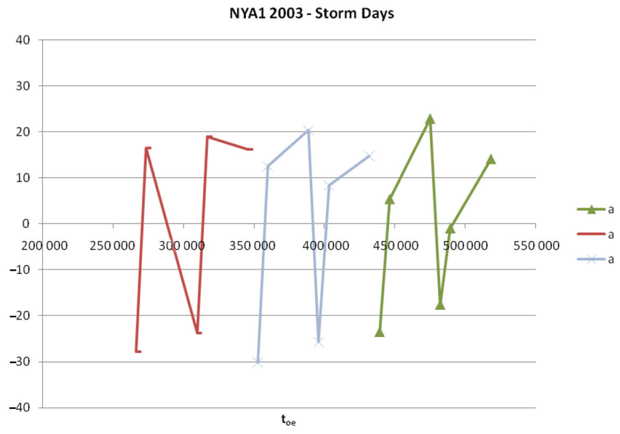

Fig. 8. A semi-major axis of three stormy days in 2003 using CPOS stations (NYA1)

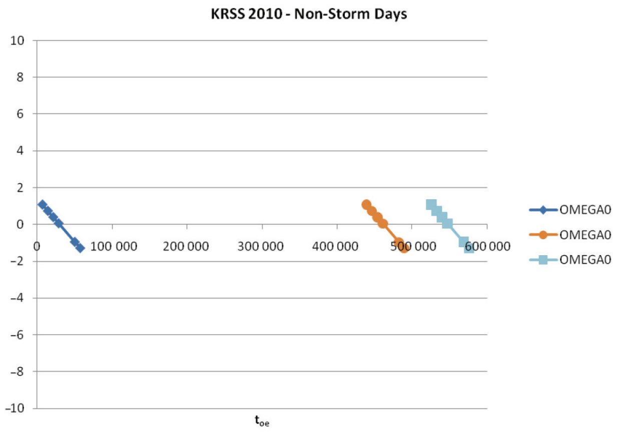

Fig. 11. Right ascension of the ascending node during three stormless days in 2010 using CPOS stations (KRSS)

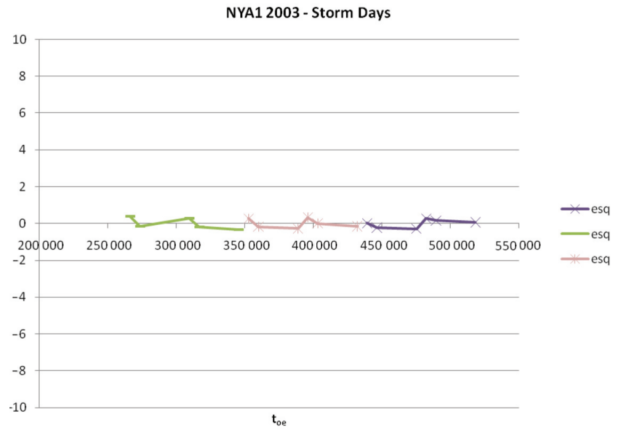

Fig. 9. The eccentricity of three stormy days in 2003 using CPOS stations (NYA1)

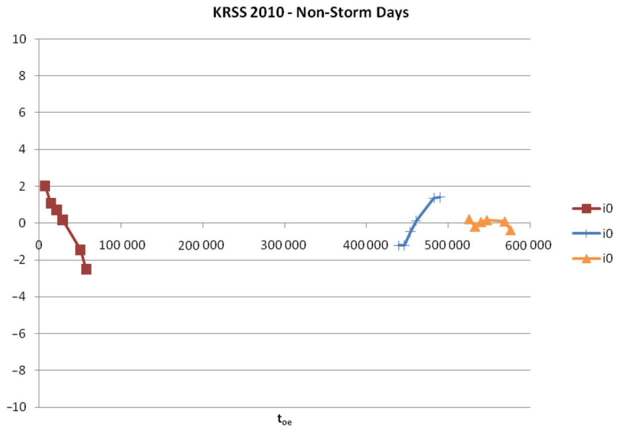

Fig. 12. Inclination for three stormless days in 2010 using CPOS stations (KRSS)

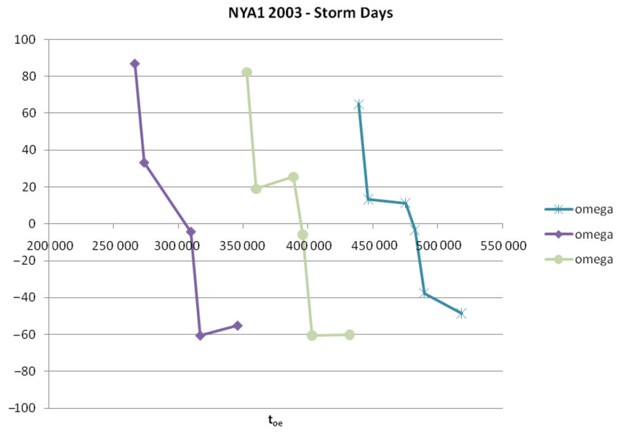

Fig. 10. Argument of perigee of three stormy days in 2003 using CPOS stations (NYA1)

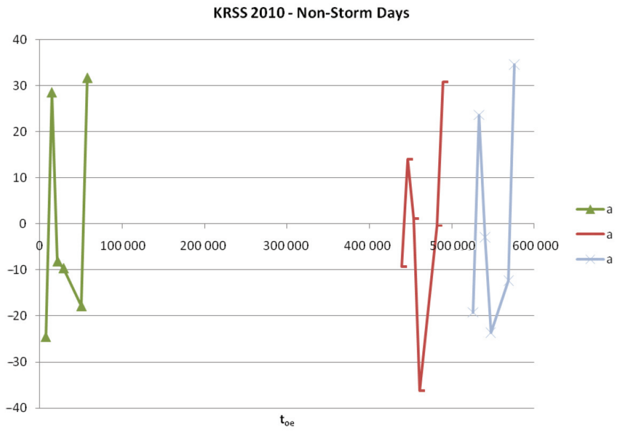

Fig. 13. A semi-major axis of three stormless days in 2010 using CPOS stations (KRSS)

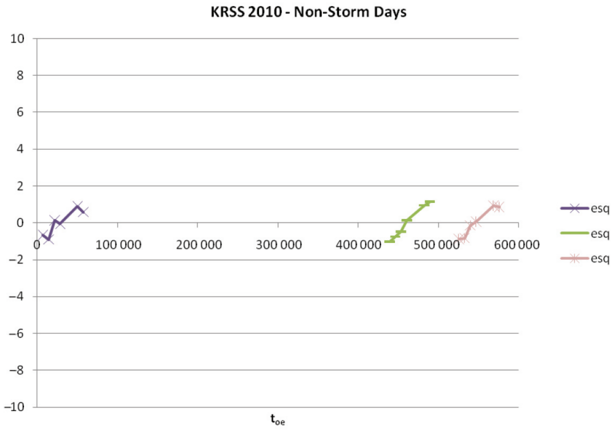

Fig. 14. The eccentricity of three stormless days in 2010 using CPOS stations (KRSS)

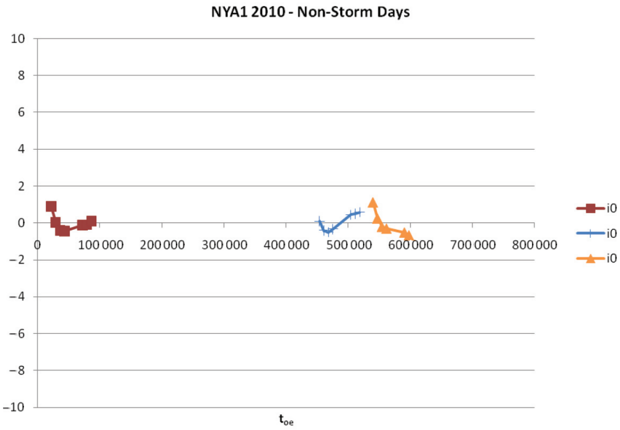

Fig. 17. Inclination for three stormless days in 2010 using CPOS stations (NYA1)

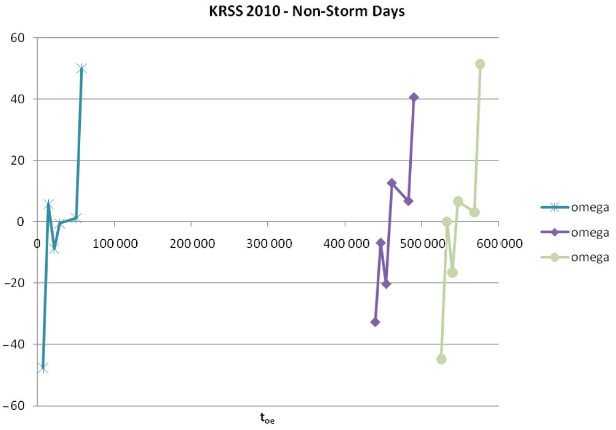

Fig. 15. Argument of perigee of three stormless days in 2010 using CPOS stations (KRSS)

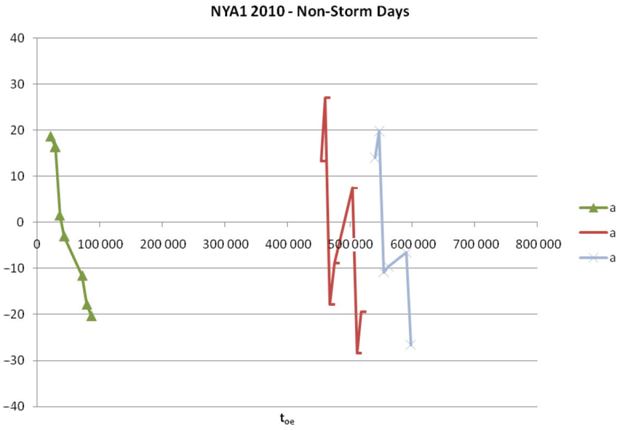

Fig. 18. A semi-major axis of three stormless days in 2010 using CPOS stations (NYA1)

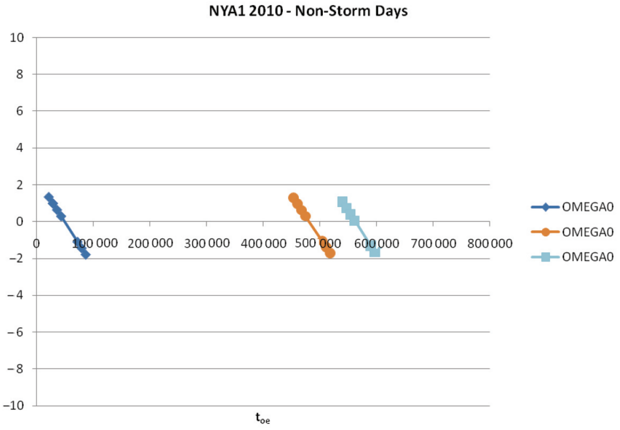

Fig. 16. Right ascension of the ascending node during three stormless days in 2010 using CPOS stations (NYA1)

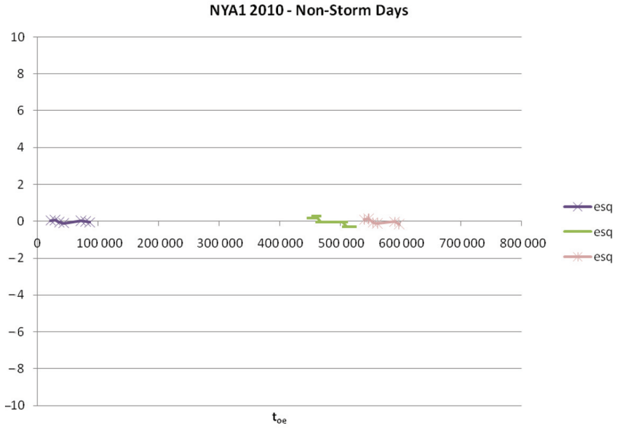

Fig.19. The eccentricity of three stormless days in 2010 using CPOS stations (NYA1)

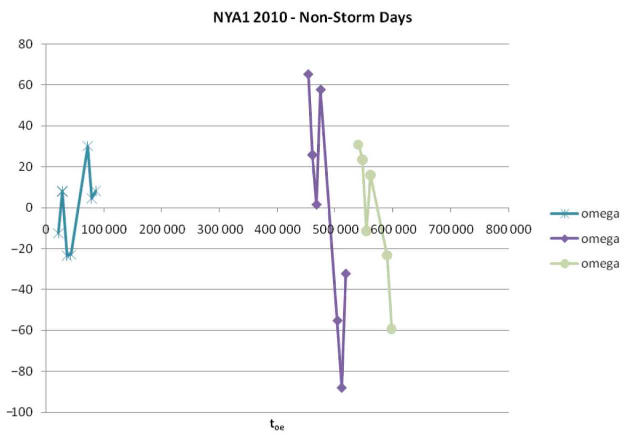

Fig. 20. Argument of perigee of three stormless days in 2010 using CPOS stations (NYA1)

Each of these figures shows variations in one particular satellite.

Unfortunately, at the latest stage of the conducted experiment, serious gaps in data collected in 2010 were discovered. The gaps remain unexplained at the time of writing, however, the available data obtained in 2010 is considered sufficient for the purposes of these experiments.

It can be noticed that the range and variation of the presented diagrams is greater under storm (Figs. 1–10) rather than under stormless conditions (Figs. 11–20) (Table 2). However, differences in this particular experiment appear to be marginal.

Table 2. The summary of results showing the range of differences (The range in this context is defined as the difference between the highest and lowest values)

		2003	2010
Ω, radians	KRSS	3.7907	2.382
	NYA1	3.665	3.129
i, radians	KRSS	3.451	4.537
	NYA1	3.451	1.786
a, meters	KRSS	56.797	70.758
	NYA1	52.970	55.441
e, no unit	KRSS	0.748	2.180
	NYA1	0.730	0.589
ω, radians	KRSS	171.286	98.968
	NYA1	147.238	153.141

4. Discussions and Conclusions

1. While the overall differences between 2003 and 2010 (respectively stormy and stormless) appear to be marginal, two of Keplerian elements seem to be significantly affected. These are the semi-major axis of orbit and argument of perigee (see Table 2).
2. The semi-major axis and argument of perigee are more sensitive to solar activity, while orbital inclination for the equatorial plane is relatively unaffected.
3. Meanwhile, the results obtained in the south of Norway are similar to those from northern Norway, i.e. the findings are not accepted to be a function of latitude.
4. The results are received from only one experiment, and therefore significant additional experiments are necessary for drawing valid conclusions.
5. However, unusually a low level of solar storm activity has been noticed within the period of collecting data on GPS tracking in Norway.

A hypothesis that variations in Keplerian elements can be used as indicators for changes in orbit due to solar storm activity has been put forward. There is no doubt that, if a solar event diverts a satellite from its orbit, then, its new orbit will have different Keplerian elements. It is also clear that, at least for GPS, Keplerian elements are immediately available from the navigation message without extensive computing effort.

The practical usefulness of these variations, however, is more debatable, when compared with unexpected changes in satellite coordinates in meters. A departure in meters is much more readily understandable than a small change expressed in a tiny fraction of a radian.

In conclusion, therefore, it seems to be more appropriate to accept additional computing power necessary to produce satellite coordinates change, rather than to rely on changes in Keplerian elements that are probably much more difficult to interpret.

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