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Research Article

The Impact on Geographic Location Accuracy due to Different Satellite Orbit Ephemerides

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The current Brazilian System of Environmental Data Collection is composed of several satellites (SCD-1 and 2, CBERS-2 and 2B), Data Collection Platforms (DCPs) spread mostly over the Brazilian territory, and ground reception stations located in Cuiabá and Alcântara. An essential functionality offered to the users is the geographic location of these DCPs. The location is computed by the in-house developed "GEOLOC" program which processes the onboard measured Doppler shifts suffered by the signal transmitted by the DCPs. These data are relayed and stored on ground when the satellite passes over the receiving stations. Another important input data to GEOLOC are the orbit ephemeris of the satellite corresponding to the Doppler data. In this work, the impact on the geographic location accuracy when using orbit ephemeris which can be obtained through several sources is assessed. First, this evaluation is performed by computer simulation of the Doppler data, corresponding to real existing satellite passes. Then real Doppler data are used to assess the performance of the location system. The results indicate that the use of precise ephemeris can improve the performance of GEOLOC by reducing the location errors, and such conclusion can then be extended to similar location systems.

1. Introduction

The Brazilian System of Environmental Data Collection (SBCDA) can be organized in three subsystems: the space subsystem, the data collection ground subsystem, and the tracking and control ground segment [1, 2]. The space subsystem is composed of SCD-1, SCD-2, CBERS-2, and CBERS-2B satellites. The ground subsystem of data collection is composed of

Figure 1: Typical meteorological data collection platform.

hundreds of Data Collection Platforms (DCPs) that are deployed on ground, fixed or mobile (see Figure 1). The INPE's tracking and control ground segment is composed of the Satellite Control Center and Ground Stations in Cuiabá and Alcântara.

In this system, the satellite works as a message retransmitter, that is, providing a communication link between data collection platform (DCP) and a reception ground station. One of the functionalities offered by the system is the Geographic Location of the DCPs. The location is computed by the in-house developed "GEOLOC" program which processes the Doppler shifts suffered by the signal transmitted by the DCPs, together with a statistical least-squares method [3, 4]. The DCPs transmit data signals to the satellites in the UHF frequency band. Aboard the satellite, the DCP is identified and the payload data and the received frequency data are relayed to the tracking reception station. Then, the Geographical Location software GEOLOC developed by INPE is fed with Doppler shift data and the corresponding satellite orbit ephemeris. In general the most common format of orbit ephemeris exchange is the Two Line Elements (TLE) set [5, 6]. The TLEs can be obtained through the Satellite Control Center at INPE or through Internet, for example, [5]. The TLE format is composed of seven parameters and time and is basically defined by orbital mean motion, eccentricity, inclination, right ascension of the ascending node, perigee argument, mean anomaly, and a modified ballistic coefficient [5, 6]. Figure 2 shows a representation of Two Line Elements format.

To evaluate the impacts on geographic localization errors generated by the GEOLOC software, satellite orbit ephemerides from several sources were used such as: accurate PVT (Position, Velocity, Time), TLEs from INPE's Control Center, and TLEs from Internet. Then actual passes of the satellite were used to compare the errors considering such different orbital data sources for the location software. To foresee the magnitude of the expected errors, a comparison with ideal (simulated) case is also performed as detailed in the next section.

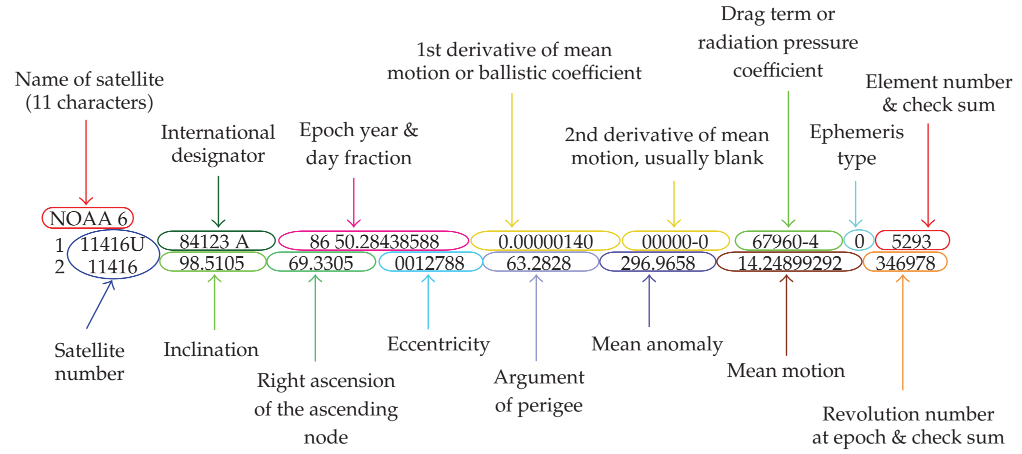


Figure 2: Presentation of the two line elements. Source: [5]

It is expected that conclusions arising from this work can be extended to similar systems using Doppler data and artificial satellites for location purposes.

2. Data and Work Outline

In order to get a benchmark to allow the analysis of location errors due to orbit ephemeris, the work followed the following steps.

(i) A survey on the satellite passes (samples) and the feasibility of obtaining the accurate orbit ephemeris (PVT format) were made to select the test period.

(ii) Three reference DCPs (no. 113, no. 32590, and no. 109) were selected whose locations are: DCP113 (12.0960°S, 77.0400°W), DCP32590 (15.5550°S, 56.0698°W), and DCP109 (5.1860°N, 52.6870°W). Such locations are accurate to the GPS level, that is, 10 to 30 m. The nominal frequency is 401.650 MHz (UHF). The Doppler shift data corresponding to the passes were obtained by the reception stations of Cuiaba and/or Alcântara, consistent with the location of the DCPs. The test period was from November, 21st to 27th, 2008.

(iii) The Doppler shift data of SCD-2 satellite passes were considered. The orbit inclination of this satellite is 25°, that is, a near equatorial orbit. The orbit ephemerides in Two Line Element (TLE) format were obtained from both the Satellite Control Center (CCS) at INPE [7–9] and Internet at [5].

(iv) The accurate orbit ephemerides (PVT format) were provided by the INPE CCS Orbit Determination System [7] with steps of one minute for each considered day. The GEOLOC location software was executed with this accurate ephemerides. Then, the accuracy of the SCD2 satellite orbit ephemerides was verified.

(v) To foresee the magnitude of the error when using TLEs instead of accurate PVTs, another program simulated the errors for the ideal case.

(vi) The GEOLOC location software was run using the PVT, TLEs from CCS, and TLEs from Internet, covering 4 SCD2 satellite actual passes. For each satellite pass, considering the established period above, the reference DCP locations are done using the Doppler shift measurements and the ephemerides obtained from two different sources (TLEs from both CCS and Internet). The location errors are compared with the ones obtained using accurate PVT state vector, considered as reference.

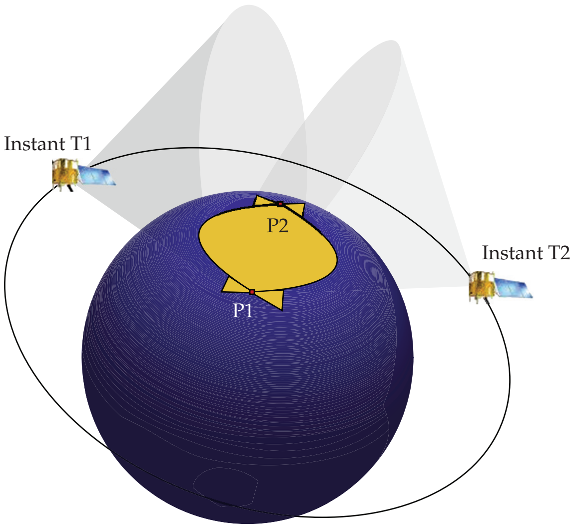


Figure 3: Location cones.

3. The System for Geographic Location of DCP's

During the pass of a satellite, the signals transmitted from the DCPs are immediately relayed, through the satellite, to the reception stations. In the reception station, the signals are received and the Doppler shifted frequencies, computed on board, are collected. The difference between the frequency of the received signal and the nominal frequency supplies the Doppler shift. For each Doppler measure it corresponds to a solid cone of location, whose intersection with the terrestrial sphere represents the possible positions of the transmitter. The intersection of the two cones in the altitude sphere supplies two possible position solutions, in a single pass (Figure 3).

With the apriori knowledge of an approximate position, it is possible to distinguish which is the correct one. However, because the Doppler measurement is corrupted by several error sources, a direct solution is not possible. Therefore, one should use statistical methods to solve the problem.

To do so, the parameters of position location and the ephemeris of the satellite are related through expression [3, 4]:

$$h(\mathbf{x}) = \frac{(x-X)(\dot{x}-\dot{X}) + (y-Y)(\dot{y}-\dot{Y}) + (z-Z)(\dot{z}-\dot{Z})}{\sqrt{(x-X)^2 + (y-Y)^2 + (z-Z)^2}} + b_0 + b_1 \Delta t, \tag{3.1}$$

where $x = (x, y, z)$ and (X, Y, Z) are the position coordinates of the transmitter and the satellite respectively; $(\dot{x}, \dot{y}, \dot{z})$ and $(\dot{X}, \dot{Y}, \dot{Z})$ represent the velocity vectors of the transmitter and the satellite; b_0 and b_1 are the bias and drift associated with each Doppler curve; Δt is time interval from the time of closest approach.

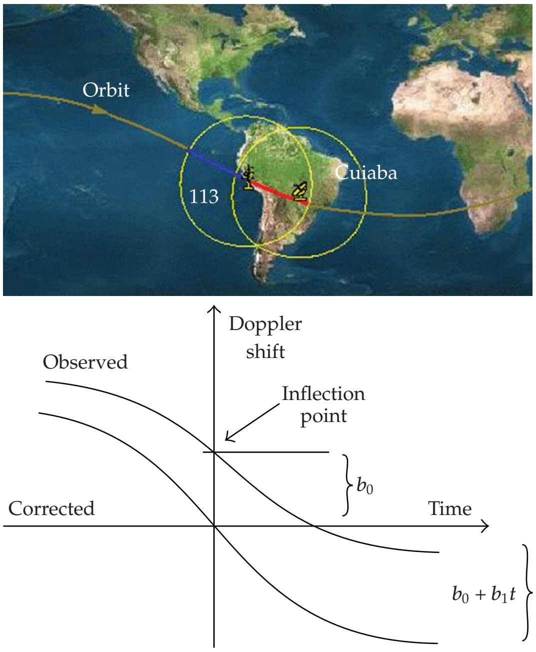


Figure 4: Typical SCD-2 pass and Doppler curve.

Figure 4 shows an example of a typical pass of satellite SCD-2 over DCP 113 and Cuiaba reception station. In this figure, the blue line represents positive Doppler shifts, and the red line the negative ones, with respect to DCP 113. The yellow circles are visibility circles where the contact with satellite is possible. Also a Typical Doppler curve is depicted.

4. TLE-S Accuracy: CCS and Internet

With the aim at studying the impact of ephemeris accuracy of SCD2 satellite on the location system, some tests were made to compare the accuracy of different sources of orbit ephemeris. Four satellite passes on November 22-23, 2008 were used, and these ephemerides were compared with TLEs from CCS and Internet.

The CCS carries out precise orbit determination based on ground tracking data of type “ranging” and Doppler [7]. The orbit determination using “ranging” is called “ranging” solution, and the orbit determination using Doppler data is called Doppler solution. The differences between both solutions agree to the level of 15 m [10]. The orbit ephemerides are provided as Inertial True of Date (“True Of Date”) PVTs (Position, Velocity, Time), equally spaced at one-minute intervals. To recover the ephemeris to the desired time, the PVTs from CCS are interpolated using a sixth-degree Lagrange polynomial.

CCS provides also TLEs of SCD2. The TLEs obtained from CCS are generated using an approximate period of one week data. Analyses have shown that the errors, compared to the PVTs, are zero mean with standard deviations around 300 m, however, sometimes presenting peaks of errors of 1000 to 1500 m in along-track (transversal) components [8, 10, 11]. Such accuracies are consistent with the ones presented elsewhere [12].

Table 1: Satellite SCD2 passes considered in the comparisons of the orbit ephemeris differences.

Pass	Date Nov. 2008	Initial time (UTC)	End time (UTC)
1	22	17:27:44	17:35:18
2	22	19:13:49	19:25:56
3	23	16:40:25	16:52:32
4	23	18:27:00	18:40:08

The TLEs obtained by Internet are refreshed with a not well-defined periodicity but, in general, fresh TLEs are available every 2 to 3 days. It is claimed that accuracy [6, 12] enough for tracking purposes is provided. The orbital ephemerides of many satellites are broadcast by NASA in the TLE format in the electronic addresses of Internet, for example, [5]. To recover the ephemerides for the desired time, the model SGP4 [6] is conventionally used.

All the ephemerides are in Inertial True of Date ("True Of Date") system. The inertial coordinates are transformed to the ECEF system ("Earth Centered Earth Fixed") of WGS-84 system, taking into account the polar motion and equation of the equinoxes, which are the most relevant corrections. The SCD2 satellite passes considered in the tests are presented in Table 1.

From the former considerations, the PVTs from CCS are taken as reference to the comparisons. Figures 5 (a) and (b) show the differences between the ephemerides using TLE from Internet (NORAD) and from CCS, respectively, in terms of the radial (R), transversal or along-track (T), and normal (N) components.

Considering the different ephemerides from PVTs and TLEs of CCS, one observes that all R, N, and T component differences are inferior to around 450 m. On the other hand, the differences between the PVTs and Internet TLEs present values similar for the R and N components; however, the transversal component T presents much higher values near 1000 m.

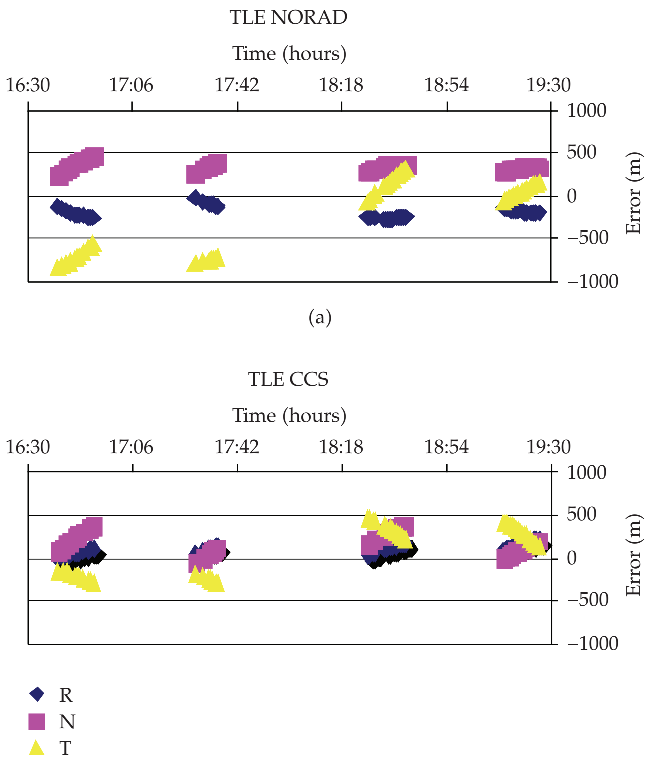
Therefore, for the TLEs from Internet, there is a more pronounced difference in the transversal component T. It is very likely that it can cause a biased error on the geographic location, because of the usage of different source of orbit ephemeris.

5. Test Results

In the tests, SCD-2 satellite and three DCPs in different locations were used. The SCD-2 satellite is in a quasi-circular low orbit around of Earth, with 25° inclination, and altitude of 750 km. The 3 DCPs are DCP109, DCP113, and DCP32590.

5.1. Ideal Case

Considering a fictitious ideal case, the Doppler measurements for DPCs 109 and 32590 were simulated computationally using the more precise PVTs provided by the CCS Satellite Control Center as orbit ephemeris, with SCD2 satellite relayed by the reception station of Cuiabá. On the other hand, TLEs from Internet and from CCS were used as orbit ephemeris in the GEOLOC location software, and the results are presented in Table 2. This test gives an idea of the errors magnitude expected when using ephemeris of different accuracies. For days 21 and 22, of November 2008, the Table shows that these errors are mostly near 1 km, which, as expected, is a rather direct translation of ephemerides differences as shown in Figure 5.



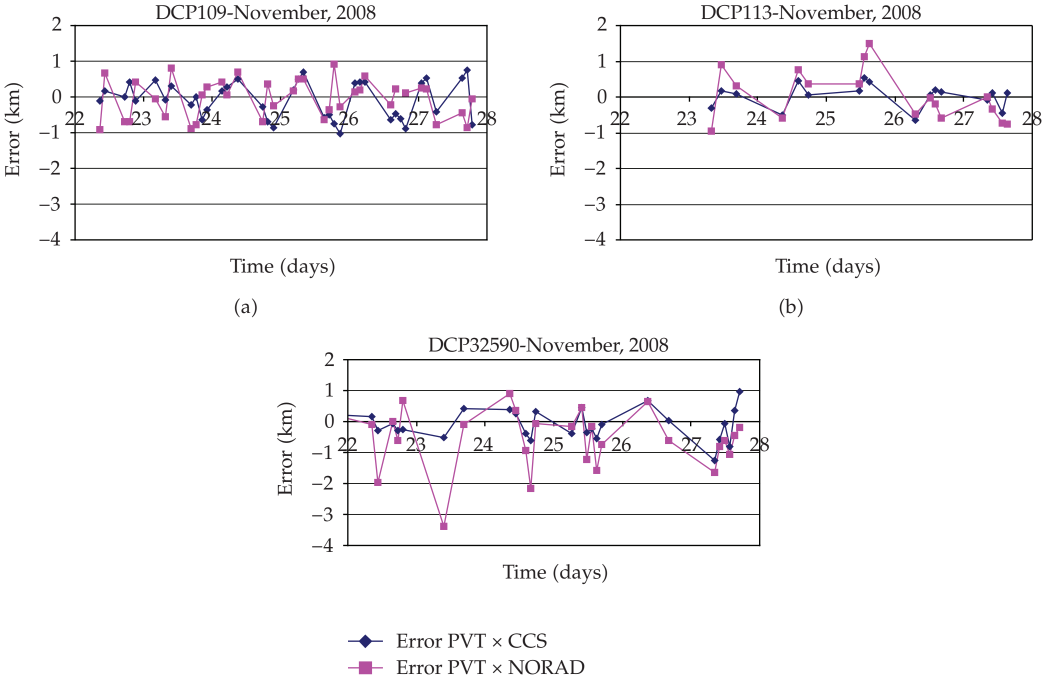
(a)

(b)

Figure 5: Radial (R), Normal (N), and Transversal (T) deviations between CCS PVTs and TLEs from Internet (a) and from CCS (b).

Table 2: Location errors for a simulated ideal case.

DPC no.	Date Nov. 2008	Time (UTC)	Internet TLE error (km)	CCS TLE error (km)
109	21	16:29:50	1.07	0.59
109	21	18:14:20	0.67	0.42
109	22	08:31:30	0.99	0.28
109	22	10:19:50	0.83	0.20
109	22	17:27:20	0.88	0.32
109	22	19:13:50	0.85	0.29
109	22	21:02:00	0.61	0.66
32590	21	09:16:40	0.59	0.38
32590	21	11:02:50	0.49	0.27
32590	21	18:09:40	0.94	0.23
32590	22	08:29:50	0.64	0.46
32590	22	10:15:40	1.04	0.32
32590	22	15:36:10	1.25	0.51
32590	22	17:22:30	1.28	0.17
32590	22	19:09:40	0.24	0.42



(a) (b) (c)

Figure 6: Difference between location errors using the PVT location compared to locations from CCS TLE and NORAD TLE.

5.2. *Real Case*

In this case, Doppler data relayed by satellite SCD2 and corresponding to days from November 22–28, 2008, were retrieved from the SBCDA archives for the three DCPs 109, 113, and 32590. For this actual test case, Doppler data were processed by the GEOLOC software, and the results are presented in Figure 6. Figure 6 shows the difference in location errors using all three sources of orbit ephemeris: PVTs from CCS, TLEs from CCS, and TLEs from Internet. The figure contains, for all 3 DCPs, the location error differences between CCS and PVT, and TLE and PVT. That is, they show the differences in location when using 3 different sources of orbital ephemeris. Notice that DCP 32590 presents the highest differences when using TLEs from Internet (NORAD), similar to what occurred in the simulated ideal case.

6. Conclusions

This article presents the impact on the accuracy when different sources of orbit ephemeris with heterogeneous accuracies are used to perform location of ground transmitters using the Doppler shifted data recorded on board satellites. Three different sources were analyzed (i) precise PVTs (Position, Velocity, Time) arising from INPE's Control Center orbit determination system, (ii) TLEs computed by INPE's Control Center on weekly basis, and (iii) TLEs obtained freely from Internet. For a restricted period of 2-day comparison, analyses show the differences in accuracy which could arise between the different orbit ephemeris sources. The comparisons showed that the ephemerides have minor and similar differences in radial and normal components. Nevertheless, extending the comparison to the transverse (along-track) component, the difference ranges from 500 to 1000 meters. Therefore, it is straightforward to conclude that this is the major contributing error to the location system. A simulated location session using ideal measurements, but with orbit ephemeris of different accuracy, showed clearly the along track error being transposed to the location error at similar levels. Actual data confirmed the same behavior. A future work can make use of more precise orbit ephemerides available via on-board GPS, to confirm the location errors steaming from ephemeris with different accuracies. At the end, the results point that usage of precise ephemeris can improve the performance the GEOLOC location system, and such conclusion can then be extended to similar systems.

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