Performance Analysis of a L1-C/A Code Smoothing Receiver Under Field Conditions of Land Reform in Brazil

Julio C. Farret[1] and Marcelo C. Santos[2]

[1]*Setor de Geodésia, Departamento de Engenharia Rural*
Universsdade de Santa Maria, Santa Maria, Brasil
[2]*Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering,*
University of New Brunswick, Fredericton, Canada

BIOGRAPHY

Julio Cesar Farret is Professor at the University of Santa Maria, in Santa Maria, state of Rio Grande do Sul, Brazil, where he teaches Surveying and is responsible for research and extension activities involving GPS and providing technical consultation on rural and legal surveys. He holds a doctoral degree in Geodetic Sciences from the Federal University of Paraná, Curitiba, Brazil.

Marcelo Santos is an associate professor in the Department of Geodesy and Geomatics Engineering at UNB. He holds a M. Sc. in geophysics from the National Observatory in Rio de Janeiro, and a Ph.D. in geodesy from UNB. He has been involved in research in the fields of space and physical geodesy, GNSS, and navigation. Dr. Santos is currently the president of the Geodesy Section of the Canadian Geophysical Union and chair of the International Association of Geodesy Working Group on the use of Numerical Weather Models for Positioning.

ABSTRACT

The recent law 10267/2001 [17] introduced the Brazilian National Cadastre of Rural Lands in Brazil (CNIR). It determines that legal surveys should be attached to the Brazilian Geodetic System with accuracy of 50 cm 1 sigma. It also determines that the professionals who carryout those surveys to be under legal professional responsibility and passive of punishment in case of proved technical errors. This is an aspect which concerns professionals who make intensive use of satellite positioning. The capability of a GNSS receiver to keep in the field conditions same accuracy as its design is not always seen with care and attention needed. It is common professionals not being able to realize in the field the nominal performance of the system, especially in situations which represent a challenge in terms of signal obstruction and, mainly, the multipath. This may bring serious consequences if the professional is penalized for technical errors. Said that it is important to know the quality indicators given by the manufacturers, the adequate use conditions of the receiver and, mainly, analyze correctly the real capability of the internal characteristics of the receiver for realizing the measurements according to its design. The receiver internal characteristics include several ways to treat the interferences, noise, and multipath. This work analyzes the characteristics of a specific receiver, the Leica GS20, due to its use in surveys aiming at attending the CNIR, where it has been an option for problematic sites in terms of coverage, since it gets to maintain tracking in order to estimate the desired coordinates with relatively short occupation time. However, there are still some uncertainties with respect to the real capability of it, especially when using smoothed pseudoranges as basic observable. In this work, we tried to reproduce the common conditions of surveying for georreferencing as given by CNIR. The main technologic characteristics of the analyzed system are the use of special antennas, code smoothing pseudorange by carrier-phase measurements, and the use of correlators with spacing specially reduced in the tracking loops. The analysis of the results was done based on noise, measurement precision and, mainly, in the external analysis of the coordinates accuracy.

INTRODUCTION

Regardless efforts of researchers, it has still been common the reference of multipath as the last frontier, challenging the scientific community and the equipment industry [9]. The proposed solutions to treat the problem before the signal gets in the receiver, i.e., adequate location of the antenna and design of it, do not have strong practical connotation, once there is no environment which is totally free of multipath, as well as the special antennas still have deficiencies, with occasions in which the problem is not totally solved. This challenge is even bigger when the user is forced to use the antenna in a location which is not the most appropriate in the sense of the geometry of the signals between satellites and receiver, nature of the materials of the environment and presence of signals alien to the system, when deficiencies appear for given applications. This occurs because the receivers are designed for optimal performance within determined noise levels, which can be reached in situations with bad geometry and unexpected nature of the reflecting materials. Make the receiver to maintain the good performance even without the best tracking conditions, such as in case of signal attenuation, low satellite availability and, mainly, multipath, is a challenge. It can be confronted with adequate algorithms of signal treatment within the receiver, which is a challenge to the designers of it. Equipment companies have developed research to overcome this challenge.

1.1 Justification

A problem encountered by final users is not being capable of realizing, in the field, the full capability of positioning given by the use of modern technologies, as well as identifying and understanding the parameters provided by the manufacturers as indicators of this quality. It is a concern when repetitions of the survey under the same conditions return results with discrepancies different from expected. This brings serious consequences when problems in the technical work translate themselves into legal punishments to the professionals, what can become a legal problem, as well to the manufacturer or its representative, especially in the case of the current registering Brazilian system. It is common for the manufacturers to link the realization of the nominal accuracy of the system to factors such "reasonable conditions of multipath, closeness of buildings or density of foliage of trees". These terms can be declared as ambiguous and not enough, having to be better clarified, especially in terms of distance, material nature and reflector size. One of the reasons for eventual lacks of performance of technologies based on receiver in limit situations appears to be the conditions in which their performances are analyzed when they are being developed, sometimes only in a synthetic manner. It is impossible to predict the diversity of adverse conditions in terms of signal geometry, interference and materials nature to which the receiver will be used over its lifetime.

Because of this, more than a simple comparative analysis between receivers, it is interesting the analysis of the capability of them in assuring certain levels of accuracy for positioning which are required in specific applications and considering realistic scenarios.

1.2 The use of GNSS in rural cadastre in Brazil

An interesting case of application of navigation satellite systems is the current land register system in Brazil. In this system the technical components (descriptive memorial and plot) have to be certified by the National Institute of Colonization and Land Reform (INCRA) before they go to the public registry. The surveys have to be realized according to the Technical Norms of Georreferencing of Rural Land, from now on, called here simply as Norm [17]. Certifying is the legal act of analysis of agreement with the Norm. Even though there are deficiencies in the Law text, which make difficult a rigorous interpretation of it, it is understood that the legislators want to set the realization of the SGB with minimum accuracy of 50 cm, with an uncertainty level of 1 standard deviation, what means 68 % already included the random and systematic errors.

1.3. The Technical Norm

The principle of the Norm is that the survey carried out according to it will necessarily have the quality required by the Law. However, the problem of multipath, mainly, does not allow this statement to be totally valid, what is a legal problem to its implementation, since it is possible to have worse accuracies than the one required, even strictly following the Norm. The multipath is not a completely detectable and controllable phenomenon. For this reason this Norm, as all others in general, does not show value indicators and safe parameters which treat in an adequate way the problem of multipath in surveying, but only preventive suggestions, such as the adequate location of the antennas. The Norm, therefore, is far from treating the multipath problem. This represents a problem for the surveys control, since eventual faults might be attributed to multipath, whose verification is complicated.

1.4 Technical Responsibility

Another fundamental aspect of the Law 10.267/2001 [17] is defined in its 3rd paragraph, which legally links the realization of the registry survey to the technical responsibility of whoever has done it, through a document called "Technical Responsibility Annotation" – ART, making it subject to control also allowing the due legal penalties in function of technical errors, in specific and proven cases, denying the professional activities of the professional. At this moment it is fundamental the domain and the security, at the professional side, and at the manufacturer side, of the real capability of the system to assure the realization of the survey with the quality required by law and according to the recommendations of the Norm. Here there is a doubt: In case of professional penalization for an eventual error, having him worked according to the Norm, is it a fair the punishment? Or, on other hand, will he/she be able to connect the error to an eventual deficiency of the equipment? In this case, it is acceptable the allegations of the companies which do not make themselves responsible for eventual losses caused by the use of the system for being only receivers of signals from systems which they have no control over the integrity?

1.5 Objectives

The present work tries to help the professionals who act in rural land georreferencing in Brazil, as well as in applications with similar conditions as the ones studied here (such as forestry surveys), which use the package of technologies merged in the analyzed receiver. Other technology packages put together in other receivers for realization of the CNIR are analyzed in other works. We hope also to help the designers, letting them know eventual deficiencies which might be improved in the future.

2 RECEIVER LEVEL ALTERNATIVES

In signals of the type *Phase Shift Keying (BPSK*), as in the case of GNSS, some alternatives for signal treatment might be explored for the correlation of the replica generated in the receiver with the signal which arrives from the satellite, in a way that the multipath can be attenuated at this level. This will generate the phase measurements, Doppler and emission time by the satellite with better accuracy. It might be searched the estimating of the multipath parameters and their corrections, as done by the technology *Multipath Estimating Delay Lock Loop (MEDLL)*, for example, or the separation of the line-ofsight of the direct signal with respect to the composed signal, which is the resultant of the direct signal contaminated by multipath, as done by the technologies Narrow Correlator and Strobe Correlator, for example. Simultaneously, it is possible to act in the duration of the integration time of the joint pre-detection with an adequate choice of the corresponding loop bandwidth (phase or code) and in the spacing between the correlators. There are also alternatives such as the use of multiple correlators, code smoothing with phase and the so called reference-waveform, with possibilities of extension, modification or conjugation among these techniques. The exploration of these alternatives over the past years resulted in processing techniques, usually patented, such as: *Narrow Correlator* [11] and *Multipath Estimating Delay Lock Loop* – MEDLL [27] – NovAtel receivers, *Strobe Correlator, Enhanced Strobe Correlator* and *Edge Correlator* [12] – Ashtech receivers, *Gated Correlator* [3], *Multipath Mitigation Correlator* [26] and *Smoothing* [15] – Leica receivers, among others. This makes the receiver processor to be the "heart" and, at the same time, the "black box" of the user segment, where there might exist performance differential factors between them.

2.1 Techniques used by Leica GS20

The conjunct of resources used in this receiver is what the manufacturer calls ClearTrak^{TM} Technology, which includes some results of the developments achieved by it over the years, presented in scientific publications [14, 16] and registered patents (U.S. Patent No 4,972,431, emitted in November 20th 1990 and U.S. Patent No 5,535,278 emitted in July 9th 1996, among others). The complete aspect of this package was implemented for the first time in receivers of the 500 series [16] involving the optimization of the L2 tracking, the "true" attenuation of the multipath, protection against interferences to the signal and the compatibility with future signals coming from the modernization of the systems ("optimized L2 tracking, true multipath mitigation, interference protection and future signal compatibility"). Due to the receiver used in this work to be a L1 receiver, the major focus will be given to the capabilities of multipath and interference attenuation present in the design of the processor of it. In this work these techniques are analyzed looking into the worst case scenario, i.e., until it is known from the literature, under limit conditions. It known that receivers which have an adequate and well design package of resources for signal tracking, mainly in terms of processor, might get accuracies of 0.50 meters or better in position of corrected points with respect to a reference station e having as basic observable the pseudorange with smoothed code, for cases of weak obstruction, multipath or signal interference.

2.2 Anti-Interference

Measurement errors are made by the tracking loop receivers. The L1 frequency is worldwide protected by the governments for navigation purposes. Even then, there is no guarantee of non-interference caused by very near sources or by superimposed signals, producing time side lobs in the ideal signal. This causes more problems in signal acquisition than in tracking it, which might require a longer time to the receiver to start tracking than causing deterioration on the quality of the tracking of the signal. Excluding the big problem which is the multipath, the interferences are the main error sources in range measurement at the receiver side, together with the thermal noise jitter. According to [18], the reception errors and noise of modern receivers, at 1 sigma, are in the order of decimetres in nominal conditions (no external interference), i.e., they are negligible if compared with code multipath. The proposals included in the receiver used in this work to reject interference are a filter of the type SAW ("Surface Acoustic Wave") to eliminate the interference "out-of-band" and an "adaptative, multi-level signal sampling" to minimize the interference "in-band". Details and results of these resources can be found in [26].

2.3 Anti-Multipath

The anti-multipath tools implemented in GS20 receiver include the use of antennas with special characteristics, filtering code measurements with carrier aided smoothing, and the technology called by the company as "MM Correlator" [26], for which details were not possible to be obtained. Other alternatives could be the estimation of multipath by means of multiple correlators and the use of correlators with reduced spacing in the correlation windows between the replica of the signal (code and phase) generated in the receiver and the signal received from each satellite, to detect the peak of the correlation function aiming at obtaining the transmission time of the signal, even though they are not totally excluding. According to [26], the use of multiple correlators is not done for cost and complexity reasons, since many correlators would be necessary for each satellite to model a limited number of the most significant multipath signals. This is an important statement, in the sense that the use of multiple correlators is an alternative of signal treatment used in other narrow band receivers and it is object of analysis in a separated work. The pure and simple comparison of these technologies is not a goal of this work. The capacity of answer to a specific demand according to the norm is analyzed in this work.

For a signal BPSK-1020(1), as the case of C/A code on GPS L1 carrier and using a noncoherent early-late power DLL discriminator, it is possible to compute the thermal noise code tracking jitter, represented by the standard deviation of the error of code tracking, given by (1), (2), and (3), according to [18].

$$\sigma_{tDLL} = \sqrt{\frac{B_n}{2C/No} D \left[1 + \frac{2}{TC/No(2-D)}\right]}, \quad para \quad D \geq \frac{\pi R_c}{B_{fe}} \tag{1}$$

$$\sigma_{tDLL} = \sqrt{\frac{B_n}{2C/No}\left(\begin{array}{c}\frac{1}{B_{fe}T_c} + \frac{B_{fe}T_c}{\pi - 1} \\ \left(D - \frac{1}{B_{fe}T_c}\right)^2\end{array}\right) x \left[1 + \frac{2}{TC/No(2-D)}\right]}, \quad para \quad \frac{R_c}{B_{fe}} < D < \frac{\pi R_c}{B_{fe}} \tag{2}$$

$$\sigma_{tDLL} = \sqrt{\frac{B_n}{2C/No}\left(\frac{1}{B_{fe}T_c}\right)\left[1 + \frac{1}{TC/No}\right]}, \quad para \quad D \leq \frac{R_c}{B_{fe}} \tag{3}$$

σ_{tDLL} = Thermal noise code tracking jitter (in code “chips”)
$B_n =$ Code loop noise bandwidth (Hz)
$T =$ Predetection integration time
$D =$ Correlator spacing
$C/No =$ Signal-to-Noise Ratio

The expression (1), (2), and (3) show the relation between the pre-detection integration time, the correlator spacing, the noise bandwidth and the signal-to-noise ratio. Interesting results using this expression can be found in [18]. For example, considering $B_n =$ 0.2 Hz, $T =$ 0.020 sec, $D =$ 1 and with a front-end receiver bandwidth equal to twice the chip rate we have C/A code accuracy values varying from 4 meters, to a $C/No = 27$dB-Hz, until 0.5 meters to a $C/No = 45$ dB-Hz. The same source show the same analysis varying the correlator spacing, noise bandwidth and predetection integration time values.

2.3.1 Correlator spacing

This resource is essential for an efficient GNSS receiver signal tracking performance especially along with an appropriate detection integration time values and signal tracking loops bandwidth. According to [1] and [2] Leica receivers detection integration time is 5 ms and clock sample rate is 40 MHz, although it was not possible to confirm these values with the manufacturer for the specific case of the receiver analyzed here. The detection integration time must be long enough to tolerate low values in the processor’s operation limit (lower C/N_0 threshold) what happens also to bandwidth reduction. It directly influences the correlation function slope, in which the peak detection is essential to distance measurements precision. Wide correlators were used in the first GPS receiver generation and they are equivalent to a C/A code chip (293 metros length) and it is ideal to signal acquisition process. After this period, the variation to smaller intervals, showed by [11] and [27], helped to improve signal tracking performance especially under the presence of multipath, but they have a limit due to the tracking dynamic sensibility. A narrow correlator has, on average, 10% of a wide correlator length. The GS20 manufacturer has patents for different correlator spacing.

2.3.1.1 Results provided by the manufacturer

The multipath attenuation methodology used in the receiver analyzed in this paper is described in [14] and [26]. It was initially named Leica “Type A” Multipath Mitigation Correlator, Leica “Type B” Multipath Mitigation Correlator and Phase Multipath Mitigation. The relation of the last two with respect to the first one was presented in a technique called Multipath Mitigation Correlator – MM Correlator with code and phase multipath and interferences attenuation capacity. The MM Correlator technique is implemented in a package that the manufacturer calls Clear Track. Synthetic results can be found in [26] where the MM Correlator is compared with the standard wide and narrow correlator, with the multipath signal having half of the direct signal amplitude, which corresponds to a quarter of its power. Pseudorange errors tend to zero to any multipath delay larger than 0.05 C/A code segment (14.7 meters) with a 25% maximum error with respect to the narrow correlator. Due to the scenario characteristics in this work, where the signal is under attenuation and multipath caused by tree leafs and vegetation from forestry near the antenna, it is interesting to look into a real situation with results under foliage. In [26], a comparison is made between the narrow and MM correlators. The last one has shown better results with 1.44 m standard deviation against 3.95 m of the former. An important detail from this result is that they took place without using phase-smoothed code exactly emphasizes the real capabilities of the MM Correlator technology.

2.3.2 Special antennas

This section deals with flat and choke-ring antennas [30] or antennas with Left Hand Circularly Polarized (LHCP) signals attenuation capacities which is the reflected signal polarization the other way round of the direct signal that have Right–Hand Circularly Polarized (RHCP) signal [4], [20], [21]. The efficiency of the LHCP technique is partial since only some parts of the left hand circularly polarized signals are attenuated along with some of the direct signal. This fact indicates that this technique should be used along with others, similarly with what happen with the Clear Track technology.

2.3.3 Carrier-smoothed code

Perhaps the main characteristic of the receiver analyzed in this study is the phase-smoothed code. According to [25] results from this technique became better after SA (Selective Availability). More precise absolute positioning is possible using code smoothing and precise ephemeris combination. An advantage of this technique is that it does not depend on ambiguity resolution. This idea was presented in [15], without any patent following it, with further improvements shown in [19]. The algorithm is designed in such a way as phase and code measurements are weighted differently during the survey. An estimate of this weighting scheme is showed in [19]. Reference [8] determined experimentally that the mean tracking time for the GS20 code smoothing to achieve better accuracy in static mode is 2.5 minutes. This time may be needed in the optimization algorithm against fortuitous cycle slips. In case of a cycle slips the algorithm calls for a new initialization process, causing errors depending on how the cycle slip is treated, e.g., using Doppler values between consecutive epochs. This is an important aspect for the good behaviour of this methodology and became of practical interest especially in hard tracking environments under multipath, with frequent occurrence of cycle slips. In the present work we tried to glance at these slips in a real environment while the receiver approaches the forestry reflector and its influence on the position quality.

2.3.4 SNR and code measurements error

As shown in equations (1), (2), and (3) the receiver depend, among another factors, on signal-to-noise ratio (SNR) or C/N_o to measure the receiver-satellite distance. The C/N_o express the ratio between the received signal power (in Watts or Joules/sec) and the noise power spectral density (in Hertz). The C/N_o measurement is connected with the I (in-phase), Q (quadrature-phase) signals and noise integration time and its quality is fundamental (which also justify importance of the integration time) since it is considered the more important quality control parameter on baseband receiver level. Based on this it is possible to project the receiver signal processor behaviour as the noise function specially the tracking threshold. Taking into account code loop noise bandwidth, double-sided front-end bandwidth, chip period, pre-detection integration time, correlator spacing and SNR/CN_0 values we can evaluate, for example, the theoretical tracking errors. Indicative values to this parameters receiver's trademark analyzed in this work can be seen in [1] and [2] even so it was not possible to confirm, from the manufacturer company, the values used specifically in the GS20. Using these values and taking into account the observed SNR value on this work we find very low tracking error values even in the more problematic points where there was a decrease in SNR values due to a, increase in noise caused by multipath. However; this reduction did not reach the lowest tracking threshold limits which let the receiver continuing working. The big problem however is that the multipath has direct effect in the receiver measurements with consequences in the estimated positions, as can be seen here.

3 DATA COLLECTION METHODOLOGY

For the data collection used in the present work we used GS20 receivers under multipath and signal blockage conditions, i.e., near and under forest canopy, which is a common scenario in rural legal surveys in Brazil. The data were processed to generate statistics to help analyze the receiver's capability to provide coordinate estimates as near as possible to the reference values. However, immediately before the data collection we tried to obtain SNR values depending only on the antenna location, and not on another factors, for example, satellite geometry variation. For this purpose, phase measurements were collected for one minute on all of the test points without turning the receiver off, but only fixing the point feature in the receiver. We called this a "SNR preliminary test". This was done because the Rinex files from code smoothed surveys do not provide SNR values.

3.1 The experiment scenario

Figure 1 shows the experiment scenario along with the surveyed points numbered from 1 to 5. These points are equally spaced by 20 m. The pine forest is about 25 meters high. These points are almost perpendicularly aligned to the forest line by 80^o azimuth. This configuration provides each one of the points with distinct multipath conditions varying from very low (points 1 and 2), middle situation (point 3), to a very strong multipath condition situation (points 4 and 5).

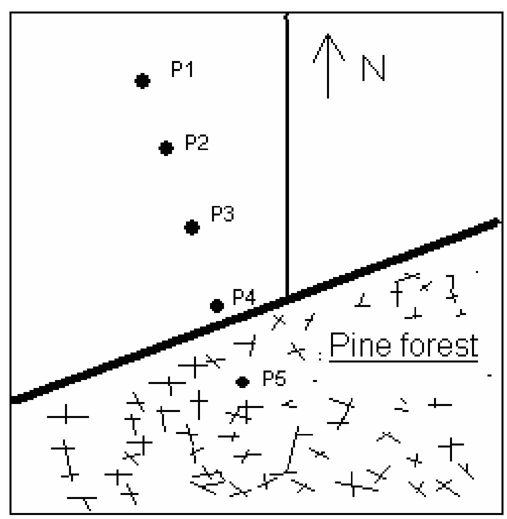

Figure 1: Surveying scheme

3.2 The experiment

The GS20 receiver was tested following the Brazilian legislation using smoothed code, in a post-processing differential positioning, equivalently to a DGPS, but not in real time. The DGPS corrections were generated from the high precision reference station SMAR, which is part of the Brazilian CORS (RBMC). Station SMAR is located 300 m from the points. Data processing was carried out using GisDataPro software [21]. Each one of the test points was occupied 30 times to produce enough information for a statistical analysis, to check for any systematic trend and to make possible to analyze the multipath attenuation methodology behaviour implemented in the receiver. Measurements were repeated in 2 consecutive days and with similar geometry, i.e., approximately in the same sidereal times which is equivalent to 60 repetitions to each point. Each repetition consisted of a 2.5 minutes session and a 1 (one) second observation interval as used. The choice of session length follows experimental results from [8]. Points 1, 2 and 3 were reprocessed using the same number of satellites in view as points 4 and 5 to ensure that loss in quality was not due to a lower number of satellites but due to multipath and noise. This extra processing confirmed this fact. Also C/N_o values were extracted to detect fortuitous signal processing problems while increasing the tracking difficulties.

3.3 Reference coordinates determination

Reference coordinates of points 1 to 5 were obtained from in the SIRGAS2000 frame and taken as "truth" in this work. To guarantee the independence of these coordinates, precise measurements of angles and distances were used. The quality of these coordinates was carefully verified and final closure on high-accuracy known points was millimetre in both azimuth and coordinates. The programs employed for this work were elaborated by the Geodesy Sector of DER/UFSM.

3.4 Receiver and tracking configuration

The GS20 is a single frequency receiver that in the present work was employed with an AT501 Pole antenna. According to the manufacturer this receiver provides "a typical 30 cm RMS precision in post-processed baselines using smoothed code". It did not state the baseline precision in ppm. Also, it does not show the tracking conditions necessary to obtain the nominal position quality, especially tracking time, interval between epochs, and distance from the reference station. There is only a note on the equipment's accompanying materials that the quality stated depends on "favourable conditions". The maximum baseline length is not evident in the manuals [20], [21]. The manufacturer representative officially informed INCRA that for rural legal surveys the distance is 250 km with respect to a known point belonging to one of the networks sanctioned by the Brazilian Institute of Geography and Statistics (IBGE). Anyway, the representative informed that the quality is conditioned by "conditions of the GPS system such as the reference station data quality, satellite's geometry, multipath, signal blockages, and atmospheric conditions", without providing any guideline on how these conditions are met or any control criteria. This work tries to address at least part of this issue.

3.5 Statistical parameter

The development of the statistical parameter used in this work can be found in [13]. The accuracy for each point is a function of its reference coordinate. In the case of large samples it can be expressed in the follow way [7]:

$$\sigma_{E_V} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(E_i - E_V)^2}\,, \tag{4}$$

$$\sigma_{N_V} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(N_i - N_V)^2}\,, \tag{5}$$

where E_v and N_v are the reference coordinates in the UTM system. As this region is close to the UTM line of no distortion, scale distortion is negligible, therefore ignored. The accuracy of the position is given by:

$$\sigma_P = \sqrt{\left(\sigma_{E_V}\right)^2 + \left(\sigma_{N_V}\right)^2}\,, \tag{6}$$

To help identifying the solutions for each of the 5 points in the 2 days we used GS1 to identify the measurements made with the GS20 at the point 1 and D1 to refer to the first day. Therefore, point 1 on day 1 is identified as GS1_1D, point 1 on day to as GS1_D2, and so on.

3.6 The challenge of limiting environments

In forest environments the reflectors can be situated very close to the antenna (a few centimetres) or far from it (several meters), they may have different sizes, textures, forms, and compositions, and eventually, they can be moved by the wind. In the case of the present study, the materials are mostly organic (mainly leaves, branches and trunks) with electric and geometric properties not very clear. This has an influence on the form and the length of reflected wave, making difficult to classify what kind of predominant multipath exists in this kind of environment: specular or diffuse. Probably both are present. The problem becomes more involving by the difficulty to foresee the behaviour of the reflected signal phase and amplitude which are a function of the reflection coefficient. The latter is a function of the reflector material properties and the incidence angle, which are also difficult to model, due to polarity inversion depending on Brewster's angle [6]. This might be the reason why the authors in [26] had used a foliage environment. In previous researches on techniques to phase multipath reduction by the manufacturer the best performance was obtained with a reflector more than 7.5 meters away from the antenna. There are empirical ways to model the signal attenuation by trees [24] in a probability distribution basis. Still from [24], the attenuation is 35% greater in trees with leaves than in trees without them. It is also a frequency function. In terms of the kind of tree, it varies from 1.1 dB/m for pin oak to 4.6 for dB/m Norway maple. For large trees, it is in the frequency of 1.575 GHz. The number 2.4 is used as a medium value, being the same value for other kinds of pin oak. The attenuation by pine trees, analyzed here, is the strongest among other types of trees, suggesting that research deals with limiting situation. These values take into consideration the width of the forestry, what justify this study directed to specific conditions. Figure 2 shows a typical environment of survey for the CNIR indicating the local of a surveyed point with tracking issues.

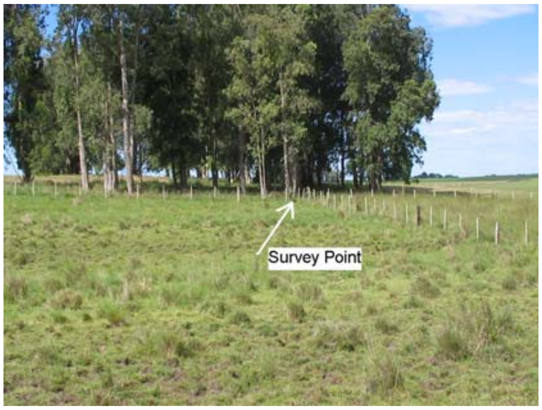

Figure 2 – Typical scenario of a rural cadastral survey in Brazil.

4 RESULTS AND ANALYZES

4.1 Signal-to-noise ratio, multipath and tracking error

The relative multipath to direct signals amplitude ratio was calculated taking into account the parameters variation during the preliminary SNR test. This calculation was made based on [12] and, because point 1 was the most distant from the reflector, it has the lowest multipath, larger SNR, and larger relative multipath to direct signals amplitude ratio (α), which has a theoretical value of 1 for this point, i.e., there are no reflected signals. The phase and code measurement RMS values were extracted from the data processing, i.e., the quality indicators of these measurements. Table 1 shows this SNR, phase and code RMS, and relative multipath to direct signals amplitude ratio linked with signal geometry (azimuth and elevation) to each satellite identified by the PRN number at the moment of tracking.

The behaviour of these parameters approaching the reflector, during the transit from point 1 to the point 5, indicates the increase in multipath and noise. Analyzing Table 1 we can see, for example, the increasing value of relative multipath to direct signals amplitude ratio with approximation of the obstacle. It happens, specially, because of the strong reduction of SNR values, mainly to satellite PRN 2, 13, 23, and 27. For all these satellites (that shown the larger SNR variations), however, phase and code RMS values were not the worst ones, specially the code in spite of the larger values of relative multipath to direct signals amplitude ratio. This behaviour apparently keeps relation with the squaring effect on the geometry between the directed and reflected signals, the tracking error, and the SNR, as shown in [2] and [12].

PRN	**2**	**4**	**8**	**13**	**20**	**23**	**27**
Az	244	285	292	166	33	113	254
Elevation	16	27	46	56	31	44	68
SNR	43-30	46-43	50-45	50-42	46-44	49-37	50-44
Phase RMS	0.005	0.006	0.004	0.004	0.005	0.004	0.004
Code RMS	0.626	0.944	0.767	0,705	0.927	0.422	0.657
Ref. Coef. - α	0.63	0.17	0.28	0,43	0.11	0.59	0.33

Table 1- Relationship between satellite geometry and quality indicators

Taking into account that the line of the main reflector has an azimuth of approximately 80°, the satellites with azimuth varying between 60° and 100° and between 240° and 280° crossed closer to the reflector's edge, as the case of the satellites 2, 23 and 27, with a geometric situation between direct and reflected signals closer to being perpendicular. These satellites showed the best code measurements RMS values but not always the same happened to phase measurements RMS values. When the azimuth is between 100° and 240°, the satellites have the line of vision blocked by the reflector, as the case of satellite PRN 13, but with a relative co-linearity between the directed and reflected signals and that showed one of the best phase RMS values and an intermediary value for the code. From 280° to 60°, they have this line unblocked too and with approximately co-linear signals, which is the case of satellites 4, 8, and 20 that indicated the worst values for code measurements.

This behaviour was coherent with [12] and [2]. Although, we should consider some important exceptions that caused variations in these values. One of those is the fact that the SNR (or C/N_o) is just a normalized estimate of the received signal power according to the bandwidth tracking loop, and it is not the direct signal power, which is taken in a special way for each manufacturer. It demands special calibration process and it was not in the scope of this work. Another important safeguard is the peculiarity of the reflector, especially with respect to its irregular shape closer to the antenna environment and regarding the nature of the material it's composed. It is very difficult to define the reflected signal behaviour in terms of direction, with consequent difficulty to define the geometry between the direct and reflected signals mainly around the antenna. Details and other results about this type of analysis can be found, for example, in [6] and [12].

4.2 Results from parameters extracted from test point surveys

Only results for point 3 (similar to points 1 and 2) and 4 (the point closer to the forest border) are shown. Results for point 5 are worse than for point 4, therefore not shown. Figures 3 and 4 show the residuals of the measurements collected at each point to each tracked satellites. While at point 3 these values have a variation between ± 1 m, at point 4 the variation is ± 4 m. One of the factors that explain the poor pseudorange measurement quality in point 4 is the huge increase of cycle slips while the receiver approaches the reflector which is a factor that affects points tracked with smoothed code.

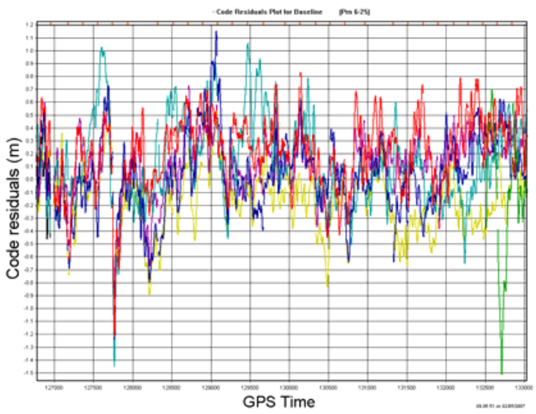

Figure 3 - Code residuals at point 3

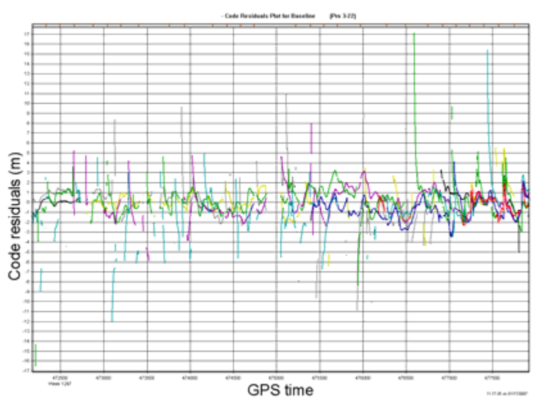

Figure 4 - Code residuals at point 4

The most direct analysis of multipath and noise was made through double difference residuals. The methodology for its calculation can be seen in [29]. Figures 5 to 8 show this quantity for satellites 15 and 21 and points 3 and 4, taking as reference satellite the one with higher elevation angle. The larger values for point 4 are confirmed according to Figures 6 and 8. Satellite 15 at point 3 shows these values varying by 3 meters, while at point 4 this variation is larger than 15 meters. For satellite 21 this variation is about 5 meters for point 3, and reaches 18 meters for point 4. These numbers prove the increase in multipath at the reflector neighbourhood. Please, note that some effects of geometry still exist in figures 5 to 8.

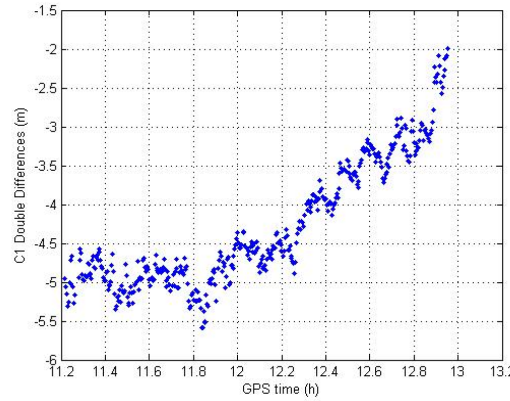

Figure 5 - residual DD for satellite 15 at point 3

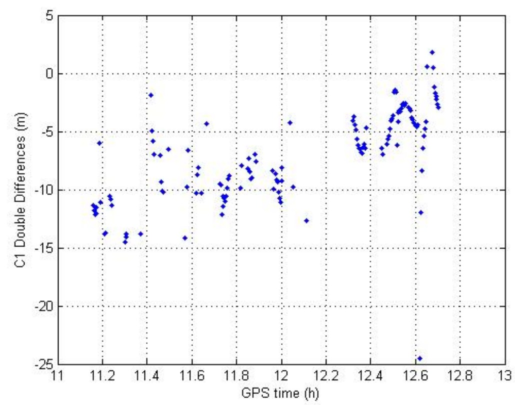

Figure 6 - residual DD for satellite 15 at point 4

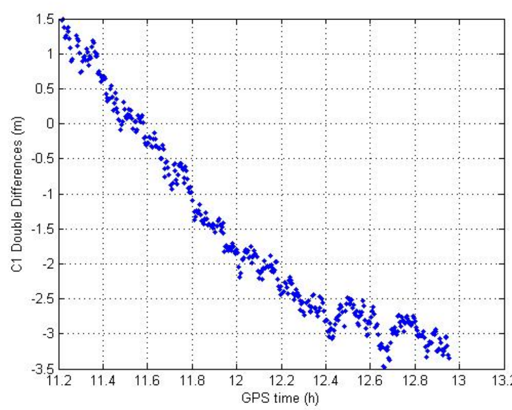

Figure 7 - residual DD for satellite 21 at point 3

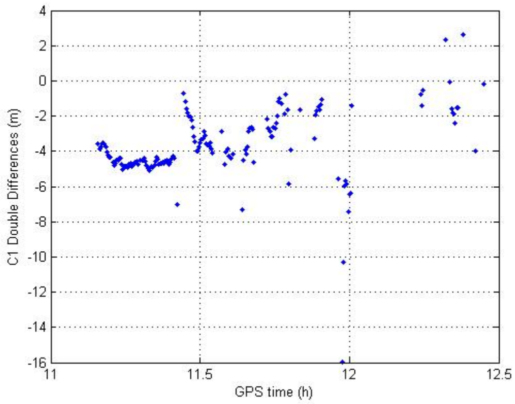

Figure 8 - residual DD for satellite 21 at point 4.

Since the presence of multipath was detected and confirmed as a function of points' position with respect to the reflector, we can analyze the technology's behaviour by comparing internal precision with accuracy.

4.3 Positioning results: comparing with reference coordinates

The results shown until now, especially through the comparative analysis between points 3 and 4, indicate the problems that the receiver had to solve when it gets closer to an obstacle like the one analyzed here. But to the user of satellite positioning technology, whose work must satisfy specifications established by law, it is fundamental to know the effects of these difficulties at the final estimated position. Taking into account the true coordinate values for each one of the test points, as well as their respective estimated values from the surveys done in each one of this points and taking into account the repetitions performed on each one of them, the standard deviation and the coordinate accuracy values for each test point were calculated according to equations (4), (5) and (6). Table 2 shows these values for each point and for each consecutive day in term of random and systematic deviation to each coordinate component and to the horizontal resultant.

Points	**Standard deviation Of East coord. σ_E (m)**	**Standard Deviation Of North coord. σ_N (m)**	**Standard Deviation Of Horiz. Position Σ_P (m)**	**Accuracy of East Coord. σ_{EV} (m)**	**Accuracy of North Coord. σ_{NV} (m)**	**Accuracy of Position σ_P (m)**
GS1_1D	0.1566	0.1590	**0.2232**	0.2152	0.1636	**0.2703**
GS1_2D	0.1784	0.1631	**0.2417**	0.3002	0.1812	**0.3507**
GS2_1D	0.1330	0.1948	**0.2359**	0.2593	0.2008	**0.3279**
GS2_2D	0.1315	0.2101	**0.2479**	0.2606	0.2113	**0.3355**
GS3_1D	0.1409	0.2045	**0.2483**	0.1441	0.3009	**0.3336**
GS3_2D	0.2154	0.2205	**0.3082**	0.2266	0.2274	**0.3210**
GS4_1D	1.0185	1.1170	**1.5116**	1.0777	2.1170	**1.9967**
GS4_2D	0.7629	0.8829	**1.1668**	0.8367	0.8880	**1.2201**
GS5_1D	1.5702	1.5802	**2.2277**	1.5772	1.7067	**2.3239**
GS5_2D	1.1895	1.2642	**1.7358**	1.2183	1.2666	**1.7574**

Table 2 – Precision and accuracy of results

The comparison between estimated (formal) horizontal position standard deviation (column 4) with the respective accuracy (column 7) for all points demonstrate larger values to the latter as well as when the receiver gets closer to the reflector, i.e., values increasing from point 1 to point 5. Another strong indicator of the magnitude of this systematic trend can be provided by the distance between mean position of each point and its true value. Using mean values between the estimated positions during the 2 (two) surveying days, the value of this distance with respect to points 1 to 5 are, respectively, 20 cm, 17 cm, 15 cm, 35 cm and 46 cm. The increase of deviations inversely proportional to the distance to the reflector is explained mainly through the increase in multipath. The receiver performance analysis against multipath passes through the analysis of factors such as the bandwidth of the received signal. This factor depend on, for example, the multipath attenuation capacity according to the additional distance that the reflected signal "travel" regarding the direct signal until it arrives at the receiver. It is has a relation with the receiver-satellite-reflector geometry, especially the receiver-reflector distance. If the clock sample value on the analyzed receiver is 40 MHz this receiver should have a good efficiency to attenuate the multipath from a reflector away more than 7.5 meters from the antenna [1], as is the case of points 1, 2, and 3. As seen in item 2.3.1.1, if the MM Correlator technology is implemented in the analyzed receiver, it is capable to keep the reflection effects with delays of 0.15 C/A code chip segment (44 meters) between acceptable limits, almost cancelling this value for larger delays. Apparently, this explains the good receiver performance in the points 1, 2, and 3, in which the small deviations could be caused by ground reflections, with intermediary distances between 7.5 and 44 meter values and, in a minor scale, by reflectors located more distant and not considered as part of the experiment scenario. The major deviations at points 4 and 5 proved the deficiency of technology used by this receiver for delays less than 7.5 meters. The receiver nominal accuracy (2 cm ± 2ppm) was not considered in this work because due to the short baseline length it does not exceed 2.1 cm. Besides the systematic behaviour we noticed that approaching limiting situations causes a strong random dispersion at the repetitions as it can be seen from the standard deviation in column 4, Table 1. It shows that in these cases and despite the standard deviation high magnitude, the simple arithmetic mean is a good option to represent the estimated coordinates. Figures 9 to 13 show the dispersion of the first survey day for each point in relation to the references values, taking into account the 0.5 meter threshold defined by Law 10267/2001 [17].

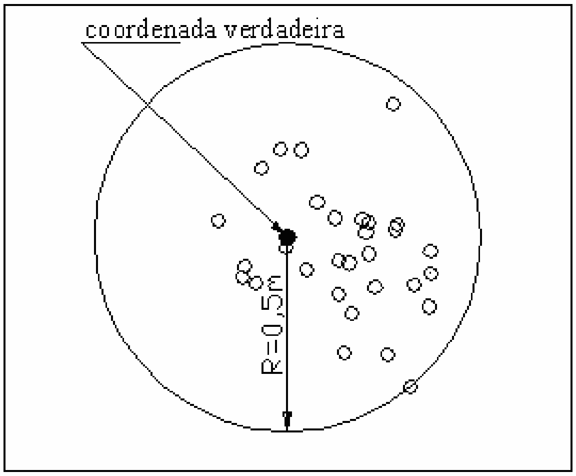

Figure 9 - Coordinates dispersion at point GS1_1D

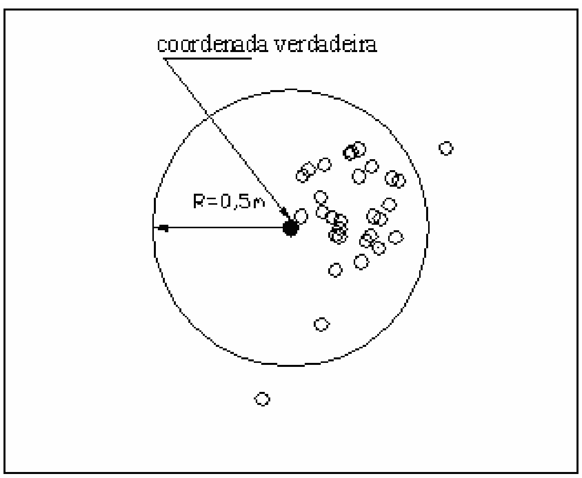

Figure 10 - Coordinates dispersion at point GS2_1D

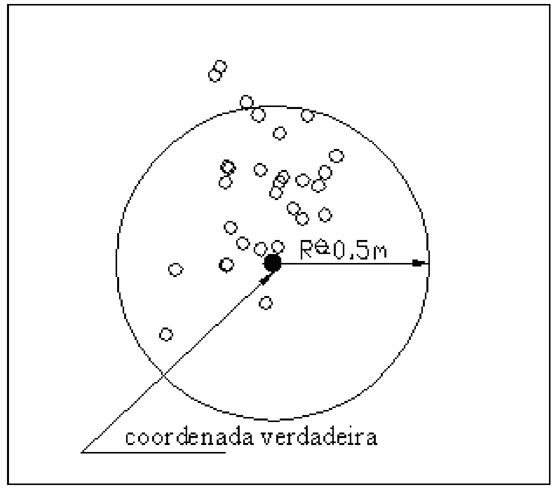

Figure 11 - Coordinates dispersion at point GS3_1D

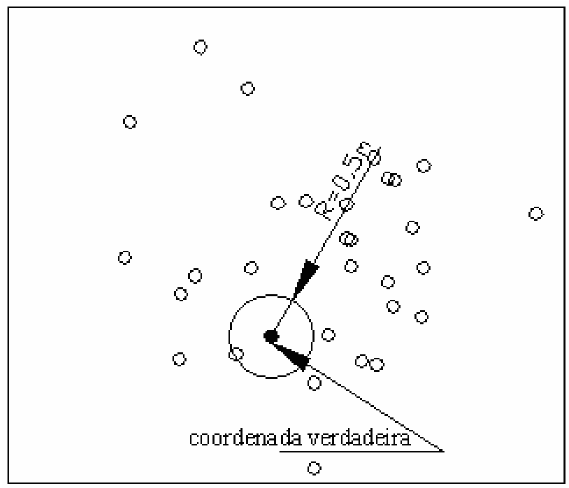

Figure 12 - Coordinates dispersion at point GS4_1D

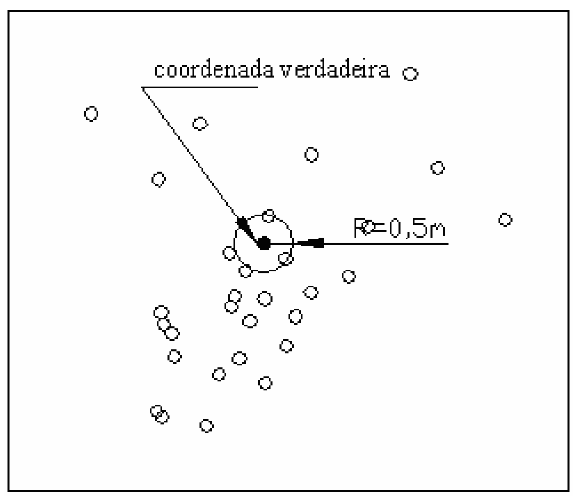

Figure 13 - Coordinates dispersion at point GS5_1D

The pattern portrayed in Figures 9 to 13 show the combination of random and systematic effects pointed out in columns 4 and 7 of Table 1. It makes evident trends at a specific region in relation to the true value. In points 1 and 2 (Figure 9 and 10, respectively), the farthest points from the reflector, we can see that the estimated coordinates have a trend to be to the East side of the true value, which can caused by reflectors localized at more than 100 meters away and at opposite side (West) of these points. At points 3 and 4 (Figures 11 and 12, respectively) we can see the trend is the estimated coordinates being North of the true value. It happens because the reflector approaches the opposite side (South) with less intensity at point 3 and with more intensity at point 4, as a function of the longer and shorter distances of these points from the reflector. It is interesting to note that in all cases the displacement happened on the opposite side of the reflector. For point 5 (Figure 13) the trend of the estimated values is at the South of the true value. This trend is probably connected to the geometry close to the antenna, since the point is located exactly under the forest foliage. The larger multipath and other noise effect can be identified clearly on the standard deviation where the dispersion is larger at points affected more intensely by multipath and the accuracy values are larger too (points GS4_1D, GS4_2D, GS5_1D and GS5_2D).

It is also interesting to notice the comparative analysis made with the results in [26] on signal tracking conditions under foliage. The 1.44 meters standard deviation was only acquired with the *MM Correlator* technology and without code smoothing. In a environment conditions similar to the one in this work we had 1.34 meters at point 4 and 1.98 meters at point 5 (of 2 survey days for both points), knowing that in this case code smoothing was applied. If the *MM Correlator* technology is also applied, the differences could be due to the forest density and to the geometry closer to the antenna.

4.4 Quality Parameters Comparative Analyze

The estimate coordinates provided by the receiver in each occupation seen to be average from the results from the 150 epochs (2.5 minutes occupation with an one second time interval between epochs). The post-processing program GisDataPro [21] outputs a quality indicator parameter to the planimetric coordinates named Position Quality. It apparently is the standard deviation of the estimated position resulting from the product between the a posteriori weight unit covariance matrix. The specific about this program can be found in [20], [21], and [23]. An important characteristic of the processing system is that the output parameter must be trustworthy. Table 3 shows the mean values of "Position Quality" parameter in comparison to the standard deviation values between 2 tracking days for each test points. At point 5, 7 out of the 30 repetitions returned only navigation solution. In this case, the mean was calculated using just the 23 positions that had received differential correction since that this situation (differentially corrected or not) is available for the user. Other situations are discussed in [26].

	P1	**P2**	**P3**	**P4**	**P5**
"Position Quality"	0.0091	0.0096	0.0107	0.0971	0.1489
Standard-Deviation	0.2324	0.2419	0.2782	1.3392	1.9817

Table 3 - Comparison between GisDataPro Position Quality and independently computed standard deviation

The values from the system are about 25 times better than the standard deviation of the position calculated in this work for points 1, 2, and 3 and 14 times better for the points 4 and 5, i.e., the system. These significant differences which make user unsure indicate quality much better than it really is.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Receiver performance and user procedures

Taking into account the way how the receiver was used, its technology shows that it is efficient and compatible with the legal registration goals according the Brazilian Cadastral Legislation, for pine forest and all other tree types that presents a low attenuation [24] located up to 20 meters from the antenna. For shorter distances the error magnitudes makes impossible the use for rural legal surveys. If the user is not sure about the local conditions site or where it is essential to approach to the reflector, some measurements can be made a measurement series and get the mean. Its comparison with the reference value demonstrated a good agreement and a systematic deviation inside of the legal limit. To satisfy the Brazilian legislation we must adopt the solution near east to the mean to represent the surveyed point, since the legislation demands that the solution be part of processing report. This may be the case of cadastral works in places where the cutting for trees is difficult for practical or technical reasons (proximity to roads or natural borders like rivers) or when it is not allowed by environmental and heritage legal questions. In limiting conditions despite of bigger errors the receiver still presented tracking capacity, i.e., the receiver kept a sufficient number of satellites and time for differential correction. This happens because the receiver use the phases only for code smoothing, without bothering with fixing the ambiguities (despite it may be used under other tracking mode, like using phase observables, for example). Moreover, the high difficulty level imposed by the pine forest lets the results to be generalized for a large number of other tree species. There is some doubt left about the reason why the results obtained under foliage using smoothed code and, perhaps, the MM Correlator, to have been worst than the ones by [26] got only with MM Correlator. A question remains on why our results are worse than those reported by [26] if we used code-smoothed observables plus the MM Correlator whereas they used on pseudoranges in addition to the MM Correlator.

5.2 Smoothed code

Regarding the C/A code measurements smoothing by the L1 carrier phase measurements we had confirmed the quality position deterioration under an increase number of cycle slips. It caused constant algorithm reinitializations to the maximum code weigh. The ideal tracking time without cycle slips for the best algorithm performance depends on the updating rate which, in the case of the analyzed receiver, seems to be 1.7 minutes. Ii would be very advantageous for practical reasons if the could show the occurrence of cycle slips, for example, the time accumulated without slips for each satellite or some index that could show that information in a general way to the users. This would permit longer sessions according to the necessity and simply not to prevent against possible mishaps, a practice that constitutes waste of time and resources if not needed.

5.3 Quality indicators of the system

A serious deficiency found by this research was about the parameter quality presented by the system, the Position Quality. This parameter apparently is not able to represent the true position quality. The only valid analysis from this parameter is the comparison between the surveyed points, where values too different can indicated eventual problems, demanding attention, or even indicative that the point had no differential solution. This is a critical point because it makes impracticable the use of this parameter as a position quality indicator. This problem can only be solved at the manufacturer level. It was not an objective of this work to find a factor which could be used to scale this parameter up closer to the reality. This should demand additional studies.

5.4 Additional recommendations

Another important deficiency found was the lack of nominal and objective recommendations from the manufacturer with respect to the tracking conditions to be observed to acquire the nominal position quality, especially in terms of tracking time, interval between epochs and distance from the reference station. The material that comes with the equipment just indicated that the quality information will be reached in "favourable conditions" which is a too ample and general term. According to the Brazilian laws this kind of information is an integral part of the receiver and it is responsibility of the manufacturer to make it clear and accessible, subject to legal sanctions. In the specific case of the Brazilian Law 10267/2001 [17], the lack of information about the maximum baseline length to acquire the accuracy demanded by the law determined that early work from this receiver model in legal cadastral survey in the Province of Rio Grande do Sul were not accepted. This problem was solved later when the manufacturer company sent a document to the governmental office communicating that distance value. Even so, the informed distance is conditioned to "GPS conditions such as the reference station data quality, satellite geometry, multipath, blockages, and atmospheric conditions", and did not indicate the minimum value for these factors. The present work tried to help the users in supplying this deficiency, but who has the ideal conditions for it is the manufacturer since he has the knowledge about the receiver's internal architecture specially signals processing.

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