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PRECISE POINT POSITIONING ANALYSIS FOR LOW EARTH ORBIT SATELLITES

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ABSTRACT

Precise point positioning algorithm is developed for ground operations to improve position accuracy achieved by the satellite on-board GNSS receiver. Single and dual frequency GPS measurements in civil mode (C1, L1, L2, C2) are used for the orbit estimation. Main estimation algorithm is based on Unscented Kalman Filter (UKF). Non Linear Least Square (LSQ) method is used in data rejection and initial state calculation. The performance of the developed algorithm is tested by using GPS raw observations of various LEO satellites (GRACE-A, ICESAT) collected from their on board receivers and published openly. Estimation results are compared with the reference trajectories of these satellites that are also published openly.

INTRODUCTION

The Global Positioning System (GPS) is a satellite-based radio navigation system owned by the United States government and operated by the United States Space Force. The Space Segment nominally consists of 24 satellites orbiting at an altitude of approximately 20,200 km above the Earth's surface. The frequencies of GPS satellites originally designed to transmit carrier signals in two L-bands are L1 = 1575.42 MHz and L2 = 1227.60 MHz. Three categories of pseudorandom noise (PRN) ranging codes are designed, including the Coarse / Acquisition (C/A) code with a 1.023 MHz chip rate and a period of one millisecond, the precision (P) code with a 10.23 MHz chip rate and a period of seven days, and the Y-code used as a substitute for P-code when the anti-spoofing (A-S) mode is activated [Chai, C., 2009]. GPS provides geolocation / position and time information to a GPS receiver anywhere on Earth or in earth orbit where four or more GPS satellites have an unobstructed line of sight. The use of satellites in LEO with GNSS receivers are in geodesy, geodynamics, geoid updating, space weather monitoring, meteorology, etc. In addition to research in these fields, in some applications (Earth remote sensing, gravitational field, investigation of melting glaciers, etc.), LEO satellites' coordinates can be positioned with decimeter and even centimeter precision [Zhalilo, A., Yakovchenko, A., 2016]. Precise Point Positioning (PPP) is a method for obtaining the absolute

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position of a single GNSS receiver using carrier phase and pseudorange observations with high-precision IGS (International GNSS Service) products to achieve better accuracy than on board receiver solutions [Zumberge, 1997; Kouba, 2001]. In this work, a PPP algorithm is developed for ground software using GPS raw measurements in order to be used in satellite operations. In order to check accuracy of the estimation method, the results are compared with the reference ephemeris of various satellites (GRACE-A and ICESAT) obtained from on board receiver solutions.

METHOD

PPP is performed on-ground segments for satellite operations. On-board receivers use the ephemeris of GNSS satellites broadcasted in GNSS signals. PPP approach mainly uses on-board receiver's raw measurements and the precise ephemeris of the GNSS satellites made by international organizations (i.e. International GNSS Services) which is more accurate than broadcasted ephemeris. This post processing technique provides better position estimation accuracy compared with the on-board receiver's results. In developed PPP algorithm, the UKF is used as the main estimator and data rejection mechanisms are implemented by the help of LSQ and other calculated parameters. In following sections, the details of the force and measurements model and estimation algorithm are presented.

Force Model

The equations of motion for an Earth orbiting satellite are given by [Vallado D.A, 2001]

$$\dot{\boldsymbol{r}} = \boldsymbol{v} \tag{1}$$

$$\dot{\boldsymbol{v}} = \frac{-\boldsymbol{\mu}}{\boldsymbol{r}^3}\boldsymbol{r} + \boldsymbol{a}_{geo} + \boldsymbol{a}_{third-body} + \boldsymbol{a}_{drag} + \boldsymbol{a}_{SR} \tag{2}$$

where r and v are the position and velocity vectors in the inertial frame. a_{geo} is the geo-potential force due to the gravitational force of the Earth. $a_{third-body}$ is the lunar/ solar gravitational perturbation a_{drag} is the atmospheric drag force. a_{SR} is the force due to solar pressure on satellite. In current work, force model includes two-body, sun and moon gravity, gravitational potential up to 20th order, solar radiation acceleration model and atmospheric drag. All the equations of motion are numerically integrated by 6th order Symplectic integrator.

Measurement Model

The equations for pseudorange and phase pseudorange GPS measurements are given as;

$$\boldsymbol{\rho_C} = \boldsymbol{r} + \boldsymbol{c} * \boldsymbol{t_r} + I_P + \varepsilon_P \tag{3}$$

$$\boldsymbol{\rho_L} = \boldsymbol{r} + \boldsymbol{c} * \boldsymbol{t_r} - I_L + \boldsymbol{B} + \varepsilon_L \tag{4}$$

where $\boldsymbol{r}$ is geometric range between receiver and GPS satellites. $\boldsymbol{t_r}$ is the clock bias of the receiver. $\boldsymbol{I_P}$ and $\boldsymbol{I_L}$ is the ionospheric error term for pseudorange and phase measurements. $\boldsymbol{B}$ is the ambiguity of the carrier phase measurements. $\boldsymbol{\varepsilon_P}$ and $\boldsymbol{\varepsilon_L}$ are psuedorange and carrier phase measurement noises. $\boldsymbol{c}$ is the speed of light.

In this work, for pseudorange measurement, C1 signal is used in estimation process. For phase pseudorange measurements, L1 and L2 signals are selected in order to use the dual frequency techniques. Following measurement combination approach, shown in Eq. 5a, is used for PPP estimation algorithms for GRACEA satellite. Since there are negative values for phase pseudorange measurements of ICESAT satellite, Eq. 5b is used as measurement combination.

$$\boldsymbol{\rho} = 0.5 * (2.54\rho_{L1} - 1.54\rho_{L2}) + 0.25 * (\rho_{C1} + \rho_{L1}) \quad (5a)$$

$$\boldsymbol{\rho} = 0.5 * \rho_{C1}(t) + 0.25 * (\rho_{C1}(t) + (\rho_{L1}(t) - \rho_{L1}(t-1))/\Delta T) + 0.25 * (\rho_{C1}(t) + (\rho_{L2}(t) - \rho_{L2}(t-1))/\Delta T) \quad (5b)$$

This combination includes all L1, L2 phase and C1 pseudorange measurements with desired weight parameters. The main benefit of this combination is to reduce the ionospheric error term. Only civilian signals are used for this analysis since P1 and P2 pseudorange measurements are only available for military purpose.

Estimation Algorithm

An UKF is used as the estimator. The states involve satellite position and velocity along with the solar radiation pressure and drag coefficients, clock bias and clock drift parameters, empirical accelerations given in satellite based RSW coordinate system and measurement (phase ambiguity) biases for all tracked GNSS satellites [Monterbruck, 2008]. Clock bias and drift are propagated as follows;

$$\frac{\partial \boldsymbol{ct_r}}{\partial \boldsymbol{t}} = \boldsymbol{c\dot{t_r}} \qquad \frac{\partial \boldsymbol{c\dot{t_r}}}{\partial \boldsymbol{t}} = \boldsymbol{e(t)} \qquad \text{where} \quad \boldsymbol{e} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\sigma e_k}) \quad (6)$$

empirical accelerations propagation is taken as [Monterbruck, 2008] and propagated with an exponential damping factor as follows;

$$\boldsymbol{m_{R,S,W}} = \boldsymbol{e}^{-(\boldsymbol{t_i}-\boldsymbol{t_{i-1}})/\boldsymbol{\tau}} \quad (7)$$

measurement biases are propagated as follows;

$$\frac{\partial \boldsymbol{b}}{\partial \boldsymbol{t}} = \boldsymbol{e_b(t)} \begin{bmatrix} \mathbf{1} \\ \vdots \\ \mathbf{1} \end{bmatrix}_{\boldsymbol{nx1}} \qquad \text{where} \quad \boldsymbol{b} = [\boldsymbol{B_1} \dots \boldsymbol{B_n}] \quad \boldsymbol{e} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\sigma e_b}) \quad (8)$$

Initial satellite position and velocity values along with clock bias is calculated using nonlinear LSQ with the first measurement set. Default values are given to measurement biases and other augmented parameters.

As the tracked GNSS satellites change, measurement bias values and their covariance for the newly tracked GNSS satellites are reset to a default value. If bad GNSS measurements exist, data rejection is performed and the predicted state is used as the estimation for that sampling time. Some control parameters are checked and UKF estimation is compared with a nonlinear LSQ estimation at every sampling time for the data rejection. Deviation between the estimated satellite positions found by UKF and LSQ are checked against a threshold. At every step UKF measurement residual (innovation) is checked whether or not exceeds a threshold. Also difference between every predicted and the actual measurement belonging to each tracked GNSS satellite are checked. According to these checks, data rejection is performed.

If bad measurement values exist during long sampling periods, data rejection is done continuously and after some time even though measurements are get better, data rejection cannot be stopped due to increased UKF prediction errors from the correct satellite position. To prevent this, some of number of past innovation values are taken. The oldest innovation value in this list is checked against the other innovations in the list and number of innovations, which have lower values than the oldest innovation, is calculated. If this number is greater than a threshold, data rejection is stopped even though other parameters indicate a data rejection.

The overall estimation process is summarized in Figure 1.

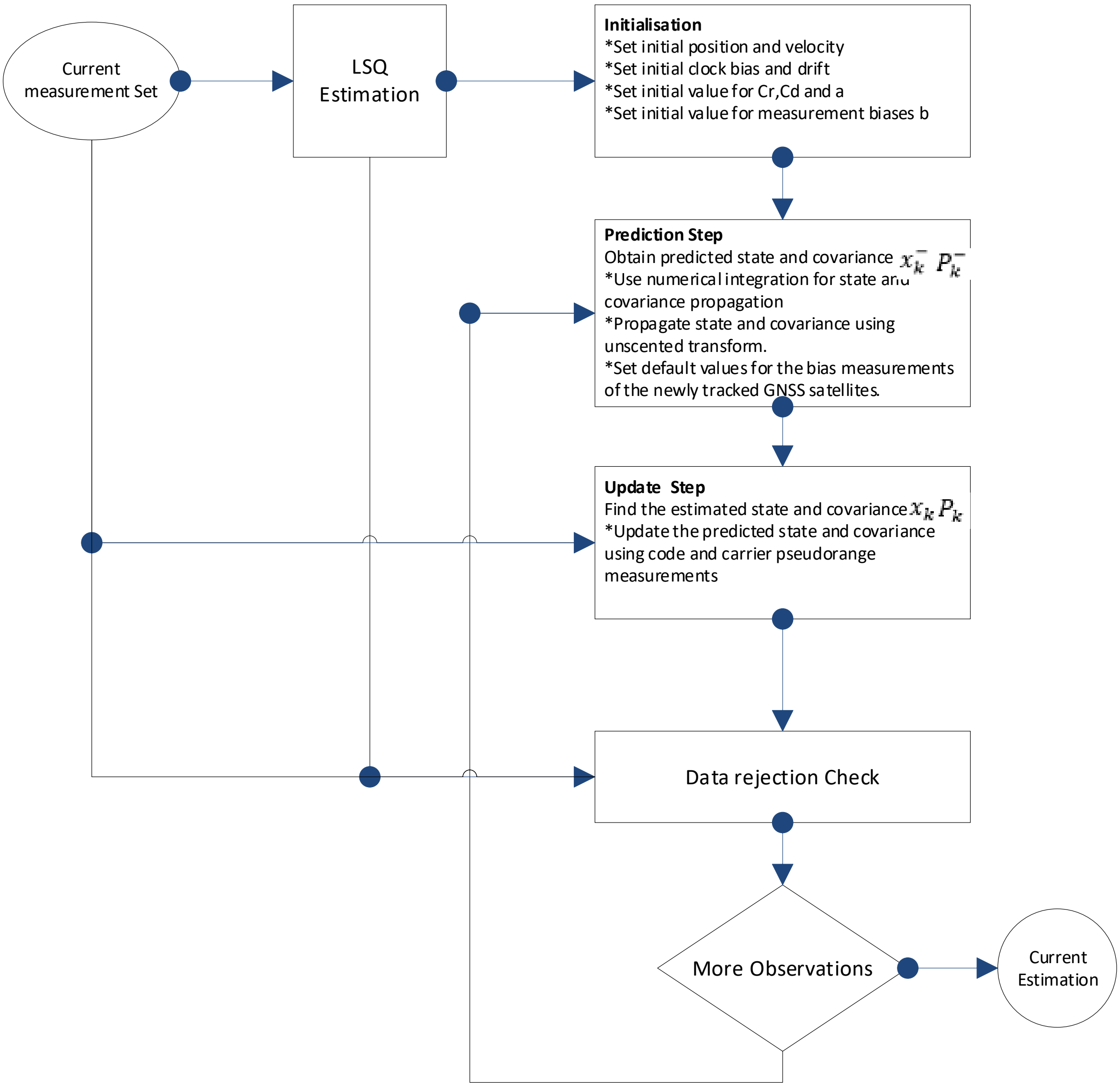

Figure 1: Overall Estimation Process

RESULTS

In numerical analysis, in order to simulate on-board receiver estimation results, the broadcast ephemeris (nav) for GPS satellites is used along with Grace-A raw GPS measurements for position estimation. In PPP method, the precise ephemeris (sp3) for GPS satellites is used in estimation process. After that, Grace-A and ICESAT ephemeris are calculated using broadcast and precise ephemeris and position estimation errors are calculated according to the reference ephemeris of Grace-A and ICESAT.

For Grace-A case, total measurement duration is about 12 hour and measurement sampling is 10 seconds. Reference trajectory for Grace-A satellite is taken from open sources in order to check performance of the PPP algorithm. In Figure 2, PPP method's position accuracy mostly less than 2.5 meter. It is clearly seen that PPP method outperforms the broadcast ephemeris's results. Data rejection approach in PPP method works well for Grace-A data since almost there is no outlier during 12-hour estimation process.

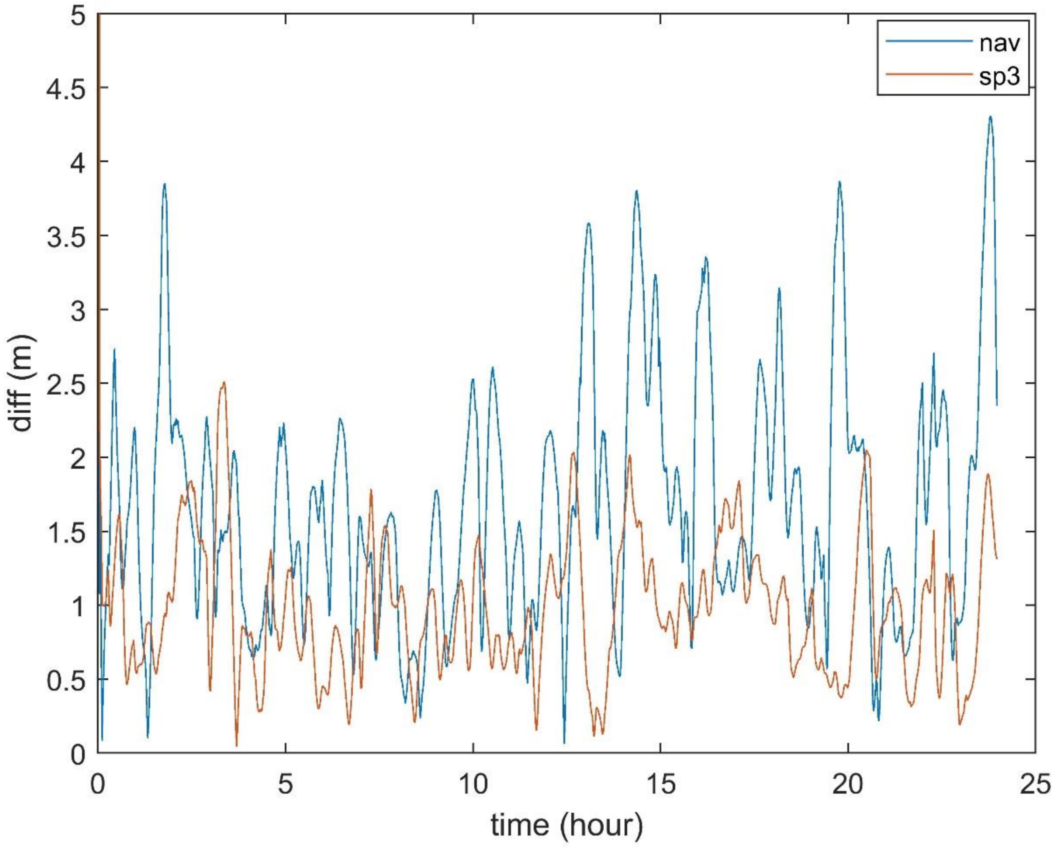

Figure 2*:* 3D Position error by comparing reference PVTs with PPP using Broadcast and Precise Ephemeris for GRACEA satellite

Similar analysis is repeated with ICESAT satellite raw GPS measurements data. Broadcast (nav) and precise (sp3) GPS measurements are taken from open sources similar to Grace-A satellite. Measurement duration is around one day with a sampling frequency once a second. In Figure 3, it is seen that there are lots of outlier for both sp3 and nav solution. We apply similar PPP approach to ICESAT data as discussed previously. Although PPP accuracy is better than onboard accuracy, PPP method's accuracy for ICESAT is worse than Grace-A case. Since negative phase pseudorange measurements values exist for ICESAT, better measurement combination can used to avoid this. Data rejection mechanism can also be improved. Better filter parameter selections such as measurement covariance can affect the performance. Also measurements taken from ICESAT may include some erroneous data.

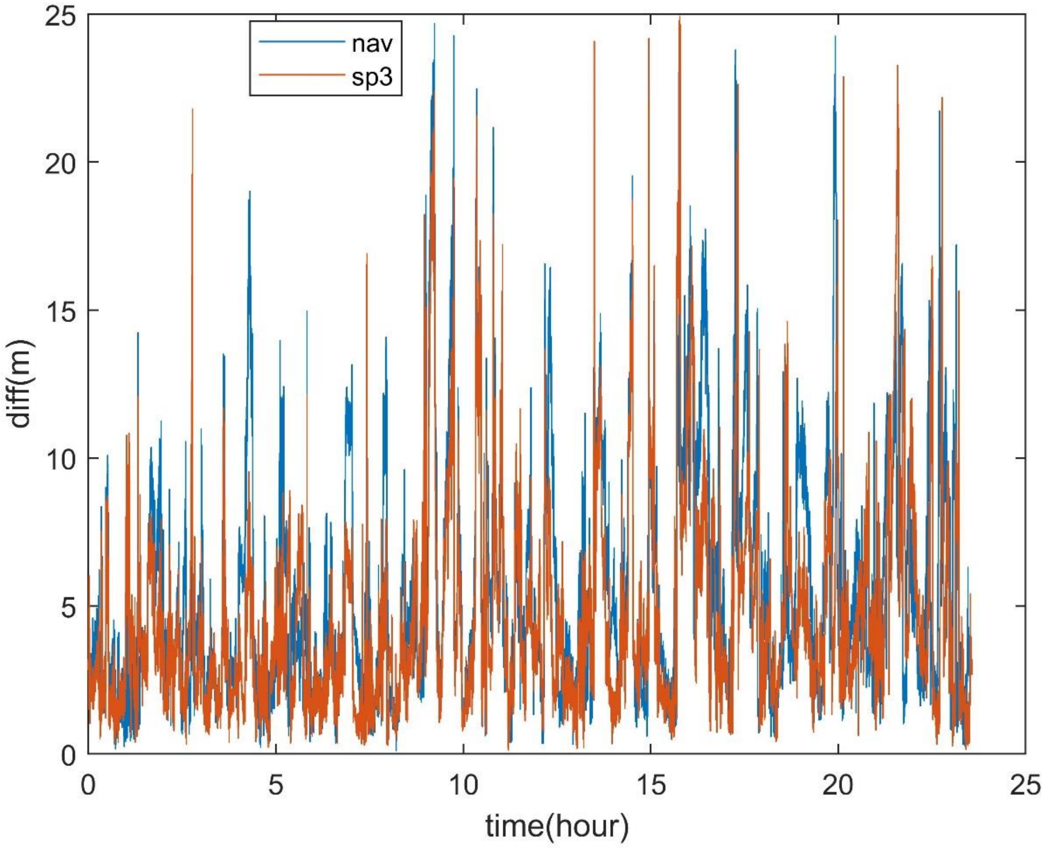

Figure 3*:* 3D Position error by comparing reference PVTs with PPP using Broadcast and Precise Ephemeris for ICESAT satellite.

The average position error of PPP method is around 1.2 and 4.6 meters while standard broadcast results are around 2 and 5.5 meters for Grace-A and ICESAT satellites respectively.

CONCLUSION

In this work, PPP method with precise ephemeris is compared to broadcast ephemeris results. Various data rejection mechanisms are also applied to remove measurement outliners. PPP method achieve better accuracy than broadcast results. As a future work, PPP method should be tested with different satellite data. Filter parameters should be better tuned for tested satellites to obtain more stable and consistent results. Data rejection mechanism may also be improved in order to remove outliers more consistently when applied to different satellite measurements. PPP method is developed for satellite ground operations. Therefore, more test will be performed to check its operation availability.

References

Chai C. (2009) *Precise Point Positioning Using Dual-Frequency GPS and GLONASS Measurements*, Department of Geomatics Engineering Calgary, Alberta, 2009.

Kouba J., Héroux, P. (2001) *Precise Point Positioning Using IGS Orbit and Clock Products.* GPS Solution, Vol.5, p: 12–28, 2001

Montenbruck O., Ramos-Bosch P. (2008) *Precision real-time navigation of LEO satellites using global positioning system measurements*, GPS solution, Vol. 12, p: 187:198, 2008

Vallado D.A. (2001) *Fundamentals of Astrodynamics and Applications*, 2nd ed., Kluwer Academic Pub., Netherlands, 2001.

Zhalilo A., Yakovchenko A., (2016) *PPP-Method Realization for Low Earth Orbit Satellite Trajectory Determination Using On-Board GPS-Observations*, Information and Controlling System, Vol.5, p: 33-40, 2016.

Zumberge J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., Webb, F.H. (2001) *Precise point positioning for the efficient and robust analysis of GPS data from large networks*. J. Geophys. Res. Biogeosci., Vol. 102, p: 5005–5017, 2001