Runaway PRN11 GPS satellite

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Abstract. The paper discusses the position of the orbit of PRN11 GPS satellite. Visual analysis of the current GPS constellation showed considerable deviation of PRN11 GPS satellite orbital parameters relative to other orbital plane D satellites. Short comparison of available GPS almanac format was included. Two almanacs per year since the launch of the PRN11 satellites in 1999 were obtained. Parameters of right ascension of ascending node and rate of right ascension of ascending node were taken into investigation. The results confirmed the fact of constant and progressive separation of the orbit from home orbital plane D since the very beginning of the satellite mission. The simulation of long-term persistence of the current trend in the postion of the PRN11 ascending node was presented.

Keywords: GPS, satellite, PRN11, satellite orbit.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

Constatnt availability of positioning and precise timing is nowadays a vital need of global population. Whole sectors of world economy rely on GNSS services. Vessels navigation (Czaplewski, K. 2004 and Nowak, A., Naus, K. 2014), shipping (Weintrit, A., Neumann, T. (Eds). 2009), transportation (Specht, C. *et al*. 2016 and Oszczak, S. *et al*. 2005), land surveying (Zienkiewicz, M. H., Baryła, R. 2015), hydrography (Popielarczyk, D. 2011), geodesy (Rogowski, J. B. 2004), GIS (Ciecko, A. *et al*. 2006) are natural applications of positioning service. However, there are many non-obvious fields, such as energetics, banking, telecommunication, which in case of deprivation of precise GPS timing would encounter serious difficulties with regular operationing.

Calculating the coordinates of satellites within its orbit is a part of determining the position of GNSS receivers, both in real time (Dana, H. P. 1997), and during post-processing of raw measurement data (Kouba, J., Heroux, P. 2001). Both methods differ in the possibility of application the final IGS orbits in the latter one (Beutler, G., Kouba, J., Springer, T. 1995). Precise orbital parameters are presented with the 13-day delay (Griffiths, J., Ray, J. R. 2009). Accuracy of calculating the position of a satellite within its orbit by the GNSS receiver in real time is greater in relation to independent calculation using the mere almanac data. It is achieved by applying the corrections to the parameters of unperturbed Keplerian orbital parameters (Specht, C. 2007) - additional data received in the GPS naigation message. Reference values, enabling to assess the accuracy of the obtained coordinates, can be final orbits calculated and made available by the IGS. Results of such comparison yielded linear deviation of the position of the satellites of about 2 km (Ma, L., Zhou, S. 2014).

The paper presents the current state of the orbit of PRN11 GPS satellite. The separation from the other satellite orbits in orbital plane D - PRN01, PRN02, PRN06, PRN21 was found. Analysis include almanacs ephemeris data generated since the launch of the PRN11 satellite into the orbit to date. Additionally, a long-term simulation of the current process was performed.

Methodology

The structure and almanac formats are defined in the official GPS document (ICD-GPS-870. 2013). Almanac is a subset of the ephemeris data and the clock data of satellites with reduced precision generated by the control sement of GPS and published by the United States Coast Guard (USCG). It comes in two formats: YUMA and SEM (System Effectiveness Model) (Specht, C., Skóra, M., Mania, M., Specht, M. 2014). The former is characterized by a clear structure containing the names of the epheeris parameters and their values for individual satellites. The latter takes the tabular form of descriptive information and is intended primarily as an input file to numerical processing. Angular values are differently expressed in both formats. The YUMA almanac's angular unit is radian, while in the

SEM it is the semicircle (π). In addition, the value of the inclination of the orbital plane to the celestial equator plane in YUMA format is given directly, while in the SEM it is only the angle of deviation from the nominal value of the angular inclination of 0.3 semicircle (55°).

The position of the satellite within its orbit is determined at the time of generating the almanac through six Keplerian parameters of undisturbed orbit. Two of them define the shape of the orbit (the square root of the semi-major axis $A^{1/2}$, and the first eccentricity e), another two are responsible for the orientation of the orbit relative to the Earth (right ascension of ascending node Ω_0 and the inclination i) and finally the last two inform about the satellite position in the orbital plane (argument of perigee ω and mean anomaly M_0) (Specht, C., Mania, M., Skóra, M., Specht, M. 2015). In order to determine the postion at a different moment of time an additional parameter of rate of right ascension of ascending node is used. The calculation process that is presented in the GPS interface specification (IS-GPS-200. 2006) should be carried out with the values of corrections to the ephemeris parameters of zero. It is assumed that the position of the satellite computed from an almanac is valid and without major mistakes for about 30 days, but it is advisable to use current constellation data (Specht, C. 2007).

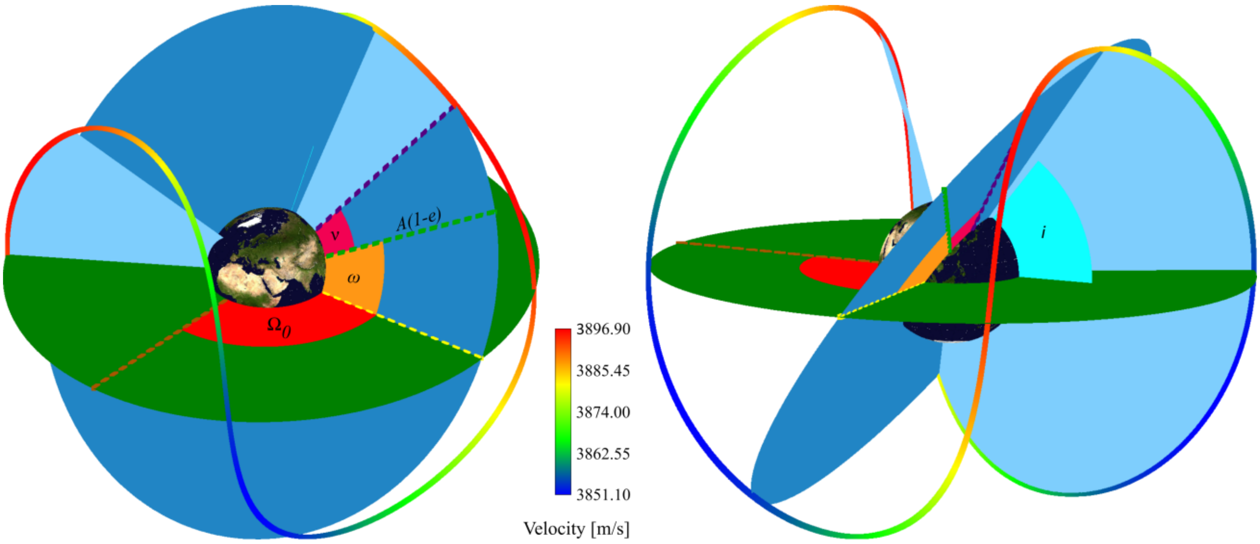

Fig. 1. - Visualization of Keplerian orbital parameters and location of GPS satellite with along-track velocity parameter (Source: own study).

The figure 1 presents six Keplerian parameters of undisturbed satellite orbit: four angles (Ω_0, i, ω and mean anomaly derivative - true anomaly v) and, marked in green, distance to the perigee equal to $A(1-e)$ binding orbital shape parameters ($A^{1/2}$ and e). The brown color line indicates the intersection of the Greenwich meridian plane with the shown in green color celestial equator plane. The other two lines are the direction to the acending node (yellow color) and the satellites radius vector (purple color). Additional description is required for orbital planes presented in two shades of blue. The darker blue color applies to the satellite orbital plane in the eart centered inetial coordinate system (ECI), while the lighter blue is for earth-centered earth-fixed coordinates (ECEF). Mentioned as the second one – the visualization of the ECEF orbital plane, for the clarity of the figure, was included only for the half of the single satellite orbital circulation (fourth part of the daily orbital period around the Earth from the detemined the position the GPS satellite). The last element incorporated in figure 1 is a satellite flight route in gecentric coordinate system (ECEF) with parameter informing about the instantaneous velocity of the satellite.

The parameters responsible for the orientation of the orbit are the angles of right ascension of the ascending node and inclination of the orbit to the plane of the celestial equator. The nominal value of the inclination angle is strictly defined at 55º with the operational range of 3º (SPS. 2008) for each of the six orbital planes of the GPS system. Changing the position of the orbit ascending node is caused by Earth's rotation. In order to calculate the instantanous satellite position in a given time interval from the moment of generation of the almanac, it is necessary to take acount of two factors. The first one is the value of the right ascension of the ascending node defined as a function of time indvidually for each satellite of the system, and the other is the angular velocity of the Earth (WGS 84. 2001).

Practical implementation

The aim of the study was to determine the position of GPS satellites and their orbits along with the determintion of their mutual angular deviations within a single orbital plane. For this purpose, the almanac generated on the 147456th second of 902nd GPS week (2nd cycle) was analyzed. The moment of time corresponds to the 4:57:36 p.m. on December 5th, 2016 r. of UTC time. On the day of generation of the almanac, on the orbits there were 12 Block IIR satellites, 7 Block IIR-M satellites and 12 block IIF satellites. Four satellites circled in the orbital plane A, five satellites in planes B, C, D and six in the planes E and F. Satellite PRN20 circulating in the orbital planet E is asigned to the orbital plane B due to limitations in the official nomenclature of the GPS system.

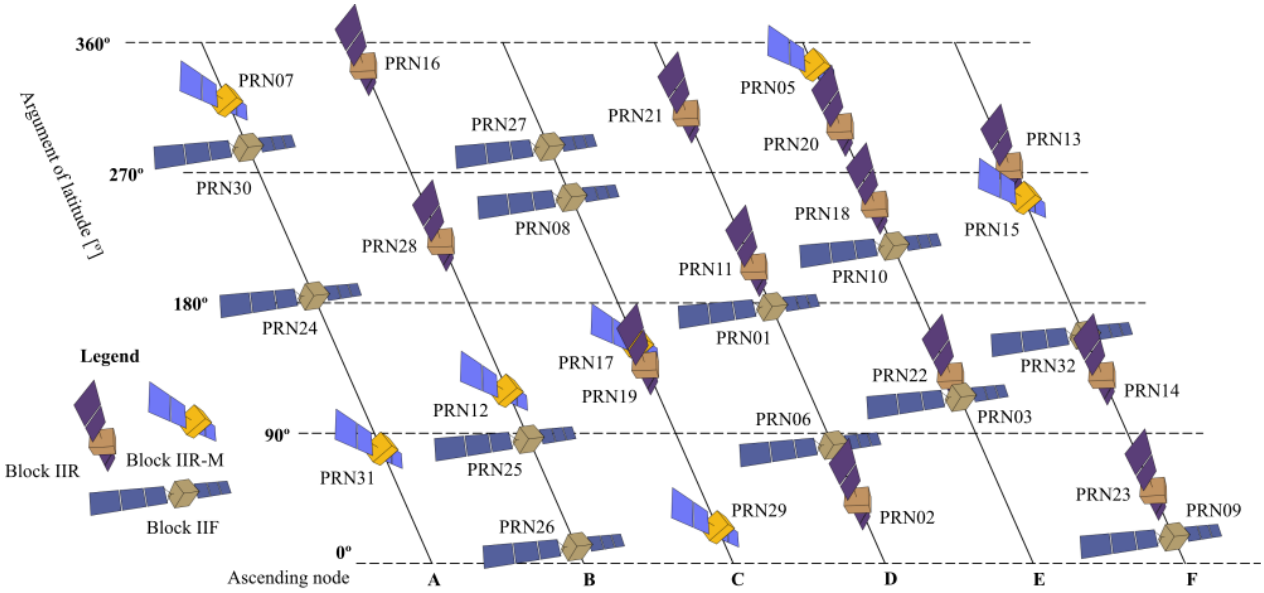

Fig. 2. – GPS satellite constellation in the almanac generation moment of time
(Source: own study).

The analysis of the shape of the GPS constellation was narrowed down to several factors. The first of these was right ascension of the ascending node of the orbit, which takes similar values for the satellites circulating in the same obital plane of the GPS system. Furthermore, closely related to the previous parameter, rate of right ascension of the ascending node, and the inclination of the orbit to the plane of the celestial equator were checked. Preliminary analyses were carried out visually in the generated three-dimensional model of the constellation, which was created on the basis of proprietary numerical algorithm.

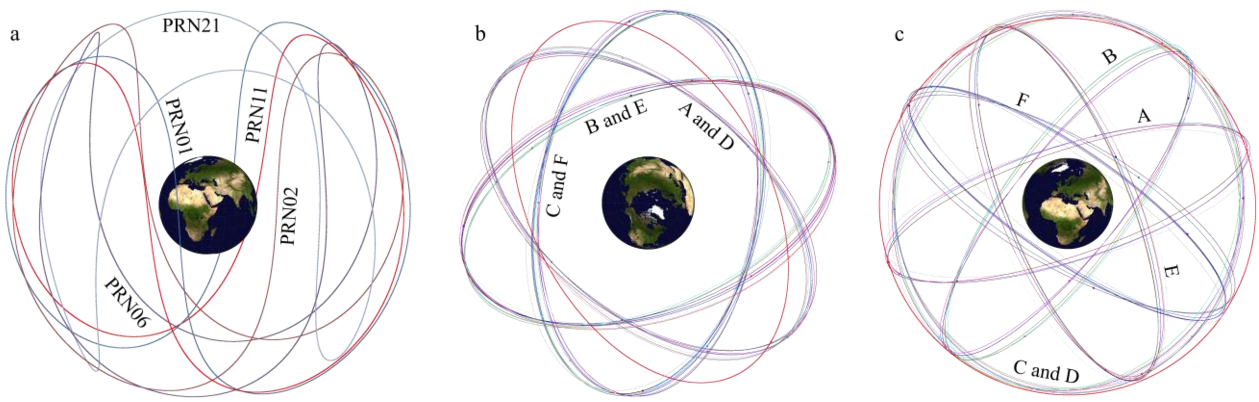

Fig. 3. - The ECEF orbits of the orbital plane D GPS satellites (a) and the ECI orbits of the GPS orbital planes in top (b) and isometric view (c) at the time of generating the almanac
(Source: own study).

Reaching the conclusions about the occurrence of anomalies in the GPS satellites circulation basing on the ECEF coordinates only is difficult. Such coordinate system finds greater use in presentation the flight tracks of satelites relative to the surface of the Earth (figure 3a.). The better visual representation of the orbit for analysis of the convergence of the proper orbital plane is inertial coordinate system (ECI) oriented with respect to the vernal equinox (figure 3b and 3c). Particularly noteworthy is orbit of the PRN11 GPS satellite, marked with red. The central part of the figure 3 presents clearly the separation of its orbit from the others, grouped in the orbital planes A, B, C, D, E and F.

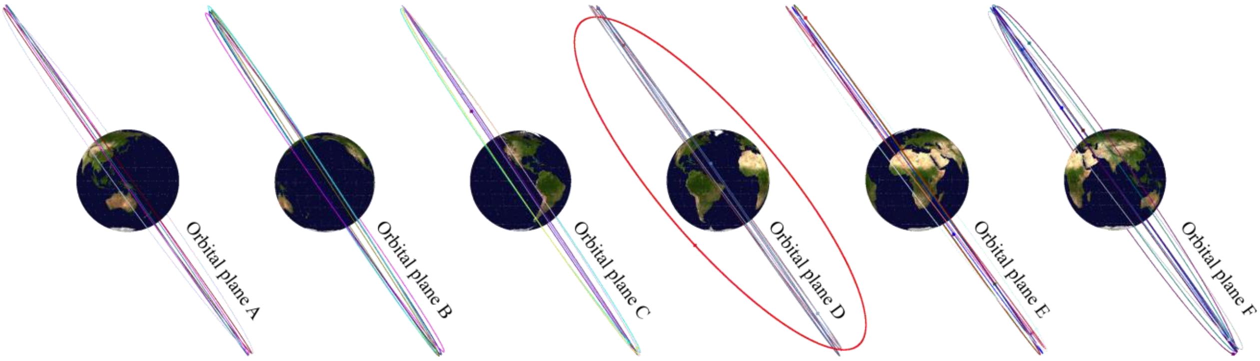

Fig. 4. - The orbits of GPS satellites in the inertial coordinate system (ECI) grouped according to the orbital planes at the time of generation of the almanac (Source: own study).

Confirmation of the fact of separation was found in the almanac. The values of right ascension of ascending node and rate of right ascension of ascending node for the PRN11 GPS satellite differs significantly from the other satellites of orbital plane D. PRN11 GPS satellite was launched on October 7th, 1999 and started its mission less than three months later - on January 3rd, 2000. It is a block IIR satellite. The letter R is for replenishment and replacement. The first launch of block IIR satellite took place on July 23rd, 1997. The designed lifespan for the satellites of the block IIR is 10 years (Hofmann-Wellenhof, B., Lichtenegger H., Wasle E. 2008). Therefore, the investigated satellite has exceeded this period by about 69%. In the upcoming modernization of the GPS space segment of the new block III satellites, the PRN11 unit can be expected as one of the first ones to be replaced.

The second stage of the study was to analyze the GPS system almanacs from the moment of launch of the PRN11 GPS satellite to date. For this purpose two almanacs per year since 2000 were acquired. Data set consisted of 32 files. From each almanac the following parameters were selected: PRN identifier, right ascension of ascending node, rate of right ascension of ascending node and the GPS week number. On that basis the magnitude of the trend of PRN11 ascending node separation from orbital plane D was determined.

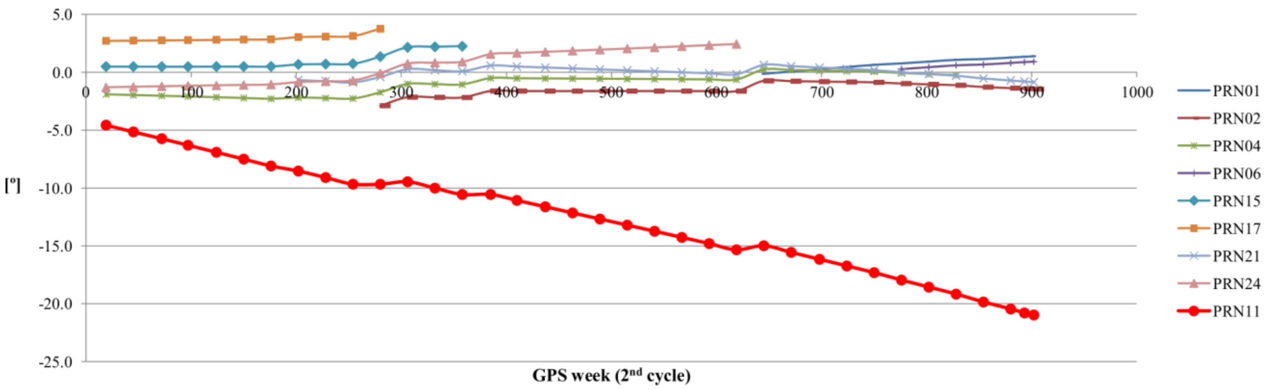

Fig. 5. – Difference in right ascension of ascending node of orbital plane D GPS satellites (Source: own study).

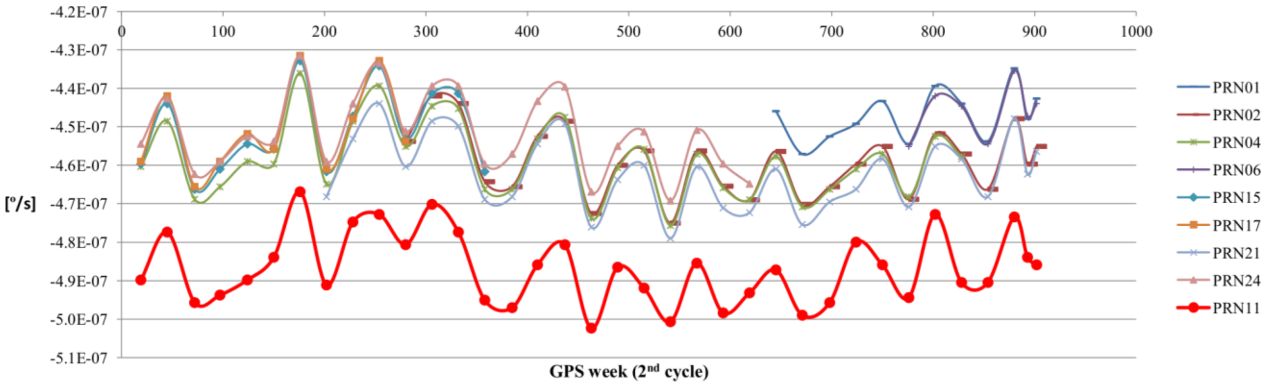

Fig. 6. - Rate of right ascension of ascending node of orbital plane D GPS satellites
(Source: own study).

Figures 5 and 6 confirm the fact of PRN11 GPS satellite orbit separation from orbits of other orbital plane D satellites. Increasing distancing of the the ascending node from the mean position for the orbital plane (figure 5) is clearly noticeable. What is more, the rate of right ascension of ascending node parameter takes a value of approximately 6.8% higher than other satellites (figure 6) from the very moment of placing the PRN11 satellite in the orbit. The general trend in the right ascension of ascending node is close to the functional dependency and clearly corresponds to its derivative - the rate of right ascension of ascending node.

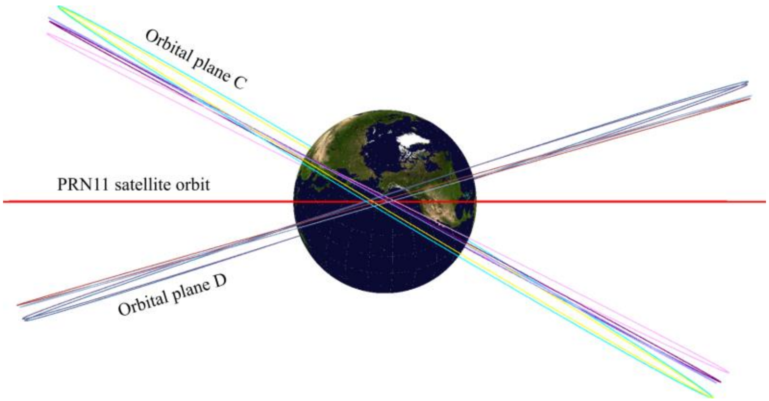

Fig. 7. - Position of the PRN11 GPS satellite orbit relative to the other orbital planes C and D satellites
(Source: own study).

During the nearly 17 years of the PRN11 satellite mission its orbit separated 21° from the home obital plane D. This is approximately the third part of the nominal angular separation of GPS orbital planes (figure 7) (Januszewski, J. 2006). Assuming a mean values of right ascension of ascending node as a determinant of the orbital planes positions, the PRN11 satellite would need additional 29 years to reach orbital plane C. Considering actual status of the GPS constellation shifting the plane would not cause eventual collision with another satellite.The argument of latitude parameter values of the newcomer and orbital plane C satellites: PRN08 and PRN17 determines that the PRN11 satellite would place almost perfectly between the closest potential neighbours (53% of PRN17-PRN08 angular orbit distance).

Conclusions

The paper presents the current status of the GPS system constellation. The main emphasis was placed on the isue of satellite orbits and their convergence with respect to their home orbital planes A, B, C, D, E and F. There is a significant deviation of the PRN11 satellite orbit relative to the orbital plane D, to which it is assigned. As a result of analysis of almanacs from the moment of launch of the satellite, a regular orbital plane deviation trend towards the orbital plane C was stated. At present, the PRN11 satellite orbit has declined about an angle of the third of the nominal 60º separation angle between GPS system orbital planes.

Maintaining the current trend, the satellite would need 29 years to shift its orbit to the adjacent orbital plane C. This seems unlikely because of the significant exceeding of the block IIR satellite design lifespan and the announced near future modernization of the space segment of the new block III satellites. However, the question of the cause of the regular excessive shift of the ascending node of the PRN11 satellite orbit seems justified. The hpothesis worth considering is imprecise satellites placement into the orbit, which would be the first or one of very few accidents of this type noted in history of space missions.

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