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SHORT ARCS ORBIT DETERMINATION USING GPS

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Abstract. *This work is concerned with orbit determination using GPS signals. An especial case of truncated arcs assuming that GPS receiver data, which is available only when the satellite carrying the receiver flies over a ground tracking station, is the main issue. To analyse the behaviour of an Extended Kalman filter (EKF) in real time satellite orbit determination using short arcs of data, the algorithm developed by [1] is used. This algorithm is a simplified and compact model with low computational cost. It uses the EKF to estimate the state vector, composed of the position and velocity components, bias, drift, and drift rate of the GPS receiver clock. Also, the algorithm may use a large 10 or 30 seconds step-size of propagation time between GPS signal measurements. Its force model in the equations of motion considered the perturbations due to the geopotential up to order and degree 10 of the spherical harmonics. Its state error covariance matrix was computed through the transition matrix, which is calculated analytically in an optimised way [2]. This algorithm has been formerly qualified using the raw single frequency pseudorange GPS measurements of the Topex/Poseidon (T/P) satellite as observations by the Kalman Filter, and for this reason, is used as reference in this work. However, these real data are truncated as if they had been collected by the tracking and control station of INPE in Cuiabá, Brazil. That is, the data are obtained only when the satellite T/P is in the viewing area of the Cuiaba Brazilian station. The behaviour of the Kalman filter is analysed under such premises. The results of research are presented showing the degradation of performance when compared to the full arc orbit determination.*

1 INTRODUTION

The orbit determination process consists of obtaining values of the parameters that completely specify the motion of an orbiting body, like artificial satellites, based on a set of observations of the body. The observation may be obtained from the ground station networks using laser, radar, Doppler, and so forth, or by space navigation systems, as the Global Positioning System (GPS). The choice of the tracking system depends on a trade-off between the goals of the mission and the tools available. The GPS has been used to determine the position, velocity, and time with high accuracy of an artificial satellite.

The GPS may provide orbit determination with accuracy at least as good as methods using ground-tracking networks. The advantages of using GPS are global coverage, high precision, low cost, and autonomous navigation resources. The ground-tracking networks provide standard precision around hundred meters and the former can provide precision as tight as some centimetres.

The GPS provides, at a given instant, a set of many redundant measurements, which makes the orbit position observable geometrically. It allows the receiver to determine its position and time geometrically anywhere at any instant with data from at least four satellites. The principle of navigation by satellites is based in sending signals and data from the GPS satellites to a receiver that is inside the satellite that needs to have its orbit determined. This receiver measures the travel time of the signal and then calculates the distance between the receiver and the GPS satellite. If the clocks are synchronized, measurements from three GPS satellites are enough to obtain its position. If the clocks are not synchronized, four measurements are required.

The artificial satellites, such as Extreme Ultraviolet Explorer (EUVE) [3]; Topex/Poseidon (T/P) [5]; MicroLab-1 [6]; Bispectral Infrared Detection Mission (BIRD) [7]; EOS ICESat [8], Jason I and II [9-11], CHAMP [12, 13], GRACE [14, 15] and KOMPSAT [16, 17], have onboard GPS receiver used to determine their orbits.

In spite of the GPS providing precision as tight as some centimetres and the ground-tracking networks providing standard precision around hundred meters, INPE still uses ground station networks to determine and to control the orbit of its artificial satellites, such as SCD1 [18, 19], SCD2 [20, 21], CBERS-1 [22], and CBERS-2 [23].

So, in this work, the man idea is to simulate the monitoring of an artificial satellite, which uses GPS receiver onboard, by the tracking and control station located in Cuiabá, Brazil, of the National Institute of Space Research (INPE). The observation data are generated only when the satellite is in the viewing area of the Brazilian station and it will be used an algorithm to determine onboard the orbit in real-time using the GPS system and Kalman filtering as method of estimation. The behaviour of the Kalman filter is analysed. The results of research are presented.

2 THE INPE GROUND STATION NETWORKS

INPE main headquarter is located in São José dos Campos, and there are seven more units in the Brazilian territory, located in the following cities: Cachoeira Paulista, Cuiabá, Natal, São Paulo, Brasília, Atibaia, and Santa Maria. In addition to these units, there are customer service of satellite images in São Luís, Eusebius, São Martinho da Serra and Santa Maria as you can see in Figure 1 [24].

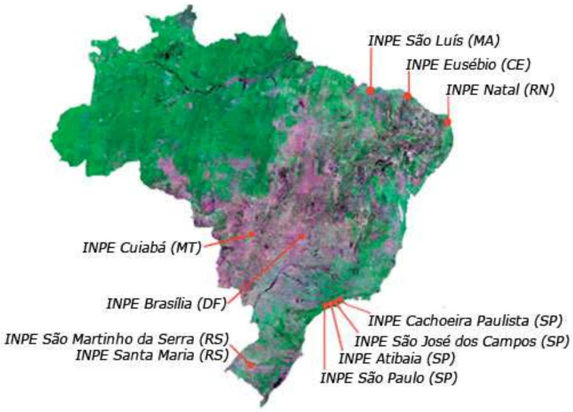

Figure 1 - Brazil Map

The ground tracking system of INPE is named Satellite Tracking and Control Centre (CRC) and it was developed to control the satellites and their functional structure. This centre is composed of the Satellite Control Centre (SCC), located in São José dos Campos-Brazil, and two S-Band ground stations, Cuiabá (23° 12' S; 45° 51'W) and Alcântara (2° 20' S; 44° 24'W) [22].

The geographical location of the station of Cuiabá, close to the geometric centre of South America, allows the coverage of most of Brazilian territory and much of the territory of the South America. Alcântara ground station is located in the neighbourhood of the Alcântara Launching Centre, it can track satellites launched from this site since its orbit injection.

The ground stations are linked by a Data Communication Network, which is called RECDAS. Cuiabá is the only one equipped with a receiver of Data Collecting Platforms (DCP) being also the data receiving station of the SCD1 and SCD2 satellites payload. The ground station hosts a copy of the SCC real time software. This feature added robustness to the INPE's ground control system, since it makes the ground stations able to replace the SCC in contingency cases. Besides, it allowed reducing the number of satellite controllers in about 50%, by transferring to the Cuiabá ground station all the satellite operation activities during periods of vacations, free days or eventual absences of SCC personnel. The SCC performs orbit determinations based on tracking data of type "ranging" and Doppler [22].

3 DESCRIPTION OF THE USED ALGORITHM

In this work, the algorithm developed by [1] is used to determine onboard the satellite orbit in real-time using the GPS system and Kalman filtering as method of estimation. The following factors were considered in this algorithm: generality, orbit accuracy, and computational cost for orbit determination in a real-time and onboard environment. Therefore, the algorithm is a simplified and compact model with low computational cost.

The simplified force model was adopted considering only forces due to the Earth gravitational field. The considered harmonic coefficients of the Earth geopotential field were set up to order and degree 10 of JGM-2 model, according to studies developed in [3], without overloading the processing time. The acceleration and the related partial derivatives matrices were computed through the recurrence relations, according to [25], in Earth-fixed (EF) coordinates. The coordinate transformation from True of Date (ToD) to Pseudo-Earth fixed equator and prime meridian (PEF) took into account the Earth sidereal rotation, but the polar motion was neglected. The integration of the satellite motion equation was carried out using the simple 4th order of the Runge-Kutta (RK4) algorithm. It was implemented without any mechanism of step adjustment or error control. An initialization procedure is not necessary and the step size is quite easy to change.

The Extended Kalman filter (EKF) was used to estimate the state vector, composed of the position and velocity components, bias, drift, and drift rate of the GPS receiver clock. The state error covariance matrix was computed through the transition matrix, which was calculated analytically in an optimized way [2].

The raw single frequency pseudorange GPS measurements were used as observations by the Kalman filter. They were modeled taking into account most of the GPS satellite and receiver clock offsets.

To analyse the developed algorithm, Chiaradia et. al. [1] used the Topex/Poseidon satellite (T/P) data, because it carried a dual frequency receiver GPS on board experimentally to test the ability of the GPS to provide precise orbit determination (POD). The satellite orbit was estimated using the developed algorithm with a good accuracy and minimum computational cost.

4 SIMULATIONS OF SHORT ARCS

The T/P spacecraft orbits the Earth at an altitude of 1336 km, inclination of 66°, and near-zero eccentricity. The period of the orbit is 1.87 hr. The satellite orbit must be determined with an RMS radial accuracy of 13 cm. This is an extremely stringent accuracy requirement for a satellite of this shape and altitude. This satellite carries a dual frequency receiver GPS onboard to experimentally test the ability of the GPS to provide Precise Orbit Determination (POD). The T/P GPS receiver can track up to six GPS satellites at once in both frequencies if antispoofing is inactive [5].

As the used algorithm to determine an artificial satellite has been qualified using the raw single frequency pseudorange GPS measurements of the T/P satellite as observations, the same data are used as reference in this work. However, these real data are simulated as if they had been collected by the tracking and control station of INPE in Cuiabá, Brazil. That is, the data are obtained only when the satellite T/P is in the viewing area of the Cuiabá Brazilian station.

So, as the range of the Cuiabá ground station is 4,300km, the T/P is visible to Cuiabá during short arcs, showed in Figure 2.

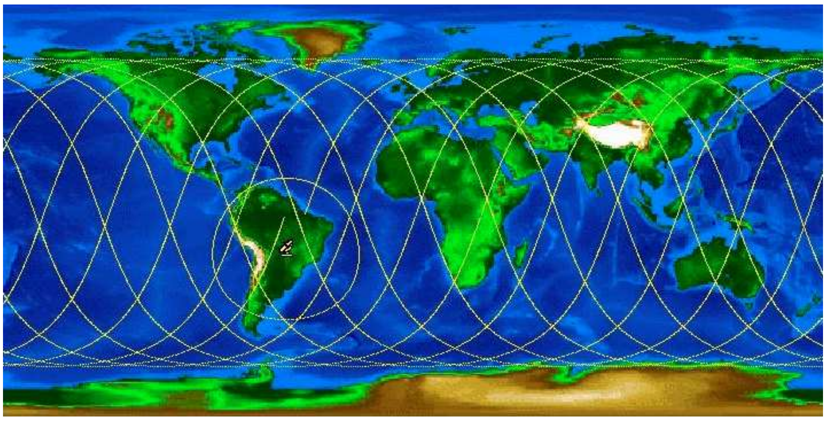

Figure 2 – Simulation of T/P orbit

Chiaradia et. al. [1] used T/P observation data for two days with SA (Select Availability) off, 11/18/1993 and 11/19/1993. Therefore, the two days are simulated as they have been monitored by Cuiabá ground station. The period of visibility of T/P is shown in Table 1 for two days. In first day (11/18/1993), there are four visible short arcs and, in the second day (11/19/1993), there are five.

11/18/1993			**11/19/1993**		
Short Arcs	**Beginning (hh mm ss.s)**	**End (hh mm ss.s)**	**Short Arcs**	**Beginning (hh mm ss.s)**	**End (hh mm ss.s)**
1	01 43 59.0	01 55 54.0	1	00 07 51.0	00 26 36.0
2	12 06 20.0	12 24 29.0	2	10 39 08.0	10 46 23.0
3	14 03 05.0	14 19 27.0	3	12 28 23.0	12 47 23.0
4	22 13 46.0	22 28 27.0	4	14 28 04.0	14 40 24.0
			5	22 35 14.0	22 52 45.0

Table 1 – Visible short arcs

5 USED DATA

In [1], the following files were used and they also are used in this work: the T/P observation files that broadcast the code and carrier pseudorange measurements in two frequencies in 10-second GPS time steps and are provided by the GPS Data Processing Facility of the Jet Propulsion Laboratory (JPL) in Rinex format; the T/P Precise Orbit Ephemeris (POE) files that are generated by JPL; and the broadcast GPS navigation message file in Rinex format provided by Crustal Dynamics Data Information System (CDDIS) of the Goddard Space Flight Center (GSFC).

It is important to remind that the T/P-POE estimated the T/P position with accuracy better than 15 cm and the states are provided in one minute UTC time steps in ToD system. The T/P GPS measurements are provided in 10 seconds of GPS time. According to International Earth Rotation Service (IERS), the difference between the UTC and GPS times is approximately an integer number of seconds, increasing timely with the introduction of leap seconds. For example, the difference is 9 seconds for 1993 [26].

In [1], the states were interpolated through an interpolation (Polint) subroutine [27], because they were estimated in 30-second intervals in UTC time with transmission and reception time corrections and these data instants were not coincident. The mean error of the interpolated states was 0.068 m and 2.5×10^{-4} m/s for position and velocity, respectively, which did not add any significant bias to the accuracy evaluation of the results.

As well as in [1]. the real position error is given by:

$$\Delta\mathbf{r} \equiv \left[\sum_{i=1}^{3}\left(x_i - \hat{x}_i\right)^2\right]^{\frac{1}{2}} \tag{1}$$

where x_i and $\hat{x}_i$, i = 1,2,3, are the reference components (or real) and estimated position vectors, respectively. The estimated position error is given by:

$$\Delta\hat{\mathbf{r}} = \left[\sum_{i=1}^{3}\mathbf{P}_{ii}\right]^{\frac{1}{2}} \tag{2}$$

where $\mathbf{P}_{\mathbf{ii}}$, i = *1,2,3,* represents the values of the diagonal elements of the state covariance matrix of the estimated position. The real velocity error is given by:

$$\Delta\mathbf{v} \equiv \left[\sum_{i=4}^{6} \left(x_i - \hat{x}_i \right)^2 \right]^{\frac{1}{2}} \tag{3}$$

where x_i and $\hat{x}_i$, i = 4,5,6, are the components of the reference (or real) and estimated velocity vectors, respectively. The estimated velocity error is given by:

$$\Delta\hat{\mathbf{v}} = \left[\sum_{i=4}^{6} \mathbf{P}_{ii} \right]^{\frac{1}{2}} \tag{4}$$

where $\mathbf{P_{ii}}$, $i = 4,5,6$, represents the values of the diagonal elements of the state covariance matrix of the estimated velocity. And, the residual is given by:

$$\Delta\boldsymbol{\rho} = \mathbf{z} - \boldsymbol{\rho}_c \tag{5}$$

where $\mathbf{z}$ e $\boldsymbol{\rho}_c$ are the observed and calculated pseudorange measurements, respectively.

Chiaradia et. al. [1] noted that, for two days tested, the real position and velocity errors are less than the estimated position and velocity errors by the filter. In two cases, the filtering took around one hour to converge. Before achieving the convergence, the onboard computer can use the GPS navigation solution provided by GPS receiver with 100-meter position error. Table 2 shows the obtained results by [1]

DATE	**Δr (m)**	**Δv (m)**	**RESIDUALS (m)**
11/18/1993	15.5 ± 6.8	0.014 ± 0.006	0.027 ± 13.2
11/19/1993	17.4 ± 6.7	0.016 ± 0.006	-0.130 ± 13.4

Table 2 – Results obtained by [1].

On November 18th and 19th, 1993, the SA is off and the standard deviation of the residuals is around 13.3 m.

6 SIMULATIONS

The data of short arcs for two days are simulated using algorithm developed by [1] obtaining the following results. Some adjusts have been done in Kalman filter initial conditions. Figure 3 shows the position and velocity errors throughout the entire day with the four short arcs for the first day. Figure 4 shows the position and velocity errors throughout the entire day with the five short arcs for the second day. The circles, in Figures 3 and 4, show error in position and in velocity for each short arc.

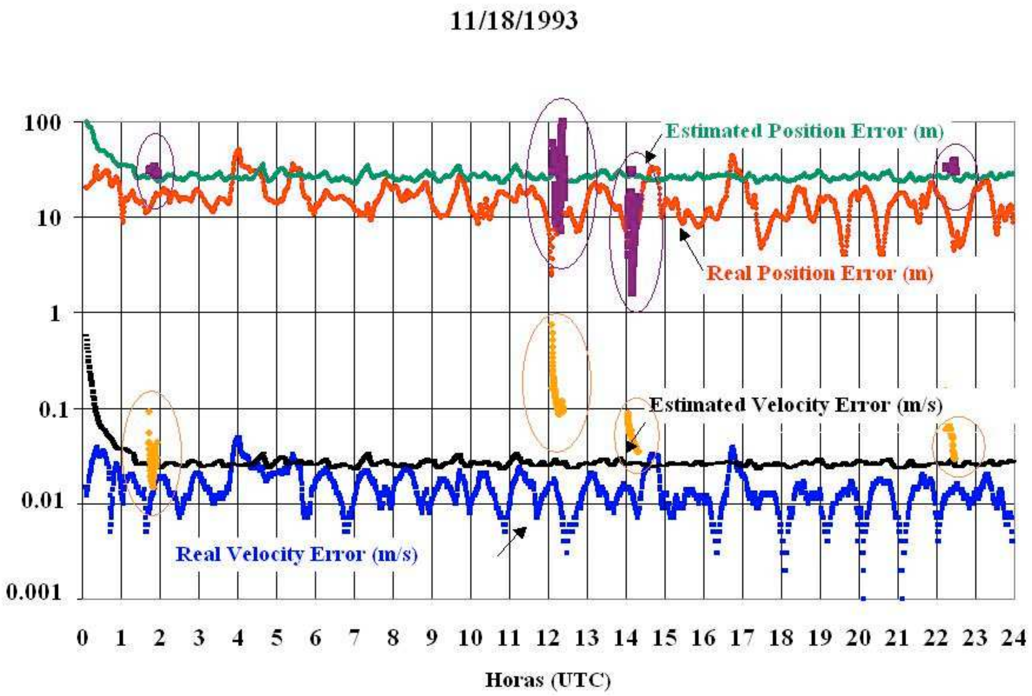

Figure 3 – The position and velocity error for 11/18/1993.

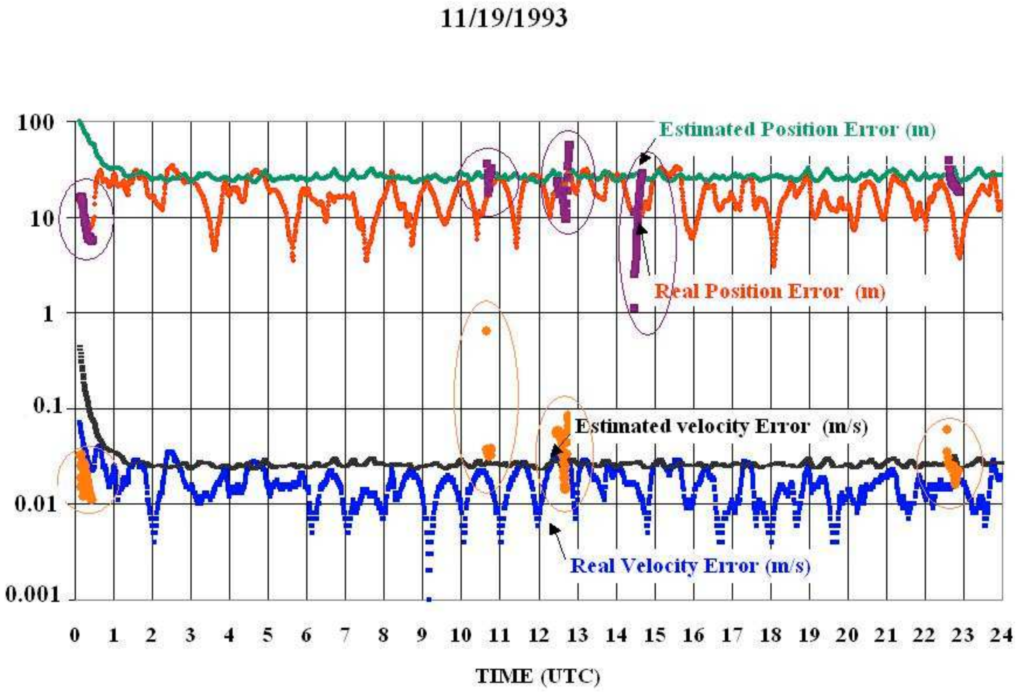

Figure 4 – The position and velocity error for 11/19/1993.

Table 3 shows the results obtained for each short arc of the first and second days, respectively. For all cases, the errors in position and velocity and the residuals are shown with its respective standard deviations, calculated according to the Eqs. (1) - (5).

18/11/1993	**Δr (m)**	**Δv (m)**	**Residual (m)**
Short arc 1	31.2 ± 1.4	0.025 ± 0.011	-2.112 ± 9.59
Short arc 2	32.6 ± 21.3	0.140 ± 0.100	-1.640 ± 87.60
Short arc 3	10.1 ± 5.7	0.049 ± 0.013	2.112 ± 10.90
Short arc 4	34.5 ± 6.3	0.062 ± 0.023	1.564 ± 16.40
19/11/1993	**Δr (m)**	**Δv (m)**	**Residual (m)**
Short arc 1	9.33 ± 3.96	0.019 ± 0.006	1.05 ± 4.87
Short arc 2	68.19 ± 165.84	0.072 ± 0.150	8.24 ± 41.93
Short arc 3	21.47 ± 12.65	0.045 ± 0.020	-0.83 ± 11.69
Short arc 4	13.23 ± 8.98	0.051 ± 0.003	1.72 ± 9.24
Short arc 5	26.28 ± 12.77	0.024 ± 0.007	-1,83 ± 24.27

Table 3 – Results for two days

It can be noted that, for two days tested, the real position and velocity errors and residuals for second arc have the worst accuracy.

7 CONCLUSIONS

The man goal of this work is to simulate the monitoring of an artificial satellite, which uses GPS receiver onboard, by the tracking and control station of INPE. An algorithm for artificial orbit determination onboard is used, which was tested with real data from a satellite with a GPS receiver onboard. The obtained position accuracy of orbit was better than 20 m with the SA on or off.

In this work, the same observation data used in that algorithm are generated only when the satellite is in the viewing area of the Brazilian station. The visibility of the satellite is simulated and the results show that it is possible to monitor it using the proposed algorithm. The accuracy degraded with respect to the full arc orbit determination, but it is not enough to damage the orbit tracking by the control center.

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REFERENCES

[1] Chiaradia, A. P. M. Kuga, H. K; Prado, A. F. B. A. Onboard and real-time artificial satellite orbit determination using GPS **Mathematical Problems in Engineering,** V 2013, Article ID 530516, p. 1-8, 2013.

[2] Chiaradia, A. P. M. Kuga, H. K; Prado, A. F. B. A. Comparison between Two Methods to Calculate the Transition Matrix of Orbit Motion. **Mathematical Problems in Engineering** (Print). V. 2012, Article ID 768973, p.1- 12, 2012.

[3] Chiaradia, A. P. M. Kuga, H. K; Prado, A. F. B. A. Single Frequency GPS measurements in real-time artificial satellite orbit determination. **Acta Astronautica**. Vol. 53 Issue: 2 pp. 123-133 Published: JUL, 2003.

[4] Gold, K.; Bertiger, W. I.; Wu, S.; Yunck, T.; Mullerschoen, R.; Born, G.; Larson, K. A study of real-time GPS orbit determination for the extreme ultraviolet explorer. **National Technical Meeting Proceedings of ION**, Jan., 1994.

[5] Fu, L. L.; Christensen, E. J.; Yamarone Jr., C. A.; Lefevre, M.; Ménard, Y.; Dorrer, M.; Escudier, P. TOPEX/POSEIDON mission overview. **Journal of Geophysical Research**, v. 99, n. C12, p. 24369-24381, Dez., 1994.

[6] Montenbruck, O.; Gill, E. **Satellite orbits – models, methods, and applications**. Heidelberg: Springer Verlag, 2000.

[7] Gill, E.; Montenbruck, O.; Terzibaschian, Th. An autonomous navigation system for the german small satellite mission BIRD. AAS/AIAA **Space Flight Mechanics Meeting**, AAS00-122, Jan., 2000.

[8] Rim, H. J.; Webb, C. E.; Schutz, B. E. Comparison of GPS-based precision orbit determination approaches for ICESAT. AAS/AIAA **Space Flight Mechanics Meeting**, AAS00-114, Jan., 2000

[9] Haines, B; Bertiger, W.; Desai, S.; Kuang. D.; Munson, T.; Reichert, A.; Young, L.; Willis, P. Initial Orbit Determination Results for Jason-1 towards a 1-cm orbit. **Proceedings of the ION GPS 2002**, Portland, Oregon, USA, 2002.

[10] Luthcke, S.B; Zelensky, N. P; Rowlands, D.D; Lemoine, F.G; Williams, T. A. The 1-Centimeter Orbit: Jason-1 Precision Orbit Determination Using GPS, SLR, DORIS, and Altimeter Data. ***Marine Geodesy***, V. 26, pp. 399–421, 2003. DOI: 10.1080/01490410390256727.

[11] Choi K.R.; Ries J.C.; Tapley B.D.; JASON-1 precision orbit determination by combining SLR and DORIS with GPS tracking data. ***Marine Geodesy*** V. 27(1–2), pp.319–331, 2004.

[12] Kuang D, Bar-Sever Y, Bertiger W, Desai S, Haines B, Iijima B, Kruizinga G, Meehan T, Romans L Precision orbit determination for CHAMP using GPS data from BlackJack receiver. In: **Proceeding of the ION national technical meeting 2001**, Long Beach, January, 2001.

[13] Zhu S, Reigber C, Koenig R Integrated adjustment of CHAMP, GRACE and GPS data. **J Geod** 78(1–2):103–108, 2004.

[14] Kang Z.; Nagel P.; Pastor R. Precise orbit determination for GRACE, Adv Space Res 31:1875–1881, 2003.

[15] Kang, Z; Tapley, B; Bettadpur, S.; Ries, J; Nagel, P.; Pastor, R. Precise orbit determination for the GRACE mission using only GPS data. **Journal of Geodesy**, Volume 80, Number 6 (2006), 322-331, DOI: 10.1007/s00190-006-0073-5.

[16] Lee, B. S. ; Yoon, J.C; Hwang, Y. ; Kim, J. Orbit determination system for the KOMPSAT-2 using GPS measurement data. Acta Astronautica, Volume 57, Issue 9, p. 747-753. 2005. DOI: 10.1016/j.actaastro.2005.03.066.

[17] Lee, B.S; Lee, j. S; Kima, J. H; Lee, S. P; Yoon, J. C; Roh, K. M; Park, E. S; Choi, K. H. Reconstruction of KOMPSAT-l GPS navigation solutions using GPS data generation and preprocessing program. Acta Astronautica 54 (2004) 571 – 576.

[18] Kuga, H. K.; Kondapalli, R. R. Satellite Orbit Determination: A First-Hand Experience with the First Brazilian Satellite SCD1, **44th. Congress of the IAF**, Graz, Austria, October 1993.

[19] Orlando, V.; Lopes, R. V. F.; Kuga, H. K. INPE’s Flight Dynamics Team Experience throughout Four Years of SCD1 In-Orbit Operations: Main Issues, Improvements and Trends, **ESA International Symposium on Spaceflight Dynamics**, ESA, Darmstadt, Alemanha, junho, 1997.

[20] Kuga, H. K.; Orlando, V.; Lopes, R. V. F. “Flight Dynamics Operations During Leop for the INPE’s Second Environmental Data Collecting Satellite SCD2”, Revista Brasileira de Ciências Mecânicas, Vol. XXI, Special Issue, ISSN 0100-7386, 1999, pp. 339-344.

[21] Orlando, V.; Kuga, H. K. Os Satélites SCD1 e SCD2 da Missão Espacial Completa Brasileira– MECB, Chapter of book **A Conquista do Espaço - Do Sputnik à Missão Centenário** (in portuguese), 1_a edição, São Paulo, SO, Editora Livraria da Física, v.1, p. 151-176, outubro de 2007.

[22] Kuga, H. K.; Orlando, V. Orbit Control of CBERS-1 Satellite at INPE, **16th International Symposium on Spaceflight Dynamics**, JPL/NASA, Pasadena, USA, 2001.

[23] Orlando, V.; Kuga, H. K.; Tominaga, J. CBERS-2 LEOP Orbit Analysis , **18th International Symposium on Spaceflight Dynamics**, Munich, Germany, Oct. 2004, ISBN 929092859X, pp. 221-225.

[24] INPE, http://www.inpe.br/ Access online on 3rd Jun, 2013.

[25] Pines, S. Uniform representation of the gravitational potential and its derivatives. **AIAA Journal**, 1973, v. 11, n. 11.

[26] International Earth Rotation Service (IERS). **1995 IERS Annual Report**. Observatoire de Paris, Paris, 1996.

[27] Press, H. W.; Flannery, B. P.; Teukolsky, S. A.; Vetterling, W. T. **Numerical Recipes**. Cambridge: University Press, 3. ed., 1987. 818p.