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GEO-LOCATION OF TRANSMITTERS USING REAL DATA, DOPPLER SHIFTS AND LEAST SQUARES

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ABSTRACT

In this paper we describe a new method implemented at INPE (Brazilian Space Research Institute) for obtaining the geographic location of transmitters, using Doppler shifts and a batch estimator based on least-squares technique. Near real-time geographical location of transmitters through satellite can be useful for many applications, such as to monitor and rescue people in remote areas, and to track animals and oceanographic buoys for scientific research. A representative data set used for the tests was collected by means of a portable reception station located in the Antarctic Brazilian Station (Antarctica), using the NOAA-12 satellite as data relay, and a transmitter placed in the nearby Elephant Island. In addition, we obtained data collected in Cuiabá Satellite Reception Station (Central Brazil) using the Brazilian satellite SCD-2 and a nearby Data Collecting Platform transmitter. This paper addresses the modeling of the Doppler shift measurements, the satellite dynamic motion, and the non-linear least squares technique applied to the problem. The results and analysis of the geo-location method are shown and depicted here, demonstrating the location accuracy of 3.13±1.51 km and 2.74±2.41 Km for the two data sets respectively, achieved by such a near real-time system. © 2003 Published by Elsevier Science Ltd.

1 INTRODUCTION

In Brazil, geographic location of transmitters is applied in the following areas:

a) in biology research, by fixing mini-transmitters in wild animals, to monitor their displacements and habits [1];
b) in oceanography research, launching drift buoys to study oceanic streams [2];
c) in emergency location and rescue of aircrafts and ships [3];
d) in field location and support to researchers of the Brazilian Antarctic Program - PROANTAR in Antarctica [4].

Up to now, the location of these mobile targets has been achieved through the purchasing of data from the French system Argos [5], which uses the NOAA satellites. The newly developed geo-location software presented here, will make possible to obtain geo-location data independently, using Brazilian satellites and reception stations. This method of near real-time (right after data reception) geographic location of transmitters and data collecting platforms (PCDs) through satellite is based on a recently developed work [6].

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In the following sections we summarize the modeling of the geo-location problem, using the Doppler shift measurements, the satellite dynamic motion, and the non-linear least squares technique. Then we show the results and analysis for two different transmitters in a typical condition, in which transmitter and ground reception station are close to each other.

2 BASIC MODEL: 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, the nominal UHF frequency signals periodically sent by the transmitter are received by the satellite and sent down to the reception station as shown Figure 2.1.

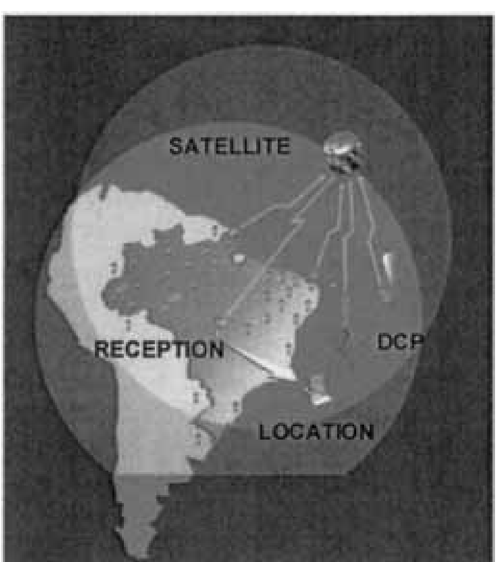


Figure 2.1 - PCDs location.

In a typical condition, where both are close enough, this period can last up to 10 minutes. The received data is then processed to generate the transmitter position information.

The satellite velocity relative to the transmitter ($v\cos\alpha$) in vacuum conditions, denoted by $\dot{\rho}$ is given by the Doppler effect equation [7] as follows:

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

where:

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

The Doppler curve is given by Figure 2.2, where b_0 and b_1 are constants associated with each Doppler curve to account for unknown bias in the Doppler measurements and a possible drift in the transmitter oscillator.

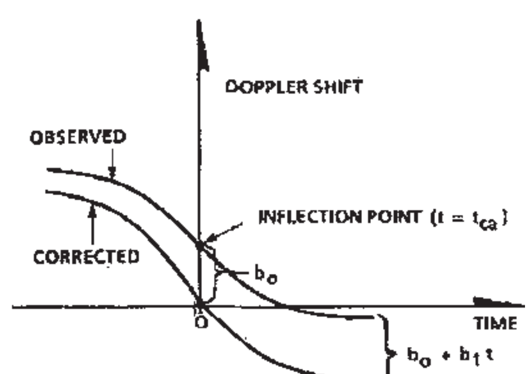


Figure 2.2 - Doppler curve.

The satellite ephemeris generator uses the SGP8 model of NORAD [8], for obtaining the satellite orbit at the measured Doppler shift times. The updated ephemeris are used within the Doppler effect equation to model the observations. Therefore, given the observations modeled by:

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

where:

a) y is the set of Doppler shifts measured during a single pass of the satellite over the transmitter;
b) $h(x)$ is the non-linear function relating the measurements to the location parameters and is also a function of the satellite ephemeris;
c) v is a noise vector assumed zero mean Gaussian;

the non-linear least squares solution [9] 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 orthogonal transformation [10] T such that:

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

where:

a) 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, drift, drift rate) around the reference values;
b) $W^{1/2}$ is the square root of the measurements weight matrix;
c) $S_0^{1/2}$ is the square root of the information matrix.

The δy_1 is such that:

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

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

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

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

3 RESULTS

The results and analysis of the geographic location method developed are shown here, demonstrating the location accuracy achieved by this near real-time system. We gathered representative data sets from two different transmitters collected in typical conditions, transmitter and ground reception station nearby:

i) Fixed Data Collecting Platform (PCD) with transmitter ID #32544, relaying data through the SCD-2 (Brazilian Data Collecting Satellite 2) to the nearby Cuiabá Reception Station (center of Brazil);

ii) Transmitter #23840 fixed in the Elephant Island (Antarctica) sending data through the NOAA-12 (National Oceanic and Atmospheric Administration) satellite to a portable reception station placed in the Antarctic Brazilian Station – EACF.

The following criteria were established for the analysis and validation of the results:

i) **σ > 10 Hz:** when the standard deviation of the Doppler measurement residuals is greater than 10 Hz the location estimate is rejected. The initial standard deviation is set to 5 Hz, and a result twice this value may indicate excessive interference or noise in the measured Doppler shift values and such results are discarded. This situation is identified by a triangle symbol (▲);

ii) $\mathbf{El_{máx} \leq 4^o}$: Collected Doppler data corresponding to satellite elevation lower than 4^o may suffer considerable effects of the atmospheric refraction and noise due to transmitter power attenuation, and also are discarded. These results are indicated by a square symbol (■);

iii) All Doppler samples > 0 or all < 0: if in a single satellite pass we obtain frequency samples covering only one side of the Doppler curve (Figure 2.2), i. e. either only positive (n/0) or negative values (0/n), where n is the quantity of positive or negative Doppler shift samples, the geographic location is obtained with degraded precision and also must be discarded. This situation is marked with a circle symbol (•);

iv) Finally, if we know a former position of slowly moving transmitters, we can compare it to the obtained geo-location for cross-validation.

3.1 Transmitter - PCD #32544, SCD-2 Satellite, Cuiabá Reception Station.

The sampling rate for this PCD is one transmission burst every 45 seconds, which leads to at most 13 possible Doppler data samples for a 10 minutes duration LEO (Low Earth Orbit) satellite pass. From July to August 2000 we collected 21 SCD-2 (750 km altitude) satellite passes with Doppler data for the #32544 transmitter as shown in Table 3.1.

From this table we can see that eleven results were rejected, because of the first criteria of Doppler shift residuals standard deviation greater than 10 Hz (σ > 10 Hz). Those results are marked with a triangle symbol in the column on location error. One location with circle symbol was rejected, because of the the third criteria, i. e., of all Doppler samples > 0 or all < 0.

The sample column shows a good Doppler shift curve coverage, with up to 10 samples per pass. This reflects a good geometry between reception station and transmitter, both at Cuiabá, obtaining simultaneous contact with the SCD-2 satellite.

After facing the established criteria, we ended up with 8 valid geo-location results (marked with stars) as shown in Table 3.2, with complementary latitude and longitude location information.

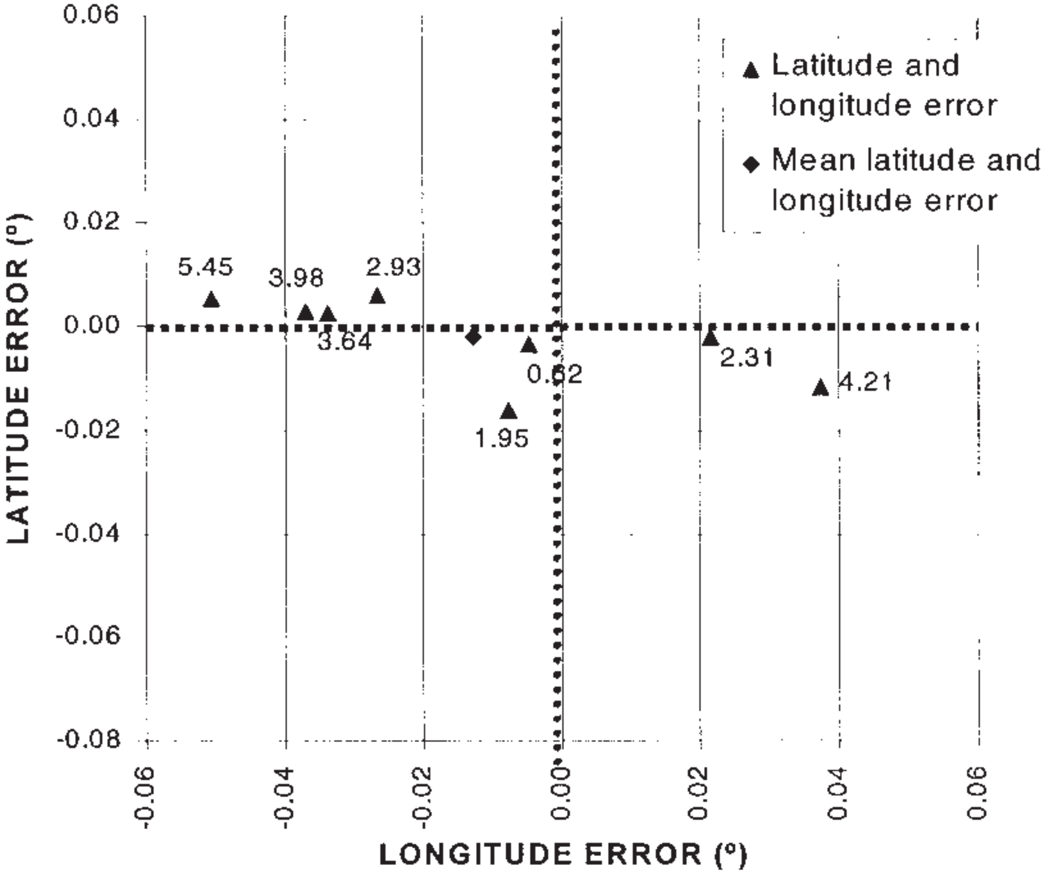


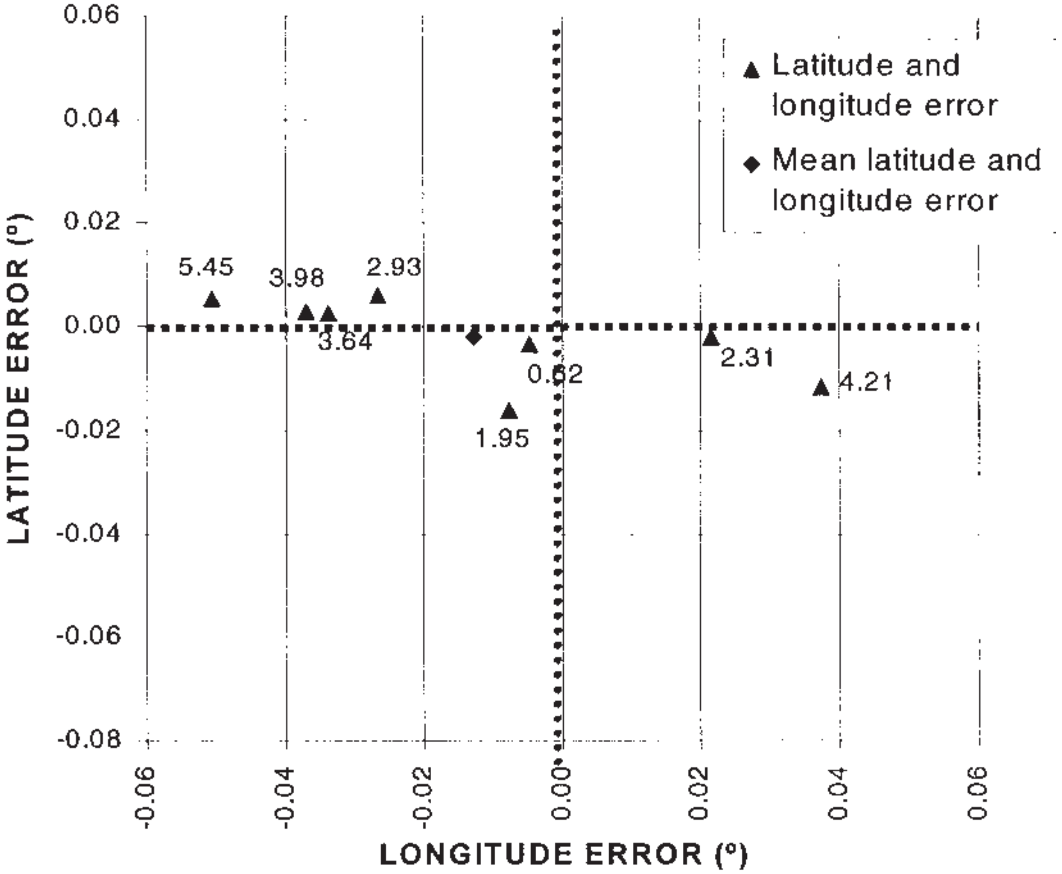
Figure 3.1 - Location error of Transmitter 32544, from July to August 2000, using SCD-2 satellite (values on side the symbols represents the distance to reference in km).

The latitude and longitude errors are represented in Figure 3.1. The location mean error obtained is 3.13 km and its standard deviation is 1.51 km, meaning that with 1σ confidence level the errors should range between 1.62 km and 4.64 km.

3.2 Transmitter - MTR #32840, NOAA-12 Satellite, EACF Reception Station

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) satellite pass. The MTR (see Figure 3.2) was build at INPE to support researchers in Antarctic missions. It has message codes that informs several situations, as for example, emergency. It was placed in the north of Antarctic Peninsula at Elephant Island as shown in Figure 3.3.

The Doppler data were acquired for this MTR operating from November 1998 to January 1999. After application of the validation criteria, resulted 6 geo-locations for the #32840 transmitter, as shown in Table 3.3.



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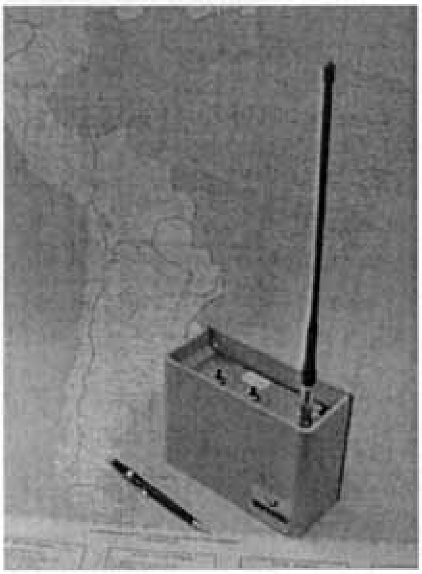

Figure 3.2 - Mini Remote Transmitter - MTR.

Figure 3.3 - Antarctic Peninsula - Elephant Island.

<Residual±σ> (Hz)	Samples(+/-)	Location Error (km)	Longitude(°)	Latitude (°)
3.E-01±0.8	1/2	1.75	304.650	-61.206
3.E-02±0.3	3/1	2.24	304.659	-61.235
1.E-01±0.3	2/1	4.14	304.700	-61.201
2.E-01±0.6	2/2	0.80	304.647	-61.216
6.E-01±1.6	4/1	0.57	304.627	-61.216
4.E-01±0.8	2/1	6.92	304.642	-61.281
	Mean	2.74±2.41	304.654±0.02	-61.226±0.03
	Reference	**0**	**304.634**	**-61.219**

Table 3.3 - Valid Geo-Locations for Transmitter - MTR #32840

From Table 3.3 we can see that the standard deviation of the Doppler shift residuals obtained are smaller then the standard deviation obtained for the SCD-2 satellite (Table 3.1). This is probably because of the better on-board NOAA oscillator stability.

The location mean error obtained is 2.74 km and its standard deviation is 2.41km, meaning that the errors mostly range between 0.33km and 5.15km.

All the reference latitude and longitude values were assessed by means of GPS receivers or geodetic means.

4 CONCLUSION

This paper showed geo-location results for two typical cases, using both the Brazilian SCD-2 and the NOAA-12 satellites, for transmitters located in center of Brazil and Elephant Island in Antarctica. The location errors were 3.13±1.51km and 3.97±2.30km respectively, which are suitable to the applications described herein. In oceanography research, an error of about 10 km is acceptable. In people monitoring and rescue, this error should be lower, from 2km to 500m. Depending on the application the required error level changes, nevertheless, the developed geo-location system has handled all these situations with relative success.

For valid geo-locations, the standard deviations of the Doppler shift residuals using SCD-2 satellite data were greater than 1 Hz (between 1 and 10 Hz). For NOAA satellite they were lower than 1 Hz, reflecting better quality of measurement samples. This fact can be credited probably to the better oscillator stability on-board NOAA satellite than of the SCD-2 satellite.

5 REFERENCES

1. 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 Portuguese) VII Seminars on Antartica research. São Paulo 2000. Program and abstracts. São Paulo, USP. IG. 2000. p.38.
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 V International Congress of the Brazilian Geophysical Society, São Paulo, 1997.
3. Techno - Sciences. COSPAR/SARSAT. [online] www.technosci.com/ 2000, Oct. 2000.
4. A.W. Setzer, "Manual do sistema de dados remotos." (in Portuguese) São José dos Campos, INPE, ProAntar project, 1997.
5. CLS - Service Argos: guide to the Argos System. Toulouse, September, 1989.
6. C. T. S Sousa,. 2000, "Geolocalização de transmissores com satélites usando desvio Doppler em tempo quase real." (in Portuguese) PhD dissertation, São José dos Campos, INPE, 2000.
7. R. Resnick, "Introdução à relatividade especial." New York, Wiley, 1968
8. F. R. Hoots and R. L. Roehrich, "Models for propagation of NORAD element sets," Aerospace Defense Command, Peterson, AFB, Co., Spacetrack no. 3, Dec., 1980.
9. G. J. Bierman, Factorization methods for discret sequential estimation. New York., Academic, 1977.
10. C. L. Lawson and R. J. Hanson, "Solving least Squares Problems." Englewood Cliffs, Prentice, 1972.