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RESEARCH NOTE

Reference Satellite Strategic Methods to Improve Position Accuracy of Rover with Resolved Integer Ambiguities Using Linear Combination in DIRNSS System

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ABSTRACT

IRNSS is a regional system designed to procure, an accurate user position in all circumstances with 24/7 coverage. This system is used in a wide range of applications with accuracy better than 20 meters in the primary service area. The IRNSS provided position, velocity, and timing services are useful for the Indian users and also the users 1500km from the Indian frontier. The accurate positioning in the phase measurement technique depends on the resolution of ambiguities. In this paper, the main focus is on the effective resolution of ambiguities and thereby position estimation. This paper proposes a Carrier Phase (CP) differencing based Wide Lane (WL) measurement. To resolve the ambiguities, estimate the position of the WL classified methods, Single Frequency Single Difference (SFSD), Single Frequency Double Difference (SFDD), Dual Frequency Single Difference (DFSD), and Dual Frequency Double Difference (DFDD) are used. These four types are processed through the Reference Base and Reference Satellite (RBARS) algorithm to estimate the position of the user/rover. In this paper, direct amalgamate of three estimations are utilized: WL, Narrow Lane (NL), and Ionosphere Free (IF) carrier phase estimations. Using this combination, the estimations of ambiguities are determined for individual satellites by utilizing WL and NL techniques. Thereby the user/rover position is computed, by assessing these real number ambiguities. In this work, every single condition is utilized and together with the least-squares modifications, the positional errors are computed in 3D plane. The computed root mean square errors are compared for all classified methods.

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1. INTRODUCTION

The Indian Space Research Organization has started implementing India's indigenous regional (IRNSS) navigation system. The IRNSS system is designed to provide navigation services to the Indian geographical area. The basic idea behind this regional system is an alternative to the Global Positioning System, in any land, air, sea, and navigational type of applications. The main objective of the IRNSS system is, to provide an accurate position in all circumstances with 24/7 coverage.

The IRNSS provides two types of services to the users, such as Standard Positioining Services (SPS) and Restricted Services (RS) [1]. The regular civilian users are serviced with SPS. The authorized (military) users are serviced with RS. In its primary service area, it is designed to provide accuracy better than 20 meters.

In the last few years, researchers have concentrated on India's indigenous IRNSS system. The positioning topic is high interest of the research communities for a newly added GNSS system i.e. IRNSS. The main intent of the positioning topic is, to determine the user/rover position by measuring the distance between the satellite and receiver (range). This range is calculated either by the travel time (pseudo-range) of the signal or in terms of a number of cycles (phase measurement). In this paper, the Carrier Phase (CP) measurement is used to estimate the position.

The IRNSS is a Dual Frequency (DF) receiver (L5/S1 bands), however, in most of the investigations solely Single Frequency (SF) (either L5 or S1) is considered. In IRNSS system depending on the adopted

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application either the SF or DF is selected. The adopted SF resulted in an inaccurate position and unstable ambiguities. However, the expensive DF receivers have an advantage of a shorter time for ambiguity resolution.

In this work, the ambiguities are fixed using WL, Wide Lane linear mix (Wide-Narrow-Lane, or WNL), and observed the reliability. The RBARS algorithm is developed to estimate the user position in WL technique. The convergent time is going to be reduced if these ambiguities are quickly fixed. This paper presents an amalgamate approach, to compute a 3D user/rover position. With this linear combination, the 3D RMS errors are computed and compared for WL classified measurements.

In Section 2, a detailed description of WL is presented. In Section 3, a detailed concept of position estimation using the RBARS algorithm is explained. In section 4, the results are discussed and concluded the paper in Section 5.

2. DESCRIPTION OF WIDE LANE TECHNIQUE

Differential IRNSS (DIRNSS) is the most acquainted and well-liked methodology that works based on correction information of Carrier Phase (CP) measurement and forwarding this correction to end-users. Figure 1 shows the setup of DIRNSS system for user/rover position estimation. The DIRNSS system consists of two receivers which simultaneously track the same IRNSS satellites. In the DIRNSS system with more than two satellites and two receivers, the CP measurement can achieve accuracy in a few centimeters.

In this work, the CP measurement is used to estimate the position. The CP based positioning technique provides a more accurate positioning solution compare to the code-based positioning technique [2]. But the CP measurement included with integer ambiguity as an extra parameter. In CP measurements, the ambiguities have to resolve for the desired accuracy in user position. Once the ambiguities are correctly fixed, the time required to determine the user position is decreased. The IRNSS navigation message file contains the data, included with the satellite positions, receiver-satellite range, ionosphere delay, satellite clock bias, and receiver position. The information of these parameters is collected either from a data file or from the video record. The data sets are noted and the proposed algorithm is practically implemented in MATLAB software. The estimated reference receiver positions are validated with respect to the survey location. The positional errors and their RMS values are calculated using the DIRNSS system. The obtained RMS errors are compared for SF and DF combinations.

The frequencies of L5 and S bands are considered as (1176.45 MHz and 2492.028 MHz). The corresponding WL frequency is 1315.578 MHz and NL frequency is 3668.478 MHz [1].

Table 1 shows the various parameters of WL and NL techniques. The WL frequency is less compare to NL frequency therefore the WL wavelength is longer compare to NL wavelength. The better integer estimate is obtained with the longer wavelength (f_{WL}). Therefore, to resolve ambiguities the WL is best to compare to NL. It is harder to determine the Ambiguity Resolution (AR) in NL technique. In position estimation, the combination of WNL is used popularly known as WL linear mix [3]. This combination is very helpful for the determination of ambiguities. Therefore, with this combined technique more accurate results are obtained than individual measurements.

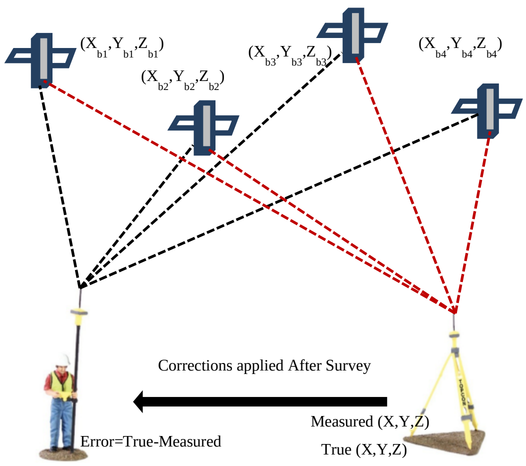

Figure 1. DIRNSS system setup

TABLE 1. Comparison of WL and NL calculations

Parameter	NL	WL
Frequency	$f_{NL} = f_{L5} + f_S$	$f_{WL} = f_{L5} - f_S$
Wavelength	$\lambda_{NL} = 81.8\text{cm}$	$\lambda_{WL} = 0.2280\text{m}$
Integer Ambiguity	$N_{NL} = N_{L5} + N_S$	$N_{WL} = N_{L5} - N_S$
CP	$\phi_{NL} = \phi_{L5} + \phi_S = \left[\frac{r_{L_5S}}{\lambda_{NL}} + N_{NL}\right]$	$\phi_{WL} = \phi_{L5} - \phi_S = \left[\frac{r_{L_5S}}{\lambda_{WL}} + N_{WL}\right]$
Integer (fixed)	$\hat{N}_{NL} = \left[\phi_{NL} - \frac{\rho_{L5S}}{\lambda_{NL}}\right]$	$\hat{N}_{WL} = \left[\phi_{WL} - \frac{\rho_{L_5S}}{\lambda_{WL}}\right]$

where λ_{L_5S} is the wavelength of L5 and S bands, r_{L_5S} is the pseudo range of L5 and S signals, I_{L_5s} and T_{L_5s} is WL ionosphere, troposphere delay, N_{L_5S} is the WL DD integer ambiguity, and $\varepsilon_{\phi_{L_5S}}$ is the effects due to multipath.

2. 1. Amalgamate of WL, NL and IF Mode In this section to dispense with the ionosphere delay on estimations, the IF model straight amalgamate is used. In this combined linear technique, WL and NL are useful in ambiguity determination. The estimations of ambiguities are determined for individual satellites by utilizing WL and NL techniques. These obtained real number ambiguities are assessed to compute the user/rover position. To acquire centimeter precision, the precise IGS IRNSS satellite orbital parameters, satellite clock offsets, etc. are required. With this combined augmentations, the equipment delays, comparative offsets of receiver, satellites, and other different errors are reduced. In this amalgamate, the IF model is utilized to decrease the effect of the ionosphere and a WL linear mix is utilized, for ambiguity resolution. This combined amalgamate is termed as RBARS algorithm. This algorithm is used for position estimation. The required accuracy is achieved with this linear combination. Three amalgamations of WL, NL, and IF model are utilized for position estimation [3]. With the accurate IGS IRNSS satellite orbital parmeters, the cm-level accurcy in the IRNSS system is achieved. To get the benefit of every one of these strategies, the three methods are combined and solved together with the least-squares modification [4]. Therefore, the ambiguities are resolved for the corresponding CP measurement, and the baseline solution is determined. When the ambiguities are settled, the carrier phase is expressed in the units of length for position estimation. The computed results of fixed ambiguities and the baseline errors are forwarded to the reference base position to get the precise user/rover position.

3. POSITION ESTIMATION USING RBARS ALGORITHM

In DIRNSS system, due to differential measurements, these errors are greatly reduced or eliminated. To reduce the impact of ionospheric dealy in this paper IF linear combination is used [4]. In IF method, the first-order effect of the ionosphere is eliminated. In addition to the IF combination, the proposed RBARS algorithm eliminates the effects of multipath, receiver/satellite offsets etc. Due to the differentiation of two receivers, the hardware delays are also reduced. The convergent time is greatly reduced, and thereby the position accuracy is improved. Therefore, this is the advantage of using of RBARS algorithm. The following are the steps to determine the positional errors in RBARS algorithm.

a. Initially, the two IRNSS receivers (manufactured by Accord software Pvt limited) are kept a few meters distance away from each other at known coordinates. Measure the baseline length and collect the data sets in RINEX/CSV format from IGS IRNSS-GUI.

b. Select the WL classified type: SFSD/SFDD /DFSD/DFDD.

c. Apply the integer fixing using WL/WNL calculations and compute the fixed ambiguity and averaging of cycles (Table I). [5].

d. The carrier phase measurement also contains the hardware delay, phase bias, and receiver, satellite offsets. The WL phase observables of Single Difference (SD) between two receivers and a single satellite is written as

$$(\Phi_{L_5S})_{iWIDE} = r_{L_5S} + \lambda_{L_5S} N_{L_5S} - \frac{f_S I_S}{f_{WL}} + \frac{f_{L_5} I_{L_5}}{f_{WL}} + T_{L_5S} + \varepsilon_{\phi L_5S} - c(\delta_{rx,clk} - \delta^i_{clk}) \tag{2}$$

where, I_{L_5} and I_S are the WL ionosphere delay in the IF model, i represents the satellite number, c is the speed of light in m/s, $\delta_{r,clk}$ is receiver offset and δ^i_{clk} is the satellite offset [6].

e. The straight mix of the WL, NL, and without ionosphere is used to fix the ambiguities (N_{WL}, N_{NL}). Here, for a couple of satellites, the position of user/rover is determined with these fixed ambiguities. The unknown state vector of size 13x1 is defined as

$$X = \left[x, y, z, N_{WL}, N_{Nl}\right]^T_{13X1} \tag{3}$$

where x, y, z are the unknown user/rover position in 3D plane.

f. The Line of sight vector of estimated rover position and satellites ephemeris for the design matrix is defined as:

$$U = \begin{bmatrix} (u_{xyz})_{ref,i\ (n-1)\mathrm{x}3} & 0 & 0 \\ (u_{xyz})_{ref,i\ (n-1)\mathrm{x}3} & I & 0 \\ (u_{xyz})_{ref,i\ (n-1)\mathrm{x}3} & 0 & I \end{bmatrix}_{15\mathrm{x}13} \tag{4}$$

$$(u_{xyz})_i = \frac{[(x_{est} - x^i),(y_{est} - y^i),(z_{est} - z^i)]^T}{\sqrt{(x_{est} - x^i)^2 + (y_{est} - y^i)^2 + (z_{est} - z^i)^2}} \tag{5}$$

where n is the number of satellites.

The size of vector u_{xyz} is (n-1) x3 and identity matrix of size (n-1) x (n-1).

g. The refreshed covariance lattice at each epoch is given as

$$\boldsymbol{P(t_+) = U^T P U + P(t_-)^{-1}} + \varepsilon_{noise} \tag{7}$$

where, P is a weight lattice for wide path mixes.

This designed weight lattice depends upon two factors like the correlation between satellite and receiver, and the standard deviation of WL/NL estimations. Therefore, the weight lattice is characterized as:

$$DRD = D\sigma_{WL}^2 ID^T \quad (8)$$

The D indicates the correlation between individual receivers and satellites. The size of D depends on the type of differencing technique (SD/DD). The $D = [-I]_{15x15}$, is a unitary matrix of size (15x15) and σ_{WL} is the standard deviation of WL estimations. The characterization of NL weight grid is similar to WL. Therefore, by considering all these characteristics the weight grid is written as:

$$P = (DRD)^{-1} \quad (9)$$

h. The adjustment in the incremental rover position is characterized as:

$$\nabla X = [(U^T PU) + (P(t_-)^{-1}]^{-1} U^T PL \quad (10)$$

where, $P(t_-)$ is the initial estimated covariance matrix and L is a miscellaneous vector obtained from WL, NL measurements.

i. Finally, the assessed rover position is equivalent to a steady position and prior positional vector. Therefore, the final rover position is estimated using the least square modified method as:

$$x = x_{est} + \nabla x, y = y_{est} + \nabla y, z = z_{est} + \nabla z \quad (11)$$

j. Similarly, for remaining cases DFSD/SFDD/SFSD estimated the position and compared the results.

Figure 2 represents the RBARS algorithmic steps. The first step in this algorithm includes the selection of frequency, selection of differentiation techniques, and correlation vector. The size of matrices depends on the type of differencing technique (SD/DD).

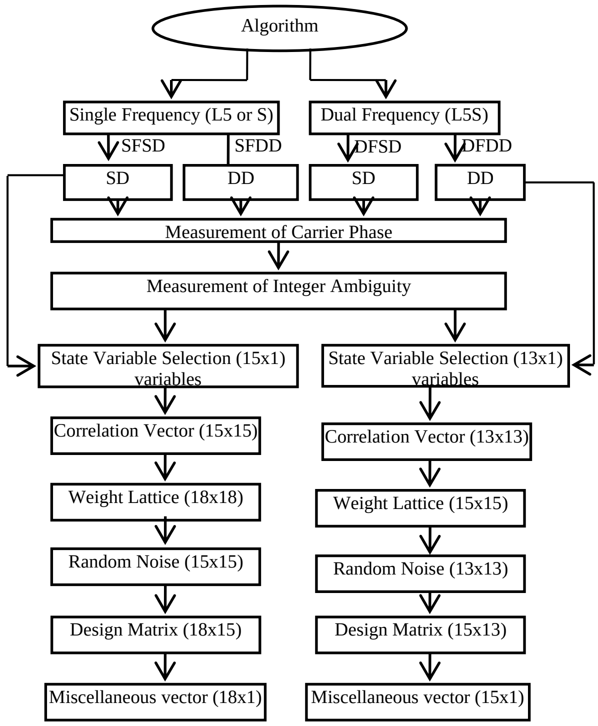

Figure 2. RBARS algorithmic steps

4. RESULTS AND DISCUSSIONS

The IF linear method eliminates the impact of the first-order ionosphere effect on the measurements. This linear combined IF method can stop the full ambiguity value determination. Therefore, to see the full ambiguity values and fixing these ambiguities as integers, the mixture of the WL and NL is used [7-8]. In this analysis, to fix the ambiguities the WNL is employed, and it doesn't have a direct impact on the positional error determinations [3].

In this section, the ambiguities are fixed by WL and WNL combination techniques. The uncorrelated estimations from many epochs would lessen the standard deviation of estimation [9]. These results are obtained using MATLAB software.

Table 2, represents the comparison of standard deviation with successive epochs for WL and WNL ambiguities (cycles). By averaging process, the deviation in ambiguities is decreased from SFSD to DFDD for both WL and WNL measurements. In WL the standard deviation is reduced from 4.7403 to 1.5749 cycles, whereas in WNL linear mix it is reduced from 1.3293 to 0.2354 cycles.

Figure 3 shows the baseline solution for SFSD (0.4 m), DFSD (0.7-0.8 m), SFDD (0.2-0.3 m), and DFDD (0.2 m). Figure 4 indicates the baseline solution in WL measurements with standard deviation. After fixing the WL ambiguities the distance error for four methods is calculated. With the fixed ambiguities, the baseline solution is better accurate compare to without averaging. It is in the range of 10-3 cm. The maximum error is obtained with SFSD and minimum error with DFDD measurement.

The main motto of WL is to generate the signal with a slightly longer wavelength; the WL can fix the ambiguities as integers in less than three minutes. In NL more than three minutes are required to fix the ambiguity because of shorter wavelength. Therefore, in a combinational mix, less than one minute is required to fix the ambiguities [10-11]. It is impossible for a single receiver to compute the initial full cycles for each

TABLE 2. Standard deviation of ambiguities in cycles

Parameter	SFSD	SFDD	DFSD	DFDD
WL (cycles)	4.7403	3.6934	3.578	1.5749
WNL (cycles)	1.3293	1.0024	0.6283	0.2354

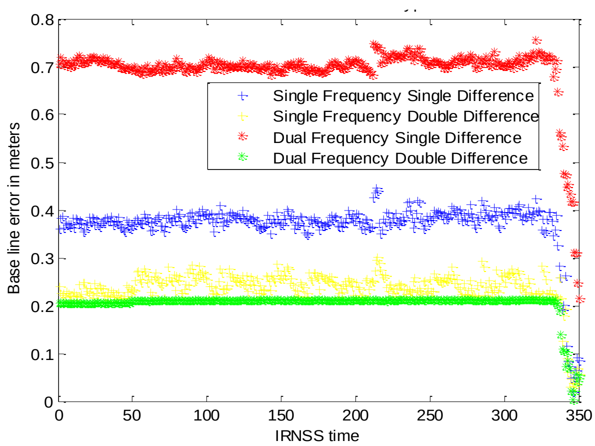

Figure 3. Baseline solutions for WL measurements without averaging

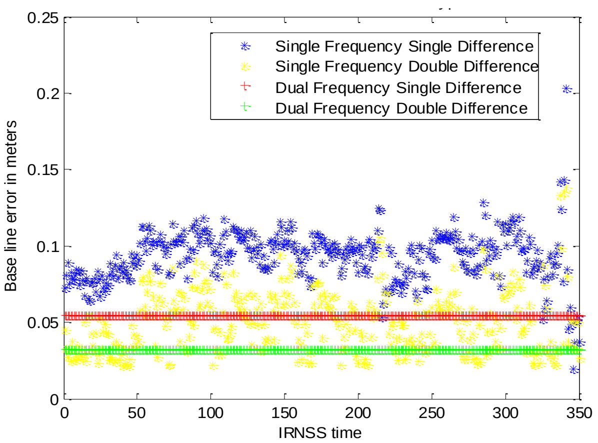

Figure 4. Baseline distance Δd with WL in meters with averaging

satellite. The RBARS algorithmic program is employed, to determine the integer value of the ambiguities by WNL combination. Using WNL linear combination the integer ambiguities are fixed. The fixed AR would have an immediate impact on position estimation. The fixing time is less in RBARS algorithm; therefore, more accurate results are obtained in position estimation. The best outcomes are obtained in the dual-carrier case.

Figure 5 indicates the estimated error in cycles. This error is calculated at every single epoch (nearly 350 epochs are taken). Here, continuous lines represent the estimated real values, and dots represent the corresponding rounding values (rounded-off integers).

From the Table 2 a succession of intervals the reduction in the standard deviation of carrier cycles ends up in higher position accuracy. At starting epochs, the utilization of RBARS algorithm ends up peak at maximum value and then stabilizes at minimum error. This stabilization is, because of the correlation between satellite, receiver, updated covariance, and state vector.

The rover position incremental values are assessed in 3D (X, Y, Z) using RBARS algorithm and forwarded this error to get the precise user/rover position [12-13]. The improvement in position occurred after fixing the ambiguities. In Table 3, the positional errors are calculated and compared for proposed WL classified methods. The RMS errors are listed in 3D (X, Y, Z) plane for a short baseline. The minimum RMS error is obtained in DFDD (50.32 cm).

From Figures 6-8, it is observed that about 30 seconds the error values are [1.5 1.2 -0.5] meters in 3D plane for DFDD, thereafter this error is diminished to

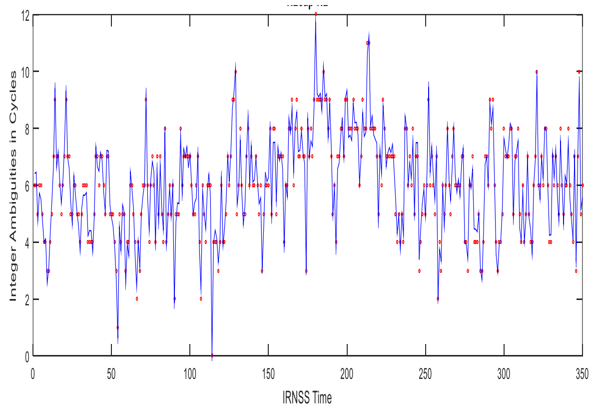

Figure 5. Resolved ambiguities and the estimated errors in cycles

TABLE 3. The RMS errors in 3D (X, Y, Z) directions of WNL four kinds

Type of WNL	RMS error (meters)			Average RMS error in 3D (meters)
	X	Y	Z	
SFSD	1.5825	1.0415	0.7575	1.1271
SFDD	0.6658	0.8278	0.3944	0.6293
DFSD	0.6700	0.8207	0.3715	0.6207
DFDD	0.7470	0.5287	0.2340	0.5032

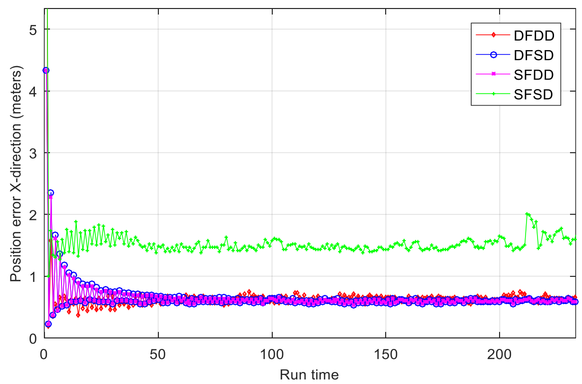

Figure 6. Positional error comparisons in four types using RBARS algorithm (X direction)

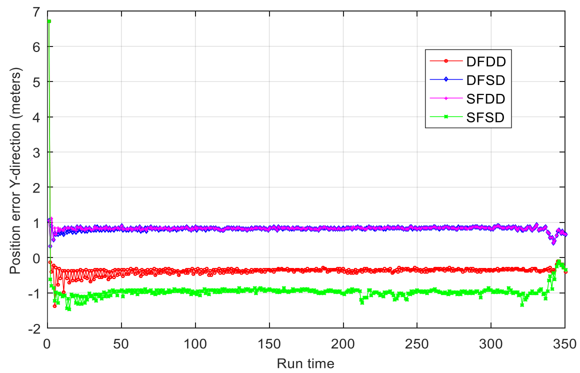

Figure 7. Positional error comparisons in four types using RBARS algorithm (Y direction)

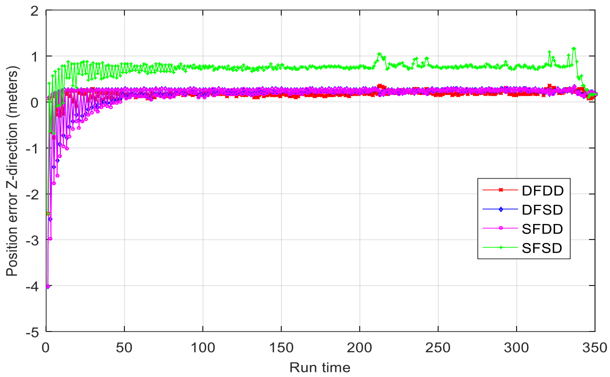

Figure 8. Positional error comparisons in four types using RBARS algorithm (Z direction)

[0.8 -0.5 0.2] meters and reaches to stable due to the correlation of measurements. Similarly, 3D positional errors are evaluated for SFSD, SFDD, DFSD, and DFDD with the least-squares modifications.

The linear combination of WNL and IF with CP measurements is implemented. These models help to resolve the ambiguities and to reduce the first-order ionosphere impact on measurements. Therefore, due to decreased convergent time the high reliable position is obtained for DF compare to SF.

5. CONCLUSION

In this paper, the WL and WNL techniques are used for AR. Using WL, WNL ambiguities are fixed, and their standard deviation is compared. The least standard deviation of 0.2354 cycles is obtained in DFDD using WNL linear mix. Therefore, a reduction in the standard deviation of carrier cycles ends up in higher position accuracy. With the averaging process, the least distance error ~3 cm is obtained for DFDD. To estimate the position combination of WL, NL, and IF CP estimations are utilized. Hence with direct amalgamate of the three methods, the incremental rover positional error in (x, y, z) 3D plane is resolved with modified least squares.

Thereby, the precise rover position in latitude, longitude, height is computed. Due to fewer error impacts in baseline solution and AR, the DFDD is reliable. This RBARS algorithm is implemented by the MATLAB software and this gives the user position at the highest accuracy. The average obtained RMS errors in the 3D position are compared for different types. Therefore, AR process, baseline solution, and position estimation (3D plane), the DFDD is reliable and best technique because of fewer error impacts.

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Persian Abstract

چکیده

یک سیستم منطقه ای طراحی شده برای تهیه ، موقعیت دقیق کاربر در هر شرایط با پوشش ۷/۲٤ است. این سیستم در طیف وسیعی از برنامه ها با دقت بهتر از ۲۰ متر در منطقه سرویس اولیه استفاده می شود. خدمات موقعیت ، سرعت و زمان بندی IRNSS برای کاربران هندی و همچنین ۱۵۰۰ کیلومتری مرز هند برای کاربران مفید است. موقعیت یابی دقیق در تکنیک اندازه گیری فاز به حل ابهامات بستگی دارد. در این مقاله ، تمرکز اصلی بر حل موثر ابهامات و در نتیجه تخمین موقعیت است. در این مقاله اندازه گیری (Wide Lane (WL مبتنی بر تفاوت فاز حامل (CP) پیشنهاد شده است. برای رفع ابهامات ، موقعیت روشهای طبقه بندی شده WL ، تخمین تک فرکانس (SFSD)، فرکانس دو فرکانس (SFDD) ، اختلاف فرکانس دوگانه (DFSD) و دو فرکانس دو فرکانس (DFDD) را تخمین بزنید. این چهار نوع از طریق الگوریتم Reference Base و (Reference Satellite (RBARS برای تخمین موقعیت کاربر / مریخ نورد پردازش می شوند. در این مقاله ، از آمیخته های مستقیم سه برآورد استفاده شده است WL :، باریک باریک (NL) و برآورد فاز حامل آزاد یونوسفر .(IF) با استفاده از این ترکیب ، تخمین ابهامات برای ماهواره های جداگانه با استفاده از تکنیک های WL و NL تعیین می شود. بدین ترتیب با ارزیابی این ابهامات تعداد واقعی ، موقعیت کاربر / مریخ نورد محاسبه می شود. در این کار ، از تک تک شرایط استفاده شده و همراه با حداقل تغییرات مربع ، خطاهای موقعیتی در صفحه سه بعدی محاسبه می شوند. میانگین خطاهای مربع ریشه محاسبه شده برای تمام روشهای طبقه بندی شده مقایسه می شود.