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ACCURACY OF TRANSMITTERS GEO-LOCATION ALGORITHM USING REAL DATA FROM SATELLITES

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ABSTRACT

The main goal of this work is to show the accuracy achieved by an algorithm for geographic location of transmitters, within a near real-time environment. The results and analysis were obtained using real data from three different transmitters in two different areas and three kinds of satellites. The geographical location answers several needs, as search and rescue of people in remote areas, tracking of ocean buoys, movement of animals, ships, people, equipment, either for scientific or security purposes. The location procedure uses measurements of Doppler shifts of transmissions, satellites ephemeris, and batch estimation based on least squares statistical techniques. Results using such real database were satisfactory, with accuracy ranging from 0.5 to 6.5 km.
Key words: Geographical location , Transmitters, Doppler shift.

1. INTRODUCTION

In Brazil, near real-time geographical location of transmitters and its monitoring through satellites is used to monitor and rescue people in remote areas, for example, in the Brazilian Antarctic Program - PROANTAR (Setzer, 1997); to track displacements and habits of animals by fixing mini-transmitters on them (Muelbert, 2000); to monitor oceanographic buoys for scientific research (Kampel and Stevenson, 1997); and in emergency location and rescue of aircraft and ships (Techno, 2000).

The method of near real-time (right after data reception) geographic location of transmitters through satellite is based on a recently developed work (Sousa, 2000; Souza et al., 2001). In the following sections we outline the modeling of the geographical location problem, using the Doppler shift measurements, the satellite dynamic motion, and the non-linear least squares technique. After that, we show the results and analysis of three transmitters, two of them located in the Antarctic peninsula - Elephant Island - with transmitters and ground reception station close to each other; and the last one in French Guyana, distant 3° in longitude and 20° in latitude from the Brazilian Cuiabá Reception Station.

2. BASIC MODEL OF TRANSMITTER LOCATION

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. When the transmitter and the reception station are inside the satellite visibility circle of around 5000 km diameter for 5° minimum elevation angle (Figure 1), the nominal UHF frequency signals periodically sent by the transmitter are received by the satellite and immediately (real-time) sent down to the reception station (Figure 2). In a typical condition, in which both transmitter and receiver are close enough, this period can last up to 10 minutes. The received data is then processed to generate the transmitter position information.

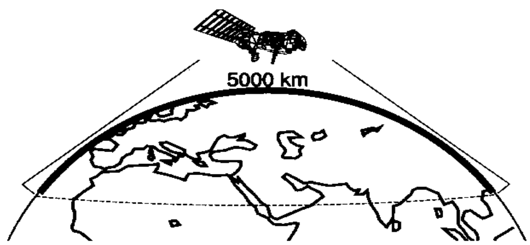

Figure 1 - Circle of visibility (Source CLS, 1989)

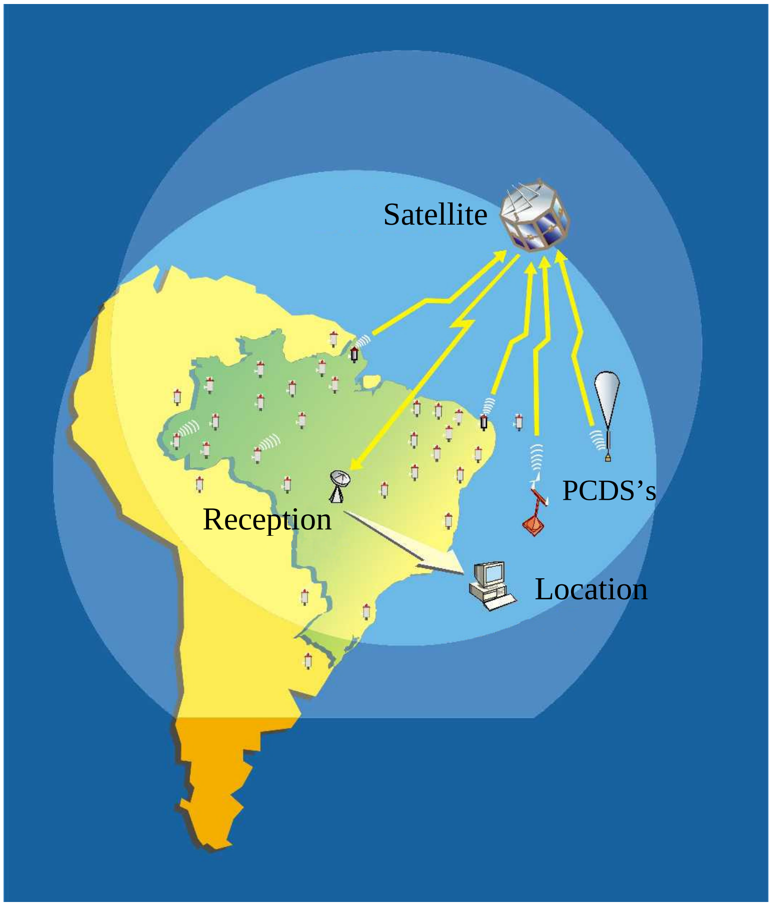

Figure 2 - Transmitter location

3. BASIC PRINCIPLE OF LOCATION

The basic principle of transmitter location considers that for each signal transmitted a cone of location is obtained (Figure 3). 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 positions is the correct one, additional information is required, as for example, the knowledge of an initial position. A second overpass removes any uncertainties.

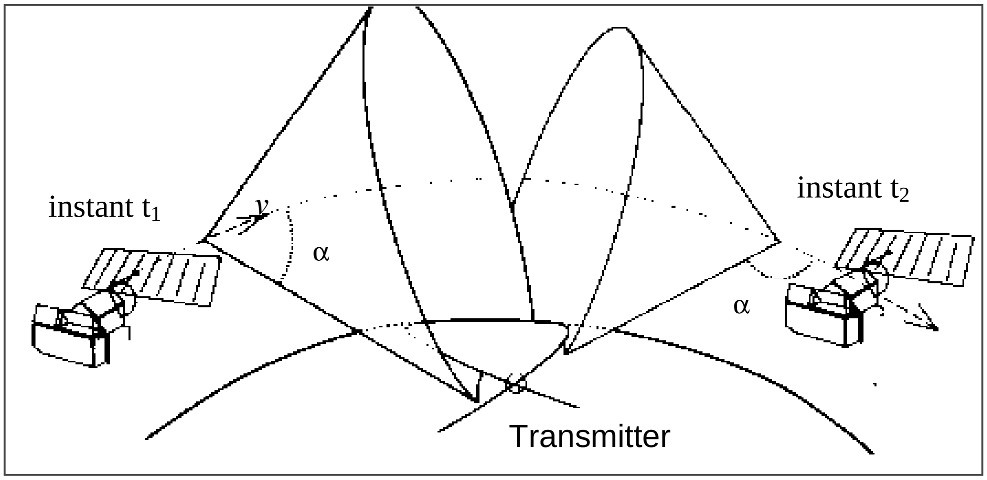

Figure 3 - Location cones (Source: CLS, 1989)

The satellite velocity relative to the transmitter ($v \cos \alpha$) in vacuum conditions, denoted by $\dot{\rho}$ is given by the Doppler effect equation (Resnick, 1968) as follows:

$$\dot{\rho} = \frac{(f_r - f_t)}{f_t} c \tag{2.1}$$

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. Given the observations modeled by:

$$y = h(x) + v \tag{2.2}$$

where y is the set of Doppler shifts measured; $h(x)$ is the non-linear function relating the measurements to the location parameters and function of the satellite ephemeris (Souza, 2000), that is, $h(x) = \left[(x\text{-}X)(\dot{x}\text{-}\dot{X}) + (y\text{-}Y)(\dot{y}\text{-}\dot{Y}) + (z\text{-}Z)(\dot{z}\text{-}\dot{Z})\right] / \sqrt{(x\text{-}X)^2 + (y\text{-}Y)^2 + (z\text{-}Z)^2} + b_0 + b_1 \Delta t$, (x, y, z) and (X, Y, Z) are the satellite and transmitter coordinates position, and v a noise vector; the non-linear least squares solution (Bierman, 1977) is:

$$H_1 \delta\hat{x} = \delta y_1 , \tag{2.3}$$

where $\delta\hat{x} = \hat{x} - \bar{x}$, H_1 is a triangular matrix, and therefore the solution $\delta\hat{x}$ is obtained straightforwardly. 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 (Lawson, 1872) orthogonal transformation T such that:

$$\begin{bmatrix} H_1 \\ ------ \\ 0 \end{bmatrix} = T \begin{bmatrix} S_0^{1/2} \\ ------ \\ W^{1/2} H \end{bmatrix}, \tag{2.4}$$

where H is the partial derivatives matrix $[\partial h / \partial x]_{x=\bar{x}}$ of the observations relative to the state parameters (latitude, longitude, altitude, bias, bias rate) around the reference values, that is, $x=(\phi, \lambda, H, b_0, b_1)$; $W^{1/2}$ is the square root matrix of the measurements weight matrix; and $S_0^{1/2}$ is the square root of the information matrix. The δy_1 is such that:

$$\begin{bmatrix} \delta y_1 \\ ------ \\ \delta y_2 \end{bmatrix} = T \begin{bmatrix} S_0^{1/2} \delta\hat{x}_0 \\ ------ \\ W^{1/2} \delta y \end{bmatrix} \tag{2.5}$$

where δy is the residuals vector. The final cost function can be written:

$$J = \|y_1 - H_1 \hat{x}\|^2 + \|y_2\|^2 \tag{2.6}$$

with $\|\delta y_2\|^2 = J_{min}$, where J_{min} is the minimum cost.

4. RESULTS

The results and analysis of the geographic location method developed are shown, demonstrating the location accuracy achieved by this near real-time system. We gathered representative data sets of three different transmitters and two ground reception station i) Transmitters #23840 and #23837 fixed in the Elephant Island (Antarctica) (Figure 4) sending data through the NOAA-12 (National Oceanic and Atmospheric Administration) satellite to a portable reception station placed in the Antarctic Brazilian Station (EACF); ii) Fixed Data Collecting Platform (PCD) with transmitter ID #109, relaying data through the SCD-2 (Brazilian Data Collecting Satellite-2) and the China Brazil Satellite Earth Resources Satellite (CBERS-1) to the Cuiabá Reception Station (center of Brazil).

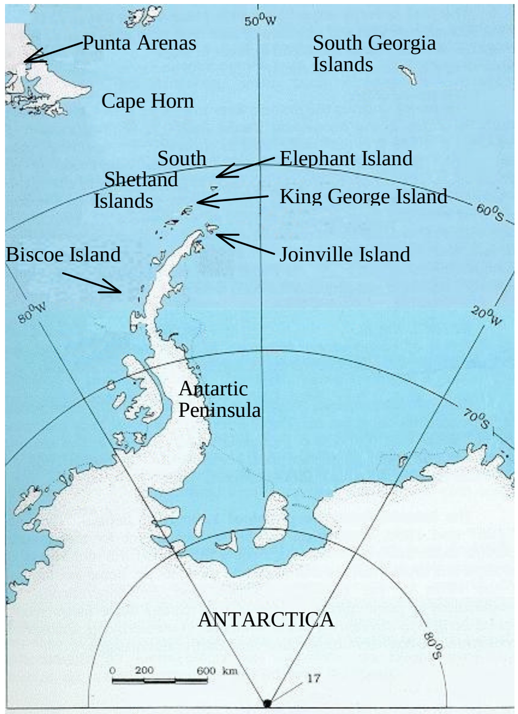

Fig. 4 - Antarctic peninsula - Elephant island

The following criteria were established for the analysis and validation of the results: i) when the standard deviation of the Doppler shift residuals is greater than 10 Hz the location estimate is rejected. The initial standard deviation is set to 5 Hz, and a result twice bigger may indicate excessive interference or noise in the measured Doppler shift values; ii) data for satellite elevation lower than 5° may suffer considerable effects of the atmospheric refraction and noise due to transmitter power attenuation, and also are discarded; iii) if in a single satellite pass we obtain frequency samples covering only one side of the Doppler curve, i. e. either only positive or negative values, the geographic location is obtained with degraded precision and also must be discarded. Finally, if we know a former position of slowly moving transmitters, we can compare it to the obtained geo-location for cross-validation.

4.1. Transmitter - MTR #23840 and #23837, NOAA Satellite, EACF Reception Station: error effect in the measurements time

The sampling rate for this Mini Remote Transmitter (MTR) is one transmission burst per 90 seconds, or 6 possible Doppler data samples for a 10 minutes NOAA-12 (800 Km of altitude) satellite pass. From November 1998 to January 1999. The ephemeris were obtained daily via “internet” through the home page (www.celestrak.com).

It was noted that the measurements instants (“time tagging”) were uncorrect: the sample time information decoded at the portable station did not exactly correspond to the instant of the MTR signal transmission to the NOAA satellite, with an error up to 32 seconds, configuring an abnormality at the portable reception station. The location results with “time tagging” error are shown in Table 4.1:

TABLE 4.1
RESULTS FROM MTR'S 23840 AND 23837, NOAA-12: WITH TIME ERROR

Samples (+/-)	<residual±σ> (Hz)	Elevation (°) min/max	Location error (km)	Date	Time	Longitude (°)	Latitude (°)
1/2	4.E-01 ± 0.9	30.0 / 48.3	184.65	24-Nov-98	9:04:41	307.633	-60.443
3/1	1.E+00 ± 4.1	13.9 / 38.8	149.54	1-Dec-98	23:34:01	307.367	-60.993
2/1	1.E-01 ± 0.3	29.8 / 48.6	202.40	16-Dec-98	23:04:07	308.402	-61.311
2/2				26-Dec-98	8:56:56		
4/1	-2.E+00 ± 270	14.4 / 46.5	208.53	1-Jan-99	23:49:21	301.672	-62.462
2/1	-5.E-01 ± 26	35.8 / 67.6	200.37	6-Jan-99	8:13:52	308.352	-61.418
1/2	3.E+00 ± 162	26.2 / 88.4	919.58	19-Nov-98	2:49:07	295.539	-68.535
2/2				27-Nov-98	23:24:01		
2/2	-9.E-02 ± 258	27.0 / 72.7	91.84	4-Dec-98	22:29:52	304.369	-62.034
2/2				18-Dec-98	22:20:09		
1/2	-4.E-01 ± 116	45.1 / 81.4	593.33	19-Dec-98	6:23:00	293.722	-60.689
3/1				1-Jan-99	8:23:55		
2/2	9.E-01 ± 1020	31.9 / 64.5	404.58	3-Jan-99	9:20:19	300.279	-58.325
1/2				3-Jan-99	23:05:25		
1/2				5-Jan-99	22:21:46		
2/1	-2.E+00 ± 6.6	18.9 / 29.3	183.26	6-Jan-99	9:54:54	301.224	-61.316

Each line of Table 3.1 represents a single pass of the satellite NOAA-12. The first six satellite passes are related to the MTR 23840 and the others to MTR 23837. In six situations (blank samples above), the algorithm did not converge. Other six passes had absurd standard deviation. Left were four valid results ($\sigma < 10$ Hz) but they are distant from the actual location as can be seen from the column of location error.

The correction of the error of 32 seconds in time was reported to the developers of the data decoding software. We should also note that the incorrect data were estimated comparing data archives obtained from the French Argos system, with the milliseconds information disregarded. After all the corrections, the new results are shown in Table 4.2:

TABELA 4.2
RESULTS FROM MTR'S 23840 AND 23837, NOAA-12: CORRECTED TIME

Date	Samples (+/-)	< residual ±σ> (Hz)	Elevation (°) min/max	Location error (km)
24-nov-98	1/2	3.E-01 ± 0.8	34.3 / 55.3	1.75
1-dez-98	3/1	3.E-02 ± 0.3	17.0 / 44.4	2.24
16-dez-98	2/1	1.E-01 ± 0.3	34.3 / 56.6	4.14
26-dez-98	2/2	2.E-01 ± 0.6	32.4 / 62.5	0.80
1-jan-99	4/1	6.E-01 ± 1.6	12.7 / 38.0	0.57
6-jan-99	2/1	4.E-01 ± 0.8	36.8 / 65.2	6.92

19-nov-98	1/2	-1.E-01 ± 0.7	27.5 / 41.1	3.37
27-nov-98	2/2	8.E-02 ± 0.3	31.2 / 49.9	3.80
4-dez-98	2/2	-8.E-02 ± 0.3	25.3 / 75.4	3.73
18-dez-98	2/2	-4.E-02 ± 0.1	35.3 / 66.6	2.02
19-dez-98	1/2	-1.E+00 ± 5.4	29.5 / 51.7	3.03
1-jan-99	3/1	-2.E-01 ± 0.4	18.2 / 56.1	6.45
3-jan-99	2/2	8.E-02 ± 0.3	31.0 / 45.3	4.50
3-jan-99	1/2	-4.E-02 ± 0.1	45.9 / 63.4	5.90
5-jan-99	1/2	3.E-01 ± 1.2	39.5 / 67.3	8.73
6-jan-99	2/1	-4.E-01 ± 1.5	18.5 / 26.2	5.56

The location error column shows that after the time correction all satellites passes resulted fairly good. Location error before time correction were between 150 and 920km, while after this, location error were from 0.6 to 9km. As a result we conclude that time tagging accuracy is extremely important for the geographical location accuracy. The residuals also result excellent, with low level noise and reduced standard deviation. Results of angular and location errors are shown in Figure 5:

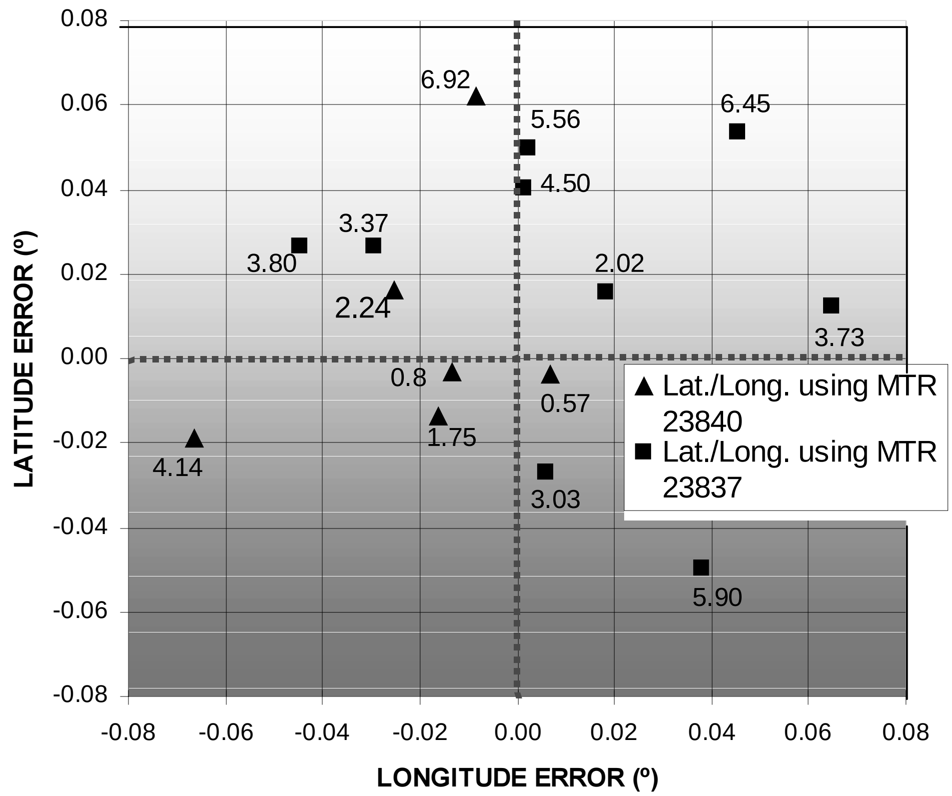

Fig. 5 - Location deviation of the MTR's 23840 e 23837, from November 1998 to January 1999 using NOAA-12 (values aside the symbols represent the distance (km) from the reference).

The x- and y-axis are the longitude and latitude deviation from reference; the triangles are the errors obtained from MTR 23840, and squares from MTR 23837. Location error standard deviations are 2.41 km using MTR 23840 and 1.97 km using MTR 23837. So we conclude that the positions 1-sigma deviations have maximum errors of 5.15 km and 6.68 km and minimum of 0.33 km and 2.74 km respectively.

4.2 Transmitter #109, SCD-2 and CBERS-1 satéllite, and good Doppler samples

The Tables 3.3 contains location results for the transmitter 109 situated in French Guiana, from July to August 2000. The reception station is located at Cuiabá. The SCD-2 and CBERS-1 "two-lines" formatted satellite ephemeris are periodically updated by the Satellite Center Control (CCS) at São José dos Campos, which are made available through Internet address: www.dem.inpe.br.

TABLE 4.3

RESULTS FOR TRANSMITTER 109, SCD-2 (▲ = σ > 10 Hz; ■ = $El_{máx} \leq 5^0$; • = all Doppler measurements > 0 or all < 0; ✯ = valid location)

Samples (+/-)	< residual ±σ> (Hz)	Elevation (°) min/max	Location error (km)
5/3	-1.E-01 ± 204	7.2 / 16.2	▲ 61.05
4/4	-2.E-01 ± 2.0	21.7 / 60.8	✯ 1.76
1/7	-1.E-01 ± 1.0	4.2 / 36.9	✯ 1.99
3/2	3.E-01 ± 84.5	1.2 / 8.0	▲ 95.40
4/0	-7.E-02 ± 0.5	1.6 / 25.5	• 6.91
4/4	-2.E-01 ± 7.9	26.6 / 51.8	✯ 4.81
4/2	-3.E-01 ± 1.2	0.4 / 41.8	✯ 1.81
2/4	-4.E-01 ± 6.8	1.4 / 3.5	■ 34.81
6/9	-2.E-02 ± 41.9	6.1 / 23.1	▲ 17.94
6/10	-6.E-02 ± 59.4	2.2 / 35.0	▲ 11.44
8/7	-8.E-02 ± 1.4	4.1 / 11.9	✯ 2.54
6/6	-5.E-02 ± 55.0	5.7 / 15.3	▲ 28.53
2/8	-3.E-02 ± 1.3	4.9 / 65.4	✯ 1.69
0/10	-4.E-01 ± 6.2	2.9 / 48.5	• 7.75
4/12	-7.E-02 ± 68.3	5.1 / 69.6	▲ 6.41
8/8	-5.E-02 ± 204	5.3 / 26.3	▲ 53.71
10/8	-6.E-02 ± 54.4	2.4 / 9.4	▲ 17.87
4/10	-7.E-02 ± 59.4	6.8 / 42.2	▲ 10.33
4/5	-1.E-01 ± 5.6	5.8 / 14.0	✯ 3.04
6/5	-2.E-01 ± 2.5	0.1 / 3.3	■ 3.04
5/7	-7.E-02 ± 61.1	4.6 / 21.7	▲ 13.60
5/7	-7.E-02 ± 36.6	2.9 / 32.7	▲ 8.67

Observing Table 4.3, we can see that eleven passes marked with triangle (▲) are rejected, because of the standard deviation greater than 10 Hz (σ > 10 Hz), other two are rejected due to maximal elevation constraint ($El_{máx} < 5^0$) and marked with squares (■). Two more passes with only one side of the Doppler curve marked with circle (•) also are rejected.

Finally, we notice for the SCD-2 orbit equatorial satellite that among 23 passages or Doppler curves, only 7 resulted in valid locations (with ✯). The high noise level in the measured Doppler (11 passages marked with ▲) can be basically credited to hardware problems such as: unstable on board oscillator of satellite that measures the sign frequency; unstable transmitter; PLL problems (" Phased Locked Loop ") to compensate for Doppler shift; satellite-station reception link problem; imprecise time stamp ("time tagging"); and others.

The Table 4.4 shows the results obtained for the same transmitter 109, in the same period, but using CBERS-1 polar orbit satellite.

TABLE 4.4
RESULTS FOR TRANSMITTER 109, CBERS-1 (▲ = σ > 10 Hz; ■ = $El_{máx} \leq 5^0$; • = all Doppler measurements > 0 or all < 0; ✯ = valid location

Data	Hora	Samples (+/-)	< residual ±σ> (Hz)	Elevation (°) min/max	Location error (km)
16-Jul-00	1:09	3/0	8.E-01 ±**13.7**	4.6 / 21.2	▲46.15
17-Jul-00	2:17	4/2	-4.E-01 ±3.3	7.0 / 47.0	✯0.89
18-Jul-00	1:41	**4/0**	-1.E+00 ±4.6	13.4 / 53.1	•14.54
19-Jul-00	1:05	3/0	1.E+00 ±**15.1**	4.1 / 18.1	▲210.23
20-Jul-00	2:12	5/0	-1.E+00 ±**312**	4.2 / 62.4	▲174.98
21-Jul-00	1:38	3/1	-7.E-01 ±2.8	12.3 / 58.3	✯7.30
23-Jul-00	2:09	9/1	2.E-01 ±**59.2**	0.7 / 55.4	▲15.16
27-Jul-00	14:06	1/5	1.E-01 ±**87.3**	3.4 / 73.7	▲5.49
2-Ago-00	1:19	**4/0**	3.E-02 ±1.9	7.9 / 16.2	•295.18
3-Ago-00	13:24	0/9	-8.E-02 ±**54.7**	1.8 / 29.3	▲91.63
4-Ago-00	1:53	**10/0**	-9.E-01 ±2.3	2.0 / 76.6	•79.76
5-Ago-00	1:18	**7/0**	-2.E-02 ±0.6	3.9 / 28.1	•1.49
7-Ago-00	1:49	8/1	-6.E-01 ±2.6	5.9 / 79.0	✯10.84

In this table, out of 13 only three locations marked with stars, were qualified. Six passes marked with triangles resulted in standard deviation greater than 10 Hz (σ>10 Hz), and the 4 marked with circles have just one Doppler curve section. The CBERS-1 polar orbit and the unfavorable position in latitude between transmitter and reception station, one in Guyana and the other in Cuiabá, contributed to the bad Doppler curve coverage. Eight passes also have only a section (+ or -) of Doppler curve, reflecting unfavorable geometry among satellite pass, transmitter, and receiver.

Figure 6 shows valid locations for both SCD-2 and CBERS-1 satellites. In total, we obtained 7 locations with SCD-2 and 3 with CBERS-1 satellites.

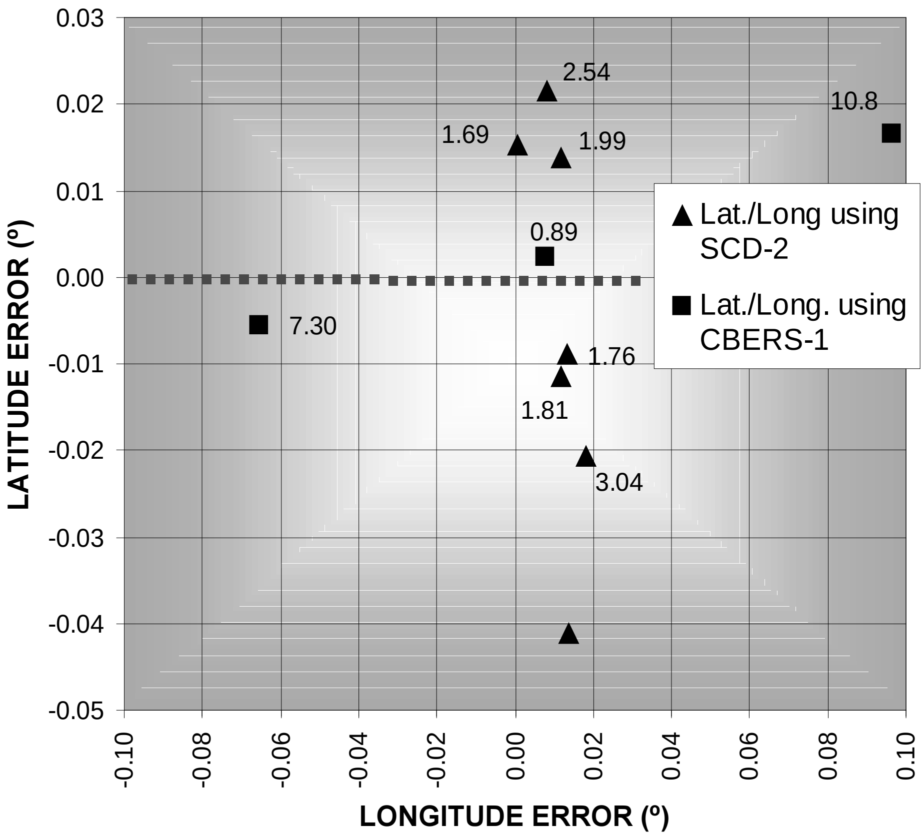

Fig. 6 - Location deviation of the Transmitter 109, from July to August 2000 using SCD-2 and CBERS-1 (values aside the symbols represent the distance (km) from reference).

Location error standard deviations are 1.20 km using SCD-2 and 5.04 km using CBERS-1. So we conclude that the positions 1-sigma deviations deviate from the actual positions with errors from 1.32 to 3.72 km using SCD-2 satellite; and errors from 1.30 to 11.38 km using CBERS-1 satellite.

5. CONCLUSIONS

This work described tests of a geographical location procedure and its performance, using real data obtained through three transmitters, several satellites (SCD-2, CBERS-1 and NOAA), and two different reception stations (one fixed in Cuiabá and one portable in Antarctica). It was also noticed that most of the samples rejections (not valid) were caused by the high residual standard deviation (> 10 Hz) of the Doppler data. For valid locations, the Doppler shift residual standard deviations using SCD-2 and CBERS-1 satellites were larger than 1 Hz (between 1 and 10 Hz); for NOAA satellites were smaller than 1 Hz, reflecting the different measurement system quality. Finally, we conclude that the procedure proposed and tested with real data is robust enough to supply reliable locations in several or even most adverse situations. In the monitoring oceanographic buoys, an error of up to 10 km can be acceptable. For person's monitoring and rescue, that error should be preferably smaller, around 500 m. For wild animals tracking, this error can vary depending of the animal type and application used. The results obtained in this work can be used in most of these situations successfully.

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