

Research Article

Simulations under Ideal and Nonideal Conditions for Characterization of a Passive Doppler Geographical Location System Using Extension of Data Reception Network

**Cristina Tobler de Sousa,¹ Rodolpho Vilhena de Moraes,¹
and H lio Koiti Kuga²**

¹ UNESP-University, Estadual Paulista, Guaratinguet , CEP 12516-410, SP, Brazil

² INPE-DMC, CP 515, S.J. Campos, CEP 12245-970, Brazil

Correspondence should be addressed to H lio Koiti Kuga, hkk@dem.inpe.br

Received 30 July 2009; Accepted 5 November 2009

Recommended by Maria Zanardi

This work presents a (Data Reception Network) DRN software investigation considering simulated conditions inserting purposely errors into the Doppler measurements, satellites ephemeris, and time stamp, to characterize the geographical location software (GEOLOC) developed by Sousa (2000) and Sousa et al. (2003). The extension of reception stations in Brazilian territory can result in more precise locations if the network is considered in the GEOLOC. The results and analyses were first obtained considering the ground stations separately, to characterize their effects in the geographical location (GL) result. Six conditions were investigated: ideal simulated conditions, random and bias errors in the Doppler measurements, errors in the satellite ephemeris, and errors in the time stamp in order to investigate the DRN importance to get more accurate locations; an analysis was performed considering the random errors of 1 Hz in the Doppler measurements. The results are quite satisfactory and also show good compatibility between the simulator and the GEOLOC using the DRN.

Copyright   2009 Cristina Tobler de Sousa et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1. Introduction

This work presents the validation, through software simulations, of the passive Doppler GEOLOC system using extended DRN. The Doppler measurements data of a single satellite pass over a (Data Collecting Platform) DCP, considering a network of ground reception stations, is the rule of the DRN. The DRN uses an ordering selection method that merges the collected Doppler shift measurements through the stations network in a single file. The preprocessed and analyzed measurements encompass the DCP signal transmission time and

the Doppler shifted signal frequency received on board the satellite. Thus, the assembly to a single file of the measurements collected, considering a given satellite pass, will contain more information about the full Doppler effect behavior while decreasing the amount of measurement losses, as a consequence of an extended visibility between the relay satellite and the reception stations.

The simulations software was developed to produce simulated Doppler measurements according to several error simulation scenarios. A test scenario composed by SCD-2 (Brazilian Data Collecting satellite) and NOAA-17 (National Oceanic Atmospheric Administration) satellite passes, a single DCP and five ground receiving stations were used. This software is integrated to the developed GEOLOC system that uses the method of near real-time (just after data reception) LOCATION of transmitters through satellites [1].

Nowadays there are more than 600 (fixed and moving) DCPs transmitting several types of payload data (meteorological, hydrological, agricultural, deforestation, CO₂ gas concentration, etc.) through (Low Earth Orbit) LEO satellites. In Brazil, near real-time LOCATION of transmitters and its monitoring through satellites is particularly useful for monitoring moving DCPs [2] (drifting buoys in sea or rivers), to track displacements and habits of animals by fixing minitransmitters on them [3], for checking if the DCP is still in place, or for insuring that goods reaches the destiny, to monitor emergency location and rescue of aircraft and ships [4], and others.

The relay satellite measures the Doppler shift suffered by the DCP transmitted signal, which in turn, together with the payload data, downlinks the Doppler measurements to ground receiving stations. Such Doppler shift measurements are freely available (passive), being further processed to compute the DCP location through the location software.

The results and analysis with table and graphics are represented under six conditions:

- (1) ideal conditions from simulated Doppler shift measurements;
- (2) random Gaussian errors in the Doppler measurements;
- (3) bias errors in the Doppler measurements;
- (4) errors in the satellite ephemeris;
- (5) errors in the time stamp;
- (6) errors of 1 Hz in the Doppler measurements using DRN.

For the Doppler shift measurements simulations we considered two transmission intervals: either 600 Doppler measurements per pass (good statistical condition with lots of measurements, approximately one measurement every second) or 7 Doppler measurements per pass (realistic condition and not so good statistical scenario, approximately one measurement every 90 seconds).

2. Geographical Location with Doppler Shift Measurements

Basically the satellite receives the UHF signals from DCPs and relays such signals to ground reception stations in range. The Doppler shift measurements are computed in the ground station. In the Data Collection Mission Center, the Doppler measurements are sorted and merged to input them to the geographic location software, which provides the DCPs location.

When the transmitter and the reception stations are inside the satellite visibility circle of around 5000 km diameter for 5° minimum elevation angle, the nominal UHF frequency signals periodically sent by the transmitter are received by the satellite and immediately



Figure 1: Brazilian Environmental data collection system and Cuiabá and Alcântara station visibility circles.

(realtime) sent down to the reception station. The platforms installed on ground (fixed or mobile) are configured for transmission intervals of between 40 to 220 seconds. In a typical condition, in which both transmitter and receiver are close enough, this period can last up to 10 minutes. The DCP messages retransmitted by the satellites and received by the Cuiabá and Alcântara stations are sent to the Data Collection Mission Center located at Cachoeira Paulista, for processing, storage, and dissemination to the users, as seen in Figure 1.

The difference between the received signal frequency and the nominal frequency supplies the Doppler shift. The basic principle of transmitter location considers that for each signal transmitted a location cone is obtained (Figure 2). The satellite is in the cone vertex and its velocity vector v lies in the symmetry axis. Two different cones of location intercept the surface and its intersection contains two possible transmitter positions. To find which of the two ambiguous positions is the correct one, additional information is required, as for example, the knowledge of an initial approximate position. A second satellite overpass removes any uncertainties.

The transmitter geographic location can be determined by means of the Doppler shift of the transmitted frequency due to the relative velocity between the satellite and the transmitter. The satellite velocity relative to the transmitter ($V \cos \alpha$) in vacuum conditions, denoted by $\dot{\rho}$, is given by the Doppler effect [5] equation

$$\dot{\rho} = \left[\frac{(f_r - f_t)}{f_t} \right] c, \quad (2.1)$$

where f_r is the frequency value as received by the satellite; f_t is the reference frequency sent by the transmitter; $(f_r - f_t)$ is the Doppler shift due to the relative velocity satellite transmitter; c is the speed of light; α is the angle between the satellite velocity vector V and the transmitter position relative to the satellite.

The satellite ephemeris generator uses the SGP8 (Special General Perturbation) model of (North American Aerospace Defense Command) NORAD [6, 7], for obtaining the satellite

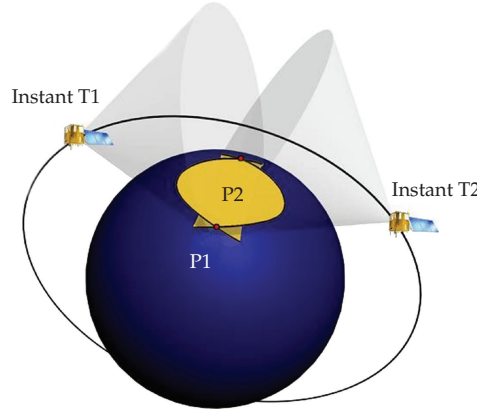


Figure 2: Location cones.

orbit at the measured Doppler shift times. The updated ephemeris are used within the Doppler effect equation to model the observations. Given the observations modeled as

$$y = h(x) + v, \quad (2.2)$$

where y is the set of Doppler shifts measured data; v is a noise vector assumed zero mean Gaussian; $h(x)$ is the nonlinear function relating the measurements to the location parameters and function of the satellite ephemeris:

$$h(x) = \frac{[(x - X)(\dot{x} - \dot{X}) + (y - Y)(\dot{y} - \dot{Y}) + (z - Z)(\dot{z} - \dot{Z})]}{\sqrt{(x - X)^2 + (y - Y)^2 + (z - Z)^2}} + b_0 + b_1 \Delta t, \quad (2.3)$$

where (x, y, z) and (X, Y, Z) are the satellite and transmitter coordinates position; b_0 (drift) and b_1 (drift rate) are constants associated with each Doppler curve to account for unknown bias in the Doppler measurements and a possible drift in the transmitter oscillator; Δt is the difference time between the first Doppler measurement and the current one.

The nonlinear least squares solution [8] is

$$H_1 \delta \hat{x} = \delta y_1, \quad (2.4)$$

where $\delta \hat{x} = \hat{x} - \bar{x}$, and H_1 is a triangular matrix. The method turns out to be iterative as we take the estimated value $\hat{x}$ as the new value of the reference $\bar{x}$ successively until $\delta \hat{x}$ goes to zero. The H_1 matrix is the result of the Householder orthogonal [9] transformation T such that

$$\begin{bmatrix} H_1 \\ 0 \end{bmatrix} = T \begin{bmatrix} S_0^{1/2} \\ W^{1/2} H \end{bmatrix}, \quad (2.5)$$

where H is the partial derivatives matrix $[\partial h / \partial x]_{x=\bar{x}}$ of the observations relative to the state parameters (latitude, longitude, height, bias, drift, drift rate) around the reference values;

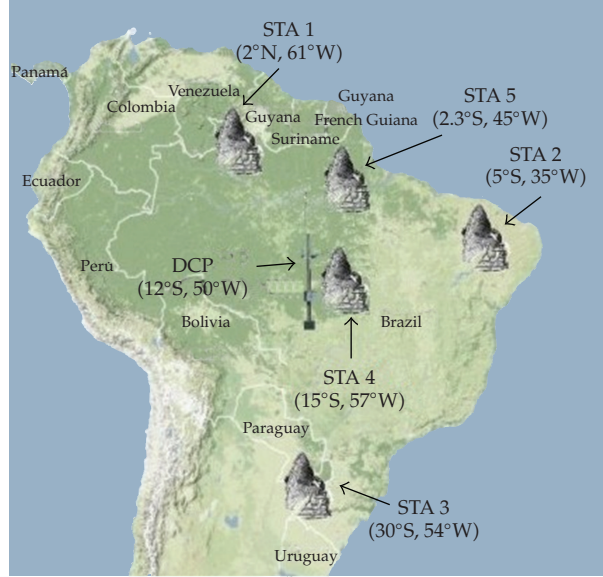


Figure 3: Reception stations configuring ideal geometry.

$W^{1/2}$ is the square root of the measurements weight matrix, and $S_0^{1/2}$ is the square root of the information matrix.

The δy_1 is such that

$$\begin{bmatrix} \delta y_1 \\ \delta y_2 \end{bmatrix} = T \begin{bmatrix} S_0^{1/2} \delta \hat{x}_0 \\ W^{1/2} \delta y \end{bmatrix}, \quad (2.6)$$

where δy is the residuals vector. The final cost function is

$$J = \|\delta y_1 - H_1 \delta \hat{x}\|^2 + \|\delta y_2\|^2 \quad (2.7)$$

with $\|\delta y_2\|^2 = J_{\min}$, where $J_{\min}$ is the minimum cost. The whole detailed procedure is fully described in [10]

3. Results

In this section we show the results of the simulated Doppler shift measurements for ideal conditions, inserting random errors in the Doppler measurements, bias errors in the Doppler measurements, errors in the satellite ephemeris, errors in the time stamp and realistic random errors in the Doppler measurements using DRN.

For this analysis we initially considered the results using ideal conditions from simulated Doppler shift measurements of a transmitter located in the center of Brazil at latitude 12.1200°S and longitude 310.1100°W and five simulated ground reception stations configuring the ideal geometry as illustrated in Figure 3.

Table 1: Ideal conditions.

Satellite	Number of samples per pass	Mean location error (km)				
		STA 1	STA 2	STA 3	STA 4	STA 5
SCD-2	600	$7.E-5 \pm 3.E-5$	$4.E-5 \pm 1.E-5$	$6.E-5 \pm 2.E-5$	$4.E-5 \pm 2.E-5$	$6.E-5 \pm 2.E-5$
	7	$3.E-4 \pm 1.E-4$	$7.E-4 \pm 4.E-4$	$3.E-4 \pm 1.E-4$	$5.E-4 \pm 7.E-4$	$6.E-4 \pm 4.E-4$
NOAA-17	600	$6.E-5 \pm 2.E-5$	$1.E-5 \pm 4.E-5$	$1.E-5 \pm 3.E-5$	$3.E-5 \pm 3.E-5$	$3.E-5 \pm 1.E-5$
	7	$2.E-4 \pm 1.E-4$	$2.E-4 \pm 1.E-4$	$3.E-4 \pm 1.E-4$	$1.E-4 \pm 7.E-4$	$2.E-4 \pm 8.E-4$

The data were gathered from March 10 to 19, 2008. The SCD-2 ephemerides were provided by the Control Center of INPE and the NOAA-17 ephemerides were obtained from Internet at "<http://www.celertrak.com/>".

3.1. Simulated Doppler Shift Measurements in Ideal Conditions

Table 1 shows results under ideal conditions, without any errors (ideal).

In the third column (mean location error) we have the geographical location mean errors from the transmitter nominal position. They are listed for the 5 reception stations (STA1, STA2, STA3, STA4, STA5) of Figure 3, in terms of mean and standard deviations. From Table 1, we can observe that the mean location errors and their deviation standards for both SCD-2 and NOAA-17 satellites, in the case of 600 samples (Doppler measurements) per pass, are around 10^{-5} km. This is an evidence that the developed GEOLOC software (Sousa, 2000) using data that simulates ideal conditions provides precise results.

The files corresponding to high sampling rate (600 samples), which represent a transmission rate of one burst per second yield results one order of magnitude more precise than the files resulting that from low sampling rate (7 samples or around one transmission burst each 90s). This emphasizes that a large number of measurements imply a better statistical result as expected.

3.2. Random Errors in the Simulated Doppler Measurements

In this section we present the analyses and results of simulated files under nonideal conditions inserting purposely errors in the Doppler shifts.

With the aim of verifying the effect of inserting Doppler measurements errors, the estimator of "bias" was turned off. Thus, the GEOLOC assumes that there is no "bias" in the Doppler measurements.

The random Gaussian errors (zero mean) with 1 Hz, 10 Hz, and 100 Hz (standard deviations) were inserted in the Doppler measurements. The corresponding results are presented in Tables 2(a) and 2(b) as follows.

From Tables 2(a) and 2(b) we can observe that as the random errors inserted in the Doppler measurements increase, the corresponding mean location errors increase.

We can also verify in the mean errors column that the resulting errors for STA 4 were smaller than for the other stations. This is a consequence of a higher number of measurements obtained by this station per each satellite pass and occurs because the fourth reception station is nearby the transmitter, and so they are almost inside the same satellite visibility circle of around 5000 km diameter for 5° minimum elevation angle.

Table 2

(a) Random errors in the doppler measurements for satellite SCD-2.

Satellite	Number of samples per pass	Random errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA 1 to STA 5 (km)
SCD-2	600	1	394	0.06 ± 0.02
				0.03 ± 0.01
				0.03 ± 0.05
				0.02 ± 0.04
				0.04 ± 0.06
	7	1	408	0.36 ± 0.27
				0.44 ± 0.22
				0.39 ± 0.10
				0.31 ± 0.14
				0.33 ± 0.22
	600	10	385	0.16 ± 0.12
				0.14 ± 0.11
				0.23 ± 0.05
				0.13 ± 0.04
				0.34 ± 0.06
	7	10	386	2.54 ± 1.51
				3.39 ± 2.87
				2.43 ± 1.84
				2.33 ± 1.78
				2.91 ± 1.82
	600	100	385	1.68 ± 0.98
				1.43 ± 0.03
				2.53 ± 1.81
				1.12 ± 0.29
				2.62 ± 0.48
	7	100	408	34.15 ± 23.39
				30.74 ± 22.31
				24.59 ± 11.46
				23.67 ± 12.97
				27.37 ± 17.40

(b) Random errors in the Doppler measurements for Satellite NOAA-17.

Satellite	Number of samples per pass	Random errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean Location error for reception stations STA 1 to STA 5 (km)
NOAA-17	600	1	173	0.04 ± 0.09
				0.06 ± 0.06
				0.06 ± 0.06
				0.09 ± 0.08
				0.08 ± 0.01
				0.31 ± 0.24
	7	1	157	0.30 ± 0.17
				0.47 ± 0.14
				0.29 ± 0.18
				0.30 ± 0.15
				0.19 ± 0.01
				0.18 ± 0.02
NOAA-17	600	10	173	0.10 ± 0.02
				0.12 ± 0.02
				0.28 ± 0.14
				2.87 ± 1.00
				3.87 ± 2.06
				3.58 ± 1.60
	7	10	154	2.00 ± 1.11
				3.56 ± 1.18
				1.44 ± 0.57
				1.69 ± 0.81
				1.69 ± 0.31
				1.24 ± 0.62
NOAA-17	600	100	173	2.71 ± 0.71
				34.71 ± 24.55
				35.97 ± 25.32
				37.86 ± 20.07
				21.80 ± 11.69
				24.25 ± 15.20
	7	100	153	

Also when we consider the low sampling (7 measurements) compared to the high sampling (600 measurements) cases, for the same reason the location errors were about one order of magnitude higher. Thus, greater measurements quantity during one satellite pass will provide a better location result.

The conclusion is as expected: to improve the quality of the presented geographical location results, considering the reception stations independently, it would be necessary to install more receptions stations around Brazil territory, nearby the transmitters, to get full Doppler curve reconstitutions without loss of Doppler shift measurements.

3.3. Bias (Systematic) Errors in the Simulated Doppler Measurements

This section presents the results of purposely inserted bias errors effect in the simulated Doppler measurements. For the simulation we used the SCD-2 and NOAA-17 satellites and bias errors of 1 Hz, 10 Hz, and 100 Hz. The results are presented in Table 3 as follows.

We can observe in Tables 3(a) and 3(b) that, due to the inserted errors in the simulated Doppler measurements being systematic errors and not random errors nature, the results considering high and low sampling are in the same order of magnitude. Thus we conclude that the location errors resulting from bias errors are influenced in a lesser extent by the rate of the sampling.

Also, considering the differences among the random and biased simulations results, we can conclude from Tables 2 and 3 that the random errors are filtered out. They produce mean locations results that tend to zero, mainly for high sampling rate (600 measures per pass). The location errors maintain some consistency and proportionality; thus, high sampling random errors of 1, 10, and 100 Hz result in location errors of 0.02, 0.2, and 2 km, respectively. For low sampling rate (7 measures per pass) the obtained results are also consistent: random errors of 1, 10, and 100 Hz produce location errors of 0.2, 2, and 20 km, respectively.

These results obtained were expected, due to the errors intrinsic characteristics. We can conclude that the smaller the measured Doppler error, the smaller becomes the location error, especially for high sampling rate. The inclusion of biased errors produces more degradation in the location results than that for random errors.

The GEOLoc location process with tendency (bias) in the Doppler measurements was calculated without estimating the drift in the measurements; however, these tendencies may be removed if the bias estimator is turned on in the location algorithm.

3.4. Errors in the Satellite Ephemerides

In this section we present the transmitters location error results considering inserted errors of 10 km in the satellites ephemerides. This analysis was performed to verify how the accuracy in the satellites ephemerides impacts the location accuracy. We also included errors of observation (Doppler measurements) of 10 Hz random and/or bias. The results considering ephemerides errors adding and not adding observation errors are described in Table 4.

Observing Tables 4(a) and 4(b) we verify that for the obtained locations, both using SCD-2 and NOAA-17, the largest errors appear when we insert all errors types simultaneously (see the last line for each satellite). From the table, we can see that the largest error contribution is due the errors inserted in the ephemerides. The random errors are filtered by the least squares algorithm and produce marginal inaccuracy. The systematic errors (bias) result in a greater final inaccuracy, and the added error levels are similar to those obtained in Table 3 for bias errors.

We can then conclude that the precision in the “two-lines” elements (ephemerides) produces direct impact in the location accuracy, that is, an error of 10 km in the ephemerides results in location errors of the same order of magnitude. Therefore considering the analyzed satellites, we can claim that, in low sampling rate conditions, precisions of 1-2 km order can only be obtained if the ephemerides errors are less than 2 km and the random and biased errors lower than 10 Hz.

Table 3

(a) Bias errors in the simulated Doppler measurements for satellite SCD-2.

Satellite	Number of samples per pass	Bias errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA1 to STA5 (km)
SCD-2	600	1	385	0.30 ± 0.03
				0.27 ± 0.01
				0.25 ± 0.05
				0.21 ± 0.05
				0.22 ± 0.07
	7	1	410	0.38 ± 0.09
				0.44 ± 0.07
				0.30 ± 0.08
				0.23 ± 0.02
				0.39 ± 0.04
	600	10	385	2.99 ± 0.21
				2.78 ± 0.52
				2.46 ± 0.21
				2.10 ± 0.48
				2.27 ± 0.70
	7	10	419	3.47 ± 0.34
				3.34 ± 0.97
				2.87 ± 0.46
				2.77 ± 0.19
				2.90 ± 0.14
	600	100	385	21.37 ± 4.88
				23.76 ± 6.07
				23.82 ± 8.74
				20.00 ± 4.80
				24.02 ± 8.64
	7	100	420	28.72 ± 7.91
				30.37 ± 10.05
				26.14 ± 9.80
				25.48 ± 5.40
				26.63 ± 6.83

(b) Bias errors in the simulated Doppler measurements for satellite NOAA-17.

Satellite	Number of samples per pass	Bias errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA1 to STA5 (km)
NOAA-17	600	1	173	0.27 ± 0.01
				0.24 ± 0.02
				0.31 ± 0.06
				0.21 ± 0.05
				0.22 ± 0.05
				0.32 ± 0.07
	7	1	155	0.28 ± 0.07
				0.28 ± 0.07
				0.24 ± 0.05
				0.34 ± 0.05
				2.71 ± 0.89
				2.41 ± 0.43
NOAA-17	600	10	173	2.49 ± 0.39
				2.12 ± 0.24
				2.19 ± 0.47
				3.69 ± 0.59
				3.64 ± 0.52
				3.64 ± 0.52
	7	10	161	3.22 ± 0.18
				3.49 ± 0.91
				26.52 ± 2.48
				23.56 ± 3.11
				27.75 ± 7.81
				20.42 ± 2.36
NOAA-17	600	100	173	21.994 ± 9.72
				28.79 ± 9.93
				29.05 ± 5.05
				28.23 ± 8.71
				21.97 ± 5.72
				31.82 ± 10.88
	7	100	158	

Comparing the presented Tables 2, 3, and 4, we can observe that the mean location error from the five simulated reception stations considering a transmission burst every 1s (600 samples per pass) is lower than for a burst every 90 s (7 samples per pass). This shows the importance of having a high rate DCP transmission burst to gather more Doppler data and a better location result.

Also, the obtained location results using NOAA-17 satellite are better than those using the SCD-2 satellite. This occurs because we simulate random errors of 0.1 Hz to the NOAA-17 and 1 Hz to the SCD-2 in the Doppler shift measurements, which is more consistent with their respective on board oscillator accuracies [10].

Table 4

(a) Satellite ephemeris and observed error for satellite SCD-2.

Satellite	Number of samples per pass	Errors in the satellite ephemeris (km)	Random errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA 1 to STA 5 (km)
SCD-2	600	10	No	357	8.48 ± 0.14
					8.57 ± 0.13
					8.53 ± 0.11
					8.38 ± 0.13
					8.67 ± 0.14
	7	10	"	410	8.84 ± 0.18
					8.72 ± 0.11
					8.83 ± 0.18
					8.59 ± 0.11
					8.75 ± 0.07
	600	10	10 random	357	8.79 ± 0.23
					8.71 ± 0.26
					8.74 ± 0.18
					8.67 ± 0.18
					8.68 ± 0.27
	7	10	"	410	9.19 ± 0.35
					9.01 ± 0.27
					9.64 ± 0.14
					9.77 ± 0.12
					9.23 ± 0.32
	600	10	10 biased	357	10.53 ± 0.26
					10.96 ± 2.42
					10.60 ± 0.38
					10.76 ± 0.24
					10.78 ± 0.43
	7	10	"	412	11.41 ± 0.41
					11.10 ± 0.32
					11.17 ± 0.21
					11.58 ± 0.12
					11.50 ± 0.31

(a) Continued.

Satellite	Number of samples per pass	Errors in the satellite ephemeris (km)	Random errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA 1 to STA 5 (km)
SCD-2	600	10	10 random + 10 biased	357	10.89 ± 0.32
					10.89 ± 0.39
					10.63 ± 0.24
					10.76 ± 0.26
					10.81 ± 0.30
					11.30 ± 0.37
	7	10	"	410	11.58 ± 0.33
					11.99 ± 0.31
					11.73 ± 0.23
					11.88 ± 0.34
					10.65 ± 0.36
					10.62 ± 0.37
	600	10	10 biased	174	10.44 ± 0.22
					10.79 ± 0.26
					10.68 ± 0.33
					11.72 ± 0.33
					11.82 ± 0.32
					11.02 ± 0.28
	7	10	"	155	11.04 ± 0.23
					11.84 ± 0.36
					10.69 ± 0.48
					10.62 ± 0.37
					10.45 ± 0.14
					10.21 ± 0.12
	600	10	10 random + 10 biased	174	10.86 ± 0.34
					11.97 ± 0.32
					11.47 ± 0.28
					11.10 ± 0.36
					11.05 ± 0.31
					11.36 ± 0.39

(b) Satellite ephemeris and observed error for satellite NOAA-17.

Satellite	Number of samples per pass	Errors in the satellite ephemeris (km)	Random errors in the simulated Doppler measurements (Hz)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA 1 to STA 5 (km)
NOAA-17	600	10	No	174	8.32 $\pm$ 0.10
					8.22 $\pm$ 0.10
					8.57 $\pm$ 0.11
					8.12 $\pm$ 0.10
					8.58 $\pm$ 0.12
	7	10	"	164	8.77 $\pm$ 0.14
					8.87 $\pm$ 0.12
					8.70 $\pm$ 0.19
					8.66 $\pm$ 0.11
					8.78 $\pm$ 0.12
	600	10	10 random	174	8.62 $\pm$ 0.24
					8.69 $\pm$ 0.27
					8.67 $\pm$ 0.15
					8.55 $\pm$ 0.14
					8.71 $\pm$ 0.28
NOAA-17	7	10	"	160	9.56 $\pm$ 0.21
					9.15 $\pm$ 0.21
					9.11 $\pm$ 0.31
					9.58 $\pm$ 0.10
					9.19 $\pm$ 0.31
	600	10	10 biased	174	10.65 $\pm$ 0.36
					10.62 $\pm$ 0.37
					10.44 $\pm$ 0.22
					10.79 $\pm$ 0.26
					10.68 $\pm$ 0.33
	7	10	"	155	11.72 $\pm$ 0.33
					11.82 $\pm$ 0.32
					11.02 $\pm$ 0.28
					11.04 $\pm$ 0.23
					11.84 $\pm$ 0.36
NOAA-17	600	10	10 random + 10 biased	174	10.69 $\pm$ 0.48
					10.62 $\pm$ 0.37
					10.45 $\pm$ 0.14
					10.21 $\pm$ 0.12
					10.86 $\pm$ 0.34
	7	10	"	148	11.97 $\pm$ 0.32
					11.47 $\pm$ 0.28
					11.10 $\pm$ 0.36
					11.05 $\pm$ 0.31
					11.36 $\pm$ 0.39

The SCD-2 satellite ephemerides used are computed just once a week by the INPE Control Center of São José of Campos. In order to improve the quality of the obtained results it would be necessary that the ephemerides be calculated with a higher precision, that is, it is recommended a daily computation instead of a week one. The NOAA satellite ephemerides used are obtained with high precision by (Collecte Localisation Satellites) CLS/Argos using their own method and not supplied to the public. The two-line format NOAA's ephemerides supplied by Internet site, like SCD-2's, are also imprecise, according to [1].

From the tables' results, we conclude that it is fundamental to minimize the errors in the satellite ephemerides, because the location algorithm cannot compensate for them. The errors inserted in the satellites ephemeris are approximately similar in magnitude to the resulting errors in the transmitters' location.

3.5. Errors in the Time Stamp

In this section we present the results and analysis of inserted errors of 1 and 0.1 seconds ahead in each transmitted signal frequency time stamp. This analysis was accomplished to verify how the accuracy in time impacts the location accuracy. The results are described in Table 5.

Observing Table 5 we verify that the mean location error values increase in the same order the errors in the time stamp increase. We can also conclude that a time delay of up to 1 s regarding the uplink signal transmitted to the satellite can cause an inaccuracy of up to 10 km in the location.

Thus, to avoid losing the quality on the transmitters geographic location results the measurements time tagging should be very stable; otherwise we will have one more unexpected error in the final location result.

4. Simulation Using the (Data Reception Network) DRN

In Section 3 we showed the analyses of the location results using collected measurements of several reception stations during a satellite pass and the impact of inserting errors on the transmitters geographical locations. Now the main goal of this present section is to show the location results when merging the Doppler measurements of all reception stations during the satellite pass in the location algorithm. We notice that using this approach, the final location results enhance considerably.

In this section the simulations consider a (Data Reception Network) DRN composed of five reception stations according to Figure 3. We insert random errors of 1 Hz in the Doppler shift measurements and consider one transmission each 90 s for a period of 10 minutes of the SCD-2 and the NOAA-17 satellite passes.

Tables 6 and 7 present the location errors considering five reception stations separately and as a network (DRN) during March 10 and 11, 2008.

In Tables 6 and 7, the first and second columns of the tables present the day and hour of each satellite pass. The next six columns present the location errors inserting random error of 1 Hz in the simulated Doppler measurements, over (sign /) the respective measurements amount obtained during the satellite pass.

The last column shows the location errors using the DRN network. In the cells without results, the symbol “—” means that there were no data to compute the location. As shown in the last column, when we use the DRN to merge data from the five reception stations, we can obtain results that were not present before, as well as improved results.

Table 5: Errors inserted in the time stamp.

Satellite	Number of samples per pass	Error in the time (seg)	Locations processed (sum of the 5 stations)	Mean location error for reception stations STA 1 to STA 5 (km)
SCD-2	600	1	385	1.54 $\pm$ 0.13
				1.16 $\pm$ 0.30
				1.02 $\pm$ 0.46
				0.71 $\pm$ 0.23
				0.90 $\pm$ 0.23
	7	1	411	9.35 $\pm$ 0.16
				8.96 $\pm$ 0.41
				8.88 $\pm$ 0.36
				7.48 $\pm$ 0.17
				8.28 $\pm$ 0.18
	600	0.1	385	0.18 $\pm$ 0.39
				0.11 $\pm$ 0.19
				0.10 $\pm$ 0.13
				0.08 $\pm$ 0.05
				0.09 $\pm$ 0.09
	7	0.1	411	1.03 $\pm$ 0.14
				1.05 $\pm$ 0.50
				1.11 $\pm$ 0.02
				0.89 $\pm$ 0.09
				0.97 $\pm$ 0.29
NOAA-17	600	1	173	1.29 $\pm$ 0.10
				1.68 $\pm$ 0.20
				1.68 $\pm$ 0.30
				2.13 $\pm$ 0.13
				2.33 $\pm$ 0.23
	7	1	166	11.81 $\pm$ 0.17
				8.87 $\pm$ 0.14
				7.94 $\pm$ 0.19
				9.51 $\pm$ 0.13
				9.51 $\pm$ 0.13
	600	0.1	173	0.47 $\pm$ 0.19
				0.62 $\pm$ 0.21
				0.62 $\pm$ 0.31
				0.64 $\pm$ 0.16
				0.22 $\pm$ 0.24
	7	0.1	170	1.26 $\pm$ 1.28
				0.85 $\pm$ 0.17
				1.09 $\pm$ 0.29
				0.65 $\pm$ 0.17
				0.65 $\pm$ 0.27

Table 6: Location error considering the DRN and SCD-2.

March 2008		Location error (km) with simulated Doppler measurements (with 1 Hz random error and transmission burst of 90 s), using the following reception stations					/Number of samples per pass:
Day	Hour	STA 1	STA 2	STA 3	STA 4	STA 5	All 5 stations
10	10	0.28/6	0.31/7	0.16/7	0.39 /9	0.46/9	0.14/38
10	12	0.12/6	0.08/6	0.16/9	0.12/9	0.11/8	0.05/38
10	14	0.36/3	0.41/4	0.15/8	0.30/8	0.22/6	0.05/29
10	16	—	0.61/5	0.29/8	0.16/7	0.17/6	0.13/26
10	17	0.31/5	0.51/5	0.18/7	0.13/8	—	0.11/25
10	19	0.30/8	0.31/7	0.25/6	0.14/8	0.25/8	0.13/37
10	21	0.15/7	0.03/5	—	0.47/6	0.38/7	0.02/25
11	08	0.07/6	0.21/7	—	0.09/6	0.14/7	0.07/26
11	09	0.26/7	0.08/7	0.35/7	0.17/9	0.35/9	0.08/39
11	11	0.08/5	0.07/6	0.06/8	0.19/8	0.18/8	0.03/35
11	13	1.36/4	0.95/4	0.13/8	0.15/8	0.19/6	0.12/30
11	15	—	0.19/5	0.06/8	0.20/8	0.09/6	0.04/27
11	17	0.61/4	0.35/6	0.06/8	0.16/8	0.32/7	0.03/33
11	18	1.79/8	0.13/6	0.99/7	1.55/9	0.69/7	0.03/37
11	20	0.17/8	0.17/6	0.61/3	0.30/7	0.14/7	0.12/31

Table 7: Location error considering the DRN and NOAA-17.

March 2008		Location error (km) with simulated Doppler measurements (with 1 Hz random error and transmission burst of 90 s), using the following reception stations					/Number of samples per pass:
Day	Hour	STA 1	STA 2	STA 3	STA 4	STA 5	All 5 stations
10	00	0.09/6	0.05/9	0.06/6	0.05/9	0.11/8	0.02/38
10	02	0.14/4	—	0.10/5	0.38/5	— /1	0.07/15
10	12	—/—	0.08/7	0.26/4	0.14/6	0.08/7	0.06/24
10	13	0.17/7	0.20/5	0.25/6	0.43/8	0.12/6	0.07/32
11	00	0.13/4	0.50/7	0.48/4	0.19/7	0.41/7	0.28/29
11	02	0.52/6	—	0.66/5	0.22/7	0.55/5	0.03/23
11	11	—	0.49/5	0.57/3	0.64/4	0.34/4	0.13/16
11	13	0.11/7	0.17/7	0.15/6	0.26/8	0.10/8	0.05/36

In most of the results the locations obtained for satellite passes with a larger number of measurements are better than those for smaller number of measurements.

As we see in the last column, the quality of the obtained results was improved when considering measurements collected by all reception stations compared to one single station alone. Therefore, there is an enhancement in the location results when generated using the DRN. For example we notice in Table 7 that Stations 2 and 5 (STA 2 and STA 5) on day 10

at 02 o'clock have only 0 and 1 data points, respectively, insufficient for a location. When we merge the whole data set (all other stations), the Doppler curve is fully recovered and the location error drops (improves) drastically to 0.07 km.

5. Conclusions

We conclude that the developed GEOLOC is operating appropriately as we can see by the obtained results under ideal conditions, say, without errors in the Doppler measurements, ephemeris, and time.

Considering the random and biased simulations results, we conclude that the random errors are filtered out by the least squares algorithm. They produce mean locations results that tend to zero error, mainly for high sampling rate (600 measures per pass). The simulation results considering biased errors yield errors that equally degrade the location for both sampling rates (600 and 7). The inclusion of biased errors degrades the location results more than the random errors. From the tables with results inserting errors in the satellite ephemerides, we can conclude that it is fundamental to minimize such errors, because the location system cannot compensate for them. The satellites ephemeris errors are approximately similar in magnitude to their resulting transmitters' location errors.

The simulation results using the DRN showed that to improve the location results quality it would be necessary to have more Reception Stations than the existing Cuiabá, Cachoeira Paulista, and Alcântara, spread over the Brazilian territory, to increase the data amount. Then, on the other hand, it improves the geometrical coverage between satellite and DCPs, and recovers better the full Doppler curves, yielding as a consequence more valid and improved locations.

Acknowledgment

The authors thank FAPESP (Process no. 2005/04497-0) for the financial support.

References

- [1] C. T. Sousa, H. K. Kuga, and A. W. Setzer, "Geo-Location of transmitters using real data, Doppler shifts and Least Squares," *Acta Astronautica*, vol. 52, no. 9, pp. 915–922, 2003.
- [2] M. Kampel and M. R. Stevenson, "Heat transport estimates in the surface layer of the Antarctic polar front using a satellite tracked drifter—first results," in *Proceedings of the 5th International Congress of the Brazilian Geophysical Society*, São Paulo, Brazil, September 1997.
- [3] C. M. M. Muelbert, et al., "Movimentos sazonais de elefantes marinhos do sul da ilha elefante, Shetland do sul, antártica, observações através de telemetria de satélites," in *Proceedings of the 7th Seminars on Antarctica Research*, p. 38, USP/IG, São Paulo, Brazil, 2000, program and abstracts.
- [4] Techno-Sciences, COSPAR/SARSAT, October 2000, <http://www.technosci.com/>.
- [5] H. Resnick, *Introduction to Special Relativity*, John Wiley & Sons, New York, NY, USA, 1968.
- [6] F. R. Hoots and R. L. Roehrich, "Models for propagation of NORAD element sets," Spacetrack Report 3, Aerospace Defense Command, Peterson Air Force Base, Colorado Springs, Colo, USA, 1980.
- [7] R. Vilhena de Moraes, A. Silva, and H. K. Kuga, "Low cost orbit determination using GPS," in *Proceedings of the 5th International Conference on Mathematical Problems in Engineering and Aerospace Sciences*, S. Sivasundaram, Ed., pp. 495–502, Cambridge Scientific, Cambridge, UK, 2006.
- [8] G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York, NY, USA, 1977.

- [9] C. L. Lawson and R. J. Hanson, *Solving Least Squares Problems*, Prentice-Hall, Englewood Cliffs, NJ, USA, 1974.
- [10] C. T. Sousa, *Geolocalização de transmissores com satélites usando desvio doppler em tempo quase real*, PhD dissertation, Space Engineering and Technology, Space Mechanics and Control Division, INPE-Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil, 2000.

